(Draft)
ALCATOR C-MOD
FY07-09 WORK PROPOSAL

March 2007

Submitted to:
Office of Fusion Energy Sciences
Office of Science
U.S. Department of Energy
Germantown, MD 20874

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1. Introduction

Alcator C-Mod is *the* high-field, high-density divertor tokamak in the world fusion program. The overall theme of the Alcator program is

Compact high-performance divertor tokamak research to establish the plasma physics and plasma engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors.

Organization of the program is through a combination of topical science areas supporting integrated thrusts. The topics relate to the generic plasma science, while the thrusts focus this science on integrated scenarios, particularly in support of ITER design and operation. There are currently four topical science areas: transport; plasma boundary; wave-plasma interactions; and macrostability. As discussed in more detail below, these areas correspond directly to four of the six science Campaigns identified by FESAC in 2005: Multi-scale Transport Physics, Plasma-Boundary Interfaces, Waves and Energetic Particles, and Macroscopic Plasma Physics respectively. Integrated scenarios encompass the ITER baseline inductive H-Modes, and Advanced Tokamak (AT) operation including partially inductive hybrid modes and fully non-inductive weak and reverse shear operation with active profile control. AT operation takes advantage of the unique long-pulse capability of the facility (relative to skin and L/R times), at $B \leq 5$ Tesla, combined with new current drive and density control tools, to investigate the approach to steady-state in fully non-inductive regimes at the no-wall beta limit; this is particularly relevant to the prospects for quasi-steady operation on ITER. The connections among the topical science areas and the integrated scenarios are illustrated in Figure 1.1

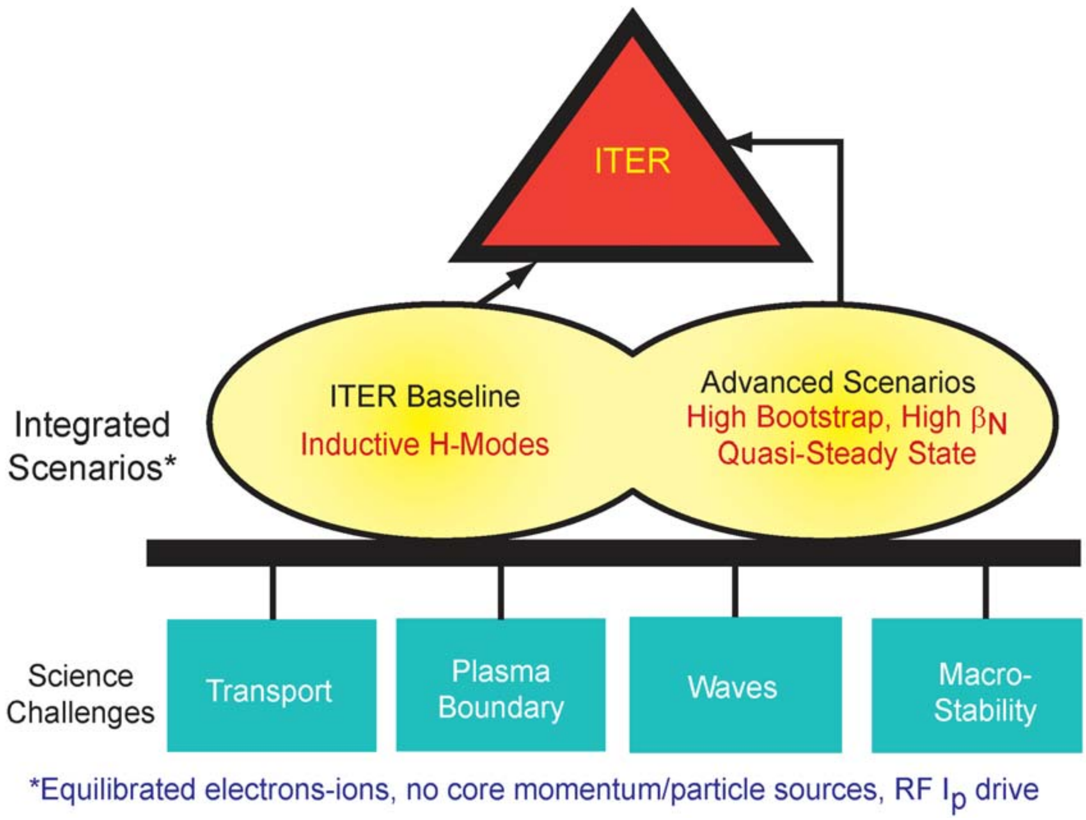

Figure 1.1 Integrated scenarios and topical science areas.

Unique aspects of the Alcator C-Mod facility provide the logical foundations for the scientific areas of emphasis in our research endeavors to answer key outstanding questions in the development of practical fusion energy:

- **Long pulse capability** — C-Mod has the unique ability among highly-shaped, diverted tokamaks, to run high pressure plasmas with pulse length equal to the L/R relaxation time, at $B_T > 4$ Tesla. This provides an outstanding opportunity to investigate the extent to which enhanced confinement and stability of Advanced Tokamak configurations can be maintained in steady-state, using active profile control.

- **High magnetic field** — With capability to operate at very high absolute plasma densities (to 10^{21} m^{-3}) and pressures (approaching 10 atmospheres), and with magnetic field spanning the ITER field (5.3 Tesla) and beyond (to 8 Tesla), C-Mod offers a unique test-bed for exploring the physics and engineering which is prototypical of ITER.

- **Exclusively RF driven** — C-Mod does not use beams for heating, fueling or momentum drive. As a result, the heating is decoupled from particle sources and there are no external momentum sources to drive plasma rotation. It is likely that the same constraints will exist in a fusion power plant; the studies of transport, macro-stability and AT physics in C-Mod are thus highly relevant to reactor regimes.

- **Unique dimensional parameters** — C-Mod is dimensionlessly comparable to larger tokamaks, but dimensionally unique, which allows us to provide key points on scaling curves for confinement, H-Mode threshold, pressure limits, etc. At the same time, joint experiments with other facilities allow for important tests of the influence of non-similar processes, including radiation and neutral dynamics. Many of these experiments are coordinated through the International Tokamak Physics Activity (ITPA).

- **Very high power density scrape-off layer plasma** — With parallel power flows approaching 1 GW/m^2 (as expected in ITER), C-Mod accesses unique divertor regimes which are prototypical of burning plasma conditions. The issues of edge transport and power handling which are explored go beyond those specific to the tokamak, being relevant to essentially all magnetic confinement configurations.

- **High Z metal plasma facing components** — The molybdenum plasma facing components on C-Mod are unique among the world's major facilities. The use of high Z PFC's is also reactor prototypical, and leads to unique recycling properties, and wall conditioning, density and impurity control challenges. Because of the tritium retention issues, ITER must consider high Z plasma facing components as one option, and studies of hydrogenic retention in C-Mod, both with molybdenum and tungsten, will contribute significantly to this decision.

Education is an integral part of the Alcator project mission, and the project has a large contingent of graduate students working toward their PhD degrees. They are drawn from four departments at MIT, as well as from collaborating Universities. Currently 29 graduate students are doing their research on Alcator C-Mod.

High Priority ITER R&D

C-Mod is positioned to investigate many of the key outstanding issues that need resolution to support successful operation of ITER. Research has begun on most of these, and all will be studied in the FY06-FY08 period:

MHD:

- **Continue development of the new disruption DB including conventional and advanced scenarios** to initially study fast Ip quenches and halo currents
- **Develop disruption mitigation techniques particularly at high** performance and by noble gas injection and understand influence of MHD on impurity

penetration. **Validate 2 and 3-D codes, in particular MHD and radiation models, on gas injection.** Develop reliable disruption prediction methods.

- **Understand intermediate-n AEs** ; redistribution of fast particles from AEs; and perform theory-data comparisons on damping and stability

Steady State Operation:

- Continue the **focussed modeling activity on ITER Hybrid and Steady state cases**, using standard (and common) sets of input data.
- Pedestal studies: **Experiments to document pedestal in advanced scenarios**, modeling of pedestal, pedestal conditions in ITER (maximum T_{ped})
- **Code benchmarking of LHCD** and NBCD **and implications for ITER**.

Transport Physics:

- Utilize upgraded machine capabilities to **obtain and test understanding of improved core transport regimes with reactor relevant conditions, specifically electron heating, Te~Ti and low momentum input,** and provide extrapolation methodology
- Develop and demonstrate **turbulence stabilization mechanisms compatible with reactor conditions**
- **Study and characterize rotation sources, transport mechanisms and effects on confinement and barrier formation**
- **Quantitative tests of fundamental features of turbulent transport theory** via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings.

Confinement database and modeling:

- Resolve the differences in β scaling in H-mode confinement
- **Resolve which is the most significant confinement parameter, ν* or n/n_G**
- Define a program to **understand the density peaking**
- Develop a **reference set of ITER scenarios for standard H-mode, steady-state, and hybrid operation** and submit cases from various transport code simulations to the Profile DB

Pedestal and Edge:

- **Improve predictive capability of pedestal structure** through profile modeling and experimental studies
    - o **Dimensionless cross machine comparisons** to isolate physical processes; assess dependence on ρ* , ripple, rotation, and shape
    - o Measurement and modeling of inter-ELM transport
    - o **Establish profile database for modeling joint experiments including effects of neutrals**
- Physics based empirical scaling
    - o Collaboration with CDBM to improve scalar database characteristics and utilization

- **Improve Predictive Capability of ELM characteristics** through experimental studies and theory / modeling analysis, and **develop small ELM and quiescent H-mode regimes** and ELM control techniques
    - Integrate **observations of ELM crash dynamics** and initiate comparisons with developing models
    - **Categorize small ELM regimes based on cross machine comparisons**

Divertor and SOL:

- **Understanding of Tritium retention, and development of efficient T removal methods**
- Understand the effect of ELMs/disruptions on divertor and first wall structures.
- **Improve measurements & understanding of plasma transport to targets and walls**, for better prediction of heat load, and effects on the core plasma
    - Exploring the role of **non-diffusive radial transport** (i.e. blob/ turbulence) on wall heat/particle loadings, macroscopic transport(χ and D), and **driving SOL flows** (parallel transport).
    - **Neutral density benchmarking of physic models in current experiments and ITER**
- Understand how **conditioning and operational techniques** can be scaled to reactor devises
    - **Implications of a metal wall for startup, fuel retention, density control and core impurity levels**

Diagnostic Development:

- **Dust dynamics** (including new dust injection diagnostic)
- **Erosion/redeposition** (Surface Science Station)

Much of this research is coordinated through the International Tokamak Physics Activity (ITPA), especially for topics which require joint experiments on multiple facilities. Approved ITPA experiments, in which C-Mod participates, include:

- CDB-4 Confinement scaling in ELMy H-modes: β degradation
- CDB-8 ρ^* scaling along an ITER relevant path at both high and low β
- CDB-9 Density profiles at low collisionality
- TP-6.1 Scaling of spontaneous rotation with no external momentum input
- PEP-7 Pedestal width analysis by dimensionless edge identity experiments
- PEP-10 The radial efflux at the mid-plane and the structure of ELMs
- PEP-16 C-Mod/NSTX/MAST small ELM regime comparison
- DSOL-1 Scaling of type I ELM energy loss
- DSOL-3 Scaling of radial transport
- DSOL-4 Comparison of disruption energy balance in similar discharges and disruption heat flux profile characterization
- DSOL-5 Role of Lyman absorption in the divertor

- DSOL-11 Disruption mitigation experiments
- DSOL-13 Deuterium codeposition with carbon in gaps of PFCs (boron in C-Mod)
- DSOL-15 Inter-machine comparison of blob characteristics
- DSOL-19 Impurity generation mechanism and transport during ELMs for comparable ELMs across devices
- MDC-1 see DSOL-11
- MDC-3 Joint experiments on NTMs (including error field effects)
- MDC-5 Comparison of sawtooth control methods for NTM suppression
- MDC-10 Measurement of damping rate of intermediate toroidal mode number Alfven Eigenmodes
- MDC-12 Non-resonant magnetic braking
- SSO-1.1 Document performance boundaries for steady state target q-profile
- SSO-2.1 Qualifying hybrid scenario at ITER-relevant parameters
- SSO-3 Modulation of actuators to qualify real-time profile control methods for hybrid and steady state scenarios

US Fusion Program Priorities

In April 2005, FESAC identified six research campaigns covering 15 topical scientific questions. C-Mod plays an integral role in addressing all of the magnetic fusion relevant topical questions:

- T1. How does magnetic field structure impact fusion plasma confinement?
- T2. What limits the maximum pressure that can be achieved in laboratory plasmas?
- T3. How can external control and plasma self-organization be used to improve fusion performance?
- T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?
- T5. How are electromagnetic fields and mass flows generated in plasmas?
- T6. How do magnetic fields in plasmas reconnect and dissipate their energy?
- T7. How can high energy density plasmas be assembled and ignited in the laboratory?
- T8. How do hydrodynamic instabilities affect implosions to high energy density?
- T9. How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?
- T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?
- T11. How do electromagnetic waves interact with plasma?
- T12. How do high-energy particles interact with plasma?
- T13. How does the challenging fusion environment affect plasma chamber systems?
- T14. What are the operating limits for materials in the harsh fusion environment?
- T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

The C-Mod program makes key, unique contributions to most of the recommended areas of US “opportunities for enhanced progress”:

- Carry out additional science and technology activities supporting ITER including diagnostic development, integrated predictive modeling and enabling technologies.
- Predict the formation, structure, and transient evolution of edge transport barriers.
- Mount a focused enhanced effort to understand electron transport.
- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas.
- Study relativistic electron transport and laser-plasma interaction for fast ignition high energy density physics.
- Extend understanding and capability to control and manipulate plasmas with external waves.
- Increase energy ion pulse compression in plasma for high energy density physics experiments.
- Simulate through experiment and modeling the synergistic behavior of alpha-particle dominated burning plasmas.
- Conduct enhanced modeling and laboratory experiments for ITER test blankets.
- Pursue optimization of magnetic confinement configurations.
- Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments.
- Extend the understanding of reconnection processes and their influence on plasma
- instabilities.
- Carry out experiments and simulation of multi-kilo-electron-volt megabar plasmas.
- Expand the effort to understand the transport of particles and momentum.

Detailed discussions of how C-Mod's specific topical science plans address the programmatic objectives are given in the respective sections of this Work Proposal.

Budget and Schedule

The baseline (A) budget for the C-Mod project in FY2008 is based on guidance from the Office of Fusion Energy Sciences, with total national project funding of $23.5M, including $20.9M at MIT, and major collaborations totaling $2.6M. These budgets will accommodate 15 weeks of research operations in FY2008. In the event of a 10% cut from the FY2008A guidance, research run time would be reduced to 10 weeks. For FY2009, we have taken a flat budget (relative to the FY2008A guidance) with an assumed 2.7% increase for cost of living. This results in a plan for 15 research weeks in FY2009. A 10% cut relative to FY2008A leads to a plan for 9 research weeks in the FY2009D case. Major items that the guidance budgets permit us to fund are shown in table 1.1.

Table 1.1: Major items funded in guidance budgets (FY07-FY09)

Item	Cost (k$)	Notes
Lower Hybrid CD: 2nd launcher	850	Reduce power density (increase coupled power); increased net forward power; compound spectrum
Lower Hybrid CD: add 4th MW	1200	Required for hybrid modes, fully non-inductive AT modes
Polarimeter/Interferometer	980	j(r) at high density; ITER geometry
4-strap ICRF Antenna	560	Preserve full ICRF power capability with addition of 2nd LH launcher
Advanced tungsten outer divertor	600	Required for full power, long pulse operation; ITER prototypical. Begin procurement in FY09 (250k), complete FY10
Alternator inspection	550	Required after completion of FY08 operations
Spare Klystron	500	Prudent to have at least one spare to maintain full source power capability; currently in FY09

Within the guidance budgets, run time is very constrained, and many important initiatives cannot be funded. We therefore also propose higher, national B budgets, totaling $29.9M in FY08 and $30.7M in FY09, which permit the following additions (in approximate priority order).

Table 1.2(a): Major items requiring budget increments (FY2008B)

Item	Cost (k$)	Notes
3 weeks additional run time	750	Total of 18 weeks research operation
Real-time matching (ICRF)	275	Increased productivity (complete in FY2009)
Spare 4.6 GHz Klystron	500	Strongly prefer to order in FY08
Outer Divertor Upgrade	300	Implementation in FY09
4 weeks additional run time	900	To 22 weeks total
4.6 GHz Klystrons	1000	Prudent for increased operations
MSE second view	400	Direct E_r measurement
3 weeks additional run time	750	25 weeks total; full facility utilization

Table 1.2(b): Major items requiring budget increments (FY2009B)

Item	Cost (k$)	Notes
3 weeks additional run time	750	Total of 18 weeks research operation
Polarimeter upgrade	100	Increased spatial resolution
5’th MW Lower Hybrid	3100	Implementation for FY10
7 weeks additional run time	1650	25 weeks total; full facility utilization

Table 1.3 summarizes the items which would be cut in the event of a 10% budget decrement (case D) for FY2009.

Table 1.3: Major items cut under a 10% decrement in FY2009D (relative to FY2008A)

Item	**Cost (k$)**	**Notes**
6 week decrease of research run time	1300	9 weeks research operation
Personnel cuts	1250	2 Engineers, 2 Techs, 3 Scientists, 1 Student
LH 2nd launcher completion deferred	375	1 year delay in implementation

Proposed facility research run time is given in table 1.4. In addition to the guidance cases, we show the incremental (program planning) (B) and the 2009D decremental case.

Table 1.4: Research operation for guidance (07-09A), incremental (08B-09B) and decremental (09D) budget cases

Fiscal Year	**07**	**08A**	**09A**	**08B**	**09B**	**09D**
National Budget ($M)	22.3	23.5	24.2	29.9	30.8	21.2
Research Operation Weeks	15	15	15	25	25	9
Research Operation Hours	480	480	480	800	800	288

Alcator C-Mod is operated as a National Facility, and includes contributions from major collaborations at PPPL and the University of Texas (Austin), as well as from a large number of smaller national and international collaborations. The present Work Proposal covers in detail the MIT responsibilities in the program, and assumes an integrated effort involving all of the collaborators. Sections 4.1 and 4.2 explicitly cover the contributions from Princeton and Texas, respectively.

Research Goals in Plain English

In order to communicate the excitement of plasma fusion science to a wider audience, each year we develop research goals, expressed in non-technical language, which reflect some highlights of our program plans.

Current Profile Control with Microwaves [September 07]
These experiments are aimed at developing efficient steady-state tokamak operation by launching microwaves into Alcator C-Mod plasmas. The location of current driven by the "Lower Hybrid" waves we will use depends on their wavelength as measured parallel to the magnetic field. We will vary this wavelength and measure the location and amplitude of the driven current, with the intention of demonstrating an improvement of the plasma confinement through current-profile control. By adding independent plasma heating, the plasma pressure will be raised, and by varying the location of the RF-driven current, we can begin to investigate the stability limit of the plasma, i.e. the maximum pressure the plasma can sustain without developing global instabilities.
Status: Initial experiments in FY2006 were very successful. We expect that continued LHCD investigations will be a strong focus of the FY2007 campaign.

Active Density Control [September 07]
A new divertor cryopump will be installed in C-Mod and pumping properties will be tested during FY06. Beginning in FY07 the configuration will be evaluated for density control, particularly for target plasmas suitable for Advanced Tokamak regimes with efficient lower hybrid current drive combined with high bootstrap fraction.
Status: Installation of the cryopump was completed prior to the start of the FY07 campaign, and we expect to complete this goal during the upcoming operations.

Confinement at High Plasma Current [September 08]
The operational space of C-Mod in the plasma current range at and above 1.5 MA has not yet been extensively explored. The potential for improvements in plasma confinement and pressure can be exploited in this regime at magnetic fields of 5.4 Tesla and above. With the successful implementation of the non-axisymmetric field error correction coils in FY04, this regime, which was previously precluded because of locked mode induced disruptions, has become accessible in C-Mod for study, and will be exploited in the coming campaigns. Elucidation of the implications of these results for extrapolation to burning plasma regimes, including ITER, will be a major goal of these studies.

Active control of ICRF antenna [Sept 2008]
To maximize coupled power through an ICRF antenna, the transformation or match of the antenna load to the transmitter needs to be maintained with low reflected power. The antenna load varies with plasma conditions that can evolve during the course of a discharge, especially for the long-pulse quasi-steady-state scenarios, and from discharge to discharge. One means to maintain the match is to use active tuning elements based on

ferrite tuners. A system and its characteristics will be tested and evaluated for performance over a range of C-Mod operating conditions.

Self-generated plasma rotation [Sept 2009]
Rotation has been found to improve plasma performance by regulating instabilities on a wide range of spatial scales. However, fusion reactors, like C-Mod but unlike most other current experiments, will not have heating systems that provide significant external torque. C-Mod will carry out experiments aimed at improving predictions of self-generated plasma rotation in ITER.

Hybrid Advanced Scenario investigation [Sept 2009]
With the implementation of Lower Hybrid RF for current profile control, and active cryopumping for density control, C-Mod will investigate advanced scenarios for improved performance of the tokamak. Investigations into the so-called "hybrid" mode of operation, being considered as one possible advanced approach for ITER, will be carried out to evaluate the potential to maintain central safety factor near or slightly above 1 and to assess the effects on plasma transport and confinement.

Goals Accomplished in FY2006

Achieve research operating time of 14 weeks (±10%) [September 06] (JOULE milestone).
Alcator C-Mod operates on an 8 hours/day, 4 days per week schedule. One research week corresponds to 32 hours of facility operation.
The FY06 campaign concluded on July 28, 2006, with 16.7 research weeks accomplished. Quarter by quarter run statistics can be found at
http://www.psfc.mit.edu/research/alcator/facility/Operations/FY06_research_table.html
and links to details about each run day can be found at
http://www.psfc.mit.edu/research/alcator/program/cmod_runs.php.

Sustaining Plasma Current without a Transformer [March 07]
In standard tokamak operation, the plasma current is induced by a transformer coil, which limits the available pulse length. To operate steady-state, a tokamak needs other means, such as RF current drive and self-generated current. The long-term C-Mod objective calls for fully non-inductive sustainment, with 70% of the current self-generated. In the nearer term, as a first step, we intend to demonstrate discharges on Alcator C-Mod with at least 50% of the current driven non-inductively, using the newly installed antenna, which comprises Phase I of the 4.6 GHz microwave system. This should help to verify the theoretically predicted current-drive efficiency and our ability to control the various plasma parameters needed to optimize it.
The target was completed on July 28, 2006. Using current driven by Lower Hybrid Radio-Frequency (LHRF) waves in Alcator C-Mod, close to 100% of the current in a 1 million Ampere discharge has been driven using 800 to 900 kilowatts (kW) of RF power, with surface inductive loop voltage being reversed or zero for pulse lengths approaching

one current profile rearrangement time. Detailed modeling indicates that .8 MA of non-inductive current was achieved. These results are in line with theoretical and numerical predictions, and imply that with increased RF power and pulse length, at higher densities and temperatures, plasmas in Alcator C-Mod could be entirely sustained without the aid of a transformer under conditions close to those required for near steady-state operation in ITER.

Disruption Mitigation of high pressure plasma [September 06]
Tokamaks are subject to major disruptions, which are sudden, undesirable terminations of the plasma discharge. Disruptions result in severe thermal loading of internal surfaces, large electromagnetic forces on conducting structures, and uncontrolled high-energy beams of electrons. These damaging effects will be particularly severe in burning-plasma-grade devices such as ITER. A number of methods have been proposed and/or tested to mitigate the consequences of disruptions, including injection of high-pressure gas jets. This technique has been shown to work in relatively low pressure, low energy density plasmas, but it is not at all clear that this method will work in high pressure, high energy density burning-plasma-grade discharges. Alcator C-Mod plasmas have absolute pressures and energy densities that are characteristic of those expected in ITER, and therefore will provide an excellent test bed for the gas jet disruption mitigation experiments planned in FY05-06.
The target was completed on August 31, 2006. Initial experiments with pre-programmed gas jet injection into stable C-Mod plasmas have proven to be very successful at mitigating the effects of disruptions, even though the gas jet does not penetrate much beyond the plasma edge. Detailed measurements, combined with 3-D MHD modeling, show that deep penetration of the neutral gas is not required for successful mitigation. Edge cooling provokes strong MHD instabilities, which in turn drain energy from the core plasma. This energy is then radiated from the plasma mantle, where the impurity concentration is high.
More recent experiments have concentrated on real-time detection and mitigation of actual disrupting plasmas. In this case, the response time of the gas jet system (several milliseconds) becomes an issue, since it is similar to the disruption timescale. The first experiments with real-time mitigation have used VDEs, since they are relatively simple for the digital plasma control system (DPCS) to detect. The DPCS has been coupled to the high-pressure gas jet valve, and fires the gas jet when the vertical position deviates by more than a prescribed amount from nominal. The first of these experiments, which were done with argon, successfully mitigated halo currents and thermal loads, but not quite as well as the earlier pre-programmed cases with stable plasmas. This could possibly be due to the finite response time of the gas jet system, which is dominated by the flow speed (~ sound speed) of the argon gas. Additional experiments using mixtures of helium and argon successfully demonstrated excellent mitigation (which requires the higher-Z argon gas) but on time scales consistent with the propagation of the lighter helium gas through the supply system. It is likely that some variation of this technique can be used to ameliorate the effects of major disruptions on ITER.

Additional goals which were achieved in FY2006 include:

Hydrogen isotope control technique demonstrated in the all-metal wall Alcator C-Mod tokamak. Controlling hydrogen-like fuels in wall materials will be critical for fusion's safety and economics because fusion reactors like ITER will burn tritium fuel, a special heavy form of hydrogen that is radioactive and must be bred in the fusion reactor itself. Experiments on Alcator C-Mod have shown that its purely metallic walls, a unique feature among present advanced fusion experiments, can soak up large amounts of hydrogen fuel, in disagreement with expectations from ion beam experiments. However, closely related C-Mod experiments have shown that controlled heating of the metal walls, using the energy provided by sudden terminations of the C-Mod plasma itself, can be used to liberate the hydrogen fuel from the wall at a rate which exceeds the retention. This technique is predicted to be applicable for tritium recovery in ITER.

Regulation of transport through high confinement boundary plasmas studied on Alcator C-Mod. Core plasma performance in tokamaks is routinely improved by establishing a thermal and particle transport barrier at the plasma edge. However, if this barrier becomes too good, it must somehow “relax", allowing particles and heat to escape. This relaxation can occur either in bursts that are potentially very detrimental to a reactor like ITER, or continuously (as is typical in C-Mod), which is relatively benign. On C-Mod, we are investigating a recently discovered operational space where either relaxation mechanism can be accessed in a controlled manner, thus allowing study of this critical aspect of high-performance tokamak operation.

Plasmas spin spontaneously in high pressure C-Mod plasmas. In future reactors such as ITER, there may not be available the external drives for the plasma rotation necessary for accessing enhanced confinement regimes and for suppressing instabilities. The spontaneous rotation (intrinsic, not externally driven) investigated extensively on Alcator C-Mod may provide the required velocity. The parameter scaling studies performed on C-Mod plasmas, which indicate a spontaneous rotation velocity that increases with normalized plasma pressure, bodes well for ITER, and ongoing coordinated comparisons with experiments on other tokamaks are aimed at refining the extrapolation.

RF sheath rectification identified as key process in plasma interactions with high-Z metal walls in Alcator C-Mod. Recent operation of the Alcator C-Mod tokamak, with tiles that absorb the plasma heat loads made of molybdenum, has enabled the identification of the plasma surface interaction process whereby tile surfaces are eroded. Comparisons of the surface erosion rate utilizing plasma heating by both Ohmic and radio-frequency (RF) techniques have shown that the erosion process with RF waves is much faster than with Ohmic, most likely due to the RF enhancement of voltages at tile surfaces which accelerates ions into the surface with much higher energy. The molybdenum tiles and RF heating used in C-Mod are typical of what is expected for ITER and for a fusion reactor. Techniques to ameliorate these effects are under investigation.

2. Alcator C-Mod Research

2.1 Boundary Physics

The C-Mod boundary physics program continues to make important contributions in a number of areas. This is in part due to the uniqueness of the plasmas studied (high density which leads to differences in collisionality), high-Z Plasma Facing Component (PFC) surfaces, and parallel power densities. The C-Mod boundary and divertor plasmas can uniquely approach those of ITER in a number of areas: parallel SOL power density; opacity of the SOL and divertor to neutrals; recombination and Lyman series absorption in the divertor. Overlaying these unique characteristics are research capabilities and emphases that lead to a steady march forward of understanding in a number of areas – transport (section 2.1.1), neutral physics including D retention (2.1.2), the effect of low-Z coatings on operation (2.1.2), divertor physics (2.1.3), D retention (2.1.4), and dust (2.1.5). In addition the boundary physics research staff continues to play a central role in machine improvements for high heat flux & particle handling (2.1.6).

Given its breadth and uniqueness, the C-Mod boundary research program plays an important role in supporting general research in both the national and international arenas. The specific overlap with ITPA high priority tasks, IEA-ITPA collaborative work and the priorities identified in the 2005 FESAC Panel report are covered explicitly in section 2.1.7, as well as more generally throughout this chapter.

2.1.1 Transport

Edge transport research is rich and productive on C-Mod. Over the past few years, significant progress has been made towards developing a first-principles understanding of the underlying physics. Our edge transport research is organized into two complementary thrusts. The first is the study of time-averaged cross-field plasma fluxes, profiles and flows (toroidal and poloidal), averaged over time scales greater than 1 ms. This allows us to characterize the level of transport, to develop empirical scaling relationships and, with the guidance of theory and numerical modeling, to identify the key plasma parameters that might 'control' the level of transport fluxes and flows. Such a framework helps to expose the underlying physics. Further, it allows comparisons to be made with other tokamak experiments and offers insight into what one should expect under reactor conditions, such as in ITER. Our second approach is to study the detailed time evolution of the plasma turbulence and how it leads to the time-averaged profiles and transport that we observe. These measurements are made with the help of state-of-the-art fast-camera and photodiode imaging systems, enabling direct comparisons with first-principles numerical simulations. Most recently these unique diagnostics have begun to reveal interesting aspects of ELM dynamics – a new and fruitful area of investigation for C-Mod.

Time-averaged transport

Experiments in C-Mod have revealed that the scrape-off layer (SOL) exhibits fundamentally different transport phenomena in the regions 'near' and 'far' from the separatrix. The 'near' SOL (0-5 mm from the separatrix) is characterized by steep gradients and near-Gaussian fluctuation statistics while the 'far' SOL exhibits flattened gradients and intermittent transport events. Analysis of SOL profiles in L-mode has uncovered evidence that pressure gradients near the separatrix are set by electromagnetic fluid drift (EMFD) turbulence[2]. The local pressure gradient, normalized by the poloidal magnetic field strength squared (i.e., α_{MHD}) appears to be invariant in plasmas with the same normalized collisionality despite having vastly different currents and magnetic fields. Fig. 2.1.1. shows normalized edge pressure gradients (α_{MHD}) plotted versus an inverse collisionality parameter, α_d, which, as defined in [1], is ~ $(1/q)\ (\lambda_{ei}/R)^{1/2}\ (R/L_n)^{1/4})$ for a wide range of plasma conditions. These data suggest that local gradients are pinned to a 'critical gradient' condition that is sensitive to local collisionality – a behavior that connects with first-principles EMFD turbulence simulations [3,1]. Pressure gradients in the H-mode pedestal are found to follow a nearly identical scaling[4]. Thus, the near SOL appears to form the base of the H-mode pedestal and may play a key role in the formation and development of the H-mode pedestal – a connection that we will continue to pursue aggressively over the next few years. Higher collisionality (i.e. lower α_d), leads to smaller pressure gradients, rendering a region of this 'phase-space' to be inaccessible. This high-collisionality physics is associated with the tokamak density limit, behavior which is consistent with a recent theoretical analysis by Guzdar [5].

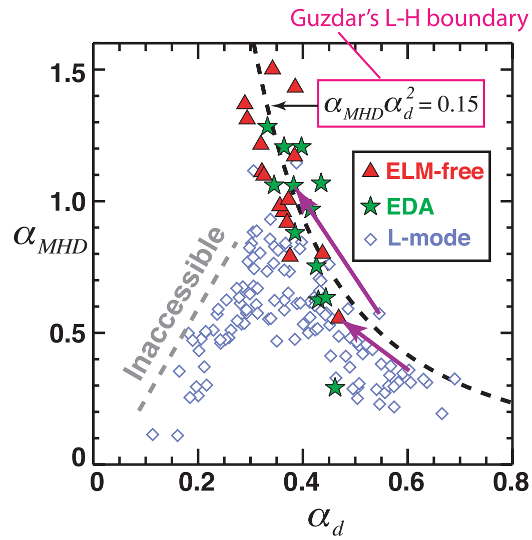

Figure 2.1.1: Normalized pressure gradient versus normalized (inverse) collisionality in the near SOL for a wide range of plasma conditions.

As a result of these observations, a fundamental shift in our views of edge transport physics has occurred: transport in the near SOL may be more appropriately described in terms of a critical gradient phenomena rather than a diffusive and/or convective transport paradigm. Certain 'control parameters', such as plasma collisionality, appear to affect the observed 'critical gradient' value. Theory suggests that other 'control parameters' such as magnetic shear and/or plasma flow shear should also be observed. Figure 2.1.2 shows results from recent experiments [6,7] (2006 campaign), where the dependence of α_{MHD} on magnetic topology (upper/lower x-point) and magnetic field direction was examined. Remarkably, higher values of α_{MHD} are recorded when $B\times\nabla B$ is pointed toward the x-point, independent of the direction of B – a hint that edge plasma flows (Fig. 2.1.3) may play a role in setting the observed 'critical gradient' value. We plan to explore this effect with the help of recently installed diagnostics: inner-wall scanning Langmuir-Mach probes as well as spectroscopic views of intrinsic plasma impurities (discussed further below). These diagnostics will provide detailed information on plasma profiles, including parallel and perpendicular (*ExB*) flow profiles in a region that spans the separatrix.

Experiments are presently being planned to explore the effect of magnetic shear on edge profiles and ‘critical gradient’ observations. These include discharges where the separatrix is systematically shifted relative to a limiter-defined last-closed flux surface (LCFS). Does the ‘critical gradient’ that we observe near the LCFS depend on the shift of this x-point containing flux surface? Does the width of the steep gradient region (which is related to the pedestal width in H-mode) depend on the characteristic shear length in the x-point region? We will use our extensive set of high-resolution edge plasma diagnostics and edge database to address these questions and to design follow-on experiments. We will also draw on our theory and modeling collaborators for guidance, including: B. Rogers (Dartmouth), P. Guzdar (U. Md), M. Umansky, X.Q. Xu., R. Cohen, D. Ryutov (LLNL).

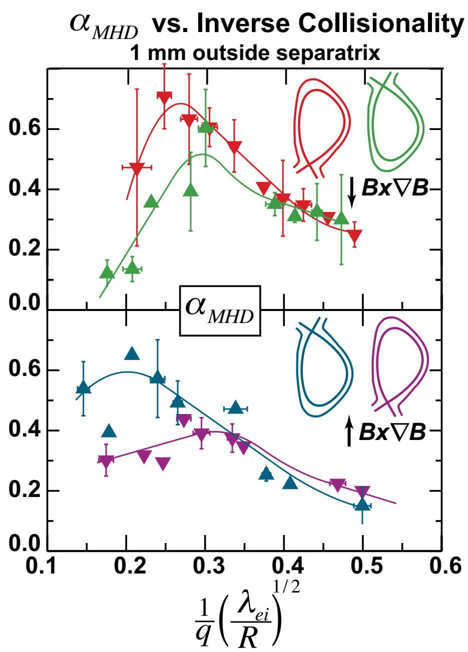

Figure 2.1.2: Normalized pressure gradient versus normalized (inverse) collisionality (similar to α_d*, see* [1,2]*) for different x-point topologies and field directions. Downward pointing triangles are LSN, upward are USN.*

Another important topic is the study of conditions in the edge plasma at the onset of the L-H transition (i.e. gradients, flows, etc.). Data from ohmic L-H transitions (see Fig. 2.1.1) have suggested some tantalizing physics: discharges just prior to the L-H transition are found to lie on a boundary very similar to that predicted by Guzdar [8,2]. We hope to test the existence of this boundary in more detail in the upcoming campaigns, operating with an expanded range of plasma currents and probing edge conditions in detail.

Finally, we hope to elucidate further the role of electromagnetic effects in the plasma turbulence by direct measurement. Using a novel scanning probe head with embedded coils, we will build on our database of poloidal magnetic field fluctuations as a function of distance into the SOL. These will be compared with output from first-principles numerical computations (e.g., BOUT).

Strong parallel plasma flows are found to exist in the tokamak scrape-off layer, far from material surfaces. C-Mod experiments have shown these flows to be driven largely by ballooning-like cross-field transport asymmetries[9]. As indicated above, such flows may have important consequences for plasma discharges, in addition to transporting impurities in the boundary layer. They may influence the L-H power threshold (via changes in magnetic topology[10]) and/or change the flux-gradient relationships of local plasma

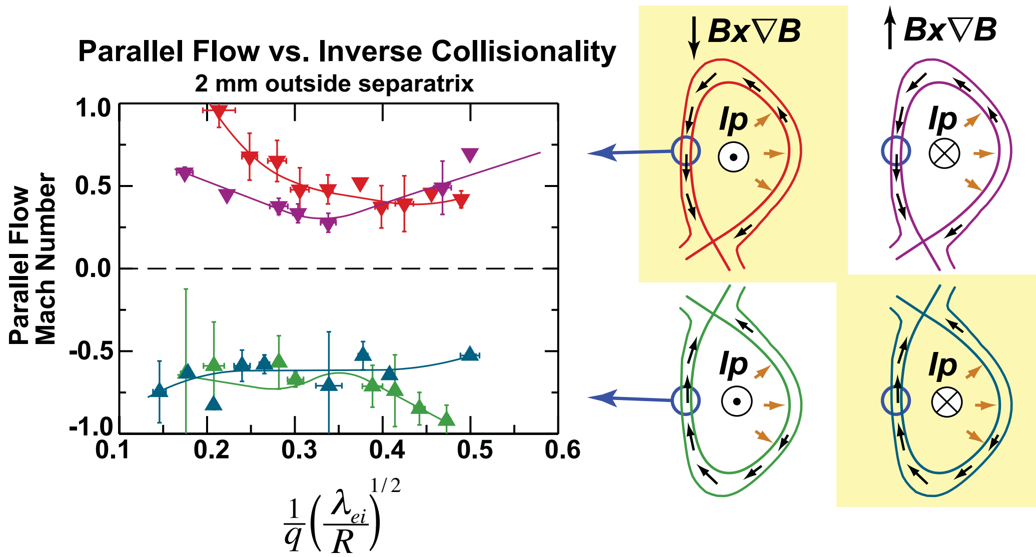

Figure 2.1.3: The direction of strong parallel flows (near Mach 1) in the high-field SOL depends on the location of the x-point, NOT the direction of magnetic field. Co-current directed SOL flows (yellow highlight) corresponds to higher α_{MHD} in SOL (Fig. 2.1.2).

transport in the near SOL[11]. Recently, we have explored the sensitivity of parallel flows in the SOL to magnetic topology with reversed magnetic field direction (Fig. 2.1.3). These data confirm that the flows on the high-field side are largely 'transport driven' with *ExB* and Pfirsch-Schulter flows being minor contributors to the overall flow vector there. With the recent improvements to our edge flow diagnostics (new scanning Mach probes and Doppler spectroscopy) we will explore SOL flows, the physics of their origin and their influence on edge profiles/transport in more detail. One immediate goal is to obtain a measure of flow velocities independent of the Mach probe to confirm the probe-derived flows. Experiments are planned using both the Gas-Puff-Imaging (GPI) D_2 puff at the inner wall and the DNB to make CX measurements of B^{+5} ion flow velocities (graduate student project). A second goal is to determine how the strong parallel ion flow towards the inner divertor leg forms a 'closed loop' – Is there a mechanism of cross field ion convection into the closed flux surfaces or does neutral fueling from the inner divertor leg dominate? The possible role of an inward fluctuation-induced particle flux will be investigated using the capabilities of the new inner-wall scanning probe system. Through dedicated experiments, we plan on quantifying the contribution that neutral recycling can make to 'closing the flow loop'. This will involve a combination of particle flux measurements on the inner divertor surface and simple neutral transport modeling. Lastly, we will continue to compare our detailed flow measurements with those simulated by 2-D transport codes. In particular, flow measurements that span the separatrix on the high-field side will allow critical tests of the flow fields produced by A. Pigarov (UCSD) using the UEDGE code. S. Lisgo (U. Toronto) plans to model the flows using the interpretive code package, OSM-EIRENNE. We also will continue to work closely with P. Catto (MIT) and A. Simakov (LANL) in analyzing the symmetry properties of the observed SOL flows. These analyses extract the topology-dependent parts of the plasma flow field.

Transport processes in the far SOL are also important since they determine the conditions under which a 'shoulder' forms in the profile, increasing the level of plasma interaction with main-chamber wall surfaces. Through collaborative effort, the technique used in the analysis of the time-averaged radial transport in C-Mod [12] has been applied to dimensionlessly similar discharges from DIII-D and JET and compared to the C-Mod results. The radial transport in the SOLs of these various tokamaks, given by effective transport coefficients, D_{eff} or v_{eff}, are found to be very similar, both in magnitude and radial scaling, indicating little or no dependence on ρ^*, ν^*, or β [13,14]. We hypothesize that the differences in SOL profiles between JET and C-Mod are due to differences in the opacity of the SOL to neutrals [14]. We have recently begun to explore lower density, reduced neutral opacity discharges on C-Mod, with the aim of unfolding such effects. These experiments will continue with the aid of the new C-Mod cryopump (see section 2.1.6) and with a new toroidal-viewing Lyman-alpha diode array to extract neutral profiles and ionization sources in the SOL. Drawing on these new tools, our 'phase-space' mapping experiments (e.g., data in Fig. 2.1.1) will continue, expanding towards higher magnetic fields (8 tesla) as well as lower density discharges. We will use data from this expanded operation to: (1) Determine if the inferred weak dependence on dimensionless parameters holds over a much larger dataset; (2) Vary the neutral opacity over a much wider range, matching that of JET, and determine if the JET SOL profiles are achieved (without changes in transport); and (3) Compare the characteristics of the far SOL transport (v_{eff}) with that of local turbulence (e.g. phase velocities of filaments/blobs). Augmenting the C-Mod work, we intend to continue inter-tokamak collaborations that include analysis of SOL data from DIII-D (H-mode), MAST and ASDEX-Upgrade. This work is part of IEA/ITPA collaboration DSOL-5 and the ITPA high-priority research task, "*Improve measurements & understanding of plasma transport to targets and walls, to better predict heat load, and effects on the core plasma.*"

A number of important upgrades to our edge diagnostic set will begin to bear fruit during the 2007 run campaign, allowing us to address many of the physics questions outlined above. The old inner-wall scanning-Mach probe has been replaced with two new units with advanced head geometries. These are able to plasma measure parallel and cross-field plasma flows as well as plasma turbulence as a function of radius, up to and beyond the LCFS (graduate student project). The outer-wall and vertical scanning probe drives have also been changed to this new tungsten-tipped probe geometry with improved heat handling capability. As part of an upgrade to the bolometry system on C-Mod, a new array of toroidally-viewing Lyman-alpha diodes is also being installed (graduate student project). These data will allow neutral density and ionization profiles to be routinely inferred. Lastly, over the past year we have been successful in developing a new Langmuir probe electronics package that can produce and sample very fast I-V characteristics (< 1 μsec sweep). This equipment will be tested during the 2007 campaign on the outer-wall scanning probe to obtain proof-of-principle measurements of density, temperature and plasma potential fluctuations in the SOL with 1 MHz bandwidth (graduate student project).

Turbulence

Boundary research on C-Mod will continue to focus on gaining a first principles understanding of the dominant turbulence in the C-Mod SOL, since the SOL profiles and transport are largely determined by this turbulence. The time-averaged SOL characteristics cannot at the present time be predicted from a first-principles physics model, although the time-averaged cross-field transport on the outboard - "bad" curvature - region of the SOL, characterized by the (large) values inferred for D_{eff} or v_{eff}, is clearly anomalous. The turbulent transport appears to set the density profiles in the outboard far-SOL and is the root cause of the high levels of main-chamber-cycling in C-Mod. (For a unifying discussion of main-chamber-recycling see[15]).

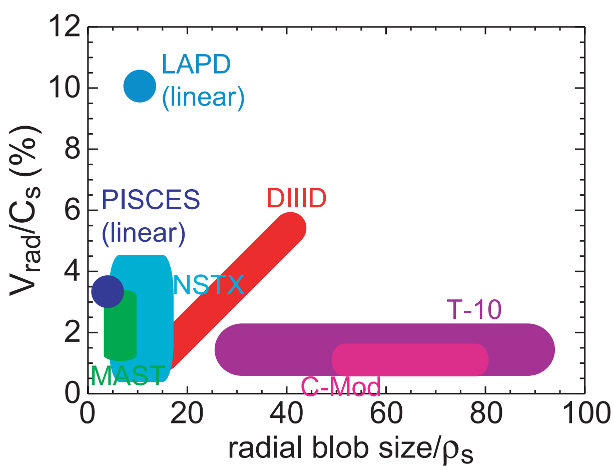

Fig. 2.1.4: Turbulence filament size and radial velocity in the SOL normalized to the local ion Larmor radius at the electron temperature, ρ_s, and the local ion sound speed, c_s, for a number of devices.

Turbulent transport in the outboard far-SOL is dominated by intermittent expulsions of plasma "filaments" (i.e., they are aligned with the magnetic field with $k_{||} << k_{perp}$ and appear as "blobs" when viewed parallel to the field). We have been studying the properties of these filaments on C-Mod and are leading an ITPA-organized multi-machine effort to find the unifying physics basis for their creation and dynamics (ITPA high-priority task – "Inter-machine comparison of blob characteristics"). An initial attempt at such a unification is shown in Fig. 2.1.4, where normalizations of the local ion Larmor radius and ion sound speed have been applied to the radial size and outward propagation speed of the filaments as measured on a number of the world's devices[16]. We are continuing these studies of filament properties and dynamics by systematically measuring their dependences on machine parameters (e.g. B_t, ν^*) and confinement mode. We will also continue to search for dimensionless parameters which best unify the basic filament properties among the world's machines, since, as evidenced by Fig. 2.1.4, the simple normalizations do not appear to be sufficient.

So far we have successfully used both optical and probe diagnostics for the edge turbulence studies. The optical diagnostics use the Gas-Puff-Imaging (GPI) technique to localize the measured emission fluctuations, including one 2D view coupled to an ultrafast-framing camera and 1D and 2D arrays of views coupled to filtered photodiodes. In addition these diagnostics, we have in 2007 added another 2D view of the region just outboard of the lower x-point. It spans a 6x6 cm region and looks approximately parallel to the local field. We have also acquired another fast-framing camera capable of *continuous* acquisition of 64x64 frames at 148 kHz. This view will be used to study the edge turbulence near x-point region, where theory predicts that the dynamics are different from those at the outboard midplane [17]. A schematic of the different SOL turbulence diagnostics, including this new view, is shown in Fig 2.1.5.

