(Draft)
ALCATOR C-MOD
FY06-07 WORK PROPOSAL

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1. Introduction

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 and programmatic thrusts. The topics relate to the generic plasma science, while the thrusts focus this science on integrated fusion objectives crucial to the international program. The two thrusts are **Advanced Tokamak** and **Burning Plasma Support**. The Burning Plasma Support thrust takes advantage of the high-field, high-pressure capability of the facility and includes critical research aimed at resolving questions related to high performance H-mode regimes for next-step fusion experiments, particularly ITER. The Advanced Tokamak thrust 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 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 programmatic thrusts are illustrated in Figure 1.1

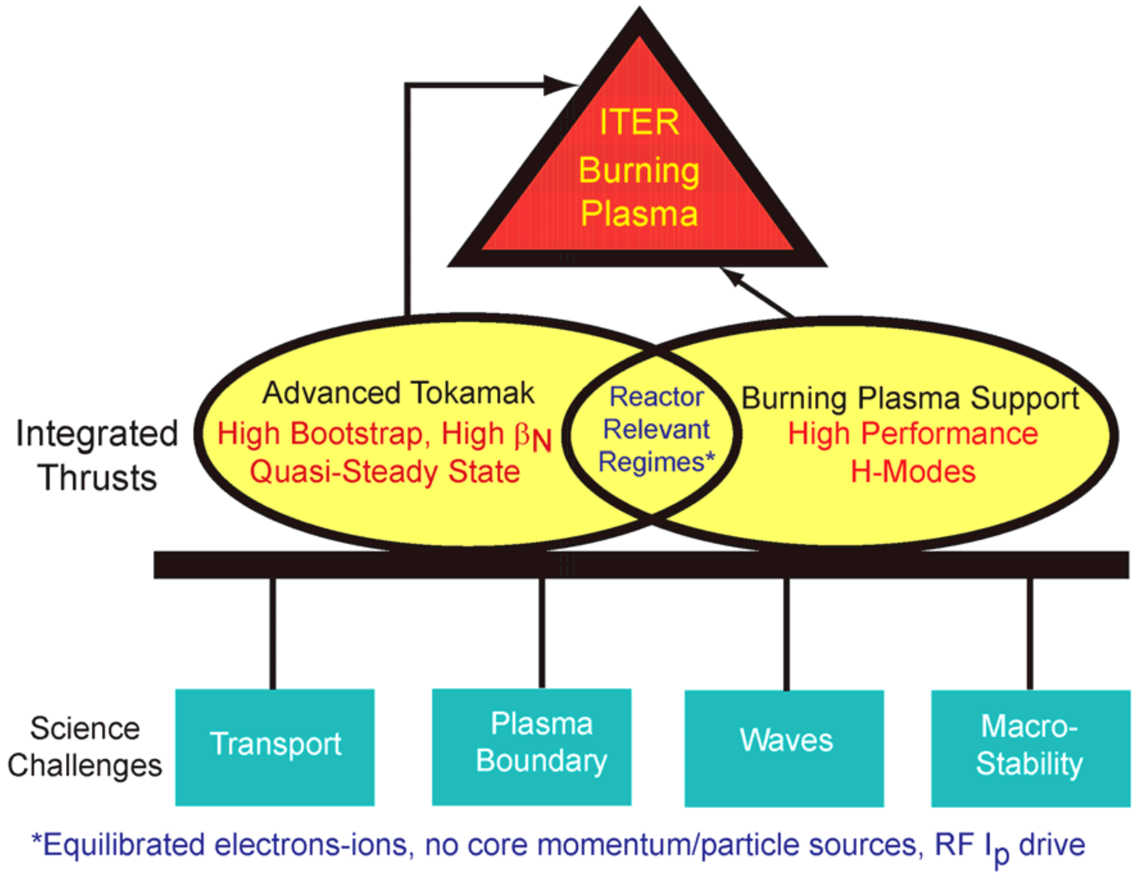

Figure 1.1 Programmatic thrusts and topical science areas.

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 atmosphere), 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 and proposed compact ignition experiments.

- **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, coordinated 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 FY05-FY07 period:

- Steady state operation
  - Hybrid scenarios
    - Priority for AT thrust

  - Develop real time j profile control using heating and CD actuators; assess predictability, in particular for off-axis CD
    - Main thrust of LHCD program; also MCCD, FWCD
    - State of the art modeling tools being developed and applied
- Transport Physics
  - Address reactor relevant conditions, e.g. electron heating, $T_e \sim T_i$, impurities, density, edge-core interaction, low momentum input …
    - >90% of C-Mod operation is in these regimes
  - Encourage tests of simulation predictions via comparisons to measurements of turbulence characteristics, code-code comparisons and comparisons to transport scalings
    - Upgraded turbulence diagnostics
    - Increasingly strong interactions with theory and modeling
  - Obtaining physics documentation for transport modeling of ITER hybrid and steady-state demonstration discharges
- MHD
  - Develop disruption mitigation techniques, particularly by noble gas injection
    - Will investigate at absolute plasma pressures comparable to those on ITER
  - Study fast particle collective modes in low and reversed shear configurations: identify key parameters; perform theory data comparisons
    - Active and passive MHD, PCI, ICRF
    - Strong theory and modeling effort
  - Perform MHD stability analysis of H-mode edge transport barrier under type I and tolerable ELM conditions
    - Focusing on small ELM and EDA regimes
    - Access to type I ELMs in 2004; will pursue further
  - Investigate/determine island onset threshold of NTMs … seed island control
    - Study at increased β
    - Sawtooth stabilization (ICRF, LH)
  - Construct new disruption DB including conventional and advanced scenarios and heat loads on wall/targets
    - Contribute data from all scenarios at high absolute power/energy densities
- Pedestal and Edge
  - Construct physics-based and empirical scaling of pedestal parameters
    - Priority of transport task group; coordinated experiments through ITPA
  - Improve predictive capability for ELM size and frequency and assess accessibility to regimes with small or no ELMs
    - Emphasis on small ELMs at higher β, and EDA
      - Effects of collisionality studied through joint experiments
  - Improve predictive capability of pedestal structure through profile modeling

        - Supplying data to new pedestal profile database
- Confinement Database and Modeling
  - Evaluate global and local models for plasma confinement by testing against databases
    - C-Mod operates with unique dimensional parameters, providing important constraints
- Divertor and SOL
  - Understand the effect of disruptions on divertor and first wall structures
    - IR and ultra-fast imaging
    - Disruption mitigation
  - Improve understanding of tritium retention and the processes that determine it
    - Understanding D levels on tiles (including sides) for B and Mo
    - Understanding removal of H at low tile temperature
  - Improve understanding of SOL plasma interaction with main chamber
  - Develop improved prescription of SOL perpendicular transport and boundary conditions for input to modeling
    - Transport studies are a central emphasis addressing both issues
- Diagnostics
  - Develop new methods to measure steady state magnetic fields accurately in nuclear environment
    - Polarimetry is inherently steady-state; in-principle no special difficulty with nuclear environment
  - Assess techniques for measurement of dust
    - Dust detection system being developed for in-situ measurements during plasma pulses

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 is one of the key participants, can be found in the following table:

ITPA Designation	**Topic for Coordinated Joint Research**
CDB-4	Confinement scaling in ELMy H-modes: ν^* scans at fixed n/n_G
CDB-8	ρ^* scaling along an ITER relevant path at both high and low β
TP-1	Steady-state plasma development
TP-3.2	Physics investigation of transport mechanisms with $T_e \sim T_i$ at high density
TP-4.1	Similarity experiments with off-axis ICRF-generated density peaking
TP-6	Obtain empirical scaling of spontaneous plasma rotation
PEP-7	Pedestal width analysis by dimensional edge identity experiments
PEP-12	Comparison between C-Mod EDA and JFT-2M HRS regimes
PEP-16	C-Mod/NSTX/MAST small ELM regime comparisons
DSOL-3	Scaling of radial transport
DSOL-7	Multi-machine modeling and database for edge n and T profiles
DSOL-11	Disruption mitigation experiments

DSOL-13	Deuterium co-deposition with carbon in gaps of plasma facing components
DSOL-15	Inter-machine comparison of blob characteristics
MDC-1	Disruption mitigation by massive gas jet
MDC-3	Joint experiments on NTMs (including error field effects)
MDC-5	Comparison of sawtooth control methods for NTM suppression
MDC-6	Low β error field experiments
MDC-9	Fast ion redistribution by high energy ion driven Alfven modes and excitation threshold for Alfven cascades
MDC-10	Measurement of damping rate of intermediate *n* Alfven eigenmodes

As our research emphasis shifts to concentrate on quasi-steady-state AT regimes, we expect to become more heavily involved with the Steady State Operations ITPA Group.

Links to the IPPA MFE Goals

The Integrated Program Planning Activity has developed four high level goals, endorsed by FESAC, for the Magnetic Fusion program in the US:

1) Advance fundamental understanding of plasma, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation;

2) Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems, by investigating a broad range of innovative magnetic confinement configurations;

3) Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements, and participate in a burning plasma experiment;

4) Develop enabling technologies to advance fusion science, pursue innovative technologies and materials to improve the vision for fusion energy, and apply systems analysis tools to optimize fusion development.

The Alcator program contributes to all four of the goals, with our strongest efforts concentrated on goals 1 and 3. For goal 1, Figure 1.2 gives a graphical representation of the mapping between specific C-Mod program components and the 5-year objectives identified by the IPPA for this science goal. Note that our program targets specific scientific contributions, and many of our initiatives address overlapping topics.

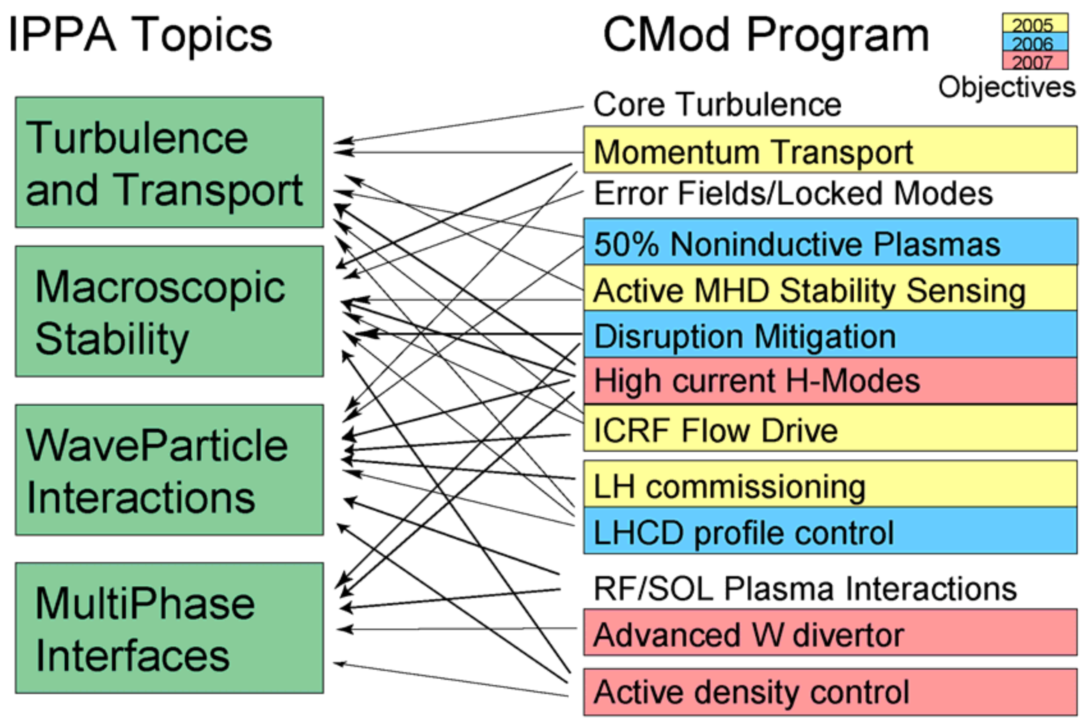

Figure 1.2 Mapping between Alcator program and IPPA Goal 1 objectives

Regarding IPPA goal 3, the two main thrusts of the C-Mod program are quasi-steady state Advanced Tokamak research and Burning Plasma Support investigations. These are focused on addressing the 5-year objectives related to Steady State, High Performance and Burning Plasma, as illustrated in Figure 1.3. Both thrusts will help to resolve outstanding questions about the optimal integrated design of next-step devices and future reactors, as well as addressing the fundamental science underlying their challenges. In the near term, we plan to focus heavily on the issues which are most important for the ultimate success of ITER.

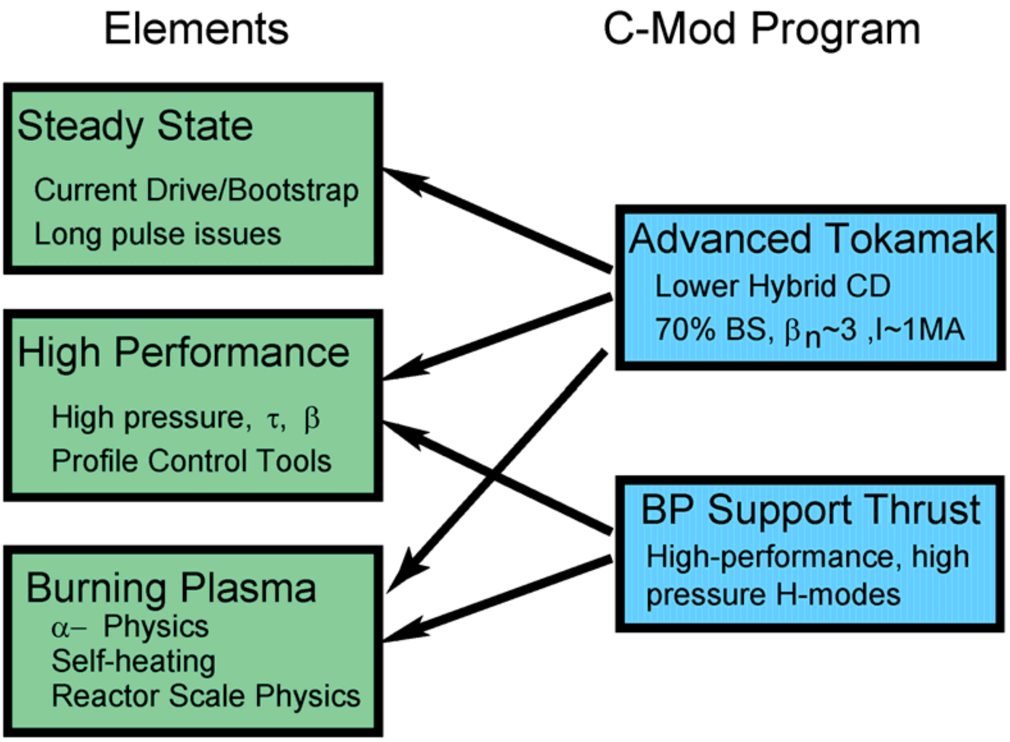

Figure 1.3 Mapping between Alcator program and IPPA Goal 3 objectives

Concerning IPPA goal 4, the C-Mod program focuses attention in selected areas: ICRF and Lower Hybrid technologies, and high Z metal walls/divertors with reactor level heat flux. The Advanced Tokamak is an innovative concept that is a critical part of the broad range emphasized in goal 2.

Detailed discussions of how Alcator's specific topical science plans address the key 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 FY2005 is based on guidance from the Office of Fusion Energy Sciences, with total national project funding of $21.5M, including $19.0M at MIT, and major collaborations totaling $2.50M. These represent an overall decrease, relative to FY2005 funding, of $508,000, with the majority of the decrease coming out of the MIT portion of the Facility Operations budget. Had the budget remained flat, research operations would have been decreased, due to cost of living increases, from the planned 17 weeks in FY2005, to 15 weeks in FY2006. The $508,000 cut leads to a further decrease of 3 weeks, to a planned total of 12 weeks in FY2006. For FY2007, we have considered several budget scenarios, which would allow for 0, 6 12 16, 20 or 25 weeks of research operations, respectively. The 12 week case is taken as the base case, and the others are incremental or decremental relative to the 12 week case. The major items that the guidance and base budgets permit us to fund are shown in table 1.1.

Table 1.1: Major items funded in guidance budgets (FY05+FY06+FY07)

Item	Cost (k$)	Notes
Cryopump	520	Required for density control (AT), lower collisionality (BP)
W divertor modules	75	ITER prototype
Lower Hybrid CD: 2nd launcher	720	Reduce power density (increase coupled power); allow compound spectrum
Polarimeter/Interferometer	600	j(r) at high density; ITER geometry
4-strap ICRF Antenna	500	Preserve full ICRF power capability with addition of 2nd LH launcher
Core Thomson upgrade	120	Resolve detailed ITB gradients
DAC infrastructure	190	Data collection doubling on 2 year time scale
MPP Cluster Upgrade	40	Shared resource with PSFC Theory Group

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 $26.26M in FY06 and $28.17M in FY07, which permit the following additions (in approximate priority order).

Table 1.2(a): Major items requiring budget increments (FY2006)

Item	Cost (k$)	Notes
6 weeks additional run time	1400	Total of 18 weeks research operation
Outer divertor upgrade	375	Power handling for >8MW, 5 seconds (complete in FY2007)
Active MHD upgrade	50	Add second location: toroidal mode number control
4th MW Lower Hybrid	300	Required for high current fully non-inductive AT (complete in FY2007)
Real-time matching (ICRF)	275	Increased productivity (complete in FY2007)
SOL Thomson Scattering	250	Pedestal and SOL physics
7 weeks additional run time	1600	25 weeks total; full facility utilization
Spare 4.6 GHz Klystron	500	Currently have no spares for 16 klystron system

Table 1.2(b): Major items requiring budget increments (FY2007)

Item	Cost (k$)	Notes

6 weeks additional run time	1500	Total of 18 weeks research operation
Complete outer divertor upgrade	375	Power handling for >8MW, 5 seconds
Spare 4.6 GHz Klystron	500	Prudent to have 3 spares
Complete and install 4th MW LH	300	Required for high current fully non-inductive AT
3 weeks additional run time	750	To 21 weeks total
High resolution x-ray upgrades	100	Additional tangential views for rotation, T_i profiles
Outer divertor upgrade	300	Power handling for >8 MW, 5 seconds
ICRF real-time matching	300	Add to remaining antenna(s)
MSE second view	400	Direct E_r measurement
ICRF cavity conversions	350	Transmitters 1&2 from fixed freq. to tunable
Advanced material divertor	500	ITER/BP tungsten divertor
Laser Scattering Fluctuation diagnostic	300	Core fluctuations, complete in FY2008
4 weeks additional run time	950	25 weeks total; full facility utilization

Table 1.3 summarizes the items which would be cut in the event of a 15% budget decrement (case D) for FY2007.

Table 1.3: Major items cut under a 15% decrement in FY2007

Item	Cost (k$)	Notes
12 week decrease of research run time	1900	No operation in FY07
Personnel cuts	1200	3 Engineers, 2 Techs, 2 Scientists, 2 Students
LH 2nd launcher deferred	375	At least 1 year delay
ITER tungsten divertor prototype deferred	75	At least 1 year delay

Proposed facility research run time is given in table 4. In addition to the guidance cases, we show the incremental (program planning) (B) and 2 decremental cases (C and D).

Table 1.4: Research operation for guidance (05A-07A), increment (07B) and decrement (07C, 07D) budget cases

Fiscal Year	**05**	**06A**	**07A**	**06B**	**07B**	**07C**	**07D**
National Budget ($M)	22.0	21.5	22.2	27.7	28.8	21.1	18.9
Research Operation Weeks	17	12	12	25	25	6	0
Research Operation Hours	540	390	390	800	800	190	0

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 4.0 and 4.1 explicitly cover the contributions from Princeton and Texas respectively.

A summary of the planned facility schedule, assuming the guidance (FY06) and base (FY07) budget levels, is shown in figure 1.4. Items shown in red require incremental funding. Planned research weeks are shown in the green operations blocks.

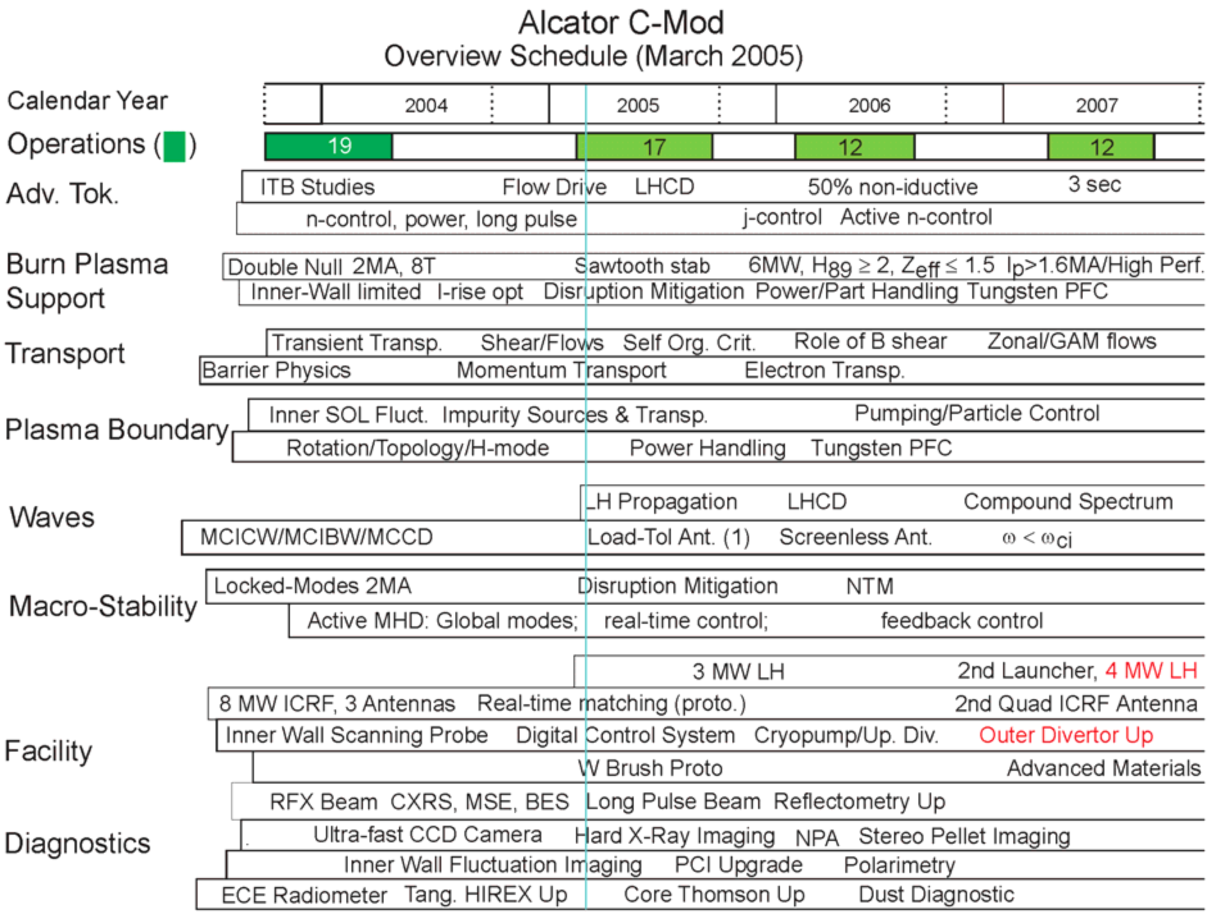

Figure 1.4. Schedule of Programmatic Emphasis and Major Installations (Guidance (FY06) and Base (FY07) Budgets). Items shown in red require incremental funding.

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.

Commissioning of the Microwave Current Drive System [May 05]
Theory and past experiments show that microwaves launched as so-called Lower Hybrid waves can be used to drive toroidal plasma currents with high efficiency, and that these currents can be localized radially. Importantly, hollow current profiles can be formed which lead to improved stability, higher plasma pressures, and nearly steady state "Advanced Tokamak operation. To pursue this research on Alcator requires the installation of a microwave transmitter system and an appropriate launcher. We plan to complete this engineering and commence experiments in FY 2005.

Measure plasma behavior with high-Z antenna guards and input power greater than 3.5 MW. [September 05]
These experiments address issues related to first wall choices, and the trade-offs between low-Z and high-Z materials. This choice can affect many important aspects of tokamak operation, including: impurity content and radiation losses from the plasma; hydrogen isotope content in the plasma and retention in the walls; disruption hardiness of device components. All of these issues are significant when considering choices for next step devices to study burning plasma physics, especially ITER. Definitive experimental results will be compared to model predictions. This goal is an FY05 level 1 science target for the DOE Office of Fusion Energy Sciences.

Current Profile Control with Microwaves [September 06]
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.

Sustaining Plasma Current Without a Transformer [September 06]
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 will serve to verify the theoretically predicted current-drive efficiency and our ability to control the various plasma parameters needed to optimize it.

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.

Active Density Control [September 07]
A new divertor cryopump will be installed in C-Mod for first operation in FY06. The pumping properties will be tested in FY06, and the configuration will be evaluated for density control, particularly for Advanced Tokamak regimes suitable for efficient lower hybrid current drive combined with high bootstrap fraction, during FY07.

Confinement at high plasma current [September 07]
The operational space of C-Mod in the current range 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 field 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, has become accessible 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.

Goals Accomplished in FY2004

Power and Particle Handling for Advanced Tokamak Plasmas

Techniques for safely radiating away the extremely large heat flow encountered in magnetic confinement plasma exhaust have been demonstrated at relatively high density. Quasi-steady state Advanced Tokamak plasmas may require lower density and involve techniques that are constrained by the needs of optimizing confinement. We will establish the limits of the divertor techniques and their performance in regimes appropriate for these plasmas.

Report:

Scaling of general heat load
A study has been made of C-Mod divertor heat load handling capability and the implications for future performance. Two methods of extrapolation to 5 second plasmas with full LH and ICRF power were investigated. *In both cases we will assume that the heat load profile on the divertor surface does not vary with power or confinement mode.* The first method scales from measured parallel heat fluxes in shots near in density to

expected Lower Hybrid regimes. For shots with 600 ms of 3.0 MW RF (plus 1 MW of Ohmic) we find that the heat flux perpendicular to the surface (field line angle 0.5 degrees), $q_{\perp}$= 2-3.3 MW/m^2. Using the following formula:

$$\Delta T(^oC) = q_{\perp}\,(W/m^2) \times \gamma_{Mo} \times (t(sec))^{0.5} \qquad (1)$$

with γ_{Mo} = 6x10^{-5} m^2-^{o}K/Watt-sec$^{0.5}$). We then scale to 5 second pulses and doubling the total power (assumed 2.5 MW of LHRF reaches the plasma in addition to the 0.5 MW Ohmic and 5.0 MW ICRF -> factor of 2 increase in overall power) to get 4-6.6 MW/m^2 which corresponds to ΔT~ 580-960 ^{o}C (assuming the heat flux profile does not change).

The second method relies on scaling from measured surface temperatures for a shot with higher operating densities than envisioned for the LHCD (see example in Figure 1.5). The surface temperature measurements are made with an IR camera. We measure ~ 120^{o}C rise for the current power loading conditions mentioned above and for non-leading-edge tiles. Scaling to 2.5x the overall power and from 0.6 to 5 seconds gives a value of ΔT ~ 870^{o}C based on eq. 1.

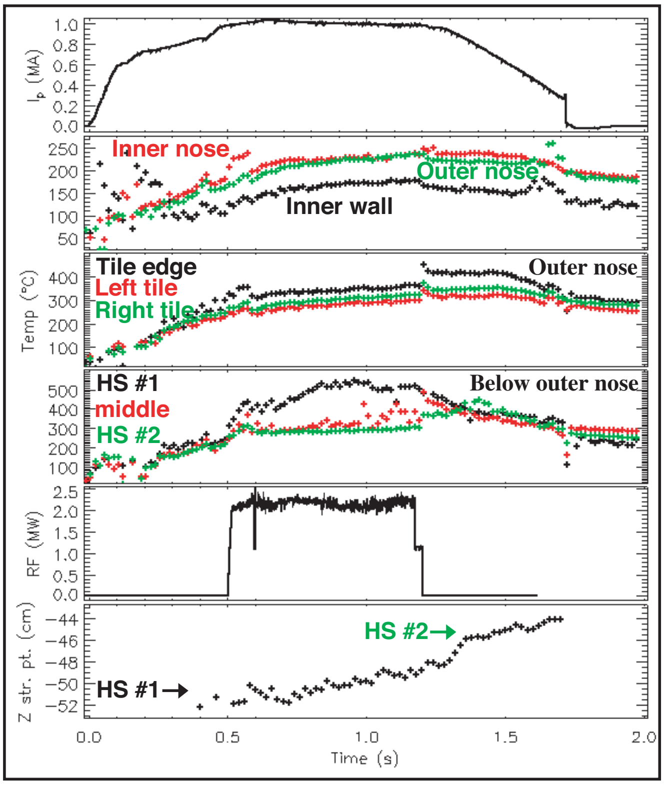

Figure 1.5. Measurements of surface temperature rise using IR imaging for a medium density shot with 2 MW of ICRF. As shown in the bottom trace, the strike point was swept during the pulse.

We have also done the scaling of measured surface temperatures from a long-pulse (3 second) discharge which had line-averaged densities a factor of 4 below that envisioned for AT operation and very low input power. In addition the strike point position was such that the field angle to the surface was 3x higher than usual (3 x higher perpendicular heat flux compared to the normal 0.5 degree surface incidence angle). Scaling that shot (pulselength, power, AND field line angle) to LH operation leads to a predicted ΔT ~ 1400^{o}C. We slightly discount this shot because it is hard to assess whether operation with such low densities and powers, as well as poor strike point position, is truly scalable to LH operation.

By either of the above methods we should experience a significant temperature rise during the shot. The outer divertor is poorly thermally connected to the vessel meaning that the structure temperature will likely ratchet up to ~ 550°C (825 °K) after a number of shots, such that blackbody radiation will remove the heat between shots. So, the ultimate front surface temperature on 'standard' Mo surfaces should remain well below the point of damage due to melting (2600°C).

Other operational aspects which affect the divertor temperature

In the above estimate we have not made a prediction of what happens at leading edges. The typical peaking factor assumed for these situations is ~2. Based on the worst case low-density, low-power discharges, the scaled AT regime surface temperature would be 3350°C (550°C base temperature + 2x1400 °C). Using the other shots at powers and densities closer to expected LHCD operation leads to final surface temperatures below melting.

'Hot spots' have been observed in parts of the plate where tiles become loose or have been improperly beveled. We have observed temperature rises at those points that ~3x the average ΔT. The factor of 3 is very uncertain, but in any case such hot spots could melt if they occur.

Ameliorating effects

The heat flux profile on the divertor plate is fairly peaked. The e-folding length poloidally along the outer divertor is ~ 1 cm with about 11 cm length along the vertical section. If we sweep the strike point during the shot, the peak heat load will be on a given tile for a limited amount of time. If we assume that the high heat flux duration specified above is 1/4 of the pulse length, then the temperature rise is reduced by a factor of two. Our estimates indicate that this would keep leading edges and potential hot spots below the melting temperature of Mo.

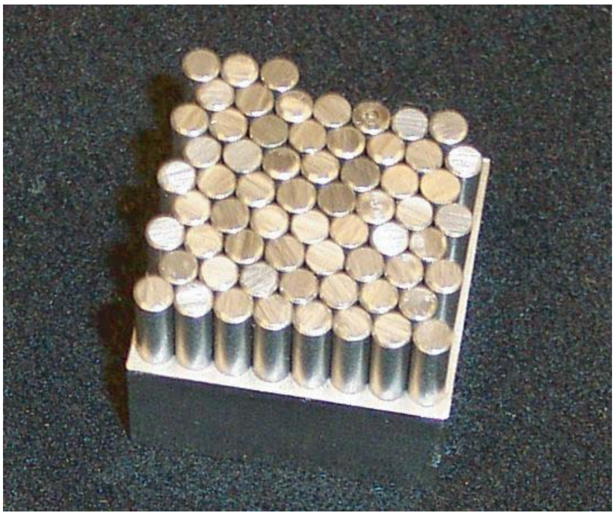

Figure 1.6. W brush tile. 1/8" W rods are inserted into an inconel base. They are locked into the base with inconel cross-rods.

The above analysis is done for Mo. We are also developing tiles using a tungsten brush design (see Figure 1.6) - 1/8" diameter W rods inserted into an inconel base. Such rods have a 600 °C higher melting temperat58

ure than Mo (3200 °C), giving additional operating margin. In addition, such tiles are prototypical of the proposed ITER divertor. We plan to install 12 such tiles during the

2004 vacuum break, both at leading edge and at normal heat-flux locations. Assuming the development is successful, we plan to replace all tiles on the outer divertor with W brush tiles.
The outer divertor itself is also slated for improvements. The plan is to replace the outer divertor with a simpler design and realign it. This would reduce hot spots.

Summary
The scaling to long-pulse Advanced Tokamak conditions with non-inductive current drive, including high power Lower Hybrid, indicates that the majority of the divertor surfaces will remain well below melting. Leading edges and hot spots are more difficult to predict, but several factors should allow us to minimize, if not eliminate, their melting. These include the use of strike point sweeping, better alignment of the outer divertor and use of W-brush tiles.

Sensing approach to instability using active coils

Plasma performance can be limited by large scale instabilities, which cause loss of confinement and in severe cases lead to termination of the plasma. These oscillations are normally stable but may be driven unstable by unfavorable combinations of pressure and current profiles which may develop as the plasma evolves. By using external currents in specially designed antennas to excite the oscillations at small amplitudes, it may be possible to assess their damping in stable plasmas, and thereby determine when the plasma is close to becoming unstable. If this technique is successful, it opens the possibility of avoiding the onset of these instabilities, using a feedback scheme to control the profiles.
Experiments probing the stability of the plasma to large scale perturbations have been performed with specially designed antennas inside the vacuum vessel that excite small amplitude "seed" perturbations to determine at what rate they may grow into unstable modes. If the modes become unstable, they may adversely affect energy and particle confinement and under extreme conditions even terminate the plasma. In plasma conditions where these modes are expected to remain stable, a small "seed" perturbation is launched into the plasma and the frequency of the perturbation is swept across the range where a resonant mode is expected theoretically. Alternatively, the plasma conditions are swept across a fixed antenna frequency to sweep the plasma through the expected resonant frequency. Then, a small resonant mode is detected with sensitive magnetic coils at the wall and the width of the resonant peak determines how close to instability the mode may be. By varying the plasma conditions, it is then possible to determine which conditions are more stable to such modes and which are less stable so that instabilities can be avoided or controlled through feedback on heating power, plasma shape, or other plasma parameters.
For lower frequency modes, the "seed" perturbation frequency was swept across the audio range as the plasma conditions were varied to slowly approach unstable conditions. No stable resonances were detected even with plasma conditions leading to unstable modes that terminate the plasma. This may be because the antennas are much smaller than the large scale perturbations that lead to plasma terminations and so they do not

couple well to these modes; alternatively, a substantially larger amplitude perturbation may be required at low frequency to overcome the higher noise levels there.

