(Draft)
ALCATOR C-MOD
FY05-06 WORK PROPOSAL

March 2004

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

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

ALCATOR C-MOD
FY05-06 WORK PROPOSAL

Table of Contents

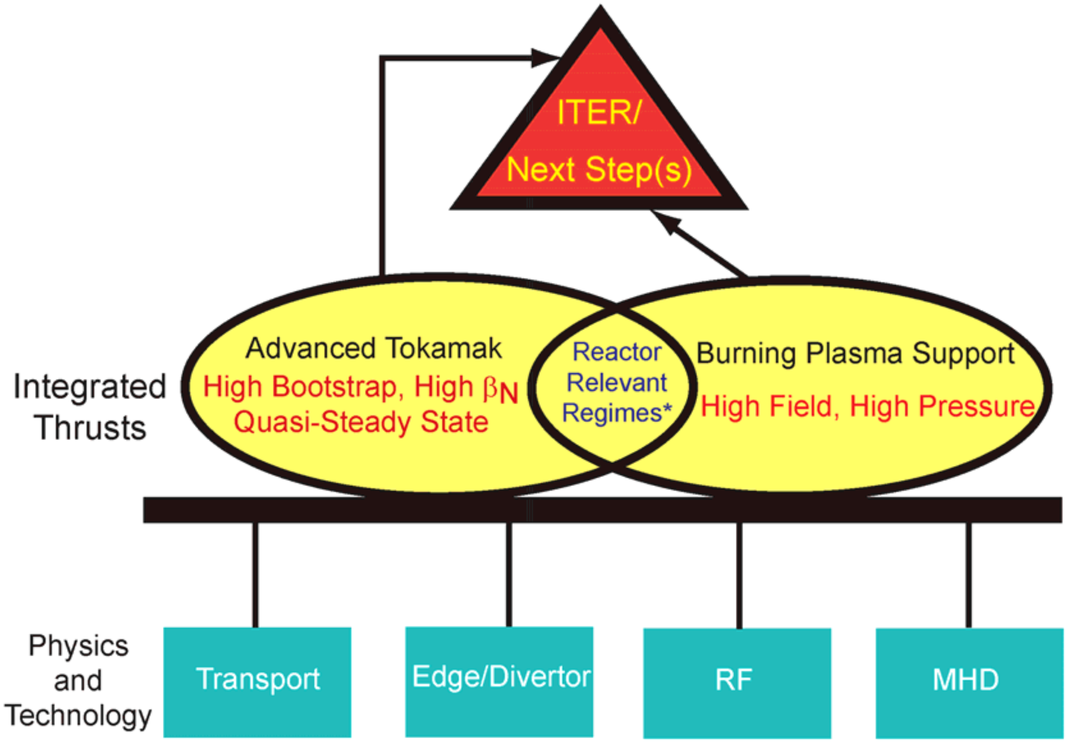
1. Introduction

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 performance questions related to 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 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 programmatic thrusts are illustrated in Figure 1.1.



*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive

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 and pressures, and with magnetic field up to 9 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, MHD 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.

- **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 reactor 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 walls** — 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 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 multiple departments at MIT, as well as from collaborating Universities. Currently 24 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 FY04-FY06 period:

- Transport and confinement with equilibrated electrons and ions
    - Equilibrated electrons and ions
    - Dominant electron heating
    - Relevant densities, edge-core interaction
    - No direct core momentum input
- Pedestal physics
    - Small/no ELM regimes
    - Scaling

- All metal plasma facing components
  - T retention
  - Effects of disruptions on materials
- Disruption mitigation in high absolute (ITER) pressure plasmas
- Rotation in the absence of direct momentum input
  - H-mode dynamics
  - RWM stabilization
- Error fields and locked modes
  - Size and field scaling
- ICRF heating/current drive/flow drive at high (ITER) field
- ICRF technology
  - Load tolerant antenna configurations
  - Antenna-plasma interaction, modeling
- Alfven Eigenmode physics
- NTM physics
  - Direct stabilization
  - Elimination of sawtooth seed
- Hybrid scenarios
- Advanced Tokamak physics toward steady-state

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.