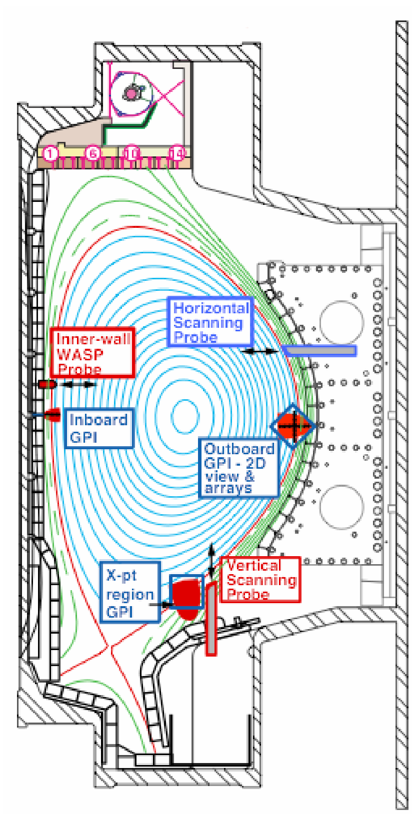

Fig. 2.1.5: The optical (GPI) and probe diagnostics installed on C-Mod as of 2007 to be used for studying SOL turbulence. The two blue-rimmed boxes show the poloidal locations of the 2D GPI view, while arrays of dots are array-views coupled to photodiodes. The red "cones" indicate schematically the local gas-puffs.

We are also expanding our studies of turbulence around the separatrix using the optical diagnostics and GPI. We have previously observed the poloidal propagation characteristics of the broadband turbulence using probes [18]. More recently, using GPI, we have observed a dependence of the poloidal propagation of the broadband turbulence around the separatrix upon magnetic configuration (e.g, LSN, USN, DN) and confinement mode. We plan in-depth investigations of these initial observations. For the coming years we plan experiments to determine whether or not there is a link between this broadband turbulence and the Quasi-Coherent-Mode, the dominant pedestal relaxation mechanism for the Enhanced-D_α H-mode in C-Mod.

Since a predictive first-principles physics basis for SOL transport is a primary goal of C-Mod's boundary program, we are continuing detailed experimental comparisons with first principles models of turbulence. Initial comparisons of turbulence measurements with simulations [19] were made using the NLET code[20]. A number of quantities calculated in that simulation were compared directly with the experiment: time-averaged particle fluxes were found to agree to within about a factor of two and good matches between experiment and simulation were found for the k_{pol} spectra and for the autocorrelation times vs. ρ. More recently quantitative comparisons have been made between the BOUT edge turbulence code of LLNL and C-Mod SOL turbulence data for a specific diverted plasma condition [17]. The BOUT simulations predicted fluctuation levels and correlation lengths within a factor-of-two of the experimental results. In addition, a specific experiment was done using inner-wall-limited plasmas to test the GEM code[21] simulations of B. Scott from IPP Garching, where again, agreement to within about a factor-of two was found for the correlation lengths and correlation times. These initial theoretical comparisons are promising, and we plan more work in this area, with experiments to test scalings predicted by the modeling, e.g. for the B_t and ν^* scalings.

We view our program – of studying both the time-averaged profiles and the "microscopic" turbulence – as necessary step on the path to the development of a predictive understanding of the SOL for both existing devices and for ITER.

ELMs in the SOL

To date on C-Mod the Quasi-Coherent Mode, *not* ELMs, has been the typical relaxation mechanism for the H-mode edge-pedestal, despite its often being close to the ballooning pressure limit. Recently an operational space has been accessed in C-Mod for which discrete, relatively large ELMs comprise the relaxation mechanism for the pedestal. This operational space is one of large triangularity for the lower half of the plasma, small upper triangularity, and a normalized collisionality in the pedestal $0.2 < \nu^* < 1$. Within this operational space we have been able to study many aspects of ELMs [22], in particular the characteristics and dynamics of the ELM filaments as they move through the SOL. For example, we observe multiple filaments per ELM event, with the initial filament – which we have named the "primary" – having the largest perturbation on the optical emission. Typically the primary is followed by 2 to 5 "secondary" filaments. Typical radial widths for the primary are 0.5 to 1 cm, and its outward radial propagation is quite rapid, with a distribution of radial speeds that is peaked around 1 km/s, as shown in Fig. 2.1.6. As in the case for the turbulence filaments, we are seeking and will continue to seek unification of the observations of ELM filament radial propagation among many of the world's machines [16]. The secondary filaments move more slowly, 0.3-1 km/s, and some are seen to decelerate as they move out. We also see evidence of non-thermal electron generation at the moment of filament ejection. We will continue and expand our research in this area, an ITPA high-priority issue – "Understand the effect of ELMs/disruptions on divertor and first wall structures".

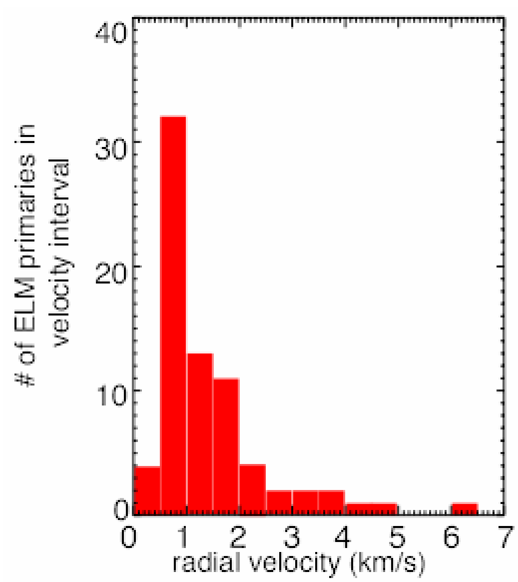

Fig. 2.1.6: The distribution of radially-outward speeds measured for the primary ELM filaments.

In particular, successful use of C-Mod's new cyropump (see Section 2.1.6) should allow access to lower values of pedestal collisionality in *standard* C-Mod shapes. This in turn may lead to the routine appearance of ELMs in the standard shapes. We plan to exploit this anticipated capability further by studying the ELMs in a variety of collisionalities and shapes, which may access different regions of peeling/ballooning stability in edge-current/pressure gradient space. Among the questions we will investigate are: 1) What are the effects of such variations on the ELM filament dynamics? 2) What is responsible for the generation of non-thermal electrons and what are the consequences of this phenomenon on sheath dynamics, material sputtering, etc.? 3) What is the power flow to the divertors during the ELMs? (This investigation will exploit the instrumentation by existing probes in the lower and those newly-installed in the upper divertor.) 4) What are the differences, if any, between ELM filament dynamics at the outer midplane and the newly-viewed region just outside the x-point?

It is generally believed that, by the time the ELM filaments move through the SOL, they are the highly non-linear manifestation of MHD peeling/ballooning instabilities[23]. We plan to continue our collaborations with modelers of ELMs, i.e. with P. Snyder at GA, developer of the ELITE (ideal MHD) code, and with L. Sugiyama at MIT, who is part of the team developing and using the M3D (3D resistive MHD) code. Testing of detailed models will be crucial for predictive understanding in this area.

2.1.2 Effect of low-Z coatings on operation (Boronization)

The C-Mod boundary physics program continues to study the processes whereby boronization coatings are eroded and the underlying molybdenum surface exposed and eroded. This knowledge is important for optimizing C-Mod operation as well as impacting decisions of whether high-Z PFCs are compatible with reactor operation. The C-Mod 2005 campaign results indicated that the R~ 70 cm region at the top of the outer divertor was the location of the strongest erosion. Experiments from that run period [24] raised the possibility that the erosion is linked to the RF as opposed to general power loading of surfaces (with subsequent sputtering and evaporation). One 2006 campaign experiment was aimed at testing the hypothesis of erosion linked to the RF heating. In it we compared the rise in core plasma radiation following between-discharge boronization for 2 sequences of discharges: 1) As usual, RF-heated H-mode discharges; and 2) Ohmic H-mode discharges of similar total energy injected into the plasma. Figure 2.1.7 shows that the RF-heating leads to much faster erosion of the boron coating and thus the underlying Mo.[25] The comparison with the Ohmic H-mode plasmas indicates that the faster erosion is due to an RF-specific process. Enhancement of the sheath potential has been measured previously on C-Mod [26] and is likely the cause.

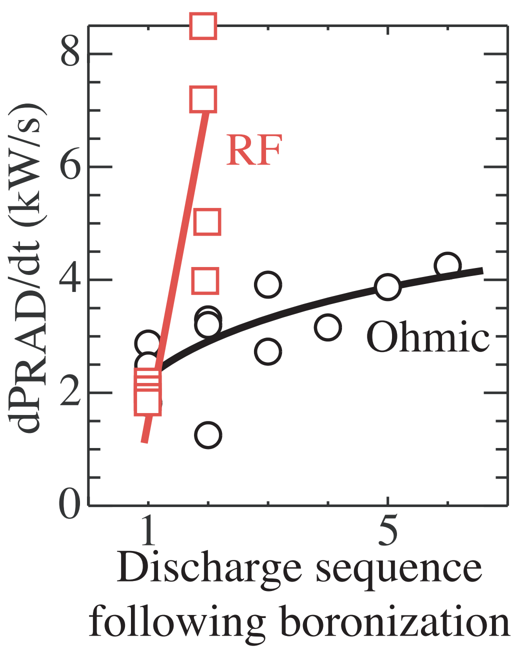

Figure 2.1.7: Degradation in stored energy as discharges are repeated under Ohmic and RF-heated conditions.

The second experiment that implicated the RF waves in creating large sheath potentials utilized the 2 sets of antennas at D/E and J ports. The hypothesis tested was that the sheath rectification primarily occurs on flux tubes that pass in front of a particular antenna. On that basis it was reasoned that if one heats the first discharge of a sequence with one antenna only (e.g. that at D/E ports) the engendered erosion at the outer divertor will be limited in toroidal extent to where flux tubes map back from the divertor top to in front of that antenna. If a second discharge is run with similar RF heating power but with the second antenna (e.g. J port) only, the boron on surfaces mapping in front of the second antenna will not have been eroded, thus keeping Mo impurity levels low. This would be contrasted with running 2 sequential discharges with the same antenna heating the plasma. The latter case led to much higher plasma radiation (as shown by RF-heating cases of Fig. 2.1.7) than if an alternate antenna was used for the second discharge [27].

Several boronization-related experiments are planned for the FY2007 experimental campaign. A set of tiles at the top of the outer divertor (R~70 cm) has been coated with ~80 microns of boron. These tiles do not map to antennas along flux tubes and so their performance during the run campaign (i.e. resilience to disruptions) will give us information on whether a B-coated tile can be utilized in place of boronization. If this is successful, and we gain further confidence in the erosion location, then B-coated tiles may be a substitute for boronization which leads to coating of most of the machine. The goal is to minimize the B in the vessel and thus have the PFCs that can be characterized as high-Z-like as possible.

A second set of outer divertor tiles has been coated with niobium (25 microns thick) to be used as marker impurities to be monitored during RF-heating. After a boronization the time till appearance of those specific impurities in the core plasma will be a measure of how fast the boron coating is eroded. Nb was specifically selected such that corresponding resonance lines appear in nearby regions of the VUV and x-ray spectra to those for Mo, thus making it easy to monitor their levels along with Mo.

A second technique has been proposed to enhance the lifetime of the boron coatings. By modifying the magnetic equilibrium, flux tubes that pass in front of the antenna will then be forced to contact portions of the outer divertor on the vertical plate section. This does not change the erosion rate. Rather it shifts the erosion to a location where the probability of the resultant impurity reaching the core plasma is much reduced (x10-100) compared to being launched from the top of the divertor. The change in equilibrium involves increasing the lower x-point triangularity. We will compare two discharge sequences following a between-discharge boronization – the first with the standard shape equilibrium where flux tubes map to the top of the outer divertor. The second discharge sequence will use the high triangularity equilibria. If this experiment works as expected we will have learned more about the erosion mechanism (shown that it is related to flux tubes mapping to the front of the antenna) as well as developed an equilibrium that can be used for conditioning the RF antennas to high power while preserving the boron coatings for standard equilibrium discharges.

A third research effort is aimed at understanding the boronization process more directly. The surface science station (S^3) head, which has been installed in the 2006-07 vacuum break, is initially equipped with 2 quartz microbalances (QMBs) that will be used for understanding boronization. One QMB will be oriented to measure B deposition coming in the major radial direction (we assume only by atoms), along the axis of the S^3 scanning movement. The second QMB is oriented perpendicular to the first. That, together with the ability to rotate the S^3 head about a major radius, allows the second QMB to measure deposition in the toroidal and vertical directions. Lastly, the S^3 head can be scanned in major radius to map out the boronization spatial deposition profile. Alternatively, the head can be held fixed in major radius and the boronization resonance radius scanned past the head. In any case we will have measured the local deposition rate which is now only estimated. This is of importance in determining how fast the erosion rate is and thus better understanding the erosion process.

A fourth research effort seeks to optimize the boron deposition process itself through modifications of the magnetic field topology during boronizations. Unlike most devices that use D.C. biased-probe glow discharges for conditioning, C-Mod uses an Electron Cyclotron Discharge Cleaning (ECDC) plasma. For boronizations, a 10% diborane – 90% helium mixture is used with ECDC, and the EC resonance for the 2.5 GHz RF source (~0.1 Tesla) is scanned in major radius by varying the current in the toroidal field magnet. The purely toroidal field results in outward ExB drift of the EC-created plasma, and as a result plasma density forms a stepfunction in major radius, being practically zero inside the EC resonance, and nearly constant outside [28]. For plasma-deposited boron films (dissociated neutrals also play some role), this scheme results in a boronization pattern which is spread out radially. The proposal is to apply a fixed vertical field during the ECDC/boronization using the equilibrium coil set on C-Mod. The vertical field will not cancel the ExB drifts, but will instead channel the ionized B toward the lower and upper divertor target plates due to free-streaming along the field, which should raise plasma flux and hence boronization film growth rate at desired regions (e.g. top of the outer divertor), while minimizing unwanted boronization film growth at regions further out radially (e.g. in the antenna structures). Based on previous measurements [28] a factor of 5-10 increase may be possible in boron film growth, and will probably be limited by cutoff issues as the local density is increased near the resonance. We will characterize the effectiveness of the technique use the QMB system on S^3, as well as through overall plasma performance.

2.1.3 Divertor physics

The codes currently being used to model the ITER divertor plasma are benchmarked against results from tokamaks running in low density regimes, where the neutral mean free path is long compared to the divertor and divertor plasma dimensions. Such comparisons with experiment fail to test 2 important aspects of ITER-relevant physics in the models: 1) Lyman–α radiation trapping – which potentially strongly affects the ionization balance and ability to achieve detachment (required in ITER to dissipate the power flow to the divertor); and 2) the diffusive, or short neutral mean free path, regime – which determines the neutral densities in the divertor and thus pumping rates for D, T and He ash.

Conditions in the C-Mod divertor plasma are closest to ITER in mean free paths normalized to the divertor size. In the detached cases the photon absorption mean free path is ~ 1mm, smaller than the plasma fan, as will be the case in ITER. The high neutral densities give n-n and D^+ - D_2 mean free paths small compared to the relevant plasma fan or divertor dimension (λ_{nn} ~ 1.3-7.8 mm, $\lambda_{p\text{-}D2}$ ~ 1-8 mm for the ranges in cases under study). JET divertor conditions are somewhat farther from ITER than those on C-Mod and achieve the short normalized mean free paths by the size of the divertor as opposed to the shortness of mean free paths. Experiments are planned at JET to acquire similar data to that of C-Mod for testing codes but, as yet, the data are not available. This work is part of the IEA/ITPA DSOL-5 collaboration with JET and has furthermore been specified by the ITER team as one of 5 calendar year 2006 ITER-US sub-tasks for US research to provide answers for ITER.

A set of data from each of 3 C-Mod discharges has been collected and partial modeling utilizing the OSM-EIRENE code combination, in collaboration with the U. Toronto group (S. Lisgo) and U. Bochum (D. Reiter), is well underway. Preliminary results are shown in Figure 2.1.8. The three C-Mod density cases correspond to the outer divertor being attached (P_{DIV} = 25 mTorr), detached (75 mTorr) and detachment reaching the x-point (150 mTorr). Also shown are the results of C-Mod divertor modeling done previously where the radiation trapping and neutral-neutral collisions were not taken into account [29].

As seen in Figure 2.1.8, photon and neutral collision processes play important roles in neutral transport and in determining the pressure in the divertor.

For the coming year the goal is to complete these divertor neutral modeling studies as follows: Refine the plasma model for the range of divertor densities examined thus far, examining the impact of re-interpreting the CCD camera and Stark broadening data; Apply 3D code extensions to include intrinsic neutral particle leakage through the divertor substructure; Incorporate a parallelized version of the EIRENE neutral transport code in order to reduce computation times for full-torus, 3D simulations. Lastly, we have initiated a collaboration with the U. Bochum group to take the modeling to the next step - predictive modeling, using the B2-EIRENE combination. This will provide a self-consistent solution, a more stringent test, and will be more usable for determining the importance of certain processes in the divertor solution. The U. Bochum group (D. Reiter and V. Kotov) has committed to this for FY07.

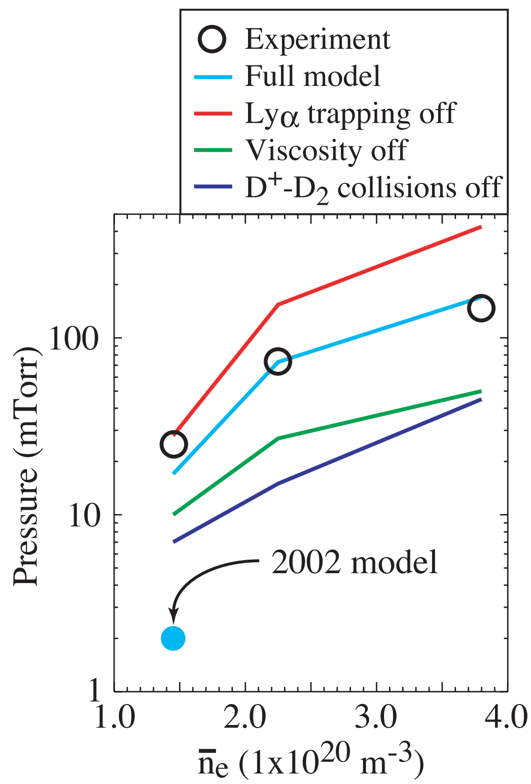

Figure 2.1.8: Turning processes off in EIRENE one at a time, to see what is important (static plasma solution) for the three neutral pressure cases.

In parallel with analysis of the existing data we are moving towards revitalizing our current complement of divertor diagnostics with the goal of much better spatial coverage of Ly_{α} emission such that Ly_{α} tomography can be performed. This will allow much more detailed studies of radiation transport. The enhanced Lyman views of the divertor will start (currently installed for use in FY07) with an array of 20 AXUV detectors mounted just outboard of the outer divertor filtered for Ly_{α} – the so-called 'ledge' array. These can be used in concert with the McPherson spectrograph to provide data about Ly_{α} absorption for modeling. In FY08 additional Ly_{α} views of the divertor will be added with the goal of doing tomography. These Ly_{α} detectors will be supplemented by re-installation of the divertor bolometry arrays (FY08) to allow for divertor tomography of total emission losses. During FY07 we will begin trials of using Dγ for tomographic inversion (spectral and spatial) of those data for extraction of local n_e and T_e through the spectral analysis.

The renewed emphasis on divertor diagnostics will also allow us to revisit the achievement of detachment under high heat flux H-mode conditions. In such cases it is difficult to achieve and control detachment. We believe that further studies at high heat fluxes will be very useful for ITER operation.

2.1.4 Deuterium fuel retention

Tritium is a radioactive isotope of hydrogen, and for safety reasons the amount of tritium retained in-vessel must remain under a certain limit, 350 g in the case of ITER. The requirements for efficient T recovery are clear when considering that a full-power ITER discharge will fuel ~100g of tritium, i.e. ~30% of the allowed in-vessel inventory. Fortunately, this issue can be studied in devices that only use deuterium fueling. Fuel gas retention in current carbon-PFC (Plasma Facing Components) tokamaks is in the range 3-30% of that injected implying potential stoppage of ITER operation after a few discharges for T removal. Tungsten is currently projected for use in ITER and reactors, partly due to its very low natural solubility to hydrogenic (H) species (~ 10^{-6} H/W) as compared to the high solubility in low-Z PFC material such as C (~ 10^{-1} H/C). However, tokamak experience providing support for this assumed result is lacking. We have undertaken to investigate hydrogenic (H/D) retention in molybdenum (Mo) on C-Mod since the fuel retention/solubility for Mo is similar to W. Since C-Mod is presently the only divertor tokamak in the world with bulk high-Z armor, timely results from C-Mod could be critical to informing the choice of PFC materials that must be made for ITER in its ongoing design review.

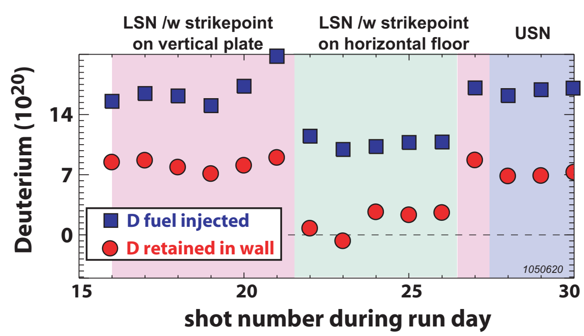

Figure 2.1.9: Fueled and retained D per shot with varying divertor magnetic geometries. LSN: lower single-null, USN: upper single-null. Experiment: boronized wall, I_p = 1 MA, P_{ICRF}=1 MW n_e ~ $1.6x10^{20}$ m^{-3}.

Initial measurements in C-Mod discharges during the 2005 run campaign showed the surprising result that a large fraction (~30-50%) of injected D fuel gas was retained in the walls, despite thorough removal of low-Z boron coatings from the PFC surfaces [30,25]. Therefore co-deposition of D with B in boron films was *not* the cause, but rather retention in the Mo itself, with the likely location of retention being the outer divertor, since this was the only location where the boronization films are naturally eroded by plasma operations to uncover the bulk Mo. The importance of the divertor is further supported by two additional observations: The gas retention increases sharply as the divertor becomes high-recycling with concomitant large increases in ion fluxes to divertor surfaces; The fuel gas retention is dependent on magnetic geometry (see Fig. 2.1.9).

Since the gas fuel retention is localized at particular PFC surfaces we have utilized multiple D_α measurements to infer local ion fluxes. Like the global gas fuel retention there is a linear relationship between the retained D in the wall and the cumulative D ion flux to the wall (Fig. 2.1.10), with approximately 0.75% D retention fraction. (The fueled D is much higher, since the fueling rate is 1-2% of the plasma recycling rate at the wall.) The lack of saturation is worrisome since it implies a constant loss of tritium for long-pulse shots (~500 s) in ITER. The linear retention rate was unexpected from extrapolation of ion beam exposure of Mo in laboratory experiment where retention shows a weaker 0.35 power law dependence with fluence.

Another important observation is that it was necessary to avoid disruptions (e.g. in the current rampdown) in order to obtain the data in Fig. 2.1.10. If one operates with the typical frequency of disruptions in C-Mod, it is found that the long-term wall D inventory buildup was close to zero, while the intentional termination of discharges with disruptions leads to *depletion* of D and H from the wall. These results indicate the central role of surface temperature in setting retention, since the disruptions lead to rapid transient heating of the PFC surfaces but increment D ion fluence to the wall by only a small amount. The disruptions show the promise of manipulating the thermal history of the wall surfaces to control fuel inventory, a technique which may be applicable in ITER.

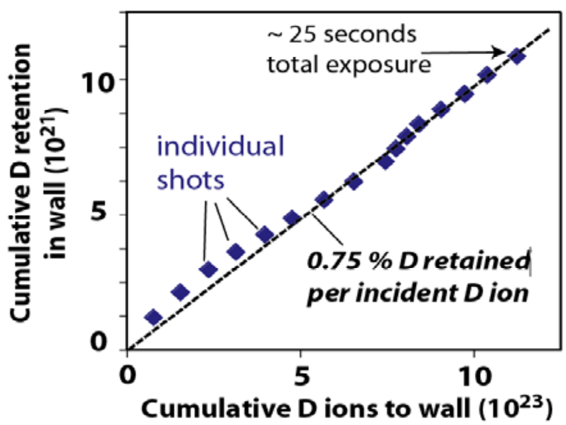

Figure 2.1.10: Cumulative D retention in cleaned Mo walls vs. incident D ions to wall.

Extensive laboratory studies were carried out on the DIONISOS facility in collaboration with the University of Wisconsin –Madison to discover possible retention mechanisms for D in Mo under C-Mod divertor conditions (T_e ~30-350 eV, & Mo target temperatures, 300-700 K). The DIONISOS results showed a very complex interplay between several physical processes, including D diffusion, D trapping, beam and plasma produced damage and traps, and high-temperature annealing. The most important observation was that the high-flux plasma D exposure could create D traps in the Mo. Traps are damage locations at which D can reside in an energy well. The traps created by high-flux plasma exposure (and birth rate scaling approximately linearly with incident plasma flux) were able to migrate deep into the material due to surface temperature increases. A 'ratcheting' process (surface heating with simultaneous ion fluence, followed by surface cooling) is created whereby each exposure and thermal cycle increases the retained D, giving retention rates of 0.35% of incident D^+ fluence. The DIONISOS results are consistent with the lack of saturation in D retention in C-Mod, with repeated shot cycles, without any transient heating from disruptions (Fig. 2.1.10) and that the divertor is where the retention is occurring.

The proposed "ratcheting" retention mechanism for D in Mo, which is closely linked to the dynamics of the surface temperature evolution coincident with high particle flux, is different than co-deposition (D with C in C PFC tokamaks) in that it does not rely on the plasma producing D/T rich films. It is clear that such a retention mechanism must eventually saturate, however ~1% D/Mo or T/W in the *bulk* of the material would be unacceptable. Deep retention in the bulk of the Mo/W also affects strategies for recovering the fuel. With this physical model in hand, upcoming campaigns will focus on both validating and enhancing our understanding of D retention C-Mod in order to extrapolate the results with more confidence to ITER. Operationally for C-Mod, efficient recovery of H isotopes from the wall is also sought, since this reduces conditioning time required to reduce H/D in the core plasma to ~5%, required for efficient ICRH absorption.

We will apply the retention model in a more self-consistent way to C-Mod conditions. In particular this requires integrating plasma diagnostics from various locations (probes in divertor, D-alpha in the main chamber), along with a surface heating calculation, in order to capture more accurately the thermal and particle fluence to the Mo surfaces. It will be possible to apply this first to the results from our previous retention experimental campaigns on C-Mod, which will then help to guide future experiments. The initial focus of these experiments will be to validate further the model with the final goal of developing plasma scenarios with minimum D retention.

In a similar vein, we will apply the retention model obtained from DIONISOS, in particular the fitted D diffusion and de-trapping rate, to the C-Mod disruption recovery experiments. The successful recovery of H/D from the wall was demonstrated in FY06, however the extrapolation of this technique to long pulse devices like ITER was hampered by the lack of good physical data on the D release from the Mo. Again the long-term goal is to be able to maximize the efficiency of the H/D recovery through a combination of experiments and applied modeling.

Another line of research will focus on release of H/D from the C-Mod walls over periods of time significantly longer than between-shots (~15 minutes). The purpose of these experiments, which will occur by closing pumping valves overnight or on weekends, will be to characterize even better the long-term global inventory. While the long-term release rate of H/D from the wall is expected to be small, due to the room temperature walls, it will nevertheless be important to integrate this release over long periods of time. Furthermore, real-time gas composition using an in-vessel RGA will reveal information on isotope exchange in the walls.

Finally, an experiment will be carried out to test the efficiency of low-density plasmas in recovering H from the wall. The principle of this technique is similar to the disruption cleaning, but rather than a short-time (ms) increase in surface temperature, these discharges will seek to maintain second-long high target surfaces temperature, but with relatively weak D plasma flux to the wall (i.e. high edge plasma temperature). Under such conditions we hope to force net H/D gas out of the wall during the discharge. These cleaning shots are possible due to the new C-Mod capabilities to control particle throughput, and hence plasma density, using the cryopump. Understanding T recovery in high-Z materials appears to be a more urgent matter for ITER than previously assumed, and therefore the development of multiple recovery techniques is critical.

2.1.5 Dust

In D-T burning devices such as ITER, the creation and inventory of dust will be an important safety issue, because the dust particles will be radioactive due to tritium contamination, and may also be chemically hazardous. In addition, large amounts of dust can adversely affect plasma performance. In order to understand the accumulation of dust in a tokamak, it is important to know not only what processes produce dust, but also how and where the dust is transported around the vacuum chamber. Theoretical and computational modeling of dust transport is in progress, but there is very little experimental research on dust transport in tokamaks. Dust characterization and measurement techniques are therefore high-priority ITPA research tasks.

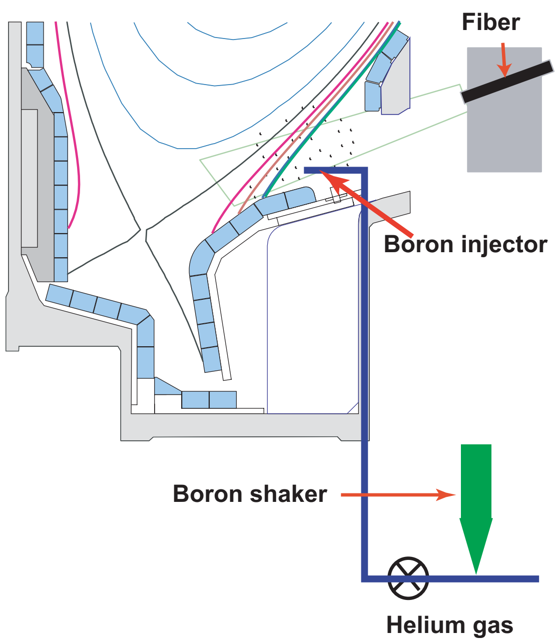

Figure 2.1.11: Geometry of new dust injection system

A new diagnostic is being installed on Alcator C-Mod specifically to study transport of dust in the scrape-off layer during normal plasma operation. Since earlier dust observations on C-Mod have shown that intrinsic dust is usually quite sparse except at disruptions, the diagnostic includes a dust puffer system that will inject boron particles into the outboard SOL near the divertor shelf (Fig 2.1.11). The dust will be illuminated by laser light, and imaged by one or more cameras fitted with narrow spectral bandpass filters around the laser wavelength in order to reduce background plasma light. The proof-of-principle experiments will be carried out during the next year, and will initially study dust transport in the vicinity of the divertor. Based on those results, further refinements and/or upgrades will probably be done in following years.

There are a number of forces that can act on dust particles in a tokamak. Calculations suggest that the dominant force on dust in the SOL should be the frictional force, in which case the particles should follow the plasma flow. However, there are other forces, such as electrostatic (which may be particularly important near the wall or limiters) and ablation forces, which may also be important. Current numerical codes, such as DUSTT, have not been benchmarked against experiment due to lack of available measurements. Therefore this diagnostic on C-Mod should play an important role in improving our understanding of dust transport physics.

2.1.6 High heat flux & particle handling

As boronization experiments have demonstrated (section 2.1.2), the performance of C-Mod plasmas is intimately connected to the performance of the divertor and first-wall components. Consequently, the boundary physics and operations groups work closely together in developing and optimizing these components. Over the past year, we have completed our development of an ITER-relevant tungsten lamella tile design for C-Mod (Fig. 2.1.12). Prototype versions of these tiles were successfully tested for heat flux handling at Sandia and Julich. A full toroidal ring of 120 tiles has recently been installed near the outer strike-point location on the lower divertor cassettes. During the upcoming 2007 campaign we will monitor the performance of the tiles with the divertor IR imaging system, and toward the end of the campaign the tiles will be deliberately exposed to extended high power fluxes. The levels of tungsten in the core plasma and the mechanical integrity of the tiles will be tested as well.

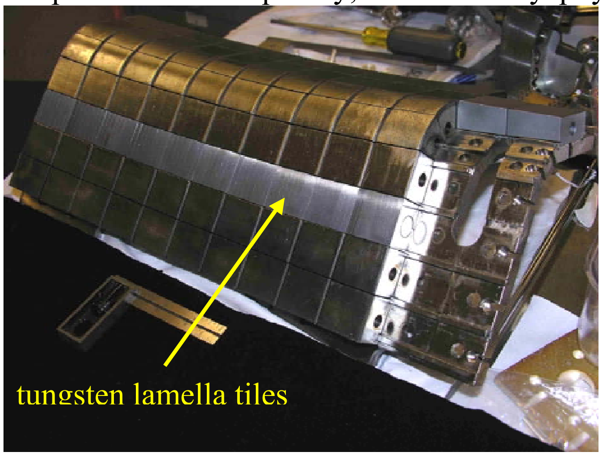

Figure 2.1.12: Row of tungsten lamella tile modules (light gray tiles) being assembled onto a lower divertor cassette.

Another area where the boundary physics group supports the C-Mod program is in cryopump development. Figure 2.1.13 shows the geometry of the cryopump system that has been recently installed in the upper divertor. We anticipate that this system will become an important tool for controlling and reducing the core plasma density – allowing lower hybrid current drive efficiency to be explored at reduced densities as well as providing key access to lower collisionality regimes. For example, low collisionality H-

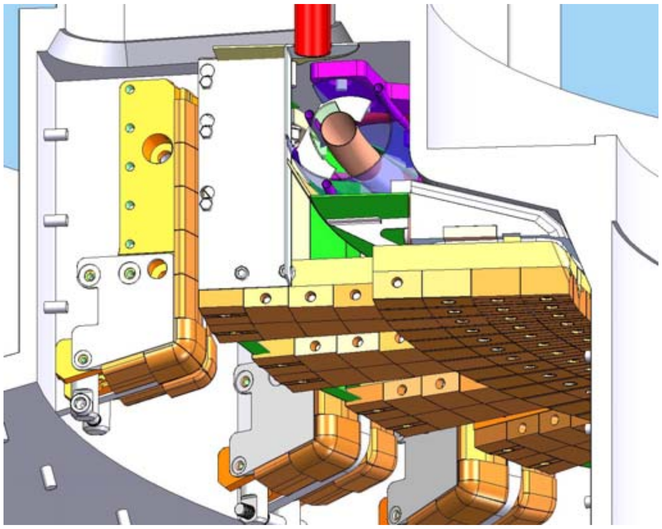

Figure 2.1.13: Unique geometry of the upper divertor cryopump system in C-Mod, employing a regular array of 30 'pumping slots'. The pumping slots sample plasma in the outer divertor leg. The strike point hits the first continuous toroidal ring of tiles.

modes may help C-Mod to access different ELM regimes.

The design of the upper divertor cryopump system is unique among tokamaks, featuring a regular array of 30 pumping slots instead of the traditional axisymmetric design. This design is the outgrowth of a set of dedicated experiments that were performed in 2005 that assessed different pumping/baffle geometries. Significantly higher plenum pressures were found in the pumping slot geometry compared to the axisymmetric geometry, with reduced sensitivity to upper strike point location. The close proximity of the tile surfaces to the upper null also leads to excellent heat-flux handling via increased flux expansion.

We will commission the cryopump during the 2007 campaign. First we will assess its performance, with the help of newly installed instrumentation: two in-vessel Penning gauges and one Baratron gauge for plenum pressures and an array of 14 probes embedded into the divertor target to measure incident particle fluxes. Then we will explore density control scenarios with a variety of different magnetic equilibria and gas-puffing schemes. Finally, we will utilize the cryopump as a density control tool in support of C-Mod physics experiments.

2.1.7 Relationship of the C-Mod boundary program to ITPA, FESAC priorities

The C-Mod boundary physics program addresses a number of **high priority ITPA issues** including:

- *Understanding of tritium retention, and development of efficient T removal methods.*
    - Understanding D levels on tiles and tile sides for B and Mo
    - Understanding removal of D at low tile temperature
- *Improve measurements & understanding of plasma transport to targets and walls, for better prediction of heat load, and effects on the core plasma*
    - Wall flux measurements (‘main chamber recycling’)
    - Impurity influx and screening studies
    - Inner SOL flow measurements, models of what drives SOL flows
    - Radial flux analysis - transport coefficients
    - Gradient scaling work (near SOL) connection to fluid turbulence theories
    - Dimensionless comparisons and scalings of SOL characteristics across tokamaks
    - SOL flows and effect on core
- *Understand the effect of ELMs/disruptions on divertor and first wall structures*
    - Measurements of ELM velocities and size in the SOL
- *Understand how conditioning and operational techniques can be scaled to reactor devices*
    - Studies of boronization erosion processes
    - Studies of how the eroded molybdenum affects the core plasma
    - Development of tungsten tiles in ITER-like design.
    - Marker tiles
    - Use of S3 to determine boronization deposition rate and profile

The C-Mod group is involved in a number of **IEA-ITPA collaborations:**

- DSOL-3 ‘Study of radial transport’, B. Lipschultz organizer

- DSOL-4 'Comparison of disruption energy balance and heat flux profile', D. Whyte, J. Terry, contributor
- DSOL-5 'Role of Lyman absorption in the divertor', J. Terry, contributor
- DSOL-11 'Disruption mitigation experiments', R. Granetz contributor
- DSOL-13 'Deuterium co-deposition in gaps of plasma facing components B. Lipschultz participant
- DSOL-15 'Inter-machine comparison of blob characteristics' J. Terry organizer

The C-Mod Boundary physics researchers are leading one of the CY2007 ITER tasks requested of the US – subtask #3: '**'Effects of radiation transfer on divertor plasma'**

Lastly there is clear support of the FESAC priorities –
Topical questions:

- **T10**: "*How can we interface a 100 million degree burning plasma to its room temperature surroundings*"
    - C-Mod addresses this at the highest parallel power levels with Mo (& W) surfaces
    - Studies of transport in the SOL (parallel and perpendicular to magnetic field)
    - Plasma-materials interactions (Mo, W, boron coatings)
    - Materials development (e.g. W tiles) and operational experience

"Selected High Priority Activities":

- "*Carry out additional science & technology activities supporting ITER including diagnostic development, predictive modeling and enabling technologies*"
    - Predictive modeling - collaborative work with modelers to provide radiation transport and divertor plasma data at ITER conditions.
    - Enabling technologies - development of ITER-like bulk W tiles.
- "*Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments*"
    - D retention and removal studies in a high-Z environment
    - Compatibility with core (melting, impurities)
- "*Expand the effort to understand the transport of particles and momentum*"
    - C-Mod a world-leader in the study of cross-field transport of particles

The source of parallel flows, their transport and effect on core confinement are central studies

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2.2 Transport

Recent Highlights

Transport research on C-Mod emphasizes areas important for plasma science and of strong relevance to ITER. Embedded in a national and international transport program, we concentrate on those issues where we have unique capabilities, where we run in unique parameter regimes and where we observe unique or unusual phenomena. Comparisons with theory and modeling form a critical part of the program, motivating and influencing the design of most experiments in the transport area. We have established close collaborations with theory and modeling groups at MIT and elsewhere. Topics of recent interest include rotation and momentum transport in plasmas with no external torque; particle transport and density peaking at low collisionality; internal barrier physics with equilibrated ions and electrons and no core particle or rotation sources, edge barriers, including threshold, confinement, pedestal scaling and mechanisms which control the pedestal such as ELMs and the quasi-coherent mode. There are obvious close connections with the integrated scenario research, but also strong coupling to the boundary, stability and wave-particle topics. A good deal of the most interesting physics occurs at the interfaces between topical areas.

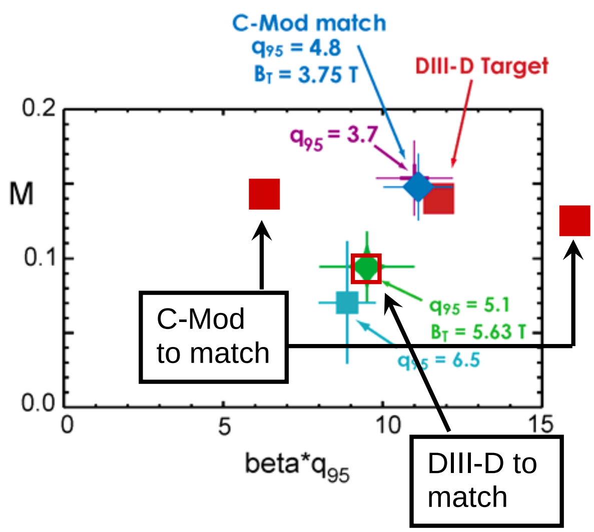
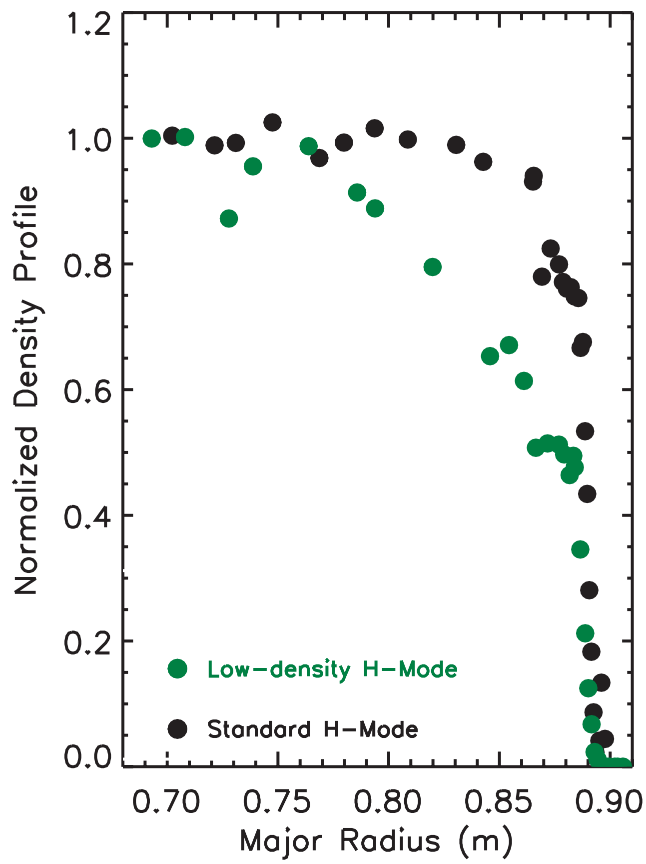


Fig. 2.2.1. Dimensionless comparisons of spontaneous rotation in C-Mod and DIII-D. The plot includes one comparison already made and three more conditions which will be tested

Work on self generated rotation in torque-free plasmas has included a number of inter-machine comparisons. As part of an ITPA effort, data from several devices have been assembled and empirical scaling studies have begun. Data from C-Mod, JET, Tore-Supra, JT-60U, TCV and DIII-D can be roughly overlaid when the normalized velocity M_A (rotation velocity divided by the Alfven velocity) is plotted vs β_N. This result, if extrapolated to ITER, would predict $M_A \sim 0.02$, which may be adequate for suppression of RWMs. Surprisingly, no strong dependence on ρ^*, which characterizes the diamagnetic velocity, is observed. This work will be augmented by additional data and more rigorous statistical analysis. Dimensionless identity experiments have been carried out in concert with DIII-D. Fig. 2.2.1 shows results along with plans for future work.

With recent results from ASDEX-U, the possibility of producing plasmas in ITER with moderately peaked density profiles has attracted a great deal of interest. These experiments showed density peaking which increased as the plasma collisionality was lowered. Typical H-modes in C-Mod have very high collisionality and very flat density profiles, however a series of experiments run at high triangularity $\delta_L \sim 0.8$ and low elongations, $\kappa \sim 1.5$, did allow operation at, for C-Mod, low density and showed strong peaking. A pair of profiles is plotted in figure 2.2.2, which shows the peaking occurring over the outer 60% of the plasma cross section. Using the parameterization proposed by the ASDEX-U group, the density peaking is plotted in fig 2.2.3 against ν_{EFF}, the collision frequency normalized to the diamagnetic frequency. These data overlap ASDEX-U and JET data which have been collected by Angioni and Weisen. Those authors noted that the strong covariance between collisionality, ν_{EFF} and the normalized density, $n_G = n_e/n_{LIMIT}$, did not allow extrapolation to ITER, which, uniquely, will run at low ν_{EFF} and high n_G. Addition of C-Mod data helps to break the covariance and suggests that ν_{EFF} is the appropriate scaling parameter and that peaking might be expected on ITER.



.Fig 2.2.2. Normalized density profiles for standard high-density H-modes $<n_e> \sim 4 \times 10^{20}$ and low-density, low-collsionality H-modes, $<n_e> \sim 1.8 \times 10^{20}$ produced by modifying the plasma shape.

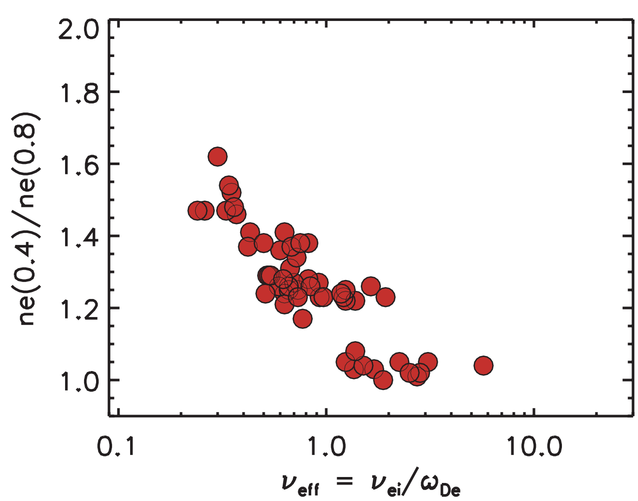


Fig 2.2.3. Density peaking plotted against ν_{EFF}, the collision frequency normalized to the diamagnetic frequency.

Studies of internal transport barriers have focused on

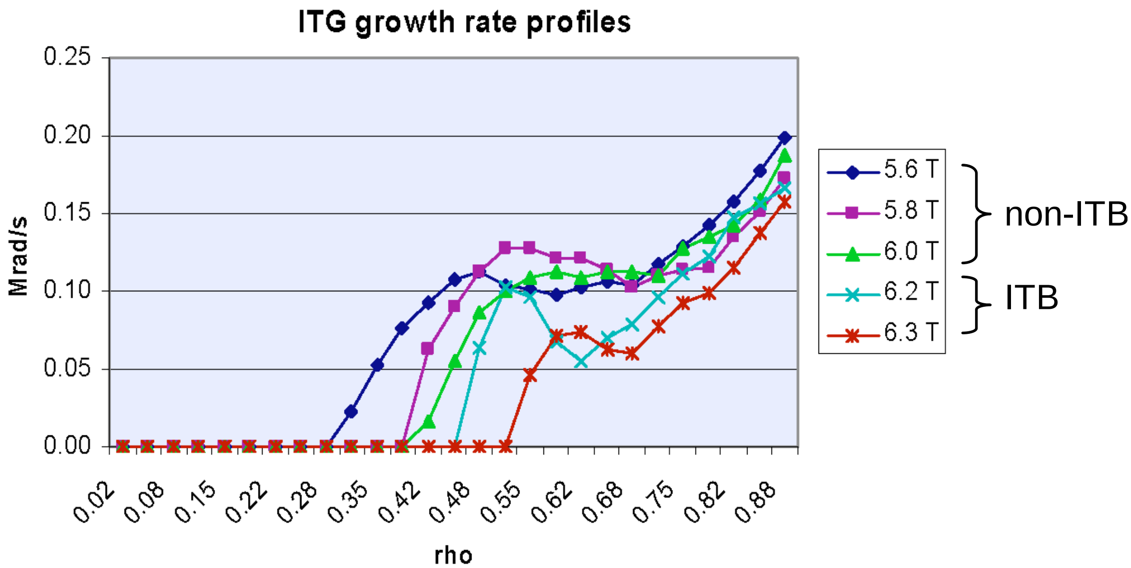


Fig 2.2.4. Linear ITG growth rates plotted vs radius for different values of the magnetic field. These correspond to different ICRF resonance locations and the result supports the hypothesis that ITBs are formed when the temperature gradient is sufficiently modified to suppress ITG turbulence.

formation and control issues. In C-Mod, barriers are routinely produced by application of off-axis ICRF heating. These discharges have steep density profiles and sharply reduced thermal and particle diffusion over the inner half of the plasma. An early hypothesis, that the barriers were formed due to reduction of the core temperature gradient was supported by gyrokinetic simulations. This model had, however, some difficulty explaining the extreme sensitivity to RF resonance location. A change in the magnetic field by only a few percent could determine whether a barrier formed or not. A recent set of experiments making careful measurements of the temperature profile over the relevant range in fields, was carried out to investigate this issue. A significant and systematic change in the gradient was seen to occur near the barrier threshold field. These data were then used as input to gyrokinetic simulations using the gs2 code. Results are shown in fig 2.2.4 where the linear growth rate is plotted vs radius for different locations of the magnetic field/ICRF resonance. Consistent with our hypothesis, ITG growth is suppressed when the resonance is moved off-axis and drops to zero at the barrier foot location under conditions where ITBs will form.