For higher frequency modes, the stable resonances are easily measured under a wide range of plasma conditions. For the broad range of modes that are excited from a single antenna location, the rate at which the modes damp out is in the same range as measured on JET, but the dependence of this damping rate on plasma shape appears to disagree with what was found on JET for longer wavelength perturbations. More detailed comparisons with JET will be made in the future now that JET is installing smaller antennas similar to the C-Mod antennas so that the relative scale of the perturbations will be the same as that of C-Mod and be in the range expected in ITER.

Comparisons of Single-Null, Double-Null and Inner-wall Limited Plasma Configurations.

The effects of magnetic topology on neutral dynamics have been assessed in the three areas: divertor neutral compression; plasma-neutral plugging; and SOL plasma transport and flows.

Report:

Assess neutral particle dynamics in single-null, double-null and inner-wall limited discharges

The effects of magnetic topology on neutral dynamics have been assessed in the three areas: divertor neutral compression; plasma-neutral plugging; and SOL plasma transport and flows.

Divertor neutral compression and particle control

A series of experiments were performed to determine the range of neutral pressures in the upper divertor and its sensitivity to the magnetic flux balance (See MP#323, *Scoping Experiments for Upper Divertor Cryopump Operation in Unbalanced Double Null H-mode discharges*). Representative results are shown in Fig. 1. This work focused on moderate power-density H-mode discharges (3 MW total input power) with near-balanced double null equilibria that would be prototypical for operation with an upper divertor cryopump. It was found that with suitable secondary separatrix programming (SSEP set at values of -3 mm or greater) upper divertor pressures could be maintained near or above the 1 mtorr range, over a wide range of target densities. These data, combined with total particle inventory measurements, indicate that a cryopump in the upper divertor chamber with 27,000 torr-liters/second pumping speed should be adequate for density control.

In inner-wall limited discharges, the neutral pressures in the upper and lower divertor chambers were found to be reduced (factor of ~10 or more) with the outer midplane neutral pressures remaining approximately unchanged. The magnitudes of the upper and lower divertor chamber pressures remain sensitive to the details of the magnetic flux surface topology in the far scrape-off layer, including the location of secondary x-points relative to the divertor structures.

Plasma-Neutral Plugging
Plasma-neutral plugging physics and its role in maintaining the high neutral pressures seen in the upper divertor during upper null discharges were investigated in a set of dedicated experiments (See MP#313, *Instrumented Divertor Leakage Experiments*, and research report PSFC/RR-03-6, *In-Situ Gas Conductance and Flow Measurements Through Alcator C-Mod Divertor Structures With and Without Plasma Present*). These results demonstrate that plasma plugging reduces the effective neutral conductance for gas leaving the upper divertor region by a factor of 5 below that based on free-molecular flow. In addition, measurements of neutral conductances in the lower divertor indicate that a simple baffle structure in the upper chamber should further increase neutral compression there (and particle pumping) by a factor of 2 in upper null discharges.

SOL Plasma Transport and Flows
Using a newly installed inner wall scanning probe (ISP) and a fast-diode array looking at the high-field side scrape-off layer, experiments were performed to investigate SOL profiles and plasma flows in a variety of magnetic topologies. Probe measurements verified the existence of a short density e-folding length on the high-field side (as suggested previously from Balmer-alpha emission profiles) that tracks with the location of the secondary magnetic separatrix. Probe and diode systems also measured plasma fluctuation levels to be a factor of five to ten lower on the high-field side of the torus relative to the low-field side. These results indicate that scrape-off layer turbulence is driven by magnetic curvature effects and exhibits a strong ballooning-like mode structure. Strong parallel plasma flows are found to be associated with the ballooning-like transport. Particle fluxes to the upper/lower divertors predominately flow via the outer legs in double-null discharges. A cryopump designed to operate in near double-null discharges should therefore be optimized to pump the outer leg only.

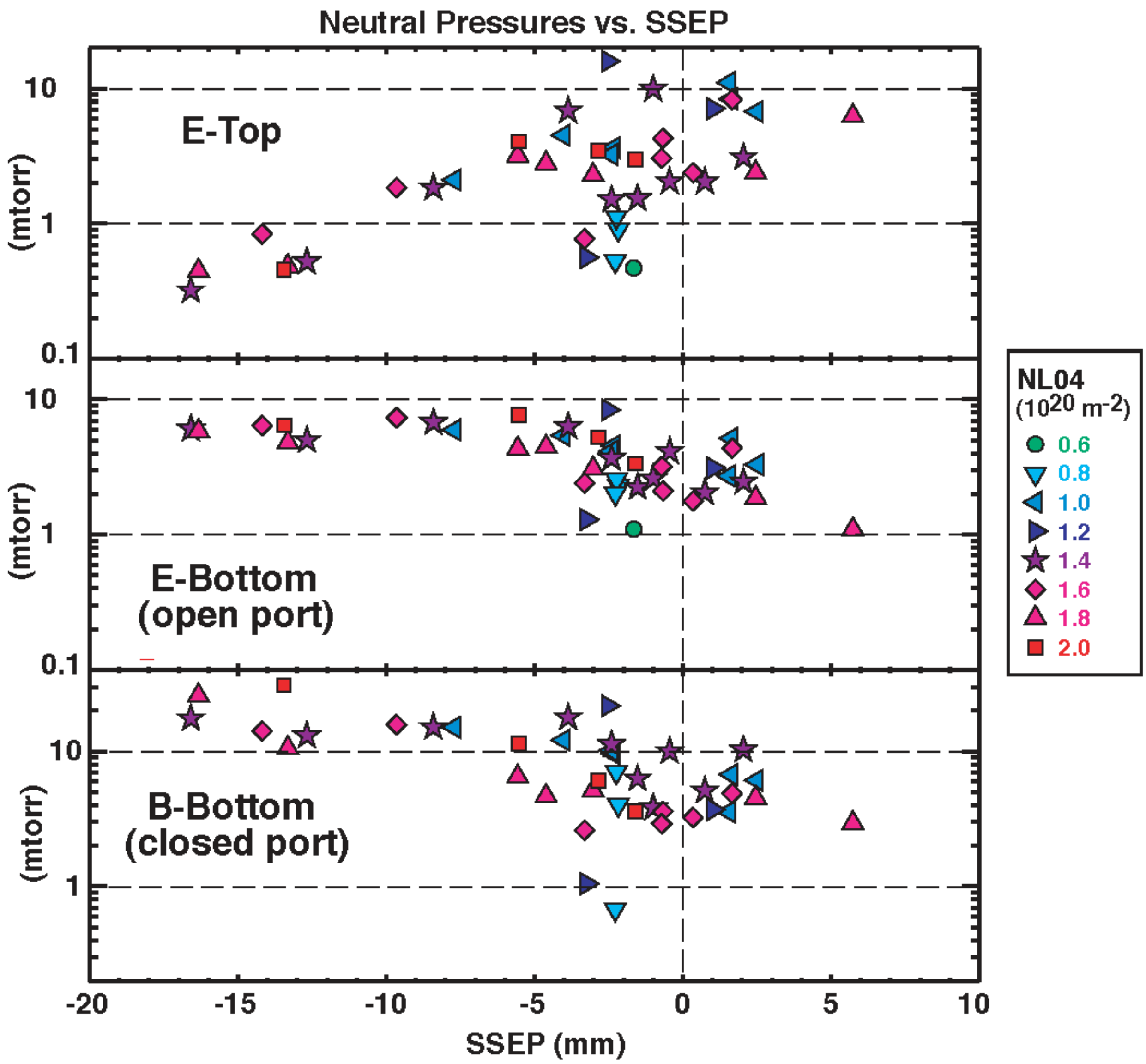

Figure 1.7. Dependence of upper chamber pressures (E-Top) lower chamber pressures (E-Bottom, B-Bottom) on magnetic flux balance (SSEP) for plasmas with a variety of line-integral densities (NL04). Negative values of SSEP correspond to lower single-null.

Assess energy confinement, comparing single-null and double-null configurations

Dedicated experiments were run to compare global energy confinement in single-null with balanced double-null topology. The balance for the double-null shots was determined from EFIT to have separation of the two separatrix surfaces of less than 2 mm at the outboard midplane. To minimize any possible effects of changing wall conditions, the discharges were alternated between single- and double-null. There is a small, but systematic difference, with double-null having between 10% and 15% increased confinement in H-Mode. Figure 1.8 shows the comparison from one run day. These are all 1 MA plasma current discharges, with similar density, 5.4 Tesla toroidal field and hydrogen minority ICRF heating.

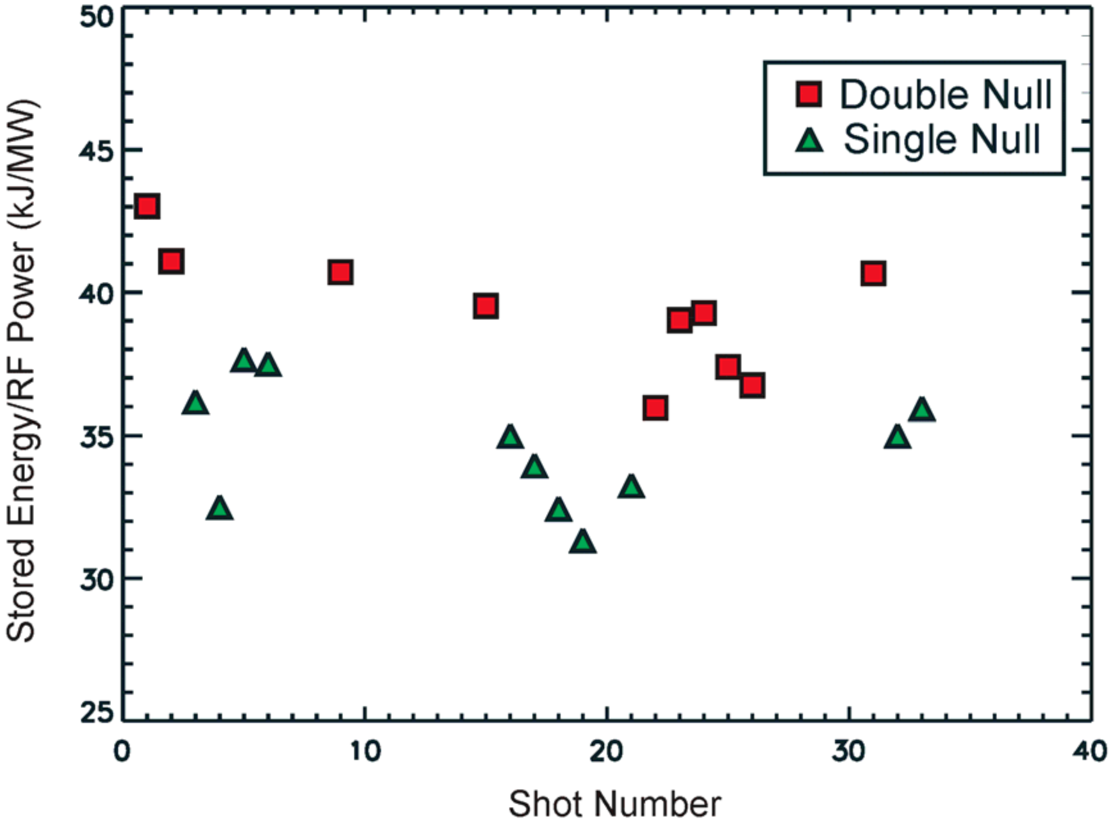

Figure 1.8. Comparison of global H-Mode confinement single-null and balanced double-null topology over the course of 1 run day. The double-null topology shows systematically higher confinement, as parameterized by the ratio of stored energy to ICRF heating power.

Two different upper triangularities were explored for lower single null, with no significant difference found in confinement. In addition, target density was scanned in steps from 6 x 10^{19} up to 1 x 10^{20} m^{-3}, again with no obvious trends in confinement revealed.

Explore H-Mode threshold for double-null discharges

H-Mode thresholds were systematically explored for double-null discharges, upper- and lower-single-null discharges, and inner-wall limited discharges. In addition, a new, fifth configuration, with the plasma limited on near the bottom of the vessel on the inner-wall nose, has also been investigated. The 5 configurations are shown in figure 1.9.

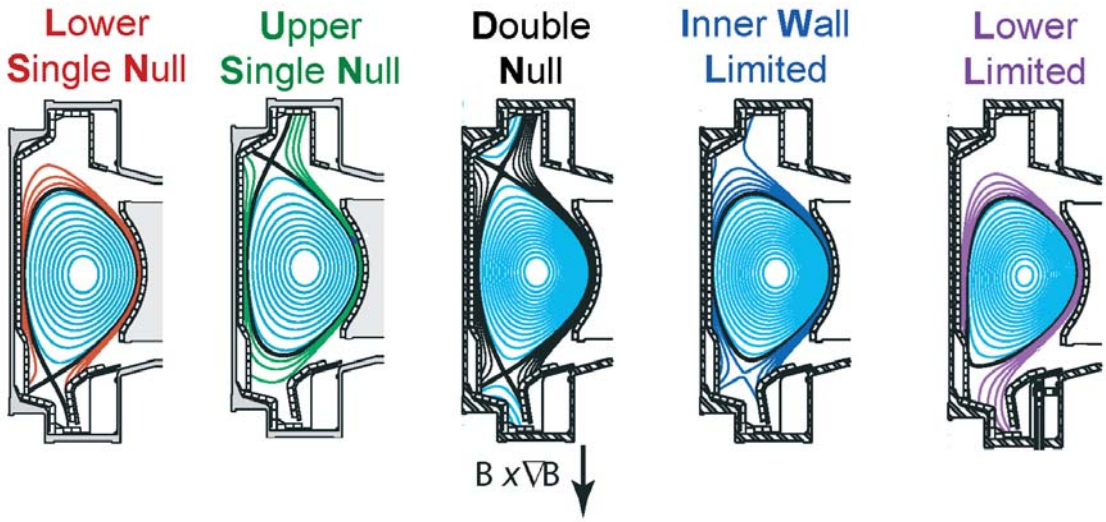

Figure 1.9. Five magnetic configurations in which the H-Mode thresholds have been compared. In all cases, the ion grad-B drift is in the downward direction. ICRF power was varied to find the thresholds.

The threshold for double-null is found to be intermediate between that for lower- and upper-single-null (with the ion grad-B drift direction downward), as shown in figure 1.10. Inner-wall limited discharges have substantially higher H-Mode threshold than even the unfavorable upper-single-null configuration (also shown in figure 1.10). Another important result of these studies is the extreme sensitivity of the double-null threshold to the proximity to exact double-null, as quantified by the difference in primary and secondary separatrix locations, mapped to the outboard midplane. Just a 1 or 2 mm change in this parameter (S_{SEP} from EFIT) can dramatically change the threshold, as shown in figure 1.11. This sensitivity may explain previous reports of inconsistent double-null thresholds from other tokamaks. The lower nose limited configuration has a threshold which is similar to the favorable lower single-null. We are currently investigating the role of flows in the scrape-off layer, which provide the boundary condition for core flow, and when combined with core flows driven by pressure gradients, may provide a unifying picture for the sensitivity of the H-Mode threshold to magnetic configuration.

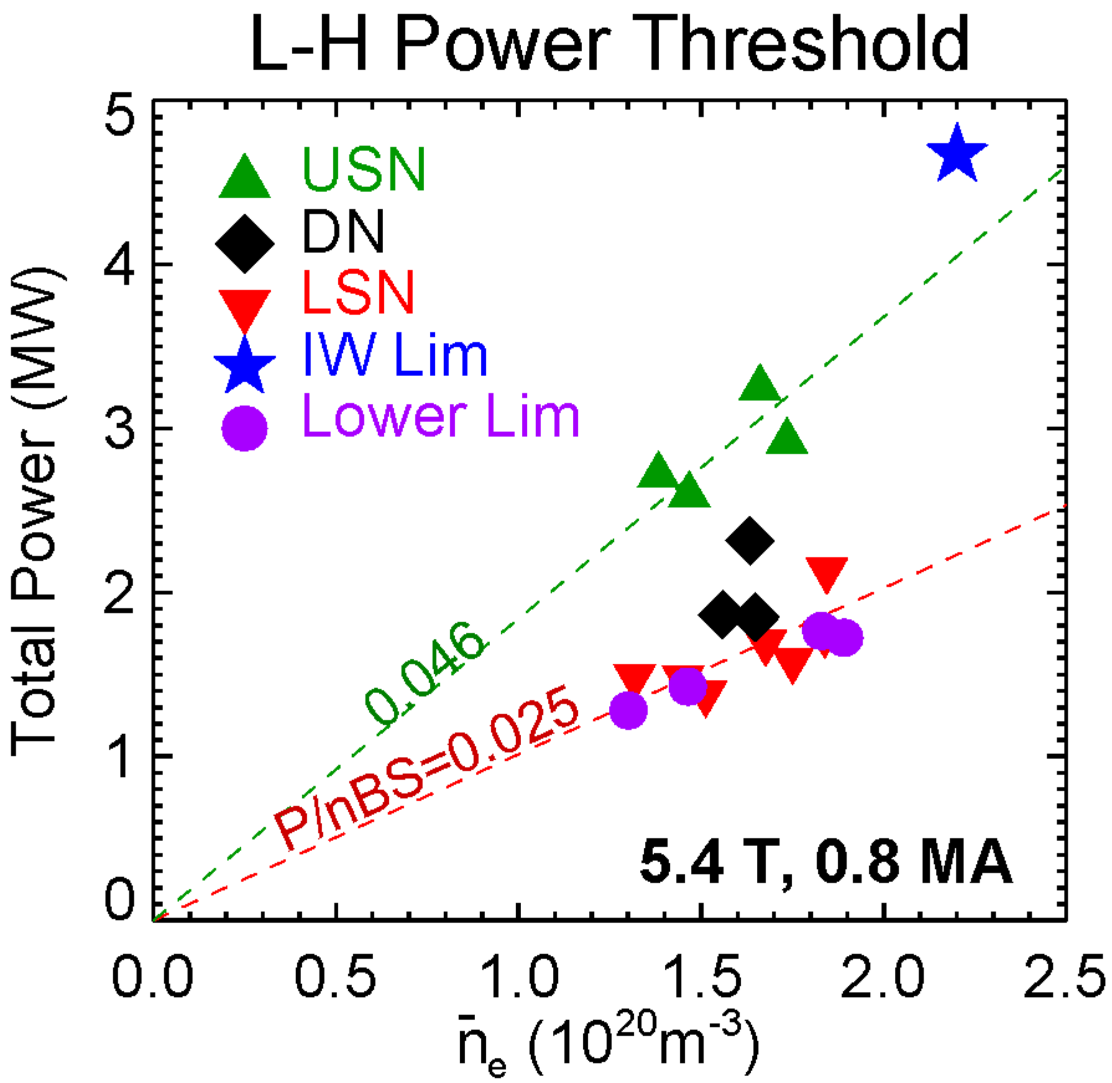

Figure 1.10. H-Mode threshold for 5 different magnetic configurations. The double-null points (black diamonds) are intermediate between the lower- and upper-single-null. Inner-wall limited has the highest threshold, while the threshold for limited on the nose near the bottom of the vessel is similar to lower-single-null.

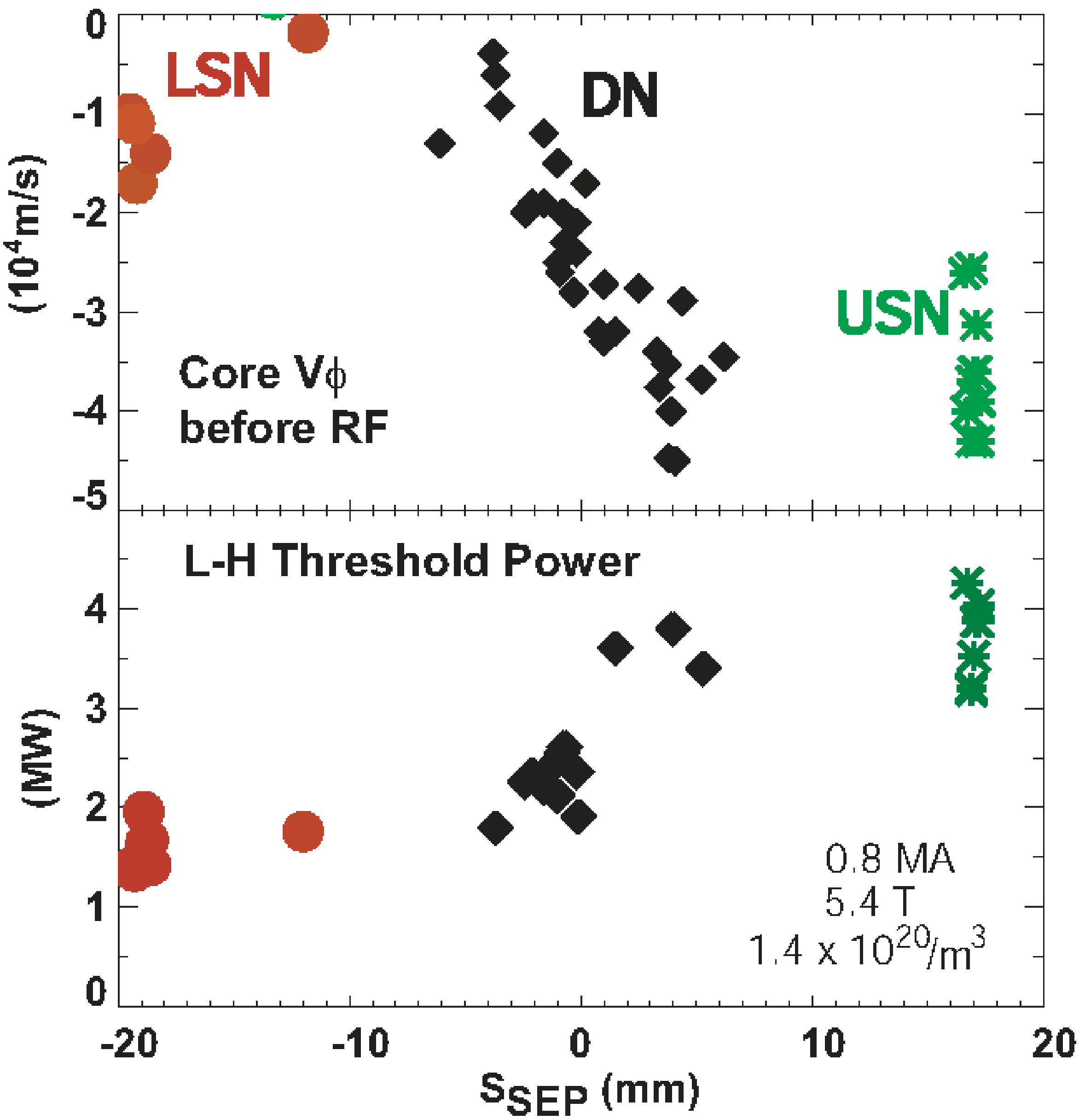

Figure 1.11. Rotation and H-Mode threshold as functions of midplane-mapped distance between the primary and secondary X-points (S_{SEP}), as determined from EFIT. The top plot shows core toroidal rotation, and the bottom plot shows the threshold. Note the extreme sensitivity to this parameter.

2. Alcator C-Mod Research

2.1 Advanced Tokamak Thrust

Recent Research Highlights

The long term goals of the C-Mod AT program, as outlined in the Five Year grant proposal, to:

- Demonstrate and develop predictive models for current profile control, leading to full non-inductive current drive, using LH and ICRF waves, in high density regime ($>10^{20}$ m^{-3}) for pulse lengths long compared to current relaxation times.
- Produce, understand and control core transport barriers in LH and ICRF driven regimes with strongly coupled electrons and ions.
- Attain and optimize no-wall β limits, with β_n of at least 3, and explore means of achieving higher values.

During the past year the Advanced Tokamak Task Force has continued to focus primarily on the first two, nearer term, goals. Some highlights of the progress made follow.

Because of the importance of LHCD to our program, readying the LH system for operation was a top priority. The launcher was installed on C-Mod during the recently completed shutdown, and commissioning is about to commence. Details of the hardware, and of the LHCD program, are given in Section 2.6. An important new diagnostic, a hard x-ray camera to measure the fast electrons generated by LHCD, has also been installed.

Particularly during the early phases of the LH program, it will be important to maintain well controlled, relatively low, densities so that coupling and current drive efficiency can be documented. We have previously demonstrated suitable low density H-modes, with pedestal densities below 1.4 $x10^{20}$ m^{-3}. Recent experiments on the L-H threshold dependence with magnetic configuration have shown that L-modes can be sustained in 'unfavorable' configurations up to high powers, typically 3 MW ICRH in upper null discharges, and over 4 MW in inner wall limited configurations (Figure 2.1.1)[1]. These discharges can have very low densities and correspondingly high temperatures, well suited to producing large LH driven currents.

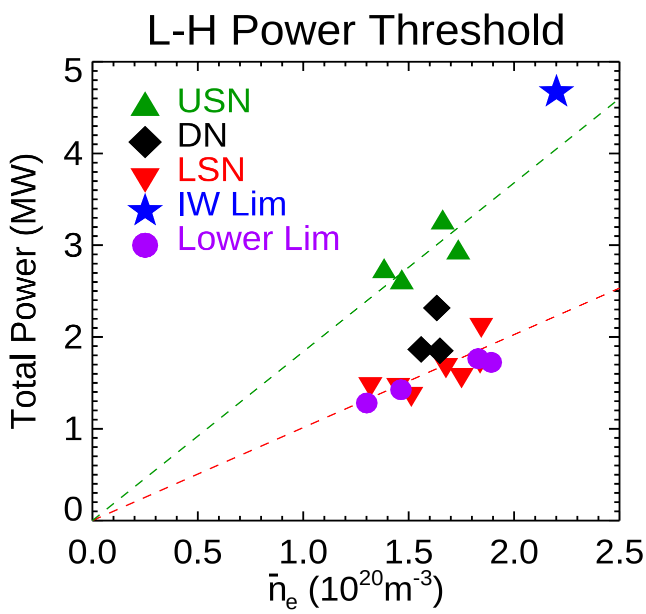

Figure 2.1.1: Power threshold for LH transition showing a strong dependence on magnetic configuration; upper null (green) and inner wall limited (purple), have higher thresholds than the usual Lower Single Null (red) configuration enabling high power L-modes to be studied.

Recent improvements in measurements and modeling of mode conversion experiments, again covered in detail in the RF section, have increased confidence in the feasibility of Mode Conversion Current Drive for C-Mod. The improved TORIC code predicts that by reducing the J-port ICRF frequency to 50 MHz, up to 100 kA could be driven on axis for B_T=5.4 T[2]. This would be a valuable complement to off-axis LHCD, and advanced scenarios utilizing MCCD are being developed.

There has been good progress in understanding and extending the regime discovered on C-Mod in which Internal Transport Barriers are triggered via off-axis ICRF heating, in discharges with normal shear and without external rotation drive[3]. In previous experiments, it had been possible to stabilize the barrier with up to 0.6 MW of on-axis heating; with more power the barrier collapsed. Because of this, little increase and peaking of core ion and electron temperatures occurred, despite thermal conductivities at the ion neoclassical level. In 2004 experiments, by increasing the levels of off-axis heating to 3 MW, it was possible to couple up to 1.8 MW inside the barrier, resulting in dramatic increases of, and peaking in, the central temperature as well as density; central pressures of up to 0.4 MPa (4 atmosphere) were achieved (Figure 2.1.2).

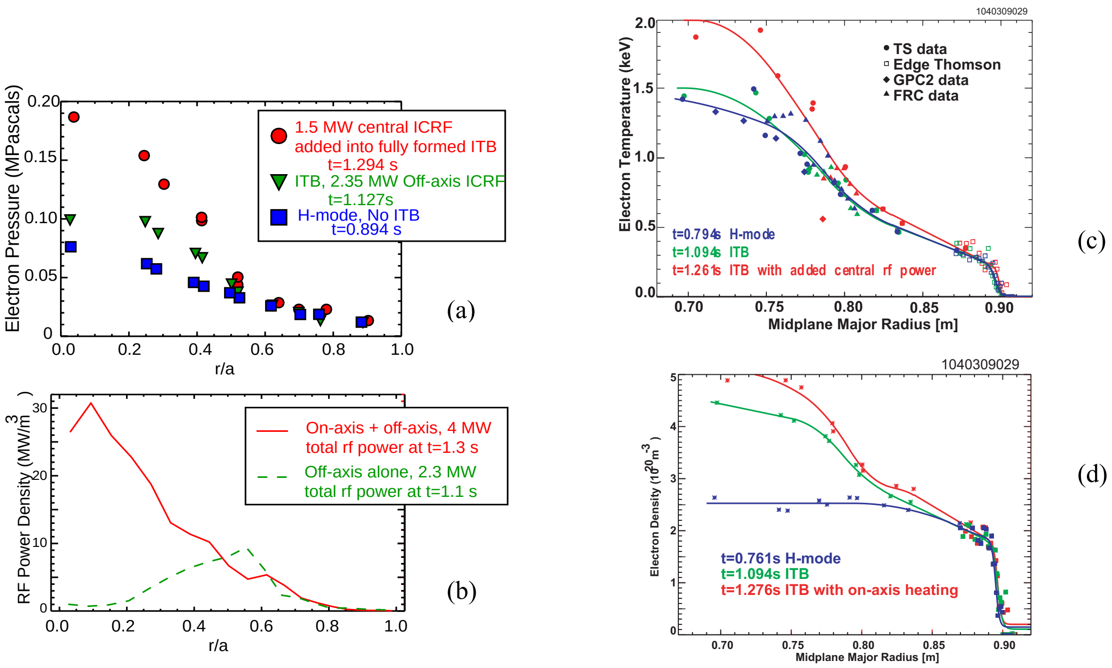

Figure 2.1.2: Internal transport barriers produced by high power ICRF. Blue curves represent the H mode phase before the ITB. 2.4 MW of Off-axis power is applied with a profile shown in (b) (green curve), leading to a strong increase in central density (d) and pressure (a). The addition of 1.7 MW on axis power (red curves) leads to increases in electron temperature (c) and pressure.

There have also been accompanying advances in understanding the mechanisms for the barrier formation, and of the stabilization, in terms of Ion Temperature Gradient and Trapped Electron Modes[4]. These are discussed in the Transport section 2.3.

Research Plans for FY06-FY07

The primary focus of Advanced Tokamak experimental work in FY05 will be the commissioning of the recently installed Lower Hybrid Current Drive system. This work, will begin with low power coupling studies and progress to determination of power limits. Extensive scans will then be carried out, extending into FY06, to measure the driven current as a function of plasma density, grill phasing and other parameters. These will be compared with modeling calculations with ACCOME and CQL3D, which will be used in conjunction with experiments to optimize the magnitude and location of the driven current. The MSE diagnostic and Hard X-ray camera, as well as detectors of non-thermal Electron Cyclotron Emission, will provide important measurements of current and of the LH-driven fast electrons for these studies. A polarimeter is also under development.

Once LHCD has been demonstrated and understood, the program will progressively work during FY06 and FY07 to combine it with other current drive tools including MCCD and FWCD and to develop optimized scenarios with high non-inductive fraction. Our interim goal for this period, with one LHCD grill, is 50% non-inductive current drive. Both L-mode and H-mode target plasmas will be used. In late FY07 a second launcher will be added, allowing optimal use of the 3 MW source power for long pulses of up to 5 seconds, which corresponds to several current relaxation times even at T_e=6-7 keV. This will also allow experiments with simultaneous launching of spectra with two $N_{//}$ peaks, which has been shown by both experiments and modeling to give greater control of the deposited waves and driven current profile. The addition of a cryopump in FY06 will be an important tool for density control, which is critical for maintaining good LHCD efficiency and deposition control in a range of confinement regimes.

Optimization of the bootstrap current will be equally important for current profile control, and will require good confinement and control of kinetic profiles. To this end, our studies of internal transport barriers will be continued. In FY05, we will work to optimize and understand in more detail barriers triggered with off-axis ICRH. Starting from the lower density H-modes demonstrated to be attractive target plasmas for LHCD, we will investigate whether lower density double-barrier discharges can be produced by this technique; these could be very attractive for advanced scenarios. In FY06 and 07, taking advantage of the LHCD and MCCD capability, the research emphasis will shift towards investigations of the effects of current profile and local shear on barrier formation, location and control. 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 even higher on-axis power. This would give a substantial increase in the bootstrap fraction. Simulations also show an important synergy between bootstrap current and LHCD; when LHCD is applied the bootstrap fraction increases due to the change in poloidal field near the axis.

The complexity and number of control tools and non-linear interactions between RF and transport physics make scenario modeling a key part of the AT program, used for both planning and interpreting experiments. We plan to increase our efforts on time-dependent scenario modeling. A key task for the next few years is, in collaboration with the MIT theory group and with researchers at other institutions, to incorporate the recent improvements in RF and transport models into time-dependent codes such as TRANSP and TSC.

As the plasma β increases due to increased input power and improved confinement, issues of MHD stability will become more important. In the FY05-FY07 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, in collaboration with Univ. Columbia, begin studies of possible methods to stabilize MHD 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. In FY05-06, long pulse (3 second) discharges with higher RF power and using improved diagnostics, such as IR cameras will enable better assessment of local heat loads and of amelioration techniques such as strike point sweeping. Compatibility of high heat loads with the lower densities needed for optimal non-inductive current drive will be a particular challenge through FY07; our results will be important in planning advanced scenarios for ITER.

Overall, C-Mod experiences in demonstrating integrated, near steady-state scenarios with high power density, high non-inductive fraction and high confinement, in regimes without particle and momentum input and with strongly coupled electrons and ions, will be extremely relevant to the development of advanced scenarios for ITER. We will continue to address the urgent research needs of ITER in this regard and to communicate results through active participation in all of the relevant ITPA groups. High priority ITPA research needs to which the Advanced Tokamak program intends to make direct and significant contributions include the following:

Steady State Operation:

- Investigate hybrid scenarios for prolonged plasma operation and develop full current drive plasmas with significant bootstrap current: assess beta limits.
- Develop real time current profile control using heating and CD actuators: assess predictability, in particular for off-axis CD.

Transport Physics:

- Improve experimental characterization and understanding of critical issues for reactor relevant regimes with enhanced confinement, by:
    - Obtaining physics documentation for transport modeling of ITER hybrid and steady-state demonstration discharges.
    - Addressing reactor relevant conditions, e.g., electron heating, Te~Ti, impurities, density, edge-core interaction, low momentum input...
- Contribute to and utilize international experimental ITPA database for tests of the commonality of hybrid and steady state scenario transport physics across devices.