By operating with reversed B, that is with the ion ∇B drift away from a single-null x-point and with a greatly increased power threshold, H-mode transitions were obtained with two distinct phases. Typical traces are shown in figure 2.2.5, where the transition at 0.8 seconds is preceded by a period of about 30-40 ms of “slow” profile evolution. A modest temperature pedestal is formed and slowly grows during this time accompanied by changes in rotation velocity and density fluctuations. Stored energy increases with the H_{89} factor reaching about 1.5 before the “classic” transition. This second transition is accompanied by a further prompt drop in fluctuations, and increases in temperature and density pedestals. There is some evidence that significant changes in E_r do not occur until the second transition. The physics determining pedestal structure has been explored

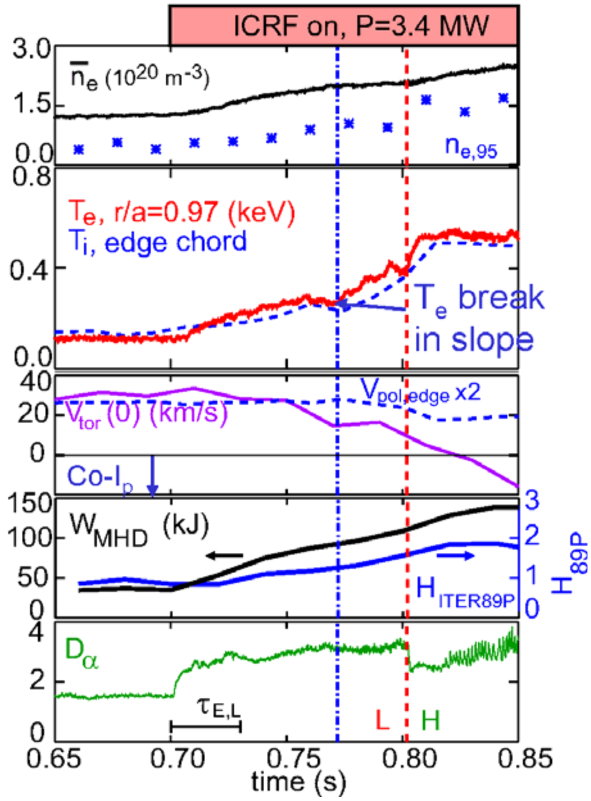


Fig 2.2.5. Slow, 2 stage L-H transitions are observed when the threshold is raised by running with the ∇B *ion drift in the unfavorable direction.*

through experiment and modeling. Experimentally, the density pedestal width varies little, while the height is set primarily by the value of driven plasma current and varies weakly with available neutral source. Indeed, a high degree of density pedestal resilience is observed even when aggressive gas puffing is applied to H-mode plasmas. H-modes of higher than usual threshold, obtained by running at high magnetic field (8T) or with the ∇B drift in the unfavorable direction, did have consistently lower density and lower collisionality, though with the same pedestal pressure as standard H-modes. Reversed field results are consistent with the important role for SOL flows in the L-H transition, which was reported previously.

Exploration into the mechanisms that regulate edge transport, namely ELMs and the quasi-coherent mode (QCM), has moved forward. The low-density, low-collisionality H-modes, described above, were accompanied by discrete ELMs, larger than normally observed on C-Mod. The shape and collisionality requirements for obtaining this ELM regime have been roughly determined, and the pedestal stability analyzed using the ELITE code. Properties of the QCM, which is responsible for the enhanced D-alpha (EDA) H-mode, have been studied using numerous fast diagnostics, resulting in clear observation of harmonics, as well as apparent coupling to higher-frequency core modes. By moving the plasma relative to PCI channels, it was possible to demonstrate an interaction between the x-point location and the structure of the QC mode. Figure 2.2.6 shows a series of such discharges. These results are qualitatively consistent with BOUT code simulations of an x-point mode, which is a resistive ballooning mode strongly modified by the flux expansion near the x-point. Quantitative comparisons with the code are planned.

Research Plans

Recent and planned facility upgrades offer exciting opportunities well aligned with transport research interests. The high-power LH system has the capability for efficient, off-axis current drive and thus the direct manipulation of magnetic shear. The cryopump

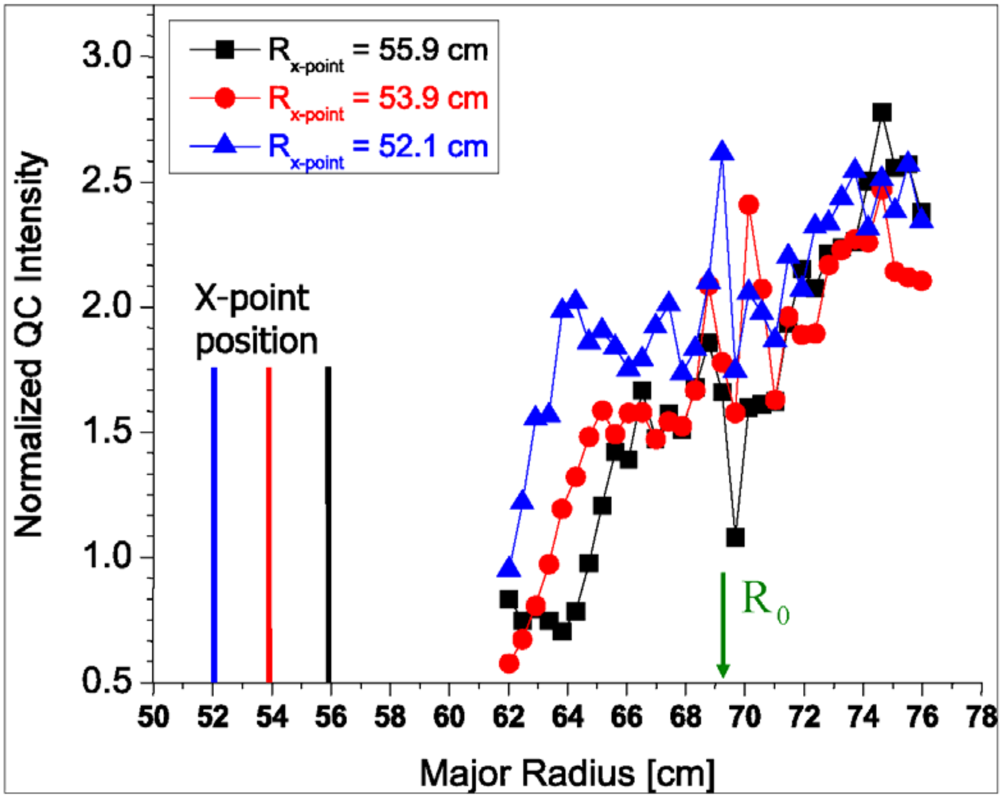


Fig 2.2.6 PCI observations of the QC mode suggest a strong effect of the x-point location on the mode structure.

should allow study of high-performance plasmas at significantly reduced collisionality. Both parameters are predicted to have important effects on turbulence and on the marginally stable temperature profile. The expansion of parameter space will also allow for greater overlap in joint experiments. There are significant enhancements of profile and fluctuation diagnostics underway, most notably improvements in the coverage of ion temperature and velocity profiles; a pair of diagnostics for the plasma current profile; and upgraded fluctuation diagnostics for turbulence studies. As prediction and control are the ultimate goals of transport studies, validation of turbulence codes is an emerging theme in the transport community. Experiments and theory have progressed to the point where meaningful quantitative tests are now being made and theory plays a critical role in motivation, design and analysis of most experiments carried out on C-Mod. Transport research over the next two years will focus on areas motivated by emerging theoretical issues and enabled by these new diagnostic and facility capabilities. In collaboration with the PSFC theory group, the local Beowulf cluster is undergoing a major upgrade which will allow nonlinear gyrokinetic runs locally with reasonable turn-around.

Areas of study will include quantitative tests of the “standard” model for ion energy transport – drift-wave turbulence regulated by zonal flows; experiments into momentum transport and self-generated rotation; particle and impurity transport; and investigations into the nature of anomalous electron energy transport. The manipulation of magnetic shear should also open up avenues for creation and manipulation of internal transport barriers in steady-state plasmas. Experimental time will be devoted to edge barriers including investigations of the L/H threshold and its connection to equilibrium and fluctuating flows; edge barrier relaxation mechanisms especially small ELM and EDA regimes; pedestal scaling; momentum transport in the pedestal; transition and bifurcation dynamics and a search for evidence of turbulence spreading.

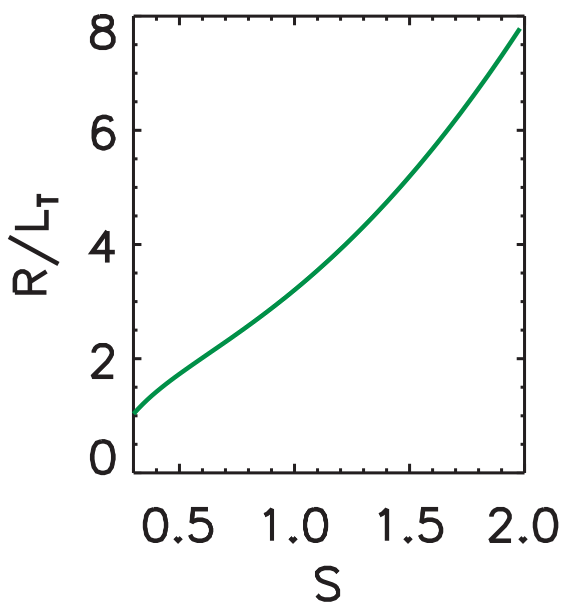


Fig 2.2.7. A theoretical prediction of the effect of magnetic shear on the normalized temperature gradient.

Theory and simulations predict that magnetic shear can have a substantial effect on the stability of drift-wave turbulence and the overall levels of transport (see fig 2.2.7). In fact, in reactor-like regimes, with confinement time much longer than electron-ion equilibration, ($T_e \sim T_i$), low rotation ($\gamma > \omega_{ExB}$), low impurity content, ($Z_{EFF} << Z_{AV}$) and relatively flat density profiles, ($R/L_n < R/L_T$), magnetic shear, $\hat{S}$, is one of the very few "free" parameters which can modify transport. We plan to exploit the newly commissioned lower-hybrid current drive system in experiments aimed at exploring the role of magnetic shear in turbulent transport. Work will begin in L-mode at relatively low densities and progress to H-modes as increased LH power is available. Quantitative comparison will be made with gyrokinetic codes which predict that very low or reversed magnetic shear can significantly reduce or eliminate the drive for important micro-instabilities. The experimental goal will be to create and maintain simultaneous electron and ion ITBs in the presence of strong central heating and weak momentum drive. These studies underpin future AT work, where increased pressure gradients are required to provide bootstrap current. In the regime of strong electron-ion coupling, typical of C-Mod or ITER, transport barriers in one channel are not sufficient. Previous work on other devices suggests that modification of magnetic shear is a necessary condition for creation of electron barriers. Because of the relatively large ratio of discharge time to current penetration time on C-Mod, it is not possible to maintain modified shear configurations created during current-rise; however, with LHCD it should be possible to vary this important parameter in a steady-state manner and investigate control of barrier position and strength via control of the LH *k* spectra and power. The high efficiency of lower hybrid waves for driving off-axis current may allow the creation of discharges where a large portion of the plasma volume is within the ITB. Studies of the role of magnetic shear in pedestal and edge transport are also planned and are discussed below.

Collisionality is predicted to have a significant impact on ion transport. Collisionality can enter directly through the instability drive or indirectly via its effect on zonal flows, which is believed to be the main nonlinear saturation mechanism for drift-wave turbulence. In this case, collisions are competing with nonlinear dissipation of the zonal flows via additional turbulence effects. Early non-dimensional experiments on C-Mod at high levels of collisionality, ($\nu^* = 0.2 \rightarrow 1$), found a result which was superficially consistent with the linear zonal flow damping model. That is, if collisions were regulating the zonal flows, then higher collisionality should lead to lower levels of zonal flows and consequently higher levels of drift wave turbulence and transport. This interpretation is in contradiction to results of nonlinear simulations which found that the reduction of the ITG drive was more important than zonal flow damping in setting the overall level of transport. These simulations were carried out at somewhat lower values of collisionality than the experiments however. We are planning experiments to extend these studies to lower density via the cryopump and to carry out computational studies of TEM driven turbulence, which has a somewhat different balance between instability drive and dissipation.

Spurred in part by the need to predict the density profiles and impurity content in ITER, there is renewed interest and emphasis on particle transport. As discussed above, studies will be carried out, using the cryopump to access lower collisionality regimes and investigate density peaking with no core particle source in our standard configuration and plasma shapes. This should provide a more definitive test of the predictions and would provide more overlap with other experiments. Results from C-Mod described above, along with results from ASDEX-U and JET, suggest that the important dependencies to explore include ν^*, triangularity and q_{95}. Scans of these parameters are planned. Corresponding theoretical studies will assess the relative importance of TEM and ITG turbulence in this regime. Simultaneous studies of pedestal transport will be carried out. The LHCD system should allow investigation of the anomalous particle pinch. With $E_{\Phi} = 0$, as it would be for a fully non-inductive discharge, the Ware pinch is eliminated as a cause for inward convection.

Recent enhancements to the PCI diagnostic allow us to distinguish core modes from edge fluctuations and to determine the direction of propagation in the plasma frame directly. This differs from standard methods, which measure the lab-frame phase velocity from the ω-k spectrum and must subtract the measured flow velocity. Since the driven rotations are typically much larger than the phase velocity, the uncertainties of this procedure do not allow unambiguous identification of mode propagation direction, which is a key signature for the underlying drift-wave mode. Measurement of the fluctuation propagation in the plasma frame would help determine the nature of the drift wave turbulence, ITG or TEM, that dominates and could be compared directly to simulations. C-Mod will continue to develop a unique diagnostic for zonal flows which is based on the motion of plasma ablated from lithium pellets.

Transient particle transport experiments will be carried out in both ITB and H-mode regimes, with the results compared to numerical simulations. These studies use the transient density evolution, which follows regime transitions, to allow extraction of transport coefficients. The CXR diagnostics will enable studies of impurity transport, especially in the outer regions of the plasma. The laser blow-off system is being rebuilt to allow routine study of impurity transport in a wide variety of discharge conditions. The new system will use a 10 Hz YAG laser and an optical scanning system to allow multiple injections per plasma. Correlations between impurity and momentum transport are of particular interest as both show similar behavior in many respects.

Plasma rotation has been shown to be an important stabilization mechanism for micro and macro-instabilities. However, as we move toward ITER and to reactors, which will have little or no external torque, it is not clear how much rotation to expect. In this light, the observations of strong, self-generated flows on C-Mod are a significant result and one that needs to be better understood. To improve spatial coverage of the core rotation profiles, a new high resolution x-ray spectrometer is being installed on C-Mod. A prototype for an ITER design, this instrument consists of a pair of spherically bent crystals (one set to measure Ar^{17+} and one for Ar^{16+}) and a set of high-throughput 2D detectors. It will record spectra from multiple sightlines, measuring $T_i(r)$ and $V_\phi(r)$ with spatial resolution ~1 cm and time resolution of 5-10 ms. Significant upgrades have also been made in the CXR systems which measure toroidal and poloidal rotation in the outer third of the plasma cross section. The higher throughput of the new HIREX system should allow high-quality measurements with less injected argon and facilitate more routine profile measurements. Experiments to measure momentum confinement will be carried out by analyzing transient evolution of the rotation profiles. Transients will include L-H and H-L transitions, ITB transitions, magnetic braking from external non-axisymmetric coils and changes in plasma topology. Multi-machine scaling experiments, coordinated through the ITPA, will continue along with dedicated inter-machine dimensionless identity experiments carried out with DIII-D.

With better spatial coverage, a key question which we can address is the spatial structure of the self-generated flows and perhaps their spatial origin. Previous work has shown that, in L-mode, the SOL provided a boundary condition for core rotation, but that there are additional transport mechanisms at work. We should be able to identify regions of strong inward momentum transport and shed light on coupling mechanisms. A goal will be to characterize rotation and momentum transport through the pedestal region. (The flatness of currently available core rotation profiles in steady-state H-modes suggests a steep gradient region, perhaps a rotation pedestal with a structure on the same spatial scale as the temperature and density pedestal). We will attempt to determine the relative importance of plasma processes such as turbulent Reynold's stress and collisional viscosity as well as the role of atomic processes like charge exchange in coupling momentum across the separatrix from the SOL to the confined plasma. Experiments will examine regimes where the neutral interactions could be modified, including variations in neutral density, fueling, cryopumping and studies in helium plasmas. The mechanism by which momentum is transported from the edge into the core will be investigated, using gyrokinetic codes "instrumented" to output quantities relevant to momentum transport. In addition to profile comparisons, these studies may point to fluctuation measurements which may allow further tests of the simulations. The improved spatial coverage will also allow a more quantitative assessment of the role of ExB stabilization across the entire plasma cross section.

The enhanced core fluctuation measurements will be employed to answer several important questions in transport physics. Anomalous electron transport is perhaps the most important unresolved issue in the transport area. In reactors like ITER, the ions and electrons will be closely coupled and thus the electron channel cannot be ignored. Little is known about the mechanisms at work; there is not even a clear picture of what range of spatial scales are important. With the PCI diagnostic, which has excellent signal to noise and can measure fluctuations up to 5 MHz with wavenumbers up to 50 cm^{-1}, we will attempt to identify the relevant spatial scales in various plasma regimes. This wavenumber range is appropriate, for example, to study the coupled ITG-TEM-ETG turbulence found in GYRO runs by Waltz and Candy. The first experiments are aimed at very low density Ohmic plasmas where the transport channels are decoupled and where ion transport is near neoclassical levels. Discussions over joint experiments with DIII-D and NSTX have begun. Modifications to the PCI diagnostic allow spatial localization of the observed fluctuations. For short wavelengths, this localization should be sufficient to allow measurement of the isotropy of the plasma turbulence. If short wavelengths modes, like ETG, are responsible for electron transport, they must develop extended radial structures which can increase the radial energy flux to the levels seen in experiments. This topic is currently a subject of great controversy and interest in the theory community. The LH system, operated in heating mode, will provide a moderately localized electron heating source that can be used for further studies of transient electron transport.

Further research will be carried out on ITBs produced by off-axis ICRF heating. Using improved profile and fluctuation diagnostics, we will carry out additional tests of the transport model proposed for this regime: suppression of ITG via reduction of temperature gradient, reinforced by reduction of ITG by density peaking, then saturation via TEM turbulence driven by the density peaking and central heating. Low density ITBs should be accessible with the cryopump, allowing highly localized measurement of low k fluctuations at the barrier foot. To improve the level of sensitivity for turbulence studies, all reflectometer channels are being set up to isolate the phase signals from the upper and lower sidebands and outputting the individual phases (baseband) as well as the difference (AM). The main benefit of this method is that the signal is no longer acquired by subtracting two closely related signals. An additional channel at 140 GHz has been added, extending the density accessible by this diagnostic to $2.4 \times 10^{20}/m^3$, which should allow the core regions of advanced secnario plasmas to be probed. Radial correlation measurements will be carried out using a swept-frequency source (Δf = 5-10 GHz) and poloidal correlation measurements made using poloidally displaced antenna and receiver sets. As the LHCD experiments progress, studies of transport suppression and barrier formation via modification of the magnetic shear will be performed. As discussed above, these prepare the ground for future AT studies.

SOL flows are seen to have a significant impact on the H-mode power threshold, which is observed most dramatically in the transition's topology dependence; it has been shown that the power threshold and flows are extremely sensitive to the magnetic balance of the discharge in near double-null geometry. Such experimental work should provide input for potential modifications to L-H transition and bifurcation theory. Studies of the “slow” or “two-stage” L-H transitions, described above, will benefit from the improved diagnostic coverage, especially for edge ion temperature and flow profiles. These experiments hold out the hope of isolating important elements of the L-H transition and putting predictions of the threshold on a firmer basis.

The structure and scalings of the edge pedestal will be explored further, as the range in operational parameters over which H-modes are obtained is expanded. Additional emphasis will be placed on pedestal scalings at low collisionality, where ELMs may replace EDA as the dominant regulation mechanism. To this end, we are beginning comparisons with the XGC code, being developed under the CPES project. New diagnostics will allow systematic studies of ion temperature and velocity profiles across the C-Mod parameter range. We have previously noted that, with the exception of an observed dependence on δ and q_{95}, the pedestal width does not vary strongly with most external control parameters. To follow up these results, a concerted effort to study the effect of magnetic shear on pedestal structure will begin. Related experiments will look at the roles of magnetic shear and plasma flows in regulating SOL transport. The systematic comparison of pedestals with favorable and unfavorable ion ∇B drift will continue. Progress in modeling the neutral fueling of the density pedestal will be followed up with further analysis of the kinetic neutral results, comparisons to fluid modeling results, and incorporation of a critical-gradient assumption for the plasma transport. Neutral fueling studies will be aided by new neutral emissivity measurements, a set of Ly_{α} arrays, which will allow routine diagnosis of pedestal fueling and particle sources and provide more information about the poloidal distribution of neutrals. There will be continued examination of the critical-gradient hypothesis for H-mode pedestal structure, and an attempt to discern the physical connection between the observed H-mode pressure gradient scaling and that seen in the near-SOL of Ohmic plasmas. Dimensionless inter-machine comparisons of pedestals will be carried out, to assess the importance of factors, such as neutral physics, not considered in the standard Connor-Taylor formulation for scaling invariance. An additional question to be considered is what mechanisms are responsible for the region of intermediate temperature gradient observed between the narrow pedestal region and the main core plasma. This region is observed to be 1-2 cm in extent, or roughly 20 poloidal ion gyroradii, and could be evidence of turbulence spreading analyzed by Hahm and Diamond.

We have already seen that operation at low density is correlated with the appearance of large ELMs which have appeared in a high-triangularity, low elongation plasma shape. Studies with the cryopump should allow us to investigate this phenomenon in our standard shape. Details of ELM studies are described elsewhere, but experiments will emphasize benign ELMy regimes on C-Mod and work toward an improved mapping of their existence criteria in both dimensional and non-dimensional edge parameters. Further studies of precursors and ELM propagation dynamics will proceed, as will an experiment attempting to match the small ELMy regime of NSTX. The QCM in EDA H-mode will also be studied further, as ongoing work attempts to uncover more information on the mode's radial structure and harmonics. Through comparisons of results with predictions of Kelvin-Helmholtz instability and analysis with the BOUT code, a more definite identification of the mode (resistive ballooning, K-H or other) will be sought, along with answers to persistent questions about the mode, in particular, its ability to drive strong particle transport while maintaining good energy confinement, the mode's saturation mechanism, the radial extent of the mode and the role of the poloidal x-point in determining the mode structure.

In summary, with its capable and unique facilities, strong diagnostic set and wide collaborations with theory and modeling, the C-Mod experiment offers excellent opportunities to advance the state of transport science. In the coming years, all three of these components will be improved and expanded. The cryopump and LHCD represent important opportunities to extend C-Mod parameters in important directions and are accompanied by significant upgrades in core profile and fluctuation measurements.

Support for ITER and Connection to ITPA Activities

C-Mod transport research makes or is planning contributions to the following ITER High Priority Research Tasks (most recent version, defined for 2006-2007):

- Utilize upgraded machine capabilities to obtain and test understanding of improved core transport regimes with reactor relevant conditions, specifically electron heating, $T_e \sim T_i$ and low momentum input, and provide extrapolation methodology
- Develop and demonstrate turbulence stabilization mechanisms compatible with reactor conditions, e.g. s-α-stabilization, shear flow generation, q-profile. Compare these mechanisms to theory
- Study and characterize rotation sources, transport mechanisms and effects on confinement and barrier formation
- Quantitative tests of fundamental features of turbulent transport theory via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings
- Resolve the differences in β scaling in H-mode confinement
- Develop a reference set of ITER scenarios for standard H-mode, steady-state, and hybrid operation and submit cases from various transport code simulations to the Profile DB
- Resolve which is the most significant confinement parameter, ν^* or n/n_G (for confinement scaling)
- Understand the aspect ratio dependence of the L-H power threshold
- Understand the collisionality dependence of density peaking

- Develop common technologies for integrated modeling, e.g. frameworks, code interfaces, data structures
- Improve Predictive Capability of Pedestal Structure through Profile Modeling and Experimental Studies
    - Dimensionless cross machine comparisons to isolate physical processes; assess dependence on ρ^* , ripple, rotation, and shape.
    - Measurement and modeling of inter-ELM transport
    - Establish profile database for modeling joint experiments including effects of neutrals
- Physics based empirical scaling of pedestals
    - Collaboration with CDBM to improve scalar database characteristics and utilization
- Improve Predictive Capability of ELM characteristics through experimental studies and theory / modeling analysis, and develop small ELM and quiescent H-mode regimes and ELM control techniques
    - Define physics requirements for ergodic field application as ELM control schemes in ITER
    - Integrate observations of ELM crash dynamics and initiate comparisons with developing models
    - Categorize small ELM regimes based on cross machine comparisons

C-Mod is currently involved in the follow set of transport related ITPA joint experiments

CDB-4 Confinement scaling in ELMy H-modes, ν^* scans
CDB-8 ρ^* scaling
CDB-9 Density peaking at low ν^*
TP-1 Steady state plasma development
TP-3.2 Investigation of transport mechanisms with T_e~T_i
TP-6 Obtain empirical scaling of spontaneous plasma rotations
PEP-7 Pedestal width analysis via dimensionless identity experiments
PEP-16 C-Mod/NSTX/MAST small ELM regimes
TP-2 Hybrid regime development
TP-3.1 Sustained high performance operation with $T_i \sim T_e$
TP-4.2 Low momentum input operation of hybrid/AT plasmas
TP-4.3 Electron ITB similarity experiments with low momentum input

The C-Mod transport program is also well aligned with the recommendations of the 2005 FESAC priorities panel. Top recommendations for additional funding for high-priority activities included the following areas of particular emphasis on C-Mod:

- *"Carry out additional science and technology activities supporting ITER…"*

- *"Predict the formation, structure and transient evolution of edge transport barriers."*
- *"Mount a focused enhanced effort to understand electron transport"*
- *"Expand the effort to understand the transport of particles and momentum"*

2.3 Wave –Plasma Interactions

C-Mod exclusively uses RF for auxiliary heating (predominantly ion cyclotron range of frequency - ICRF) and current drive (lower hybrid range of frequency - LHRF) to heat and control the current profile for a wide range of plasmas. Both ICRF and LHRF are considered excellent candidates for future reactors and experiments, as evidenced by the current ITER plans to include ICRF and possibly LHRF in its initial phase. We seek to develop an understanding of the underlying technological and physics issues associated with high power ICRF and LHRF operation. C-Mod is an excellent facility to investigate a number of unresolved physics and technological issues since the wave characteristics in C-Mod are similar to those expected in ITER. In ICRF, the single pass absorption in H minority heating in C-Mod can be more than 80%, similar to the expected single pass absorption in ITER. In the LHRF, the C-Mod system is optimized for off-axis current drive and operates at the ITER B-field and density resulting in similar wave accessibility and absorption physics as expected in ITER. Thus, the C-Mod experiments are well positioned to contribute to the evaluation of LHCD physics for ITER. Furthermore, C-Mod has several advanced diagnostics (hard x-ray camera, phase contrast imaging, compact neutral particle analyzer) for RF wave measurements that facilitate experimental benchmarking of advanced simulation tools through collaboration with the SciDAC Center for Simulation of Wave Plasma Interactions (CSWPI).

2.3.1 ICRF

2.3.1.1 Antenna coupling and Antenna/Plasma interactions

A primary concern regarding the planned ICRF system on ITER is antenna operation. An ideal ICRF system would have the generator isolated from the load and/or would be resilient to load variations and efficiently couple power to the plasma with minimum negative impact on the plasma, particularly the plasma edge. We have identified two principal areas where C-Mod can efficiently and effectively contribute: understanding the underlying physics of antenna power and voltage limits and understanding RF-plasma edge interactions that lead to impurity production, enhanced sputtering, and localized hot spots.

In C-Mod, we have reliably operated two 2-strap (D and E antennas) and a 4-strap (J antenna) antenna at high power density (>10 MW/m^2) and are planning to design and install a new four strap antenna in FY09. We have used the J antenna (4-strap antenna) to test various protection tiles, power feeds, and Faraday screen configurations which will inform the design of the new antenna. We have continued our work on a small test facility by adding a magnetic field to the device to investigate the role of magnetic field in RF breakdown. We found that the pressure at which a discharge is initiated is significantly lowered in the case when magnetic field is parallel to the RF electric field. We can eliminate this discharge for parallel plate geometries by lowering the secondary electron coefficient of the electrode surfaces. In the case of coaxial geometries, the pressure at which breakdown occurred could be raised but not eliminated altogether as in the case for parallel electrodes. Varying the gas also affected the pressure at which a discharge formed where those with low electron ionization cross-sections required higher pressure to achieve breakdown. An outstanding question for the so-called neutral pressure limit is the initial fault. We plan to modify the setup to allow this fault scenario to be investigated. We also plan to investigate the influence of magnetic field in parallel plate geometry at high power. This is motivated by the observation on C-Mod and a number of other devices where the ultimate voltage is set by locations where the RF electric field is parallel to the magnetic field. We would like to quantify the voltage degradation between the cases of RF electric field perpendicular and parallel to the magnetic field.

The compatibility of high power ICRF with all metal plasma facing components (PFC) and high plasma performance is a critical issue for C-Mod and future devices, such as ITER. The key to high plasma performance on C-Mod has been determined to be the control of impurities, particularly Mo, through boronization.[1] Through a series of experiments, the primary source responsible for the increased Mo and associated radiation was linked to the active antenna and located on the outer divertor.[2] The mechanism is likely a result of enhanced sputtering due to RF sheaths.[3] We plan to investigate this further in the near term by investigating boronization lifetime dependence using marker tiles magnetically linked to the J antenna. An outstanding question is why this source location is the most important in the present configuration. One thought is that the convective cells driven by the RF-enhanced sheaths may be responsible for enhanced impurity penetration from this location. To investigate we will perform experiments where the magnetic topology is changed to attempt to move the source location or change the direction of the convective cell. Another issue is to investigate filament transport in the presence of RF heating and we will begin by using the existing gas puff imaging diagnostic at low plasma current. Depending upon the results, we would like to expand this investigation to more standard 1 MA discharges. With the installation of the new antenna, a new, prototypical ITER ICRF antenna reflectometer (in collaboration with ORNL) is planned and will have the option to measure the local density near the top, middle, and bottom of the antenna to determine the extent of the up-down density asymmetry near the antenna. In addition to identifying the location of the important Mo sources, we need to develop a technique to improve the boronization lifetime or reduce the impurity influx. One line of research is to use low Z-coatings deposited by vacuum plasma spray onto specific tiles. We will test a set of B coated tiles in the near term to investigate how well they perform in a tokamak environment, particularly disruptions. Another means is to reduce the parallel electric field excited by the antenna to reduce the enhanced sheath potential and the strength of the convective cells.

Plasma load variations are commonly encountered during L/H transitions and edge localized mode activity (ELM's). In the past campaign, we have begun to study ELMs with fast digitizing of the reflection coefficient measurements. Comparing with the gas puff imaging diagnostic, we can identify the so-called precursor, primary, and secondary ejections in the reflection coefficient time history. The relative perturbation of the reflection coefficient is dependent upon the ELM size and we often get to the limit of the arc protection circuit and trip the transmitter. We also note that the time scale for the loading variation is faster than an L->H or H->L transition. One potential solution to the load variations is to deploy a fast matching system and we plan to investigate the integration of a fast ferrite stub system into the E antenna matching network. We have received and refurbished two fast ferrite stubs tuners (FFT) previously tested on AUG

and have implemented new power supplies. The FFT system is designed to perform real-time matching (transform antenna input impedance to 50 Ω) by varying the effective electrical length of the stub tuners via currents in the magnetic coils surrounding the ferrite materials. In order to achieve and maintain matched condition, a real-time control system (similar to the C-Mod digital plasma control system [[4]]) calculates the magnetic coil currents from the measured complex reflection coefficients and sends them to the power supply at the beginning of the next clock iteration. The computation time per iteration is about 100 μsec and the system has been shown to be stable using 200 μsec per iteration. In a bench test, the FFT system was able to match a fast varying RF load at a time scale of approximately 1 ms. This time response is expected to be sufficient to prevent the antenna from faulting as a result of mismatched conditions. We have begun installation of this system on the E antenna and if initial experiments are successful we will design an additional 3 sets of ferrite stubs. Implementation of these stubs in the future is budget dependent. With fast matching networks, either passive or active, arc detection becomes an increasingly important aspect of the antenna system. We will continue to investigate new techniques and strategies for arc detection and mitigation.
We plan to continue our collaboration with the RF SciDAC Group and R. Maggiora of Politecnico de Torino on the development of an electromagnetic solver that has a realistic ICRF antenna geometry, presently coupled to 1-D, soon to be 3-D plasma field solver. To properly analyze and predict antenna performance, geometry is probably the single most important determining factor. Initial results from the modeling of the E antenna were encouraging and we have taken new data on the screen-less J antenna. In the near term, we will compare these measurements with the simulations and in the future we plan to simulate fast changes in loading to understand the antenna behavior during confinement changes associated with H-mode transitions and ELM's. We also plan to analyze the antenna fields to investigate the role of RF radial B-fields in impurity production from the antenna strap which were seen during the J antenna screen-less operation. If their importance is confirmed, we will analyze the new 4-strap antenna design to investigate antenna geometries to minimize these fields. The planned upgrade of the MARSHALL Beowulf cluster will greatly improve our ability to study the effects of different antenna geometries on predicted antenna operation.

2.3.1.2 Propagation, Absorption and Mode Conversion Physics

C-Mod provides a unique opportunity to explore ICRF wave propagation, absorption, and mode conversion physics. These investigations are facilitated by a flexible ICRF system, access to sophisticated ICRF simulation codes (through the RF-SciDAC Initiative), and the availability of advanced diagnostics for RF wave measurements. Realizing high heating efficiencies in D(^{3}He) discharges, where the single pass absorption is weak, is important for planned 2 MA, 8T operation in C-Mod and future experimental devices. We have confirmed that the heating efficiency is a sensitive function of the ^{3}He fraction, more so than expected from theory and more sensitive than the H concentration in D(H). In L-mode, the heating effectiveness compared to D(H) is similar as determined by analysis of stored energy and H-mode thresholds. We have limited H-mode comparison discharges but the plasma performance obtained thus far has been ~10% lower (for global energy confinement) compared with D(H) H-mode discharges and the improved performance resulting from boronization appears to erode more quickly compared to D(H). An outstanding question regarding D(^{3}He) is the role of parasitic absorption, e.g. B minority resonance, loss mechanisms near the plasma edge. A similar parasitic minority resonance will be present in ITER from the planned use of Be coating on plasma facing components (PFC's). In the near term, experiments are planned to move the parasitic ion edge resonances either into the plasma core or out of the plasma. We also plan to continue experiments where a direct comparison of D(H) and D(^{3}He) can be done in the same discharge using the D and E antennas at 80 MHz and J antenna at 50 MHz. Further experiments will investigate the effect of additional heating power on heating efficiency with higher power density and consequently higher bulk plasma temperature, where we expect to increase the single pass absorption in D(^{3}He). This work will also take advantage of new simulation capabilities where self-consistent ion distributions can be evolved within the simulation to investigate the impact of energetic ions on wave absorption.

An emerging area of interest is second harmonic heating due to both its utilization planned in ITER and theoretical calculations which suggest that it may have stronger damping than previously thought. With the compact neutral particle analyzer[[5]], the ion distribution can be measured on C-Mod and used to benchmark the simulations. A code to code comparison (often referred to as code verification) was performed on the ITER scenario 2 which is dominated by second harmonic absorption and electron Landau damping. Initial experiments will investigate second harmonic H absorption and allow benchmarking of the codes to experiment (code validation). Future experiments could examine the role of parasitic edge ion absorption, predicted by the codes which could have significant effects on impurity generation.

We have extended the investigation of ICRF mode conversion and have made the first measurements of all three waves in the mode conversion region using Phase Contrast Imaging (PCI) diagnostic (DoE Diagnostic Initiative). Furthermore a synthetic PCI diagnostic has been implemented in TORIC in collaboration with the RF SciDAC Group. The data and simulation are in remarkable agreement suggesting that the physics model and numerical algorithm in TORIC models the mode conversion process very well. We wish to revisit these comparisons with upgraded diagnostic and simulation capabilities. We have implemented a masking technique in the PCI system that relies on magnetic pitch angle dependence of the scattered signal to provide localization information along the measurement chord. This will allow us to explore the predicted up-down asymmetries associated with mode conversion and make detailed local measurements of the short wavelength modes. An optics upgrade will allow resolution of higher wavenumber (k) and when combined with the localization may allow observation of the rapid k up-shift associated with the mode converted waves. We plan to complete an improved calibration and spatial referencing upgrade that will allow a more accurate density fluctuation level and position to be determined. Furthermore, additional code to code benchmarking has identified an overestimation of the field strength in TORIC which has been corrected. Thus an outstanding issue from the previous analysis regarding amplitude discrepancies can potentially be resolved because of these diagnostic and code improvements. Taking advantage of this unique capability, studies will initially focus on

$D(^3He)$ and D(H) the primary species mixes used in C-Mod. An important aspect of these studies is comparing the measured spectrum with TORIC simulations. In collaboration with the RF Sci-DAC Initiative, we have local access to the MARSHALL Beowulf cluster to perform fully resolved full-wave simulations (up to at least 511 poloidal modes) routinely and an upgrade to this cluster will enable more detailed analysis.

2.3.1.3 ICRF Current Drive

While not expected to be as efficient as LHCD, ICRF current drive (mode conversion (MCCD) and ion cyclotron minority (ICCD) current drive) can be used to tailor the local current profile for controlling instabilities and Fast Wave current drive (FWCD) can provide the central seed current for fully non inductive advanced tokamak scenarios.

We have investigated MCCD both experimentally and theoretically. We have found that MCCD is a good candidate for sawtooth pacing where the local current profile is modified to destabilize the sawteeth.[6] This should be beneficial for high performance discharges where large sawtooth crashes can terminate the high performance phase, and also may prevent neoclassical tearing modes (NTM) by reducing or eliminating the seed island. Using a Fokker-Planck code (DKE [7]) to calculate the electron distribution function, more detailed calculations of the driven current are possible that can directly account for trapped particles and wave polarization. The results show that wave polarization and precise accounting of trapping reduces the expected driven current by factors of 2-3 compared with the Ehst-Karney parametrization utilized previously. Thus, the original target MCCD case of 100 kA for 3 MW of power yields ~50 kA. Previous work done on MCCD in TFTR [8] was reanalyzed and found to be mode conversion to ion cyclotron wave (ICW) instead of the reported ion Bernstein wave (IBW). In addition, the fast wave can mode convert to one of the two or a combination of IBW and ICW. The balance between the two is set approximately by the ratio βp (plasma pressure to poloidal magnetic field pressure) where higher βp results in mode conversion to IBW rather than ICW. For discharges with sawteeth, the fast wave is largely converted to ICW and net current can result. For mode conversion to IBW, the current profile has a dipole structure; thus, MCCD in an advanced tokamak scenario is likely to be ineffective for on-axis current drive because the net current will be vanishingly small. However, MCCD experiments can provide important information regarding the inherent up-down asymmetry associated with the mode converted waves. Recent experiments sweeping the mode conversion location from inside to outside the q=1 surface with heating and current drive have shown that the heating phase may have net driven current. This would be consistent with the up-down asymmetry in the mode converted spectrum predicted by simulation. Further experiments are planned to test this prediction and these experiments will provide a good test of simulations and their associated current drive models.

An important application of MCCD for C-Mod is sawtooth pacing where the sawtooth period and amplitude are kept short to avoid the crash of monster sawteeth. We have shown that the sawtooth period can be shortened or lengthened by changing the antenna phasing or deposition location. A principle question yet to be addressed is sawtooth pacing in the presence of a stabilizing energetic ion population. We plan to add MCCD to discharges with monster sawteeth to investigate the current drive power required to

pace the sawtooth period. These experiments will be performed within the framework of the ITPA experiment MDC-5.
For the reference C-Mod advanced tokamak discharge, a central seed current of approximately 20 kA is required.[9] Fast wave absorption on electrons is a strong function of plasma β giving a centrally peaked absorption and current drive profile. In the near term, we will modify the matching network and verify transmitter performance at the relevant frequency (60 MHz) for the J antenna. Initial experiments will focus on the deposition profile in a variety of conditions to determine the deposition profile and absorbed power fraction. The absorption fraction should increase as higher β plasmas are obtained. Another issue will be impurity generation due to the low single pass absorption anticipated for these discharges. Tests of the driven current can also be performed as soon as interesting scenarios are developed. Furthermore, the current drive experiments will provide added data to experimentally benchmark the simulation codes and their respective current drive models.
A third current drive technique, ICCD, should be useful for local current profile tailoring, in particular sawtooth pacing. The physics of ICCD is complicated but essentially there are two regimes: classical and finite orbit. In the classical regime current is carried by passing particles and has a peak efficiency near the critical energy. The finite orbit regime generates current as a result of finite width trapped particle orbits. C-Mod has access to both regimes and will allow benchmarking of the simulation codes. Furthermore, the two regimes have opposite dipole current profiles and will have opposite affect on instabilities, like sawteeth. Experimental time devoted to this current drive mechanism is resource dependent.

2.3.1.4 Flow drive (MC)

Another important research theme, relevant to triggering and controlling transport barriers, is RF driven flows. Theoretical calculations are difficult because one must calculate the plasma response in addition to the RF fields and resulting force. Experiments may provide insight into which of the many terms in these equations are important. For example flows can be driven by pondermotive forces or Reynolds stress. In the former case, damping on electrons may result in driven current but in the latter case damping on electrons will be small (electron to ion mass ratio is small) and ineffective. Depending on species mix, deposition location, and plasma current, the power can be channeled to ions or electrons. With upgraded diagnostics, the poloidal rotation, RF power deposition, and RF density fluctuation profiles can be simultaneously measured. These data will allow an assessment of the amount of poloidal flow, its profile, and its relation to RF wave propagation and absorption. Simulation[10] indicates that the scenarios most likely to drive significant sheared flow are those that have significant damping on ions near the cyclotron resonance where the forcing term switches sign as the resonance is crossed. This suggests current drive experiments where the plasma conditions are tailored to maximize electron damping, while flow drive experiments will require different plasma conditions so that ion cyclotron damping will dominate. Thus the first task is to identify a discharge scenario where significant power can be absorbed at the cyclotron layer. Once a target discharge is established, we plan to assess the poloidal flow characteristics. Depending on its success, RF driven flow shear can be investigated to determine RF power required to trigger or maintain internal transport barriers.

2.3.1.5 Connection to FESAC Priorities Panel Recommendations and ITP Activities

C-Mod is also well aligned with FESAC Priorities Panel recommendations. Under the waves and energetic particle recommendations, a fundamental issue raised in the report is the interaction of electromagnetic waves with plasma. The proposed research strategy is three pronged: optimize externally-launched wave spectra and power coupling limits; develop detailed understanding of wave propagation, absorption and plasma responses required for practical applications, and elucidate the interaction between waves, stability, and transport for potential development to control and optimize of fusion plasmas. As noted above, research in all three of these areas can be readily identified from ICRF antenna development and modeling through off axis current drive with LHCD to influence plasma stability and transport. In addition, another area of interest is interaction of high energy particles with plasma. Here, C-Mod can address the interaction of energetic ions created via ICRF and energetic electrons driven by LHRF. The FESAC Priorities Panel recommends a parallel approach developing an understanding of the internal features of energetic particle-excited instabilities and synergistic behavior of alpha particle-dominated burning plasmas. C-Mod is well positioned to contribute on developing a fundamental understanding of energetic particle modes and these modes can be explored over a wide range of plasmas with access to sophisticated diagnostics and simulation codes.

Although no dedicated ITPA organization exists to address heating and current drive, C-Mod contributes in joint experiments utilizing the RF for localized tailoring of temperature, momentum, or current profiles. In the near term, we contribute to MDC-5, comparison of sawtooth control methods for NTM suppression.

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2.3.2 Lower Hybrid Current Drive

2.3.2.1 Recent Accomplishments

Initial experiments with Lower Hybrid Current Drive were carried out in the 2006 campaign. Up to 900 kW of RF power at a frequency of 4.6 GHz were coupled into L-Mode plasmas in C-Mod. The launcher is a grill formed by 88 waveguides arranged in 4 poloidal rows, each with 22 waveguides in the toroidal direction [1].
(The grill was originally designed to have 24 waveguides in each row, however the outermost waveguides were sealed off due to concerns over the mechanical stability of the vacuum windows in those guides.) Adjacent pairs of waveguides are fed by a single klystron. All 12 klystrons supplying the RF power are excited by the same master oscillator; the amplitude and phase of each klystron's excitation is electronically controlled, which allows flexible control over the parallel index of refraction $n_{||}$ of the launched waves. As is well known, $n_{||}$ is a key parameter in LHCD physics, determining whether the coupled waves are accessible to the plasma radius where current is required to be driven, where the waves will damp, and the efficiency of current drive ($\sim 1/ n_{||}^2$). Dynamic $n_{||}$ control capability is unique to the C-Mod LHCD system and was exploited in the initial experiments. One of the goals of these experiments is to determine how well current drive can be localized by $n_{||}$-control, and whether dynamic control will be necessary to achieve stable, high-performance operating regimes. Results from the C-Mod LHCD experiments will be useful in informing a decision on whether to install LHCD on ITER.

LHCD highlights from the 2006 campaign include:

- 1 MW of net coupled power, with reflection coefficient $\Gamma^2 \sim 15\%$
- Reasonable agreement with Brambilla coupling code with vacuum gap
- Nearly 1 MA of driven LH current with figure of merit, $n_{19}IR/P \sim 3$
- Sawtooth stabilization, central heating observed
- Generally good agreement with GENRAY/CQL3D model regarding total current, hard X-Ray and cyclotron emission synthetic diagnostics. X-Ray profiles broader than code prediction
- Experimental results so far are in-line with requirements for high performance SS operation.

We expand on these results below.

2.3.2.1.1 Coupling

By varying the phase (and therefore $n_{\parallel}$ of the launched waves), and the density at the grill, systematic measurements of the net reflection coefficient, Γ^2, were obtained. The experimental data are compared with results from Brambilla's coupling code [2] in Figure 2.3.2.1. In order to obtain reasonable agreement with the model, a small vacuum gap (0.8 mm) has been inserted between the grill and the

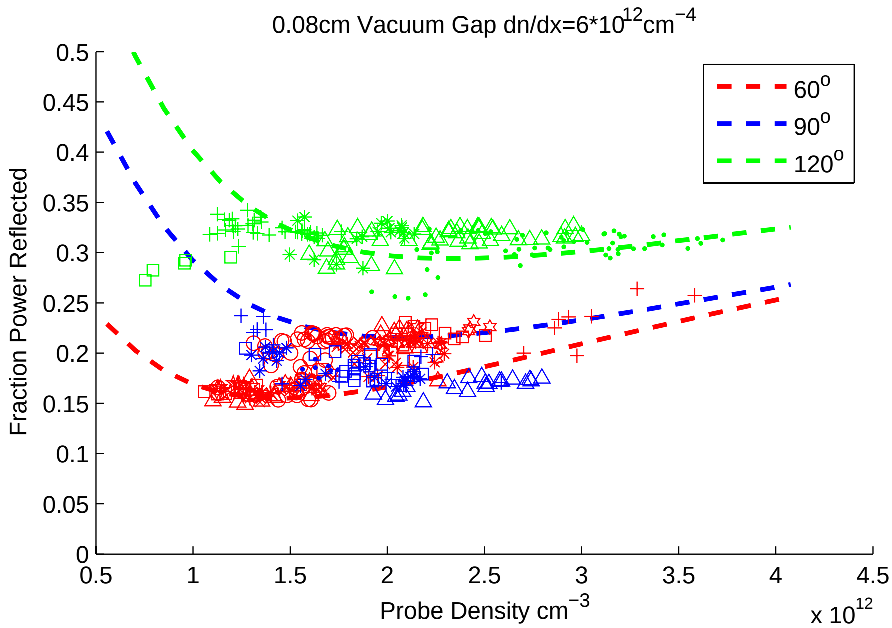


Figure 2.3.2.1. Reflection coefficient vs density at the grill for three phases, corresponding to $n_{/\!/}$ = 1.6 (60°), 2.3(90°) and 3.1(120°).

plasma. The plasma density in the model then jumps to about twice the cutoff density (i.e., where $\omega_{pe}^2 = \omega^2$) and then increases with a constant gradient of 6×10^{20} m^{-4}. Whether the vacuum gap is "real" is uncertain, however the fact that increasing $n_{\parallel}$ results in poorer coupling can be easily explained by a thin layer of evanescence at the grill. Close inspection of the data shows that only qualitative agreement with the model is obtained as the probe density (measured at the face of the grill) increases. Also, the minimum reflection coefficient of ~ 15% is disappointingly higher than desired, since it means that a significant fraction of the incident LH power is reflected and not available for current drive. A mismatch between the shape of the grill and protective limiters, and the shape of the plasma could be responsible for some of the observed reflection. Optimizing the coupling under a variety of plasma conditions -- including H-Mode -- is clearly important and this will be addressed in the upcoming 2007 campaign.

2.3.2.1.2 Current Drive

As co-current phased lower hybrid power is applied to C-Mod plasmas, a decrease in the loop voltage at fixed current is observed. This is of course expected since for fixed total current the Ohmic contribution diminishes as the current driven by RF waves increases. A synergistic effect also occurs, due to the fact that the LH waves pull out a tail of energetic electrons which reduce the plasma resistivity. Consequently it is not as straightforward as it might seem to estimate the amount of driven current simply from the drop in loop voltage. Figure 2.3.2.2 shows the fractional decrease in loop voltage vs. the current drive parameter P/nIR. The data in the

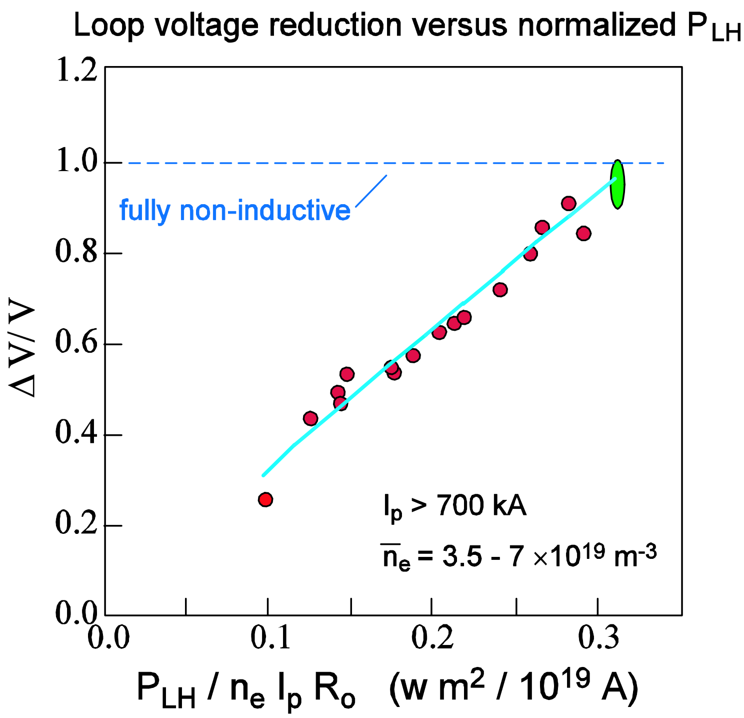


Figure 2.3.2.2 Fractional reduction in loop voltage vs. $P_{LH}/n_eI_pR_o$. The solid curve is a fit based on the method of Giruzzi, et al. [3]

figure have been analyzed by a simplified theory due to Giruzzi [3], based on the classical work on LH current drive by Fisch and Karney [4,5]. Interestingly, the data fit a nearly straight line indicating that the above mentioned synergistic effect is weak in these experiments. Nevertheless it is to be emphasized that while impressive currents have been driven, e.g., nearly 1 MA at about 800 kW of power, a stationary state with zero loop voltage has not as yet been obtained. During the 2007 campaign, more source power will be available (~ 3 MW vs 2 MW in the 2006 campaign) and achieving a stationary state with zero loop voltage will be a high priority objective. This will then unambiguously determine the current drive efficiency, at least for the conditions under which zero loop voltage is obtained.

2.3.2.1.3 Sawtooth Stabilization

While no direct measurement of the driven current density profile has been possible, there is indirect evidence that the current profile is broadening as a result of the application of LHCD. One indication is from measurements of the internal inductance, which drops from typically 1.3-1.4 to ~ 1.0, the other from sawtooth stabilization, an example of which is shown in Figure 2.3.2.3. The left panel shows fully developed sawteeth in the ECE emission in a discharge before the RF was turned on, the right panel the same ECE traces near the end of the RF pulse. In the same discharge, the central electron temperature rose from 2.7 to 3.7 keV during the application of LH power. As the sawteeth stabilize, the inversion radius shrinks suggesting that the mechanism for stabilization is the central q rising above 1, rather than, e.g., more subtle changes in the shear near the q=1 surface. With the improvements to the MSE diagnostic there is optimism that more direct evidence of the driven current profile can be obtained in the upcoming campaign. Looking further to the future additional diagnostic capability for $j(r)$ will become available with Faraday rotation polarimetry.

2.3.2.1.4 Simulation

A key aspect of our LHCD program is the tight connection between experiment and simulation. The workhorse codes used for this purpose are GENRAY, which provides a description of the wave physics -- ray propagation, electric field and damping -- and CQL3D, a bounce averaged Fokker-Planck code that evolves the electron distribution function taking into account the quasi-linear term due to the wave fields. These codes are run iteratively until a steady-state solution is reached. The codes not only predict global observable quantities such as the driven current and residual loop voltage, but they also provide two important synthetic diagnostics, namely the predicted hard X-Ray and ECE emission, taking into account the detector geometries. Examples are shown in Figure 2.3.2.3. In the case of the X-rays (the experimental data are from a hard X-Ray imaging spectrometer), the

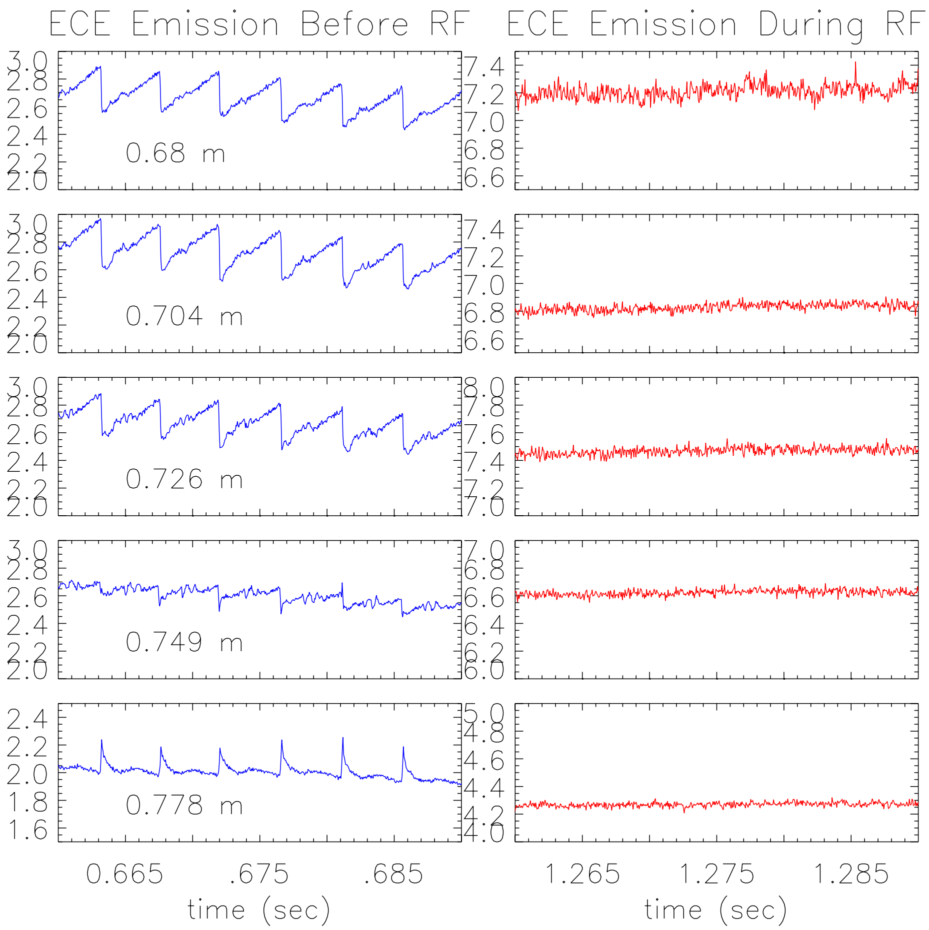
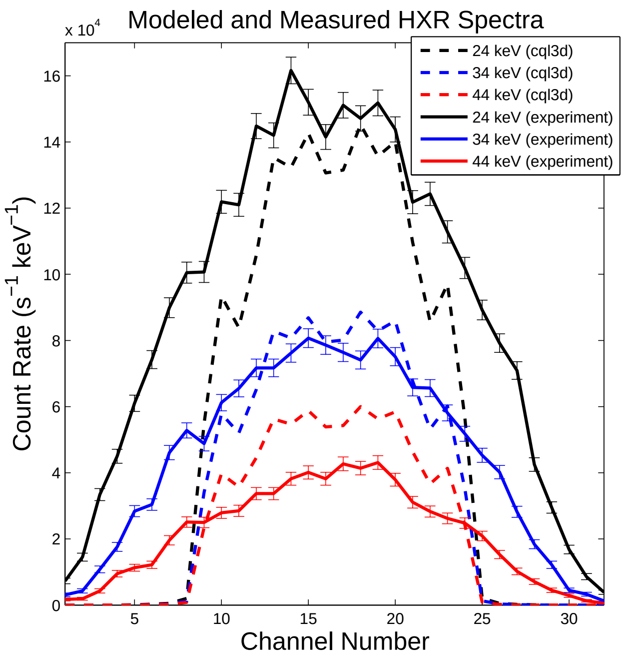


Figure 2.3.2.3. Electron cyclotron emission before (left panel) and during (right panel) application of LH power.

absolute value of the flux in the three energy bins is close to that predicted by the code, but the spatial width of the emission recorded by the spectrometer is broader than predicted, suggesting that there is spatial diffusion of the fast electrons that is not accounted for in the code. The shape of the ECE emission agrees quite well with the code predictions, however the peak amplitude predicted by the code is 5 times larger than the measured peak. Efforts will continue in the upcoming campaign to resolve these differences.



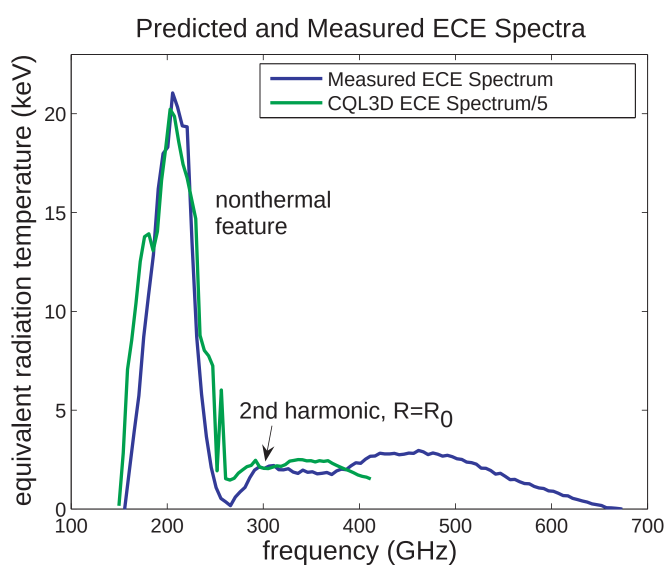


Figure 2.3.2.4. Top: Comparison of X-Ray emission recorded by X-Ray camera with prediction of CQL3D. The 3 energy bins are 10 keV wide and centered at the energy indicated in the box. Bottom: Comparison of emitted ECE spectra with prediction of CQL3D. The code result has been reduced by a factor of 5.

2.3.2.2 Near Term Plans (Remainder of 2007 and 2008)

The objectives for the 2007 run campaign and the following campaign in 2008 are highlighted in the bullets below.

- Achieve Vloop = 0 for ~ 0.5 s (several resistive diffusion times) Demonstrate $dI/dt > 0$ with $d\Phi_{trans}/dt=0$ and evaluate efficiency of transformerless startup, compare with Fisch-Karney theory.

Thus far we have not been able to achieve zero loop voltage for times in excess of the resistive relaxation time, the latter being ~ 100 ms. As discussed above, the presence of even a weak electric field complicates the interpretation of the amount of current actually driven by the RF waves due to the synergistic effect of the electric field acting on the population of RF-generated fast electrons. In order to unequivocally measure the RF generated current it is necessary to apply sufficient power to force the loop voltage to zero, for fixed total current. Since the last campaign, we have brought the power in all 12 klystrons up to the nameplate rating of 250 kW and, if successfully coupled, this would increase the power available for current drive by nearly 50%. An additional factor is the maintenance of low density since the driven current is proportional to P/n. The new cryopump should be helpful in maintaining the density at levels which permit full current drive with the available power. If in fact we end up with an excess of current drive, we will explore using LHCD to enhance plasma startup thereby saving volt-seconds for use in the flat top portion of the tokamak pulse. This would be of especial interest to ITER since the pulse length could be substantially lengthened if RF assisted startup were implemented.

- Explore parametric dependence (n, T, $n_{||}$,B_T, Z_{eff}) of efficiency and compare with Fisch-Karney theory and simulation (CQL3D/GENRAY and DKE/GENRAY)

Our preliminary results described above were obtained at fairly low density (mid 10^{19} m^{-3}) whereas our target AT discharges have densities in the low 10^{20} m^{-3} range. LHCD experiments generally run into an upper density limit, which may be due to parametric decay instability (PDI). It will be important to explore the current drive efficiency as a function of density, as well as other parameters such as temperature, field and Z_{eff} to investigate whether the experimental results remain in agreement with code predictions as new regimes are entered. We are also well equipped to detect PDI's and will be looking for evidence of their onset, particularly if a degradation in efficiency with density is observed. Determination of the density limit for effective operation in these conditions is critical for the selection of the frequency for LHCD on ITER.

- Compare in detail X-Ray and ECE emissions with GENRAY and CQL3D and DKE FP models

These items were singled out in the discussion above. While qualitative agreement with code predictions has been obtained, discrepancies in the width of the X-Ray profiles and height of the ECE peaks were observed. It will be important to resolve such discrepancies in order to have full (predictive) confidence in our modeling results.

- ➢ Optimize coupling in L-Mode, ICRF-heated and H-mode plasmas and develop improved coupling model

- ➢ Operate at high power and drive significant current in H-Mode target discharge

The most important goal of the upcoming campaign, and one that will no doubt extend into the 2008 campaign, is to successfully couple LH waves into H-Mode plasmas. In H-Mode, the gradient of the density in the SOL increases and the density at the grill falls. Both effects make coupling more difficult. A mitigating action would be to install a perforated pipe for injecting gas near the grill, a technique that has been successfully used on JET and is also being considered for ITER. It is unlikely that such a pipe could be installed in the 2007 campaign, but would certainly be installed before the 2008 campaign if the evidence warrants it

- ➢ Simulate alpha particle absorption of LH waves on ICRF generated proton tail

A key issue in the choice of LH frequency for ITER is the interaction of LH waves with fusion-generated alpha particles. Using ICRF generated proton tails, we may be able to simulate the ITER situation and assess whether this is likely to be a problem. We have had success in measuring the energy spectrum of the proton tails using the Compact Neutral Particle Analyzer (CNPA). We are also considering the installation of a lost-energetic-ion diagnostic that would complement the data made available by the CNPA. These would be key diagnostics in this experiment.

- ➢ Measure current profile modification – MSE and/or Polarimetry

Improvements to the MSE system made following the 2006 run campaign may resolve the problem that we have had in using this diagnostic to measure j(r). If so, direct measurement of j(r) with LHCD would be invaluable in comparing with simulation results. Longer term, perhaps in the 2008 campaign, Faraday rotation polarimetry will be implemented and should complement the information provided by the MSE measurement.

- ➢ Begin using LHCD as tool to access AT modes

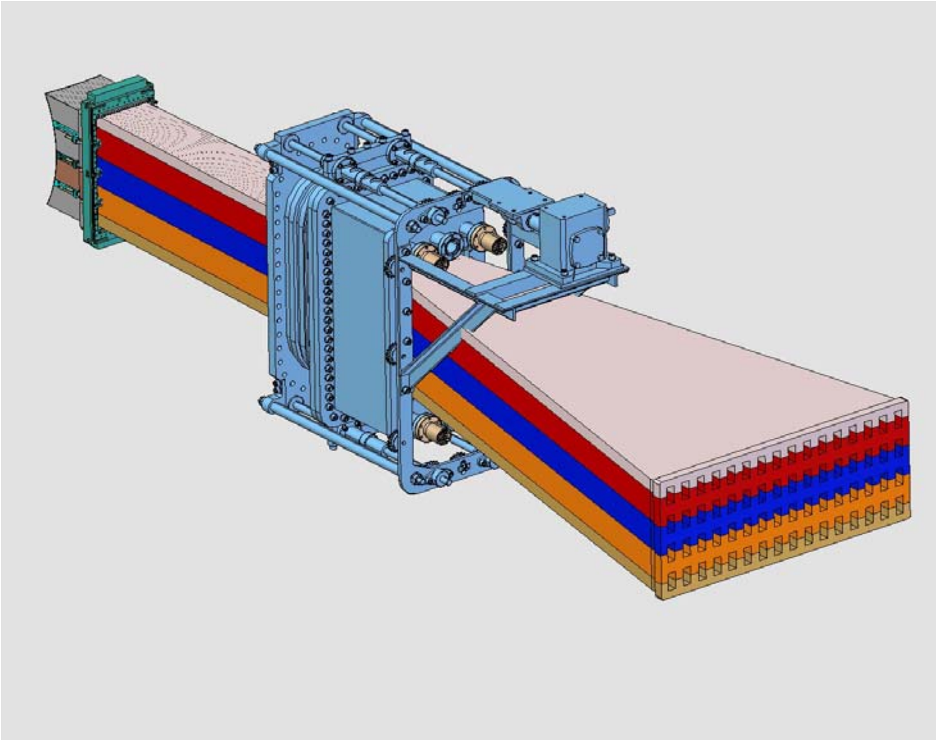
Finally, we emphasize that while LHCD is rich in physics and we believe our results will help to inform an ITER decision on installing it, our top level goal is to use LHCD as a tool to optimize tokamak performance. In ITER the results would bear directly on the so-called hybrid mode in which improved confinement is obtained by regulating the central q at or slightly above one. The LHCD experiments in C-Mod were motivated by the possibility of producing efficient, high-performance steady-state regimes that can be extrapolated to ITER and ultimately a reactor. As LHCD experiments mature, and the capability of the LHCD system is more fully explored, our attention will turn to using LHCD tool to access and optimize AT modes of operation. These plans are discussed in detail in Section 2.5

As mentioned above, the number of waveguides in the present launcher has been reduced from the original design of 96 to 88. A consequence of this is that only half the power from the klystrons feeding the end columns is applied to the grill. We are in the final stages of fabricating 4 new 24 waveguide couplers which will replace those now being used, for the 2008 campaign. Once the new couplers are installed, the power available for LHCD will increase by nearly 10% (at constant power density).

2.3.2.3 **Longer Term Plans (2009)**

By 2009 we expect to have a reasonably complete understanding of LHCD physics and its capability to affect the current profile in C-Mod plasmas. In order to proceed toward our goal of producing optimized steady-state regimes it will be necessary to add more power. Thus our plan in 2009 is to install a second LHCD launcher and to add additional klystrons to power it.

The design of the new launcher is well underway. Figure 2.3.2.5 shows the concept under development. The grill is composed of 64 waveguides arranged in four toroidal rows of 16 waveguides each. This compares with 24 waveguides in the present grill. The waveguides in the new grill have the same vertical dimension, but are larger in the smaller dimension b.   According to the empirical scaling that maximum power density scales as f^2b, where f is the frequency, the new grill should be capable of handling nearly 50% more power. Also, the cut in



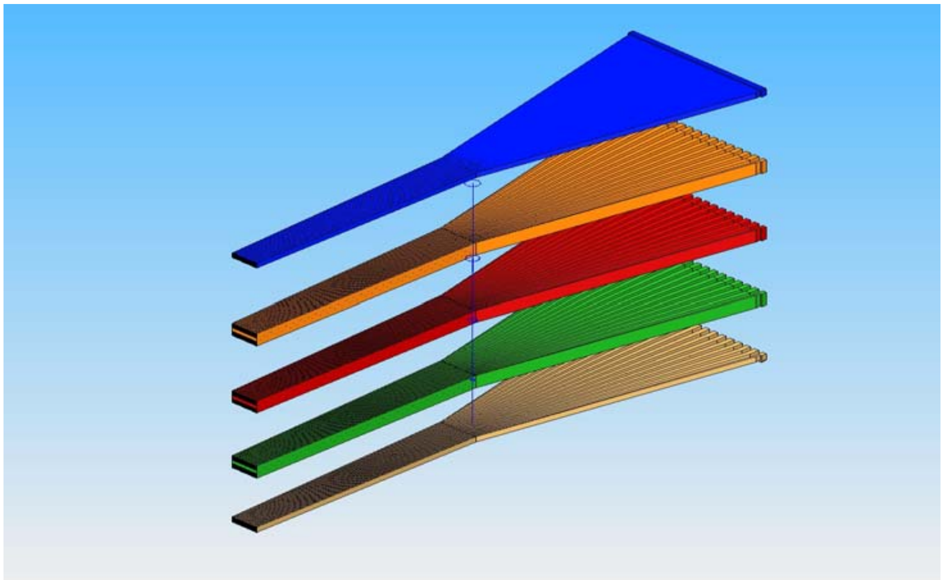


Figure 2.3.2.5. New launcher concept. The launcher is composed of 5 plates in which half-height waveguides are milled. The assembled guides are tapered in both the narrow and wide waveguide dimension.

the waveguides is horizontal, the so-called E-plane, rather than vertical, or H-plane, as in the present launcher and this will lead to lower losses in the launcher. Thus the new launcher will have higher power handling capability with less insertion loss. A small price is paid in directivity, as the new launcher will have slightly less directivity than that of the present one. The target date for fabrication of the new launcher is the end of 2008, so that it will be ready for installation before the 2009 campaign.

The plan for upgrading the RF power in 2009 calls for refurbishment (regunning) of the 4 remaining klystrons from the Alcator C experiment. A new cart will be fabricated and installed during 2008 in the C-Mod cell and the existing transmission system will be re-plumbed so that each launcher (the present one, outfitted with new grills, and the new one) will be fed by 8 waveguides. Considering the reduction in losses, and improved power handling capacity, this arrangement should more than double the power available for LHCD in 2009.

A somewhat more ambitious plan would be to add 4 new klystrons to the mix of 16 from the Alcator C experiment. This would also require the addition of a 5th cart in the C-Mod cell, and would bring the total source power to 5 MW. In this case, the present launcher, or perhaps a modified version similar to the new launcher in concept, would be fed by 12 klystrons as is the present case, while the new launcher would be fed by 8 klystrons. This plan, if adopted, would require incremental funding in 2009 and would not be operational until 2010. The logic for adopting this plan will be better evaluated after the 2007 run campaign which should shed light on the efficiency of LHCD in higher density H-Modes, as outlined in the plans described above.

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2.4 Macroscopic Stability

The Alcator C-Mod macrostability research program addresses issues relevant to the overall C-Mod program goals, as well as within the context of international research thrusts. A large fraction of the MHD research on C-Mod involves close collaboration with other facilities, many through official ITPA-coordinated joint experiments. This leverages C-Mod's unique region of parameter space to better determine scaling laws relevant to ITER and future reactors. The C-Mod MHD program also has excellent connections with theory and modeling.

2.4.1 Disruption mitigation

Disruptions are one of the most urgent ITER physics issues. The development of practical disruption mitigation techniques is a critical item for any tokamak burning plasma experiment and reactor prototype. Disruption-related challenges that are particularly important for ITER and future reactor devices include thermal damage (ablation/melting) to divertor surfaces, $J \times B$ mechanical forces on conducting structures arising from halo currents, and runaway electron populations generated during the current quench by avalanche amplification. Tests of disruption mitigation using high-pressure noble gas jet injection are specified as a high priority item by the ITPA MHD expert group. Experiments with *pre-programmed* firing of high-pressure gas jets into *stable* plasmas in Alcator C-Mod have shown very good disruption mitigation using neon, argon, or krypton, but not with helium. The 3D MHD code NIMROD has been modified to include impurity physics, such as ionization, transport, and radiation. Modeling of C-Mod helium and argon cases with this upgraded NIM*RAD* code clearly reproduces the specific differences seen for these two gases, such as the larger density increase for helium, as seen in Fig. 2.4.1, and the gigawatt radiated power levels for argon (Fig. 2.4.2).

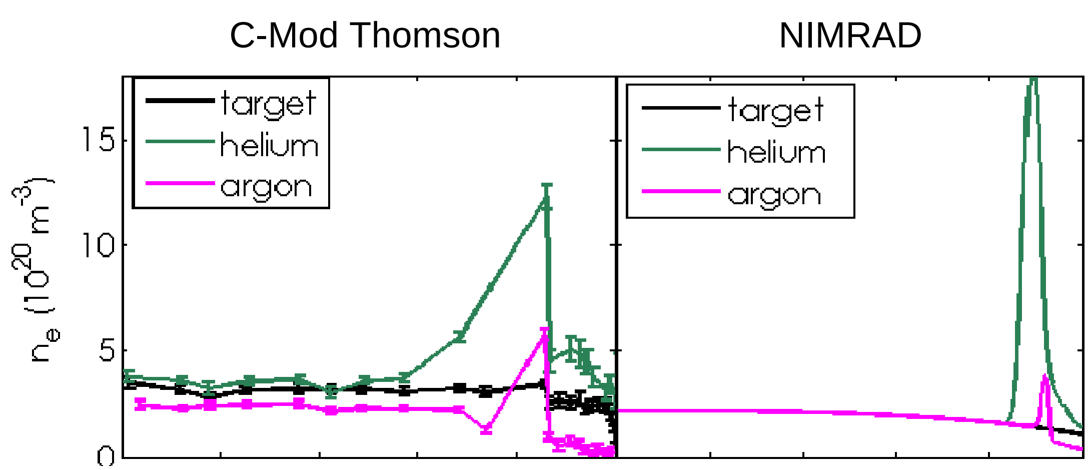

Figure 2.4.1 *— Prior to the thermal quench, helium gas jet injection yields a larger increase in plasma electron density than argon injection (left). The NIMRAD code reproduces this observation (right).*

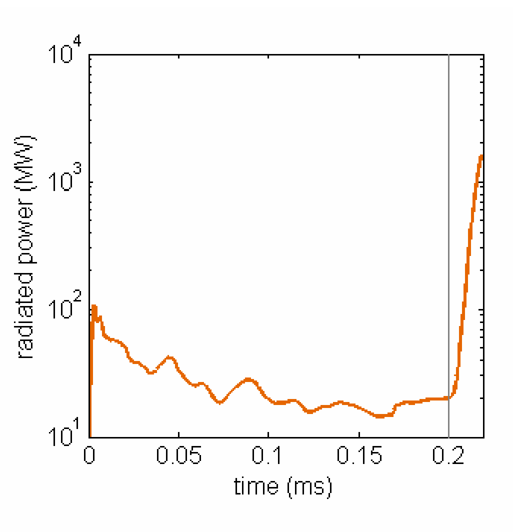

Fig. 2.4.2 – The radiated power as calculated by NIMRAD reaches the gigawatt level for argon gas jet injection. This is consistent with experimental observations.

Of course, disruption mitigation actually has to work on unplanned, unstable plasmas. Recent experiments on C-Mod have begun studying the effectiveness of gas jet mitigation on unstable plasmas. In this case, the response time of the gas jet system, which is a few milliseconds, becomes an issue, since it can be similar to the disruption timescale. Initial tests have been done on purposely-generated VDEs, either by turning off the vertical position feedback at a predetermined time, or by ramping up the elongation. A software routine has been added to the C-Mod digital plasma control system (DPCS) to continuously monitor the plasma vertical position and send a real-time trigger to fire the gas jet when the position deviates from the desired value by more than a
preset amount, as shown in Fig. 2.4.3.

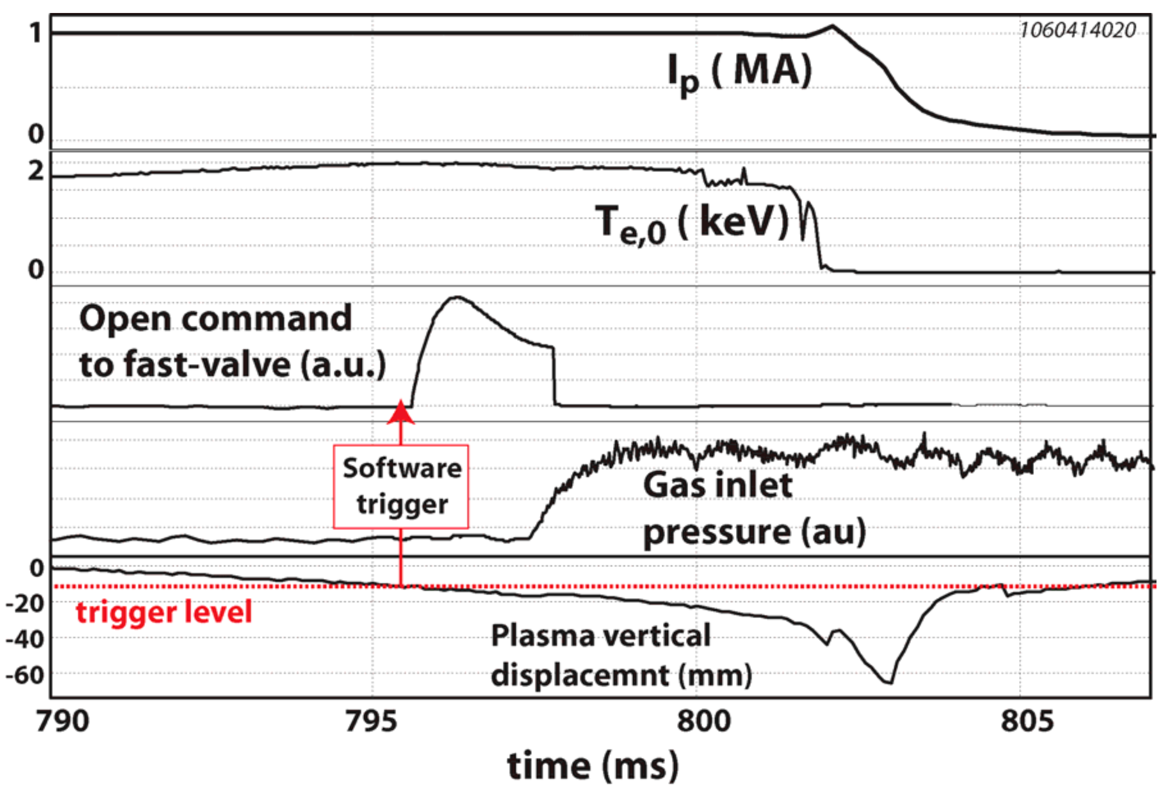

Fig. 2.4.3 - Example of real-time detection of a VDE by the C-Mod DPCS, and the firing of the gas jet valve.

The initial VDE experiments have shown clear mitigation of halo currents (Fig. 2.4.4) and thermal deposition, but not quite as well as with stable plasmas. The ultimate goal is

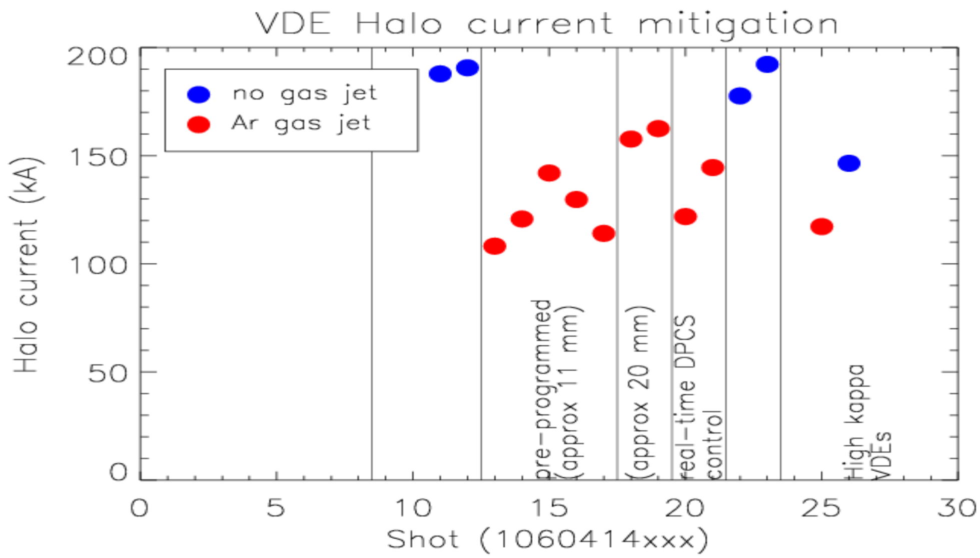

Fig 2.4.4 – Halo currents are reduced by gas jet injection into VDEs (red points vs blue points), but not quite as well as with stable plasmas (which is typically 50%). This may be due to the finite response time of the gas jet system.

to be able to recognize and act on an impending disruption due to a number of different causes, such as locked modes, impurity injections, ß-limits, etcetera, in addition to VDEs. This may involve the development of neural network predictors, and will be a significant challenge given the characteristically short response times necessary to mitigate C-Mod disruptions.

The initial tests of real-time mitigation of VDEs with argon gas jets suggests that the finite response time of the gas jet system may be playing a role. This time is dominated by the flow speed (~ sound speed) of argon through the delivery tube. A lighter gas, such as helium, is faster, but the higher-Z gases are much better at disruption mitigation. This suggests that an effective solution might be to mix a small amount of high-Z gas, such as argon, into a helium jet. Since the flow through the injection system is in the viscous regime, the heavier gas will be carried along at the faster speed of the helium. These experiments have just begun on C-Mod, and they show that an optimum mixture of 10-15% argon in helium is nearly as effective as pure argon for mitigation purposes, and shortens the response time by 2 ms, which is a significant improvement (Fig 2.4.5).

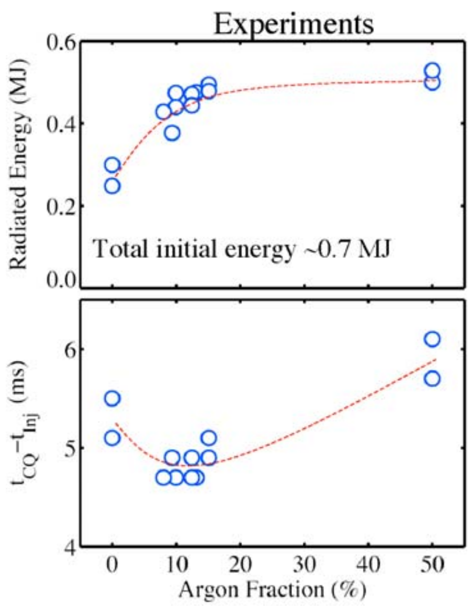

Fig 2.4.5 – 10-15% argon mixed into a helium gas jet is found to be nearly as effective as pure argon, but with a response time about 2 ms faster.

A redesign of the gas jet delivery system may also be necessary to shorten the gas delivery time by moving the fast actuating valve closer to the port, and to increase the amount of gas delivered by replacing the valve with a new one being developed by ORNL which has a throughput diameter of 24 mm, in contrast to the present 4 mm valve.

2.4.2 Cryopump halo current measurements

New first-wall structures have been installed in the upper part of the vacuum vessel as part of the protection for the cryopump. These structures will modify the flow of halo currents for upward-going disruptions, but also provide a unique opportunity to integrate new halo Rogowskis diagnostic coils into the first-wall structures during assembly. A set of 10 such coils have been fabricated and installed, as shown in Fig. 2.4.6. This new array will provide measurements of the toroidal distribution of halo currents flowing from the top of the plasma into the ceiling tiles and then into the vacuum vessel wall. In addition, an existing Rogowski coil at the top of the machine will continue to provide the total halo current flowing through the vessel ceiling near the inboard wall. This should allow for rudimentary radial resolution of the halo current pattern across the upper regions of the chamber.

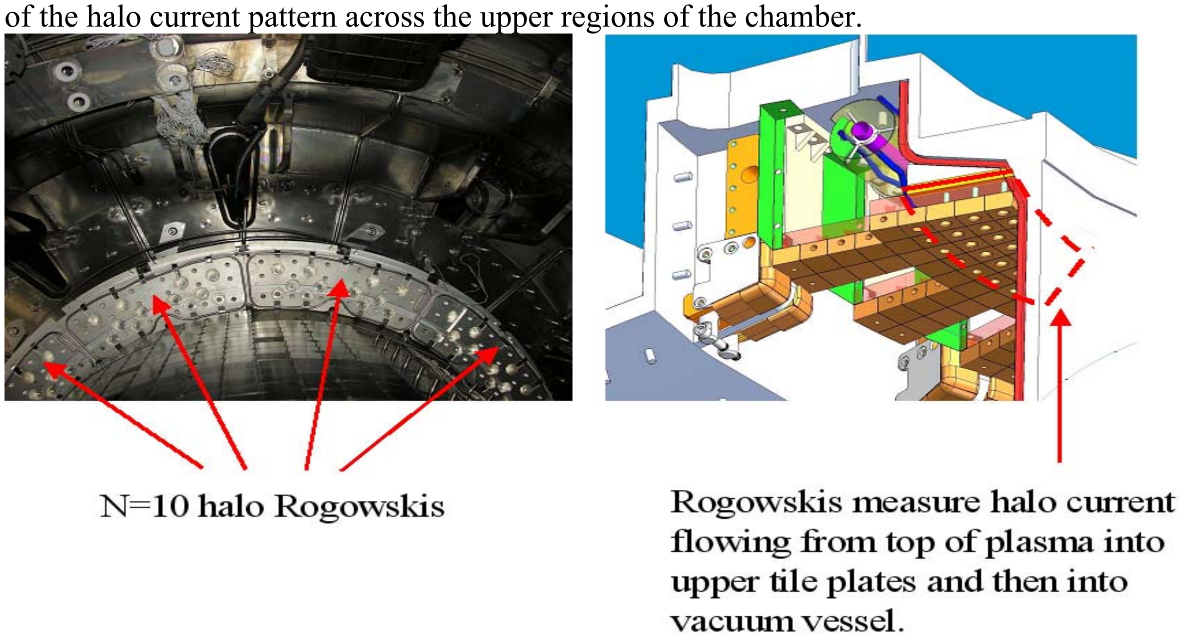

Fig 2.4.6 – A new array of halo Rogowski coils will be able to measure the toroidal distribution of halo currents flowing into the first-wall structures protecting the cryopump.

2.4.3 Locked Modes and Error Fields

Two experiments studying B_T scaling and size scaling of the locking threshold have been completed as part of an ITPA series of joint experiments with JET. The C-Mod results for toroidal fields higher than 4 tesla support the standard simple power law scaling of the error field locking threshold, and yield a field scaling that goes like B^{-1}. For ITER's size, this implies an error field threshold, $\partial B/B \sim 10^{-4}$, which is well within the design capability of the ITER correction coils. The identity experiments with JET also validate non-dimensional scaling over a factor of 4 in size, at least at medium and high toroidal fields. These ITPA experiments have now been declared officially closed. However, there is an additional, unmatched low-field point from C-Mod (at 4.1 T) which is inconsistent with a simple power law, but a corresponding low-field point from JET (at 0.6 T) is needed to verify its significance. JET is planning to acquire these data in the next year or two.

During the next few years, the primary emphasis for this topic on C-Mod will be to study magnetic braking due to non-resonant error fields, in particular, $n = 2$. Non-resonant error fields have been shown to have important effects on DIII-D. The C-Mod studies are being planned as a joint ITPA experiment with JET, using similar applied $n = 2$ error field structure. An initial result from JET shows that a transiently-applied non-resonant $n = 2$ field does indeed slow down the plasma rotation.

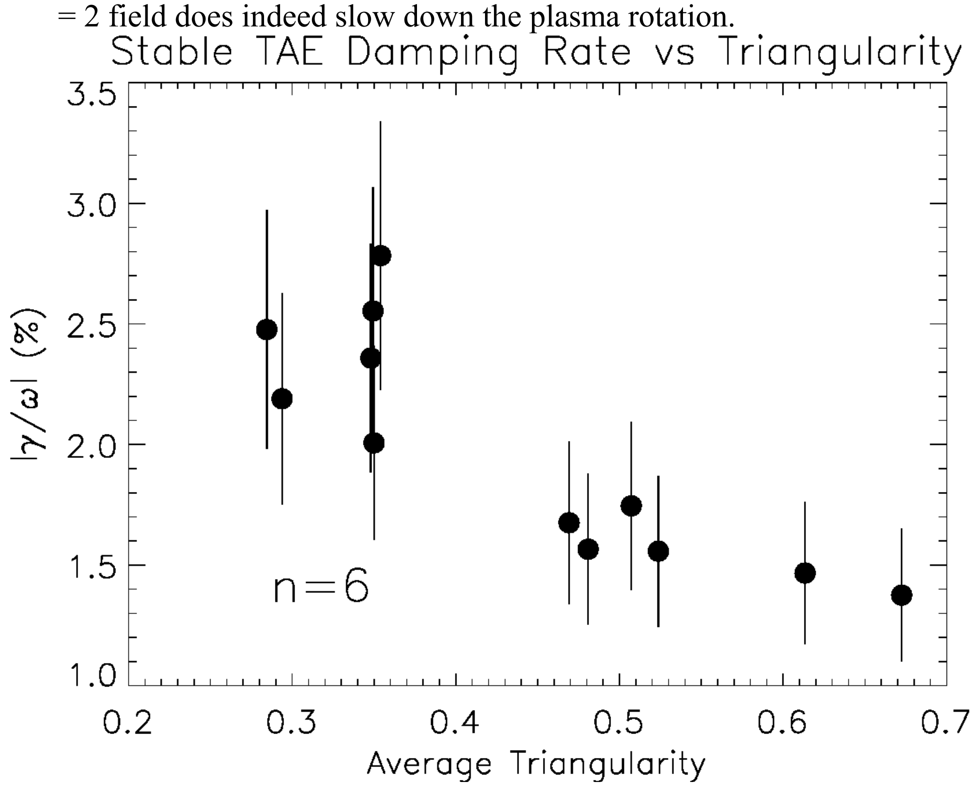

Fig. 2.4.7. Measured TAE damping rate vs average triangularity for n=6 modes.

The joint experiments are aimed at experimentally determining the toroidal viscosity in each machine, as well as the neoclassical velocity. These results from dimensionally different machines should provide a stringent test of neoclassical toroidal viscosity (NTV) theory. A successful outcome would bolster our confidence in predicting rotational effects in ITER.

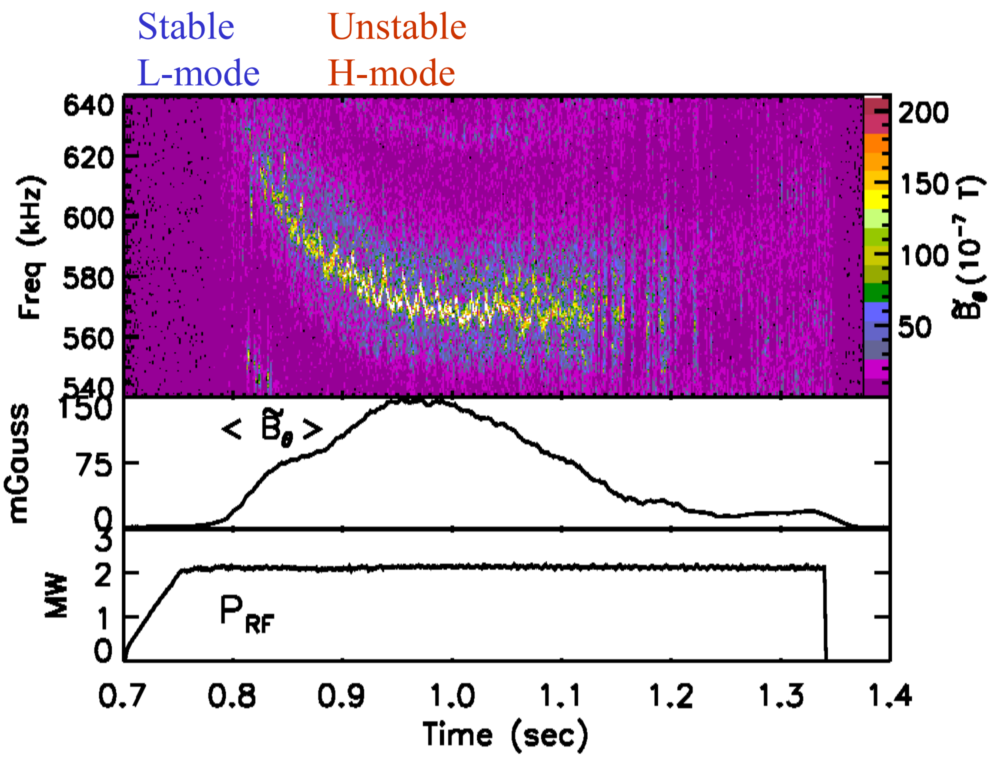

Fig. 2.4.8 Unstable TAEs during the H-mode phase of an ICRF heated discharge while the preceding L-mode phase remains stable.