Resolution of these key issues is also prominent in the Integrated Program Planning Activity (IPPA), notably *MFE Goal 3, Advance understanding and innovation in high-performance plasmas*, and the 10 year IPPA objective of "Advanced Tokamak Operation for pulse lengths much greater than current penetration times". A unique feature of the C-Mod experiment is that nearly all of our discharges have durations much greater than τ_{CR}.

References:

[1] A.E. Hubbard, B. LaBombard, J.E. Rice, et al, , *Dependence of the C-Mod L-H Threshold on Magnetic Configuration and Relation to Scrape-off-layer Flows*, Proc. 31st European Physical Society Conf. on Plasma Physics, London, UK, June 2004, ECA Vol 28G, Oral Paper O-1.04.

[2] S. Wukitch, "*ICRF Mode Conversion Physics in Alcator C-Mod: Measurements and Model Validation.*"APS Invited Talk, Savannah, 2004. To be published in Physics of Plasmas.

[3] C. Fiore, Invited talk, *"Internal Transport Barrier Production and Control in Alcator C-Mod,"* 31st European Physical Society Conf. on Plasma Physics, London, UK, June 2004, ECA Vol 28G. Plasma Phys. Control. Fusion **46** No 12B (2004) B281.

[4]D. Ernst et al, *Mechanisms for ITB Formation and Control in Alcator C-Mod Identified thorugh Gyrokinetic Simulations of TEM Turbulence*, 20th IAEA Fusion Energy Conference, Vilamoura, Portugal, Nov 2004.

2.2 ITER Support and Burning Plasma Thrust

Alcator C-Mod offers unique capabilities for research and development activities in support of a next-step burning plasma experiment. The high field B<8 T, plasma density $n_e < 10^{21}\ m^{-3}$ and power density of Alcator C-Mod are all highly relevant to a burning plasma experiment or reactor. Unlike lower density tokamaks, the electron-ion equilibration time is typically short compared to the energy confinement time, which is characteristic of a reactor or burning plasma experiment. C-Mod is an RF driven device, with respect to both heating and current drive, which is also characteristic of the planned Burning Plasma Experiments. The use of high-Z metallic walls and plasma facing components in C-Mod is also prototypical of next-step proposals. The demonstrated C-Mod capability of operation for multiple current relaxation times at 5 T, and $\sim 1\tau_{CR}$ at 8 T, permits exploration of current penetration issues of direct relevance to advanced scenario development for ITER or other burning plasma proposals.

The Burning Plasma Support Program on Alcator C-Mod emphasizes two complementary themes:

> Development and validation of the Physics Basis underlying the key issues (transport, stability, heating, ...) in the relevant parameter ranges for a tokamak Burning Plasma Experiment (moderate beta, collisionality);
>
> Development and demonstration of Operational Scenarios and Techniques for optimization of burning plasma experiments.

The C-Mod research program will explore the relevant parameter range for Burning Plasma Experiments, with the exception of ρ^* and alpha-heating. In particular, experiments will be carried out at prototypical values β, β_N, β_p, f_{boot}, q and q_0, collisionality (ν^*, ν/ω_*, $\nu_{\varepsilon\iota}\tau_E$), with Te≅Ti. Demonstration discharges which match the BPX non-dimensional plasma physics parameters other than ρ^* will be carried out on C-Mod as part of a series of coordinated experiments involving a range of suitable tokamak facilities world-wide. In addition to matching these dimensionless parameters, the C-Mod experiments, due to its unique high- field capability and compact size, will be carried out at absolute values of plasma pressure, field, and power density similar to those of the burning plasma experiment. For example, discharges with the same β and ν^* as ITER could be carried out at the ITER toroidal field of 5.3T, and would therefore operate at the ITER volume-average pressure of 2.8 atm; moreover, assuming H89 = 2, the normalized power P/R□10MW/m would also be close to the ITER value, implying that some aspects of the SOL/divertor physics would also be scaled appropriately.

It should be pointed out that ITER and ITPA related research is carried out not only under the auspices of the Burning Plasma Support Thrust but as part of the research programs of each of the Topical Science groups and of the Advanced Tokamak Thrust.

Recent Accomplishments

During the 2003-2004 C-Mod experimental campaign a total of 6.5 research days (9% of the total) were devoted to the Burning Plasma thrust. In addition, 19 research days (25% of the total) were spent on ITPA Joint Experiments under the auspices of the various topical science areas.

Experiments carried out by the Burning Plasma Thrust concentrated on configuration optimization, including comparisons of performance in Single and Double null equilibria. Shaping and control development of ITER-like equilibria with high normalized current I_N, was also carried out, in preparation for ITER demonstration discharge experiments. In addition, C-Mod operation was extended to 2 MA, 8 tesla, in preparation for high performance experiments, rho-star scaling studies, etc. An example of a 2 MA ohmic discharge is shown in the figure 2.2.1. Achievement of this goal required application of the error field compensation techniques developed under the MHD topical science area to eliminate locked modes, which had previously restricted high current operation.

ITPA research in the topical science areas included studies of H-mode transition thresholds, SOL transport, rotation and momentum transport, non-dimensional identity studies of locked mode thresholds, Alfvén mode damping experiments, and tests of sawtooth control using ICRF. Details of these experiments can be found in the relevant sections of this report.

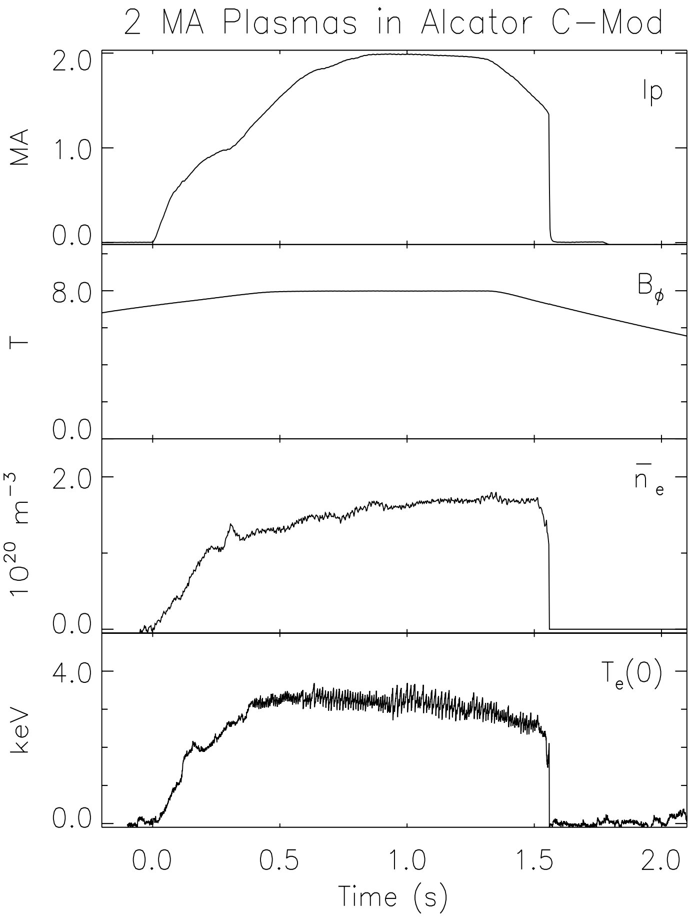

Figure 2.2.1

Proposed Research

ITER support and Burning Plasma Research will continue to be major C-Mod program elements in the 2005 and future campaigns. In FY 2005, approximately 1/3 of the available research run time is allocated to ITPA Research Activities and Joint Experiments and to the Burning Plasma Thrust. This total includes about 30% of the designated high priority experiments proposed under the topical science areas and Advanced Tokamak Thrust. Furthermore, the Level-1 (JOULE) OFES Target for Alcator C-Mod, “Measure plasma behavior with high-Z antenna guards and input power greater than 3.5 MW”, addresses first wall issues which directly impact ITER and reactor design and operation.

The research underlying the Level-1 Target represents a major programmatic effort drawing on one of the unique features of the Alcator C-Mod facility, the use of all-metallic plasma facing components in internal structures. During the vent following the 2004 experimental campaign, all of the non-metallic (mostly Boron Nitride) guard and protection tiles associated with the ICRF antennas and other internal structures were removed and replaced with molybdenum tiles. Operation in this configuration will be compared to prior experience on C-Mod with the BN tiles in place. This research addresses issues related to first wall choices, and trade-offs between high-Z and low-Z materials, which can affect many important aspects of tokamak operation, including impurity content and radiation losses; hydrogenic isotope content in the plasma and retention in the walls; and disruption hardiness.

Proposed research under the Burning Plasma Thrust includes integrated operational issues, and scenario development. In coordination with the Divertor/Edge group, we will undertake materials studies of a novel, reactor-relevant divertor option. A set of tungsten brush modules have been installed in one section of the C-Mod outer divertor. These will be tested at the ITER-relevant heat fluxes available in C-Mod discharges. During the course of the campaign we will be monitoring the heat loads and tungsten influx from these tiles, in comparison with the adjacent molybdenum tiles. Dedicated experiments will be performed to test these components at high power during multi-second discharges, simulating the harsh environment of a burning plasma.

Building on the successful extension of C-Mod operation to 2 MA, we propose to apply high power ICRF, using $D(He^3)$ minority heating, to high current discharges in order to extend database parameter spaces and access higher pressure, lower collisionality regimes for physics studies, including Joint Experiments with other facilities. This effort will also require continued development of our plasma control techniques in order to produce and maintain these high performance plasmas.

Additional experiments proposed by the Burning Plasma Thrust include a burn control simulation using ICRF, in order to study the evolution and stationary states of plasma with power dependent on plasma parameters, as will be the case in a burning plasma. ICRF minority heating would be used for centrally peaked fast ion heating with the ICRF power varied to mimic alpha particle production ($P_{ICRF} \sim n^2\ f(T)$); feedback would then be applied to try to maintain a constant burn power against perturbations such as ELMs, sawteeth, MHD activity, density excursions, etc.

A range of ITER-targeted ITPA Joint Experiments are also proposed, under the Burning Plasma Support Thrust as well as through the Topical Science groups and AT Thrust. Of particular importance are studies of pedestal and edge relaxation mechanisms. These include a non-dimensional pedestal identity study, in coordination with JET, ASDEX-U and DIII-D, designated as ITPA Joint Experiment PEP-7. We will also be completing our comparison of EDA and HRS regimes with JFT2-M under ITPA Joint Experiment PEP-

12, and continuing to address aspect ratio effects in small/no-ELM regimes in coordination with NSTX and MAST under the new ITPA Joint Experiment PEP-16. Additional research will be concerned with documenting characteristics of large ELMs encountered in the course of experiments in non-standard shapes in the past year, including the JFT2-M joint experiments, and investigate the possible effects of non-axisymmetric error fields on pedestal properties.

Because of its unique dimensional parameters, C-Mod provides stringent tests of non-dimensional plasma physics concepts through joint experiments with larger, lower-field devices. In the near future, we will be completing our locked mode threshold non-dimensional identity experiment with JET and DIII-D (ITPA MDC-6). We also propose to undertake a ρ^*scan in coordination with JET, DIII-D, and ASDEX (ITPA CDB-8) and a ν^* / n_G scaling experiment with JET. The former experiment benefits from C-Mod's high field capability, while the latter depends on the large ratio in absolute size between C-Mod and JET to differentiate between effects differ only weakly in dependence on scale size.

Additional ITPA Joint Experiments proposed for C-Mod participation are shown in the accompanying table.

CDB-4	Confinement scaling in ELMy H-modes: ν^* scans at fixed n/n_G
CDB-8	ρ^* scaling along an ITER-relevant path at both high and low beta
TP-1	Steady-state plasma development
TP-3.2	Physics investigation of transport mechanisms with $T_e \sim T_i$ at high density
TP-4.1	Similarity experiments with off-axis ICRF-generated density peaking
TP-6	Obtain empirical scaling of spontaneous plasma rotation
PEP-7	Pedestal width analysis by dimensionless edge identity experiments on JET, ASDEX-U, Alcator C-Mod, and DIII-D
PEP-12	Comparison between C-Mod EDA and JFT2-M HRS regimes
PEP-16	C-Mod/NSTX/MAST small ELM regime comparison
DSOL-3	Scaling of radial transport
DSOL-5	Role of Lyman absorption in the divertor
DSOL-7	Multi-machine modeling and database for edge density and temperature profiles
DSOL-11	Disruption mitigation experiments
DSOL-13	Deuterium codeposition with carbon (boron) in gaps of plasma facing components
DSOL-15	Inter-machine comparison of blob characteristics
MDC-1	Disruption mitigation by massive gas jet
MDC-3	Joint experiments on NTM's (including error field effects)
MDC-5	Comparison of sawtooth control methods for NTM suppression
MDC-6	Low beta error field experiments
MDC-9	Fast ion redistribution by beam driven Alfvén modes and threshold for Alfvén cascades
MDC-10	Measurement of damping rate of intermediate n Alfvén modes

Alcator C-Mod research will continue to address key issues for ITER and Burning Plasma. The accompanying table lays out key goals and objectives for this research program over the next several years.

Goal	Intermediate Objectives	
Identify optimized H-mode edge relaxation mechanism with respect to core confinement, particle control, power exhaust	Characterize pedestal parameters, transport and stability as function of shaping, q	2004-5
	Determine effect of dissipative divertor techniques on pedestal parameters, stability	2005-6
	Assess RF coupling/heating efficiency with different edge relaxation phenomena	2004-6
	Determine compatibility of unbalanced DN particle control with EDA, typeII ELMs, other edge relaxation	2005-6
	Determine divertor heat load associated with relaxation phenomena	2005-6
Demonstrate high power operation with acceptable heat loads, steady-state density	Test unbalanced DN pumping concept for density control	2005-6
	Test high heat flux components	2005-6
	Test high heat flux advanced divertor	2007-8
	Demonstrate sustained high performance operation	2007-8
Demonstrate RF core heating in BP relevant scenario	Evaluate $D(He^3)$ heating scenario at relevant density and field	2005
	Demonstrate real-time matching system to improve ICRF heating reliability	2006
Demonstrate control of neoclassical tearing modes using localized RF current drive	Confirm presence of NTM in BP parameter regime of β, ν_{eff} in C-Mod	2005-6
	Evaluate suitability of LHCD and/or MCCD for NTM stabilization	2005-6
	Evaluate necessary current drive parameters for open-loop stabilization of NTMs	2006
	Develop and test feedback stabilization of NTM in high-performance H-mode	2007-8
Develop and test high performance scenarios	Operate at ITER-scaled physics parameters, q, β, collisionality, shaping	2004-5
	Determine influence of pedestal parameters, edge relaxation on core performance	2004-6
	Investigate ITER hybrid scenario, using LHCD for current profile control	2005-6
	Apply AT/ITB techniques for density profile control, optimized reactivity	2006-7
	Demonstrate sustained high-reactivity operational scenarios	2007-8

2.3 Transport

Recent Highlights

Transport research on C-Mod emphasizes areas important for plasma science and of strong relevance to ITER. Imbedded 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; 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 AT and Burning Plasma thrusts, but also strong coupling to the boundary, stability and wave-plasma topics. A good deal of the most interesting physics occurs at the interfaces between topical areas.

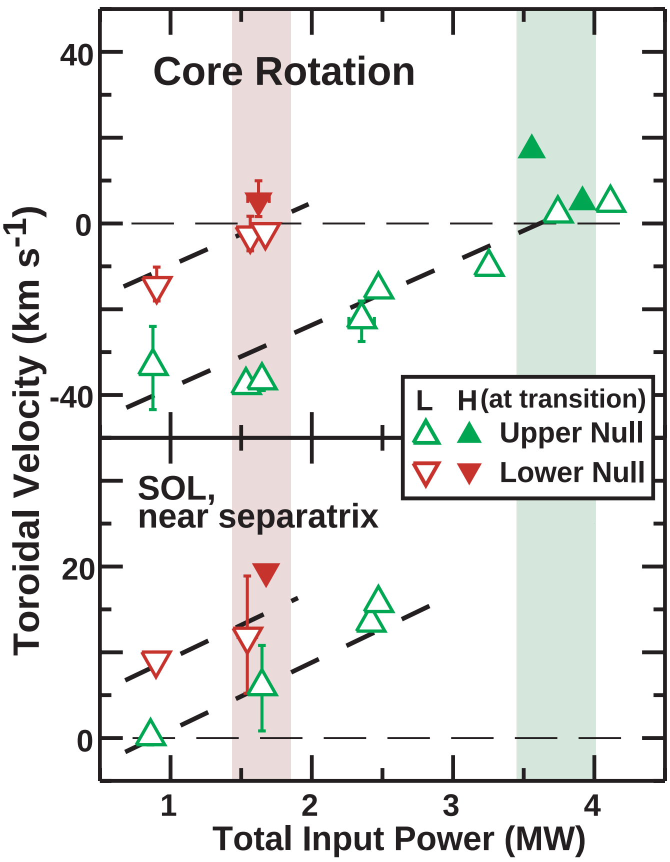

Fig.2.3.1. Core and SOL flows are plotted vs input power for lower single null (favorable topology for the L/H transition) and for upper single null. The upper null discharges begin "farther" from the threshold point and thus require more power for the transition.

Research into self-generated rotation and momentum transport has focused on the coupling between core and SOL flows. Analysis of the transient response of the rotation profiles to changes in the edge shows that momentum is conducted and convected from the outer regions of the plasma into the core. Further, the SOL and core flows are strongly correlated and both vary dramatically with subtle changes in the discharge topology. A shift in the distance between the primary and secondary separatrices (SSEP) of a few mm can cause both flows to shift by several 10s of km/sec. Taken together, these observations suggest that the SOL flow provides the boundary condition for core rotation. The processes by which momentum is carried inward across the separatrix into the confined plasma are not yet clear.

These observations have led to a novel hypothesis for the effect of the ∇B drift direction on the L/H threshold. In this effect, the power threshold for the transition is two to three times higher when the ion ∇B drift is directed away from a single null x-point than when the ∇B drift is toward a single x-point. This difference between the favorable and unfavorable topologies has been observed on many experiments over a period of almost twenty years, but until now, no convincing explanation of the mechanism has emerged. In our picture, there are two contributions to the equilibrium flows which add or subtract depending on the discharge topology. The first contribution is a topology dependent flow created via resymmetrization of the SOL plasma in response to poloidally asymmetric (ballooning) transport in the SOL. Evidence for this process comes from fast scanning probes which sample both the high-field (inner) and low-field (outer) sides of the plasma. For single null plasmas, where there is a parallel connection between the inner and outer sides, the same plasma pressures are observed on each. However for double null plasma, where the magnetic connection is broken, the plasma pressure is much lower on the high-field side. For all cases the level of density fluctuations is about an order of magnitude lower on the high-field side. Thus for the single null discharges, the plasma on the high-field side arrives via parallel flows from the low-field side. These flows are observed in our experiment and approach sound speeds on the high-field side, consistent with free-streaming from the low-field side. The parallel component of this flow reverses direction when the topology is reversed. That is, for all combinations of directions for I_P and B_T, the flow is in the co-current direction when the ∇B drift is in the favorable direction and counter-current when it is in the unfavorable direction. At the same time there is a pressure dependent contribution to the flow which is seen in measurements in both the core and SOL. The net rotation is the sum of these two contributions, which add or subtract depending on geometry (see fig. 2.3.1.) The L/H threshold corresponds to a particular rotation state (probably linked to rotational shear suppression of turbulence). For the unfavorable drift direction the plasma begins "farther" from the threshold condition and thus requires more pressure and more power to reach the threshold. Further experiments have shown that the threshold and flow patterns for discharges which are limited on the lower divertor nose are identical to diverted discharges with lower single-null discharges (i.e. favorable with respect to the threshold). Midplane limited plasmas, with symmetric flow patterns, have a much higher threshold. This supports the notion that flows in the co- direction make the transition easier even for limited plasmas.

We have shown that the height of the temperature pedestal in an H-mode plasma is tightly correlated to its core gradient and to its fusion performance. Thus the physics and scaling of the pedestal is a critical element for prediction of the performance of future machines like ITER. Extensive investigations of pedestal scaling have been carried out on C-Mod including dimensionless identity experiments with DIII-D, ASDEX-upgrade and JET. Multi-machine studies have been coordinated through the ITPA along with significant contributions to the shared databases. Identity experiments found that matching the dimensionless parameters β, ν^* and ρ^* (along with geometric factors) at one point in the pedestal, will lead to a match across the entire pedestal. Since the atomic physics parameters are not matched in these cases, this result presents a strong argument that plasma physics is the dominant mechanism for determining the pedestal shape. However scaling experiments on DIII-D have suggested an important role for neutral penetration. This apparent inconsistency was addressed by kinetic modeling of neutral transport in the plasma edge. The kinetic treatment is necessary because the plasma profile scale lengths and the neutral interaction distances are of comparable size. It was found that the thermal equilibration of the neutrals and plasma ions is a critical process and reduces the sensitivity of the pedestal width to neutral penetration in C-Mod.

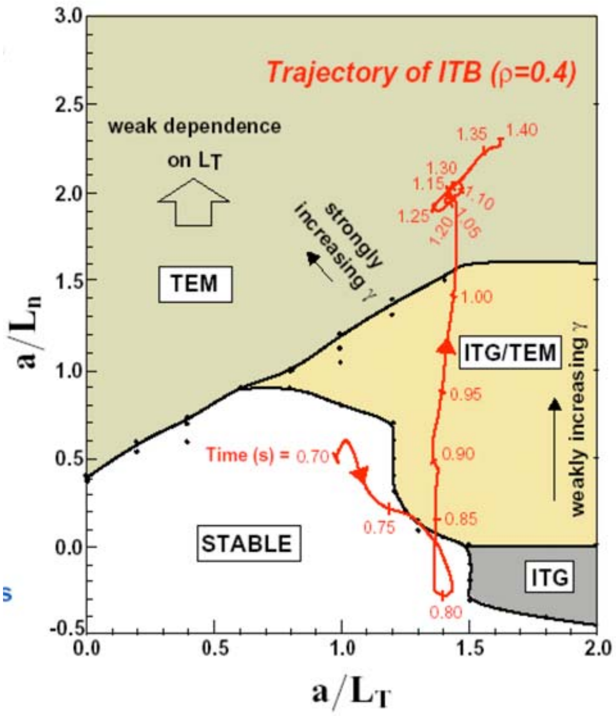

Fig. 2.3.2 A series of linear gyro-kinetic simulations shows the stability boundaries for ITG and TEM. The red curve is the trajectory of an ITB discharge and demonstrate the formation and control mechanisms.

Similar calculations carried out for lower field devices find a greater sensitivity due to the deeper penetration of neutrals in these machines. It is worth noting that ITER, with a poloidal field identical to C-Mod, will be in the same regime with respect to neutral transport.

There is an evident need to understand the mechanisms by which the H-mode pedestal is regulated. For future machines, like ITER, it is highly desirable to run in regimes with good energy confinement, without impurity buildup but without large ELMs. On C-Mod we study two such regimes: EDA (Enhanced D-alpha), where the pedestal is apparently controlled by an edge localized quasi-coherent (QC) mode and a regime of small, grassy type ELMs. Mixtures of the two are also accessible. Experiments have been conducted to map out the "phase" space for the different regimes and to compare the results with theoretical calculations of macro and micro stability. Comparisons with the MHD code ELITE has found the peeling-ballooning mode to be unstable for plasmas where small ELMs predominate and to be stable for EDA discharges. The small ELM regimes tend to occur at lower collisionality where the bootstrap current is computed to be higher. Studies of the QC mode have centered on detailed comparisons with edge simulations. The previously reported contradiction with the BOUT code, which predicted a pair of high-frequency companion modes to the QC mode and which was not observed, has been resolved by the code developers who uncovered a computational error. Future comparisons will focus on the predictions for the radial extent of the mode.

Testing has begun on a theory for the formation and control of Internal Transport Barriers with combinations of off- and on-axis ICRF heating. In this picture, barrier formation is driven by off-axis heating via the flattening of the temperature gradients which lowers the drive for ITG turbulence. With the ITG turbulence reduced, the neo-classical particle pinch is sufficient to begin peaking the density profile. This lowers ηi and in turn further reduces the ITG drive. This picture was supported by a series of gyro-kinetic simulations using the gs2 code. These simulations may also explain the control of the barrier strength in which the degree of density peaking and impurity accumulation are arrested by adding on-axis ICRF power to an ITB discharge. The simulations suggest that when the density peaks in an ITB discharge, TEMs are destabilized, increasing the level of turbulence. A steady state is reached if the TEM turbulent diffusive flux can balance the neo-classical pinch (see figure 2.3.2). On-axis heating increases the level of TEM transport through the gyro-Bohm temperature scaling of the turbulence induced flux. Support for this model comes from density fluctuation measurements using phase contrast imaging (PCI) and heterodyne ECE. An example is shown in figure 2.3.3 where fluctuations measured with PCI increase sharply at the onset of on-axis heating. A set of hysteresis experiments has shown that an ITB can be formed when the power deposited inside the barrier foot drops below 40% of the total power and is lost when that power fraction rises to 60%. Barriers were maintained with on-axis heating up to 1.5 MW by raising the off-axis power, leading to plasmas with central pressures above 4 Atmospheres.

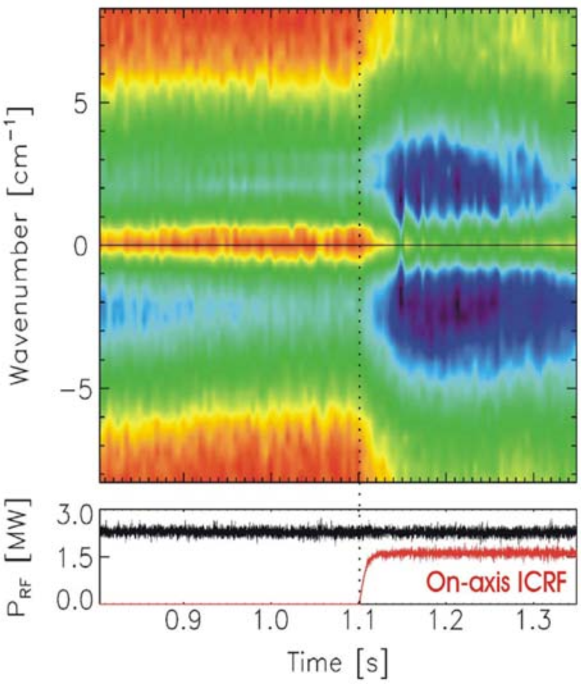

Fig 2.3.3. Wavenumber spectra from the PCI diagnostic during an ITB discharge with on-axis heating used to control the barrier strength. The increase in fluctuations is consistent with gyro-kinetic simulations.

Research Plans

Future C-Mod experiments will include scoping studies of the particle, momentum and electron thermal transport channels, as well as further quantitative comparisons of ion thermal transport with gyrokinetic simulations. The exclusive use of RF power for auxiliary heating and current drive can lead to more reactor relevant discharges when compared to neutral beam heated experiments. There are no core particle sources and no direct momentum source associated with the ICRF or LHCD. Thus the effects of heating, fueling, flow drive and current drive can be decoupled. Particular attention will be given to self-generated flows, their relation to transport barrier formation and the exploitation of particle transport as a paradigm for the study of off-diagonal transport coefficients.

With ions and electrons equilibrated in most C-Mod regimes and with the factors mentioned above, core barriers in this device are of particular relevance to burning plasma regimes. In the edge plasma, the practical goal is to produce plasmas with large temperature pedestals, no impurity accumulation and no large ELMs. Fundamental understanding of edge pedestal physics will be required to extrapolate favorable regimes to reactors. In all these areas, experimental progress is linked to the development and deployment of advanced diagnostics and close comparison with theory and modeling.

Investigations into self-generated rotation will be extended to a wider parameter range and focus on core/edge couplings. Diagnostic enhancements from charge exchange recombination, which will benefit from the long pulse diagnostic beam, should extend the radial coverage of the rotation profiles. An additional x-ray spectroscopic system which is designed to look at hydrogen-like neon will allow measurements in the pedestal region. Transient momentum transport experiments will be carried out using the recently discovered shift in SOL flows which occurs when the topology is modified. In these studies, a rapid and localized change in the rotation boundary condition can be introduced by shifting the SSEP parameter during an otherwise steady discharge. The transient response can be analyzed to determine momentum conduction and convection under a variety of discharge conditions. The improved diagnostic coverage will also allow detailed comparisons of poloidal rotation with neo-classical predictions. The processes by which momentum is carried across the separatrix into the confined region are presently unknown. Possible mechanisms include neutral or plasma collisions or turbulent Reynold's stress. It is worth noting that the turbulent effects are expected to be more important in the edge regions. Reynold's stress creates a rotation "dipole" by moving equal amounts of momentum inward and outward. In the more dissipative regions of the plasma the difference in damping between the two lobes can lead to a net rotation. In effect the core plasma can "push off" against the edge. Neutrals are also expected to be effective in carrying momentum via charge-exchange interactions. Experiments will examine regimes where the neutral interactions could be modified, including variations in neutral density, fueling, cryopumping and studies in helium plasmas. Theoretical work on momentum transport is relatively immature. We plan to increase our contacts with modelers in order to motivate additional in this area. For example, the PSFC theory group is planning to begin gyrokinetic simulations using the GYRO code in support of this effort.

The connections found among topology, SOL flows, core flows and the L/H transition will be explored extensively. The parameter ranges of these observations will be expanded in an attempt to answer important questions about the threshold. It has been found that the strong topology effects on core rotation described above, tend to disappear at very low densities ($<0.8 \times 10^{20}$). This is a density at which C-Mod runs into the low-density limit for the L/H threshold – that is, below this density the power threshold increases dramatically. We will investigate whether there is a causal connection between these two observations through, for example, momentum coupling mechanisms. We will also extend the range of plasma currents in a search for the origin of the lack of I_P dependence in the power threshold. When the plasma current is changed, the absolute value of rotation changes, but the topology offset remains. We note that the core rotation is found to scale with p/I_P (where p is the plasma pressure). Since stored energy increases linearly with current for L and H-mode, there is a cancellation which tends to make the rotation independent of plasma current. Thus the connection between self-generated rotation and the threshold may help to explain the lack of I_P scaling in the threshold, which is widely observed. We will duplicate experiments carried out in MAST, NSTX and ASDEX-upgrade in which the threshold was found to be lower (by a factor of 2 on MAST below the nominal value, by 10% on ASDEX) for precisely double null discharges. This unexplained effect requires precise balance of the primary and secondary separatrices; SSEP needs to be equal to zero to within about one gyroradius. These experiments can be easily carried out by running with power just below the nominal threshold then slowly scanning the SSEP parameter across zero. Comparisons with theories of the transition based on zonal flow generation will continue. Based on previous results it seems likely that both equilibrium and zonal flows are important elements in the picture. Finally, experiments into the transition dynamics aimed at uncovering the basic physics of the bifurcation will be carried out.

Studies of pedestal scaling will continue using the high-resolution edge Thomson scattering system. With most of our previous work focused on EDA H-modes, proposed experiments will explore pedestal scaling in ELMy and ELM-free discharges. The latter may be more typical of conditions between large ELMs in the conventional type I ELM regime. Specific tests of a model by Chang which is based on a neo-classical particle orbit mechanism will be carried out. These involve power and toroidal field scans employing ICRF at 50 and 80 MHz. Other studies will emphasize multi-machine experiments coordinated through the ITPA. Further dimensionless scaling experiments with JET and ASDEX-upgrade are planned. Investigations into the role of atomic vs plasma processes in setting the pedestal width will be carried out by varying the neutral interactions. Experiments with helium plasmas and with the cryopump may be particularly useful in this regard.

Investigations into the mechanisms which regulate the H-mode pedestal will emphasize regimes where ELMs are small or non-existent. We will continue to map out the phase space of the various regimes and attempt to connect these to boundaries of micro and macro stability. This work is of great interest to ITER and several ITPA groups. Multiple machine experiments including joint experiments on small ELM regimes with the NSTX team are planned. Large ELMs which occur on C-Mod only in a few very special circumstances will be studied with an aim toward understanding why they are rare in our device. The lower hybrid work should push us to conditions with high power and very low collisionality under which large ELMs may be more likely. Studies of EDA and the QC mode will center on detailed comparisons with simulations. A near-term focus will be to remove uncertainty in the radial extent of the mode. Simulations with the DBM and BOUT code predict that the mode should "fill" the pedestal. By contrast, the best measurements we have, find the radial width to be on the order of 1-2 mm – that is significantly less than the width of the pedestal. However, these measurements, with a scanning electrostatic probe and with reflectometry are subject to some uncertainty. The insertion of the probe may damp the mode on the flux tube being studied and thus give a spuriously low width. Quantitative interpretation of reflectometry data is notoriously difficult. Other measurements of the QC mode width, with BES and passive optical arrays, currently have insufficient resolution. To resolve these questions, a new probe head is being designed which will have probe tips with a small radial spacing, allowing us to determine whether the probe perturbed the earlier measurement. At the same time, a new array of fibers for BES have been constructed which will allow higher resolution for that measurement. Comparisons with HRH regime found on JFT-2m will continue. This regime looks like EDA H-mode in most respects. A preliminary set of discharges on C-Mod which were designed to match the JFT-2M shape and dimensionless parameters showed similar behavior and similar operational boundaries for the respective regimes.

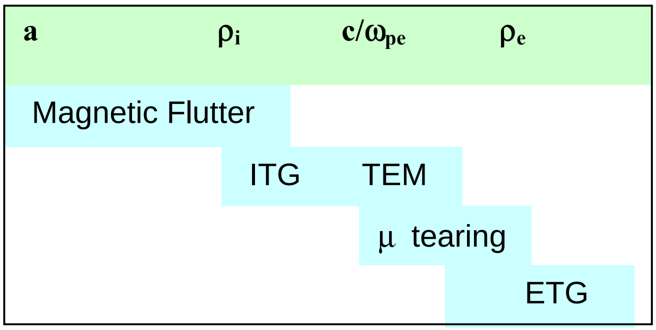

Fig 2.3.4. Possible mechanisms for electron transport span the entire available spatial range.

Anomalous electron transport is perhaps the most important unresolved issue in the transport area. Little is known about the mechanisms at work; there is not even a clear picture of what range of spatial scales are important. Figure 2.3.4 shows some mechanisms that have been proposed and the scales over which they are expected to operate. These span the entire range available. With the PCI diagnostic, which has excellent signal to noise and will measure fluctuations up to 5 Mhz with wavenumbers up to 30 cm^{-1}, we will attempt to identify the relevant spatial scales in various plasma regimes. The first experiments will be aimed at very low density Ohmic plasmas where the transport channels are decoupled and where ion transport is near neoclassical levels. Modifications to PCI will 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. We will carry out further quantitative studies of the marginal stability/critical gradient length paradigm, adding improved fluctuation and profile diagnostics (Ti(r), V(r) from CXR and q(r) from MSE). Lower hybrid current drive will provide an important tool for these studies as well. By controlling the magnetic shear, we can vary the parameter which is predicted to have the largest effect on the stability of ITG modes in our plasmas.