2.4.4 TAE modes, Alfvén cascades, and active MHD

The stability of toroidal Alfvén eigenmodes (TAEs) has been studied on Alcator C-Mod using a pair of active MHD antennas, which generates an ITER-relevant intermediate-*n* mode spectrum at the same toroidal field and density as in ITER. Understanding the physics of moderate *n* TAEs may prove to be important for fusion burn control or controlling the loss of fast ions in ITER. Recent experiments have measured the damping rate of stable TAE resonances as a function of triangularity, ion ∇B drift direction, density, toroidal field, and ICRF power. The damping rate does not increase for $n = 6$ modes with increasing triangularity (Figure 2.4.7), in contrast to the JET result for $n = 1$ [5] where increased triangularity increased the damping rate. The measured moderate n TAE damping rate also shows little or no dependence on the ion ∇B drift direction, in contrast to JET results for low n where the damping rate increased strongly when the ion ∇B drift direction was toward the X point. These data suggest that the radial structure of moderate *n* modes is not dominated by edge shaping effects as it is for low *n* modes. Initial experiments to determine the effects of ICRF generated fast ions on the measured damping rate of stable modes indicated no clear dependence, but modeling with the NOVA-K code showed that the core localized fast ions may not have interacted with the modeled eigenmode, which was peaked outside of $r/a > 0.5$. Future experiments are planned to study the effects of fast ions on the measured damping rate of stable AEs with either off-axis ICRF or choosing the active MHD frequency to correspond to more core

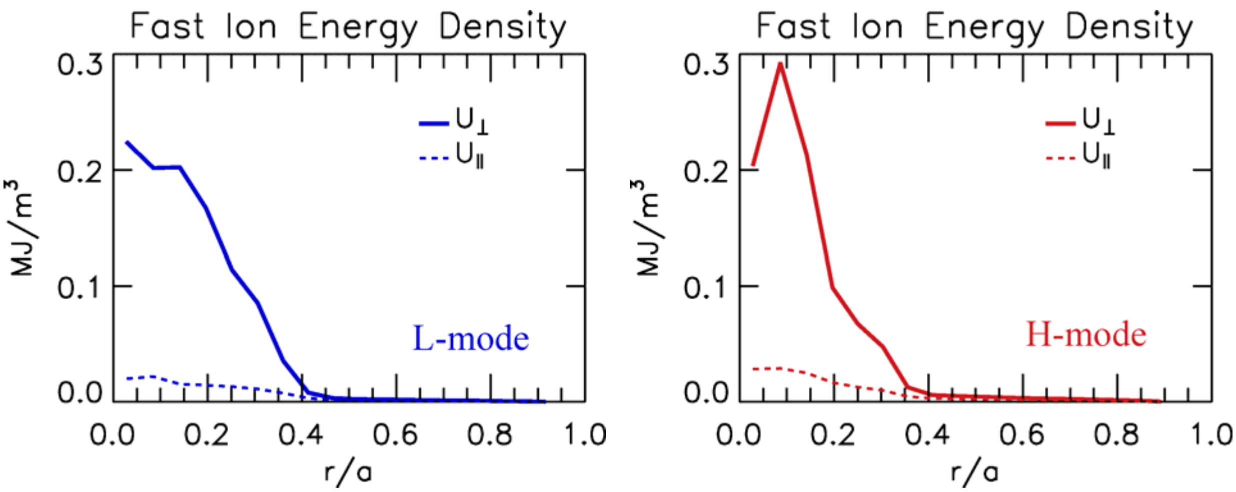

Fig. 2.4.9. TORIC calculated fast ion energy density profiles in the L-mode and H-mode phases of the discharge shown in Fig. 2 indicating more peaked RF power deposition in H-mode with steeper gradients than in the L-mode phase.

localized modes near q=1. Now that JET also has their moderate n TAE antennas operational, high priority joint ITPA experiments comparing the scaling of TAE damping rates across plasma conditions between these devices will continue in the coming years. MAST has also just installed three TAE antennas and should also take part in these joint ITPA experiments in the near future.

The stability of AEs also seems to depend on the confinement phase of the discharge: Unstable AEs are usually found in the H-mode phase while in the preceding lower density L-mode phase the modes remain stable (Figure 2.4.8). A comparison of the calculated damping and fast ion drive in these two phases with the NOVA-K code indicates that the H-mode is indeed more unstable than the L-mode, apparently because the fast ion drive increases despite the increased density. This may be an effect of increased focusing of the ICRF waves at higher density since the TORIC calculated ICRF power deposition is more peaked with steeper gradients enhancing the TAE drive in the H-mode phase (Figure 2.4.9). Further comparisons with the AORSA/CQL3D codes need to be done to determine if the more off-axis fast ion profiles that were found under lower density conditions with this code will also occur at high density. Initial calculations with artificially produced off-axis fast ion profiles indicate that TAEs are even more unstable in the H-mode phase, while the L-mode phase remains marginally stable.

A high-priority ITPA research topic is to determine if TAEs cause loss of the fast NBI or ICRF ions that couple the auxiliary heating power to the thermal plasma. Most other machines are concentrating on NBI, but an experiment is being planned on C-Mod to look for any reduction in ICRF heating efficiency due to driven TAEs. The active MHD antenna system, however, does not have significant power, so instead plans call for using the relatively strong beat wave produced by the interaction of the D and E ICRF transmitters. These are normally run at 80.0 and 80.5 MHz, resulting in a beat wave at

500 kHz which is clearly seen on the Mirnov pickup coils. With some effort, the frequency difference can be adjusted to 400 kHz, which is within the normal range of stable TAE modes in C-Mod. By varying the density, the TAE resonance can be excited at will with the strong beat wave, and any reductions of heating efficiency in phase with the TAE excitations will be searched for. A new fast ion loss diagnostic (FILD) that is presently being designed will measure lost ICRF generated fast H ions to provide a more accurate measure of the effects of AEs and other MHD activity on the transport of fast ions.

Reversed shear (RS) discharges on C-Mod can presently be obtained during the I_p rampup, but LHCD experiments in the next few years are expected to produce near steady-state reverse shear profiles. In RS plasmas, Alfvén cascades (reversed shear Alfvén eigenmodes, or RSAEs) are observed with both the magnetic pickup coils and the phase constrast imaging (PCI) diagnostic. The cascades are excited at integer and half-integer values of q_{min} and exhibit a characteristic frequency 'chirp' up due to the mode's sensitivity on (q-q_{min}), which is evolving throughout the I_p rampup. Modeling the RSAE modes with the NOVA code together with a synthetic PCI diagnostic to calculate what the PCI signals should observe through their line integrated measurements shows good agreement with the observed structure of the modes and the calculated structure (Figure 2.4.10). So, the radial structure and frequency time evolution of the modes can be combined to provide a measure of the evolution of the q-profile, particularly $q_{min}(t)$ as well as the structure of the eigenmodes. The addition of the lower hybrid current drive on C-Mod will extend the usefulness of this technique by extending the reversed shear phase of the discharge.

New high radial and time resolution ECE measurements should also be able to measure the radial structure of the AEs. Additional pick-up coil limiters at four toroidal locations around the machine will also improve the toroidal mode number resolution of both the AEs and other large amplitude MHD activity. The NOVA-K calculated AE radial structure can then be compared with the new measurements to better benchmark the code and improve consistency with calculated q profiles.

2.4.5 High β instabilities and NTM's

With the combination of high ICRF power and LH power, high $\beta_N \geq 1.7$ conditions may be more readily achievable in C-Mod in the near future, allowing access to regimes where neoclassical tearing modes may be expected to go unstable. In addition, the cryopump should allow controlled operation at low densities and therefore lower collisionalities where NTMs are more likely to occur. Joint dimensionless experiments are planned between C-Mod and DIII-D to determine if the threshold of $\beta_N \approx 1.7$ found on DIII-D will also be found on C-Mod. The corresponding dimensional parameters are $B_T = 5.3$ T, $a = 22$ cm, and $n_e = 2.5 \times 10^{20}$ m^{-3}.

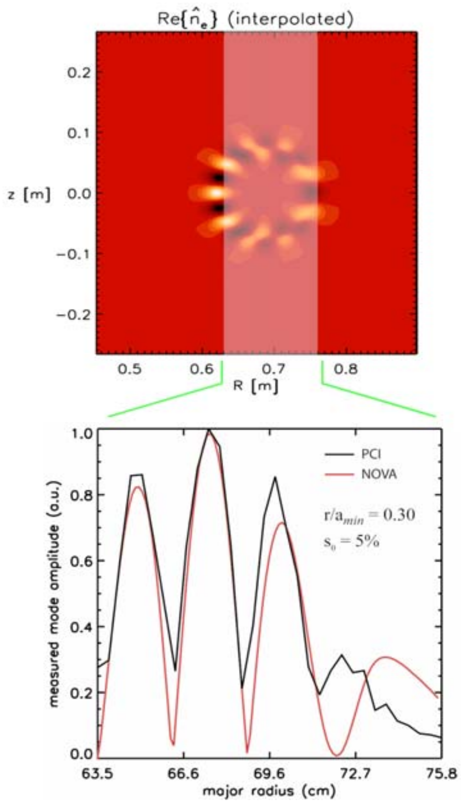

Fig. 2.4.10. Comparison of NOVA calculated 2D mode structure of an Alfvén Cascade with the measured structure from PCI line integrated along vertical chords together with a synthetic PCI calculated signal from NOVA showing good agreement.

Research on the control and/or elimination of NTM's with RF is also planned. There are several schemes that can be tried, either to reduce or eliminate sawteeth, which would remove the seed island trigger, or by direct stabilization with current drive in the islands at the resonant surface. The possible RF techniques for doing this (ICRF, FWCD, LHCD, MCCD, ICCD) are discussed in detail in the Wave Plasma Interaction of this Work Proposal chapter.

2.4.6 Macrostability support for ITER and Connection to ITPA Activities

C-Mod macrostability research is well-aligned with the ITER high-priority research tasks, including the following ITPA activities:

- Validate 2 and 3-D codes, in particular MHD and radiation models, on gas injection.
- Develop reliable disruption prediction methods.

C-Mod is working hard on all of these tasks (ITPA-IEA joint experiment #DSOL-11, ITPA topics #MDC-1, DSOL-4).

- Continue development of the new disruption DB including conventional and advanced scenarios to initially study fast I_p quenches and halo currents.

The new disruption database currently has more shots from C-Mod than from any other machine.

- Understand intermediate-n AEs ; redistribution of fast particles from AEs; and perform theory-data comparisons on damping and stability.

Intermediate-n AEs are C-Mod's primary focus. (ITPA #MDC-10).
Plans call for studying the redistribution and/or losses of ICRF-generated fast particles, as opposed to NBI (ITPA #MDC-9).

C-Mod is participating in a joint ITPA experiment with JET pertaining to the effect of non-resonant error fields on plasma rotation.

With the LH and cryopump systems now operational, C-Mod is poised to look for NTMs, possibly contributing to the work on beta thresholds, and on effects of error fields (ITPA #MDC-3). C-Mod can also investigate LHCD stabilize NTMs, if they are observed (ITPA #MDC-8).

2.5 Research for Integrated Scenarios on ITER

This research activity includes experiments and modeling aimed at reaching attractive operating points, generally cutting across multiple science topics and often involving interaction and compatibility issues between different plasma processes or regions. As such, it *integrates* work described in the four preceding topical science sections, and corresponding Scientific Campaigns as defined by the 2005 FESAC panel on Scientific Challenges, Opportunities and Priorities for the US Fusion Energy Sciences Program.

Given the recent signing of the ITER Agreement, C-Mod is focusing its integration work to an even greater degree than previously on the target scenarios which are to be demonstrated and explored on ITER. The three main planned ITER scenarios are[1,2]:

1. *Conventional H-Mode "Baseline" Scenario.*

   This scenario, arguably the most important since it is relied on to provide the target Q=10 fusion performance, features an edge transport barrier but no core barrier and has positive shear, without external current drive; non-inductive fraction of ~25% comes primarily from bootstrap current. Target parameters are q_{95}=3, β_N=1.8 and density ~ 10^{20} m^{-3}, all similar to current C-Mod values.

2. *"Hybrid" Scenario.*

   This scenario, so-named because it is in a sense intermediate between the H-Mode and steady state scenarios, has weak core shear and q_{min} ~1. This has been shown to provide modest core peaking and confinement improvement, though the mechanisms for the sawtooth avoidance and transport reduction, and whether they will operate in ITER, are as yet unclear. Higher levels of external heating and current drive are used to reach β_N=2.8 and 50% non-inductive fraction, projecting to Q=10 performance at reduced current, q_{95}=4, and for increased pulse lengths.

3. *"Steady-state" scenario*.

   This 'advanced' scenario relies on strong off-axis current drive to produce weak or reversed shear profiles with q_{min}~2 and q_{95}~5. Projected confinement improvements (H_H~1.2) lead to β_N=3.0, close to the ideal stability limit, and allow 100% non-inductive current drive and long pulse (~3000 s) operation at a reduced fusion Q = 5. Successful demonstration of this regime on ITER would be an important step towards an attractive tokamak DEMO design. Lower hybrid current drive is under serious consideration for both this and the hybrid scenario, as it has the highest off-axis CD efficiency.

[1] ITER Technical Basis Plant Description Document, published by IAEA (2001)
[2] W. Houlberg et al, Nuclear Fusion 45 (11) 1309 (2005).

It should be recognized that, in ITER experiments as on C-Mod, ranges of parameters will be explored in each scenario. However, reaching these ambitious targets serves as a useful goal to focus attention on the challenging combination of conditions which must be simultaneously met on burning plasmas. This research therefore contributes most strongly to the second overarching theme of the US fusion sciences program, *"Create a Star on Earth"* (i.e. burning plasmas), as expressed by the 2005 FESAC panel. Detailed contributions are discussed below.

2.5.1 Recent Research Highlights

2.5.1.1 H-mode Baseline

Recent experimental work on C-Mod has focused principally on the first, "Conventional H-Mode", scenario, tackling several of the key remaining issues important for extrapolation to ITER. Experimental efforts during the FY2006 campaign concentrated on support for ITPA/IEA Joint Experiments, in conjunction with U.S. and international collaborators at NSTX, DIII-D, JET, MAST, and ASDEX-UG. These experiments exploit the high leverage provided by the unique C-Mod parameters for non-dimensional scaling studies.

The ITPA/IEA Joint experiment MDC-6, Low beta Error Field Experiments, begun in 2004, was completed last year with experiments on C-Mod at 7.8 tesla. These experiments, led by T. C. Hender (UKAEA), were aimed at improving the prediction for the error field threshold for onset of locked modes in the low density ITER ohmic target plasma, and thereby validating the specification of the ITER error-field correction coils. JET and C-Mod were operated with matching shapes and non-dimensional plasma parameters at the ITER safety factor q_{95}=3.2, and with matching poloidal mode spectra for the imposed non-axisymmetric perturbing field. Following the standard plasma physics scalings, non-dimensional identity is imposed by maintaining the quantities ($aB^{5/4}$, na^2), along with all naturally dimensionless quantities such as shape, safety factor, Z_{eff}, etc., constant; for ohmically-heated plasmas this combination should ensure that the remaining scalar quantity ($Ta^{1/2}$) will also be constant, providing only plasma physics processes above the Debye scale are important. Previous results[3] had established the non-dimensional identity in the normalized perturbation threshold (B_{21}/B_T) between C-Mod (at 6.3 T) and JET (at 0.98 T), as well as a linear dependence of the threshold on plasma density. For extrapolation in major radius to ITER, it was necessary to establish the scaling of the threshold with magnetic field. Experiments at higher field on JET had indicated a power law scaling with toroidal field with an exponent α_B =-1.2. However, experiments in 2005 on C-Mod at 4.1 T indicated a much stronger scaling like $\alpha_B \approx$-2.4, which would imply a rather pessimistic prediction for the ITER threshold. No corresponding dimensionlessly matched data was available from JET, and the C-Mod data employing the JET shape and perturbed mode spectrum was inconsistent with other C-Mod results[4] which found α_B =-1.1, similar to JET and DIII-D. In 2006 additional experiments were undertaken on C-Mod, at a higher field of 7.8 T, which corresponded

[3] S. M. Wolfe, et al., Physics of Plasmas **12**, 056110 (2005)
[4] R. S. Granetz, et al., Bull Am Phys Soc Soc **50**, 316 (2005).

to an existing JET dataset at 1.3 T. The results, shown in Figure 2.5.1, were found to

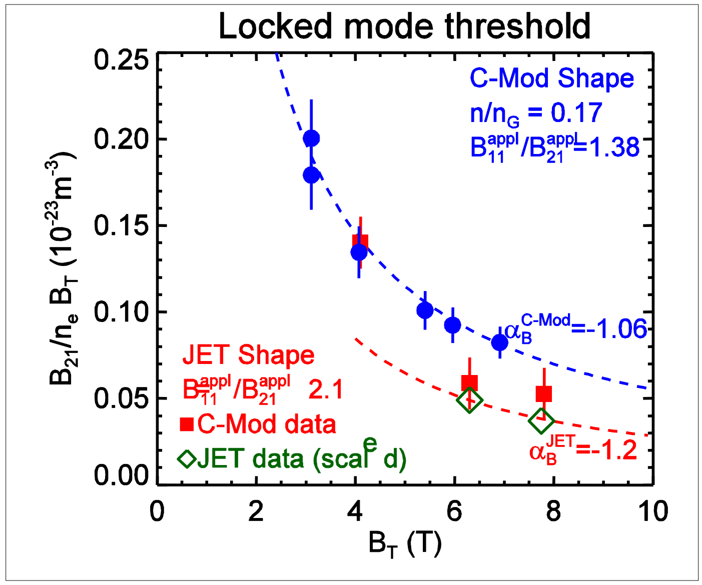

Figure 2.5.1 Scaled locked mode threshold data for C-Mod and JET as a function of toroidal field

agree within error bars with the JET data, consistent over this range with a power law exponent α_B =-1.1. Based on this scaling, the extrapolation to the ITER scale, using the non-dimensionally constrained expression $\alpha_R=2\alpha_n+1.25\alpha_B$, corresponds to $(B_{21}/B_T) = (0.9 \pm 0.5)\times10^{-4}$ at the nominal ITER target density of $2\times10^{19}m^{-3}$. The deviation from a simple power law form at lower C-Mod field remains unexplained, but may be related to observations of similarly strong field scaling reported by COMPASS-C and COMPASS-D.

During 2006, C-Mod also carried out experiments in support of ITPA/IEA Joint Experiment PEP-7, "Pedestal width analysis by dimensionless edge identity experiments on JET, ASDEX-Upgrade, and C-Mod". The goal of these experiments is to investigate the physics governing the width of the edge transport barrier in H-mode, which together with MHD stability determines the height of the pedestal and, because of the stiff profile associated with core transport, the overall confinement and reactivity of the ITER plasma. C-Mod obtained data for these investigations at a field of 7.8 T, with q_{95}=5.2, 4.2, and 3.2. These experiments were carried out using the D(He^3) ICRF heating scenario at f≈80 MHz. The corresponding target parameters for JET and ASDEX-U are 1.3 T and 2.5 T, respectively; due to technical difficulties those facilities have not yet carried out their experiments in support of PEP-7. The C-Mod data obtained to date has contributed to extending our pedestal scaling dataset, as reported at the recent APS-DPP meeting[5], and discussed in more detail in the Transport section. Further C-Mod experiments at higher RF power will be carried out once data from the other facilities is available.

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[5] A. E. Hubbard, et al., "H-mode pedestal and threshold studies over an expanded operating space on Alcator C-Mod.", to be published in Physics of Plasmas

Another set of experiments were carried out in conjunction with the Spherical Torus facilities MAST and NSTX, to establish a dimensionless pedestal comparison between small ELM regimes in these devices and in conventional tokamak aspect ratio plasmas in C-Mod. These experiments, designated ITPA/IEA Joint Experiment PEP-16, follow up a successful Joint Experiment on pedestal relaxation phenomena between C-Mod and JFT-2M, which operates at higher aspect ratio. Motivation for PEP-16 includes the identification of similarities and differences between the type-V ELM regime observed on NSTX and the EDA regime on C-Mod and HRS-mode on JFT-2M, as well as to the "small ELM" regime which develops at higher power on C-Mod. In addition to the comparison of edge relaxation mechanisms, these experiments, to be carried out with matched non-dimensional parameters *with the exception of aspect ratio* are also expected to contribute to the understanding of the scaling of the pedestal width.

All three facilities made progress on the program of PEP-16 during 2006. C-Mod achieved the specified target pedestal temperature in the designated common lower single null (LSN) shape, and observed a brief period of small ELMs. The desired pedestal density, and therefore the target β_{ped}, was not achieved, and additional experiments at higher ICRF power will be required. NSTX successfully developed the plasma shape, but has not yet carried out the high power experiments. MAST was successful in accessing the type-V ELM regime in a double-null shape, but still needs to obtain data in the LSN configuration; higher power will also be required for completion of the MAST portion of the Joint Experiment. All three facilities expect to devote additional run time to this experiment during 2007.

2.5.1.2 Advanced Scenarios

Work in FY06 on the development of 'advanced scenarios', in which we include both 'hybrid' and 'steady state' modes of operation, focused, as was planned, primarily on the advancement of profile control tools. Major progress was made on Lower Hybrid Current Drive (LHCD), most notably the high power operation (up to 900 kW) and high driven current fraction in L-mode plasmas, described in detail in Section 2.3.2. These levels exceeded our expectations for the first full experimental campaign. The driven currents agreed well with model predictions, increasing confidence that LHCD can be used to control j(r) as needed for advanced scenarios.

The completion of the cryopump in early FY07 was also highly significant. This density control tool should allow lower density target plasmas which will be highly advantageous for advanced regimes, since driven current with LH waves increases faster than $1/n_e$ as the density is decreased. Integrated use of both of these tools will begin in FY07, as described in the following section.

Progress was also made in experiments and modeling in FY06. In particular, 1.5 D time-dependent simulations of a number of near-term scenarios were carried out using the TSC code, as part of the PPPL collaboration This code includes a free-boundary equilibrium solver and a number of heating and current drive modules, including LSC for lower hybrid current drive. While it can be coupled to TRANSP and GLF23 for predictive modeling, realistic kinetic profiles based on recent C-Mod experiments were used in recent cases as an aid to experimental planning.

As an example, one such experiment focused on producing Internal Transport Barriers by off-axis ICRF, at lower I_p than in prior experiments so as to maximize the non-inductive current fraction. These experiments succeeded in producing clear barriers down to 450 kA, at moderate pedestal densities, about $1.7x10^{20}m^{-3}$, which should be suitable for future LHCD (Figure 2.5.2). Figure 2.5.3 shows TSC simulations of this experiment. The H-mode profile corresponds to the experimental target, and has 22% bootstrap current. The dashed curve is a prediction assuming that the ITB can be sustained as in other experiments, which will require simultaneous on-axis power, and corresponds to f_{BS} > 30%. Future modeling, and subsequent experiments, will explore the prospects of adding LHCD to this scenario.

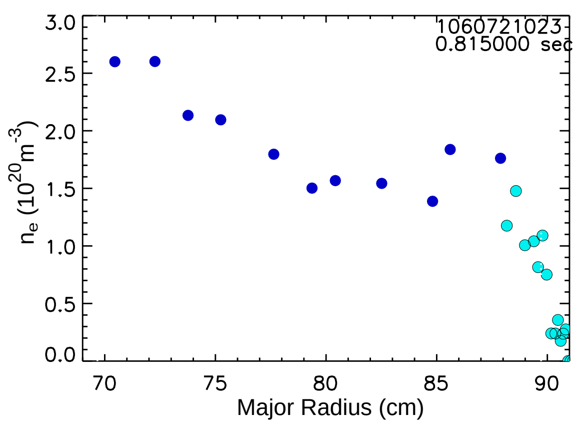


Figure 2.5.2 Density profile from a 450 kA discharge with internal transport barrier.

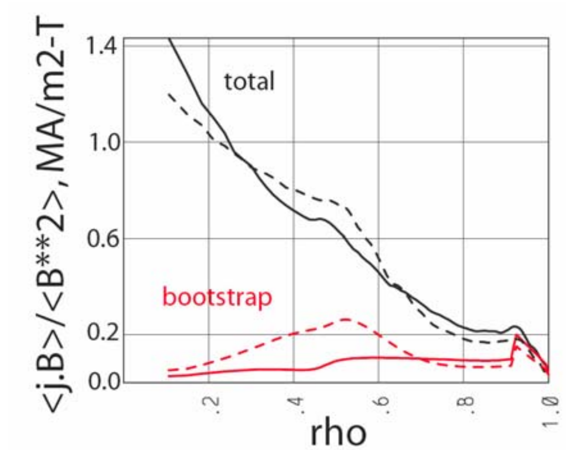
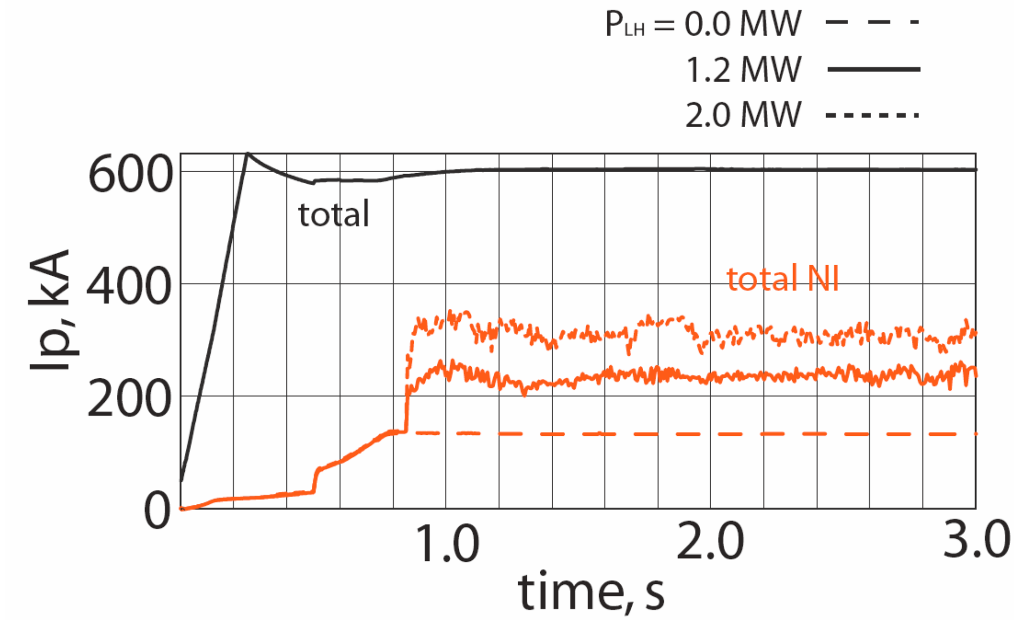


Figure 2.5.3 Current profiles modeled using TSC code, based on the same 450 kA discharge.

Other modeling, aimed at planning for FY07 experiments with LHCD, was focused on the hybrid scenario, which is of great interest for ITER and a current ITPA priority. This case used as a target experimental profiles from a 600 kA H-mode with higher performance and temperature, and again modest n_{ped}. Figure 2.5.4 shows the non-inductive current and j(r) profiles predicted from adding LHCD power (1.2 to 2. MW) to such a target. As in prior simulations with the fully self-consistent 2-D (velocity space) Fokker-Planck CQL3D code, good accessibility is found. Significant non-inductive current drive (I_{LH} 75-145 kA, I_{NI} up to 300 kA) is predicted, and q(0) is raised above one; CQL3D predicts even higher LHCD, up to 200 kA. However, it should be noted that the driven current increases non-linearly with LH power and that flattening q(r) and reducing shear in this plasma is difficult, both of which motivate increasing the coupled power through addition of the second launcher in FY08-09. While this scenario appears a good starting point for hybrid scenario experiments, further reductions in density using the cryopump will be beneficial.



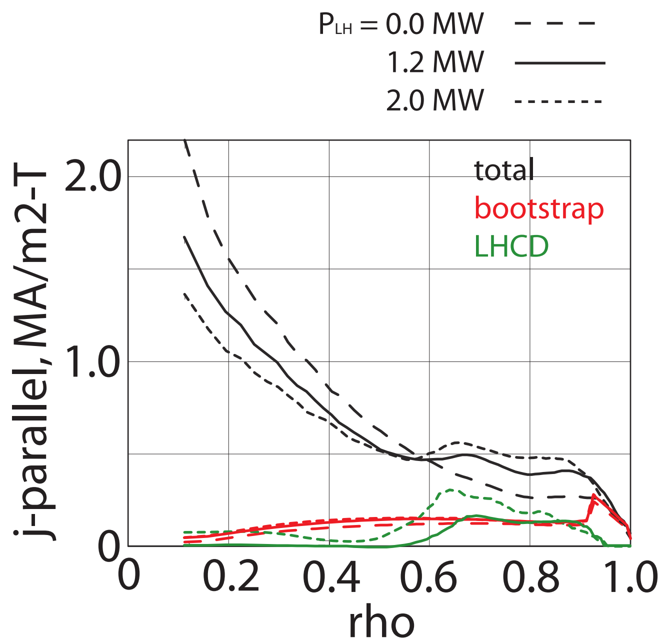


Figure 2.5.4 TSC modeling of predicted non-inductive current drive based on an experimental 600 kA H-mode, with varying LHCD power levels. (a) time dependence (b) current profiles.

Both the modeling and experimental work with LHCD are highly relevant to ITER, since C-Mod is the only device capable of performing such experiments in advanced regimes with edge and core barriers, at the ITER B_T and n_e range, and corresponding ω_{ce} and ω_{pe}. The ratio of $(\omega_{pe} / \omega_{ce})^2$ is the key parameter for LH wave propagation. The same suite of models currently being used for C-Mod is also being used, and compared, for ITER scenario modeling, with strong involvement by the C-Mod team through ITPA and the Heating and Current Drive Working Group formed as part of the ITER Design Review. C-Mod results will provide unique benchmarks for this ITER work. Crucial issues of wave coupling, density limits (which affect frequency choice) accessibility and damping, and current drive efficiency need to be assessed experimentally.

2.5.3 Research Plans

Further development of several crucial control tools will be important for all integrated scenarios. Key in 2007 will be the exploitation of the new cryopump for density control. The novel upper divertor 'slot' design should allow effective pumping in a wide range of shapes planned for both H-mode and advanced scenarios. The cryopump design, and plans for its commissioning and exploitation are presented in Section 2.1. The resulting access to lower collisionality H-mode plasmas is key to a number of new experiments in the proposed Integrated Scenarios program, as noted below.

A focus of the FY07 campaigns will be the full exploitation of the first phase of the Lower Hybrid Current Drive system, following up on the successful experiments in FY06. This work, described more fully in Section 2.3.2, will begin with further low power coupling studies, in a broader range of plasma parameters and regimes. Source power will be increased up to the maximum 3 MW. Extensive scans will then be carried out, to measure the current drive as a function of plasma density, grill phasing and other parameters. These will be compared with modeling calculations from CQL3D, TSC and other RF codes, which will be used in conjunction with experiments to optimize the magnitude and location of the wave damping and driven current. The upgraded Hard X-ray camera, as well as detectors of non-thermal Electron Cyclotron Emission, will provide important measurements of the LH-driven fast electrons for these studies. The synthetic diagnostics for CQL3D should be a particular help in this work. The MSE diagnostic should be able to measure changes in local current, following modifications of the DNB injection angle, and a polarimeter for j(r) measurements is also under development.

Installation of a second launcher is planned, with first operation in FY09. This will reduce the grill power density substantially, allowing optimal use of the full source power for long pulses of up to 5 seconds, which corresponds to several current relaxation times even at T_e=6-7 keV. Importantly, it will also enable experiments with simultaneous launching of spectra with two $N_{//}$ peaks, which has been shown by both other experiments and modeling to give greater control of the deposited waves and driven current profile. The addition of four more klystrons in FY09 will bring the source power to 4 MW, with a target of 2.5 MW coupled; this would also require a reduction in transmission losses, which is anticipated due to improvements in launcher design. This power level, as discussed below, is crucial for the most attractive non-inductive scenarios. An additional 1 MW source would be highly desirable, and is proposed for construction in FY09 and exploitation in FY10, under incremental funding.

We will continue to exploit the flexible source frequencies of our ICRF heating and current drive systems, which have 8 MW source power, half of which is tunable from 50-80 MHz. A second four-strap antenna will replace the current two-strap antennas, maintaining the full heating capability when the second LH launcher is installed.

2.5.3.1 H-mode scenarios

Over the next several years, C-Mod will extend the H-mode baseline research program to address important issues related to ITER construction and operation. These experiments build on previous results, while exploiting newly developed C-Mod capabilities, including the cryopump for density control as well as enhanced diagnostics. Continued participation in ITPA Joint Experiments and High Priority Tasks will leverage C-Mod's unique parameters and provide valuable input toward the development of improved physics understanding and predictive capability for ITER.

An important question, raised in ITPA Issue Cards LH-2 and AUX-11 for the ITER Design Review, concerns the scaling of the L-H threshold power at low density. As noted on C-Mod several years ago, and on other facilities as well, the power required to access H-mode increases rapidly below some critical density, deviating from the general trend toward lower power as the target density is reduced. The ITER H-mode scenario is predicated on accessing H-mode at relatively low density, around 2 to 5 x 10^{19} m^{-3}. However, the scaling of the low density bound is uncertain, and if the minimum in the power versus density relation is in fact near 5×10^{19} m^{-3} then the planned heating power in ITER could be insufficient to achieve H-mode operation. This issue is of critical near-term importance, since it impacts the specification of the ITER heating system. During 2007, C-Mod will be participating in multi-machine experiments to help resolve this issue by clarifying the scaling, and hopefully the underlying physics, of the low-density dependence of the L-H transition. These experiments will be facilitated by the improved density control afforded by the cryopump. In addition to contributing unique data points to the multi-machine database, we will determine the correlation of the local edge flows, temperature and density with the increase in threshold power in order to understand this phenomenon better in the context of our developing picture of the physics of the H-mode transition.

We also propose to utilize the cryopump to extend our exploration of pedestal structure and edge relaxation mechanisms to lower collisionality regimes. The H-mode pedestal height is critical for determining the core profiles and confinement in ITER. Recent work, described in the Transport Physics section, extended C-Mod H-modes to lower ν^* under specific circumstances, including high field (~8 T), unfavorable grad-B drift direction, and strong shaping. These regimes were characterized by higher pedestal T_e and lower pedestal density than our typical H-modes. Some of these cases also exhibited very steep pedestal pressure gradients. We will be continuing and extending our studies of these regimes, making use of the cryopump for additional particle control to try to access similar parameters in more typical H-mode conditions.

Also in the last year we were able to routinely access, for the first time in C-Mod, a regime of low-density H-modes with large ELMs. These plasmas were characterized by strong shaping, in particular by large values of lower triangularity. These experiments, described in the Boundary Physics section of this document, provided an opportunity to contribute to studies of ELM structure, dynamics and energetics. Using the cryopump, we will extend these studies to investigate ELM stability as a function of shape and collisionality. In particular, we should be able to pursue these studies in the ITER shape; these studies bear directly on ITPA joint activity PEP-10. Specific topics of interest include the further investigation, with improved diagnostics, of the high frequency magnetic oscillations observed at filament ejection, and the non-thermal electron generation associated with the ELM crash. In addition, we propose to follow up on a recently reported result from JET by evaluating ELM mitigation using n=1 perturbations produced by our non-axisymmetric coils (A-coils).

Building on the successful high-power H-modes demonstrated in FY05, with ITER field and β_N, H-mode high-performance scenario experiments will be extended toward conditions which are closer to those on ITER in other respects, especially collisionality and normalized current (I/aB). We have previously demonstrated ITER-shaped ohmic discharges with $\kappa>1.8$ and $q\leq3.2$ at the nominal ITER field of 5.3 T. This discharge shape is also well-matched to the new cryopump configuration. We propose to operate in this configuration at high ICRF power (P>5MW) using D(H) minority heating with $f\approx80$MHz, which provides high single pass absorption, comparable to the ITER ICRF heating scenario. This should provide an expanded parameter space for databases and extrapolation to ITER, as well as demonstrating operation at the ITER field, q_{95}, β, and absolute pressure. Using the cryopump to reduce density below that set by natural evolution from the L-mode target, the resulting increase in T_e should cause a substantial reduction of ν^*. These experiments will provide integrated tests of confinement, heating and power handling in a highly ITER-relevant regime.

Research into neoclassical tearing modes will be another topic of increasing importance. High performance H-modes on C-Mod are already close to predicted limits. With modest increases in β_N and decreases in ν^*, C-Mod will be positioned to provide important tests of NTM thresholds and RF stabilization techniques. In particular, investigation of the use of LHCD for NTM stabilization by means of Δ' modification, initially being carried out under the Macroscopic Stability Physics topical area, will, if successful, be developed as a component of an integrated scenario for application to the ITER H-mode baseline case.

Research on testing Plasma Facing Component (PFC) materials and coatings, and their impact on H-mode performance, will continue. C-Mod experiments feature divertor heat fluxes of ~0.5 GW/m^2, approaching that of ITER. Understanding and optimizing boronization application techniques and erosion mechanisms, including RF effects, will be a priority. The long term aim is to develop intershot, and ultimately *during-discharge,* boronization techniques to maintain optimal H-mode confinement and cleanliness. Such techniques would be extremely advantageous, and perhaps necessary, for ITER. Research will extend to include testing of new tungsten tile designs over a greater portion of the PFCs. The duration and input power of long-pulse experiments will be progressively extended, building on 2005 experiments with 3-4 sec pulse lengths and 6.3 MJ of input energy, enabling even more demanding tests of all PFCs. Interaction with, and effects on, the core plasma will again be key parts of the experiments.

Other H-mode experiments with direct relevance to ITER burning plasmas include burn control simulations. The newly upgraded digital plasma control system gives the capability to vary input RF power as a function of plasma temperature or neutron production. This will allow us to simulate the excursions which would occur in a burning plasma. The challenge will be to maintain performance across various plasma transients such as sawteeth or ELMs. These experiments will be carried out in collaboration with researchers at General Atomics.

Research to understand the physics of radiation trapping in the high n_oL C-Mod divertor will continue. C-Mod is the closest to ITER in this regard, and modeling predicts this will have important effects on detachment. In FY08 we will explore the prospects for radiative divertor H-mode scenarios on C-Mod at higher power than was available in past investigations. High radiated fractions are envisaged in most ITER experiments to reduce divertor heat loads. The issue and challenge here is to maintain high pedestal pressure and global confinement.

2.5.3.2 Advanced Scenarios

Now that significant LHCD has been demonstrated, the program will progressively work during FY07-FY09 to use it in developing optimized scenarios with higher non-inductive fraction and global confinement. An early focus will be on demonstrating the "hybrid" scenario in C-Mod, which will be a crucial test of whether the relevant physical mechanisms still give improved performance in the ITER-relevant conditions with coupled electrons and ions and without momentum input. As noted above, this Q=10 ITER scenario has q_{95}=4, so that present C-Mod H-mode scenarios with small ELMs make an ideal starting point. Most experiments worldwide employ tailored current rampups to create the needed flat current profile and avoid sawteeth. On C-Mod, due to the short current relaxation time, typically 0.1-0.5 seconds, LHCD will be needed to broaden the current profile and raise q_{min} above 1 for extended periods. This will require less LH power than reversing the shear.

In order to conduct these experiments, LHCD will need first to be combined with high power ICRH, and then coupled into H-mode. Possible issues to be addressed include coupling interactions in the SOL, accessibility to H-mode pedestals, and coupling through L-H transitions and ELMs. All of these issues are extremely relevant to ITER and to other proposed facilities which would exploit advanced regimes.

Hybrid scenario research will be supported by a strong effort in integrated scenario modeling to quantify these requirements and optimize the target and LH parameters. As discussed above, TSC simulations of existing H-modes have indicated attractive targets and suggested routes for improvement using the cryopump. The TSC simulations will be refined by combining with TRANSP so that more accurate modeling of the ICRH can be done using the FPPRF/TORIC module in TRANSP. Also fully predictive TSC simulations of hybrid and AT scenarios in C-Mod will be carried out using the GLF23 transport module in conjunction with TSC. In parallel, work will be initiated to couple the more accurate GENRAY - CQL3D current drive model to TRANSP, which will be an important asset for both LHCD and ICRH simulations. Finally, we plan to apply the ACCOME MHD equilibrium and current drive code to selected time slices from TSC simulations, in order to study in more detail the self-consistent MHD equilibria that can be produced using LHCD at specific points in time, especially for discharges near the no-wall ideal β-limit.

Experiments and modeling on the hybrid scenario will be carried out in close collaboration with those on other tokamaks, under ITPA joint experiments SSO-2.1, 2.2 and 2.3 and corresponding TP-2, TP-3 proposals. Unique contributions are anticipated to several High Priority ITPA Needs identified by the Transport and Steady State Operations Topical Group, described below. In particular, once the hybrid scenario is demonstrated, pedestal parameters will be thoroughly documented and contributed to an ITPA database.

Other experiments planned with the Phase I LHCD system in FY07-08 include high non-inductive fraction (f_{NI}) experiments, with lower plasma current. These experiments, again supported by scenario modeling, will progressively explore L-mode, H-mode and double-barrier scenarios. They will seek to maximize f_{NI}, and if possible to reverse the shear.

Transport control experiments will focus not only on producing internal barriers with tailored ICRH, as in prior years, but on assessing the effects of shear modification. The first experiments in this regard, in FY07-08, will use 1-1.5 MW of LHCD and explore the effects on ITB formation and barrier location.

It is clear from extensive modeling that significant increases in power, which will be enabled by the addition of the second launcher and additional klystrons, will be needed to reverse the shear in high confinement, higher density discharges. This upgrade is thus a priority for the Advanced Scenarios program. Phase II experiments will commence in FY09, enabling a research program aiming toward demonstration of high bootstrap fraction, quasi-steady state scenarios. The long-term goals for C-Mod are very similar to the ITER steady-state scenario, with 100% non-inductive current drive, 70% bootstrap fraction, achieved using modestly enhanced global confinement, reversed shear and β_N~2.9, just below the no-wall limit with optimized shaping and profiles[6]. This will again be achieved in the ITER relevant regime with coupled electrons and ions and low rotation, in contrast to other AT experiments worldwide. The compound spectra enabled by the second launcher are also important, providing greater flexibility and control of the deposition profile. Both L-mode and H-mode target plasmas will be used. The pumping capability of the cryopump is needed for density control, which is critical for maintaining good LHCD efficiency and deposition control in a range of confinement regimes. Full non-inductive CD will require combination of LHCD with other current drive tools, including FWCD and possibly MCCD, being developed by the RF topical group.

[6] P.T. Bonoli *et al.,* Plasma Physics and Controlled Fusion **39**, 223 (1997).

Stronger current drive should enable reversal of the magnetic shear in high confinement discharges, enhancing the ability to control core transport, and thus optimize the bootstrap current. It is anticipated based on results on other experiments that once shear is reduced or reversed via LHCD, it will be possible to form ITBs at a larger radius and with higher on-axis power. This would give a substantial increase in the bootstrap fraction. ACCOME and TRANSP simulations also show an important synergy between bootstrap current and LHCD; when LHCD is applied the bootstrap fraction increases due to the weaker poloidal field near the axis. Combining LHCD with tailored ICRH profiles, and using real-time feedback of both heating systems, offers exciting possibilities for active control of transport, which could potentially avoid some of the typical problems of impurity accumulation and MHD instability.

Because of the complexity and number of control tools and non-linear interactions between RF and transport physics, scenario modeling will continue to be a key part of the advanced scenario development program. New experimental and theoretical results, from C-Mod and elsewhere, will be incorporated into this modeling and used to update the target scenario for full non-inductive operation. A significant step forward in simulation capability of LHCD will be realized when coupling of the full-wave LH TORIC solver to the CQL3D Fokker Planck code is completed through the SciDAC Center for Simulation of Wave Plasma Interactions. This will make it possible to include important full-wave effects such as focusing and diffraction in LHCD simulations for the first time ever. Within about a year we expect the successor of GLF23 – the TGLF code – to be available. Significant improvements in this code should make it possible to perform more realistic predictive simulations of C-Mod hybrid and AT scenarios using TSC.

As the plasma β increases due to increased input power and improved confinement, issues of MHD stability will become more important. In the FY07-FY09 period, our plan is to modify shaping and plasma profiles so as to maximize the no-wall ideal stability limit. Stability calculations show that $\beta_n \sim 3$ is achievable. In parallel, we will initiate numerical studies of possible methods to stabilize resistive wall modes and exceed the no-wall limit.

Increased power, heat loads and pulse lengths will also increase the challenge of power handling on the metal walls and divertor of C-Mod. Long pulse (3-4 second) discharges in FY05 with higher RF power and using improved diagnostics were encouraging. Compatibility of high heat loads with the lower densities needed for optimal non-inductive current drive will be a particular challenge for steady-state scenarios through FY09; our results will be important in planning advanced scenarios for ITER. They will also determine the need for outer divertor upgrades on C-Mod, which are anticipated in the FY09-10 time frame to enable full power, five second operation.

Contributions to ITPA High Priority Tasks and to FESAC Fusion Science Campaigns

C-Mod experiments are uniquely ITER-relevant in many respects, including:

- an all-metal wall,
- high heat loading,
- equilibrated ions and electrons,
- no external momentum or internal particle sources,
- an opaque divertor and
- high magnetic field.

Furthermore, C-Mod is the only experiment in the world that can test LHCD in these conditions. Research aimed towards demonstrating integrated scenarios thus contributes strongly to a range of ITER needs, as identified by the 2006-2007 list of *ITPA High Priority Research Tasks* compiled by the ITPA Coordinating Committee. A summary of the most important contributions expected in the time frame of this proposal is given below, by Topical Group. Some of these have been described in more detail in preceding sections but are included here for completeness; the key challenge is to *simultaneously* address the many physics and technology issues which will be encountered on ITER. Many of these issues will be addressed partly through participation in ITPA joint experiments, as listed in Section 1.

MHD:

- **Continue development of the new disruption DB including conventional and advanced scenarios** to initially study fast Ip quenches and halo currents
- **Develop disruption mitigation techniques particularly at high** performance and by noble gas injection and understand influence of MHD on impurity penetration. **Validate 2 and 3-D codes, in particular MHD and radiation models, on gas injection.** Develop reliable disruption prediction methods.
- **Understand intermediate-n AEs** ; redistribution of fast particles from AEs; and perform theory-data comparisons on damping and stability

Steady State Operation:

- Continue the **focussed modelling activity on ITER Hybrid and Steady state cases**, using standard (and common) sets of input data.
- Pedestal studies: **Experiments to document pedestal in advanced scenarios**, modelling of pedestal, pedestal conditions in ITER (maximum T_{ped})
- **Code benchmarking of LHCD** and NBCD **and implications for ITER**.

Transport Physics:

- Utilize upgraded machine capabilities to **obtain and test understanding of improved core transport regimes with reactor relevant conditions, specifically electron heating, Te~Ti and low momentum input,** and provide extrapolation methodology
- Develop and demonstrate **turbulence stabilization mechanisms compatible with reactor conditions**
- **Study and characterize rotation sources, transport mechanisms and effects on confinement and barrier formation**

- **Quantitative tests of fundamental features of turbulent transport theory** via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings.

Confinement database and modeling:

- Resolve the differences in β scaling in H-mode confinement
- **Resolve which is the most significant confinement parameter, ν^* or n/n_G**
- Define a program to **understand the density peaking**
- Develop a **reference set of ITER scenarios for standard H-mode, steady-state, and hybrid operation** and submit cases from various transport code simulations to the Profile DB

Pedestal and Edge:

- **Improve predictive capability of pedestal structure** through profile modeling and experimental studies
    - o **Dimensionless cross machine comparisons** to isolate physical processes; assess dependence on ρ^* , ripple, rotation, and shape
    - o Measurement and modeling of inter-ELM transport
    - o **Establish profile database for modeling joint experiments including effects of neutrals**
- Physics based empirical scaling
    - o Collaboration with CDBM to improve scalar database characteristics and utilization
- **Improve Predictive Capability of ELM characteristics** through experimental studies and theory / modeling analysis, and **develop small ELM and quiescent H-mode regimes** and ELM control techniques
    - o Integrate **observations of ELM crash dynamics** and initiate comparisons with developing models
    - o **Categorize small ELM regimes based on cross machine comparisons**

Divertor and SOL:

- **Understanding of Tritium retention, and development of efficient T removal methods**
- Understand the effect of ELMs/disruptions on divertor and first wall structures.
- **Improve measurements & understanding of plasma transport to targets and walls**, for better prediction of heat load, and effects on the core plasma
    - o Exploring the role of **non-diffusive radial transport** (i.e. blob/ turbulence) on wall heat/particle loadings, macroscopic transport(χ and D), and **driving SOL flows** (parallel transport).
    - o **Neutral density benchmarking of physic models in current experiments and ITER**
- Understand how **conditioning and operational techniques** can be scaled to reactor devises
    - o **Implications of a metal wall for startup, fuel retention, density control and core impurity levels**

While C-Mod research on integrated scenarios is targeted particularly towards ITER needs, it should be noted that it also makes strong general contributions to fusion science. Many issues at the forefront of fusion research are those involving interaction of multiple topical areas or ‘campaigns’. This is highlighted by the *Recommended areas of US ‘opportunity for enhanced progress’* in the 2005 FESAC report, which identified 12 top priorities for fusion program resources. Of these, the Integrated Scenarios thrusts contribute most directly to

> *Integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas,*

which in fact summarizes well the overall goal of the C-Mod scenarios research.