Experiments into the mechanisms for internal barrier formation, transport and control are planned in plasmas with Ti~Te and without core particle or momentum sources. We will conduct detailed tests of our model for barrier creation by carefully documenting the temperature profile gradients which are produced as the ICRF resonance is scanned across the profile. These will be compared with calculations from gyrokinetic stability codes. Further tests of the barrier saturation and control mechanism will be conducted using improved fluctuation measurements. High frequency reflectometry channels should allow localized measurements of fluctuations and their suppression. Operation with the cryopump may allow even greater access for the reflectometry waves and open up an important avenue for study. Heat and density pulse propagation experiments will test the stiffness of the profiles at various radii and can be compared quantitatively with non-linear simulations. Transient studies of barrier dynamics and turbulence spreading will test basic models for transport bifurcation. Finally, the LHCD system will allow us to investigate the accessibility of improved confinement regimes by steady-state manipulation of the magnetic shear profile.

Particle transport is another channel which has been insufficiently studied and is only poorly understood. It is important for ITER or future reactors for which the density and density profiles are keys to fusion performance. At the present time, we do not understand and cannot predict the mechanisms by which particles move up the density gradient from the ionization source at the edge into the core. The combination of ICRF heating and lower hybrid current drive will allow us to perform an interesting set of experiments on particle confinement. By running plasmas with no Ohmic drive, we can study regimes with no core particle source and no Ware pinch. This provides a laboratory for testing theories of turbulent particle transport and especially turbulent particle pinches.

Connection to IPPA Goals

Transport research on C-Mod is well aligned with the fusion sciences mission and goals as outlined in the IPPA report of November, 2000, namely 1.1 "Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems." Most of the transport related scientific issues outlined in section 3.1.1 and appendix III of the IPPA report are addressed directly by the C-Mod program.

- *What determines the amplitude and width of edge pedestals in plasma pressure and temperature?* Experiments in this area have been enabled by the array of high-resolution edge profile diagnostics and have included scaling studies with plasma current, density, input power, and plasma shape. Studies of the EDA and small-ELM H-modes emphasize the role of micro and macro-stability in determining pedestal transport and profiles.

- *How does neutral hydrogen recycling affect stability and transport?* Utilizing its array of high resolution edge profile diagnostics, including the ability to measure Ly_{α} with mm resolution, experiments have been conducted to quantify the role of neutrals in energy, momentum and particle transport. At the same time, dimensionless identity experiments conducted in collaboration with JET, DIII-D and ASDEX-Upgrade provide valuable data on the relative role of plasma physics and atomic physics in determining the pedestal profile shape.

- *What is the influence of the plasma edge on the plasma core and on the global properties of confined plasma?* Past work has clearly shown evidence of critical temperature gradient lengths. The manifestation of this behavior is self-similarity of the profiles, where an increase in the edge temperature leads to a proportional (rather than additive) increase in the temperature profile everywhere. Current work emphasizes the role of SOL flows in influencing the L/H transition leading to the topology dependent power threshold.

- *What are the effects of finite-beta and confinement geometry on transport?* Measurements of the very strong magnetic component to the quasi-coherent oscillation seen in EDA H-modes along with a significant magnetic component observed in the L-mode plasmas indicate an important role for finite β and β' in edge transport. With available increases in heating power, we are also beginning to see β related effects in the core plasma. The modification of the inner divertor has enabled the study of a wider range of plasma shapes. Experiments have shown, for example, a strong triangularity dependence on the EDA/ELMfree boundary.

- *What are the mechanisms responsible for anomalous electron thermal transport?* A major effort to upgrade core fluctuation diagnostics is underway and will emphasize the measurement of short wavelength modes believed to be responsible for electron transport. Improvements to phase contrast imaging include better spatial coverage, faster digitization, coverage for k_R up to 30 cm^{-1}, and spatial localization.

- *How does the power threshold for internal transport barriers scale with gyroradius in the absence of externally driven rotation?* With its ability to create transport barriers without the use of neutral beams, C-Mod is in a unique position to explore this issue.

- *What is the fundamental origin of the observed density limit on tokamak operation?* Experiments on C-Mod, suggest that the density limit is due to changes in edge fluctuations and anomalous perpendicular transport which occur as the density is raised. Further studies will attempt to uncover the physical mechanism responsible for this change in transport.

Many of the transport studies, especially those involving joint experiments with other facilities, are coordinated through the ITPA process, as described in section 2.2 ITER and Burning Plasma Support.

2.4 Plasma Boundary

Transport

Transport is the central emphasis of the C-Mod boundary physics program. We feel that an accurate representation of transport is needed in order to be able to predict desired aspects of plasma-wall and plasma-divertor interaction (heat and particle loads) as well as impurity sources and subsequent impurity transport. We have recognized over the past several years that the SOL can have very different transport characteristics in the regions 'near' and 'far' from the separatrix. Figure 2.4.1 shows that the near SOL tends to have steeper density gradients than the far SOL. As will be discussed later this leads to differences in transport as well.

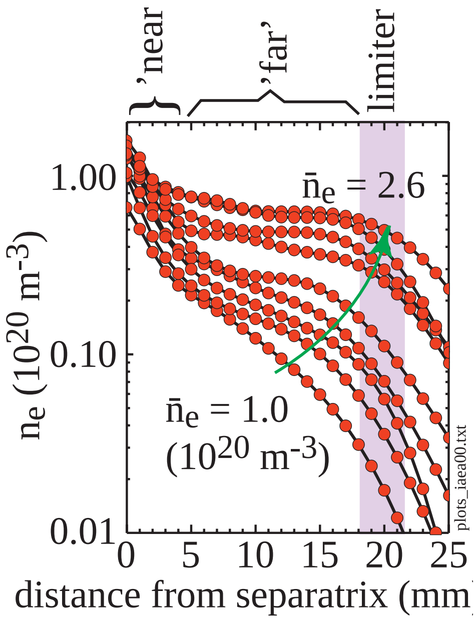

Figure 2.4.1:Density profiles in the SOL as the line-averaged density is varied. The gradients in the near SOL vary much less than in the far SOL

Our research in transport is based on a two-pronged approach. The first is a study of time-averaged transport and profiles over long time scales (greater than 1 ms) to extract an empirical understanding of how transport scales and what affects it. Such an understanding allows scaling to other tokamaks and potentially points towards the underlying physics. Our second approach is to study the detailed time evolution of the underlying turbulence and how it leads to the observed time-averaged profiles and transport.

Time-averaged transport

Fully non-linear, electromagnetic fluid drift (EMFD) turbulence models [1] identify 2 principal control parameters for turbulent-driven transport. These are: Plasma β gradient (α_{MHD} or $\hat{\beta}$) and normalized collisionality (α_d or $\hat{C}$). It has been recently found that the edge plasma state near the separatrix in C-Mod lies on a well defined curve in this same two-parameter space (α_{MHD}, α_d) over a wide range of discharge conditions, strongly supporting the hypothesis that EMFD turbulence plays a dominant role in the transport [2]. The plan for the next 2 run periods is to extend this type of measurement and analysis to a much larger operational space, and thus to test more systematically the correlation with such model parameters. Figure 2.4.2 shows that B_t, I_p operational space with both the current available data and future data marked.

Since one of the aims of the transport work is to understand the relationship between the near and far SOL, as well as between time-averaged and turbulence characteristics, the experimental proposal for the discharges with the parameters shown in Figure 2.4.2 is being designed to allow acquisition of data for all types of analysis described later in this section.

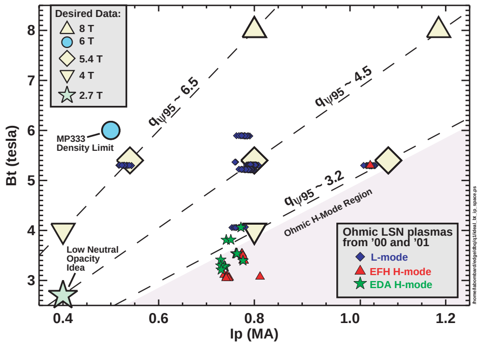

Figure 2.4.2:Proposed operational space for studies of transport. Current dataset for near SOL gradient analysis shown as small symbols.

The technique used in the analysis of the time-averaged radial transport is based on particle balance and was developed several years ago at C-Mod [3]. It allows for studies of C-Mod SOL transport as well as measurement of fluxes to main chamber surfaces. Through collaborative work, dimensionlessly similar discharges from DIII-D and JET have been compared to C-Mod. The radial transport in the SOLs of these various tokamaks, given by effective transport coefficients, D_{eff} or v_{eff}, are very similar, both in magnitude and radial scaling, indicating little or no dependence on ρ*, ν*, β [4,5]. 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 [5]. Indeed, we believe that the differences in the C-Mod profiles as a function of density (see Fig. 2.4.1) are also due to differences in the opacity to neutrals. The work in this area will be continued by utilizing the experiments covering the C-Mod operational space shown in Figure 2.4.2 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 blobs). Aside from 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.

C-Mod experiments in momentum source-free plasmas have revealed an interesting interplay among ballooning-like transport asymmetries, scrape-off layer flows and magnetic topology [6]. We plan to explore this physics both in experiment and modeling. One goal is to provide 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. A second goal is to determine if the particle "life-cycle loop" formed by transport across the separatrix at the outside edge, followed by flows from the outer SOL to the inner SOL, is closed near the inner divertor by either ion convection or neutral flow from the SOL into the core across the separatrix. The convective channel will be investigated using impurity puffing while the neutral flow will be explored with camera imaging. Lastly, we will be utilizing 2-D fluid codes (through our collaborators) to determine if the postulated physics can provide the measured flows. The primary collaborators in this area are X. Bonnin (CNRS-France), and A. Pigarov (UCSD)

Upgrading diagnostics will also mean improvements in our capability to measure flows. There are several initiatives in progress. The inner wall probe (currently a single tip) will be replaced with one that is able to measure flows and turbulence simultaneously, as a function of radius. In addition, using the outer-wall scanning probe drive, we will test a new probe head geometry which has the potential to improve measurement of poloidal flows. Lastly, a new probe electronics package is being designed that would allow fast voltage sweeps and thus direct measurement of density and temperature fluctuations.

Turbulence

Plasma turbulence is responsible for the time-averaged plasma profile shapes and cross-field fluxes that are observed in the edge of a tokamak. Over the past year we have continued to build on a number of innovative methods for diagnosing and understanding plasma turbulence in the SOL. An important tool in this arsenal is the Gas-Puff Imaging (GPI) system [7], built in collaboration with Stewart Zweben (PPPL), which now utilizes a 300 frame, 250kHz camera that records movies of the plasma turbulence with 4□s exposure in each frame. A local gas-puff is used to 'illuminate' plasma density and temperature fluctuations, recording the fluctuation in these quantities as fluctuations in visible light emission. These data provide key information on the formation and propagation of coherent structures in the SOL plasma ('blobs'), which are an important dynamic in the cross-field transport physics, and provide detailed information on the turbulent k-spectrum. An example of data analysis performed on 300 frame movies taken in both L- and H-mode plasmas is shown in Fig. 2.4.3 (from [8]). In this case a time delay cross-correlation technique is used to infer the phase velocity fields of the plasma fluctuations. Clear differences are seen between L- and H-mode phases and between open and closed field line regions; L-mode favors larger outward velocities. With the help of tools such as these, we plan to systematically explore the character of SOL turbulence (k-spectra, phase-velocity fields, coherent structures, fluctuation statistics), with a focus on how it connects to the time-averaged plasma transport fluxes that we observe and to externally controlled parameters (magnetic field, density, plasma current). To this end, we are now regularly recording calibrated D_α images at long camera exposures (~1 ms) in addition to the fast 'movies'. Determining the ionization source from the time-averaged D_α profiles will help us infer the cross-field particle fluxes via particle balance. Further improvements to the optical system are planned with a goal to achieve a spatial resolution of less than 1 mm. We also have recently installed an upgraded, discrete fiber array that views the GPI region at 40 fixed poloidal and radial locations. This system will be an important

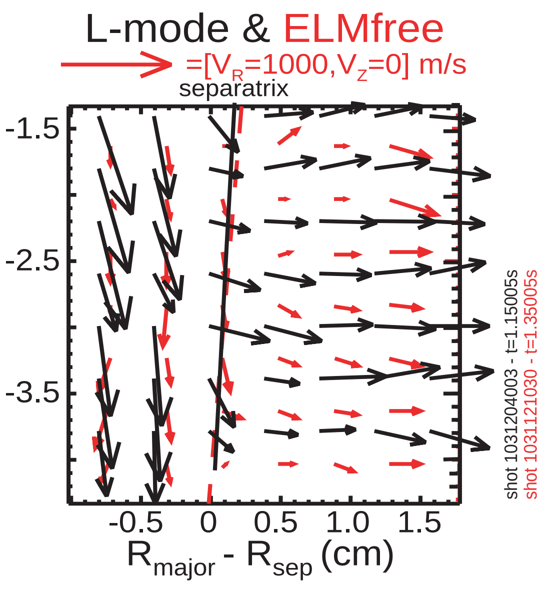

Figure 2.4.3: A comparison of the plasma fluctuation phase velocity fields seen in L- and H-mode plasmas. Closed field lines are to the left of the separatrix

complement, providing 1 MHz data sampling of visible light fluctuations through filtered photodiodes. These views are also shared with calibrated spectrometers to record time-averaged information.

Turbulence simulation and modeling is an important tool for exploring the underlying drive mechanisms, with an eye towards developing quantitative descriptions of the transport phenomena. We have had fruitful collaborations with O. Grulke (IPP-Griefswald) in performing experiments on blob transport dynamics. This in turn has lead to 2-D turbulence modeling work by the Risoe group in Denmark, where they are able to simulate many of the features observed in C-Mod experiments [9], including blob formation, scale size, radial propagation characteristics and fluctuation statistics. We plan on continuing and encouraging these productive collaborations, in particular, pursuing model-experiment comparison studies where ν^* and ρ^* are varied. In addition, we will build upon our ongoing collaboration with the LLNL group (Umansky, Xu, Nevins) in the use of the 3-D turbulence code BOUT to model C-Mod discharges. Through a set of dedicated experiments with a companion modeling effort, we plan on exploring the physics of the x-point regions. The potential role of the secondary upper x-point regions in breaking the current in between the turbulence from the low and high field regions is of particular interest.

A related area of research is the parallel structure of the blobs, as revealed by fast movie camera images when looking inward along a major radius. Non-uniformities in light emission are seen parallel to B, perhaps indicative of an underlying parallel structure to the turbulence. The parallel lengths of these structures and their connection, if any, to the role of x-point region is an interesting subject that came up in the recent C-Mod Ideas Forum [10]. We plan to design experiments to explore these phenomena.

Collaborations with Ben Carreras (ORNL) and Ghassan Antar (UCSD) are also active and will remain so in the next year. Topics include long-range time correlation phenomena as inferred by 'quiet-time statistics' [11] and the change in the character of fluctuations as the density limit is approached [12]. We are also planning cross-tokamak comparisons of the high speed movies of turbulence with NSTX and TJ-II as part of IEA/ITPA collaboration DSOL-15.

Neutrals

The study of the role of neutrals in C-Mod is very wide ranging. As mentioned earlier we plan to study whether varying SOL opacity to neutrals leads to variations in SOL n_e profile shapes. At the same time opacity of a different kind, radiation transport opacity to Lyman series line radiation, is known to be important in determining divertor ionization balance and thus the degree of detachment. The C-Mod divertor plasma is closest to ITER, in terms of Lyman opacity, among operating tokamaks, and so is an important test case for modeling. To this end we are supplying C-Mod divertor data to a team of modelers who are generating plasma models (Lisgo – U. Toronto) to test the radiation transport aspects of the EIRENE Monte-Carlo neutrals code (D. Reiter, U. Bochum).

Another area of neutral investigation is the role of tile surface condition on D/H retention. Paralleling previous analysis of C-Mod tiles done by Wampler [13], we have supplied 28 tiles, representing a poloidal distribution from C-Mod, to D. Whyte (U. Wisconsin) for surface analysis. It was found that boronized layers accumulate over most surfaces in the tokamak with the exception of the outer divertor and outer limiter. In areas where the B is not eroded by plasma discharges, the thick B layers that accumulate serve as a storehouse for D/H, potentially affecting operation. The tile analysis showed that tiles exposed to air

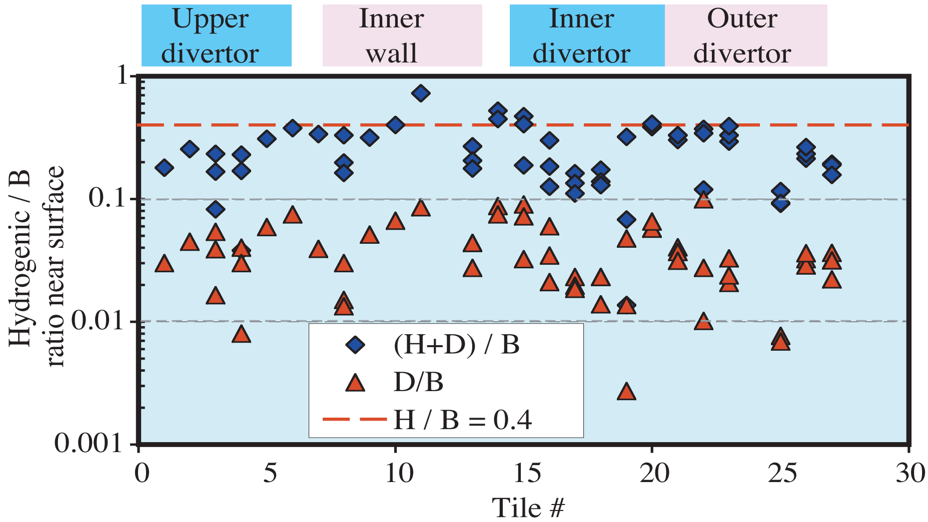

Figure 2.4.4: H and D retention in a set of tiles removed from C-Mod after a run period and analyzed by the U.W. group (Whyte). The high H levels are due to exposure to air. The D levels are what was retained in tiles during operation.

accumulate high levels of H (up to H/B of 0.4) thus making it hard to reach the H/D levels of 5% needed for ICRF heating after operation is resumed. The actual values of D retained in the B surfaces was low, of order 5%, (see Figure 2.4.4) lower than for D in C tiles. Based on these results and other operational issues we have removed all the B from the vessel, including BN tiles, for the present run period. As operation has started without B we have found that the pumpdown, typically limited by water outgassing, has been sped up considerably. Experiments are planned to accelerate the removal of H from the tile surfaces using disruptions (collaboration with D. Whyte, UW).

Furthermore, we plan to document better the difference between operation with, and without B, covering tiles (e.g. impurity sources, confinement time…). Such high-Z operational experience is very valuable as a predictor of ITER operation. The contributions to ITER will also include cleaning techniques in a high-Z first wall machine. Discussions are underway at C-Mod to try and develop a way to concentrate the ECDC cleaning plasma on specific surfaces such as the outer divertor. We hope this will allow faster reduction of the H/D levels and could provide for selective boronization of only the highest flux surfaces in the divertor. We are also pursuing ICRF conditioning, which is envisioned for ITER and believed to be more efficient than glow or ECDC at removing hydrogenic atoms.

The laboratory work will be continued at UW. D. Whyte and students plan to subject tiles to different up-to-air periods to understand better the rate of water uptake. They also plan to subject the tiles to plasmas akin to the ECDC cleaning used in C-Mod to understand better H removal. The UW group will utilize C-Mod tiles to characterize the retention of hydrogenic atoms on the sides of tiles (IEA/ITPA collaboration DSOL-13) as well as the depth of D retention into the tiles (part of IEA/ITPA collaboration DSOL-13). Lastly the poloidal variation of B deposition at the inner divertor will be explored for comparison to C PFC experiments in other machines. We note that the mixed materials in a boronized C-Mod are akin to that planned for ITER, where current plans are to have low-Z B over most of the first-wall with W (and C) in the divertor.

Impurities

The experience with high-Z walls in C-Mod will be an important contribution for predicting ITER impurity levels with a W divertor. Our experience will also bear on questions of whether ITER should move to a high-Z upper divertor, or even a high-Z main wall. We have already discussed above the issues of hydrogenic species retention in Mo. As part of the comparison of operation pre- and post-boronization, we will be gathering data relevant to ITER on the levels of Mo in the core for different operating regimes and the effect of changing the antenna shields from a low- to high- Z material.

An area we intend to continue efforts in is impurity screening – both experimentally and through modeling. A recent PhD thesis [14,15] showed that the poloidal variation in screening found experimentally was significantly affected by the flows at the inner wall and divertor. Some of these experiments are planned in collaboration with J. Strachan (PPPL) in order to see if the change in the inner divertor shape has had an effect as well as to make correspondence with recent experiments on JET [16]. A further use for such experiments is to try to understand whether convection of ions from the inner divertor region into the core plasma is the route whereby particles close the loop to the outer SOL and drive SOL flows (see earlier section on SOL transport). The dependence of screening on the magnetic geometry will be explored through screening experiments that occur as the separation between the primary and secondary separatrix is varied.

The tile analysis work by Whyte also had important implications for impurity studies. As was found in the Wampler study [13] and an experimental study at C-Mod [17], boronization covers up Mo everywhere in the vessel. It is eroded from divertor areas and, we think, some parts of the outer limiters within a few hundred high power plasma discharges. However, the boronization elsewhere on vessel surfaces, continues to accumulate through many boronizations. Whyte's analysis confirmed this description. More importantly, that analysis confirmed that Mo and O can be found in the B layer at small levels, although perhaps enough to affect the plasma, since the Mo source rate from boron-covered surfaces has been found to be significant. Lastly, Whyte's analysis showed that B was accumulating at the inner divertor surface at a rate comparable to that of C deposition at the inner divertors in tokamaks with C plasma-facing components. As discussed earlier the deposition rate is very important for understanding material migration and the potential for co-deposition, and thus burial, of D, and therefore tritium in future experiments, especially ITER.

High heat flux & particle handling

The boundary physics and operations groups work closely together in determining many aspects of the chamber surfaces from tiles to cryopumps. During the last run period and the machine vent we developed several prototype Tungsten-brush (W-brush) tiles for installation in C-Mod. This development is part of a long-term plan to increase the power-handling capability of the divertor. We need not only something that can handle the heat loads, but also materials that hold together and do not lead to enhanced impurity sources (for example, from the multiple leading edges of the rod ends). The changes will include installation of W tiles as well as an upgraded divertor plate that is better aligned and has fewer openings (fewer leading edges). 12 divertor tiles were designed and tested in collaboration with Sandia/Albuquerque. The 12 were installed on the divertor in 3 columns of 4, the columns at different toroidal locations. Two of the columns of tiles are at leading edges, having higher heat fluxes. The last column is in a 'normal' outer divertor location. All tiles are viewed by cameras. 2 columns of tiles are viewed by an IR camera; the third is monitored using a visible light camera and a spectrometer view to monitor impurity sources. Of the 12 installed test tiles 3 are such that the W rods are mechanically held in the inconel base. The other 9 are brazed to the base. All tiles are held on to the divertor plate the same way.

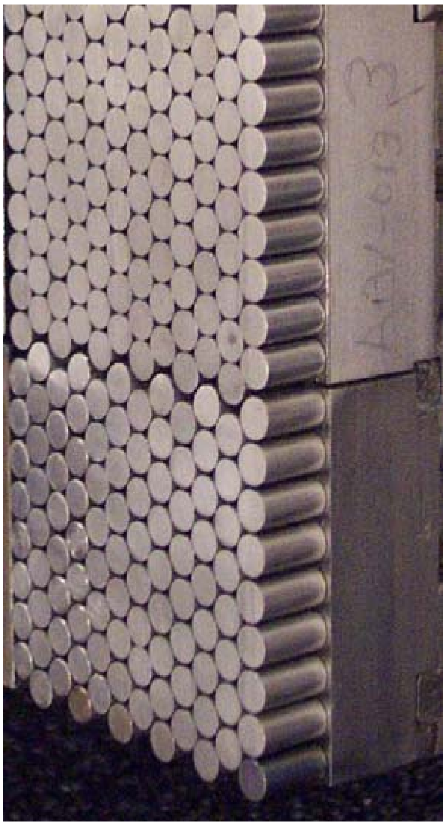

Figure 2.4.5: W brush tiles assembled onto outer divertor leading edge.

The plan for the next campaign is to monitor and test tiles to their limits. During the run campaign we will monitor their performance in terms of impurity sources and temperature. At the very end of the run campaign we intend to elevate the energy deposited on the tiles so that their surface temperature comes as close to melting as possible.

During the run period we will also continue with W-brush tile developments. Our concern about the current tiles is that each W rod represents a leading edge. One potential change is to try 'square' rods, leading to very small gaps and leading edges. A second proposal is to make the tiles out of W plates instead of rods. Designs have started, again in collaboration with Sandia. New tiles of various types will be manufactured and tested – both mechanically and thermally (at Sandia).

Another area where the boundary physics group supports the C-Mod program is in cryopump development. Experiments have been done over the past year to evaluate the pressure achieved in the top divertor as a function of SSEP, the gap between the primary and secondary separatrix referenced to the midplane. It was found that for lower single-null discharges with SSEP of 3-5 mm the upper divertor pressure was in the range of 1-2

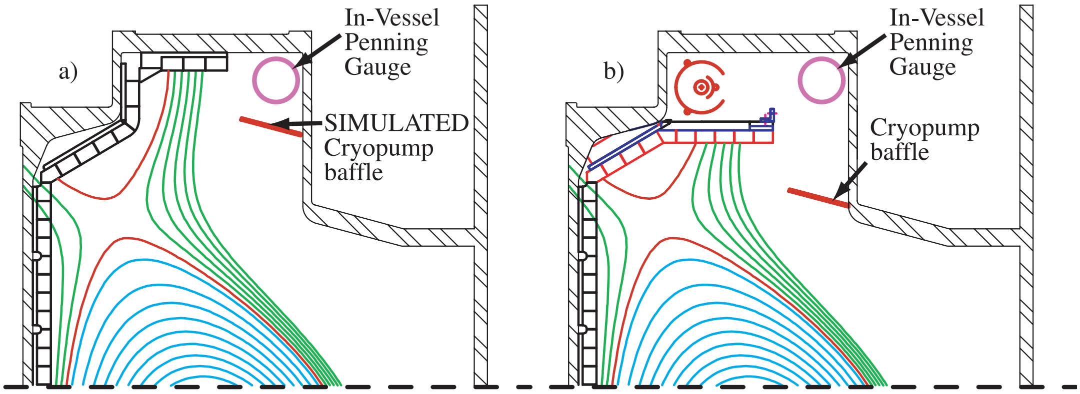

Figure 2.4.6: (a) Location of a 'simulated cryopump baffle' and Penning ionization gauge used to study gas pressures in the upper chamber. (b) Location of planned cryopump and cryopump baffle.

mT, sufficient to provide a D_2 pumping rate of 15-30 torr-liters/s. This throughput would remove the full inventory of gas injected to produce these discharges in roughly 0.5 to 1 second.

As the next step in gathering experimental experience in support of optimizing the cryopump, we have installed baffles in the upper divertor region to approximate the geometry of the pump and accompanying baffles. Figure 2.4.6 shows the current cryopump design and the simulated baffle that was installed for the present run period. The pressure gauge located behind the baffle was present (without the baffle) during the previous run period as well. Thus, a comparison of similar discharges from the two campaigns will provide information on the effectiveness of the baffle. In parallel we will continue to optimize the cryopump design. We have finished a preliminary design, as described in the operations section.

References:

[1] see for example: Scott, B., Plasma Physics and Controlled Fusion **39** (1997) 1635, Rogers, Drake, and Zeiler, Phys. Rev. Lett. **81** (1998) 4396, X.Q. XU *et al.*, Phys. Plasmas **7** (2000) 1951, X.Q. XU *et al.*, New Journal of Physics **4** (2002) 53.

[2] LaBombard, B., Hughes, J., Greenwald, M., Mossessian, D., and Terry, J.L., "Evidence for electromagnetic fluid drift turbulence controlling the edge plasma state in Alcator C-Mod," Bull. Am. Phys. Soc. **48** (2003) 52.

[3] LaBombard, B., Umansky, M.V., Boivin, R.L., Goetz, J.A., Hughes, J., Lipschultz, B., Mossessian, D., Pitcher, C.S., and Terry, J.L., "Cross-field plasma transport and main chamber recycling in diverted plasmas on Alcator C-Mod," Nucl. Fusion **40** (2000) 2041.

[4] Lipschultz, B. et al., "A Study of JET SOL Radial Transport Based on Particle Balance," in Controlled Fusion and Plasma Physics (Proc. 30th Eur. Conf, St. Petersburg, 2003), Vol. 27A, European Physical Society, Geneva (2003) 3.197.

[5] Lipschultz, B., et al, "Comparison of ion transport in the Scrapeoff Layer plasmas of Alcator C-Mod and DIII-D," submitted to PPCF.

[6] LaBombard, B., Rice, J.E., Hubbard, A.E., Hughes, J.W., Greenwald, M., Irby, J.H., Lin, Y., Lipschultz, B., Marmar, E.S., Smick, N., Wolfe, S.M., and Wukitch, S.J., "Transport-Driven Scrape-off Layer Flows and the Boundary Conditions Imposed at the Magnetic Separatrix in a Tokamak Plasma," Nucl. Fusion **44** (2004) 1047.

[7] Zweben, S.J., *et al.*, Phys. Plasmas **9** (2002) 1981., Terry, J.L., *et al.*, Phys. Plasmas **10** (2003) 1739.

[8]Terry, J., Zweben, S., Grulke, O., LaBombard, B., Greenwald, M., Munsat, T., and Veto, B., "Comparisons of Edge/SOL turbulence in L- and H-mode plasmas of Alcator C-Mod," to be published in J. Nucl. Mater. (2004).

[9] Grulke, O., "Dynamics of spatiotemporal fluctuation structures in the scrape-off layer of Alcator C-Mod and NSTX," Bull. Am. Phys. Soc. **49** (2004) 59.

[10] Zweben, S. "Parallel structure of edge turbulence", presentation at the C-Mod Ideas Forum, December, 2004,
http://www.psfc.mit.edu/cmod/sciprogram/ideas2005/Mirror_agenda/Ideas05_Zweben_parallel_st.ppt

[11] Lynch, V.E., Carreras, B., Sanchez, E., LaBombard, B., van Milligen, B., and Newman, D., "Determination of longe-range correlations by quiet-time statistics," to be published in Phys. Plasmas (2005).

[12] LaBombard, B., Greenwald, M., Hughes, J.W., Antar, G., Lipschultz, B., Smick, N., Terry, J.L., Veto, B., Zweben, S., "Phase Space of the Scrape-off-Layer Plasma",

miniproposal #409, http://www.psfc.mit.edu/cmod/operations/miniproposals/409.pdf.

[13] Wampler, W. et al., JNM **266-269** (1999) 217.

[14] Chung. T., Plasma Science & Fusion Center report #PSFC/RR-04-1, ‘Study of Recycling Impurity Retention in Alcator C-Mod’.

[15] Chung, T. et al., I.H. Hutchinson, B. Lipschultz, B. LaBombard and S. Lisgo, ‘DIVIMP modeling of impurity flows and screening in Alcator C-Mod J. Nucl.. Mater. **337-339** (2005) 109.

[16] Strachan, J.D., Corrigan, G., Kallenbach, A., Matthews, G.F., Meister, H., Neu, R., Rohde, V., and Spence, J., "Diverted tokamak carbon screening: scaling with machine size and consequences for core contamination," Nucl. Fusion **44** (2004) 772.

[17] Lipschultz, B., Pappas, D.A., LaBombard, B., Rice, J.E., Smith, D., Wukitch, S.J., ‘A study of molybdenum influxes and transport in Alcator C-Mod’, Nucl. Fusion, **41**, (2001) 585.

2.5 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-sanctioned 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 to theory and modelling.

Disruption mitigation

The development of practical disruption mitigation techniques is one of the most critical issues for any tokamak-based burning plasma experiment and reactor prototype. Disruption-related problems that are particularly severe for ITER-class 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. Injection of high-pressure jets of noble gases, such as neon or argon, has been proposed to mitigate these effects, without degrading the performance of subsequent plasma discharges. Initial tests on DIII-D have been encouraging, but questions remain about the penetration of the gas jets into high absolute-pressure reactor-grade plasmas, as well as their ability to radiate the necessary energy away on a sufficiently short timescale. C-Mod offers a much more

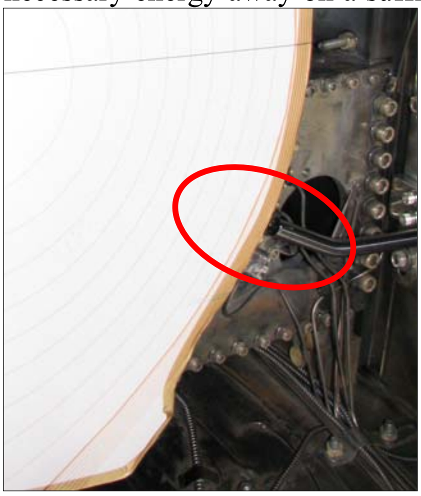

Figure 2.5.1— Outlet nozzle is just 30 mm outside of the plasma separatrix.

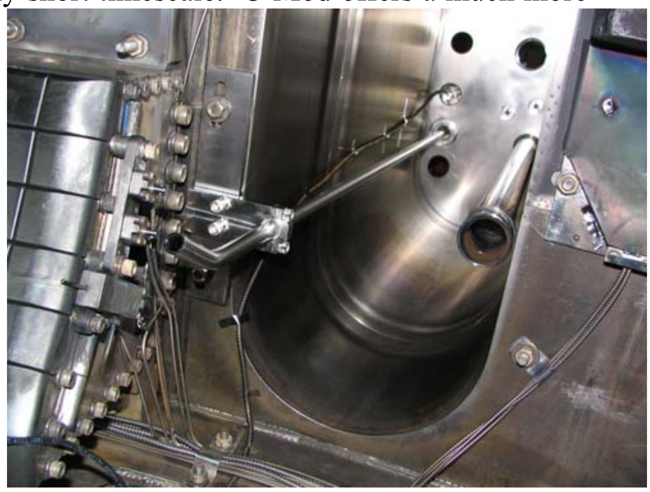

Figure 2.5.2 — A fast framing camera will view the gas plume and plasma cross-section through the periscope on the right.

challenging test due to its order-of-magnitude higher plasma pressure, energy density, and current density. Alcator C-Mod has recently initiated the installation of a high-pressure gas jet injection experiment in collaboration with the U. of Wisconsin and ORNL. Particular attention has been paid to maximizing the efficiency and speed of gas injection into the discharge. On C-Mod the outlet nozzle is positioned just 30 mm from the plasma separatrix, and aimed at the plasma center. A fast valve, mounted externally, will control the injection of high-pressure (7 MPa) jets of neon, argon, helium, or deuterium. The external gas system volume between the fast control valve and the tokamak has been minimized in order to reduce unwanted losses in pressure and velocity. A fast framing CCD camera (up to 300 images captured as frequently as every 4 μs), which has a wide-angle field-of-view of much of the plasma cross-section, will provide crucial information on gas jet penetration and dynamics. An accounting of energy balance will be obtained from existing diagnostics, including fast bolometric measurements of radiated power and infrared imaging of the lower divertor surface, and compared to KPRAD modelling of the radiation processes. Quench timescales, plasma motion, and halo current data will also be studied to determine the effectiveness of gas jet mitigation. Modelling of halo current generation using the Nimrod MHD code may help explain the penetration of the cold front into the plasma core, and also improve understanding of expected halo current reduction.

Locked Modes and Error Fields

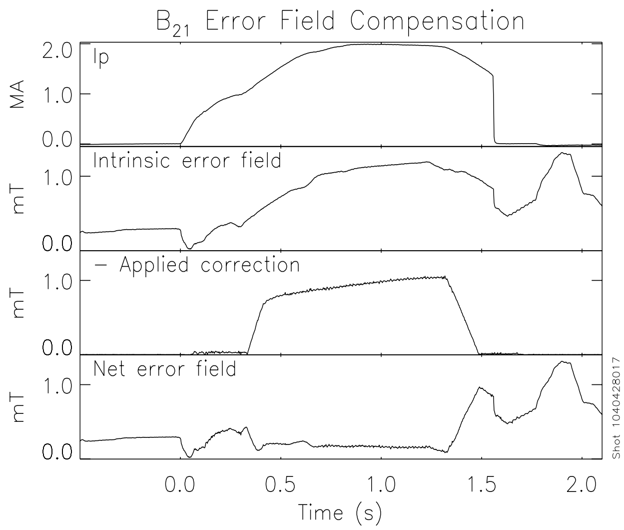

Figure 2.5.4- 2 MA plasma is obtained by using the A coils to cancel intrinsic error fields. (A locked mode disruption occurs when cancellation is turned off during rampdown).

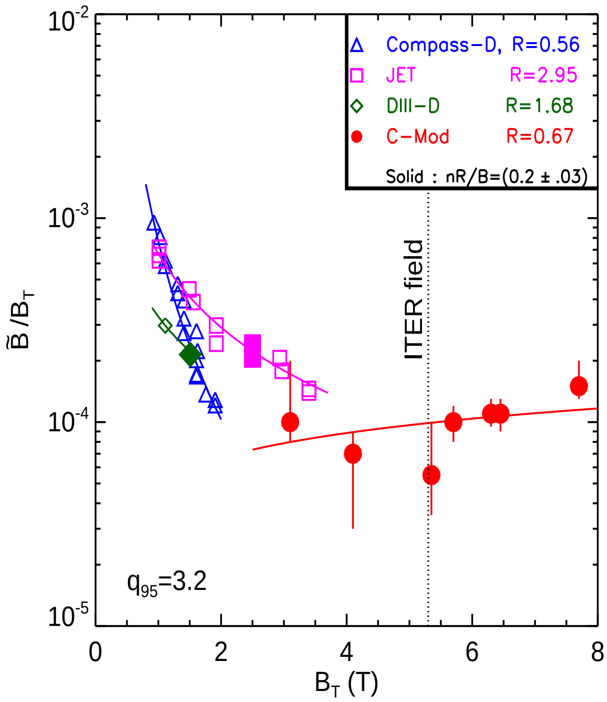

Figure -2.5.4 Locked mode threshold data, expressed as a ratio of the resonant non-axisymmetric perturbation to the toroidal field, for several devices. The C-Mod data points have the same nR/B as the ITER ohmic target plasma and span the ITER field. These data, along with data from the other tokamaks, provide a basis for extrapolation to ITER

Locked modes and error field studies have become a major topic of research on C-Mod, following the realization that locked modes are responsible for many disruptions at high plasma current and/or low density. In the past year a large effort has gone into understanding the intrinsic error fields as well as the characteristics of the recently installed A-coil correction system. This has enabled C-Mod to extend its operation up to 2 MA at 8 T. Dimensionless identity experiments with DIII-D and JET, performed under the framework of the ITPA, will continue to explore locked mode threshold scalings. To date, this work on C-Mod has confirmed a linear dependence on density, as seen on other machines, but the scaling with toroidal field has relatively large error bars. Since dimensionless scaling arguments link together the field and size scaling, there is strong motivation to pin this down more accurately. This will be done at fixed q_{95}, shape, normalized density, confinement regime (ohmic L-mode), and applied $\tilde{B}$ spectrum, so as to reduce the error bars and therefore derive a more accurate value for the field scaling, and thus the size scaling. Additional experiments to study locked mode thresholds in H-mode plasmas and to further characterize the intrinsic and applied error fields are planned as well. Effects of the error fields on the equilibrium reconstruction, particularly the position of the separatrix, will also be investigated.

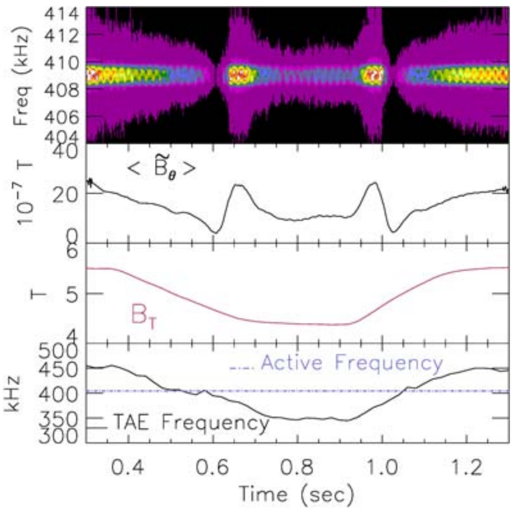

Figure 2.5.5 — Damping measured by sweeping theTAE frequency (by varying toroidal field) about the antenna drive frequency.

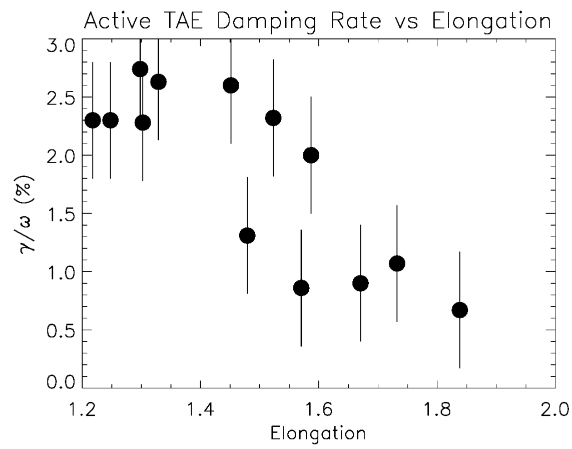

Figure 2.5.6 — Experimentally measured TAE damping rate vs plasma elongation.

Active MHD and TAE Cascades

Alfvén eigenmodes are damped by a variety of physical mechanisms. Measurements of the total TAE damping rate are useful for constraining theoretical models of these mechanisms. On Alcator C-Mod, a set of active MHD antennas is used to determine the damping rate of stable TAE's in two different ways — (a) using a constant drive frequency and sweeping the Alfvén frequency about it by ramping the toroidal field, and (b) sweeping the active MHD drive about a relatively stable Alfvén frequency. In both cases a resonance in the B-dot pickup coil signal is detected, and its width in frequency is the damping rate, γ (usually normalized to the Alfvén frequency, γ/ω). The dependence of the TAE damping rate on various plasma parameters can be measured and used to guide and constrain theoretical models of the TAE instability. For example, Fig 2.5.6 shows the behavior of γ/ω as a function of plasma elongation. Dependence on other relevant plasma parameters (shear, in particular) will be investigated and compared to results from other tokamaks.

During I_p rampup experiments Alfvén cascades are observed on both the B-dot pickup coils and the phase constract imaging diagnostic. The cascades are excited at integer and half-integer q values in discharges with very low or reversed shear. The frequency chirp depends sensitively on the value of q_{min}. Therefore these cascades can be used to deduce the evolution of the q-profile under these conditions, as shown in Fig 2.5.8. With the addition of the lower hybrid current drive on C-Mod, it will be possible to produce low shear or reversed shear profiles during the current flattop, greatly extending the usefulness of this technique for the constraining q-profiles.

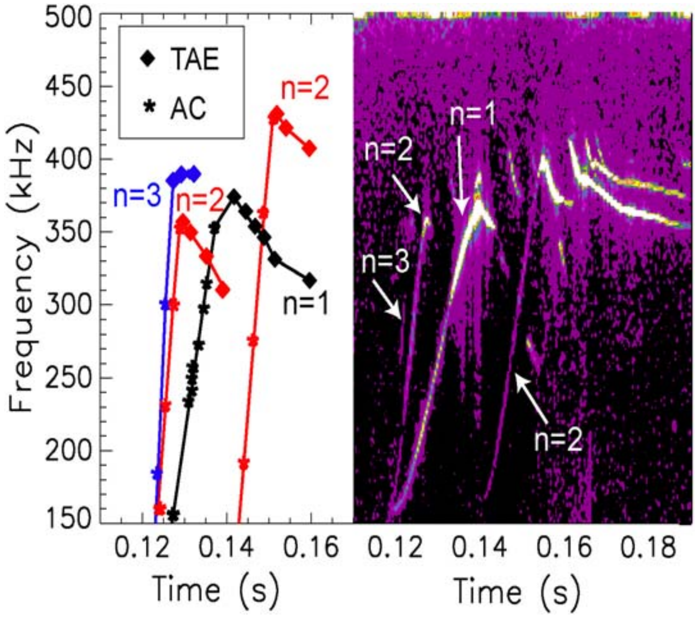

Figure 2.5.7 — Alfvén cascades during current rampup, showing characteristic frequency chirping.

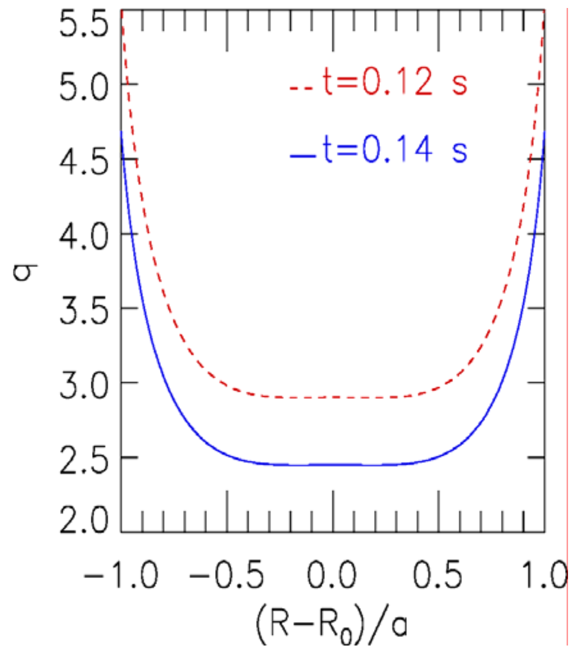

Figure 2.2.8 — q-profile evolution of a slightly reversed shear plasma, as determined from fitting the frequency chirps of the Alfvén cascades, combined with external magnetic measurements

High β instabilities and NTM's

NTM's are the focus of a planned ITPA collaboration with DIII-D and JET to determine the β_N threshold in discharges with matched dimensionless parameters (ρ_*,υ_*, q_{95}). JET and DIII-D have already made non-dimensionally similar discharges that demonstrate the onset of a 2/1 NTM at $\beta_N \approx 3.8$ on both machines, but this is beyond the reach of C-Mod. Therefore a different set of dimensionless parameter values has been proposed, for which DIII-D finds a threshold $\beta_N \approx 1.7$. This should be attainable in C-Mod, particularly with the addition of the lower hybrid power. The corresponding dimensional parameters are $B_T = 5.3$ T, $a = 22$ cm, and $n_e = 2.5 \times 10^{20}$ m^{-3}.

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 chapter 2.6.

Digital Plasma Control System (DPCS)

The new digital plasma control system has recently completed its commissioning tests and now provides the primary real-time feedback control of the plasma equilibrium. Experiments are in progress to maximize the available processor time for handling more advanced control algorithms than the current linear ones. The DPCS has 32 extra signal input ports and twice the signal output ports (32) as our previous hybrid control system. In coming years, non-linear control algorithms, including such things as real-time EFIT reconstructions in the feedback loop, will be implemented.

2.6 Wave-plasma Physics

C-Mod exclusively uses RF for auxiliary heating (predominantly ion cyclotron range of frequency - ICRF) and current drive (lower hybrid range of frequency - LHRF). ITER plans to have initially 20 MW of ICRF power to control the plasma burn and provide central current drive for advanced operation. Several important RF technological and physics issues remain to be addressed before ICRF can confidently be employed in an ITER like device. The LHRF system is optimized for off-axis current drive and the modeled current profiles using LHCD and MCCD are similar to those envisioned for ITER's weak negative shear regime. Among the many issues, we plan to investigate the following.

2.6.1 ICRF

(i) 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 the match resilient to load variations, and efficiently couple power to the plasma with minimum negative impact on the plasma edge. For C-Mod, we have implemented antennas that obtained high power density (>10 MW/m^2) and are planning to design and install a new four strap antenna in FY06. A preliminary 4-strap antenna design was completed in FY04. We plan to use the current (installed at J-port) to test specific issues. In particular, we modified the J antenna feedthrus to test the effect of vacuum transmission line on the antenna neutral pressure operation range. We have observed that the D-port and E-port antennas can operate up to ~1.5 mTorr while the J antenna in its previous configuration could only operate to ~0.3 mTorr. In the following campaign, we plan to remove the Faraday screen and test the antenna voltage and power handling capability. We will also monitor the impurity production associated with Faraday screenless operation. If a screen is unnecessary for antenna operation, a major simplification can be made to the future C-Mod 4-strap antenna. As part of a larger investigation of comparing high Z first wall and its influence on plasma performance, new Mo antenna limiter protection tiles have replaced the BN (low Z) tiles. We will monitor power and voltage limits, impurity and density production, hydrogen isotope content in the plasma, and robustness to disruption effects. To complement the experimental program, we are collaborating with RF-SciDAC and the U. of Torino on the development of an electromagnetic solver that has a realistic ICRF antenna geometry presently coupled to a 1-D, soon to be a 3-D, plasma field solver. Initial results from the modeling of the E antenna were encouraging and we plan to analyze the J antenna in the near term. We will also analyze the new 4-strap antenna design.

Plasma load variations are commonly encountered during L/H transitions and edge localized mode activity (ELM's). One potential solution is fast matching technology and we plan to investigate the integration of fast ferrites stub system into the E antenna matching network. We have received 2 fast ferrite stubs previously tested on ASDEX-Upgrade, and we to plan perform similar tests using them in C-Mod discharges in FY05. 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.

(ii) Propagation, Absorption and Mode Conversion Physics

C-Mod provides a unique test bed 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 (RF-SciDAC), 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 8T operation and future experimental devices. In previous experiments, the heating efficiency was a sensitive function of ^{3}He fraction, more so than expected from theory. Another outstanding question regarding weak single pass absorption and mode conversion absorption scenarios is the overall heating effectiveness compared to strong single pass scenarios. One might expect parasitic absorption mechanisms to compete more effectively in the case of weak single pass absorption. In FY05, direct comparison experiments comparing D(H) and D(^{3}He) are planned using D and E antennas at 80 MHz and J antenna at 50 MHz. This will allow direct comparison of the two scenarios within the same discharge at 5,3 Tesla B field. Further experiments in FY06 will investigate the effect of additional heating power on heating efficiency with higher power density and bulk plasma temperature. These are expected to strengthen the single pass absorption and improve the heating efficiency.

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 RF SciDAC. The data and simulation are in remarkable agreement, suggesting the physics model and numerical algorithm in TORIC models the mode conversion process well. As part of the PCI upgrade, we plan to implement a masking technique that relies on Faraday rotation 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. Finally an optics upgrade will allow resolution of higher k and when combined with the localization may allow observation of the rapid k up-shift associated with the mode converted waves. Taking advantage of this unique capability, studies will initially focus on D(^{3}He) and D(H) the primary species mix 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 run up to at least 511 poloidal modes routinely.

(iii) ICRF Mode Conversion Current Drive

While not expected to be as efficient as Lower Hybrid current drive, MCCD can be a valuable adjunct to LHCD. MCCD is predicted to be localized and can provide central current drive in scenarios where the LHCD is expected to be off axis. In initial experiments, sawtooth variation period was shown to be dependent on antenna phase and deposition location, suggesting a means to control the sawtooth period. For deposition near the q=1 surface, the sawtooth period was sensitive to the phase of the antenna. For situations where the deposition was away from the q=1 surface, no phase sensitivity was observed. Using the TORIC code, a more efficient mode conversion scenario was identified and indicated ~100 kA of driven current for 3 MW injected. These experiments are planned with J antenna at 50 MHz allowing MCCD experiments in $D(^3He)$ plasmas at ~5 T. The driven current will be deduced from analysis of the surface loop voltage, internal inductance, and measuring the total current profile with motional stark effect (MSE) and/or Faraday rotation diagnostic when the diagnostics become available. The driven current profile can be used to benchmark the predicted current profile from TORIC. The TORIC model presently is based upon Ehst and Karney current drive efficiency parameterization. The parameterization is computed from an adjoint solution to the Fokker Planck equation. This formulation directly includes particle trapping by convolving the local power absorbed with the current drive efficiency at that position. Furthermore, the variation of the parallel wave number is directly accounted for because the power absorption is reconstructed as a function of the poloidal mode number. This will be critically important for the mode converted waves where the poloidal component of the parallel wave number can dominate the toroidal contribution. In collaboration with RF-SciDAC, we plan to couple TORIC to a Fokker Planck solver (CQL3D). This will allow incorporation of the proper wave characteristics, including polarization, in the calculation of driven current.

For the central current drive case, the predicted driven current exceeds the local Ohmic current density. This may allow production of discharges with high-l_i, which have shown confinement improvement on other experiments. For the off-axis case, the RF current density should be a significant fraction of the Ohmic current density. This may allow a study of sawtooth stabilization as shown in the initial experiments, and stabilization of pressure drive modes through local current profile modification.

(iv) Flow drive (MC)

Another important research theme, perhaps 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 second case damping on electrons will be small (electron to ion mass ratio is small) and ineffective. Depending upon species mix, deposition location, and plasma current, the power can be channeled to ions or electrons. With present 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 to be made. Initial experiments in FY03 suggested the measured poloidal flow was proportional to the RF power and sensitive to the antenna phase but further experiments in FY04 failed to reproduce the earlier results. Modeling indicates the scenarios most likely to drive significant sheared flows are those that have significant damping on ions near the ion 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, and flow drive experiments, have different optimal plasma conditions. The emphasis here will be to assess the magnitude of the poloidal flow, its profile, and its relation to the RF power, absorption and wave propagation characteristics. Here the development of a numerical simulation will be important. We plan to begin the experiments and code work in collaboration with the Sci-DAC initiative. Depending on its success, RF driven flow shear can be investigated to determine RF power required to trigger or maintain internal transport barriers.

(v) Physics of Energetic Ions

The physics of energetic ions is of obvious importance to burning plasma experiments. In particular, the influence of energetic particles on MHD mode stability and their effect on fast particle transport are important for ICRF heating and burning plasmas. A combination of new diagnostics, increased ICRF power, and access to new sophisticated codes has placed C-Mod in position to provide strong contributions in this area.

In C-Mod energetic ion affects had been limited to experiments with relatively low density. With the successful operation of J antenna to 11 MW/m^2, energetic ion affects have become more ubiquitous. Furthermore, an active charge exchange neutral diagnostic has produced initial data yielding a new ability to monitor the energy and perhaps spatial distribution of the ICRF minority tail ions. For 0.8 MA discharges with central D(H) minority heating, the sawtooth period was observed to be antenna phase sensitive. When the ion cyclotron resonance is near the q=1 surface, however, the sawtooth period is insensitive to phase. For 1 MA discharges, the sawtooth period is lengthened for all antenna phases. We plan to determine the parameter space under which small and monster sawteeth are obtained. These results will be analyzed with a new finite banana width Fokker-Planck code with self consistent RF fields through the RF Sci-DAC initiative to identify the role of fast particles in sawtooth stabilization.

Alfvén modes driven unstable by the energetic ions are another obvious physics area of importance to burning plasma experiments. In ITER, intermediate toroidal mode number (core localized) Alfvén modes are expected to the most unstable Alfvén modes. These modes could have an impact on the slowing down of alpha particles and affect the transport of energetic ICRF minority ions. Initial experiments in C-Mod have found so-called Alfvén cascades during current ramps with high power ICRF. Both more global modes (measured by the edge B-dot probes) and core localized modes (measured by PCI) were observed. With additional high power RF a second harmonic of the cascade was observed. During high power ICRF experiments in current flat top, additional energetic particle modes were identified. These modes appear to be core localized and are modulated by the sawtooth. We have installed additional current probes at the K port limiter and an inner wall set is planned for FY06. Additional experiments will investigate the impact of deposition location and antenna phase on the excited modes. With the recent acquisition of the CASTOR code, this code will be implemented on the PSFC theory cluster MARSHALL.

2.6.2 LHRF

A major upgrade to the C-Mod facility, to provide current drive capability using lower hybrid waves, is underway. This system is optimized for far off-axis current and the modeled current profiles using LHCD and MCCD are similar to those envisioned for ITER's weak negative shear regime. In the first stage, starting in FY05, up to 3 MW of source power at 4.6 GHz will be coupled through a single 96 waveguide launcher array. To improve current drive efficiency, increase the system flexibility, and reduce the power density at the launcher, a second launcher will be completed and installed in FY07.

(i) Launcher/Plasma Interactions

Initial experiments will focus on launcher power handling, impurity production, and coupling efficiency. Compared to other experiments, the coupler will use Mo protection tiles that are a departure from past practice. Furthermore, reduced coupling and power handling have been observed when ICRF antennas on the same field line are operated in conjunction with the LH coupler. The reason cited is a decrease in the density on the field lines resulting from ICRF induced ExB drifts. Langmuir probes have been installed in the coupler to allow direct monitoring of the local density and gas nozzles have been installed in the protection limiter. The optimum density for coupling can be readily identified by finding the minimum reflection versus local plasma density and gas puffing can be used to offset potential decreases in density associated with ICRF operation. A camera to monitor the coupler-plasma edge interaction is installed to allow for between discharge evaluations of coupler operation. Timely evaluation of the first launcher is critical to incorporate design changes for the second launcher.

The initial system startup will utilize vacuum operation to verify amplitude and phase control. Initially, vacuum conditioning will be performed using one klystron at a time to degas and voltage condition the wave guides. After initial conditioning, klystrons will be operated simultaneously to verify phase settings. Low power injection experiments will be used to identify optimal launcher position, plasma position, and coupler phase. This initial system startup will be followed by high power conditioning with a goal of reaching 0.5 MW under a range of plasma conditions.

(ii) Wave and Fast electron physics, Current Drive

The initial experiments will focus on verifying driven current for power levels of ~0.5 MW. The first experiments will investigate the localization and total driven current. One means to demonstrate current drive is to sustain a discharge without Ohmic current. For the initial power levels, this means low target density and plasma current. This will allow an unambiguous demonstration of current drive.

A key diagnostic for detecting the deposition of the lower hybrid waves is an imaging hard x-ray spectrometer. The fast electron distribution will be measured with both spatial and energy resolution to allow for the LH wave deposition to be determined. To determine the driven current profile, the power deposition and energy distribution will need to be incorporated in the analysis of the local current density derived from the MSE and/or Faraday rotation diagnostics. The effects of plasma density, plasma temperature, and launcher phasing on the driven current and current profile are planned to be investigated. These experiments are expected to establish the experimental conditions under which current profile control can be demonstrated. The results of these experiments can be compared with sophisticated wave codes with self consistent 2-D Fokker Planck solvers. With the additional second launcher to be completed in FY07, the current drive efficiency and potential control through the use of a compound spectrum can be investigated and modeled.

To understand the underlying RF wave physics, a detailed comparison of self consistent, full wave Fokker Plank simulations and experiments will be pursued. The primary measure of wave absorption and deposition is the hard x-ray spectrometer that provides both spatial profile and energy distribution of the fast electrons. Advanced RF computational tools will be developed in conjunction with the RF Sci-DAC Initiative.

(iii) Synergies

Synergistic effects between ICRF and Lower Hybrid waves will be studied and simulated using the advanced modeling codes developed by RF Sci-DAC initiative. One potential interaction is between MCIBW and LH waves. The MCIBW may modify the electron distribution function to allow the LH waves to damp at a different location in the plasma from what one would expect in Maxwellian plasma. The use of a seed population of faster electrons may allow some control over location of the LH generated current. Furthermore, current drive efficiency should be a sensitive function of plasma temperature, which will vary with ICRF heating as well as LH power. Conversely, minority damping of fast waves can be affected by plasma beta, and the slowing down of the tail ions is influenced by electron temperature. All of these effects will be studied as the lower hybrid system is brought online and the total LH power

3. Operations

3.1 Facilities

The FY2004 run campaign concluded in mid April 2004, after 18.9 weeks of physics operation. Nearly 1900 discharges were produced with a startup reliability of 81%. By early May C-Mod was up-to-air with the primary goals of installing the 1st lower hybrid launcher and preparing the vacuum vessel for our level 1 JOULE milestone of comparing operation with molybdenum protection tiles rather than boron nitide ones. During the up-to-air we also removed, cleaned ultra-sonically, and re-installed 140 wall and ceiling tile modules containing over 2300 molybdenum tiles. In addition all in-vessel surfaces were carefully cleaned of boron and heavy boron compounds. All boron nitride tiles on the ICRF antennas were removed and replaced with molybdenum tiles. Boron nitride tiles were also removed from the MHD antennas and emissive probes.

A highlight of machine operation during the last year was that improvements in our ability to use the non-axisymmetric correction coils allowed C-Mod to reach a record plasma current of 2.0 MA at a toroidal field of 8.1 T.

Lower Hybrid System

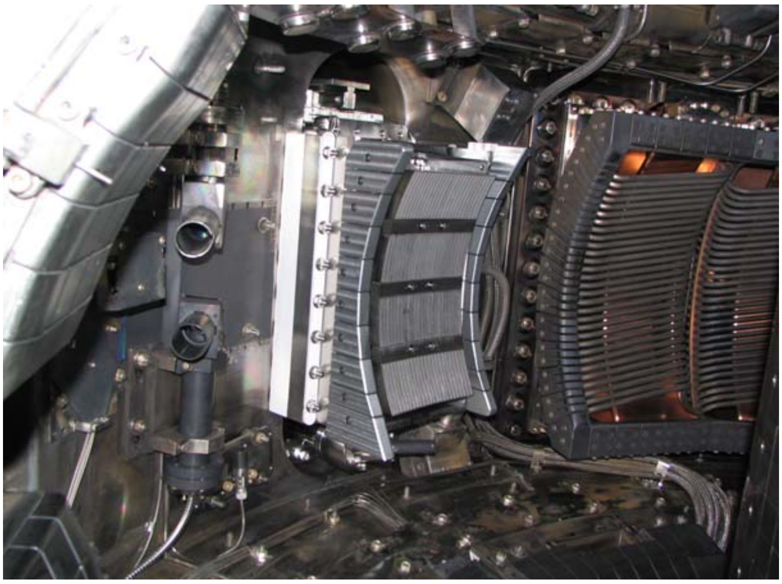

Figure 3.1: Lower hybrid launcher installed in the C-Mod vacuum vessel. The lower hybrid limiters and the six Langmuir probes can also be seen.

Another major activity during the up-to-air was the installation of the first lower hybrid launcher. Much of the year was spent developing a process to produce reliable vacuum windows for the lower hybrid couplers. Ninety-six leak-free windows are required for a lower hybrid launcher. Cracks in the outer most windows were eliminated with the addition of a thin alumina plate to the outside of the coupler. This plate balanced stresses in the end windows that caused the cracks as the coupler cooled off following the brazing operation. Several brazes were tested in an effort to find the best combination of braze quality and ease of cleanup following the brazing operation. Previous work with active brazes produced windows that required many man-hours to clean. With the proper choice of braze compounds and furnace procedures we produced four leak-tight 24-window couplers that are now installed on C-Mod (see figure 3.1). Molybdenum limiters have been installed on either side of the launcher and six Langmuir probes will measure the density locally.

Extensive high power testing of the couplers and forward and rear waveguides was also conducted during the last year. All components have been tested to at least twice their expected operation levels.

The lower hybrid phase and amplitude control system, coupler protection system, transmitter protection system, safety interlock system, waveguide runs, and rear waveguide assembly, have all been brought to the commissioning phase over the past year (see figure 3.2). Low level power at the few kW level is now being coupled into the C-Mod vessel as we check control and protection systems.

Plans are being made for a second lower hybrid launcher. The new launcher will allow us to reduce the power density expected from each launcher by a factor of two which will access a regime requiring much less conditioning for reliable operation. Two launchers will also allow compound spectra to be used for current drive experiments. If good results are obtained with the first launcher, we will reproduce the first launcher with only minor modifications.

Figure 3.2: Lower hybrid klystrons and waveguides

We are currently using twelve klystrons to feed one launcher for a total source power of 3 MW. Given adequate funds, we plan to bring online the remaining klystron cart which will bring the complement of klystrons up to sixteen for a source power of 4 MW.

Dividing this power equally between the launchers will keep the power density low and keep us out a regime requiring strong conditioning.

Long Pulse DNB

We have spent the last year preparing the cell and power room for the new long pulse DNB. This new system requires megawatt level electrical service and all the cabling, breakers, contactors, transformers, instrumentation, interlocks and safety components such high power systems entail. The beam was fabricated at the Budker Institute, Novosibirsk, Russia, and arrived at MIT late February 2005. We are now in the process of installing the beam with the help of nine engineers from the Budker Institute. The beam is a 50-55 kV, 7 A extracted, 4 A delivered, source of neutrals. It is capable of 1.5 s pulses or with a 50% duty cycle pulses up to 3 s long. The FWHM size of the beam is 6-8 cm. A picture of the beam undergoing testing in Russia is shown in figure 3. The beam produces a very pure beam with an 85% full energy fraction.

Figure 3.3: The long pulse diagnostic neutral beam undergoing testing in Russia

ICRF Systems

A new J-Horizontal flange has been installed on C-Mod with new rf feedthroughs to improve the high voltage capability of the J-Port antenna. Rf bypass capacitors were installed from the J-Port backplate to the outer vessel wall to eliminate rf induced discharges to the wall during plasma operation (see figure 4).

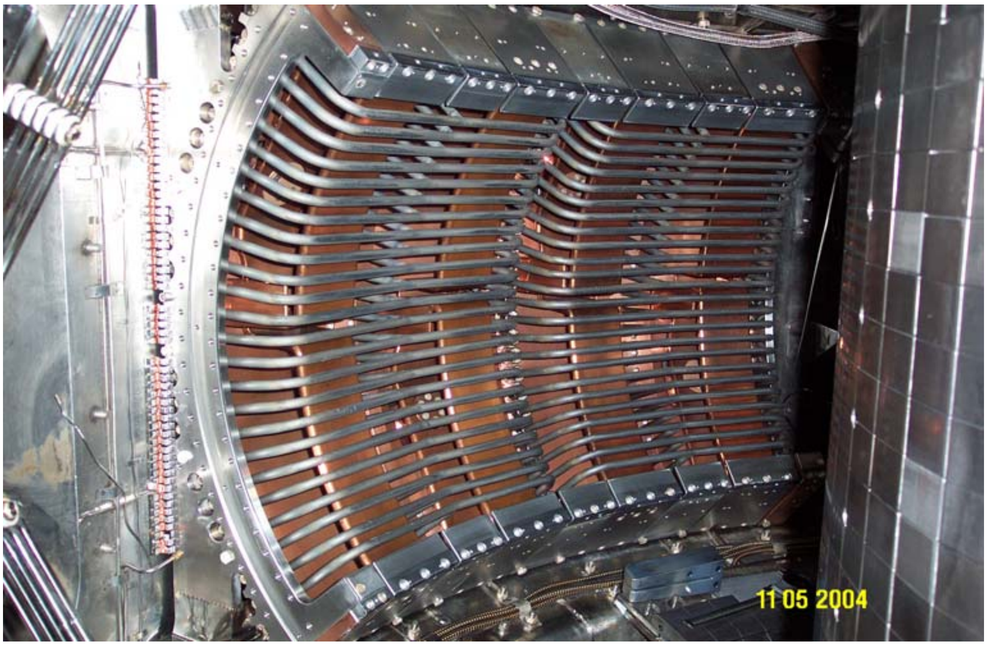

Figure 3.4: Rf bypass capacitors added between the J-Port antenna backplane and the vessel wall will eliminate rf discharges behind the antenna.

Work continued on the prototype real-time matching system (see figure 3.5). This system will allow a match between the transmitter and antenna to be maintained on the millisecond time scale. It will greatly reduce the time required from physicists and engineers to tune to changing plasma conditions.

Figure 3.5: Real-time matching system showing transmission line box which also contains the ferrites and bias magnet.

A new 4-strap ICRF antenna has been designed and will be installed in FY2006. This new antennas will allow us to replace both the D- and E-Port antennas without losing any ICRF power capability. The new antennas will use only one horizontal port so that one of the current ICRF ports can be freed up for diagnostics displaced by the second lower hybrid launcher.

MIT Alternator

After an extensive review and documentation effort the method for supplying the stator neutral ground for the alternator was modified during our up-to-air period. The original grounding system, as supplied by GE, could support large, damaging currents from the stator during a single point fault. The new system limits these currents to acceptable levels and will reduce damage to the stator in case of a fault.

A backup water cooling system for the alternator was also added during the up-to-air period. The second system can be switched in during maintenance of the primary system, or can be used in place of the primary system to reduce down time.