Other FESAC priority areas in which the integration research makes strong and unique contributions are:

- *Predict the formation, structure, and transient evolution of edge transport barriers.*
- *Extend understanding and capability to control and manipulate plasmas with external waves.*
- *Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments.*

2.6 Run Planning

The C-Mod Research Program is coordinated by the Experimental Program Committee, which consists of the leaders of the Topical Science and Operations Groups and the Thrusts and Task Forces, representatives of the major collaborating institutions and the C-Mod Project leadership. The EPC sets overall research priorities, determines the run-time schedule and allocations, and reviews and approves Miniproposals for individual experiments.

Planning of experimental campaigns at Alcator C-Mod is a multi-step process which draws on input from the entire community. The C-Mod Ideas Forum provides a mechanism by which research proposals are solicited from the entire community. These Forums are typically held at intervals of 20 to 30 Research Weeks, usually keyed to the availability of new C-Mod capabilities. Prospective resources and program priorities are advertised prior to the Forum. Research ideas are presented in a brief, conceptual format in open sessions, which are available remotely using a variety of videoconferencing tools. The most recent Ideas Forum was held in December, 2006, and resulted in 145 Ideas for experiments. Participants included representatives of 11 institutions. Follow-up sessions for each of the Task Forces and Topical Groups, including all interested participants, discuss and refine the ideas, and prioritize the proposed experiments.

An initial allocation of run-time among the various Topical Groups, Thrusts and Task Forces is established prior to the beginning of each experimental campaign, based on programmatic requirements, facility capabilities, and available resources. The allocations may be revised as the campaign proceeds as priorities and capabilities change, or in recognition of new opportunities.

Approval of specific experiments is based on submission of detailed Miniproposals, which describe the purpose of the research and the plans for carrying it out. Miniproposals are intended to cover well-defined topics requiring one or several days of dedicated experimental time. These are usually submitted under the auspices of one (or more) of the Research Groups or Task Forces. The EPC meets periodically to review and approve MP's. Criteria for acceptance include programmatic relevance, technical feasibility, and scientific importance. Preference is also given to proposals which contribute to students' thesis research.

Scheduling of experimental time for approved Miniproposals is generally done on a short term basis, typically weekly. This approach has proven most successful in terms of providing optimum use of facility capabilities and conditions as they evolve during a campaign, as well as providing flexibility to accommodate unanticipated research opportunities. An exception is made in the case of experiments involving off-site collaborators who require travel arrangements to be made well in advance, and for other time-sensitive experiments; in these cases an experimental schedule may be established well in advance. Similarly, some experiments which depend on specific facility configurations, such as those requiring a particular ICRF frequency or operation with reversed field, will normally be assigned a block of time during which the appropriate conditions are to be provided.

The FY07 Experimental Campaign is planned to include 15 Research Weeks (60 Research Days). The total run time is determined, primarily based on budgetary considerations, in consultation with the funding agency. Initial allocations for the campaign are shown in Table 1. In addition to the Topical Science groups and Integrated Scenario thrusts, the FY07 allocation includes time under "Operations" and "Diagnostics", reflecting the level of effort required to commission the newly installed cryopump and various enhancements to the diagnostic set.

Table 1

Transport Physics	10 days
Edge/Divertor/Wall Studies	6
ICRF Physics and Technology	6
MHD	6
Lower Hybrid Physics	9
Integrated Scenario (H-mode)	6
Integrated Scenario (AT)	7
Operations	6
Diagnostics	4
Total	**60**

The proposed FY07 run plan emphasizes exploitation of the Lower Hybrid current drive system which was successfully brought into operation in 2006. Use of the cryopump to access regimes of lower collisionality is also a major theme of the proposed campaign. The allocations shown do not include up to 14 days required for startup and machine conditioning activities, which normally occupy the initial phase of each campaign. The primary goal of this "pre-physics" phase is reduction of the hydrogen fraction to levels consistent with our principal ICRF heating scenario, proton minority heating (H/D < 5%). This period is also used for diagnostic check-out and calibration and for discharge development in support of planned experiments. Some research activities, including experiments which do not require boronization or ICRF heating, and which are compatible with incomplete diagnostic coverage, can also be carried out during this time.

The proposed fifteen-week FY07 campaign requires a number of configurational changes which impact scheduling. Two changes of frequency of the tunable ICRF transmitters #3 and 4 (J-port antenna) are proposed. The initial part of the campaign will be conducted with these transmitters at 78MHz; this configuration provides the maximum available on-axis heating power, with the 4MW from J-port combined with 2MW each from D- and E-port antennas, which are powered by fixed frequency transmitters at 80 and 80.5 MHz. During this phase, at least one week would be carried out with the toroidal field and plasma current direction reversed, a change which requires a few days to accomplish. Toward the end of the campaign, the J-port ICRF frequency would be changed to 50MHz in order to carry out elements of the RF physics research program. The frequency would then be changed again, to 70MHz, in support of ITB physics experiments. Each change of the ICRF frequency normally requires about a week for changes to the transmission line hardware and retuning of the transmitters.

At this time, we do not anticipate holding another Ideas Forum prior to the FY2008 Experimental Campaign. We expect that a brief up-to-air will follow completion of the

FY07 campaign, and that plasma operation will resume in the first half of the new fiscal year. The proposed budget is consistent with a total of fifteen weeks of research operation again in FY2008. The experimental program will continue to draw on the many high-quality proposals arising from the last Forum, along with new Miniproposals developed in response to evolving research opportunities as the program proceeds.

An Ideas Forum to be scheduled following the FY08 C-Mod campaign will provide the basis for planning of the FY09 experimental program. The planning process will also draw on the proceedings of the National Tokamak Workshop, to be held at MIT in September, 2007. Key considerations will include the requirements for ITER-related research and of the National and International fusion program.

3. Operations

3.1 Facilities

The FY2006 run campaign concluded in late July 2006, after 16.7 weeks of research operation, which exceeded the 14 week JOULE milestone. 1658 discharges were produced during the FY2006 campaign.

During the up-to-air period from late July 2006 to late February 2007, major upgrades to C-Mod were made including installation of the upper chamber cryopump, a toroidal belt of tungsten tiles in the outer divertor, and a fast-ferrite-tuner system for the E-Port ICRF antenna. Another major accomplishment was the operation of the lower hybrid system at the full source power of 3 MW for 0.5 s. The diagnostic capabilities of C-Mod have been greatly increased including new X-Ray doppler measurement for ion temperature and rotation profiles, upgrades to the bolometry, CXRS, BES, Thomson scattering, gas puff imaging, and magnetics systems. A 7^{o} toroidal rotation of the long pulse diagnostic neutral beam was performed that should greatly improve MSE measurements. A new shutter system for the inner wall polarimeter retro-reflectors has been installed that should allow these devices to remain operational throughout the run campaign.

3.1.1Contribution to ITER Technology

C-Mod is very similar to ITER in terms of magnetic field, density, and heat flux to the divertor. A wide range of ITER technology issues can therefore be studied on C-Mod. In addition, the development of conferencing technology, as well as data acquisition software, will be of great importance to efficient operation of the ITER program. In Table 3.1 we list major contributions being made by C-Mod to the ITER effort.

3.1.2 Cryopump

Density control during H-Mode and AT operation on C-Mod will be greatly improved with the addition of the upper divertor cryopump which was installed in the 2nd quarter of FY2007. A liquid helium cooled inconel tube in the upper divertor region of the vacuum vessel will provide the pumping. A liquid nitrogen shield surrounds the helium tube and keeps the helium cooled pump from seeing room temperature surfaces (figure 3.1.1). A novel feature of the pump is 30 radial slots in the upper divertor protection hardware that allow flow of neutral particles to the pump in a manner insensitive to plasma strike-point location (figure 3.1.2 and 3.1.3). The pumping speed of the pump is ~10,000 l/s for deuterium, as has been verified by tests of a prototype pump in the cryopump vacuum test stand. The design of the liquid helium system also allows good pumping of hydrogen which could shorten the time required for C-Mod to obtain research grade plasmas following a vent.

3.1.3 Advanced Divertor Tiles

During the FY2005 and FY2006 run campaigns, tungsten brush tiles performed well in C-Mod. For the FY2007 campaign a new more ITER-relevant design has been developed in which 4 mm thick tungsten plates are bolted together to form a tile (figure 3.1.4). This lamella design has been tested to 6.7 MW/m^2 for 7 s long pulses. A toroidal belt of these tiles has been installed in the outer divertor for the next campaign. A picture showing the new tiles installed in the outer divertor can be seen in figure 3.1.5. A paper detailing the extensive modeling required to produce these tiles can be found at

http://www.psfc.mit.edu/research/alcator/data/Lamellae%20tungsten%20tile%20design.pdf

3.1.4 Lower Hybrid System

Over the last year new stainless steel couplers were successfully operated on C-Mod. However, only the inner 22 of the 24 waveguides were used because of concerns about high stresses on the edge alumina vacuum windows. A double flange design with much lower stress in the windows has been designed, modeled, and four couplers have been fabricated and are now being prepared for brazing. These new couplers will serve as backups for the currently installed couplers during the FY2007campaign. They will then be installed before the FY2008 campaign.

The last year has also seen extensive development work on protection and phase and amplitude control systems. An upgrade to the coupler protection system (CPS) will use field programmable gate arrays with onboard fast data acquisition boards to detect and respond to fault conditions. The phase and amplitude control system allowed power and phase to be scanned during a single discharge during the FY2006 run campaign.

During the up-to-air period we have brought the lower hybrid system up to its full source power specification of 3 MW for 0.5 s. This accomplishment involved detailed investigations of the klystron operational space as well as making improvements in the performance of the circulators.

A second lower hybrid launcher will be fabricated starting in FY2008 for installation in FY2009. The new launcher will reduce the rf power density on both launchers and allow compound spectra to be investigated. This upgrade will be performed in parallel with the addition of a new klystron cart increasing our total source power to 4 MW.

3.1.5 Long Pulse DNB

Over the last year an interlock protection system was incorporated into the DNB control system that allowed the beam to run for 1.5 s of integrated “on” time at full voltage and current (50 kV, 6.5-7 amps, the design parameters) without damage to the inner wall.

This new system monitors magnetic field, vessel pressure, visible bremsstralung, and optical pyrometer data in order to decide if it is safe to operate the beam.

The calorimeter instrumentation is now fully on-line and its operation is fully automated, as is the thermocouple profile analysis needed to derive beam profile widths. The width is found to decrease as the beam current is raised (as expected because of perveance effects). The 1/e radius is 4.0 cm at 6.5 amps and 50 kV.

Effort was expended rotating the beam 7^{o} toroidally for the FY07 campaign in order to improve the MSE measurements. This task also required the relocation of some of the beam related diagnostics so that they continued to view the beam in an optimal manner. Some details of the expected benefits from this change are covered in the diagnostics section on MSE.

3.1.6 ICRF Systems

A new 4-strap ICRF antenna, with a Faraday screen, is planned for installation in FY2009. The new 4-strap antenna will replace both the D- and E-Port antennas without losing any ICRF power handling capability. This change will also free up D-Port for installation of the 2nd lower hybrid launcher.

Fast Ferrite Tuners (FFT) fabricated by Advanced Ferrite Technologies, and originally used at DIII-D and ASDEX-U, will allow a match between the transmitter and the antenna to be maintained in real-time. The original power supplies shipped with the tuners were found to be inadequate for use on C-Mod, but a new vendor with acceptable supplies was identified, and the FFT system, following extensive testing, is now being installed in the C-Mod cell. An RF power test of the tuners and supply during plasma operation is planned in FY2007. Operation with these tuners will yield valuable information regarding the design of new tuners for the two 4-strap antennas we could have in place by FY2009. Incremental funding is needed for the design, procurement, and installation of these tuners.

Over the last year the ignitron based crowbar systems have been upgraded, as have the ICRF data acquisition and control systems. Changes to the antennas have also been made to improve high voltage rf standoff capability.

3.1.7 MIT Alternator

The alternator ran very reliably during the FY2006 campaign. In September of 2006 a scheduled minor inspection of the alternator indicated that the stator and field coil were in excellent condition. Over the last year upgrades to the seal oil water cooling system were made as well as numerous upgrades to instrumentation and PLC controls.

3.1.8 Data system

Approximately 1.8 GBytes of data is taken during each shot cycle on Alcator C-Mod with our data handling requirements doubling every 1.9 years (figure 3.1.6). Continuous hardware upgrades are required to maintain adequate storage with this level of growth and also to maintain a 12 minutes shot cycle. Over the last year we have purchased and deployed a 2nd LTO3 based Tape library for archive and backup. We have continued our migration from CAMAC to faster higher density CPCI modules. Firewire camera data acquisition computers have been upgraded and five new C-Mod workstations (dual processor, dual core, 64 bit) have been added bringing the total to 44. Two new data system development computers have been added, and we continue to develop the ISCSI raid array. Upgrades to data storage, servers, and networking capability will continue over the next year.

Software development also continues. Long Pulse extensions for MDSplus have been designed and a prototype implementation has begun. New features have been added to MDSplus including: support for the retention of multiple versions of data items; a named attributes feature; and support for 64bit Linux platforms. A new WIKI based MDSplus website (http://www.mdsplus.org) has been brought on line. New development systems are being used to evaluate Linux Clustering as a tool for improving data handling performance. Ongoing tests of advanced communication technologies such as SIP, EVO, WEBEX, and AG continue.

Both on- and off-site support of MDSPlus will also continue over the next two years. MDSPlus is now used at more than thirty sites throughout the world.

3.1.9 Outer Divertor Upgrade

The heat load to the outer divertor will continue to increase as we add more lower hybrid rf power and extend discharge pulse lengths. A conceptual design for a new outer divertor with an extended vertical cylindrical section has been developed to handle these increased heat loads. The new design will be easier to manufacture than the current divertor, and also be much easier to install with precision in-vessel. Alignment of the tiles relative to the field lines is a critical issue to be addressed if we are to minimize peak heat loads on the tiles. There will also be no toroidal gaps or leading edges where enhancements to the heat load typically occur. The tiles used for the divertor are expected to follow from our advanced divertor work.

If incremental funding becomes available, a detailed design of the outer divertor is planned for FY2008 with procurement and installation completed in FY2009. Under guidance budgets, detailed design is planned for FY2009

3.2 Diagnostics

Several new diagnostics have been brought on-line over the past year as well as upgrades to existing ones. We show in Table 3.2 a list of diagnostic accomplishments and plans, while giving more detail on a few of the more extensive upgrades below.

3.2.1 Motional Stark Effect (PPPL/MIT): Significant progress was realized during FY06 in understanding the cause of serious calibration problems with the Motional Stark Effect (MSE) diagnostic. Results obtained from the 'in-vessel' calibration technique (illuminating MSE with light passing through a linear polarizer at a known angle when the torus is up-to-air) differ by several degrees from results obtained from a 'beam-into-gas' calibration, i.e. when the DNB is fired into a gas-filled torus with a pitch angle that is known from defined toroidal and vertical fields. In addition, discrepancies are observed between the pitch angle measured by MSE and that computed by EFIT at the plasma edge, where the EFIT calculation is accurate and not affected by uncertainties in the current profile shape.

It was conjectured that the cause of the beam-into-gas calibration anomaly is the peculiar injection geometry of the DNB: exactly perpendicular to the toroidal direction. Beam neutrals that ionize upon collisions with torus gas have no parallel velocity along the magnetic field line, and drift only slowly out of the MSE field-of-view. Virtually all of the ionized beam neutrals will re-neutralize before leaving the MSE viewing footprint, thereby generating a population of "secondary" beam neutrals having random gyro angles.

Experimental evidence for this conjecture was obtained during FY06 by measuring the spectrum along an MSE sightline and observing the behavior of a spectral feature on the blue side of unshifted Hα in agreement with calculations. In addition, the conjecture reproduces some qualitative trends in the observed discrepancy between the in-vessel and beam-into-gas calibrations. Based on these measurements, it was decided to rotate the DNB 7° toroidally. This is the maximum possible rotation consistent with access constraints, and is calculated to reduce the population of secondary emission by a factor of greater than 30, thus eliminating the deleterious effect on the MSE beam-into-gas calibration. The engineering tasks to rotate the beam, including re-location and/or re-aiming of several beam-based diagnostics, commenced at the end of FY06 and were completed by February 2007.

During FY2007 we will carry out MSE spectrum measurements and additional beam-into-gas calibration data to confirm that rotating the DNB has resolved the calibration issues. In addition, we will test an approach to measure the polarization properties of visible Bremsstrahlung (VB) light that contaminates the MSE signal, particularly at high plasma density. One fiber from the bundle of 16 fibers that serve a single MSE channel will be routed to a dedicated bandpass filter / avalanche photodiode assembly, where the filter's passband will be chosen to view VB light exclusively. It is hoped that this approach will enable real-time compensation for VB light and thereby allow more accurate pitch angle measurements without the need to rapidly modulate the DNB.

The DNB will be upgraded in FY07-08 with an aperturing system to reduce the horizontal beam width to 6 cm, in order to enhance the MSE spatial resolution. There are two major components, a movable water-cooled aperture at the exit of the DNB tank, and a static, passively-cooled aperture further downstream inside the tokamak port. The water-cooled aperture is being built at the Budker Institute in Novosibirsk, and will be delivered and installed in the spring of 2007. The downstream component will be fabricated at MIT and installed in FY08.

3.2.2 Surface Science Station: The C-Mod group is placing increasing emphasis on measurement and understanding of plasma surface interactions. This general area includes studies of D retention, as well as surface erosion and redeposition. In the past we have had to rely on removal of tiles from the tokamak to infer what is occurring at those surfaces. This process has the obvious disadvantage that the results are integrated over a run campaign (no information about the conditions of a specific discharge). In addition the analysis is much delayed from the experiments making feedback between analysis and planning new experiments slow with a long time constant. To address these problems we have designed and installed (2006-07 vacuum break) a surface science station (S^3). The head of the station is replaceable behind an air lock allowing multiple experiments to be planned (see figure 3.2.1). With the gate valve to the tokamak opened, the head can be scanned over most of the major radius between the inner and outer walls. The head can also be rotated 360 degrees.

The first experiments planned with S^3 involve installation of Quartz MicroBalances (QMBs) in the head. These detectors will be utilized to measure the boronization profile (section 2.1.x) and optimize the boronization deposition using vertical fields (section 2.1.x).

Additional plans for FY08 include the placement of samples in the head to be exposed to specific discharges, after which they will be withdrawn beyond the airlock and analyzed with the new ARRIBA system for erosion/redeposition as well as D retention. Assuming that this test works, the ARRIBA system will be mounted in the head to allow analysis of test surfaces exposed to plasmas in C-Mod; samples can be analyzed without being removed from the tokamak.

The ARRIBA (Alpha Radioisotope Remote Ion Beam Analysis) is a proposed diagnostic that used several innovations to make possible real-time ion beam surface analysis of erosion, redeposition, material composition and H/D/T retention. The "ion beam" is an alpha-emitting radioisotope, which along with the charged-particle detectors, is protected behind a tile surface. Measuring scattered particle spectra due to the alpha-surface interaction provides depth-resolved surface composition, including H/DT, and material erosion with ~ 10 nm resolution, sufficient for between-shot analysis. We propose to first test this portion of ARRIBA (07-08) by placing the alpha source and detectors in the "airlock" section of S3, and test material samples that are inserted and retracted on the probe head. The next testing phase involves inserting the full ARRIBA system on S^3. This system uses a "pull and flip" $\mathbf{J}\times\mathbf{B}$ activated mechanism for controlling the exposure of surfaces in tokamak discharges, and concurrently moving said surfaces into place for analysis with the alpha source.

3.2.3 CXRS Upgrades(UTexas/MIT): In order to improve mesaurements of Ti, rotation, ITB foot location, impurity transport, and SOL and pedestal flows we have made important upgrades to our CXRS systems. The number of poloidal chords has been increased from 25 to 45, and the number of toroidal chords increased from 16 to 37 (figure 3.2.2)

3.2.4 BES Upgrades (UTexas): A new high density 6X6 fiber array will improve resolution. New CPCI digitizers will increase the amount of memory available by nearly a factor of 30, and allow much better statistics to be obtained during long pulse DNB operation.

3.2.5 Gas Puff Imaging (PPPL/MIT): A new view of the lower part of the plasma just outside the lower x-point has been installed. This new view will be coupled to a new 150,000 frame/s camera and will allow comparisons to be made with the previously installed midplane views. Information about fluctuations at these two locations is of great interest.

3.2.6 Bolometry Upgrade: So that accurate power balance and impurity transport measurements can be made the resolution of the bolometry AXUV unfiltered arrays has been increased. In addition we have increased the number of filtered AXUV Lyman α chords to improve neutral density, ionization, and opacity measurement resolution. A new ledge bolometer with 20 chords each of filtered and unfiltered channels now views into the divertor. See figures 3.2.3 and 3.2.4 for details of chordal layouts.

3.2.7 Upper Chamber Rogowski Coils: With the installation of the new upper chamber protection hardware we were able to add 10 new Rogowski coils to monitor the toroidal distribution of halo currents during upwardly going disruptions (figure 3.2.5). A single Rogoski measuring the total halo current is also in place in the upper chamber.

3.2.8 Polarimetry System: Procurement of a dual beam FIR laser is underway, and a pneumatically operated shutter has been installed on the inner wall which will allow the retro-reflectors to be protected during boronization. Six retro-reflectors placed from near the midplane into the upper chamber have been installed in the shutter.

3.2.9 Core Thomson Scattering Upgrades: We will increase the number of core channels from 11 to 16 for enhanced radial resolution (cm resolution in vicinity of ITB). Compact polychromators (GA design) for light collection will be used, with delivery of the polychromators expected in early 2007. These systems provide a streamlined hardware configuration and data acquisition and also provide more efficient use of space. New fiber bundles with improved transmission in the near-IR have been installed. New fast digitizers will supplement, and eventually replace, FERA modules.

3.2.10 Dust Injection (ITPA high priority): A fiber feeding an in-vessel collimator has been placed on the outer divertor shelf that will allow dust injected into the SOL to be illuminated by laser light at 0.532 μm. Videos of the interaction region will be made. The dust (boron) will be injected through a capillary tube located next to the new collimator using helium gas. This system will be ready for operation during the FY2007 campaign.

3.2.11 Spatially Resolving HIgh REsolution X-ray spectrometer , SR HiReX (PPPL/MIT): A spherically bent crystal spectrometer looking at H- & He-like Argon emissions lines will provide impurity temperature and rotation profiles for r/a <0.8 . This new system will provide 40 chords of He-like information and 15 chords of H-like data, with a time resolution of approximately 10 ms. The velocity measurement uncertainty is expected to be ±3 km/s while temperature measurements should have uncertainties in the 80 eV range (figure 3.2.6).

3.2.12 Limiter Magnetic Pickup Coils: Seven new magnetic pickup coils have been installed for the next run campaign. The new coils will greatly improve the low n resolution (n ~1 to 5) of fluctuation measurements.

3.2.13 Penning Gauges: New gauges will measure pressures above and below the room temperature shield in the cryopump gas box. Pressure difference should be a direct measure of throughput. A previously installed gauge gives measurements outside the gas box. With the cryopump warm, difference in pressure inside and outside the box should be a good measurement of how well particles are being entrained in the gas box.

3.2.14 Inner Wall Scanning Probes: Two new scanning probes have been installed on the inner wall (high field SOL). Linear motion in major radius is driven by currents in embedded coils reacting to the C-Mod magnetic field. Four tungsten electrodes arranged in a “Mach-probe” geometry have been installed, with identical geometry to outer midplane and vertical scanning probes. The probes will be sensitive to plasma flows both ⊥ and ‖ to B. Profiles of ne, Te, and V_f , and fluctuation-induced particle fluxes will be measured.

3.2.15 Infrared Camera System (LANL/MIT): We continue to use the infrared imaging system on Alcator C-Mod to image the surface of the outer lower divertor, including the outer strike point on the divertor target plate. Depending on plasma conditions and strike point location, surface temperatures in excess of 800 ^{o}C have been observed, particularly in long-pulse, low-density experiments. The 256x256 pixel infrared images are recorded at 60 Hz for up to 4 s during each shot.

A new IR spectroscopy system is assembled, and has been tested at LANL. This new Hamamatsu self-scanning InGaAs 256-element diode array is mounted on a McPherson 0.3 meter spectrometer, and provides us with spectral details in the 0.8-2.6 micron wavelength band. No other tokamak or fusion plasma experiment has this capability. The focus 2007 & 2008 is on making companion IR measurements in the divertor region, using the new infrared spectrometer. Remote control fiber-optics, interface PCI crate, and computer system are operational. In FY2007 and beyond, infrared spectra in the 0.8-2.6 micron wavelength band will be obtained during a variety of tokamak edge plasma conditions. Initially, 50 spectra per second will be obtained, but ultimate time resolution is expected to be 1-2 milliseconds per spectral readout. Measurements in this wavelength band have never been accomplished in any prior tokamak. (ASDEX came close in 1990 with some near-IR measurements for their system to determine a good region for measuring Z-effective).

An upgraded IR imaging capability will be developed by FY09, procuring a new, compact mid-wavelength IR camera, with 14-bit dynamic range, and a 160x256 element micro-bolometer array. This will enable broader coverage of the inside of Alcator C-Mod, with a new infrared view, useful as more heating power is applied.

Table 3.1
C-Mod Contributions to ITER Technology

Tungsten Lamella Tiles	Toroidal belt of tiles have been installed for the FY2007 run campaign Design similar to those being considered for ITER
Real-Time ICRF Fast Ferrite Tuners	Maintain antenna match during ELMs and across confinement mode transitions
Wall Conditioning and Coating Technology	C-Mod results indicate low-Z coatings are required for good performance in machines with high-Z PFCs Techniques need to be developed to continuously maintain low-Z layer
Dust Detection	Dust may become a major safety issue for ITER Dust may also provide a source of impurities A system to inject dust and monitor its motion into the SOL has been installed for the FY2007 run campaign
Polarimetry	FIR poloidally viewing polarimeter being developed for C-Mod Geometry similar to that proposed for ITER Fields and plasma parameters similar to ITER

	Shutter system to protect retro-reflects installed for FY2007
Gas Jet Disruption Mitigation	Disruptions in ITER could be very damaging events Techniques are needed to detect and protect the machine from disruptions A high pressure gas jet is now operational on C-Mod and has already greatly influenced our understanding of how these systems affect disruptions Experiments will continue during FY2007-9
Remote Conferencing Technologies for ITER	Off-site session leaders routinely use audio, video, and MDS-Plus tools to communicate with on-site personnel and direct C-Mod run We are working directly with US and international teams to define remote conferencing technologies for ITER
CODAC Definition and Design for ITER	We have begun to work with the ITER team to help define CODAC requirements and a conceptual design for ITER
National Fusion Collaboratory	Effort aimed at developing collaborative technologies for current research programs, but with ITER in mind

Table 3.2
Diagnostic Development

Bolometry	Enhanced views and capability added to K-Port primary bolometry system for FY2007 Divertor viewing AXUV and Lyman α arrays installed for FY2007 Four 2D toroidally viewing pinhole cameras will be installed to investigate polodial asymmetries in radiated power and x-ray emissivity in FY2008. Single camera installed for FY2007. FY2008 capability will include 212 AXUV and 100 Lyman α chords
Neon Soft X-Ray Spectrometer	New diagnostic provides impurity poloidal rotation profile in plasma edge Measures line emission from He-like neon
X-Ray Imaging Crystal Spectrometer (PPPL/MIT)	2D position-sensitive detector Will measure $T_i(r)$ and $V_\phi(r)$ with 1 cm spatial resolution New system installed for FY2007 campaign
Correlation Reflectometer (PPPL/MIT)	Install 130-140 GHz swept frequency Gunn diode for density correlation. Operation FY2007
MSE (PPPL/MIT)	DNB rotated toroidally 7^o
Infrared Camera (LASL/MIT)	upgraded/expanded IR camera coverage inside of C-Mod 8-13 micron microbolometer uncooled IR camera, full digital, with fast binning.

CXRS Diagnostics (Utexas/MIT)	Passive measurements of B^{+4} have yielded T_i, V_θ, and V_ϕ Active measurements of B^{+5} have yielded poloidal rotation and ion temperature profiles. Increase number of toroidal chords from 16 to 37 for FY2007 Increase number of poloidal chords from 25 to 45 for FY2007

Polarimetry (PPPL/MIT/UTexas)	FIR polarimeter/interferometer system will complement the MSE effort A single chord prototype system at 10.6 μm has been installed to test edge scrape-off effects, determine noise levels, refine experimental techniques, and assess survivability of in-vessel optical components New shutter system installed for FY2007 operation Procurement of FIR laser underway Multi-chord FIR system available FY2009
Core Thomson Scattering	In FY2006 increased number of core channels from 11 to 16 – enhanced resolution in vicinity of ITB New compact polychromators (8 new channels in FY2007) New fiber bundles with improved transmission in near-IR FY2007 New fast charge digitizers available FY2007
Dust Detection (ITPA high priority)	Developed laser scattering techniques to measure dust Dust injector and laser scattering system operational for FY2007 campaign
New Penning gauge installation	Gauges can be easily mounted on vessel wall Quantify pumping/cryopump operation Installed for FY2007 operation
Advanced Inner Wall Scanning Probes	Measure plasma flows, fluctuations, and profiles in the high-field side SOL. Installed for FY2007 operation

Surface Science Station (S^3)	Measure deposition and erosion using quartz microbalance Alpha Radioisotope Remote Ion Beam Analysis Quantify boronization layers Installed for FY2007 operation

Hard X-Ray Pinhole Camera (HXR)	Poloidally viewing 32 channel CZT detector array (20 to 250 keV) (operational from FY06) Measure supra-thermal electron distribution during lower hybrid current drive experiments FY2006/FY2007
Gas Puff Imaging in Lower Divertor (PPPL/MIT)	New GPI view in divertor will allow comparisons to be made with transport effects seen near plasma midplane FY2007
New Magnetic Pick-up Coils	Seven new coils to improve low toroidal mode number resolution of poloidal field fluctuations have been installed for FY2007 operation

Figure 3.1.1 Cross-section of cryopump is shown. Liquid helium flows in central tube and is surrounded by a liquid nitrogen cooled shield. Baffle (green) protects nitrogen shield from warm neutral particles. Protection support hardware and tiles also shown.

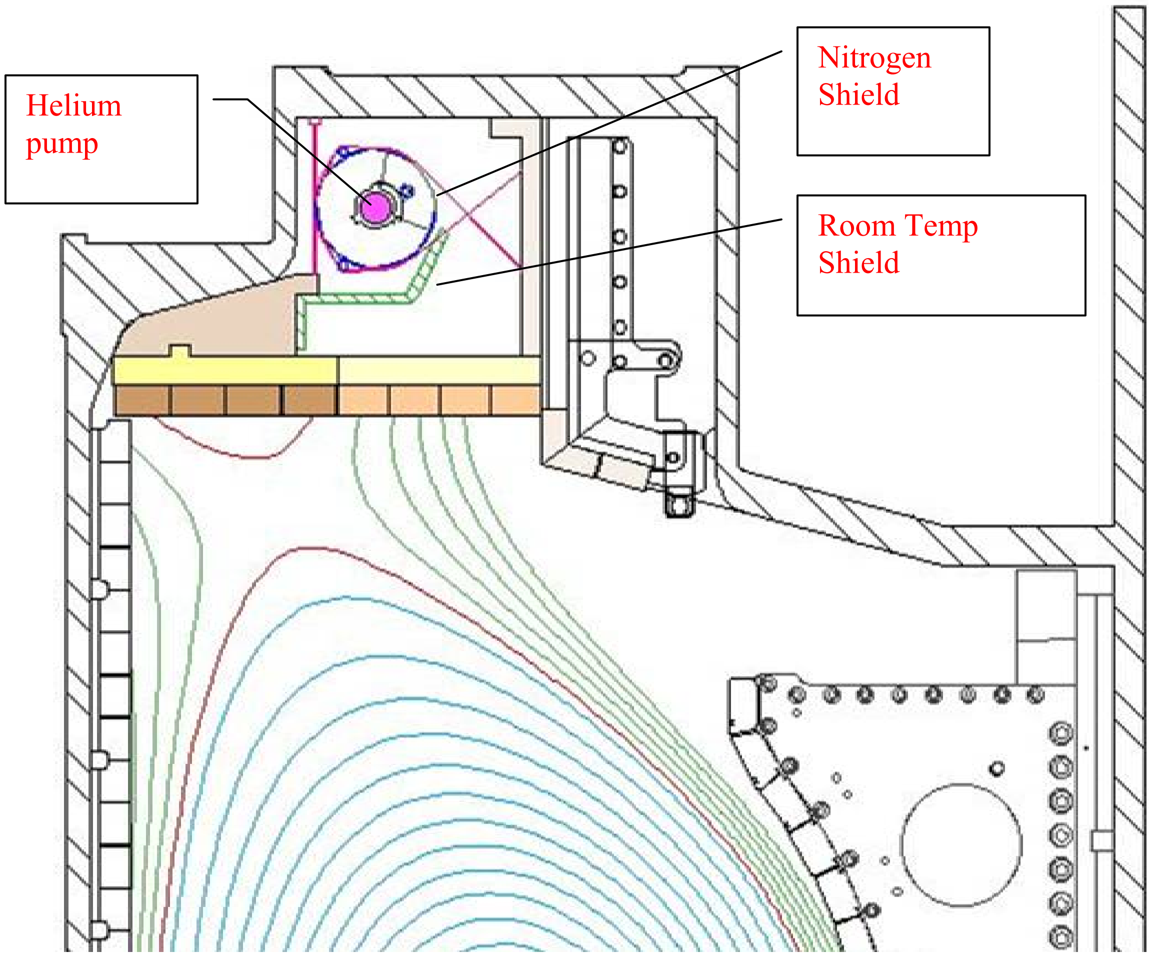


Figure 3.1.2 Thirty radial slots in the protection hardware allow neutral particles to enter cryopump pumping volume. This configuration allows the pumping rates to be insensitive to the plasma configuration.

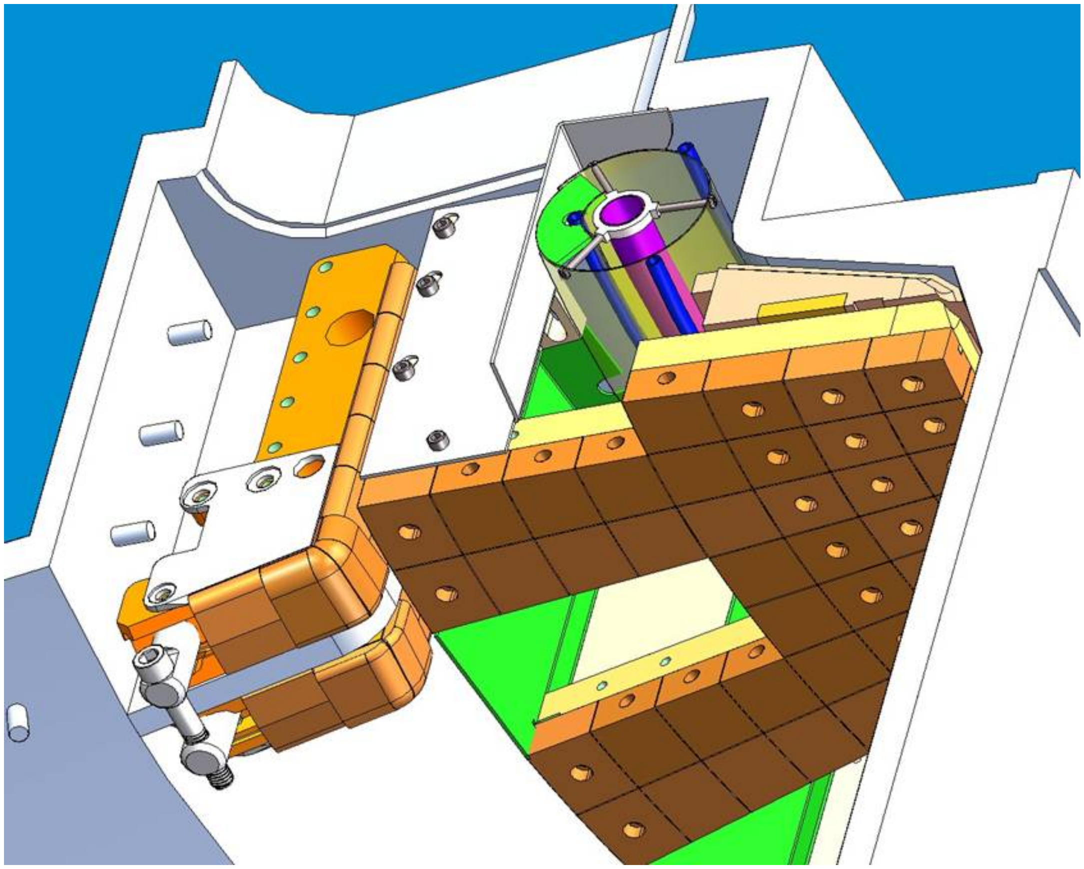


Figure 3.1.3 The protective hardware installed in C-Mod. Thirty radial slots provide neutral particle access to the cryopump.

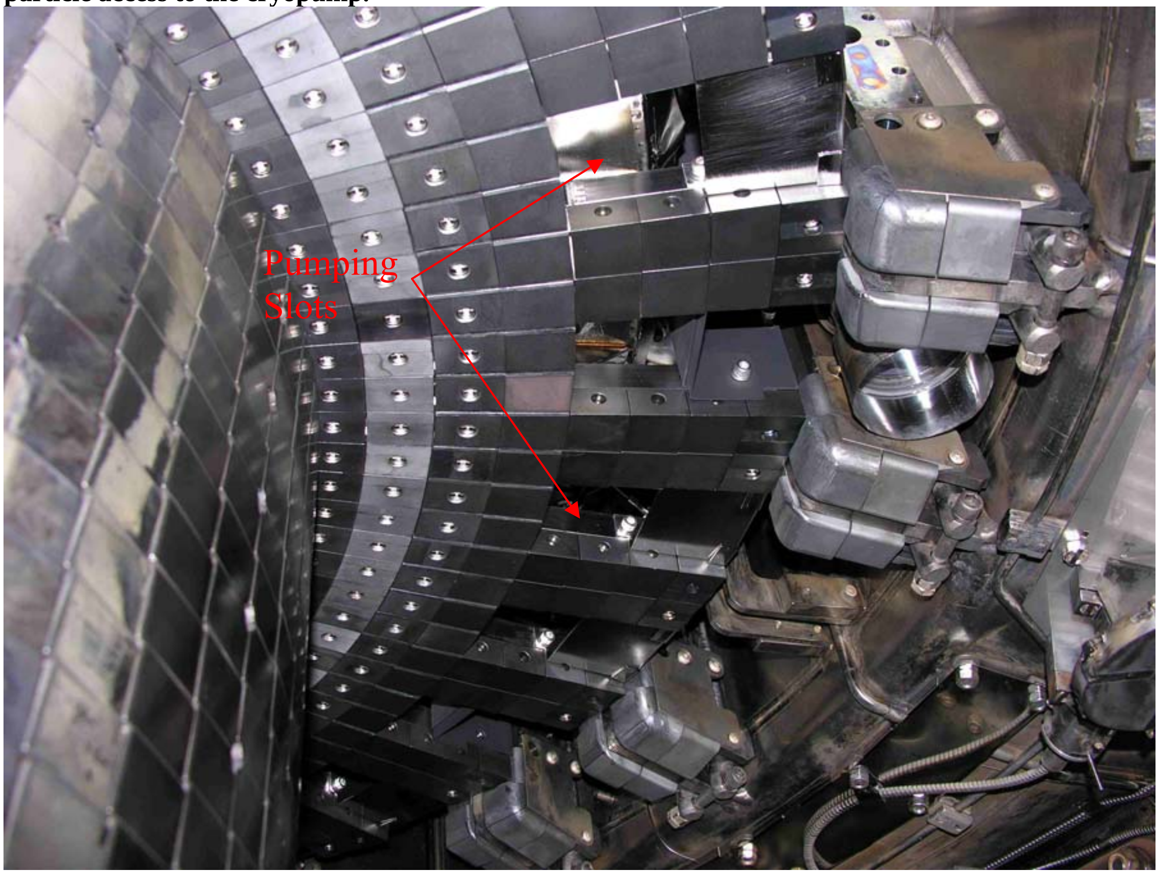


Figure 3.1.4 Lamella tiles consist of eight 4 mm thick tungsten plates bolted together with a TZM bolt. The thread in center of bolt allows the the tile to be secured to the divertor module

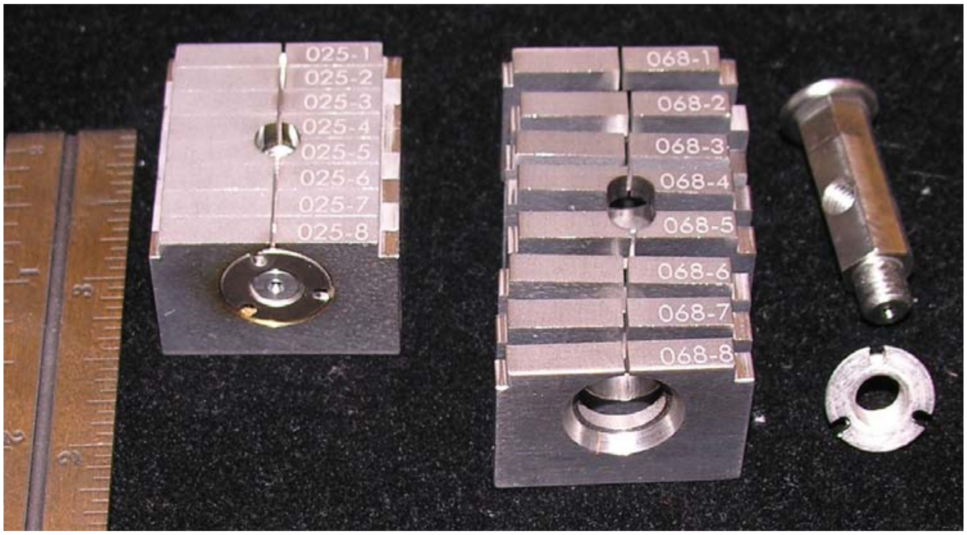


Figure 3.1.5 Lamella tiles installed in the C-Mod outer divertor

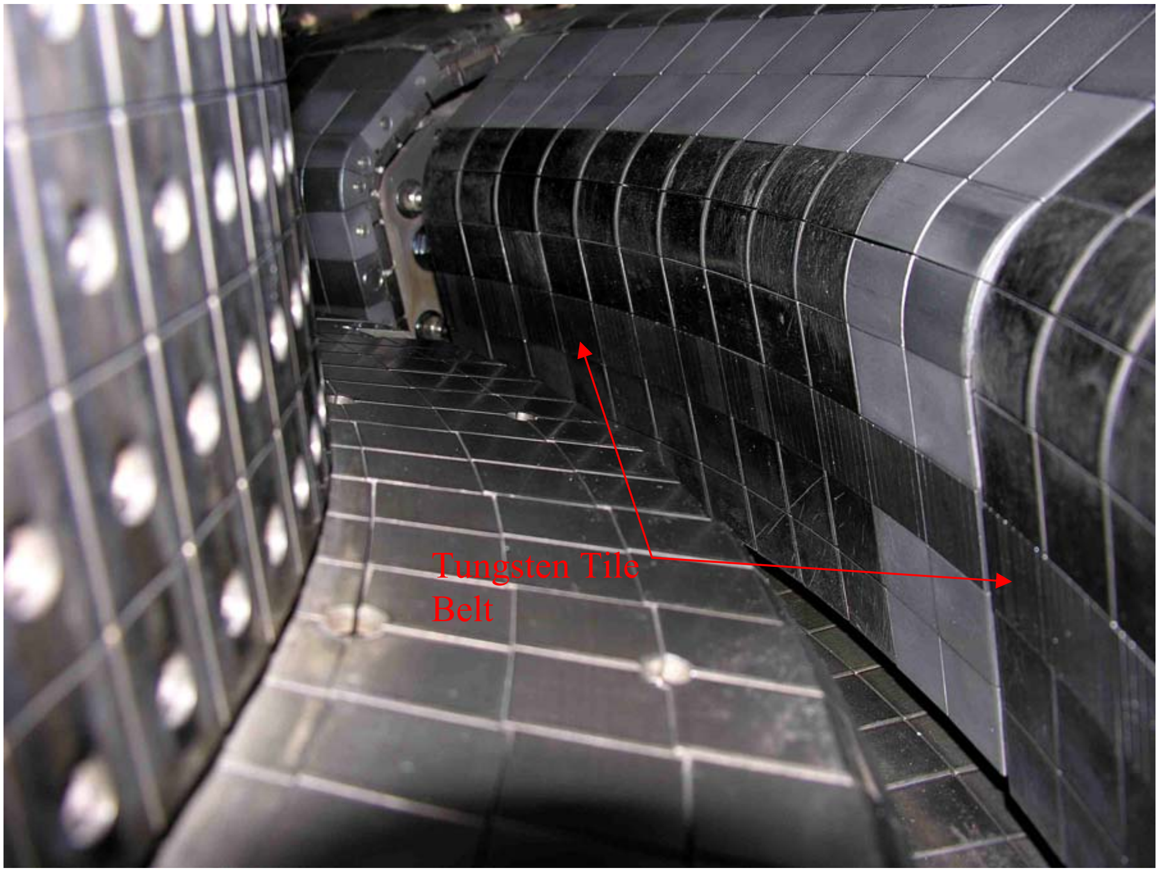

Tungsten Tile
Belt

Figure 3.1.6 Amount of data taken per shot for the entire lifetime of C-Mod. Doubling time of 1.9 years required constant updating of storage, data acquisition, and networking hardware.