Cryopump

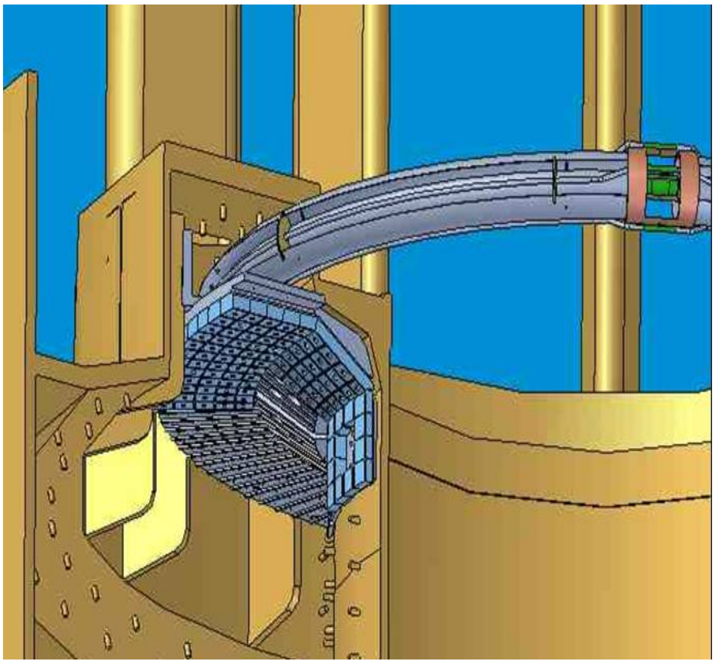

Figure 3.6: View of the upper divertor cryopump and protection tiles. Liquid He fills the inner most tube and liquid nitrogen fills the outer one. Protective tile design is still ongoing.

Density control during H-Mode and AT operation on C-Mod will be greatly improved with the addition of a cryopump (figure 3.6). The fabrication and installation of this device is now a very high priority for the C-Mod operations group. The pump itself will be similar in design to those already installed on DIIID. A liquid helium cooled 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 vessel surfaces. The effective pumping speed of the pump is expected to be 15,000 l/s for deuterium.

A set of baffles have been installed in the C-Mod upper vessel to simulate the more closed geometry we expect with the new upper divertor cryopump. Our first plasma experiments with the new baffles indicate that the pressure in the upper divertor can be doubled compared to the case without the baffles, but the experiments also indicate that the pump will be most effective when the entrance to the pump is near the plasma strike-point. We are now considering how to optimize the upper divertor tile structure to maximize the effectiveness of the new pump. Installation of the pump is planned for early FY2006.

Tungsten Brush Advanced Divertor

In collaboration with Sandia (SNLA), we have developed a set of ITER relevant tungsten brush tiles, and installed them on C-Mod (figure 3.7). They consist of an array of 1/8" diameter tungsten rods inserted into a matrix of holes machined into an inconel support plate. The rods are pinned with stainless steel rods and then brazed to the support plates. Similar tiles, but with active cooling, have been tested to approximately 20 MW/m^2 at Sandia. C-Mod will provide the first test of this type of tile in a tokamak. Twelve tiles have been installed at three toroidal locations (figure 8). Infrared and visible video and spectroscopic views of the tiles will provide information about the tile performance as the plasma strike-point and other parameters are varied. Results from tungsten brush tile tests on C-Mod will have important implications for ITER.

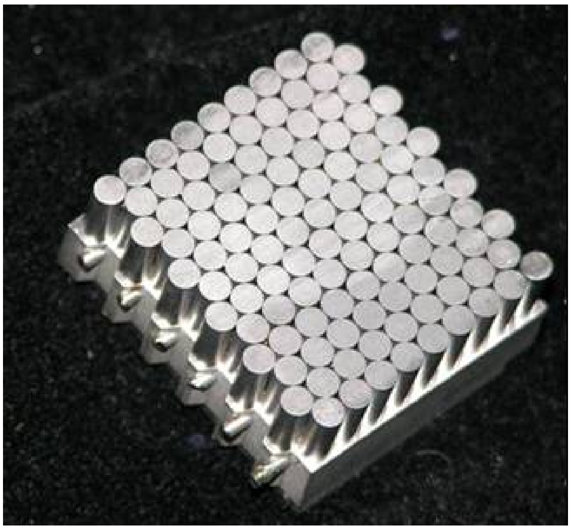

Figure 3.7: A tungsten brush tile. Pins anchor two rows of tungsten rods.

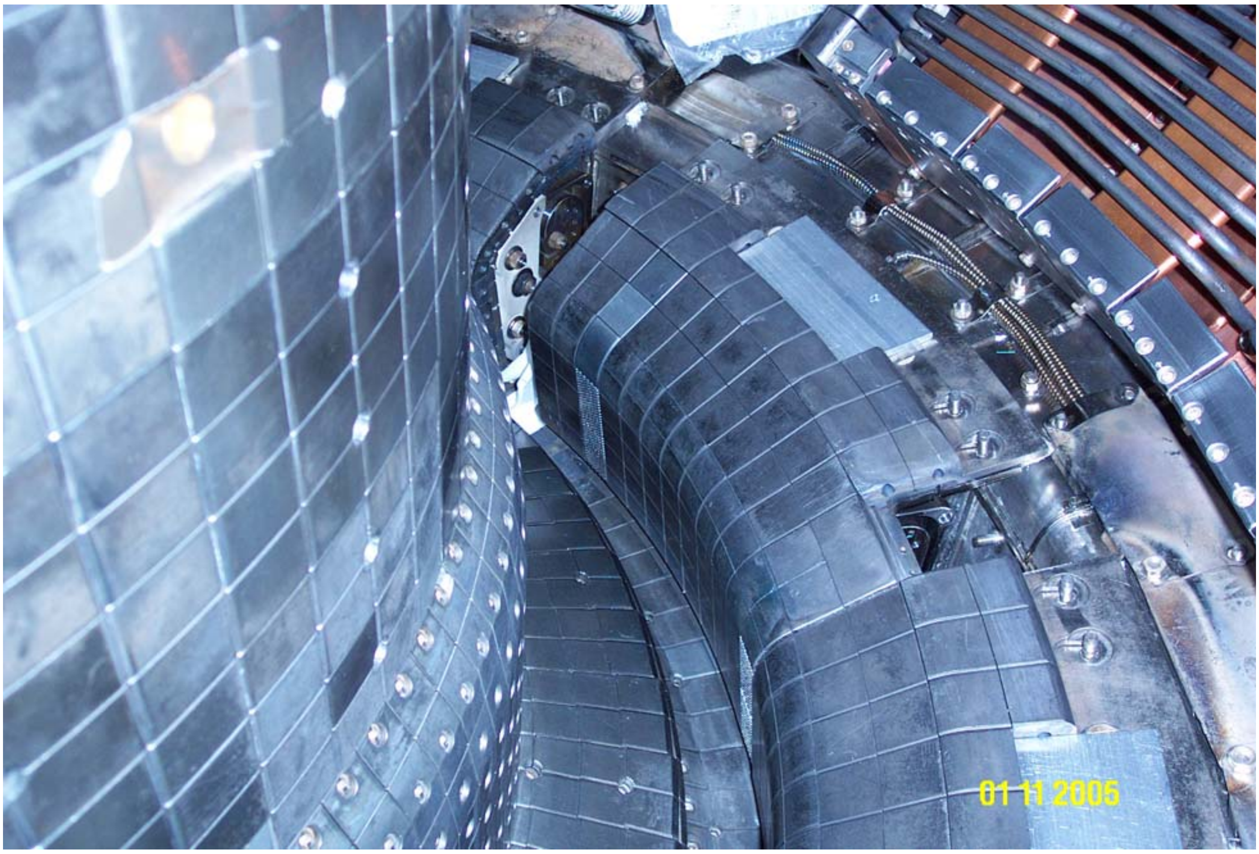

Figure 3.8: Tungsten brush tiles installed in C-Mod. Twelve tiles were installed at 3 toroidal locations (two locations shown).

Diagnostics

Over the last year we continued to add new diagnostics and to upgrade existing systems.

A poloidally viewing 32 channel hard x-ray diagnostic has been build and installed to measure changes to the suprathermal electron population during lower hybrid current drive and heating experiments (see figure 3.9). This system uses solid state CZT detectors to measure x-ray spectra in the 20 to 250 keV range. Spatial resolution of about 1.5 cm is expected.

A tangentially viewing compact neutral particle analyzer has been installed in-vessel to measure DNB charge exchange neutrals from the ICRF induced hydrogen minority tail (see figure 3.10).

An imaging Johann X-Ray Spectrometer has been installed in collaboration with KSTAR and PPPL to measure rotation velocities and ion temperatures in the pedestal.

The lithium pellet injector has been moved to the new B-Horizontal flange where several diagnostics displaced by the installation of the lower hybrid launcher at C-Horizontal have been relocated. New stereoscopic views of the pellets with 2 μs temporal resolution will allow ablation physics and possibly zonal flows to be studied.

New higher power and more stable CO_2 lasers have been procured and made operational in the TCI (two-color-interferometer) and PCI (phase-contrast-interferometer) diagnostics. In addition, both the spatial and spectral resolution of the PCI diagnostic have been doubled so that our ability to study high-k fluctuations will be improved.

New firewire based high resolution video cameras are being installed on C-Mod. These cameras can be networked to the same PC, can be controlled with external triggers, and can be procured with a variety of resolutions and frame rates. A detachable detector head on some cameras allows access to very tight spaces on C-Mod ports. Linux based widgets allow the cameras to be controlled and tested. MDSplus support for the cameras has been developed. These cameras will be used to image the new lower hybrid launcher and the ICRF antennas, and to provide wide angle views of the vessel and plasma.

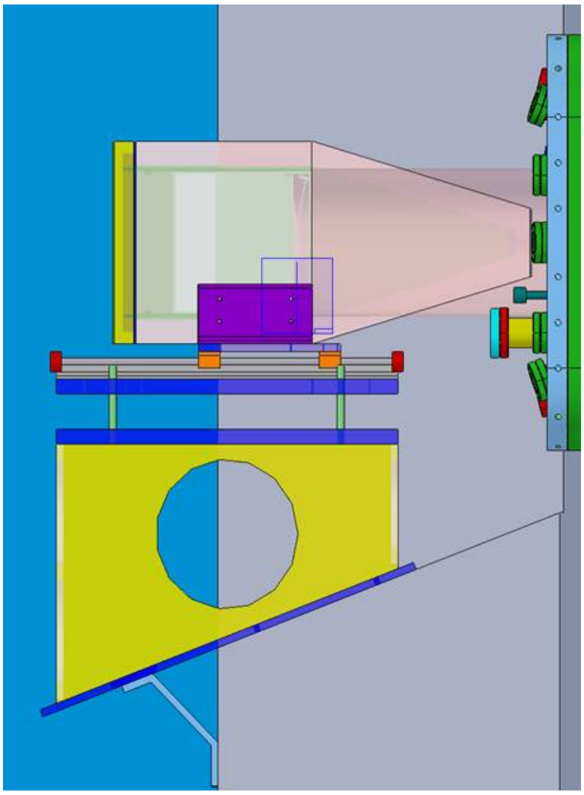

Figure 3.9: The 32-channel hard x-ray detector (HXR) will provide profile information on the lower hybrid produced hot electron population.

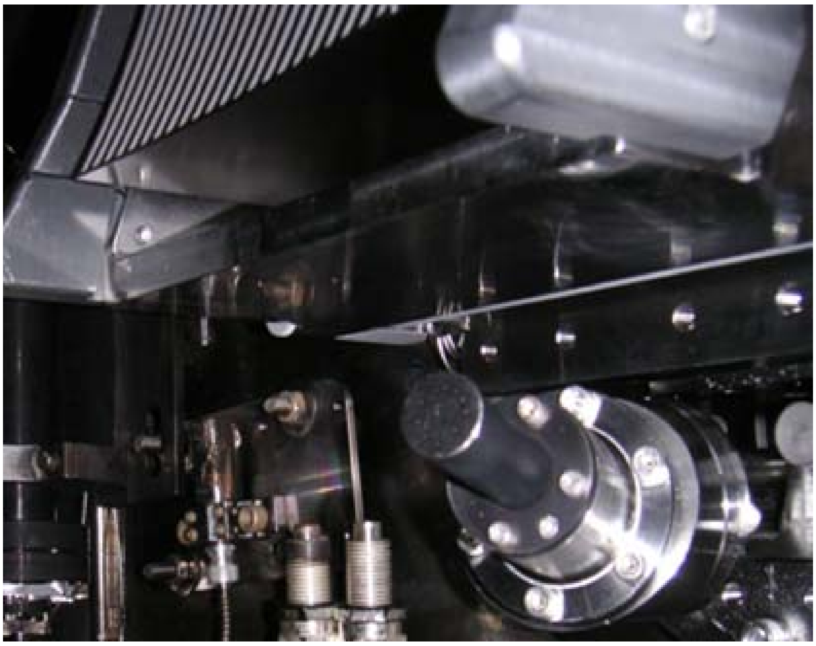

Figure 3.10: The tangential compact neutral particle analyzer (TCNPA) will measure the charge exchange neutrals from the ICRF produced ion tail.

An ITER relevant FIR polarimeter for q profile measurements is being planned for C-Mod in FY2006. In preparation for this major diagnostic installation a prototype system at 10.6 μm is being developed and installed for the current run campaign. As can be seen in figures 3.11 and 3.12 the diagnostic will view the plasma poloidally and have access to six retro-reflectors installed on the inner wall. This system will help us quantify edge plasma effects, noise levels, density measurements, and in-vessel component survivability before the FIR system is attempted.

Development has begun on a laser scattering diagnostic to look at the effects of dust in C-Mod. This system will use fibers to couple the light from a visible laser diode into the vessel and then relay the scattered signals back out. It is currently planned to view the outer shelf region of the lower outer divertor. This new diagnostic will help us determine how much dust is present during a discharge, whether or not the dust affects impurity levels in the plasma, and how the dust is generated.

The up-to-air period was used by the MSE group to very carefully check their calibrations with in-vessel instrumentation that allowed very precise polarization measurements to be made. A third position was added to the MSE/BES shutter so that a polarizer can be moved into the viewing path to allow in-situ calibration measurements to be made.

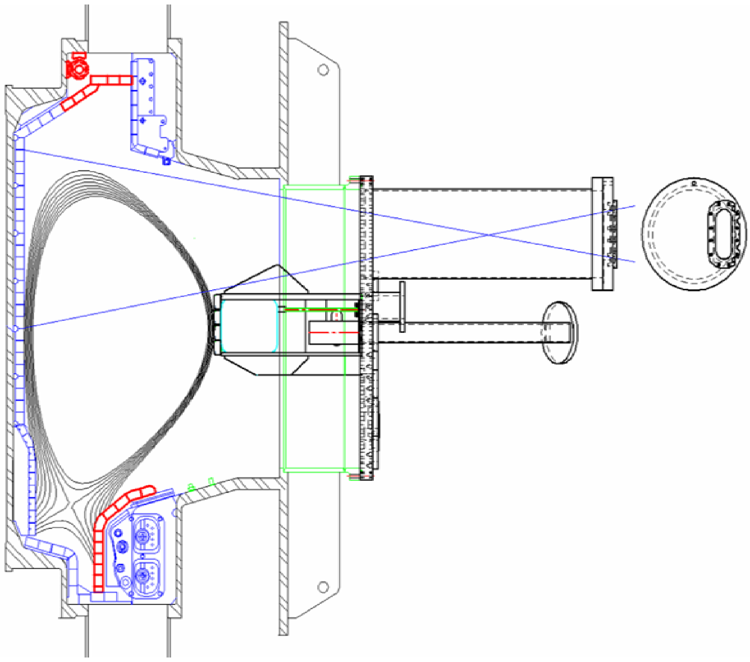

Figure3.11: The polarimeter prototype will view the plasma poloidally. Retro-reflectors on the inner wall at six locations will provide the return beam.

To maintain good performance during a run campaign, several boronizations must be performed. Performance typically degrades between boronizations, so we tend to schedule the most critical runs shortly after a boronization. In order to supply a maintenance level of boron during plasma discharges an injector has been designed and installed on C-Mod (see figure 13). This injector allows up to 25 mg of boron in the form of 40 μm diameter particles to be injected into C-Mod during normal plasma discharges. Experiments will be conducted during this run campaign to assess the effects of this boron on plasma performance. An electromechanical piston drives the boron into the vessel and a laser scattering system monitors the amount of boron being injected.

Data system

Approximately 1.2 GBytes of data is taken during each shot on Alcator C-Mod with our data handling requirements doubling every 2.2 year. To keep up with the very large data flow four new linux servers have been installed, and we continued to expand our Gigabit network. A secondary high speed data acquisition network was also installed. Twelve new linux workstations have been acquired, and we now have 43 workstations running RedHat Enterprise. Seven new CPCI based data acquisition systems have been brought into operation as we continue our migration from CAMAC based systems to the newer, faster, more reliable CPCI hardware. A diskless RedHat Enterprise boot for our diskless CPCI data acquisition systems has been created.

Web access to C-Mod run information has been greatly enhanced over the last year. All C-Mod operation information has been consolidated into a relational database that can viewed and maintained with new web based tools.

We continued to increase online storage capacity for C-Mod shot data so that all data from the first C-Mod discharge to the most recent data is immediately available.

The new digital plasma control system (DPCS) became fully operational this year. This system will allow much more complicated control algorithms to be implemented than were possible with the Hybrid system. In addition, the number of inputs has been increased from 96 to 128, and the number of outputs doubled from 16 to 32.

Over the next year we will continue to increase online data storage capability, complete the conversion of the engineering data acquisition system from CAMAC to CPCI, and continue to improve our video conferencing capability with an H.323 system for the control room.

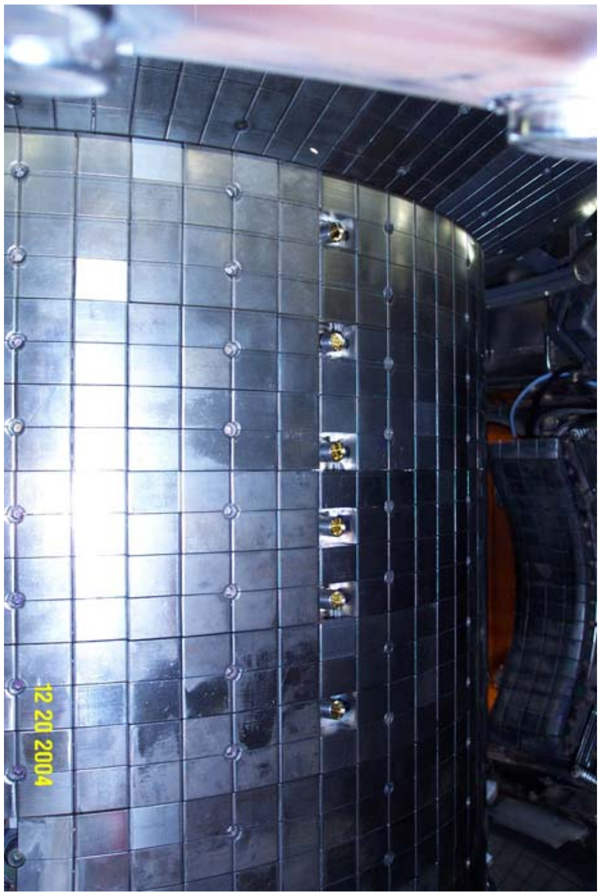

Figure 3.12: Vessel inner wall showing all six polarimeter retro-reflectors

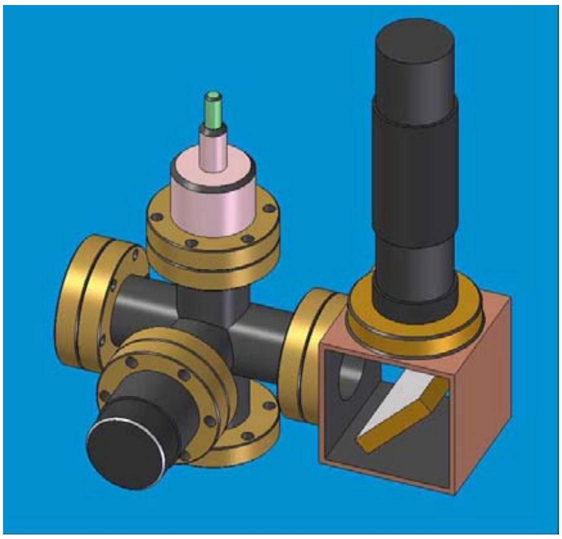

Figure 3.13: Boron injector showing injector and laser scattering system for monitoring boron deposition rate

4. Alcator C-Mod Collaborations

4.1 Introduction

Collaborations are significant in all aspects of the C-Mod program. Collaborators from 18 domestic and 19 international institutions contribute to experiments, theory and modeling. Major collaborations, with the Princeton Plasma Physics Laboratory, and the University of Texas at Austin, are detailed in the next two sections of this proposal, respectively. MIT developed the MDSplus data acquisition, display, analysis and database software tools, which are now in world-wide use. We continue to provide support and perform further software developments, as outlined in section 4.3. A small amount of explicit funding comes through the International Collaborations line of the OFES budget, which partially supports efforts on JET and with the Korean KSTAR project, as outlined in section 4.4.

4.2 PPPL Collaborations

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.

Research aims include:

- research on the effectiveness of plasma current and pressure profile modifications to achieve enhanced plasma performance in the Advanced Tokamak regime through off-axis current drive via Lower Hybrid current drive and high power ICRF heating and current drive;
- the experimental study of basic ICRF plasma-wave interaction processes and their comparison with theory in order to gain predictive capability for heating and current drive in reactor-grade experiments;
- creation and understanding of internal transport barriers through off-axis ICRF heating;
- the study of plasma turbulence and its effect on core confinement; and
- plasma edge turbulence visualization and determination of its effect on transport.

Hardware upgrades, both recent and proposed, include both plasma control and diagnostic components:

- ongoing improvements to the 4-strap ICRF antenna for plasma heating and current drive;
- a LHCD launcher and coupling hardware for control of the plasma current profile through current drive;
- current profile diagnostics to increase understanding of current drive and plasma behavior (in conjunction with a C-Mod-provided diagnostic neutral beam);

- further improvements to edge diagnostics (edge fluctuation measurements at the plasma periphery with reflectometry and 2-D imaging of edge turbulence) to increase understanding of turbulence and transport in the scrape-off region and the pedestal.

Engineering and technical support for RF power systems include:
- engineering assistance in tuning and maintaining the ICRF transmitters, and
- engineering participation in the design, fabrication, and installation of the Lower Hybrid launcher as part of the current-drive system.

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.

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.

Advanced Tokamak Studies

These studies are aimed at the achievement of enhanced plasma confinement predicted by modeling of Advanced Tokamak parameters. This will provide information for the extension of the already successful tokamak concept toward an attractive reactor. We plan to achieve these parameters through modification of the plasma current profile with the application of off-axis Lower Hybrid current drive and the application of 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 at the 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,
- heat with 4 – 8 MW of ICRF power, and
- drive current with ~ 3 MW of lower hybrid power with an efficiency of ~ 0.1 (10^{20}A/W/m^2).

The proposed Lower Hybrid power system utilizes the 4 MW 4.6 GHz system originally used on Alcator C. PPPL has designed and fabricated a waveguide launcher, procured new high power phase shifters/splitters, and is assisting in performing integrated commissioning and testing of the entire system. MIT has provided a suitable location for the equipment, the high voltage power system and controls, water and energy supply, and the installation labor.

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. The optical system, electronics, and software have been supplied by PPPL; the diagnostic neutral beam (DNB) generating the signal is supplied by MIT. Initial measurements of magnetic pitch angle have been made, and extensive in-vessel calibrations and analysis are in progress in order to derive accurate current distributions from them.

Burning Plasma Studies

In the area of high power plasma heating and current drive in the Ion Cyclotron Range of Frequencies (ICRF) our approach is twofold:

- use the increased heating power and current-drive capability to expand the C-Mod physics operating regime and enable understanding of a wider range of plasmas, especially relevant to the high-field approach to burning plasmas, and
- increase the understanding of the physics of ICRF heating and current drive at high power.

C-Mod's high auxiliary heating power allows us to:

- heat the core of internal transport barrier confinement modes produced by simultaneous off-axis heating,
- exceed the H-mode power threshold at 5.4 Tesla by a factor of 2 – 3,
- push past the H-mode threshold at 8 Tesla,
- investigate the EDA mode at lower q-values,
- explore high power divertor operation, and
- achieve higher β_N up to 2 at 5.4 Tesla with multiple frequency operation.

Wave-Particle Studies

The interaction of radiofrequency 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.

Radiofrequency heating studies in the ion cyclotron range of frequencies (ICRF) 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 heating, helium-3 minority in a deuterium majority D(^{3}He), and
- investigate the rich spectrum of phenomena associated with fast wave mode conversion.

Launching an ICRF directed wave allows us to drive plasma current by fast wave current drive (FWCD, core) and mode conversion current drive (MCCD, off-axis):

- explore further plasma rotation with directed waves without external momentum input,
- explore flow shear suppression of turbulence through off-axis mode conversion current drive,
- attempt to form an internal transport barrier through flow shear generation, and
- develop the capabilities to control the radial electric field through toroidal rotation.

Existing C-Mod ICRF diagnostics will be used to assist in these studies. These include phase contrast imaging to measure density fluctuations, RF probes, microwave reflectometry to measure edge and pedestal density profiles, and optical and X-ray spectroscopy to measure H/(H+D) ratios, impurity behavior, and plasma rotation.

Transport Studies

Our studies of plasma transport compare the results of careful measurements with a variety of models to gain insight into the effect of plasma turbulence on transport:

- the relationship between marginal stability and turbulence involves the comparison of data from all the C-Mod fluctuation diagnostics with nonlinear gyrokinetic simulations using the codes GS2 and GYRO,
- insight into electron transport is gained by measuring electron gradient scale length to high precision and comparing experimental and theoretical dependencies of the electron temperature gradient on variation of important parameters such as the q profile, and
- transport processes involved in the formation of internal transport barriers are modeled with the GS2 and possibly GYRO stability codes.

Plasma Boundary Studies

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

- 300 frame "movie" images of edge turbulence structures ("blobs") are obtained with 4μs exposure, giving growth/decay and radial/poloidal motion information, and
- this behavior is compared with a variety of edge turbulence models.

<u>TECHNICAL PROGRESS</u>

In FY2004 and early FY2005, PPPL and the MIT team made the following technical progress.

Advanced Tokamak Studies

- The Lower Hybrid launcher fabrication project was completed in April, 2003. Coupler and launcher repairs resulting from defective electroplating on the launcher and improper commercial stripping of defective electroplating on the coupler have now been completed.
- The LH launcher has now been installed on C-Mod, and final hookup and checkout are in progress.

Burning Plasma Studies

- ICRF heating power has been brought up to 6 MW for 0.35 s and 5MW for 1.0 s.
- Comparison of plasma performance for single-null vs. double-null discharges has been performed.

Wave-Particle Studies

- Although the electrical performance of the ICRF antennas has, in general, been satisfactory, with the achievement of 6 MW power with the boron nitride protection tiles, these tiles have demonstrated mechanical fragility, and are being replaced with molybdenum tiles. In addition, we have found antenna arcing in those cases where plasma parameters raise the edge neutral pressure above ~0.3 mTorr, leading to a modification of the antenna feeds.
- PPPL scientists have participated in the experiments and modeling of the physical processes involved in the mode conversion of a launched fast wave into both an ion cyclotron wave (ICW) and an ion Bernstein wave (IBW).
- We have also participated in experiments that have observed changes in the sawtooth period with changes in antenna phasing for on-axis H minority heating conditions.
- Core localized Alfvèn modes have been observed and studied in high power ICRF experiments.

Transport Studies

- Extensive discussions with the C-Mod team have produced two ideas for experiments designed to elucidate the role of microturbulence. Tools for preparing input for the GYRO turbulence simulation code have recently been extended to extract the needed input from TRANSP simulations of C-Mod plasmas.
- Gyrokinetic simulations of plasma turbulence with the GS2 code were continued to examine H-mode RF heated plasmas which exhibit internal transport barriers (ITB). Nonlinear calculations have also been started.
- A new X-ray crystal spectrometer built in conjunction with the Korea Basic Science Institute has been installed on C-Mod to measure the Doppler shift of helium-like neon and determine poloidal and toroidal rotation of the plasma edge.

Plasma Boundary Studies

- An additional fast camera with as short as 4 μs exposure time and 300 frame capability has been added, allowing improved edge turbulence visualization to increase our measurement of edge turbulence growth and motion.
- Evaluation of the velocity field of turbulent motion in the edge has been performed, showing dominantly outward radial motion outside the seperatrix, and dominant poloidal motion inside the separatrix.
- Comparison of edge turbulence with modeling by the Risø group is in progress.

PPPL Engineering Support

- PPPL engineers, physicists and technical staff provided active participation in the technical issues involved in the Lower Hybrid launcher repair activities.
- PPPL engineers, physicists and technical staff are participating in the installation and initial checkout of the Lower Hybrid launcher on C-Mod.
- PPPL RF engineers and technical staff continued to assist MIT with ICRF transmitter operation, retuning, and repairs.

Publications

- PPPL scientists published 5 first author papers on the C-Mod work in FY 2004, and were included as co-authors on 13 papers by the C-Mod group.

FUTURE ACCOMPLISHMENTS

FY2005

Continue the basic plasma heating and current drive studies at high ICRF power levels and initial Lower Hybrid power, and start to place greater emphasis on the study of those processes relevant to the generation of Advanced Tokamak discharge scenarios.

Advanced Tokamak Studies

- Repair of the first Lower Hybrid launcher has been completed, and it has been delivered to MIT and installed on C-Mod. Hookup and interfacing to the C-Mod-supplied power and control system and front-end coupler will be performed, and low-power testing will commence in plasma.
- Evaluate and optimize the coupling efficiency and power handling capability of the first Lower Hybrid launcher.
- Investigate the physics of coupling Lower Hybrid waves to high density plasmas.
- Initiate current drive in the plasma with the first Lower Hybrid launcher.
- Extensive in-vessel calibrations of the MSE diagnostic has been completed, and its applicability over a wide range of plasma parameters will be determined.

Burning Plasma Studies

- Studies of the Internal Transport Barrier mode will be extended to higher levels of heating power, and its suitability as a target plasma for the Advanced Tokamak LHCD experiments will continue to be investigated.
- The D(^{3}He) experiments performed at 8 Tesla will be repeated at 5.4 Tesla, made possible by retuning one set of ICRF transmitters to 50 MHz, allowing a comparison with D(H) heating in the same discharge.

Wave-Particle Studies

- ICRF antenna behavior will continue to be explored over the full range of plasma parameters and power and phase levels in order to validate the antenna and protection tile modifications.
- The physics study of mode conversion of a launched fast wave into an ion Bernstein wave, an ion cyclotron wave and the associated poloidal flow drive will be continued. This will be extended to include an attempt to suppress plasma turbulence through flow shear, or even to attempt to form an internal transport barrier through flow shear.
- The study of ICRF-induced core-Alfvèn modes will be continued, with ongoing use of the PPPL NOVA-K code and participation of energetic particle physicists.

Transport Studies

- Two experiments designed to elucidate the role of micro-turbulence have been proposed, and mini-proposals will be prepared. The first will search during the ITB formation phase for small changes in the ratio of Te from neighboring ECE channels, which is directly related to the electron temperature gradient scale length. This technique should be capable of reliably detecting changes as small as ~5%. Turbulence simulations codes will be used to predict whether the measured changes 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.
- Participate in X-ray measurements of plasma edge rotation to study plasma rotation and momentum transport.

Plasma Boundary Studies

- Explore edge turbulence behavior under a wide variety of conditions using the improved ultra-fast camera with 300-frame capacity.
- Take edge turbulence data with the standard Gas Puff Imaging diagnostic view and also a new side view, which should be able to image the parallel structure of the turbulence.
- Develop an H-mode trigger signal and use it to measure the time dependence of the poloidal drop in D-alpha light during the L-H transition.
- Attempt to measure the dependence of edge turbulence on collisionality by varying the plasma density and by varying q(a).

PPPL Engineering Support

- The LHCD launcher has been installed in the machine and will be commissioned. PPPL RF engineers and technical staff will assist in all phases of the Lower Hybrid startup.
- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.

FY2006

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. Increase PPPL physics participation by reducing Lower Hybrid operation engineering support, which is expected to be less than that required for LH startup in FY2005.

Advanced Tokamak Studies

- Modify the C-Mod plasma current profile with off-axis LHCD.
- Measure the resulting current profile change with the MSE diagnostic.
- Measure the resulting plasma performance changes with the C-Mod diagnostics.
- Compare the plasma behavior with transport and stability models.
- Upgrade the Motional Stark Effect (MSE) diagnostic based on experimental results from operation in FY2005.

Burning Plasma Studies

- Extend the C-Mod plasma's parameter space by means of the high levels of ICRF heating power.
- Use the high heating power to investigate divertor and inner wall power handling capability.

Wave-Particle Studies

- Continue the study of high power LH wave propagation and absorption both experimentally and through the use of improved LH modeling.
- Continue the study of all aspects of mode conversion physics, including current drive and flow drive.
- Continue the investigation of ICRF-driven energetic particle modes.

Transport Studies

- If a reliable, validated q profile measurement and electron and ion wavelength fluctuation measurements for the plasma core are available, then flux tube gyrokinetic and global code gyrokinetic calculations can be validated, or their shortcomings can be characterized in order to focus code development efforts.
- The internal transport modeling studies will be extended with the use of the GYRO stability code, allowing both linear GS2 and GYRO analysis of RF-generated and Ohmic H-mode ITBs.
- Continue to participate in X-ray measurements of plasma edge rotation to study plasma rotation and momentum transport.

Plasma Boundary Studies

- Perform further experiments based on turbulence imaging to aid in understanding the physics of the L-H transition.
- Attempt to modify plasma turbulence through the application of off-axis LH heating or off-axis current drive.
- Increase the capability of the edge turbulence imaging system by improving the spatial resolution range at the outer midplane through an upgrade to the in-vessel optics.

PPPL Engineering Support

- PPPL RF engineers and technical staff will continue to assist in all phases of the Lower Hybrid system operation. This support is expected to be less than that required for LH startup in FY2005.
- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.
- PPPL physicists, RF engineers and technical staff will assist the C-Mod RF group in the design and preparation of a second 4-strap ICRF antenna.

<u>FY2007</u>

Enable further increase in PPPL physics participation through reduction in LH operation engineering support, which is expected to be less than that required in FY2006 as the LH operation matures.

Advanced Tokamak Studies

- Achieve AT parameters in C-Mod plasmas up to the limits of launcher power and source capability.
- Study the modifications in plasma performance resulting from the changes in current and pressure profile.

Burning Plasma Studies

- Continue to extend the C-Mod plasma's parameter space by means of the high levels of ICRF heating power.

Wave-Particle Studies

- The study of mode conversion physics, including current drive and flow drive, will be continued and extended.
- Continue the investigation of ICRF-driven energetic particle modes.

Transport Studies

- Based on turbulence simulations of C-Mod plasmas with LHCD, new experimental scenarios will be designed to improve confinement and the results will be compared with simulation.
- Internal transport barrier modeling will be extended to nonlinear GS2 and GYRO analysis of the off-axis RF-generated ITBs and Ohmic H-mode ITBs.

Plasma Boundary Studies

- Increase the capability of the edge turbulence imaging system by adding parallel imaging near the X-point.
- Increase the capability by adding imaging of edge turbulence near the inner plasma scrape-off layer (SOL).

PPPL Engineering Support

- PPPL RF engineers and technical staff will continue to assist in all phases of the Lower Hybrid system operation. This support is expected to be less than that required in FY2006.
- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.
- PPPL physicists, RF engineers and technical staff will assist the C-Mod RF group in the design and preparation of a second Lower Hybrid launcher.

FUTURE ACCOMPLISHMENTS - INCREMENTAL

FY2006I

Incremental funding could be used to return the PPPL C-Mod collaboration manpower to near the FY2002 level in order to increase our physics participation. The financial burden of the LHCD launcher repair resulted in the shedding of scientific manpower from the C-Mod collaboration to other projects at PPPL. Nonlinear modeling of the effect of turbulence on transport in the plasma core had been reduced by 50%, internal transport barrier modeling had been reduced by 43%, edge turbulence imaging had been reduced by 38%, and active participation in the reflectometry measurements had been canceled. The FY2005 base budget allows no return toward the FY2002 level. This incremental budget request allows return of the 0.60 FTE to the collaboration before FY 07, with a corresponding increase in the collaboration's scientific productivity.

- Increase the collaboration scientific manpower by 0.60 FTE to return manpower toward the FY2002 level.

FY2007I

Incremental funding could be used to keep the PPPL C-Mod collaboration manpower near the FY2002 level in order to maximize our physics participation. In addition, incremental funding could be used for moderate upgrades to the Motional Stark Effect (MSE) diagnostic (possibly fabricate and install second sightline), the Gas Puff Imaging (GPI) diagnostic, or start an upgrade to the reflectometer diagnostic.

- Keep the collaboration scientific manpower near the FY2002 level.
- Upgrade the Motional Stark Effect (MSE) diagnostic, possibly with the addition of a second sightline, or
- upgrade the Gas Puff Imaging (GPI) diagnostic by optics and sightline improvements (add full poloidal imaging with a wide-angle view to obtain measurements on the poloidal distribution of turbulence), or
- start an upgrade to the reflectometer diagnostic involving the addition of a new 180 GHz channel to perform fluctuation measurements farther into the plasma than the existing equipment allows.

CONTRIBUTIONS TO THE FESAC GOALS AND 5-YEAR OBJECTIVES

(Activities that contribute to two FESAC goals are listed, with the primary goal's listing being labeled "[PRIMARY];" the other listing, for a second goal, is labeled "[SECONDARY].")

FESAC Goal	*5 Year Objectives*	*Contributions by PPPL's C-Mod collaboration*
1. Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation	1.1 Turbulence and transport: Advance understanding of turbulent transport to the level where theoretical predictions are viewed as more reliable than empirical scaling in the best understood systems.	• On C-Mod, PPPL measures edge fluctuations using (a) a reflectometer in order to determine the effect and changes of edge fluctuations on transport and (b) a 2-D edge turbulence-visualization diagnostic. Theoretical models are being benchmarked. [PRIMARY]
	1.3 Wave-particle interactions: Develop predictive capability for plasma heating, flow and current drive, as well as energetic particle driven instabilities, in power-plant relevant regimes.	• On C-Mod, PPPL is utilizing an innovative 4-strap antenna for both heating and current drive studies using fast-wave and mode-conversion current drive. Theoretical modeling of the RF is being conducted. [SECONDARY] • On C-Mod, working with MIT, PPPL will study the control of the spatial distribution of the plasma current density using directed microwave power in the form of lower hybrid waves, and will utilize the resulting profile control to optimize the performance of the tokamak plasma. [SECONDARY]
3. Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma	3.1 Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with	• On C-Mod, working with MIT, PPPL will supply lower hybrid wave launchers to study the control of the spatial distribution of the plasma current density using directed microwave power, and will utilize the resulting profile control to optimize the performance of the tokamak plasma. [PRIMARY] • On C-Mod, PPPL has started to measure the spatial profile of the plasma current density with a Motional Stark Effect diagnostic that measures the direction of the internal magnetic field in the

experiment.	efficient divertor operation, pulse lengths >> energy confinement times.	plasma at numerous locations. PPPL has designed, fabricated, installed and has brought the Motional Stark Effect Diagnostic into operation with the new RFX beam. [PRIMARY]

MILESTONE SCHEDULE

	Baseline	Actual
Complete commissioning of the Lower Hybrid Current Drive system and evaluate its performance in plasma at moderate power.	SEP 05	
Provide RF operations support in the areas of LHCD and ICRF.	SEP 05	
Drive current in plasma with Lower Hybrid launcher, measure change in plasma current profile resulting from off-axis Lower Hybrid current drive, and study changes in plasma transport and stability.	SEP 06	
Provide RF operations support in the areas of LHCD and ICRF.	SEP 06	
Investigate plasma performance over a wide range of AT parameters.	SEP 07	
Provide RF operations support in the areas of LHCD and ICRF.	SEP 07	

MILESTONE SCHEDULE - INCREMENTAL

Upgrade Motional Stark Effect (MSE), Gas Puff Imaging (GPI) or reflectometer diagnostics.	SEP 07	

EXPLANATION OF MILESTONES

- Complete commissioning of the Lower Hybrid Current Drive system and evaluate its performance in plasma at moderate power. (SEP 05)

  Operate the Lower Hybrid launcher in plasma. Start with heating phasing and evaluate coupling efficiency and power handling capability. As power increases, study physics of coupling Lower Hybrid waves at high density. Adjust phasing of launcher to current-drive settings. Study wave coupling and optimize in order to drive an electric current in the plasma.

- Provide RF operations support in the areas of LHCD and ICRF. (SEP 05)

  Provide engineering and technical support for LHCD and ICRF operations.

- Drive current in plasma with Lower Hybrid launcher, measure change in plasma current profile resulting from off-axis Lower Hybrid current drive, and study changes in plasma transport and stability. (SEP 06)

  Operate the Lower Hybrid launcher in current-drive phasing mode with sufficient power to drive an observable current in the plasma. Determine the modification of the plasma current distribution resulting from the Lower Hybrid off-axis current drive. Study the resulting changes in plasma transport and stability.

- Provide RF operations support in the areas of LHCD and ICRF. (SEP 06)

  Provide engineering and technical support for LHCD and ICRF operations.

- Investigate plasma performance over a wide range of AT parameters. (SEP 07)

  Vary plasma parameters over as wide a range as possible while driving off-axis current with Lower Hybrid and utilizing high power ICRF heating to investigate limits of AT performance.

- Provide RF operations support in the areas of LHCD and ICRF. (SEP 07)

  Provide engineering and technical support for LHCD and ICRF operations.

EXPLANATION OF MILESTONES – INCREMENTAL

- Upgrade Motional Stark Effect (MSE), Gas Puff Imaging (GPI) or reflectometer diagnostics. (SEP 07)

  Depending on the needs of the MSE diagnostic as demonstrated by its performance in FY2006, upgrade the Motional Stark Effect diagnostic through possible improvements in optics and the addition of a second sightline. If the MSE needs have been satisfied, perform evolutionary upgrades to the Gas Puff Imaging diagnostic. If funds remain, initiate an upgrade of the C-Mod reflectometer diagnostic through the addition of a new higher-frequency channel at 180 GHz, allowing fluctuation measurements to be performed closer to the plasma center.

RELATIONSHIP TO OTHER PROJECTS

PPPL participates in the C-Mod program as a major collaborator. The MIT Plasma Science and Fusion Center has primary responsibility for the operation of the Alcator C-Mod facility and the structuring of its research program. PPPL's research on C-Mod is integrated with related work world-wide through the ITPA.

4.2 The University of Texas Collaboration

Summary

The University of Texas 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 contains a brief summary of the current results and 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.

Physics Results
Fluctuations were observed by our ECE radiometer "FRCECE"in discharges with peaked density profiles such as those with internal transport barriers (ITB's). In some ITB discharges, the enhanced fluctuations are associated -- perhaps causally -- with quenching of the density rise which is the result of improved confinement in the ITB. We plan to join with other C-Mod physicists to follow up on these results with multi-diagnostic comparisons to identify the mode properties and with diagnostic improvements to the FRCECE system to improve the quality of the data and to extend measurement throughout the C-Mod long-pulse discharges.

Poloidal rotation measurements were made in the region $r/a > 0.7$ using charge-exchange recombination spectroscopy (CXRS). Diagnostic improvements and plans for additional CXRS measurements will be directed toward achieving measurements of radial electric field, searching for poloidal velocity precursors to ITB formation such as have been observed in JET and TFTR, and comparisons between poloidal rotation and neoclassical prediction. The last goal is once again important because of discrepancies identified in JET and DIII-D results.

The width of the quasi-coherent mode along with frequency and poloidal wave number were measured. Improvements to the BES diagnostic will facilitate improved spatial resolution of these measurements and may allow measurement of broadband turbulence just inside the separatrix.

Diagnostics
The FRCECE, with high spatial and temporal resolution is used to provide electron temperature profiles and is being developed as a fluctuation diagnostic. Plans for this diagnostic center on improvements to facilitate turbulence measurements and to allow measurements for the increased pulse length planned for C-Mod.

A CXRS diagnostic is operated to provide profiles of ion temperature and plasma rotation in the outer one-third of the plasma radius. This is a critical region for understanding of pedestal phenomena and is not covered by other diagnostics. The plans for this diagnostic include an increase in the available plasma views, optimization of the views for the new DNB, and improvements in the data acquisition to eliminate increasingly-unreliable CAMAC.

The BES diagnostic has been used for measurement of poloidal wave number, width, and location of the quasi-coherent mode. The plans for this diagnostic include investigation of new optical techniques to improve the measurement of the quasi-coherent mode and to measure broadband fluctuations. Replacement of the current data acquisition system will be considered to allow measurement through the increased DNB pulse length expected in the next few years.

Beam parameter measurements are also included in our collaboration primarily to support the beam diagnostics. These include component mix, neutralization, and beam width.

Theory and simulation is pursued at a significantly lower level than the areas mentioned above. At present, the work is directed toward improved comparison between turbulence theory as represented in the GYRO code (J. Candy, J. Comput. Phys. 186, 545 (2003)) and experiment, and the development of software that will convert the "infinitely detailed" output of gyrokinetic turbulence codes into the "signals" that would be produced by real-world diagnostics. The latter is a component of validating the codes via turbulence measurements.

Students

Two students completed their PhD work during the past year while contributing to the work summarized above:

Alan G. Lynn; Thesis title: "Electron Cyclotron Emission Measurements of Coherent and Broadband Density Fluctuations in the Alcator C-Mod Tokamak"

Mathew B. Sampsell; Thesis Title: "Beam Emission Spectroscopy on the Alcator C-Mod Tokamak"

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. He will be on-site beginning in the summer. Candidates are being interviewed for a second position.

Presentations and publications

A. G. Lynn, P. E. Phillips and A. E. Hubbard, "Electron Cyclotron Emission (ECE) as a Density fluctuation Diagnostic", Rev Sci Instrum **75**, 3859 (2004).

A. G. Lynn, P. E. Phillips, A. E. Hubbard and S. J. Wukitch, "Observations of core modes during RF-generated internal transport barriers in Alcator C-Mod," Plasma Phys Contr Fusion **46**, A61 (2004).

C. L. Fiore, P. T. Bonoli, D. R. Ernst, *et al.*, "Control of internal transport barriers on

Alcator C-Mod," Phys Plasmas **11**, 2480 (2004).

C. Watts, Y. In, J. Heard, P. Phillips, A. Lynn, A. Hubbard and R. Gandy, "Upper limit on turbulent electron temperature fluctuations in the core of Alcator C-Mod," Nucl. Fusion **44**, 987 (2004).

A. G. Lynn, P. Phillips, W. Rowan, *et al.*, "Density and Temperature Fluctuations in Peaked Density Profiles on Alcator C-Mod," submitted to Phys. of Plasmas (2005).

A. E. Hubbard, B. A. Carreras, N. P. Basse, *et al.*, "Local Threshold Conditions and Fast Transition Dynamics of the L-H Transition on Alcator C-Mod," Plasma Phys. Contr Fusion **46**, (2004).

William L. Rowan, M. B. Sampsell, R. S. Granetz, "Interpretation of neutral beam emission spectra as the beam-component density distribution," Review of Scientific Instruments **75**, 3487 (2004).

S. M. Wolfe, I. H. Hutchinson, R. S. Granetz, *et al.*, "Non-axisymmetric field effects on Alcator C-Mod, "submitted for publications in Phys of Plasmas (2004).

R. V. Bravenec and W. M. Nevins, "A System for Direct Comparisons of Nonlinear Simulations of Turbulence with Measurements," to be submitted to Rev. Sci. Instrum.

M. B. Sampsell, R. V. Bravenec, W. L. Rowan, *et al.*, "BES Measurements of the Quasi-coherent Mode on Alcator C-Mod," in preparation.

Presentations:

"Electron Cyclotron Emission (ECE) as a Density Fluctuation Diagnostic" A.G. Lynn, P.E. Phillips, A. Hubbard (contributed poster), presented at the 15th Topical Conference on High-Temperature Plasma Diagnostics San Diego, April, 2004.

"Temperature and Density Fluctuations during Peaked Density Plasmas in Alcator C-Mod," A.G. Lynn, P. Phillips, M. Sampsell, W. Rowan, A. Hubbard, N. Basse, C. Fiore, S. Wukitch, E. Marmar (contributed poster), presented at the 46th Annual Meeting of the Division of Plasma Physics

"Comparisons of Nonlinear Gyrokinetic Simulations of Turbulence with Measurements," R. V. Bravenec and W. M. Nevins (contributed poster), 15th Topical Conference on High-Temperature Plasma Diagnostics, San Diego, April, 2004.

"Synthetic Turbulence Diagnostics for Nonlinear Gyrokinetic Simulations," R. V. Bravenec, W. M. Nevins, D. R. Ernst, J. Candy (contributed talk and poster), 17th Annual US Transport Task Force Workshop, Salt Lake City, Utah, April 29 - May 2, 2004.

"Comparisons of Measurements and Gyrokinetic Simulations of Turbulence and

Transport in Alcator C-Mod EDA H-Mode Discharges." R. V. Bravenec, M. B. Sampsell, J. Candy, D. R. Ernst, and W. M. Nevins (contributed talk), 46th Annual Meeting APS/DPP, Savannah, GA, Nov., 2004.

"Initial Experimental Results from the Alcator C-Mod Compact Neutral Particle Analyzer," V. Tang, R. Parker, J. Liptac, J. Egedal, C. Fiore, R. Granetz, A. Hubbard, J. Irby, Y. Lin, D. Mossessian, S. Wukitch, K. Zhurovich (MIT), W. Rowan (FRC), (contributed poster), 46th Annual Meeting APS/DPP, Nov., Savannah, GA, 2004.

"Ion Temperature and Plasma Rotation in EDA H-Mode and ITB Discharges in Alcator C-Mod," William L. Rowan, R. V. Bravenec, P. E. Phillips, M. B. Sampsell (Fusion Research Center, University of Texas at Austin), R. S. Granetz, B. Lipschultz, R. M. McDermott (Plasma Science and Fusion Center, MIT), (contributed poster), 46th Annual Meeting APS/DPP, Nov., Savannah, GA, 2004.

"Measurement of Neutral Beam Attenuation from Beam Emission," R.M. McDermott, H. Yuh, W.L. Rowan, S.D. Scott, (contributed poster), 46th Annual Meeting APS/DPP, Nov., Savannah, GA, 2004.

"Interpretation of Neutral Beam Emission Spectra as the Beam-Component Density Distribution," William L. Rowan and M. B. Sampsell, and R. S. Granetz, 15th Topical Conference on High Temperature Plasma Diagnostics, Paper A40, San Diego, April 2004.

Transport Highlights and Plans

Using the FRCECE diagnostic, core fluctuations were observed in discharges with peaked density profiles. An example from A. G. Lynn, et al, ("Density and Temperature Fluctuations in Peaked Density Profiles on Alcator C-Mod," submitted to Phys. of Plasmas) is shown in Figure 4.2.1.

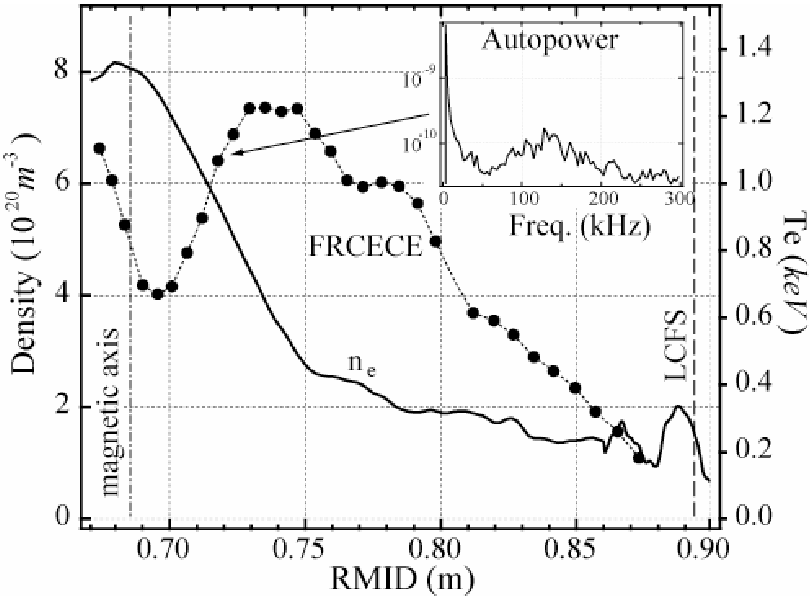

Figure: 4.2.1. Density fluctuations seen by the FRCECE diagnostic in peaked-density ITB shots.

This ITB was produced by application of off-axis ICRF. Note that the FRCECE T_e measurement has an anomalous dip near the magnetic axis. That is an opacity effect which is the key to the measurement of the density fluctuations. The fluctuations become especially interesting in discharges in which additional on-axis RF is applied. In these ITB discharges, enhanced fluctuations are associated -- perhaps causally -- with quenching of the density rise which is the result of the ITB formation. We will continue exploration of ITB fluctuations, especially the broadband fluctuations above 100 kHz which are seen in 4.5T ITB's and attempt to relate these fluctuations to GS2 simulations.

A multi-diagnostic comparison of fluctuations observed in ITB discharges at 5.4 T is warranted because of improvements in the C-Mod phase contrast interferometry system and the addition of an edge reflectometer. Intercomparison of this diverse collection of fluctuation diagnostics will significantly improve the ability of the C-Mod team to identify properties of density and temperature fluctuations and better understand formation and saturation of the ITB.

Poloidal rotation measurements were made in the region $r/a > 0.7$. These measurements will be augmented with new measurements of impurity distribution and with improved toroidal rotation measurements (following repair of the CXRS shutters) to attempt measurement of the radial electric field. This work is intended to improve understanding of the role of the radial electric field in mode transitions and turbulence stabilization, to look for poloidal velocity precursors to ITB formation, and to support comparison of the rotations to neoclassical theory.

The quasi-coherent (QC) mode measurements using BES were compared with other edge measurements including those using FRCECE. The width of the mode was found to differ among the diagnostics. The high frequency modes originally proposed on the basis of BOUT simulations were not observed. For the next campaign, a subset of the BES fibers have been consolidated into a dense 6x6 array to provide better resolved spatial measurements of the QC mode. We plan to diagnose the radial structure of the QC mode with the new fiber array and also to use it to investigate background turbulence just inside the separatrix.

<u>FY2005</u>

Using the high resolution ECE diagnostic, we will investigate the electron temperature scale length L_{Te} in ITB discharges and pellet discharges. Like other gradients, the temperature gradient is an energy source for turbulence and its measurement is important in understanding transport. In this particular instance, ETG modes are driven principally by the electron temperature gradient. From another point of view, L_{Te} is a good first step for acquiring an empirical □$_e$ for a discharge.

Continue exploration of ITB fluctuations, especially the broadband >100-kHz fluctuations seen in 4.5T ITB's and attempt to compare these with gyrokinetic simulations. Cross-correlate fluctuations observed with the FRCECE diagnostic in ITB discharges at 5.4 T with the improved PCI system and with the edge reflectometer to identify properties of density and temperature fluctuations. Comparison with fluctuations from the GS2 code with the observed fluctuations. A comparison of broadband fluctuations seen in ITB's with and without RF will be undertaken and this will also be used in the GS2 code investigation.

Develop the measurement of radial electric field in the outer regions of the ITB using the CXRS diagnostic system.

Diagnose the radial structure of the QC mode with the improved BES diagnostic.

<u>FY2006</u>

Observe non-Maxwellian tail during LHCD and coordinate similar experiments on HT-7 and C-Mod. This work will be coordinated with the modeling of non-thermal ECE emissions during LHCD now underway at MIT.

Attempt to detect background turbulence just inside the separatrix with the BES system using the new 6x6 fiber array.

<u>FY2007</u>

Possible comparison with DIII-D L-mode discharges which exhibit transient improvement in electron and ion thermal transport during the current ramp up as q_{min} traverses rational values.

Theory and Simulation

Theory and simulation is pursued at a significantly lower level than the other transport areas. At present, the work is directed toward improving the comparison between theory and experiment. A system based on the GKV suite of IDL routines (W. M. Nevins, LLNL Rept. No. UCRL-TR-206016, August, 2004) has been developed in which user-supplied "filters" can be applied to gyrokinetic code outputs to simulate individual diagnostics ("synthetic diagnostics"). The simulated "measurements" can be compared to actual measurements. In the FRC work, beam-emission spectroscopy (BES) has been synthesized and applied to a GYRO simulation of the top of the pedestal of a C-Mod EDA H-mode plasma. The simulation indicates that the sample volume of the BES system on C-Mod was too large to detect the small-scale fluctuations and motivated the development of higher resolution optics for the C-Mod BES system.

Another goal of this work is to incorporate the new CXRS measurements of T_i and E_r into GYRO simulations. This will greatly improve the reliability of this work and complement the work with GS2 which is being done within the MIT-PPPL collaboration. To further facilitate this work, we plan to work with MIT theorists to run a GYRO/GS2 benchmark using C-Mod data. The aim is to further establish validity of the codes.

<u>FY2005</u>

Run a GYRO/GS2 benchmark using C-Mod data (in collaboration with D. Ernst).

<u>FY2006</u>

Incorporate new CXRS measurements of T_i and E_r into GYRO simulations.

Highlights and Plans for the Diagnostic Systems

FRC Electron-Cyclotron-Emission System

This diagnostic provides T_e data on fine temporal and spatial scales. This capability is useful to all other experimental programs, not just those of the FRC. Core fluctuations are observed by the FRCECE in discharges with peaked density profiles. In some ITB discharges, the enhanced fluctuations are associated -- perhaps causally -- with quenching of the density rise which is the result of the ITB formation. Our plans for this diagnostic are intended to support the research in fluctuations, T_e scale lengths, and T_e measurement for long-pulse plasmas.
Figure 4.2.2 is particularly instructive. It demonstrates the means for combining the available T_e diagnostics to achieve reliable profiles. Note that the Thomson scattering diagnostic measures with limited core resolution, and provides measurements across the entire plasma. The high resolution FRCECE system adds detailed spatial resolution. The grating polychromator resolution is significantly coarser both temporally and spatially, but it provides measurement over a wider range of toroidal field.

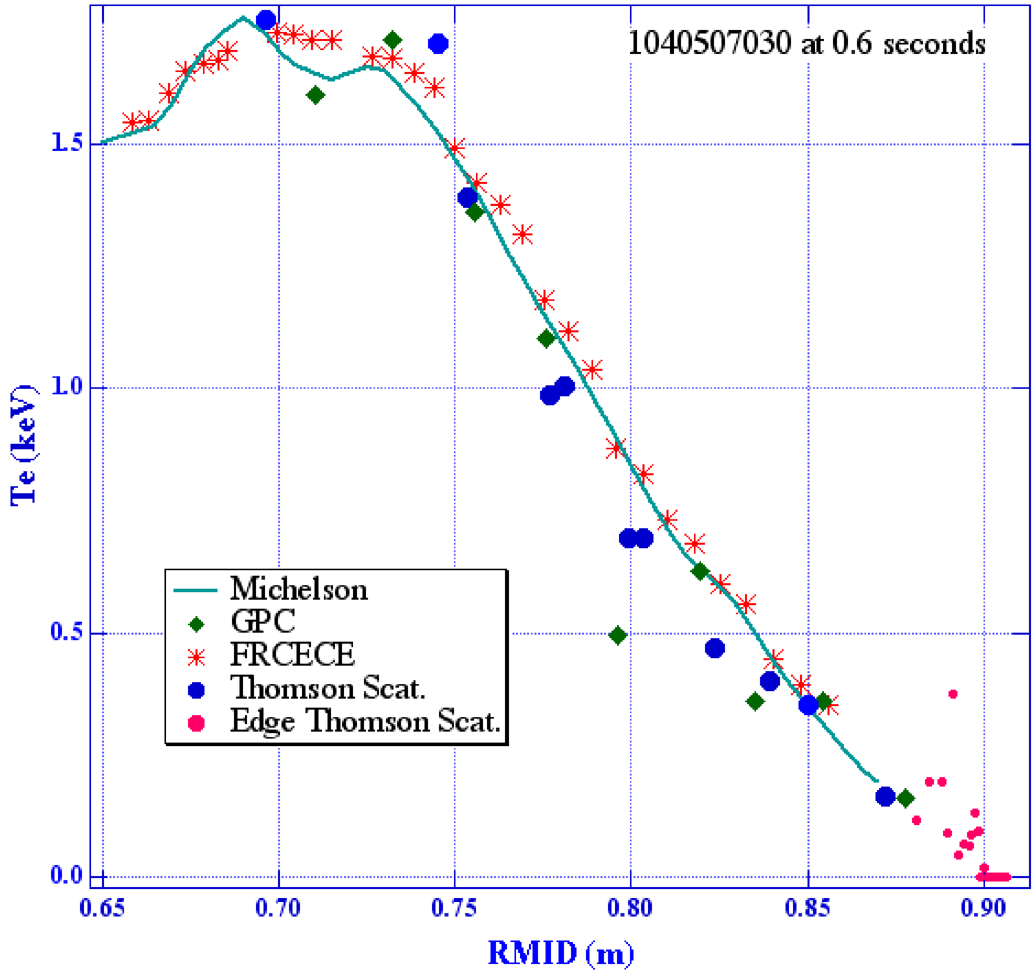

Figure 4.2.2. Electron temperature profile diagnostics on Alcator C-Mod: Michelson interferometer (absolute calibration), Grating Polychrometer (GPC) - 16 channels, Heterodyne ECE (FRCEC) - 32 channels, Core Thomson Scattering - 14 channels at 30 Hz, and Edge Thomson Scattering - 20 channels at 30 Hz.

<u>FY2005</u>

Modify the 32-channel filter box to allow the fast signals to be easily switched between the smaller number of available fast channels

<u>FY2006</u>

Increase the number of high frequency channels from 10 to 16 and implement the capability for recording high frequency data for the extended C-Mod pulse length. Fluctuation frequencies associated with broadband fluctuations as well as those associated with the EDA H-mode are often above the 100-kHz limit of the present ECE system. With more channels operating at the higher frequency limit, we can observe fluctuations in n_e and T_e over a larger spatial range in the plasma and throughout the C-Mod shot. This upgrade will be made with CPCI hardware.

Add remote power management to allow power cycling of all major components from anywhere on the internet.

FY2007

Replace CAMAC timing modules with CPCI units and thus eliminate the last of the aging CAMAC units in this system.

CXRS

A CXRS diagnostic is operated to provide profiles of ion temperature and plasma rotation in the outer one-third of the plasma radius. This is a critical region for understanding of pedestal phenomena and is not covered by other diagnostics. During the past year, the diagnostic has provided T_i and rotation measurements with the principal limitation being the short pulse length of the DNB. An example of the poloidal rotation measured using a boron impurity is shown in Figure 4.2.3.

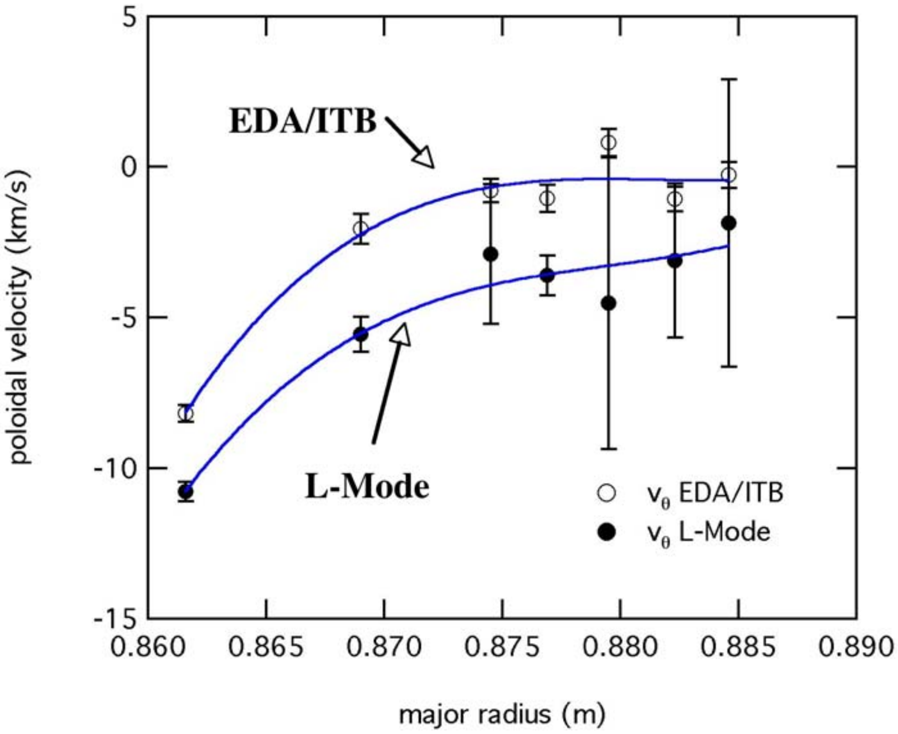

Figure 4.2.3. Poloidal rotation comparison for L-Mode and EDA/ITB discharges

There is a clear distinction between the L-Mode rotation and that observed in EDA discharges that evolve to ITB discharges. Whether this is due to a change in radial electric field or to impurity distribution is yet to be determined.

With the improved pulse length, availability of analyzed data will improve. The plans for this diagnostic include an increase in the available plasma views, optimization of the views for the new DNB, and improvements in the data acquisition to eliminate increasingly-unreliable CAMAC.

FY2005

Make detailed rotation measurements in the outer third of the plasma.
As noted in the earlier sections, this will lead to measurement of E_r and to comparison with neoclassical transport.

Redesign of the toroidal optics and shutter system:
The shutter fails to completely shield the optics during boronization. The steel mirrors have proven unnecessary and can now be replaced with higher reflectivity mirrors.

Increase the number of transfer fibers so that the full complement of available views can be used simultaneously.

FY2006

Add poloidal and toroidal channels nearer the core. Some core channels were sacrificed to implement channels which measure background emission. For the high density discharges commonly studied until now, core channels were not very useful. With increased emphasis on lower density plasmas for LHCD, core CXRS channels will be useful.

FY2007

Add another detector/spectrometer to further increase the number of simultaneous views.

Beam Emission Spectroscopy

A procedure was developed for processing the detailed fluctuation results available from turbulence simulations to obtain the expected output from the BES diagnostic. In one example, the observed strong attenuation of higher frequencies in measurements in the core plasma are successfully explained. As developed, the procedure can be applied to any BES system. The method is flexible enough to be generalized to other turbulence diagnostics.
A new fiber array with high spatial resolution was installed and will be used to diagnose the radial structure of the QC mode as well as to attempt to detect background turbulence just inside the separatrix.
The longer pulse lengths planned for C-Mod will require improvements in data acquisition. As for many other C-Mod diagnostics, the current CAMAC units are not adequate for this and with age, are becoming increasingly unreliable. CPCI will be tested during the current campaign, and if successful, the diagnostic will be converted from the present CAMAC-based DAQ to CPCI. The longer pulse length will also improve the statistics of the fluctuation measurements.
Sharing optical systems with the MSE diagnostic has proved a workable but seriously flawed procedure. The major problem is the reduction if transmission of the system due

to the polarization optics. We plan to design and install at least a small system which will be available at all times for BES measurements

FY2005

Test CPCI data acquisition.
Investigate utility of the high spatial resolution fiber-optic system

FY2006

Add CPCI channels.
Design a stand-alone BES optical system.

FY2007

Install stand-alone optics

Beam diagnostics

A spectroscopic diagnostic for beam neutralization efficiency was developed and reported during the last year. Beam emission (acquired using the MSE diagnostic) was developed for measurement of beam attenuation. Spectroscopic measurements of component mix, beam width and local measurements of beam density using the BES diagnostic will continue to be made available. In the coming campaign, these will be employed to develop the long-pulse DNB and optimize it for MSE, BES, and CXRS measurements.

4.3 MDSplus

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. The MDSplus event server software was modified to improve stability and reliability under heavy load. A PHP interface to MDSplus was created to support web based applications. New support for data acquisition hardware was added, with emphasis on CPCI devices which have become increasingly popular. Support for firewire digital camera systems has been added. Site specific work has been done for experimental groups at Columbia University, KSTAR (KBSI-Korea), CHS (NIFS- Japan), LDX (MIT), DIII-D. This work now includes support for ITPA groups which are adopting MDSplus as a standard for their profile databases. Design for these databases is complete and tools for administration and data entry are in preparation. A list of active fusion sites is appended at the end of this document. Navigation for the MDSplus web site (www.mdsplus.org) has been upgraded and documentation has been improved and though this work is still incomplete.

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 an biennial basis. The next meeting is scheduled in conjunction with the IAEA technical meeting in Budapest in July 2005. MDSplus software maintenance will continue to be a principle activity. We will continue to support the ITPA activities via technical expertise, scripts and templates for data entry and documentation.

In response to requests from several new experiments and the needs of advanced simulations, extensions to MDSplus to support long-pulse operation will begin with conceptual design work. Both applications will require the ability to store data incrementally and will need a conceptual framework for describing and browsing data sets which are too large to be displayed by conventional means. Upgrades to the Scope utility are planned, with the highest priority being the ability to display multiple traces in each panel. Capabilities for color plotting would be added at the same time. Support for additional data acquisition devices – particularly CPCI will be provided as useful modules are identified. Additional language support is ongoing at MIT and elsewhere including client access through PERL, PYTHON, SCILAB and Visual Basic.