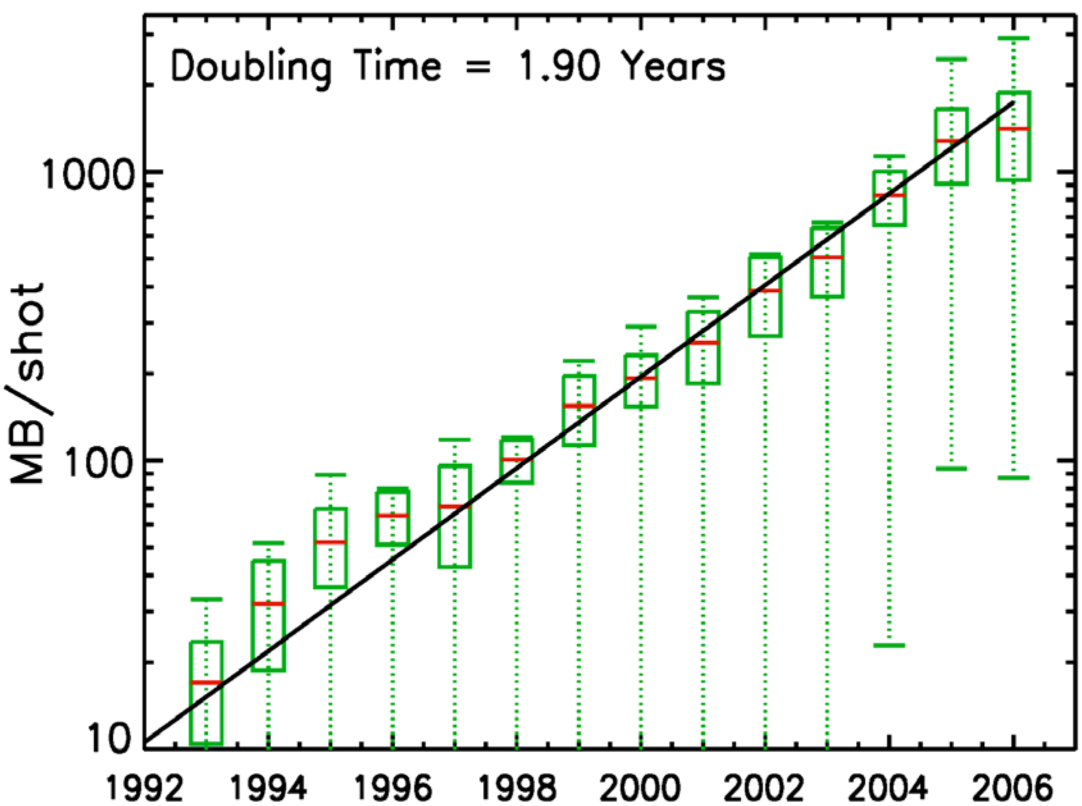


Figure 3.2.1 Location of the Surface Science Station on C-Mod is shown. Long bellows allows the S^3 head to be scanned from inner to outer wall in C-Mod. A gatevalve allows heads to be changed and samples retrieved. Also shown are components of the NeSOX, polarimeter, and SiLi diagnostics.

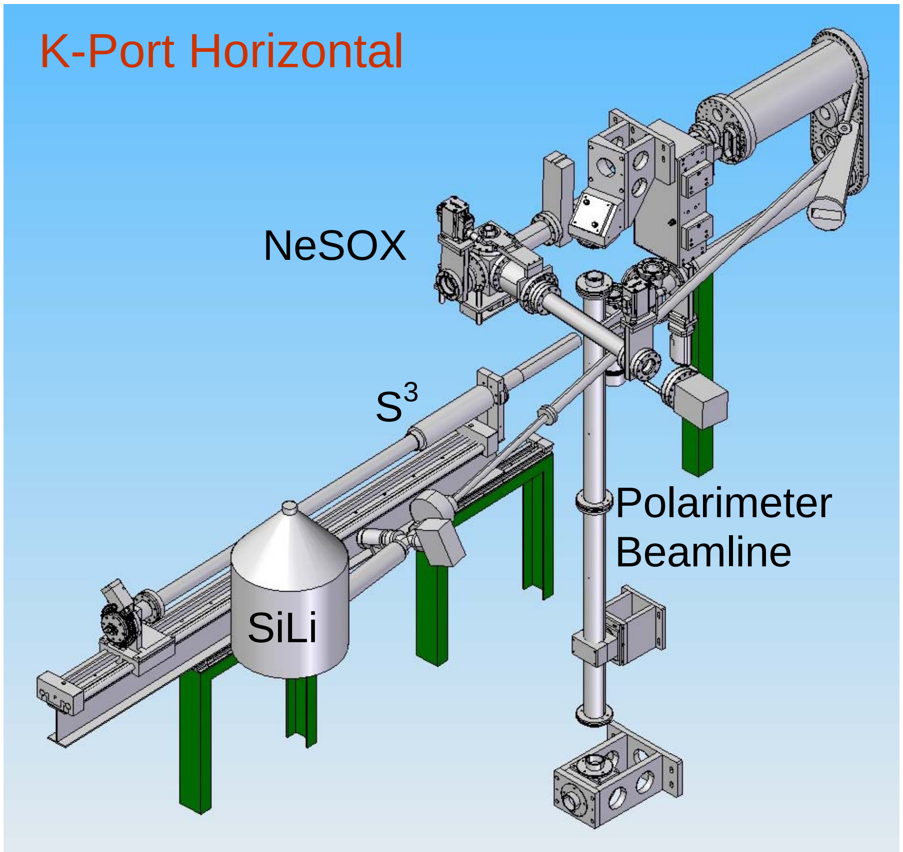


Figure 3.2.2 CXRS views are shown. The number of poloidal and toroidal chords has been increased greatly during the latest up-to-air period.

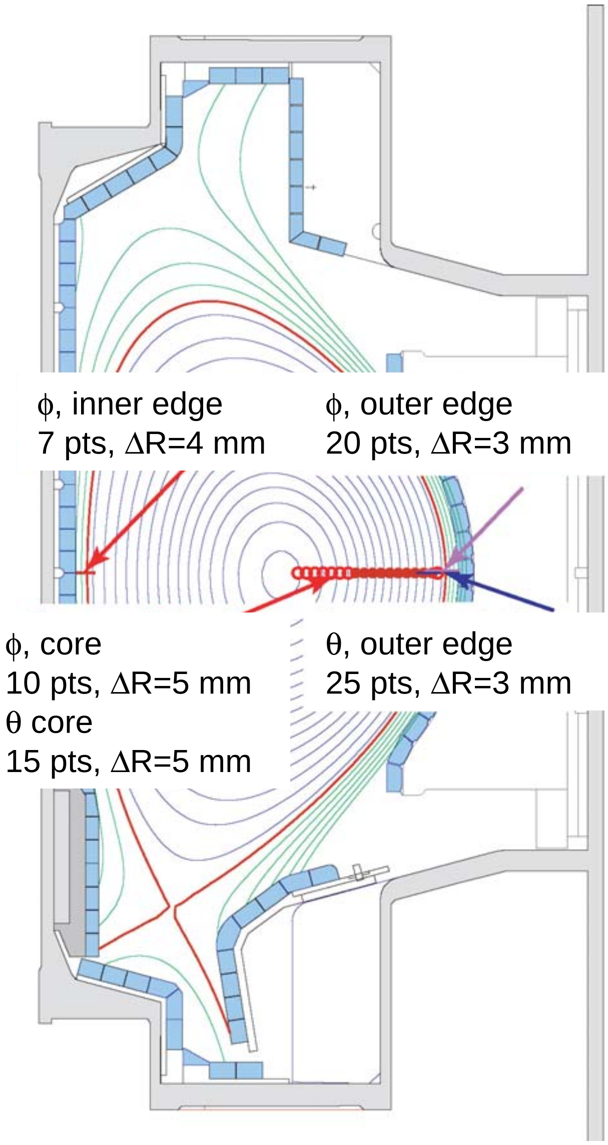


Figure 3.2.3 Unfiltered AXUV bolometery chords available for the FY2007 campaign. Curved paths are projections in the poloidal plane of the 3D chord trajectories.

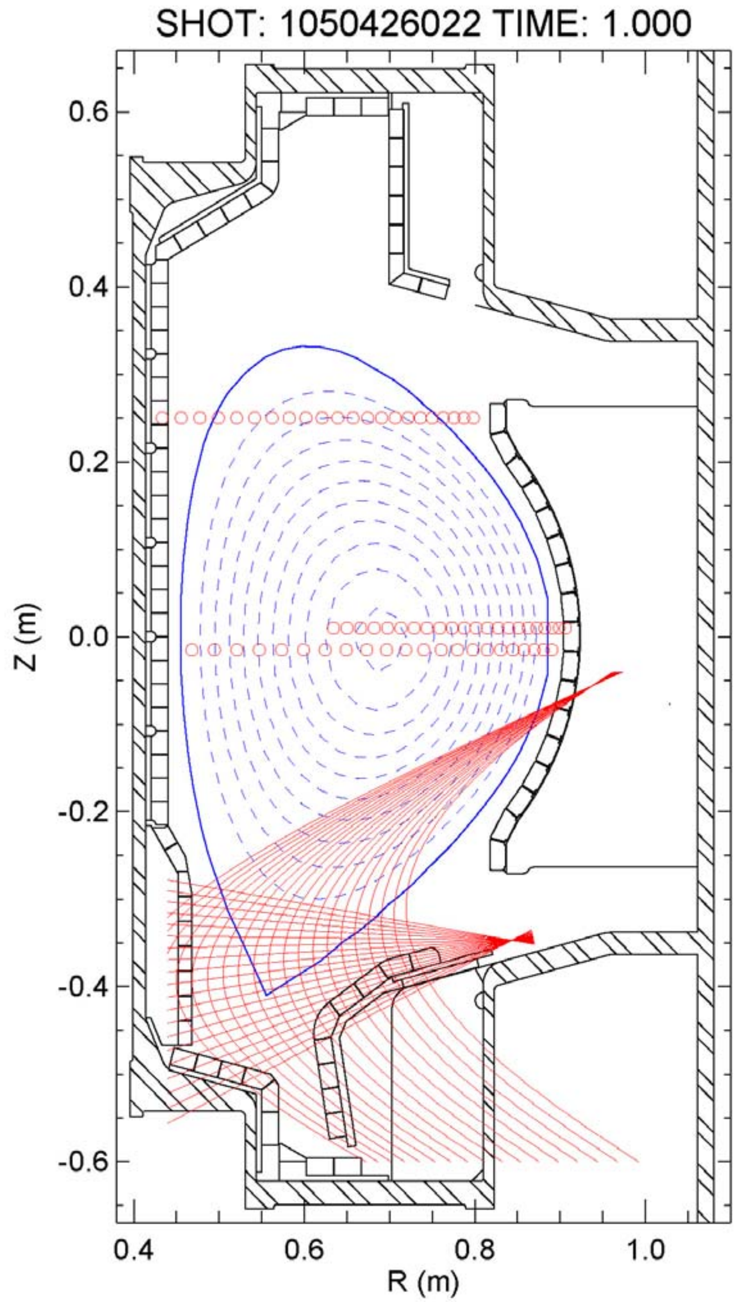


Figure 3.2.4 Filtered (Lyman α) bolometry chords available for the FY2007 campaign

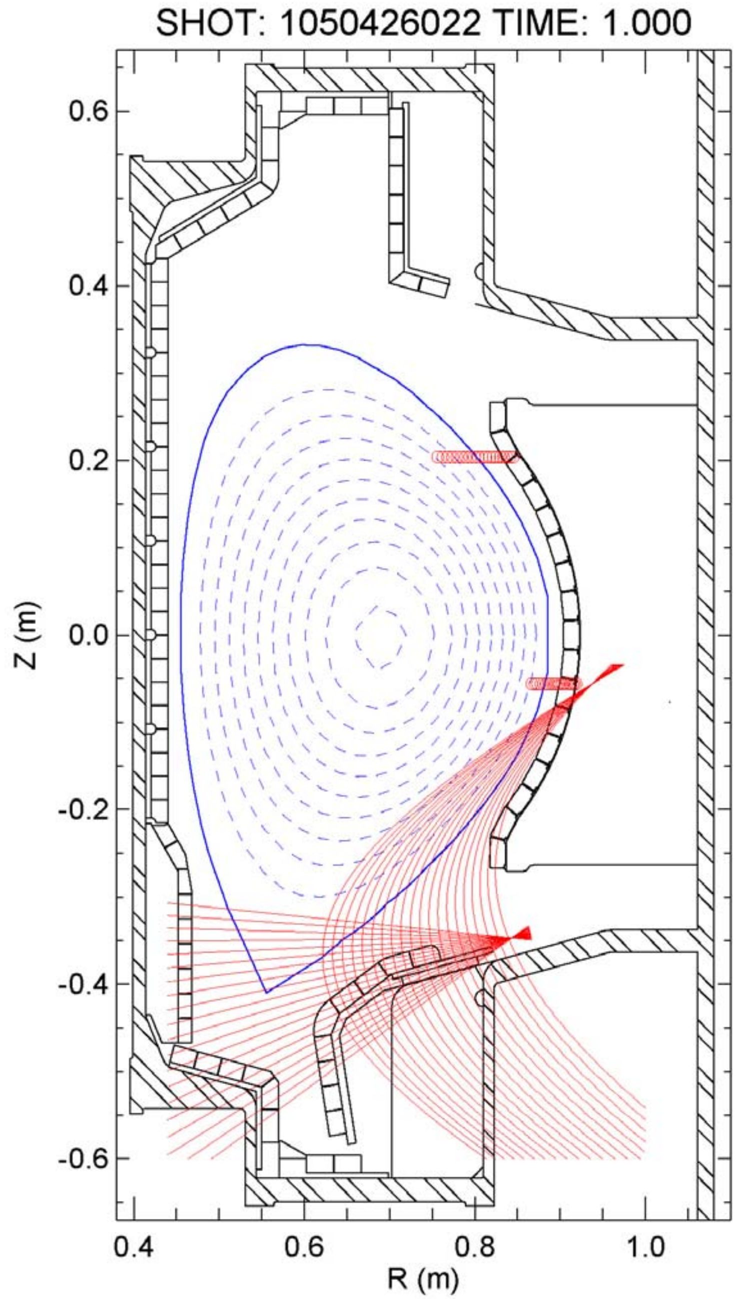


Figure 3.2.5 New Rogowski coils installed in the upper chamber.

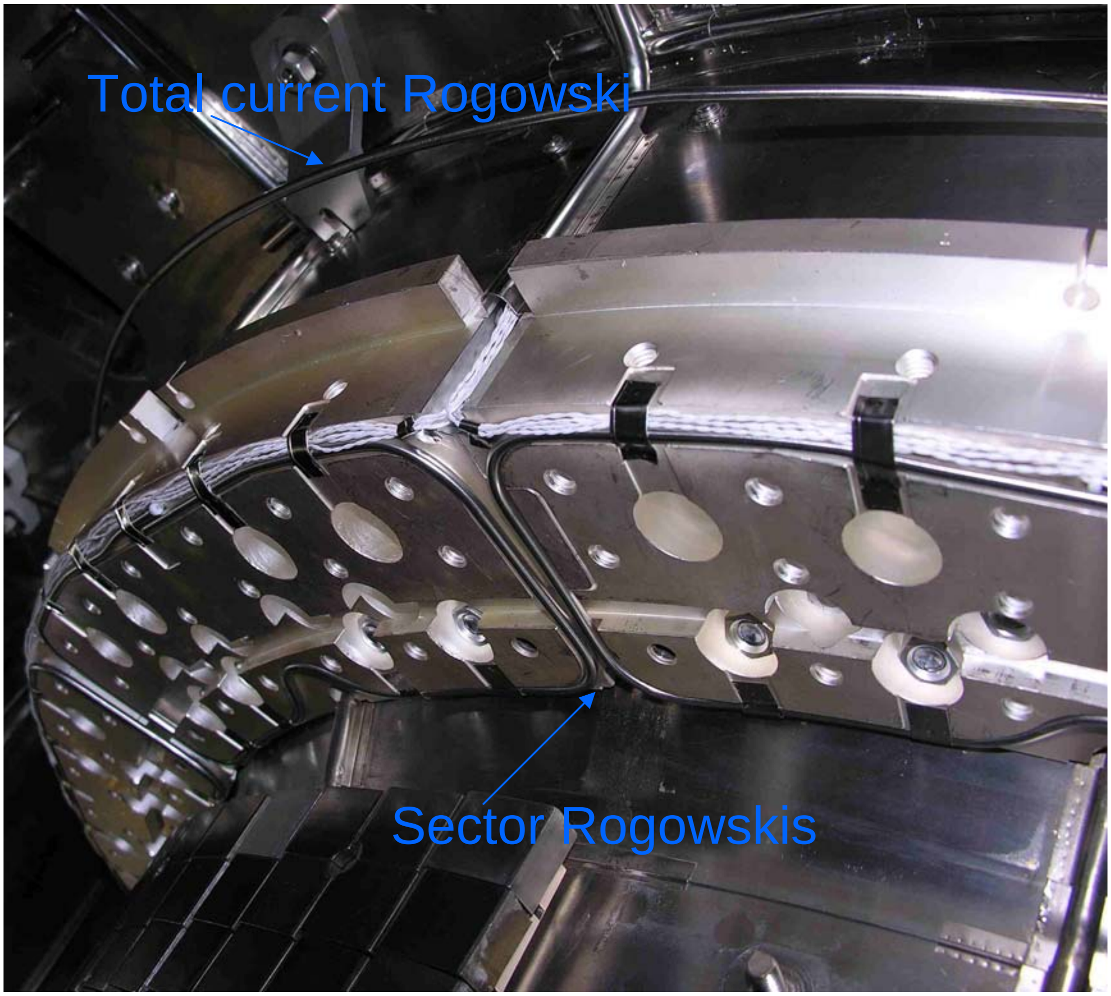
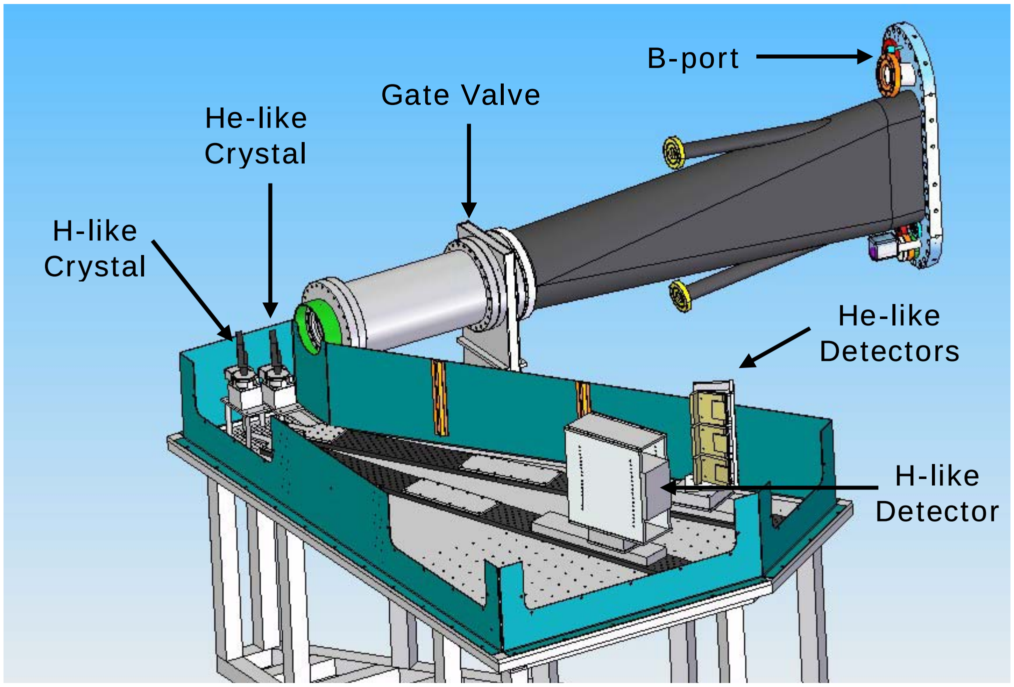


Figure 3.2.6 Installation of the Spatially Resolving High Resolution X-Ray spectrometer (SR HIReX) on B-Port. Forty He-like chords and 15 H-like chords will be available for the FY2007 campaign.



4 Alcator C-Mod Collaborations

4.1 PPPL collaboration

4.1.1 Purpose:

The purpose of the PPPL C-Mod collaboration is to conduct and enable forefront scientific research on the Alcator C-Mod tokamak and to perform engineering/technical support for the C-Mod team. The research aims of this program include:

- Measure the efficiency and achievable radial localization of currents driven by Lower Hybrid (LH) waves to (a) benchmark theoretical models thereby allowing reliable extrapolation to ITER and other next-step devices; and (b) develop Lower Hybrid current drive (LHCD) as a reliable tool for controlled modification of the current profile;

- Demonstrate the use of off-axis LHCD in conjunction with high-power ICRF heating to generate and sustain Advanced Tokamak plasma regimes having improved confinement;

- Evaluate the validity of numerical gyrokinetic models of plasma turbulence relating to radial transport rates of particles, heat, momentum in both standard plasma regimes and regimes with improved confinement;

- Study plasma rotation and radial momentum transport in the absence of applied beam torque;

- Study basic ICRF plasma-wave interaction processes and compare to analytic and numerical models in order to gain predictive capability for heating and current drive in reactor-grade experiments;

- Create internal transport barriers through off-axis ICRF heating. Sustain, control, and understand these barriers through the application of additional on-axis ICRF heating and through q-profile modifications generated by LHCD; and

- Measure the turbulence properties at the plasma edge, determine the correlation of edge turbulence with radial plasma transport at the edge, and challenge theoretical models of edge turbulence.

Areas of particular emphasis include:

- Provide a LHCD launcher and coupling hardware for control of the plasma current profile through current drive;

- Design, fabricate, and operate a Motional Stark Effect diagnostic to measure the current profile;

- Contribute to the design of a new polarimeter diagnostic to measure the current profile at high density;

- Design, fabricate and operate two fast cameras to visualize edge turbulence (Gas Puff Imaging);

- Design, fabricate, and operate curved x-ray spectrometers to measure the radial profiles of ion temperature and toroidal rotation speed with high spatial resolution;

- Design, fabricate, and operate a swept-frequency reflectometer (123-141 GHz) to measure the electron density fluctuation levels and radial correlation lengths; and

- Perform gyrokinetic turbulence simulations (GYRO code) for comparison with experimental measurements of turbulence and transport.

Engineering and technical support for RF power systems include:

- Engineering assistance in tuning and maintaining the ICRF transmitters,

- Engineering participation in the operation, maintenance, and calibration of the first Lower Hybrid launcher for current drive; and

- Contribute to the design of the second Lower Hybrid launcher.

In all these scientific and technical areas PPPL provides assistance in areas where PPPL has competence and capabilities needed by the C-Mod program while enhancing cross-cutting research opportunities for PPPL scientists. PPPL works as a strong team-player.

4.1.2 Approach:

Members of the PPPL research staff participate in experiments on C-Mod at MIT as integrated members of the C-Mod research and operations team. These scientists are supported by core teams at the laboratory for theoretical support, data analysis and modeling, and for coordination with other PPPL research endeavors through the PPPL science focus groups. In addition, PPPL provides a team of engineers and technicians for the design and construction of upgrades, and for technical support at C-Mod.

<u>Advanced Tokamak Studies</u>

We plan to study Advanced Tokamak plasma regimes by modifying the plasma current profile with off-axis Lower Hybrid current drive and on-axis ICRF fast wave current drive. The plasma pressure profile will be modified through the application of high power ICRF on- or off-axis heating.

This should allow us to:

- Achieve quasi-steady state operation up to the no-wall β limit ($\beta_N \sim 3 – 3.5$);
- Increase the β limit due to plasma current profile modification;
- Achieve non-inductive current drive with high bootstrap fraction and current profile control; and
- Heat with 4 – 8 MW of ICRF power.

The Lower Hybrid power system is based on the 4 MW, 4.6 GHz system originally used on Alcator C. The PPPL Lower Hybrid team designed and fabricated a titanium waveguide launcher (since replaced with a stainless steel launcher) and constructed a novel power divider, high power phase control and custom waveguide assembly that provides precise spectral control of the launched wave spectrum (n = 1.5-4.5). The splitting system allows launching waves in both forward and reverse direction. MIT has provided a suitable location for the equipment, the high voltage power system and controls, water and energy supply, and the installation labor and has developed a considerably improved coupler component for the launcher.

Modification of the current profile, whether by FWCD, MCCD or LHCD, requires a measurement of the resulting current profile for analysis. This will be achieved through the Motional Stark effect (MSE) diagnostic, supplemented in FY09 by a multi-channel polarimeter. The MSE optical system, electronics, and software have been supplied by PPPL; the diagnostic neutral beam (DNB) generating the signal is supplied by MIT. The polarimeter is being designed and fabricated by MIT with design assistance in FY08 and FY09 by PPPL.

Wave-Particle Studies

The interaction of radio-frequency waves with the plasma components can result both in localized plasma heating and the generation of a locally driven current. Studies and understanding of the basic physics processes will allow extrapolation of these results into the reactor-grade plasma regime.

Numerical simulation of current drive by Lower Hybrid waves will be extended to include effects from non-Maxwellian electrons.

Radio-frequency heating studies in the ion cyclotron range of frequencies will investigate various aspects of heating mechanisms:

- Compare the heating efficiency of strong single-pass absorption heating, hydrogen minority ion species in a deuterium majority D(H) with weak single-pass absorption in helium-3 minority in a deuterium majority D(3He); and

- Investigate the rich spectrum of phenomena associated with fast wave mode conversion.

Launching an ICRF directed wave allows us to drive plasma current in the core by fast wave current drive (FWCD):

- Explore further plasma rotation with directed waves without external momentum input;

- Develop the capabilities to affect the radial electric field through toroidal rotation.

Transport Studies

Our studies of plasma transport are focused on optimizing the experimental design to yield measurements that can be compared with nonlinear gyrokinetic computational turbulence simulations to gain insight into the plasma microturbulence:

- Tests of turbulent transport predictions involve the comparison of data from C-Mod fluctuation diagnostics with nonlinear gyrokinetic simulations using the codes GS2 and GYRO. Quantitative interpretation of the experiment is expected to require simulations of the reflectometers used to measure the turbulent fluctuations.

- A technique for measuring small changes in the electron temperature gradient scale length will be used to compare experimental and theoretical dependencies of the critical temperature gradient on parameters such as the q profile.

Plasma Boundary Studies

The study of plasma edge physics has been enhanced through the addition of two fast cameras to obtain 2-D imaging of edge turbulence:

- Movie images of edge turbulence structures (“blobs”) are obtained with ~150 kHz framing rate, giving growth/decay and radial/poloidal motion information. Two cameras will be available in FY07: one viewing the outer midplane, the other viewing the lower divertor.

- This behavior is being compared with a variety of edge turbulence models.

4.1.3 FY06 Accomplishments

LHCD physics

- Significant progress was realized during FY06 in the commissioning of the LHCD system and characterization of system performance. The stainless steel LH launcher was operated at power levels of ~ 1 MW coupled to the plasma and drove nearly ~1 MA of current. A high current-drive efficiency (n_{19} IR/P ~3) was inferred from the change in loop voltage in a LH power scan. Increases in central electron temperature and sawtooth stabilization were observed, confirming LH power deposition and modifications to the q-profile through LHCD.

- The observed coupling is in reasonable agreement with the Brambilla coupling code, and there is generally good agreement with the GENRAY/CQL3D models regarding total current, hard x-ray and cyclotron emission. Minimal damage to the launcher structure was observed. The experimental results obtained to date are in line with requirements for high performance operation.

Plasma Boundary Studies

- SOL turbulence for inner wall limited discharges was found to have a similar frequency spectrum, fluctuation level, and radial correlation length as diverted discharges with the same global parameters; however, the poloidal correlation length was ~ 2x larger in the limited cases, which was not expected and, as yet, not understood.

- An initial comparison of the SOL turbulence measured in the limited discharges was made with the GEM gyrofluid turbulence simulation code of Bruce Scott (Garching), with encouraging results: the autocorrelation times and correlation lengths were within a factor-of-two of each other; however, the fluctuation level was ~ 4 times larger in the measurements than in the simulation, which is as yet not understood.

Design of a curved x-ray crystal spectrometer

- A curved x-ray crystal spectrometer was designed to provide core ($r/a < 0.8$) profile measurements of ion temperature and velocity based on the helium-like and hydrogen-like argon emission. This diagnostic is based on a promising new PILATUS detector which removes a previous count-rate limitation. A PILATUS detector was tested in an existing (flat crystal) spectrometer and met its specifications including count rate and immunity from neutron noise. The diagnostic is expected to significantly improve spatial resolution (~30 independent viewing chords) of ion temperature and velocity profiles and may allow the observation of local core transport barriers in the ion channel for the first time on C-Mod.

- During FY06, procurement was initiated on the major components, with PPPL focusing on the PILATUS detectors and crystals and MIT focusing on the spectrometer housing. Fabrication, installation and initial operation are expected in FY07.

Motional Stark Effect diagnostic

- Significant progress was realized during FY06 to understand the cause of serious calibration problems with the Motional Stark Effect (MSE) diagnostic. Results obtained from the 'in-vessel' calibration technique (illuminating MSE with light passing through a linear polarizer at a known angle when the torus is up-to-air) differ by several degrees from results obtained from a 'beam-into-gas' calibration, i.e. when the DNB is fired into a gas-filled torus with a pitch angle that is known from defined toroidal and vertical fields. In addition, discrepancies are observed between the pitch angle measured by MSE and that computed by EFIT at the plasma edge, where the EFIT calculation is accurate and not affected by uncertainties in the current profile shape.

- It was conjectured that the cause of the beam-into-gas calibration anomaly is the peculiar injection geometry of the DNB: exactly perpendicular to the torus. Beam neutrals that ionize upon collisions with torus gas have no parallel velocity along the magnetic field line, and drift only slowly out of the MSE field-of-view. Virtually all of the ionized beam neutrals will re-neutralize before leaving the MSE viewing footprint, thereby generating a population of `secondary' beam neutrals having a random gyro angle.

- Experimental evidence for this conjecture was obtained during FY06 by measuring the spectrum along an MSE sightline and observing the behavior of a spectral feature on the blue side of unshifted Hα in agreement with calculations. In addition, the conjecture reproduces some qualitative trends in the observed discrepancy between the in-vessel and beam-into-gas calibrations. Based on these measurements, it was decided to rotate the DNB 7° toroidally. Further details are discussed in the section Future Accomplishments 2007.

<u>Wave-Particle Studies</u>

- The modules in TORIC for plasma dielectric response to include non-Maxwellian ions or electrons were upgraded (joining work with RF SciDAC and the PPPL/C-Mod collaboration).

<u>PPPL Engineering Support</u>

- PPPL engineers, physicists and technical staff contributed to the commissioning, operation, and maintenance of the Lower Hybrid system..

- PPPL engineers are participating in the design of the second Lower Hybrid launcher.

- PPPL RF engineers and technical staff continued to assist MIT with ICRF transmitter operation, retuning, and repairs.

FY06 Milestone #1: Support MIT in commissioning of the Lower Hybrid Current Drive system and evaluate its performance at moderate power.

With support from PPPL, the LHCD system was successfully commissioned and its performanceevaluated at moderate power in FY06. The stainless steel LH launcher was operated at power levels of ~ 1 MW coupled to the plasma and drove nearly ~1 MA of current. A high current-drive efficiency (n_{19} IP/P ~3) was inferred from the change in loop voltage in a LH power scan. The observed coupling is in reasonable agreement with the Brambilla coupling code, and there is generally good agreement with the GEN-

RAY/CQL3D models regarding total current, hard x-ray and cyclotron emission. Minimal damage to the launcher structure was observed. The experimental results obtained to date are in line with requirements for high performance operation.

FY06 Milestone #2: Compare turbulence structures in limited versus diverted discharges using Gas Puff Imaging.

This milestone was accomplished by comparing edge turbulence during inner-wall limited plasmas conditions to previous turbulence measurements in diverted plasmas. Edge turbulence data was obtained in the limited plasma experiments from both the GPI diagnostic (imaging and fast diodes) and from Langmuir probes. The results showed that SOL turbulence in limited plasmas is very similar to that in diverted plasmas with respect to fluctuation levels, frequency spectra, and size scales, despite the very different magnetic field line topology. Theoretical simulations of edge turbulence for this specific limited C-Mod plasma SOL were performed by to Bruce Scott of IPP Garching using the GEM code, and simulations of C-Mod diverted plasmas were performed by Maxim Umansky of LLNL using the BOUT code. The comparisons between the C-Mod turbulence results and these simulation codes were reported at the APS-DPP 2006 meeting.

4.1.4 Future Accomplishments: FY2007 (baseline)

Advanced Tokamak studies

The Advanced Tokamak research program for FY07 will focus on transforming LHCD from an experiment in its own right into a tool that can be used reliably to control the current profile in relevant plasmas.

- There will be two components to this effort. First, we will document the efficiency and radial localization of driven currents with LHCD parameters (vacuum gap, $n_{||}$) and plasma parameters (n, T_e, n, B_T, Z_{eff}) for comparison with theory (Fisch-Karney) and modeling (CQL3D and Genray). Measured hard x-ray emission profiles and the ECE spectrum will be compared to synthetic diagnostics applied to the LH modeling codes Genray/CQL3D to study possible radial transport of the fast electron population. This information is required to guide future experiments that seek particular changes to the q-profile to generate and sustain Advanced Tokamak plasma regimes such as Reverse Shear and the Hybrid mode.

- Second, we will extend Lower Hybrid Current Drive to plasmas with signficant levels of ICRF auxiliary heating and we will optimize LH coupling into plasmas with an H-mode edge as well as an L-mode edge. The plasma density in LHCD experiments will be increased from ~4 x 10^{19} m^{-3} to ~10^{20} m^{-3}, approximately the density anticipated in auxiliary-heated H-mode plasmas with density control provided by the new cryopump.

Motional Stark Effect diagnostic

- Based on calculations and measurements performed in FY06 relating to the effect on the MSE measurement of `secondary' emission from beam neutrals that ionize and then re-neutralize through charge exchange at a random gyro angle, a decision was reached to rotate the DNB toroidally by 7^o. This is the maximum possible rotation consistent with access constraints, and is calculated to reduce the population of secondary emission by a factor of greater than 30, thus eliminating the deleterious effect on the MSE beam-into-gas calibration. The engineering tasks to rotate the beam, including re-location and/or re-aiming of several beam-based diagnostics, commenced at the end of FY06 and were completed by February 2007.

- During FY2007 we will carry out MSE spectrum measurements and additional beam-into-gas calibration data to confirm that rotating the DNB has resolved the calibration issues.

- In addition, we will test an approach to measure the polarization properties of visible Bremsstrahlung (VB) light that contaminates the MSE signal, particularly at high plasma density. One fiber from the bundle of 16 fibers that serve a single MSE channel will be routed to a dedicated bandpass filter / avalanche photodiode assembly, where the filter's passband will be chosen to view VB light exclusively. It is hoped that this approach will enable real-time compensation for VB light and thereby allow more accurate pitch angle measurements without the need to rapidly modulate the DNB.

- The DNB will be upgraded in FY07-08 with an aperturing system to reduce the horizontal beam width to 6 cm, in order to enhance the MSE spatial resolution. There are two major components, a movable water-cooled aperture at the exit of the DNB tank, and a static, passively-cooled aperture further downstream inside the tokamak port. The water-cooled aperture is being built at the Budker Institute in Novosibirsk, and will be delivered and installed in the spring of 2007. The downstream component will be fabricated at MIT and installed in FY08.

Wave Particle Studies

- Begin simulations of lower hybrid current drive in C-Mod, using the TORIC-LH code that is being extended to include non-Maxwellian electrons (RF SciDAC and C-Mod collaboration).

- Perform initial scoping studies of ICRF heating and current drive with wave frequencies just below all of the fundamental cyclotron resonant frequencies in the plasma.

- Begin exploratory studies of driven global radio frequency eigenmodes in tokamaks using the TORIC code. (RF SciDAC, NSTX and C-Mod collaboration).

Transport Studies

- Initial measurements of local electron density fluctuations and radial correlation lengths of the density fluctuations will be obtained with a new swept frequency (123-140 GHz; $n_e = 1.9 – 2.4 \times 10^{20}\ m^{-3}$) correlation reflectometer designed and fabricated by PPPL. The high density probed by this reflectometer allows access to a variety of interesting plasma regimes including:

    - plasma core in medium density Ohmic plasmas;
    - plasma core of medium density RF-heated L-mode;
    - plasma edge of RF-heated H-mode;
    - possibly the plasma core of RF-heated H-mode using cryopump for density control; and
    - the steep gradient region of plasmas with an Internal Transport Barrier, again presuming success of the cryopump for density control.

- Typically, gyrokinetic simulations of plasma turbulence exhibit strong parameter dependences that make it possible to 'tune' the simulation to match the transport powers while remaining well within measurement errors of local temperatures and densities. The availability of measurements of local fluctuation amplitude measurements and correlation lengths, in addition to comparison of heat, particle, and momentum transport, should provide more robust tests of the validity of gyrokinetic turbulence codes. Initial tests will include the dependence of transport and fluctuations on the q-profile, either by varying the plasma current or through application of LHCD.

- Two experiments designed to elucidate the role of micro-turbulence were begun in FY06 and will be continued. The first has demonstrated that small changes in the electron temperature gradient scale length are linked to ITB formation. We will next determine how the ITB formation conditions change as plasma parameters (such as q(r)) are varied. Turbulence simulations codes will be used to predict whether the observed changes in temperature are sufficient to account for the observed change in transport. The second experiment will form ITBs in lower density plasmas that permit reflectometers to measure density fluctuations in the ITB region; we will look for a change in the reflectometer signal when central heating is added to stop the density rise. Micro-turbulence codes will simulate the plasma before and after the addition of central heating, and the predicted turbulence will be compared with the turbulence measurements.

- Internal transport barrier modeling will focus on linear GS2 stability analysis of C-Mod off-axis RF-generated ITBs, with possible extension to Ohmic H-mode ITBs.

- Install and test performance of the PILATUS detector for use in a curved- x-ray crystal diagnostic for measuring core Ti and V_ϕ profiles with high spatial resolution (~30 independent channels). This will provide a capability to resolve the ion and electron heat flux at moderate density, and may allow identification of core transport barriers in the ion channel even at higher density by observing steep, radially-localized, gradients in ion temperature.

Intrinsic toroidal rotation and momentum transport

- A major discovery on C-Mod has been the observation of toroidal plasma rotation in the absence of momentum (beam) input and its correlation with transitions from L- to H-mode confinement. This work has important implications for the physics underlying the formation of the edge transport barrier. Equally important, it may provide useful scaling projections for toroidal rotation in ITER, which has small beam momentum input.

- In FY07, we will begin studies of this `intrinsic' rotation using improved diagnostic capabilities including the curved x-ray crystal spectrometer which provides measurements of T_i and V_ϕ along ~30 independent chords. Experiments in which the plasma is quickly moved from dominantly lower-null to upper-null will be attempted to perturbatively change the edge rotation speed as the profile diagnostics monitor the propagation of the velocity perturbation into the core and thus infer momentum transport coefficients.

- The focus of the work in FY07 will be scoping out regimes where the x-ray crystal spectrometer and other V_ϕ diagnostics (CXRS) can provide velocity measurements with good spatial and temporal resolution, in preparation for more detailed studies in FY08.

Plasma Boundary Studies

- A new GPI telescope that views the lower divertor region was designed and constructed at PPPL, bench-tested at MIT, and has met its optical specifications. The new GPI fast camera and a coherent image bundle for the new GPI view were delivered to PPPL. The new and old GPI telescopes were installed in the C-Mod vessel in January 2007.

PPPL Engineering Support

- PPPL RF engineers and technical staff will continue to assist in all phases of the Lower Hybrid system operation.

- PPPF engineers and technical staff will continue to assist in the design of the second Lower Hybrid launcher, focusing on the splitter hardware.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.

4.1.5 Future Accomplishments: FY2008 (baseline)

Study the processes relevant to the generation of Advanced Tokamak discharges using high power on- and off-axis ICRF heating and LH off-axis current drive.

Advanced Tokamak Studies

- Drive significant plasma current off-axis using LHCD and validate changes in the current profile through changes in sawtooth behavior; through signatures on Alfven cascades during current ramp-up; through changes in plasma internal inductance, and if possible through q-profile measurements by the Motional Stark Effect diagnostic.

- Observe changes in plasma transport and stability that result from off-axis LHCD regimes where the q-profile is expected to qualitatively alter the confinement physics (reverse shear and/or 'hybrid' regimes).

- Compare the plasma behavior with transport and stability models.

Wave-Particle Studies

- Simulate a range of conventional ICRF heating and lower hybrid current drive scenarios in C-Mod, using the TORIC and TORIC-LH codes that were generalized in FY2005/2007 to include non-Maxwellian species.

Transport and Fluctuation Studies

- Using the combined capabilities of ICRF heating, LH current drive, and the cryopump for density control, the influence of magnetic shear on local transport will be studied over a range of plasma conditions including the reverse-shear and hybrid AT plasma regimes.

- Based on simulations of C-Mod plasmas with LHCD, new experimental scenarios will be designed to improve confinement. Experimental data on temperature and density gradients as well as fluctuation amplitudes and radial correlation lenghts will be compared with numerical simulations of microturbulence.

Intrinsic toroidal rotation and momentum transport

- Using new diagnostic capabilities installed and commissioned in FY07 including the x-ray crystal spectrometer, measure plasma rotation in absence of beam torque in both the plasma edge and core in a variety of plasma regimes including Ohmic, ICRF-heated, L-mode, H-mode (ELMing and ELM-free) and Internal Transport Barrier regimes. Using new heating, density control and current-profile control actuators, evaluate the scaling of intrinsic rotation on dimensionless parameters.

- Compare scaling of intrinsic rotation in these regimes to elucidate the potential role of the steep H-mode edge pedestal in establishing the intrinsic rotation.

- Evaluate local momentum transport coefficients through perturbative experments and compare to predictions of microturbulence codes.

- Centrally peaked velocity profiles are commonly observed during ELM-free H-mode plasmas in C-Mod, implying an inward momentum pinch. Using improved velocity profile diagnostics, measure the profile evolution during ELM-free H-mode plasmas and compare to predictions of microturbulence codes.

- Compare intrinsic rotation in ICRF versus LH heated regimes to document the effects of a fast ion population on the intrinsic rotation.

- Look for evidence of a local momentum transport barrier in ITB plasmas by looking at changes in the local velocity profile driven by the (very small) beam torque generated by the diagnostic neutral beam.

PPPL Engineering Support

- PPPL RF engineers and technical staff will continue to assist in operation and maintenance of the Lower Hybrid system.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.

4.1.6 Future Accomplishments: FY2009 (baseline)

Advanced Tokamak Studies

- Use the full 3MW (source) LHCD capability with 2 LH launchers to control the current profile and the cryopump to control the plasma density in reverse shear and 'hybrid' Advanced Tokamak plasma regimes.

- Document the plasma transport and stability response in these regimes using q-profile measurements from Motional Stark Effect diagnostic and initial q-profile measurements by the polarimeter.

- Compare transport and stability properties with predictions of microturbulence and stability codes.

- Perform integrated discharge simulation using the Tokamak Simulation Code (TSC) and TRANSP that incorporate advanced numerical modeling of LHCD.

Wave-Particle Studies

- Extend the physics included in algorithms for generating the non-Maxwellian dielectric tensor elements to the hot ion lower hybrid regime and explore effects of non-

Maxwellian species on lower hybrid wave propagation and absorption (RF SciDAC and collaboration with C-Mod).

- Continue integrated full wave simulations of ICRF and lower hybrid regime scenarios in support of C-Mod experiments.

Plasma Boundary Studies

- Investigate correlations between edge rotation and edge turbulence in order to better understand the generation and transport of momentum through the edge and scrape-off layer.

Transport and Fluctuations

- Continue local transport measurements with emphasis on transport coefficients and transport barrier physics in AT regimes and quantitative comparison to predictions of microturbulence codes.

Intrinsic rotation and momentum transport

- Continue studies of intrinsic rotation with emphasis on the effects of q-profile modifications generated with high-power LHCD.

4.1.7 Future Accomplishments: FY2008 (incremental)

Upgrade Motional Stark Effect diagnostic with high-throughput imaging spectrometer ($80k)

Currently, like MSE diagnostics on other tokamaks, the C-Mod MSE system uses optical bandpass filters to select the π-component of the MSE spectrum. We propose replacing these filters by a high-throughput imaging spectrometer. An imaging spectrometer offers several advantages:

1. It can simultaneously monitor the polarization direction of the beam-induced MSE light emission and the visible Bremsstrahlung (VB) background, which would enable subtraction of the VB contamination (which is significant in C-Mod) in real time without the use of beam modulation. Beam modulation is acceptable only if the VB emission changes on a time scale slower than the beam modulation itself. In C-Mod, events like L/H transitions and ITB transitions happen on a rapid time scale, and so beam modulation is sometimes too slow. The use of an imaging spectrometer would improve our ability to make useful q-profile measurements in interesting plasmas.

2. It would test the suitability of imaging spectrometers for MSE on ITER. Imaging spectrometers are under consideration for MSE on ITER because (a) the beams are steerable; and (b) there is a reluctance to modulate the heating

beams, so a VB-subtraction compensation is highly desirable. Note that C-Mod operates at higher plasma density than ITER's standard scenarios, so the VB background problem experienced on C-Mod should be comparable to that anticipated for ITER.

3. It would routinely measure all the MSE lines, which would provide additional insight into line ratios and might, in some cases, allow us to measure the polarization direction of both the sigma and pi lines.

4. It would allow us to measure the q-profile in plasmas for which the toroidal magnetic field is ramped. By contrast, the bandpass filters must be temperature-tuned to a particular toroidal field strength, with a time constant of about 15-20 minutes.

This project is contingent on (a) successful resolution of the MSE calibration issues following the 7^{o} rotation of the Diagnostic Neutral Beam; and (b) successful demonstration in FY07 of VB compensation technique using bandpass filters.

<u>Increased participation in design of C-Mod polarimeter ($60k)</u>

To supplement the q-profile measurements by MSE, Alcator C-Mod is designing a multi-channel polarimeter in FY08 with installation targeted for FY09. In the baseline program, PPPL is contributing an experienced interferometer/polarimeter expert to the design effort at the level of 0.3 FTE in FY08 and 0.45 FTE in FY09. An incremental effort at the level of 0.2 FTE is proposed for FY08 to improve the prospects for a successful and reliable polarimeter installation in FY09.

<u>CQL3D Integration into TRANSP ($100k)</u>

We propose a two-year incremental effort, supported jointly by the PPPL/C-Mod collaboration and NSTX, to increase the rate of progress integrating the CQL3D/GENRAY code into TRANSP. CQL3D is an all-frequencies, multispecies (ions and/or electrons), 2D-in-velocity, 1D-generalized radius, relativistic, bounced-averaged Fokker-Planck code that models LHCD, ICRF, EBW, and HHFW heating and current drive. The funding would primarily support additional efforts by the TRANSP computer scientists for integration activities.

<u>Enhanced Lower Hybrid Physics, Engineering, and Modeling ($350k)</u>

As an incremental level of effort in FY08, we propose to roughly double the PPPL research staff time devoted to Lower Hybrid current drive and its effects on plasma confinement.

The recent successful installation of a stainless steel LH launcher in C-Mod opens up significant new and exciting research opportunities in FY08 for both Lower Hybrid physics studies (coupling, heating, current drive, phase control) and the effect of modified current profiles on plasma confinement and stability. The proposed incremental level of effort will strengthen the overall Lower Hybrid research program on C-Mod and ensure that the fusion program realizes its full return on the investment in LH hardware. The incremental effort is also motivated by the need for a decision, sooner rather than later, regarding the possible inclusion of Lower Hybrid current drive capability in ITER. Data from JET and C-Mod are likely to play a key role in characterizing the feasibility and attractiveness of LHCD on ITER.

The incremental FY08 effort on Lower Hybrid would be directed at four activities:

- Increased participation in LHCD experiments;

- Enhanced numerical modeling of LHCD; and

- Additional engineering support for design of the second Lower Hybrid launcher.

- Procurement of some components for the second Lower Hybrid launcher.

Increased participation in experiments: the incremental effort would provide support for a PPPL lower hybrid physicist to be on-site for all of the C-mod experiments that involve the LH system. This would increase direct participation in LH experiments and improve communication with the remainder of the PPPL-LH team members, particularly with regard to modeling and numerical simulation activities.

Enhanced numerical modeling of LHCD: Integrated discharge simulations for C-Mod will be developed using the Tokamak Simulations Code (TSC) and TRANSP. This combination utilizes the free-boundary evolution, plasma control, and predictive transport evolution from TSC, with the sophisticated source modeling and fast particle treatments in TRANSP. This analysis is intended to:

- Reproduce experimental discharge behavior, testing particle and energy transport models and source heating and current drive models.

- Provide projections to new discharges to optimize their programming with particular focus on advanced tokamak scenarios involving internal transport barriers, lower hybrid off-axis CD, and high non-inductive current fraction,

- Provide plasma descriptions that can be analyzed by off-line computations including ideal MHD, fast particle MHD, non-ideal MHD, gyro-kinetic simulations, sophisticated RF calculations, and SOL/divertor analysis. In addition, various computational developments will be required as the work progresses.

The lower hybrid packages in the TSC and TRANSP simulation codes are based on ray tracing modules coupled to simplified Fokker-Planck treatments of the driven current. Though these models have agreed qualitatively with previous experiments on PBX-M, more sophisticated models are being developed within the RF SciDAC and in collaboration with C-Mod and PPPL. In particular, the TORIC code will be coupled with the CQL3D code to provide self-consistent full wave simulations of the lower hybrid driven current at particular single time slices of an experimental discharge. With incremental funding in FY2008 and FY2009, this integrated package would be used to benchmark the accuracy of the lower hybrid driven current used in the time-dependent models described above. This package could also be used to support modeling of conventional ICRF heating scenarios.

Enhanced modeling of fast particle physics and global eigenmodes ($60k)

The physics of ICRF-induced core-Alfvén modes as well as driven global eigenmodes are currently being studied with the PPPL NOVA-K code. This code directly calculates the eigenmodes frequency and structure, in full geometry, using a linear, perturbative treatment of the continuum damping. To complement these simulations, the TORIC linear full wave code will be utilized to study the structure and damping of driven eigenmodes, using a full kinetic treatment. This effort, which would be leveraged off of development work funded by the RF SciDAC project, would be directed towards simulation of these modes in C-Mod, in support of the experimental program. Because the TAEs observed on C-Mod are typically at 400-600 kHz, i.e. below ω_{ci}, it is likely the conductivity operator in TORIC will have to be re-derived in this regime to include finite density gradient effects.

In FY08, this incremental effort would compare the linearized damping rates for driven global radio frequency eigenmodes obtained with the TORIC code with those obtained with local kinetic models.

4.1.8 Future Accomplishments: FY2009 (incremental)

Enhanced Lower Hybrid Physics, Engineering, and Modeling ($350k)

Continue the additional research and engineering effort devoted to Lower Hybrid current drive that was begun in FY08.

CQL3D Integration into TRANSP ($175k)

This incremental effort is a continuation of the incremental project to integrate CQL3D/GENRAY into TRANSP described above.

Enhanced modeling of fast particle physics and global eigenmodes ($50k)

This incremental effort is a continuation of the incremental project begun in FY2008. In FY2009, the efforts would focus on comparing the structure and damping of driven radio frequency global eigenmodes with and without energetic particles present in the tokamak plasma (RF SciDAC and collaboration with C-Mod and NSTX.

4.2 The University of Texas Collaboration

4.2.1 Summary

The University of Texas Fusion Research Center (UT-FRC) participates in the C-Mod program through operation of plasma diagnostics and through use of the diagnostic results to contribute to the C-Mod scientific program. This section is a summary of the current results and contains some description of how this work will be expanded in the next few years. Subsequent sections contain more detail and proposed objectives for the next few years.

UT-FRC will continue responsibility for the maintenance, operation and calibration of the FRCECE heterodyne radiometer, with the goal of robust and reliable operation. Fluctuations in electron temperature T_e and precision T_e profiles (yielding high accuracy scale lengths, L_{Te}) were observed in C-Mod plasmas using the FRCECE diagnostics and correlated with various phenomena. We plan to follow up on these observations.

The FRCECE system provides electron temperature profiles with high temporal and spatial resolution. There are 32 spatial channels. At 5.4 T (the typical C-Mod operating field), the 32 channels cover the full C-Mod radius and the spacing between channels is ~7 mm. The data is used by other members of the C-Mod group because of its high resolution and high bandwidth. It also provides well-localized density fluctuation measurements for particular conditions. The main areas investigated during this past year are listed in the following.

- The quasi-coherent (QC) mode is a hallmark of EDA H-mode discharges in C-Mod. The origin of the mode is still unknown, and a major interest is in completing an empirical picture of the mode. The FRCECE data reveals very low level fluctuations well into the core(i) with radial phase variation across the edge region covering more than 2 cm. The same type of large radial phase variation has now also been observed by the Gas Puff Imaging system (GPI) over more than 1 cm.
- Large edge-localized modes (ELM's) can now be generated on C-Mod by entering a region of operational space with increased lower-triangularity and relatively low edge collisionality ($0.1 < \nu^* <1$). The FRCECE diagnostic contributed to the empirical description of this new C-Mod phenomenon via the temporal evolution of the T_e perturbation in the edge region and in the core during these large ELM's[1] and by detecting nonthermal radiation outside the separatrix simultaneous with the identification of filaments by other diagnostics.
- Localized precision measurements of L_{Te} that are independent of any calibration were measured by imposing small innocuous ramps on B_T. L_{Te} profiles were collected for a series of discharges with central ICRF power deposition ranging from zero to 3 MW. Changes were observed in the mid-radius gradient region of the discharge as RF power levels were varied. This data is being analyzed to acquire local heat flux for comparison to critical gradient models.
- In a recent result from the C-Mod reflectometer, a mode with QC-like frequencies was observed near the plasma center for low density EDA H-modes. This mode was previously observed by the FRCECE, but generally doubted. With this confirmation, we can now go forward with the FRCECE results.

- Toroidal Alvén eigenmodes (TAE's) driven by an external antenna were observed in the FRCECE signal. This opens up a new application for the diagnostic as support for TAE experiments that will be conducted on C-Mod.

Ion temperature, impurity density, and rotation measurements with CXRS have been successful and are now available for many discharges. During the last campaign, we concentrated on developing automatic analysis tools which store results in MDSPlus and display tools including scopes and IDL routines to facilitate viewing the analysis results. By the end of the FY2006 campaign, all data from the campaign was analyzed and available for view or use with these tools. We plan to concentrate on applying the data to understanding some aspects of the physics of transport and rotation. As described below, the topics will include poloidal rotation comparison to neoclassical theory, shear stabilization at the top of the pedestal, and possibly impurity transport. As support for other experiments, this will be extended to study slow transitions to H-mode and comparison of T_e and T_i pedestals.

- Poloidal rotation derived from active charge-exchange spectra was found to compare favorably to equilibrium neoclassical predictions at isolated times during a C-Mod discharge. However, there are also disagreements of varying magnitude during H-Mode. The magnitude of the disagreement can be comparable to that observed in other devices (JET, DIII-D). This comparison was first proposed in the 2005 C-Mod Ideas Forum.[2] The experiments were conducted last year and reported[3] recently. A paper is in preparation.
- Charge-exchange recombination spectroscopy (CXRS) can be used as a diagnostic for local density of fully stripped impurities. A major limitation to the common application of this diagnostic is the unavailability of cross sections which relate the observed spectroscopic emission to the impurity density. We removed this impediment for B ions in C-Mod using calculations benchmarked against experiment. This work was proposed two years ago at the C-Mod ideas forum[4] and it was reported twice this year.[5,6] The cross sections will be applied to measurement of impurity profiles for impurity transport.
- An as-yet unpublished result which will become a standard and valuable tool for our work on C-Mod in the coming year is the development of intensity calibration techniques based on measurements of the plasma bremsstrahlung. This will allow a continuous calibration to be maintained during a campaign in spite of any transmission degradation of internal optics.
- During the FY06 campaign, a novel H-mode was discovered[7] in which the transition has two distinct phases. In the first phase, T_e increases slowly following a very clear break in slope. The second phase is the familiar sudden increase in T_e and n_e. We contributed T_i and E_r profiles to the analysis of one such discharge and continue to participate directly in the work.

The BES diagnostic will be applied to measure narrow-band fluctuations. As an example of previous work, note that measurements of the narrow-band QC mode were made and compared to those from other diagnostics.[8] We will attempt to extend the utility of the diagnostic with an all-out effort to detect broadband fluctuations. Application of a "virtual" C-Mod BES diagnostic to the output of a nonlinear turbulence simulation indicated that the sample volumes of the original diagnostic were too large.[9] The diagnostic was modified accordingly and is awaiting test during the next campaign. Other improvements and tests are described below which are devised to lead to a decision as to whether the BES diagnostic will be useful for broadband fluctuation measurements on C-Mod.

In the area of verification and validation of gyrokinetic codes, we compared linear microstability analysis from GS2[10] and GKS[11] at the top of the pedestal of a high-density enhanced-D_a H-mode plasma. GYRO[12] will be included in future comparisons. During these comparisons and in the area of code validation, we published a paper on "virtual diagnostics."[9] This included a model of the prior BES system with fiber bundles composed of four 1-mm fibers each, in which we showed that the sample volumes in the plasma were probably too large to detect the small-scale fluctuations in C-Mod. Work is beginning on a model of the present system including finite decay-time effects.[13]

Microstability of C-Mod profiles at the top of the H-Mode pedestal was investigated via comparisons of empirical shearing rates with microstability code predictions for linear growth rates. An existing theory[14] posits that the steep-gradient region of an H-mode edge extends into the core only as far as the equilibrium $\boldsymbol{E}\times\boldsymbol{B}$ shearing rate can overwhelm the maximum linear growth rate of the instabilities. To examine this, we compared the maximum linear growth rates γ_{max} for $k_{\mathrm{q}} r_s < 1$ from GS2 to the $\boldsymbol{E}\times\boldsymbol{B}$ shearing rates $\gamma_{\boldsymbol{E}\times\boldsymbol{B}}$ as determined from CXRS measurements.

The results, presented at the 2006 APS/ DPP meeting[15] (and, in earlier form, at the 2006 TTF meeting[16]), are shown in Fig. 1 for various expressions for $\gamma_{\boldsymbol{E}\times\boldsymbol{B}}$. A detailed description of the analysis of the CXRS data leading to E_r and then to the $\boldsymbol{E}\times\boldsymbol{B}$ shear was presented separately.[17] Here, γ_{HB} is the original Hahm-Burrell rate[18] (only valid at the outer midplane), γ_{WM} is the Waltz-Miller rate[19] (a flux function theoretically better suited for comparisons to γ_{max}), and α_E is a factor dependant on elongation and aspect ratio determined from multiple nonlinear GYRO runs.[20] We see that for the appropriate shearing rates (all but the original Hahm-Burrrell), the growth rates exceed the effective shearing rates, implying that the $\boldsymbol{E}\times\boldsymbol{B}$ shear reduces the turbulence but does not quench it. There is a hint that the effective shearing rate may exceed the maximum linear growth rate in the steep-gradient region (r/a > 0.94). Attempts will be made to examine this in the coming campaign.

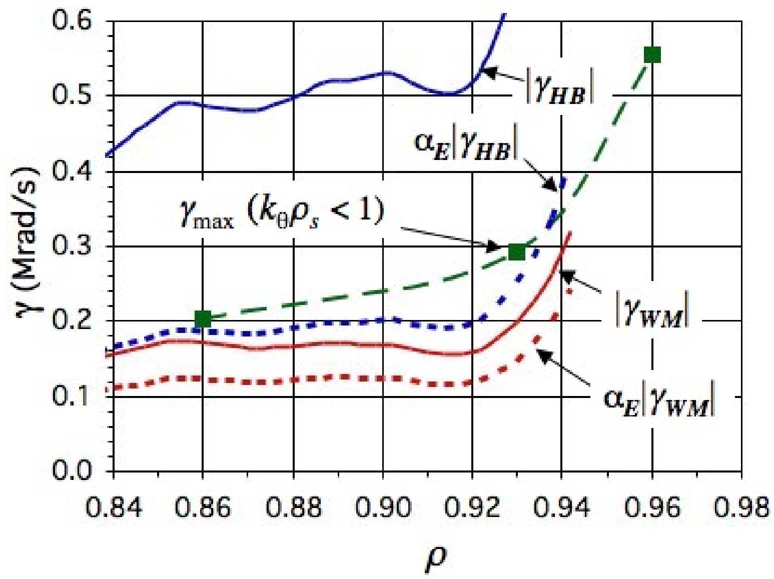


Fig. 4.2.1 Maximum linear growth rate γ_{max} for $k_q\rho_s < 1$ vs. *r/a* together with various $E\times B$ shearing rates for C-Mod shot 1050212015 at 1.027 s. γ_{HB} and γ_{WM} are the Hahm-Burrell and Waltz-Miller rates, respectively and α_E is a factor determined from numerous nonlinear GYRO simulations.

4.2.2 Personnel

The personnel contribution to the C-Mod program consists of 1.4 physics FTE's, 0.3 technician FTE, and 2 graduate students. At present, one graduate student is working on this collaboration, and another is expected to join during this year.

4.2.3 Plans for FY2007

4.2.3.1 Experiments

1) Analyze T_e scale length acquired in studies in plasmas of varying RF power deposition to investigate the dependence of microturbulence on scale length -- a search for critical gradients. A new tool developed for C-Mod data in this study will be the comparison of fluxes to scale lengths.

2) Search for direct evidence of an electron thermal transport barrier in ITB discharges using the FRCECE measurements of T_e scale length. There is evidence of a thermal barrier from pulse propagation experiments. We are proposing work that would form a very strong and definitive confirming result.

3) Continue investigations of narrow-band core T_e fluctuations observed with FRCECE in ITB discharges and EDA H-Mode. These have similar frequencies as the edge QC mode. We plan to look for other similarities (phase correlations, bandwidth, etc.) between the two apparently diverse modes. Since confirmation of the results is important, the fluctuations will be sought via BES by cross-correlating a core BES channel with a core

FRCECE channel. Note that even very low level BES signals can be retrieved through cross-correlation.

4) Density fluctuations in ITB discharges are observed through ECE refraction effects by FRCECE. Additional combined experiments with other C-Mod fluctuation diagnostics (PCI, reflectometry, etc.) are planned to verify the results and improve the understanding of the physics. The validity of the measurement and the utility of an ECE system as a density fluctuation diagnostic are the concerns here.

5) FRCECE will be used to attempt to spatially resolve high frequency (600-800 kHz) TAE's. Current evidence is that TAE's can appear when ICRF is applied. They can also be driven by active magnetic coils. The FRCECE has the ability to provide excellent spatial resolution which may lead to a better understanding of the physics of the mode.

6) Use charge-exchange recombination spectroscopy supplemented by spectroscopy of ambient emission to measure ion temperature and poloidal and toroidal rotation of impurities as well as to measure the distribution of boron impurity ionization states in the plasma. From these, infer the radial electric field from the top of the pedestal inward. The goal is to follow the dynamics of the quantities through the transitions to H-mode and to ITB.

7) Explore the possibility of impurity transport studies with our new-found ability to measure B^{+5} densities with CXRS. The goal is to measure the impurity transport in as far as the foot of the ITB. The limiting factors are beam penetration and whether a measurement of impurity diffusion relative to impurity convection is of value. The initial measurement will be in the interesting ITB region. Success there may lead to application to other discharges.

8) Compare poloidal rotation to predictions of neoclassical theory inward of the pedestal top. This will be in available discharges. One area of particular interest is the comparison in the foot of the ITB.

9) Compare fluxes from global GYRO non-linear computations including background $\boldsymbol{E}\times\boldsymbol{B}$ shear stabilization with experiment for one C-Mod discharge chosen with the assistance of M. Greenwald. Use CXRS-inferred E_r in computations.

10) Investigate the physics of the H-mode pedestal through gyrokinetic microstability analysis of the top of the pedestal. This work involves comparing CXRS-measured $\boldsymbol{E}\times\boldsymbol{B}$ shearing rates at the top of the pedestal to growth rates derived from linear microstability codes.

4.2.3.3 Experimental Support

1) Support the use of CXRS data for other experiments. Continue developing tools (scopes, IDL codes) to access the data. One interesting experiment is comparison of T_e and T_i pedestals for which we are providing data at the top of the pedestal. Another is experiment is work on slow transitions for which we are providing T_i and E_r at the very top of the pedestal.

2) Support the use of FRCECE for T_e scale length measurements in other experiments. At present, the most interesting experiment to us is the search for temperature scale length

changes associated with the ITB and with the off-axis vs. on-axis RF heating (collaboration with Mikkelsen and Greenwald).

3) Continue investigations of edge perturbations using FRCECE. In particular we will continue to examine the perturbations due to discrete ELMs, the non-thermal emission sometimes generated during the ELM crash, and anomalous ECE emission outside the separatrix observed in these discharges. Also we will continue to examine the effects of the QC mode on the ECE emission, including a nonzero correlation of the core channels with the edge channels at the QC mode frequencies.

4) Contribute to narrow-band QC-mode studies using the upgraded BES diagnostic. Measurements of the narrow-band mode will contribute absolute $\tilde{n}/n$ measurements and may confirm the doubly-peaked spatial profile seen by GPI.

5) Revisit earlier BES measurements which showed a vertical profile for quasi coherent mode $k\theta$ that departed from a field aligned model. Coordinate this with QCM measurements made by GPI, PCI, and the fast magnetic pickup coils to first confirm and then attempt to understand the result.

6) The BES diagnostic will be used to observe ELM density perturbations and thus contribute to ELM studies on C-Mod

4.2.3.4 Diagnostic Development

1) Determine whether broadband fluctuations can be observed near the edge with the upgraded BES system. The improvements include i) a higher resolution edge fiber array, ii) a higher-current long-pulse beam, and iii) four channels of 10 MHz, 3 Mb per channel CPCI data acquisition hardware. We seek to answer once and for all whether broadband fluctuation measurements are possible at the top of the pedestal in the following way: Upon start of operation (both tokamak and DNB), the system will view the edge region (R ~ 87 cm) where the radial averaging is not prohibitive yet where there exists some Doppler shift of the beam emission. Data will be taken and cross correlated from poloidally adjacent channels during a steady phase of the discharge for the full duration of the DNB. If the coherences and phases are different between beam-on and beam-off, the data will be more closely analyzed to determine its validity. If no differences are observed, even with the beam running at full capability (~7 A, 1.5 s total on time), the measurements will be declared futile. Analysis, e.g. virtual BES simulations including finite decay times (see next) would be performed to fully understand the results.

2) Improve virtual BES model by more realistic (3-D) modeling of the spatial sensitivity function which includes finite lifetime effects.[13] Apply it to a nonlinear turbulence computation for a typical C-Mod discharge, and further gauge the degree of instrumental limitations.

3) Increase the bandwidth of the FRCECE radiometer so that all 32 channels can resolve fluctuations up to 250 kHz. Also complete the design for another RF unit (mixer plus LO) to extend the frequency range down to 220 GHz that will allow edge measurements down to 4.5 T.

4) Upgrade the UT-FRC CXRS poloidal views to 15 additional poloidal chords and 10 reconditioned and realigned toroidal chords for measurements in the foot of the ITB.

Support the MIT staff in their expansion of the CXRS coverage of the pedestal with 20 additional toroidal chords (with 20 background views as well).

5) Assist in monitoring the long-pulse diagnostic neutral beam using the optical ports in the duct and in the beam chamber and the in-situ calorimeter. From this monitoring, we expect to infer beam component mix which is needed for interpretation of the CXRS signals such as boron density. It will also facilitate optimization of the beam performance to produce the maximum diagnostic signals

6) Collaborate with PPPL in assessing the result of rotating the beam to improve MSE measurements by measuring high resolution MSE spectra.

7) Continue collaborating with the MSE group by providing and maintaining an Optica™ model of the vessel optics and performing ray tracings. Assist with modifications of the optics for the tilted beam; also back-lighting, alignment of the optical components, and optical throughput measurements.

4.2.4 FY 2008

- Compare GS2 and GYRO fluxes and fluctuation characteristics from virtual diagnostics with experiment. We hope to be able to publish definitive conclusions about the predictive capabilities of GS2 and GYRO for C-Mod parameters.
- Use charge-exchange recombination spectroscopy supplemented by spectroscopy of ambient emission to measure ion temperature and poloidal and toroidal rotation of impurities as well as to measure the distribution of boron impurities ionization states in the plasma. From these, infer the radial electric field. The goal is to follow the dynamics of the quantities through the transitions to H mode and to ITB. This goal will continue throughout the three years of this proposal with addition of discharges.
- Extend the frequency range of the ECE radiometer to lower frequencies to extend T_e measurements to the lower-field ITB discharges and H-mode discharges and to attempt measurements of non-thermals during LHCD experiments.
- Formulate virtual reflectometry, PCI, ECE diagnostics (dependent on assistance of diagnosticians). Apply to GS2 and GYRO computations using C-Mod parameters.

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4.4 MDSplus

4.4.1 Recent Highlights

MDSplus software maintenance, bug fixes and ongoing support for off-site installations continues to be a major activity for the MDSplus development group. New support for data acquisition hardware was added, with emphasis on CPCI devices which have become increasingly popular. Enhancements of the support for firewire digital camera systems have been added. Site specific work has been done for experimental groups at Columbia University, PPPL, University of Wisconsin LDX (MIT), DIII-D, UCLA, University of Washington. A list of active fusion sites is appended at the end of this document. The MDSplus web site was completely reconstructed using a wiki system which will ease the task of keeping the information up to date and permit MDSplus users to contribute to the documentation effort. Support for 64 bit platforms has been added to the MDSplus code base. Data versioning capabilities and named meta-data attributes were added to the MDSplus primative libraries.

The core developers of MDSplus met during the summer to design enhancements to MDSplus to address some of the unique data handing requirements imposed by long pulse experiments. In addition, we have been included in design discussions for the ITER CODAC system to ensure that the system used on ITER includes many of the valuable capabilities provided by MDSplus.

4.4.2 Plans

Support for remote MDSplus sites will be increasing as the number of sites and the number of users increases. An ongoing effort to improve online documentation and to train local support staff at each of the major sites where the code is used will be made. The hope is to hold a MDSplus users meetings on a biennial basis. The next meeting is scheduled in conjunction with the IAEA technical meeting in Japan in April 2007 and we have already been actively involved in planning the MDSplus workshop to be held during this meeting. MDSplus software maintenance will continue to be a principle activity

Prototypes of the MDSplus enhancements for data handling for long pulse experiments and advanced simulations are currently under development. This functionality will be added to MDSplus without compromising the capability to access the large archive of existing experimental data. Once the MDSplus internal data handling features are extended to enable incremental storage and retrieval of measurements, the graphical interface tools and user application programming interfaces will be enhanced to expose these capabilities to the user. Similar API and user interface modifications will be implemented to support data versioning, and named meta data.

There has also been some exploratory work done investigating the use of high level programming languages such as Python for re-implementing the existing MDSplus expression evaluation capabilities. The expression evaluation capability found in MDSplus is one of the most important features of the system but is also is the most difficult software to maintain or enhance. Porting this functionality to a language such as Python should improve its maintainability and make it far easier for MDSplus developers and users to add new capabilities to the system.

Support for additional data acquisition devices – particularly CPCI will be provided as useful modules are identified.

4.4.3 Partial List of MDSplus sites.

US:

1. PSFC - MIT
2. PPPL
3. GA
4. U. Wisconsin
5. U. Texas
6. UCLA
7. Columbia
8. U. Washington
9. Auburn University
10. Los Alamos
11. University of Maryland
12. University of Utah
13. U.C. Irvine
14. SAIC, San Diego
15. UCSD
16. LBL
17. NASA, Huntsville

International:

1. IGI- Padua, Italy (RFX)
2. EPFL – Lausanne, Switzerland (TCV)
3. EFDA-JET – Culham, UK (JET)
4. UKAEA – Culham, UK
5. IPP-Garching, Germany
6. CEA – Cadarache, France (TORE-SUPRA)
7. Kurchatov Institute of Nuclear Fusion – Moscow, Russia
8. IPP – Hefei, China (HT-7)
9. Korean Basic Science Institute, Taejon, S. Korea (KSTAR)

10. NIFS – Toki, Japan
11. Australia National University, Canberra (HELIAC)
12. ENEA - Frascatti, Italy
13. University of Quebec
14. Institute for Plasma Research, Gandhinagar,India,

Appendix A.

Alcator C-Mod Publications –2006 to present

Papers Published in Refereed Journals

Bespamyatnov, I. O., Rowan, W. L., Granetz R. S., and Beals, D. F.,"Effects of Neutral-Beam Excited States on Charge-Exchange Emission Cross Sections," Rev, Sci. Instrum. **77**, 10F123 (2006).

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Terry, J.L., LaBombard, B., Lipschultz, B., Greenwald, M.J., Rice J.E., Zweben, S.J., “C-MOD REVIEW: The Scrape-Off-Layer in Alcator C-Mod - Transport, Turbulence, and Flows,” accepted *Fusion Science and Technology.*

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Conferences

33rd European Physical Society Conference on Plasma Physics.
Rome, Italy, 19 June - 23 June, 2006

Invited Talk
Whyte, D. “Gas Jet Disruption Mitigation Studies.”

Contributed Oral
Marmar, E. “Operation of Alcator C-Mod with High- Z Plasma Facing Components: With and Without Boronization.”
Posters
Hughes, J. “H-mode pedestal and core plasma response to gas fueling on the Alcator C-Mod tokamak.”

Snipes, J. “Moderate Toroidal Mode Number Alfvén Eigenmode Damping Rate Measurements on Alcator C-Mod.”

Wright, J. “Full wave coupling to a 3D antenna using Green's function formulation of wave particle response.”

Wukitch, S. “Recent ICRF results in Alcator C-Mod”

2006 GYRO Development Workshop
General Atomics,
Jan. 17, 2007.

Bravenec, R. V., "Status of Virtual Turbulence Diagnostics," contributed talk

Bravenec, R. V., Nevins, W. M.,"Virtual Turbulence Diagnostics for Nonlinear Gyrokinetic Computations," Bravenec, R. V., "Issues in Code/Code Benchmarking," contributed talk

2006 Transport Task Force Meeting
Apr 4, 2006 - Apr 7, 2006
Myrtle Beach, SC, USA

Talk
Greenwald, M “Falling Between The Cracks: Coupling Between Transport In The SOL, Edge and Core”

Posters

Bravenec R. V., “Gyrokinetic microstability analysis of the inner boundary of the H-mode pedestal”

Rice J.E., “Inter-Machine Comparison of Spontaneous Rotation”

Zhurovich K. “Study of triggering mechanisms for internal transport barriers in Alcator C-Mod”

16th Topical Conference on High-Temperature Plasma Diagnostics,
7-11 May 2006,
Williamsburg, Virginia.

Bespamyatnov, I. O. "Effects of Neutral Beam Excited States on CXRS Emission Cross Sections,"

Lin L. “Vertical Localization of Phase Contrast Imaging Diagnostic in Alcator C-Mod”

PSI
Hefei, China
May 2006

Talks
LaBombard, B. "The operational phase space of the edge plasma and its sensitivity to magnetic topology in Alcator C-Mod”.

Lipschultz, B. “Operation of Alcator C-Mod with high-Z plasma facing components and implications.”

Terry, J. “Investigation of ELMs on Alcator C-Mod.”

Whyte, D. “Disruption Mitigation on Alcator C-Mod Using High-Pressure Gas injection: Experiments and modeling toward ITER.”

Wukitch, S. J. “RF Plasma Edge Interactions and Their Impact on ICRF Antenna Performance in Alcator C-Mod.”

Posters
Lin, Y. “Hydrogen Control in AlcatorC-Mod Walls and Plasmas.”

Wright, G.   “Dynamics of Hydrogenic Retention in Mo: First Results from DIONISOS.”

Paper
Lipschultz, B. “High-Z plasma facing components in Alcator C-Mod: a study of the erosion mechanisms and effects on operation.”

Invited talks

Greenwald, M. Seminar, U. Texas, Austin April 2006 “A Tour of Transport Research on the Alcator C Tokamak”

Hubbard, A.E., “H-mode pedestal and threshold studies over an expanded operating space on Alcator C-Mod,” 48th Annual Meeting of the APS Division of Plasma Physics, Philadelphia, MD, Oct. 30-Nov. 3rd, 2006.

Marmar, E.S., “Alcator C-Mod: Research Highlights and Plans,” Fusion Power Associates Annual Meeting, Sept. 2006.

18th International Conference on Spectral Line Shapes
4-9 June 2006,
Auburn, AL, USA.

Rowan, W. L., Bespamyatnov, I. O., Bravenec R. V., "Flow-Shear Stabilization of Turbulence in Tokamaks: An Application of Line Shape Analysis of Impurity Spectra Excited by Interaction with a Hydrogen Neutral Beam,"

IAEA conference
Chengdu, China
16—22 October 2006

Bonoli, P. “Benchmarking of Lower Hybrid Current Drive Codes with Application to ITER – Relevant Regime.”

Ernst, D. “Identification of TEM Turbulence through Direct Comparison of Nonlinear Gyrokinetic Simulations with Phase Contrast Imaging Density Fluctuation Measurements.”

Granetz, R. “Gas Jet Disruption Mitigation Studies on Alcator C-Mod and DIII-D.”

Hughes, J. “Edge Profile Stiffness and Insensitivity of the Density Pedestal to Neutral Fueling in Alcator C-Mod Edge Transport Barriers.”

Izzo, V. “MHD Simulations for Studies of Disruption Mitigation by High Pressure Noble Gas Injection.”

Lipschultz, B. “Divertor/SOL ITPA.”

Marmar, E. “Operation of Alcator C-Mod with High-Z Plasma Facing Components with and without Boronization.”

Porkolab, M “Experimental Studies and Analysis of Alfvén Eigenmodes in Alcator C-Mod.”

Rice, J. “Inter-Machine Comparison of Intrinsic Toroidal Rotation.”

Scott, S. “Overview of Alcator C-Mod Research Program.”

Whyte, D. “Hydrogenic Fuel Recovery and Retention with Metallic Plasma-Facing Walls in the Alcator C-Mod Tokamak.”

Wukitch, S. “Alcator C-Mod Ion Cyclotron Antenna Performance.”

48th Annual Meeting of the APS Division of Plasma Physics,
Philadelphia,
October 2006

Invited Orals
Hubbard, A. “H-mode pedestal and threshold studies over an expanded operating space on Alcator C-Mod.

Parker, R. “Lower Hybrid Current Drive Experiments in Alcator C-Mod.”

Terry, J. “Investigation of Edge Localized Modes on Alcator C-Mod.”

Contributed Orals
Bakhtiari, M. “Using Mixed Gases for Massive Gas Injection Disruption Mitigation on Alcator C-Mod.”

Cziegler, I. “Structure and Characteristics of the Quasi-Coherent Mode in EDA H-mode Plasmas.”

Greenwald, M. “Density peaking at low collisionality on Alcator C-Mod.”

Izzo, V. “Simulations of gas jet disruption mitigation.”

Labombard, B. “Critical edge gradients and flows with reversed magnetic field in Alcator C-Mod.”

Snipes, J. “Alfvén Eigenmodes in Enhanced D-alpha H-mode in Alcator C-Mod.”

Tang, V. “Investigation of Energetic ICRF Minority Protons on Alcator C-Mod.”

Wukitch, S. “Overview of Recent Alcator C-Mod Results.”

Zweben, S. “Comparison of SOL Turbulence in Limited and Diverted Plasmas in Alcator C-Mod.”

Zhurovich, K. “Investigation of triggering mechanisms for internal transport barriers in Alcator C-Mod.”

Posters

Angelini, S. “Analysis of Major Disruptions With Extremely Rapid Current Quenches in DIII-D and C-Mod.”

Bader, A. “Dust Measuring Diagnostics on Alcator C-Mod.”

Bespamyatnov, I. “Study of B+1, B+4 and B+5 impurity poloidal rotation in Alcator C-Mod plasmas for 0.75 < rho < 1.0.”

Bose, B. “Progress on Stereoscopic Imaging of Ablating Lithium Pellets in Alcator C-mod.”

Bravenec, R. V. “Gyrokinetic Microstability Analysis of the Inner Boundary of the H-mode Pedestal.”

Dominguez, A. “Reflectometry Analysis of Density Fluctuations in Alcator C-Mod.”

Edlund, E. “Alfvén eigenmode activity during the sawtooth phase in Alcator C-Mod.”

Ferrara, M. “Alcasim Axisymmetric Simulation Code for Noise and Stability Analysis on Alcator C-Mod.”

Fiore, C. “Parametric Survey of ITB Plasmas in Alcator C-Mod.”

Graf, A. “Visible Doppler Spectrometer at the Alcator C-Mod Tokamak.”

Granetz, R. “Real-time VDE mitigation with gas jet injection, and mixed gas jets on Alcator C-MOD.”

Hill, K. “Application of PILATUS II Detector Modules to a High Resolution X-Ray Imaging Crystal Spectrometer for fast Measurement of Ion-Temperature and Rotation-Velocity Profiles on Alcator C-Mod.”

Hughes, J. “H-mode pedestal behavior in low collisionality regimes on Alcator C-Mod.”

Ince-Cushman, A. “Inter-Machine Comparison of Intrinsic Toroidal Rotation.”

Ko, J. “Spectroscopic investigation on the beam fast ion effects on Alcator C-Mod MSE diagnostic.”

Lin, L. “Turbulence Measurements with the Upgraded Phase Contrast Imaging Diagnostic in Alcator C-Mod.”

Lin, Y. “Fast Ferrite ICRF Matching System in Alcator C-Mod.”

Lyons, L. “Fast-switching Langmuir probe bias electronics for Alcator C-Mod.”

Marmar, E. “Overview of the Alcator C-Mod Research Program.”

Marr, K. “Study of the error associated with background variations during active CXRS analysis.”

McDermott, R. “Upgrade of the Edge Charge Exchange Diagnostic on Alcator C-Mod.”

Parisot, A. “Mode conversion current drive studies on Alcator C-Mod.”

Patacchini, L. “Ion collection by a sphere in a weakly magnetized plasma : Application to Mach probes.”

Phillips, P. “ECE Temperature Fluctuations associated with EDA H-Mode discharges in Alcator C-Mod.”

Porkolab, M. “Recent ICRF Results in Alcator C-Mod.”

Reinke, M . “Two-dimensional radiated power diagnostics for Alcator C-Mod.”

Schmidt, A. “Measurements and Modeling of X-Ray and ECE Spectra During C-Mod Lower Hybrid Current Drive Experiments.”

Schmit, P. “Investigation of Multipactor in presence of B-field.”

Sears, J. “Results from Active MHD Excitation of Toroidal Alfvén Eigenmodes in Alcator C-Mod.”

Smick, N. “Measuring the Total Flow Vector in the Alcator C-Mod SOL.”

Smith, K. “Results from the Alcator C-Mod Polarimeter Prototype and Plans for an FIR System.”

Wallace, G. “Lower Hybrid Coupling Studies on Alcator C-Mod.”

Wolfe, S. “Error field and locked mode threshold studies on Alcator C-Mod.”

Zhang, X.   “ICRF scenarios in the EAST tokamak.”

Outreach presentations for non fusion audiences

Bravenec, R. V., Rowan, W .L., et al., “Why doesn't the H-mode edge barrier extend farther into the core?," U.T. Physics Dept. Plasma Seminar, Feb. 9, 2007.

Greenwald, M. Physics Colloquium – Lehigh University, Oct. 2006, “Fusion Energy: Promise and Prospects”

Greenwald, M. Colloquium – School of Engineering, Dartmouth College, May 2006 “Fusion Energy”

Hubbard, A.E., “Fusion Research on the Alcator C-Mod Tokamak: Towards ITER and Fusion Energy,” Queen’s University at Kingston, Ontario, Seminar at Department of Applied Science, March 2006.

Hubbard, A.E., “*The Advanced Tokamak: Goals, prospects and research opportunities*,” Stanford University Global Climate and Energy Project Fusion Energy Workshop, Princeton, NJ, May 1, 2006.

Lipschultz, B., Boundary and Divertor Issues: Moving Towards a Fusion Reactor, Columbia University, April 2006.

Marmar, E.S., “Physics on the Alcator C-Mod Tokamak,” Physics Dept. Colloquium, University of California, San Diego, May 2006.

Porkolab, M., “Plasma Science and Fusion Center (PSFC) Overview”
presented at MIT to representatives of TOTAL oil company, France, November 14, 2006

Rowan, W .L. and Bespamyatnov, I., "Measuring impurity confinement in the Alcator C-Mod Tokamak: How to build the atomic models for the impurity emission; How to interpret the measurements; Why it is a critical measurement for plasma physics and for magnetic confinement," U.T. Physics Dept. Plasma Seminar, Feb. 9, 2007.

Appendix B. Summary National Budgets, Run Time and Staffing

		FY07	FY08A	FY09D	FY09A	FY09B
			Request	Reduced	C.O.L.	full
Funding ($ Thousands)						
Research		6,195	6,759	6,083	6,942	8,347
Facility Operations		13,326	13,553	12,572	14,347	18,912
Capital Equipment		280	416	0	0	0
PPPL Collaborations		1,866	2,103	1,930	2,145	2,719
UTx Collaborations		415	426	384	438	547
LANL Collaborations		100	103	93	106	132
MDSplus		150	155	140	159	159
International Activities		60	80	72	82	82
Total (inc. International)		22,392	23,595	21,273	24,218	30,898
Staff Levels (FTEs)						
Scientists & Engineers		54.05	54.91	50.03	55.38	61.95
Technicians		25.91	25.89	21.89	26.09	30.09
Admin/Support/Clerical/OH		12.38	12.59	12.08	13	14.43
Professors		0.25	0.25	0.25	0.25	0.25
Postdocs		0.75	1	2	2	3
Graduate Students		26.7	27.2	26.2	28.2	30.2
Industrial Subcontractors		1.7	1.7	1.4	1.7	1.7
Total		121.74	123.54	113.85	126.62	141.62
	FY06	FY07	FY08A	FY09D	FY09A	FY09B
	Actual		Request	reduced	C.O.L.	full
Facility Run Schedule						
Research Run Weeks	16.7	15	15	9	15	25
Users (Annual)						
Host	39	40	40	35	40	52
Non-host (US)	65	67	67	59	67	93
Non-host (foreign)	48	48	48	40	48	60
Graduate students	29	30	30	29	32	35
Undergraduate students	5	5	7	4	7	10
Total Users	186	190	192	167	194	250
Operations Staff (Annual)						
Host	67	68	68	63	68	76
Non-host	4	4	4	3	4	5
Total	71	72	72	66	72	81

Appendix C: Alcator C-Mod Program Detail in Bullet Form

FY07A: 15 weeks total research operations (1 week = 4 days, 8 hrs/day)

Areas of Emphasis

- Commission divertor cryopump density control
    - — Lower collisionality plasmas for all studies – especially important for:
        - LHCD efficiency
        - Edge pedestal stability and ELM studies
        - NTM stability
- Exploitation of Lower Hybrid system at powers exceeding 1 MW
    - — Far off-axis current drive for AT regimes
    - — Phase control – variation of radial deposition and driven current
    - — Combined LHCD and ICRF
    - — L- and H-mode comparisons
- Inductive H-Mode scenarios (ITER baseline)
    - — First wall, materials studies
    - — Integrated H-mode scenario development, performance enhancement
    - — Pedestal and edge relaxation studies
        - Edge stability; ELM transport; Large and small ELM regimes
        - Influence of neutrals (new Lyman-alpha imaging)
    - — Improve predictive capability for ELM size and frequency and assess accessibility to high performance regimes with small or no ELMs
        - Especially at low collisionality
- Hybrid and steady state operation (ITER-AT)
    - — Hybrid formation with I_p ramping and LHCD
        - Weak central shear, q_0~1, no sawteeth
    - — Internal transport barrier dynamics and control, including possible use of LHCD
    - — Development of j-profile control using current-drive and heating actuators
        - Main thrust of LDCD program
        - State of the art modeling tools being developed and applied
- Core and pedestal transport studies
    - — Self-generated flows and momentum transport
        - New diagnostics, including imaging soft x-ray, CXRS
    - — Comparisons of turbulence measurements with simulations
    - — ITB access and control mechanisms
    - — Electron thermal transport and fluctuations
        - Upgraded diagnostics
    - — Construct physics-based and empirical scalings of pedestal parameters
    - — Improve predictive capability of pedestal structure through profile modeling, comparisons with experiment
    - — Particle transport, density profiles at low collisionality
    - — Fluctuation studies (improved diagnostics, including upgraded PCI to high k, swept-frequency reflectometry for radial correlations)
- Plasma-boundary physics and technology
    - — Wall conditioning, boronization

        - New Surface Science Station
        - Marker tiles
        - IR imaging upgrade
    - Improve understanding of tritium retention and the processes that determine it
        - Understand deuterium retention dynamics on tiles (including sides) for B and Mo
        - Understand hydrogenic removal at low and high tile temperature
            - Isotope exchange, disruption cleaning, effects of cryopump
    - Improve understanding of SOL plasma interaction with main chamber
    - Tests of advanced ITER-prototype tungsten-plate tiles
    - Develop improved prescription of inter-ELM transport and perpendicular SOL transport
    - Dimensionless cross-machine comparisons for SOL physics
    - SOL dust transport studies
- Wave-Plasma Interactions
    - ICRF sheath-enhanced sputtering
    - Initial studies of real-time active ICRF antenna matching
        - Maintain coupling through transients (ELMs, L to H transitions, large sawteeth)
    - Mode conversion flow and current drive (ICRF)
    - Lower Hybrid RF
        - Increased LH power (>1 MW coupled)
            - Current drive at higher densities
            - Combined with ICRF (interactions)
            - Coupling through H-mode edge
        - Parameter scans and comparison with models (current drive, heating, accessibility, radial deposition)
- Macroscopic Stability
    - Disruption mitigation
        - Real-time adaptive control
        - Mixed gases to optimize speed and mitigation
        - Continued close coupling to 3-d MHD simulations
    - Intermediate toroidal mode number Alfven Eigenmodes
        - Active antennas, passive magnetics, PCI
            - Added magnetics diagnostics
        - Fast particle drive (ICRF minority tails)
            - Compact Neutral Particle Analyzer diagnostic
    - MHD stability analysis of H-Mode edge transport barriers under type I and tolerable ELM conditions, reduced collisionality
    - Error fields and locked modes
        - Effects of non-resonant error fields
        - Investigations to try to resolve remaining differences between single-machine and multi-machine scaling studies
    - Neoclassical Tearing Modes
        - NTM threshold investigations at reduced collisionality, higher β
        - Seed island control (sawtooth stabilization)

- LHCD and ICRF tools

Plain English Goals
- Current Profile Control with Microwaves
- Active Density Control

Awards – APS Fellowship
- John Rice
- Dennis Whyte

FY08D *10% below FY2008A Guidance (*9 weeks research operations)

Plans
- Exploitation of Lower Hybrid system at power up to 1.5 MW
  - Far off-axis current drive for Hybrid and AT regimes
  - Phase control – variation of radial deposition and driven current
- Progress for highest priority science topics, but at significantly reduced pace

Implications
- Layoff 2 engineers, 2 technicians, 3 scientists, do not replace 1 graduate student
- Reduced research runtime (by 6 weeks to 9 weeks total)
  - Even fewer of priority runs can be completed (to less than ¼)
- Delay 2'nd Lower Hybrid launcher (1 year)
  - Power handling capability of single LH launcher expected to limit total power to plasma
    - Less driven current
    - Less flexibility in launched spectrum, leading to poorer localization of driven current
- Delay 4'th MW Lower Hybrid source power (1 year)
  - Fully non-inductive AT regimes probably not accessible with reduced power
- Delay completion of polarimetry diagnostic to measure j(r)
  - ~6 month delay
    - Adjunct to MSE; only current profile measurement for highest density plasmas; overlaps with MSE in optimal density range for LHCD
  - Geometry, density and field the same as on ITER
    - Valuable prototyping lost
- Defer data acquisition and computing infrastructure upgrades
  - Hardware becomes obsolete on time scale of about 3 years

Plain English Goals
- Confinement at high plasma current
- Active control of ICRF antenna

Infrastructure needs

- Alternator inspection ($550k)

FY08A Guidance: 15 weeks research operations

Prioritized increments:

- Add 6 weeks research operation (to 15 total), and restore personnel cuts
    - — Increased productivity across all topical areas
        - Particularly important to take advantage of new tools (LH, cryopump, diagnostics)
    - — Student training maintained
- 2nd LHCD launcher on schedule
    - — optimal use of available source power
    - — compound spectrum for increased flexibility of deposition (and thus current profile control)
- 4'th MW LH source power on schedule
    - — Increased non-inductive current drive
- Polarimetry development on schedule
    - — Current profile measurements are critical to understanding of LH experiments
    - — Enhanced understanding of all regimes, particularly for high density conventional H-mode (ITER baseline)
- Data acquisition upgrade pace maintained
    - — Improving reliability and productivity

Research Plan Highlights (see body of this Work Proposal for details)

- Current profile control with Lower Hybrid
    - — Maximize power through single antenna
    - — Extensive investigations of Hybrid modes
    - — Strongly reversed-shear AT regime investigations
- Hybrid and steady-state scenarios
    - — Investigations with partial non-inductive, and approaching fully non-inductive (bootstrap + LH)
- Fast particle collective modes in low and reversed magnetic shear configurations
- Accessibility to regimes with small or no ELMs
- NTM studies
    - — threshold at increased β
    - — sawtooth seed stabilization (ICRF and LH)
- Tungsten lamella divertor tile physics and technology
    - — Isotope retention (application to tritium retention in ITER)
    - — Power handling for long-pulse, relatively low density AT regimes.

FY08B Program planning budget: 25 weeks research operation

Prioritized increments:

- 3 weeks additional research operation, to 18 weeks
- Real-time matching for 2 ICRF transmitters for improved utilization
- Spare 4.6 GHz Klystron
- Outer divertor upgrade
    - — Power handling for >8MW, 5 seconds
- 4 weeks additional research operation (to 22 weeks)
- 2 additional Klystrons (prudent for increased operations)
- MSE upgrade – 2nd view for direct E_r measurements
- 3 weeks additional research operations, to 25 weeks (full utilization)

Research Highlights (See body of this Work Proposal for details)

- Substantial increased progress across all topical science areas and integrated thrusts, with particular emphasis on high priority ITER R&D and ITPA joint research

FY09D: 10% Decrement from FY08A Guidance (9 weeks research operation)

Plans

- Progress for highest priority science topics, but at significantly reduced pace

Implications

- Layoff 2 engineers, 2 technicians, 3 scientists; do not replace 1 graduate student
- Reduced research operation (by 6 weeks, to 9 weeks total)
    - — Even fewer of priority runs can be completed (to less than ¼)
- Delay 2'nd Lower Hybrid launcher (1 year delay)
    - — Power handling capability of single LH launcher expected to limit total power to plasma
        - Less driven current
        - Harder to quantify results accurately, compare with models
- Defer data acquisition and computing infrastructure upgrades

Plain English Goals

- Self-generated plasma rotation
- Hybrid Advanced Scenario investigation

FY09A Cost of Living: 15 weeks research operation

Prioritized increments:

- Add 6 weeks research operation and restore personnel cuts
- Complete and install 2nd LH launcher, 4'th MW source power
- Begin procurement of advanced outer divertor upgrade (complete FY10)

Research Plan Highlights (Details as outlined in the body of this Work Proposal)

- Current profile control with Lower Hybrid
  - Pulse length approaching 3 seconds (up to 10 current rearrangement times)
  - Power to 2.5 MW coupled
- Density control with divertor cryopump
- Hybrid and steady-state scenarios
- Fast particle collective modes in low and reversed magnetic shear configurations
- Tungsten lamella divertor tile physics and technology
  - Evaluation of high power handling with total input power approaching 8 MW

FY09B Program planning budget: 25 weeks research operation (assuming guidance budget in FY08)

Prioritized increments:

- 3 weeks additional research operation, to 18 weeks
- Polarimeter upgrade (increased spatial resolution)
- 5'th MW Lower Hybrid source power (completion in FY10)
- 7 weeks additional research operation, to 25 weeks

Research Highlights (See body of this Work Proposal for details)

- Substantial increased progress across all topical science areas and integrated thrusts, with particular emphasis on high priority ITER R&D and ITPA joint research