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

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

4.4 International Collaborations

4.4.1 JET Collaborations

Collaborations between C-Mod and JET are ongoing in a number of topical areas, including transport, macroscopic stability, RF physics and plasma-boundary interactions. Subjects being emphasized are edge barrier stability and dynamics, core transport and confinement, error fields and locked modes, fast particle driven alfven modes, massive gas jet disruption mitigation, ICRF and Lower Hybrid physics, scrape-off-layer transport, recycling and isotope retention, as described earlier in this work proposal. Joint experiments are coordinated through the ITPA process. A portion of this effort is supported by funding from the International Collaborations budget, and the rest from the base C-Mod program. The explicit international collaboration funding supports a small number of trips to JET, as well as small fractions of the salaries for some of the scientists involved in the research. In addition to the topics already listed, we are in negotiation with JET for possible future participation with them as they consider changing a substantial fraction of their plasma facing components from carbon to tungsten; results from the tungsten prototype tiles on C-Mod should be particularly relevant to this topic.

4.4.2 KSTAR Collaboration

The KSTAR is planning on using MDSplus software for data acquisition and data management. MIT will provide support and consultation for this implementation including help for the KSTAR team as it develops drivers for data acquisition equipment not currently supported. Developments at MIT would include "grid-computing" implementations for MDSplus involving secure access to data via authentication and distributed authorization. Grid related work will also include parallel network i/o for remote access to MDSplus data. This approach helps avoid bottle-necks in data transfer which arise from the flow control algorithms in the TCP protocol. We would anticipate periodically hosting engineers from KSTAR to increase the "bandwidth" of the interactions.

Appendix A

Alcator C-Mod Publications – FY2004 to present

Papers Published in Refereed Journals

Boswell, C.J. Terry, J.L., LaBombard, B., Lipschultz, B., Pitcher, C.S., "Interpretation of the D_α emission from the high field side of Alcator C-Mod," Plasma Phys. and Control. Fusion **46** No.8 (2004) 1247.

Bonnin, X., Coster, D., Schneider, R., Reiter, D., Rozhansky V., Voskoboynikov, S., 'Modelling and consequences of drift effects in the edge plasma of Alcator C-Mod," J. Nucl. Mater. **337-339**, 301-304 (2005).

Ernst, D.R., Bonoli, P.T., Catto, P.J., Dorland, W., Fiore, C.L., Granetz, R.S., Greenwald, M., Hubbard, A.E., Porkolab, M., Redi, M.H., Rice, J.E., Zhurovich, K. "Role of trapped electron mode turbulence in internal transport barrier control in the alcator C-Mod Tokamak," Phys. Plasmas **11** No. 5 (2004) 2637.

Fiore, C.L., Bonoli, P.T., Ernst, D.R., Hubbard, A.E., Greenwald, M.J., Lynn, A., Marmar, E.S., Phillips, P., Redi, M.H., Rice, J.E., Wolfe, S.M., Wukitch, S.J., Zhurovich, K., "Control of internal transport barriers on Alcator C-Mod," Phys. Plasmas **11** No. 5 (2004) 2480.

Fiore, C.L., Bonoli, P.T., Ernst, D.R., Greenwald, M.J., Marmar, E.S., Redi, M.H., Rice, J.E., Wukitch, S.J., Zhurovich, K., "Internal Transport Barrier Production and Control in Alcator C-Mod," Plasma Phys. Control. Fusion **46** No 12B (2004) B281.

Gangadhara, S., LaBombard, B., "Impurity plume experiments in the edge plasma of the alcator C-Mod tokamak," Plasma Phys. Control Fusion **46**, No 10 (2004) 1617.

Ghosh, J., Griem, H.R., Elton, R.C., Terry, J.L., Marmar, E., Lipschultz, B., LaBombard, B., Rice, J.E., Weaver, J.L., "Measurements of ion and neutral atom flows and temperatures in the inner and outer midplane scrape-off layers of the Alcator C-Mod Tokamak," Phys. Plasmas **11** No. 3 (2004) 1033.

Grulke, O., (MPI for Plasma Physics, Greifswald Branch, EURATOM Association, D-17489 Greifswald, Germany) Garcia, O. E. et al., "Dynamics of spatiotemporal fluctuation structures in the scrape-off layer of Alcator C-Mod and NSTX," Phys. Rev. Letters **92** (16), 2004.

Hutchinson, I.H., **"**Spin Stability of Asymmetrically Charged Plasma Dust," New J. Phys. **6** (2004) 43.

Hutchinson, I.H. "Ion Collection by a Sphere in a Flowing Plasma: 3. Floating Potential and Drag Force," Plasma Phys. Control. Fusion **47** No 1 (2005) 71-87.

LaBombard, B., Rice, J.E., Hubbard, A.E., Hughes, J.W., Greenwald, M., Irby, J., Lin, Y., Lipschultz, B., Marmar, E.S., Pitcher, C.S., Smick, N., Wolfe, S.M., Wukitch, S.J., "Transport-Driven Scrape-off Layer Flows and the Boundary Conditions Imposed at the Magnetic Separatrix in a Tokamak Plasma," Nucl. Fusion **44** No 10 (October 2004) 1047.

Lin, Y., Wukitch, S., Bonoli, P., Nelson-Melby, E., Porkolab, M., Wright, J.C., Basse, N., Hubbard, A.E., Irby, J., Lin, L., Marmar, E.S., Mazurenko, A., Mossessian, D., Parisot, A.; Rice, J., Wolfe, S., Phillips, C.K., Schilling, G., Wilson, J.R., Phillips, P., Lynn, A., "Investigation of ion cyclotron range of frequencies mode conversion at the ion-ion hybrid layer in Alcator C-Mod," Phys. Plasmas **11** No. 5 (2004) 2466.

Marmar, E.S., Bai, B., Boivin, R.L., Bonoli, P.T., Boswell, C., Bravenec, R., Carreras, B., Ernst, D., Fiore, C., Gangadhara, S., Gentle, K., Goetz, J., Granetz, R., Greenwald, M., Hallatschek, K., Hastie, J., Hosea, J., Hubbard, A., Hughes, J.W., Hutchinson, I., In, Y., Irby, J., Jennings, T., Kopon, D., Kramer, G., LaBombard, B., Lee, W.D., Lin, Y., Lipschultz, B., Liptac, J., Lynn, A., Marr, K., Maqueda, R., Melby, E., Mikkelsen, D., Mossessian, D., Nazikian, R., Nevins, W.M., Parker, R., Pedersen, T.S., Phillips, C.K., Phillips, P., Pitcher, C.S., Porkolab, M., Ramos, J., Redi, M., Rice, J., Rogers, B.N., Rowan, W.L., Sampsell, M., Schilling, G., Scott, S., Snipes, J., Snyder, P., Stotler, D., Taylor, G., Terry, J.L., Wilson, H., Wilson, J.R., Wolfe, S.M., Wukitch, S., Xu, X.Q., Youngblood, B., Yuh, H., Zhurovich, K., Zweben, S., "Overview of recent Alcator C-Mod research," Nuclear Fusion **43**, No. 12 (2003) 1610-18.

Parisot, A., Wukitch, S.J., Bonoli, P., Hughes, J.W., Labombard, B., Lin, Y.,Parker, R., Porkolab, M., Ram, A.K., "ICRF loading studies on Alcator C-Mod," Plasma Phys. Control. Fusion **46** No 11 (2004) 1781.

Pigarov, A.Y. (MAE Center for Energy Res., California Univ., San Diego, La Jolla, CA, USA), Krasheninnikov, S.I.; Rognlien, T.D., West, W.P., LaBombard, B.L., Lipschultz, B., Maingi, R., Soukhanovskii, V., "Multi-fluid code simulations including anomalous non-diffusive transport of plasma and impurities in the tokamak SOL," Plasma Physics **44** No 1-3 (2004) 228-34.

Pigarov, A.Y., Krasheninnikov, S.I., Brooks, N., Hollmann, E., Maingi, R., Labombard, B., Lipschultz, B., Rognlien, T., Soukhanovskii, V., West, W. P., "Multi-ion fluid simulation of tokamak edge plasmas including non-diffusive anomalous cross-field transport," J. of Nucl. Materials **337–339** (2005) 371

Rice, J.E., Lee, W.D., Marmar, E.S., Bonoli, P.T., Granetz, R.S., Greenwald, M.J., Hubbard, A.E., Hutchinson, I.H., Irby, J.H., Lin, Y., Mossessian, D., Snipes, J.A., Wolfe, S.M., Wukitch, S.J., "Observations of anomalous momentum transport in Alcator C-Mod plasmas with no momentum input," Nuc. Fusion **44** No. 3 (2004) 379.

Rice, J.E., Lee, W.D., Marmar, E.S., Basse, N.P., Bonoli, P.T., Greenwald, M.J., Hubbard, A.E., Hughes, J.W., Hutchinson, I.H., Ince-Cushman, A., Irby, J.H., Lin, Y., Mossessian, D., Snipes, J.A., Wolfe, S.M., Wukitch, S.J., Zhurovich, K., "Toroidal rotation and momentum transport in Alcator C-Mod plasmas with no momentum input," Phys. Plasmas **11** No. 5 (2004) 2427.

Snipes, J.A., Schmittdiel, D., Fasoli, A., Granetz, R.S., Parker, R.R., "Initial active MHD spectroscopy experiments exciting stable Alfven eigenmodes in Alcator C-Mod," Plasma Phys. Control. Fusion **46** No 4 (2004) 611.

Terry, J.L., Zweben, S.J., Bose, B., Grulke, O., Marmar, E.S., Lowrance, J., Mastrocola, V., Renda, G., "High speed movies of turbulence in Alcator C-Mod," Review of Scientific Instruments, v 75, n 10 II, October, 2004, p 4196-4199

Wright, J.C., Bonoli, P.T., D'Azevedo, E., Brambilla, M., "Ultrahigh Resolution Simulations of Mode Converted Ion Cyclotron Waves and Lower Hybrid Waves," Computer Physics Communications **164** 1-3, 1-15 (2004) 330.

Wright, J.C., Bonoli, P.T., Brambilla, M., Meo, F., D'Azevedo, E., Batchelor, D. B., Jaeger, E. F., Berry, L. A., Phillips, C. K. and Pletzer, A., "Full Wave Simulations of Fast Wave Mode Conversion and Lower Hybrid Wave Propagation in Tokamaks," Physics of Plasmas **11** (5) (2004) 2473.

Wukitch, S.J., Boivin, R.L.1, Bonoli, P.T., Goetz, J.A., Irby, J., Hutchinson, I.H., Lin, Y., Parisot, A., Porkolab, M., Marmar, E., Schilling, G., and Wilson, J.R., "Investigation of Performance Limiting Phenomena in a Variable Phase ICRF Antenna in Alcator C-Mod," Plasma Phys. Control. Fusion **46** No 9 (2004) 1479.

Watts, C. (New Mexico Tech, Socorro, NM, USA), Yongkyoon I., Heard, J., Phillips, P., Lynn, A., Hubbard, A., Gandy, R., "Upper limit on turbulent electron temperature fluctuations in the core of Alcator C-Mod," Nuclear Fusion **44** No. 9 (2004) 987-91.

Lee, W.D., Rice, J.E., Marmar, E.S., Greenwald, M.J., Hutchinson, I.H., Snipes, J.A., "Observation of anomalous momentum transport in Tokamak plasmas with no momentum input," Physical Review Letters **91** No. 20 (2003) 205003/1-4.

Papers Submitted for Publication

Bonnin, X., Coster, D., Schneider, R., Reiter, D., Rozhansky, V., Voskoboynikov, S., "Modeling and consequences of drift effects in the edge plasma of Alcator C-Mod," Accepted for publication in J. Nucl. Mater.

Chung, T., **"**Study of Recycling Impurity Retention in Alcator C-Mod," PSFC/RR-04-1, September 2004. J. Nucl. Mater.

Cordey, J.G., Snipes, J.A., Greenwald, M., Sugiyama, L., Kardaun, O.J.W.F., Ryter, F., Kus, A., Stober, J., DeBoo, J.C., Petty, C.C., Bracco, G., Romanelli, M., Cui, Z., Liu, Y., Cordey, J.G., Thomsen, K., McDonald, D.C., Miura, Y., Shinohara, K., Tsuzuki, K., Kamada, Y., Takizuka, T., Urano, H., Valovic, M., Akers, R., Brickley, C., Sykes, A., Walsh, M.J., Kaye, S.M., Bush, C., Hogewei, D., Martin, Y., Cote, A., Pacher, G., Ongena, J., Imbeaux, F., Hoang, G.T., Lebedev, S., Chudnovskiy, A., Leonov, V., "The scaling of confinement in ITER with b and collisionality," Nuclear Fusion.

Greenwald, M., Andelin, D., Basse, N., et al., "Overview of the Alcator C-Mod Program," submitted for publication to the Proceedings of the 20th IAEA Fusion Energy Conference.

LaBombard, B., Rice, J.E., A.E. Hubbard, Hughes, J.W., Greenwald, M., Granetz, R.S., Irby, J.H., Lin, Y., Lipschultz, B., Marmar, E.S., Marr, K., Mossessian, D., Parker, R., Rowan, W., Smick, N., Wolfe, S.M. and Wukitch, S.J., "Scrape-off layer flows, magnetic topology and influence on the L-H threshold in a tokamak," Nuc. Fusion.

LaBombard, B., Rice, J.E., Hubbard, A.E., Hughes, J.W., Greenwald, M., Granetz, R.S., Irby, J.H., Lin, Y., Lipschultz, B., Marmar, E.S., Marr, K., Mossessian, D., Parker, R., Rowan, W., Smick, N., Snipes, J.A., Terry, J.L., Wolfe, S.M., Wukitch S.J. and the Alcator C-Mod Team, "Transport-driven scrape-off layer flows and the x-point dependence of the L-H power threshold in Alcator C-Mod," Physics of Plasmas.

Lisgo, S., Boswell, C., Bourner, P., LaBombard, B., Lipschultz, B., Elder, J D., Reiter, D., Stangeby, P.C., Terry, J.L., Weisen, S., "OSM-EIRENE modeling of neutral pressures in the Alcator C-Mod divertor," J. Nucl. Mater.

Lynch, V. E., Carreras, B. A., Sanchez, R., LaBombard, B. van Milligen, B.Ph., Newman, D. E., "Determination of Long-Range Correlations by Quiet-Time Statistics," Physics of Plasmas.

Marr, K., Lipschultz, B., LaBombard, B., Terry, J.L., "Spectroscopic measurements of plasma flow in the SOL in C-Mod."

Martin, Y.R., Snipes, J.A., Greenwald, M., Ryter, F., Kardaun, O.W.F., Stober, J., Valovic, M., DeBoo, J.C., Andrew, Y., Cordey, J., Sartori, R., Thomson, K., Takizuka, T., Miura, Y., Fukuda, T., Kamada, Y., Shinohara, K., Tsuzuki, K., Kaye, S.M., Bush, C., Maingi, R., Lebedev, S., "H-mode threshold power dependences in ITPA threshold database," Nuclear Fusion.

Rice, J.E., Hubbard, A.E., Hughes, J.W., et al., "The Dependence of Core Rotation on Magnetic Configuration and the Relation to the H-mode Power Threshold in Alcator C-Mod Plasmas with No Momentum Input," submitted for publication to the Proceedings of the 20th IAEA Fusion Energy Conference.

Smick, N., LaBombard, B., Pitcher, C.S. "Plasma Profiles & Flows in the High-Field Side Scrape-off Layer in Alcator C-Mod," J. Nucl. Mater.

Whyte, D. G., Lipschultz, B.L., Stangeby, P.C., Boedo, J., Rudakov, D.L., Watkins, J.G., West, W.P., "The Magnitude of Plasma Flux to the Main-wall in the DIII-D Tokamak" Plasma Phys. Control. Fusion

Wolfe, S. M., Hutchinson, I. H., Granetz, R. S., Rice, J., Hubbard, A., Lynn, A., Phillips, P., Hender, T. C., Howell, D. F., La Haye, R. J. and Scoville, J. T., "Non-axisymmetric field effects on Alcator C-Mod," Physics of Plasmas.

Wright, J.C., Berry L. A., Bonoli P. T., Batchelor D.B., Jaeger E. F., Carter M.D., D'Azevedo E., Phillips C.K., Okuda H., Harvey R.W., Smithe D. N., Myra J. R., D'Ippolito D. A., Brambilla M., and Dumont R. J., "Nonthermal Particle and Full-Wave Diffraction Effects on Heating and Current Drive in the ICRF and LHRF Regimes," accepted for publication in Nuclear Fusion (2005).

Xu, X.Q., Cohen, R.H., Nevins, W.M., Rognlien, T.D., Ryutov, D.D., Umansky, M.V., Pearlstein, L.D., Bulmer, R.H., Russell, D.A., Myra, J.R., D'Ippolito, D.A., Greenwald, M., Snyder, P.B., Mahdavi, M.A., "Density effects on tokamak edge turbulence and transport with magnetic X- points," Nuclear Fusion.

MIT Plasma Science and Fusion Center Reports (including theses)

Parisot, A., "Design of an ICRF Fast Matching System on Alcator C-Mod," PSFC/RR-04-2, September 2004.

Conferences
IAEA Fusion Energy Conference
Vilamoura, Portugal, 1-6 November 2004

Ernst, D., "Mechanisms for ITB Formation and Control in Alcator C-Mod Identified through Gyrokinetic Simulations of TEM Turbulence."

Greenwald, M., "Overview of the Alcator C-Mod Program."

Hutchinson, I.H., "Asymmetric-Field Mode Locking in Alcator C-Mod."

Porkolab, M., "Mode Conversion, Current Drive and Flow Drive with High Power ICRF Waves in Alcator C-Mod: Experimental Measurements and Modeling."

Terry, J., "Transport Phenomena in the Edge of Alcator C-Mod Plasmas."

Wright, J., "Nonthermal Particle and Full-Wave Diffraction Effects on Heating and Current Drive in the ICRF and LHRF Regimes."

Rice, J.E., "The Dependence of Core Rotation on Magnetic Configuration and the Relation to the H-mode Power Threshold in Alcator C-Mod Plasmas with No Momentum Input."

16th International Conference on Plasma in Controlled Fusion Devices
Portland, Maine, U.S.A. May 24–28, 2004

LaBombard, B., Smick, N., Lipschultz, B., et al., "Poloidal Transport Asymmetries, Edge Plasma Flows and Toroidal Rotation in Alcator C-Mod."

Marr, K., Lipschultz, B., LaBombard, B., Terry, J.L., "Spectroscopic measurements of plasma flow in the SOL in C-Mod."

Chung, T., Hutchinson, I.H., Lipschultz, B., et al., "DIVIMP modeling of impurity flows and screening in Alcator C-Mod."

Terry, J.L., Zweben, S.J., Grulke, O., et al., "Comparisons of Edge/SOL Turbulence in L- and H-mode Plasmas of Alcator C-Mod."

Smick, N., LaBombard, B., Pitcher, C.S., "Plasma Profiles and Flows in the High-Field Side Scrape-off Layer in Alcator C-Mod."

American Physical Society, Division of Plasma Physics
Savannah, GA, 15-19 November 2004

Invited Orals

Bonoli, P., "Full-wave Electromagnetic Field Simulations in the Lower Hybrid Range of Frequencies."

Grulke, O., "Dynamics of spatiotemporal fluctuation structures in the scrape-off layer of the Alcator C-Mod and NSTX."

LaBombard, B., "Transport-driven scrape-off layer flows and the x-point dependence of the L-H power threshold in Alcator C-Mod."

Snipes, J., "Active and Fast Particle Driven Alfven Eigenmodes in Alcator C-Mod".

Wolfe, S., "Non-axisymmetrix field effects on Alcator C-Mod".

Wukitch, S., "ICRF Mode Conversion Physics in Alcator C-Mod: Measurements and Model Validation."

Contributed Orals

Basse, N., "Turbulence associated with the control of internal transport barriers in Alcator C-Mod plasmas."

Fiore, C., "New Results from C-Mod Internal Transport Studies."

Greenwald, M., "Rotation Scrape-off Layer Flows and the Topology Dependence of the H-Mode Threshold."

Hughes, J., "Experimental and computational evaluation of neutrals in the Alcator C-Mod edge pedestal."

Hutchinson, I., "Error-field Correction Allowing 2 MA Plasma Current on Alcator C-Mod."

Marmar, E., "Overview of Alcator C-Mod Research."

Parisot, A., "ICRF loading studies on Alcator C-Mod."

Sampsell, M., "Comparisons of Measurements and Gyrokinetic Simulations of Turbulence and Transport in Alcator C-Mod EDA H-Mode Discharges."

Posters

Baumgaertel, J.A., "Marginal stability studies of microturbulence near ITB onset on Alcator C-Mod."

Bose, B., "Gyrokinetic Simulations of Zonal Flows in Alcator C-Mod."

Edlund, E., "Measurement and Modeling of Alfven Cascades on Alcator C-Mod."

Ferrara, M., "Digital Plasma Control System for Alcator C-Mod."

Graf, A., "Visible Spectroscopy measurements from a Transmission Grating Spectrometer to be used at the Alcator C-Mod Tokamak."

Graves, T., "Experimental Results of the Coaxial Multipactor Experiment (CoMET)."

Irby, J., "Interferometer-polarimeter diagnostic for Alcator C-Mod."

Lin L., "Search for TEM and ETG Modes with the Upgraded PCI Diagnostic in Alcator C-Mod."

Lin, Y., "ICRF Heating Mode Conversion, and Flow Drive Experimetns in D(^{3}He)."

“Lynn, A., Temperature and Density Fluctuations during Peaked Density Plasmas in Alcator C-Mod.”

McDermott, R., “Measurement of Neutral Beam Attenuation from Bean Emission.”

Porkolab, M., “Overview of the ICRF Program on C-Mod.”

Rowan, M., “Ion Temperature and Plasma Rotation in EDA H-Mode and ITB Discharges in Alcator C-Mod.”

Scott, S., “Invessel Calibration of the Alcator C-Mod Diagnostic.”

Sears, J., “Active MHD Spectroscopy of Alfven Eigenmodes on Alcator C-Mod.”

Smick, N., “A Multi-Electrode Inner Wall Scanning Probe for Alcator C-Mod.”

Stotler, D., “Three Dimensional Simulations of Neutral Pressure Measurements on NSTX and Alcator C-Mod.”

Tang, V., “Initial Experimental Results from the Alcator C-Mod Compact Neutral Particle Analyzer.”

Umansky, M., “Revisiting the BOUT simulation of Quasi-Coherent mode in Alcator C-Mod.”

Veto, B., “Radial Correlations of Edge/SOL Turbulence in Alcator C-Mod.”

Zhurovich, K., “Results from the new core Thomson scattering diagnostic on Alcator C-Mod.”

31st European Physical Society Conference on Plasma Physics
Portugal, June 2004

Invited Oral

Fiore, C., “Internal Transport Barrier Production and Control in Alcator C-Mod.”

Contributed Orals

Bernabei, S., “LH Design.”

Hubbard, A.E., “Dependence of the L-H Threshold on Magnetic Configuration and Relation to Scrape-off-layer Flows.”

Hutchinson, I.H., “Spin Stability of Asymmetrically Charged Plasma Dust.”

Redi, M., “Benchmarking Nonlinear Turbulence Simulations on Alcator C-Mod.”

Schilling, G., “ICRF antenna performance.”

Snipes, J., “Fast Particle Driven Alfven Eigenmodes in Alcator C-Mod.”

Posters

Basse, N., “Turbulence in Alcator C-Mod and WEndelstein 7-AS plasmas during controlled confinement transitions.”

Grulke, O., “Propagation of Turbulent Structures in the SOL of Alcator C-Mod.”

Hutchinson, I.H., “Potential & Frictional Drag on a Floating Sphere in a Flowing Plasma.”

Parisot,A. “Initial results from phased ICRF operations on Alcator C-Mod.”

Workshop Presentations

Transport Task Force Workshop
Salt Lake City, UT April 29 – May 2, 2004

Fiore, C., “Recent results from Alcator C-Mod Internal Transport Barrier Studies.”

Greenwald, M., “SOL Flows Coupled to the Core as an Explanation for the Up-Down Assymetry in the L/H Threshold.”

Hubbard, A.E., “Analysis of edge profile at the L-H transition on C-Mod and dependence on magnetic configuration.”

Rice, J.E., “Rotation and Momentum Transport.”

Snipes, J., “Fast Particle Drive Alfven Eigenmodes in Alcator C-Mod.”

Other Presentations

Greenwald, M.. UCSD Physics Dept. Seminar, May, 2004

Greenwald, M.. Columbia, Applied Physics Dept, Seminar, March 2005.

Greenwald, M.. PSFC, IAP, January 2005

Marmar, E., “Recent Results from the Alcator C-Mod Tokamak” Plasma Physics Seminar at U. Wisconsin, Madison, on May 2, 2004.

Porkolab, M., "Turbulence in Fusion Plasmas: Theory, Modeling and Experimental Status." Presented at the 2nd Hungarian Plasma Physics Workshop, Budapest, Hungary, April 22, 2004

Porkolab, M., "Progress in the Physics of Magnetically Confined Fusion Plasmas and the Outlook for ITER" Iowa State University, Department of Physics Colloquium, Sept. 20, 2005

Porkolab, M., “Phase Contrast Imaging Studies of ICRF Waves and Turbulence in the Alcator C-Mod and DIII-D Tokamaks". Weekly Seminar at the “Center for Integrated Plasma Studies " University of Colorado on March 4, 2005.

Porkolab, M., "Overview of the MIT Plasma Science and Fusion Center and the Alcator C-Mod Program," Seminar presented at the Max Planck Institute fur Plasmaphysik, Greifswald, Germany, July 6, 2004

Appendix B

Summary National Budgets, Run Time and Staffing

		FY05 Approp.	FY06 Request	FY06 12 wks	FY07 0 wks	FY07 12 wks	FY07 25 wks
Funding ($ Thousands)							
Research		6,122	5,972	5,972	5,698	6,181	7,640
Facility Operations		12,900	12,595	12,595	10,789	13,039	17,819
Research Capital Equipment		200	197	197	145	197	197
Operations Capital Equipment		100	100	100	30	100	100
PPPL Collaborations		2,052	2,002	2,002	1,702	2,002	2,250
UTx Collaborations		415	415	415	374	415	480
LANL Collaborations		100	100	100	90	100	120
MDSplus		149	149	149	149	149	149
International Activities		47	60	60	60	60	60
Total (inc. International)		22,085	21,590	21,590	19,037	22,243	28,815
Staff Levels (FTEs)							
Scientists & Engineers		53.83	54.58	54.58	48.93	54.53	68.93
Technicians		26.37	25.97	25.97	21.87	25.77	31.37
Admin/Support/Clerical/OH		13.61	13.21	13.21	11.23	12.57	14.08
Professors		0.21	0.21	0.21	0.21	0.21	0.21
Postdocs		2.00	2.00	2.00	1.00	2.00	2.00
Graduate Students		26.55	25.55	25.55	22.55	25.55	28.55
Industrial Subcontractors		1.50	1.30	1.30	0.00	1.10	1.00
Total		124.07	122.82	122.82	105.79	121.73	146.14

	FY04 Actual	FY05 Approp.	FY06 Request	FY06 12 wks	FY07 0 wks	FY07 12 wks	FY07 25 wks
Facility Run Schedule							
Scheduled Run Weeks	19	17	12	12	0	12	25
Users (Annual)							
Host	56	54	53	53	0	53	60
Non-host (US)	95	93	90	90	0	90	95
Non-host (foreign)	12	10	10	10	0	10	18
Graduate students	29	29	29	29	0	27	31
Total Users	192	186	182	182	0	180	204
Operations Staff (Annual)							
Host	71	69	68	68	62	68	77
Non-host	4	4	4	4	3	4	5
Total	75	73	72	72	65	72	82

Appendix C

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

FY05 Appropriation: 17 weeks total research operations (1 week = 4 days, 8 hrs/day)

Areas of Emphasis

- Pedestal and core transport studies
    - Self-generated flows and momentum transport
    - Edge flows, topology and H-mode threshold
    - Electron thermal transport and fluctuations
    - H-mode pedestal width scaling and physics
    - H-mode pedestal relaxation, including EDA/QC and small ELM regimes
    - ITB access and control mechanisms
- Plasma Boundary Physics and Technology
    - SOL transport (energy and particles)
    - Turbulence and EDGE/SOL transport
    - Edge flows and coupling to core rotation
    - Isotope retention and recycling
    - Tungsten brush prototype divertor tiles
- Macrosopic Stability
    - Disruption mitigation with massive gas puffs, initial studies
    - Error fields and locked modes
    - Active MHD (global and Alfven modes)
    - Alfven cascades driven by ICRF tail ions
    - NTM β threshold studies
- Wave-Plasma Interactions
    - Minority ICRF ^{3}He heating (50 MHz @ 5.3 T first, then 80 MHz @ 8 T)
    - Mode conversion flow and current drive (ICRF)
    - Installation of first LH coupler; initial experiments
        - LH coupling physics
        - Phase studies (current drive, heating, accessibility, radial deposition)
- Advanced Tokamak thrust
    - Internal transport barrier dynamics and control
    - Hybrid scenarios
    - Non-inductive scenarios
- Burning Plasma support thrust
    - First wall, materials studies
    - Integrated H-mode scenario development, performance enhancement
    - Pedestal and edge relaxation studies
    - Non-dimensional scaling joint experiments
    - D(^{3}He) heating scenarios at relevant density and field

Plain English Goals

- Measure plasma behavior with high-Z antenna guards and input power greater than 3.5 MW
- Commissioning of the Microwave Current Drive System

FY06 No operations, retain critical staff

Plans

- Analysis of FY05 results
- Limited participation in ITPA, ITER physics
- Maintain facility readiness
- Planning for FY07 operations

Impacts

- Highly constrained physics progress
- Devastating dislocation for graduate students
- Delays in all facets of the research program, including numerous high priority ITER R&D areas
  - Minimum 1 year delay in current profile control experiments with lower hybrid
  - Deferral of research on disruption mitigation, hybrid scenarios, small ELMs, tungsten PFCs, active density control, NTM studies, …
- No contributions for joint ITPA experiments
- Reductions in force
  - 2.5 Scientists, 2 Students, 3 Engineers, 2 Technicians
- Delay in implementation of key diagnostics

FY06 Guidance: 12 weeks research operation

Prioritized increments:

- Add 6 weeks research operation (to 6 total), and restore personnel cuts
- 2^{nd} LHCD launcher on schedule
- LHCD 4^{th} MW on schedule
- Add 6 weeks research operation (to 12 total)

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

- Current profile control with Lower Hybrid
- First experiments with active cryopumping for wall conditioning and density control
- Hybrid and steady-state scenarios
- Core and edge turbulence measurements with upgraded diagnostics; comparisons with modeling
  - Electron transport will be one area of emphasis
  - Particle and momentum transport
- Disruption mitigation of high absolute pressure plasmas with massive gas puff
- Fast particle collective modes in low and reversed magnetic shear configurations

- MHD stability analysis of H-mode edge barrier under type I and tolerable ELM conditions
- Accessibility to regimes with small or no ELMs
- Study NTM threshold at increased β
- Tungsten brush divertor tile physics and technology
    - Isotope retention (application to tritium retention in ITER)
    - Power handling for long-pulse, relatively low density AT regimes.
- Improved understanding of SOL plasma interaction with main chamber, parallel and perpendicular SOL transport mechanisms

Plain English Goals

- Current profile control with microwaves
- Sustaining plasma current without a transformer (50% non-inductive)
- Disruption mitigation of high absolute pressure plasmas

FY06 Program planning budget: 25 weeks research operation

Prioritized increments:

- 4 weeks additional research operation, to 16 weeks
- add 4^{th} MW to LH system, to make optimal use of two couplers
- Real-time matching for 2 ICRF transmitters for improved utilization
- 4 weeks additional research operation, to 20 weeks, with required additional personnel (science, engineering, technical)
- Outer divertor upgrade
    - Power handling for >8MW, 5 seconds
- Upgrades to data acquisition and computation infrastructure
- Spare 4.6 GHz, 250 kW klystron
    - Currently no spares for 16 tube system
- 5 weeks additional research operations, to 25 weeks (full utilization), with required additional personnel

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
    - Fewer than 1/3 of priority research proposals can be accommodated in 12 weeks annual research operations

FY07 No operations, retain critical staff

Plan

- Analysis of FY06 results
- Limited participation in ITPA, ITER physics
- Maintain facility readiness
- Planning for FY08 operations

Impacts

- Highly constrained physics progress
- Devastating dislocation for graduate students
- 1 year delay Advanced Tokamak program
- Delays in all facets of the research program, including numerous high priority ITER R&D areas
- No contributions for joint ITPA experiments
- Reductions in force
  - 2.5 Scientists, 2 Students, 3 Engineers, 2 Technicians
- Delay completion of key facility upgrades, including 2^{nd} LH launcher, 4-strap ICRF antenna

FY07 Base: 12 weeks research operation

Prioritized increments:

- Add 12 weeks research operation (to 6 total), and restore personnel cuts
- Complete design of outer divertor upgrade (power handling)
- Complete construction of second LH launcher (reduced power density/increased power, compound spectrum)
- Complete and install 4-strap ICRF antenna

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

- Current profile control with Lower Hybrid
  - Pulse length approaching 3 seconds (multiple current rearrangement times)
  - Power to 2 MW coupled
- Density control with divertor cryopump
- Hybrid and steady-state scenarios
- Core and edge turbulence measurements with upgraded diagnostics; comparisons with modeling
  - Electron transport will be one area of emphasis
  - Particle and momentum transport
  - Investigate higher current regimes (I_p>1.6 MA, higher plasma pressure, performance)
- Fast particle collective modes in low and reversed magnetic shear configurations
- MHD stability analysis of H-mode edge barrier under type I and tolerable ELM conditions
- Accessibility to regimes with small or no ELMs

- Study NTM threshold at increased β
- Tungsten brush divertor tile physics and technology
  - — Evaluation of high power handling with total input power approaching 8 MW

Plain English Goals

- Active density control with cryopump
- Confinement at high plasma current

FY07 Program planning budget: 25 weeks research operation (assuming guidance budget in FY06)

Prioritized increments:

- 4 weeks additional research operation, to 16 weeks
- add 4th MW to LH system, to make optimal use of two couplers
- Real-time matching for 2 ICRF transmitters for improved utilization
- 4 weeks additional research operation, to 20 weeks, with required additional personnel (science, engineering, technical)
- Completion of outer divertor upgrade
  - — Power handling for >8MW, 5 seconds
- Upgrades to data acquisition and computation infrastructure (replace CAMAC, upgrade MPP cluster)
- Spare 4.6 GHz, 250 kW klystron
  - — Currently no spares for 16 tube system
- 5 weeks additional research operations, to 25 weeks (full utilization), with required additional personnel

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
  - — Fewer than 1/3 of priority research proposals can be accommodated in 12 weeks annual research operations