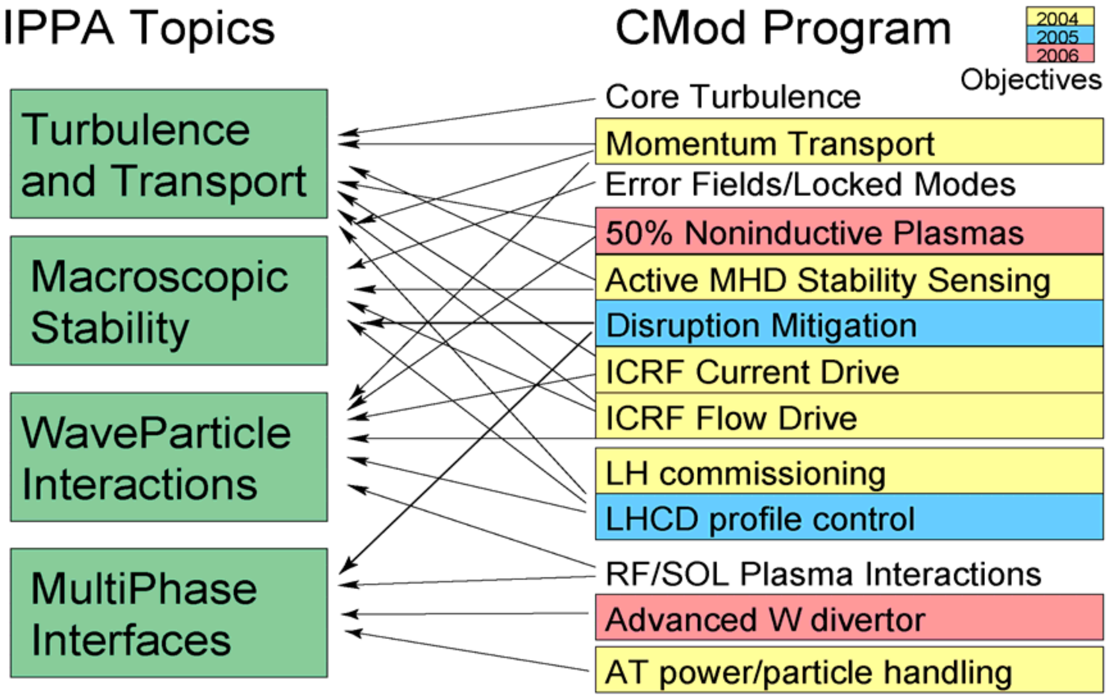


Figure 1.2 Mapping between Alcator program and IPPA Goal 1 objectives

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.

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 discussion of how Alcator's specific topical science plans address the key programmatic objectives are given in the respective sections of this Work Proposal.

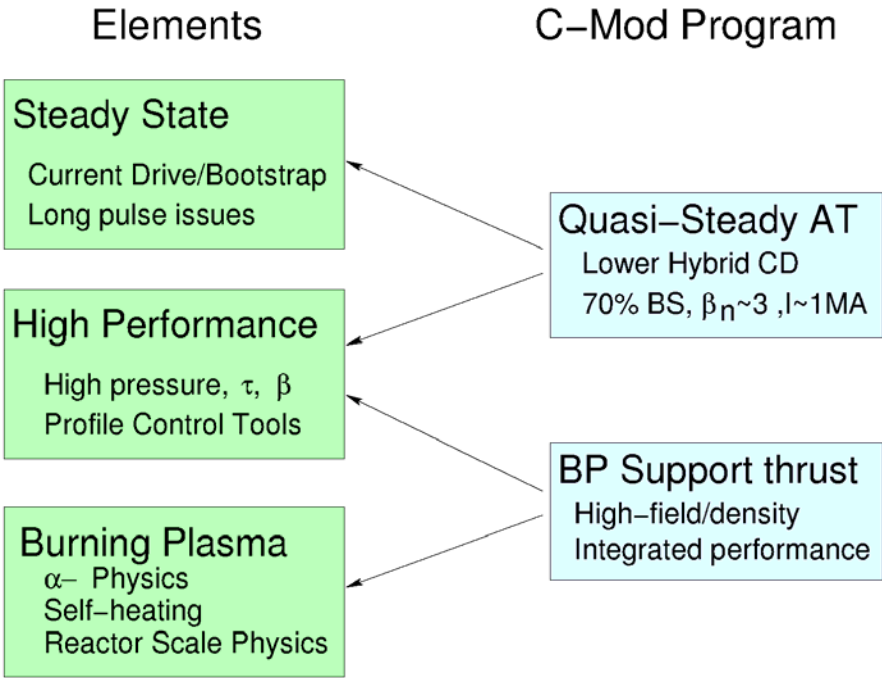


Figure 1.3 Mapping between Alcator program and IPPA Goal 3 objectives

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 $18.92M at MIT, and major collaborations totaling $2.58M. These represent an overall decrease, relative to FY2004 funding, of $722,000, with essentially the entire 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 19 weeks in FY2004, to 17 weeks in FY2005. The $722,000 cut leads to a further decrease of 3 weeks, to a planned total of 14 weeks in FY2005. Assuming flat funding from FY2005 to FY2006, cost of living increases, and an anticipated increase in the FY06 MIT overhead rates, will result in a further decrease of planned research operation to 12 weeks in FY2006. The major items that these budgets permit us to fund are shown in table 1.1.

Table 1.1: Major items funded in guidance budgets (FY04+FY05+FY06)

Item	Cost (k$)	Notes
Cryopump	520	Required for density control (AT), lower collisionality (BP)
Correction coil supply upgrades	50	Error field compensation at high current
Real time matching (ICRF)	90	1 antenna only
W divertor modules	50	prototype
Lower Hybrid CD: 2nd launcher	720	Reduce power density; allow compound spectrum
LHCD: add 1 MW	600	4 MW total source, 16 klystrons
Polarimeter/Interferometer	775	j(r) at high density; ITER geometry
ICRF Final Power Tube (rebuilds)	120	Tubes have ~2500 hour lifetime
DAC infrastructure (workstations, servers, mass storage)	210	Data collection doubling on 2 year time scale; conversion to compact PCI may accelerate this

Within the guidance budgets, personnel cuts of 1 Engineer and 1 Technician are required. In addition, many important initiatives cannot be funded. We therefore also propose higher, national, B budgets, totaling $26.26M in FY05 and 28.17 in FY06, which permit the following additions (in approximate priority order).

Table 1.2(a): Major items requiring budget increments (FY2005)

Item	Cost (k$)	Notes
7 weeks additional run time	1500	Total of 21 weeks research operation
4-strap ICRF antenna	350	Required to maintain full ICRF power capability when 2nd LHCD launcher installed (FY2006)
Spare 4.6 GHz Klystron	500	Currently have 1 spare for 16 klystron system
Core Thomson upgrade	150	Additional spatial channels
Active MHD upgrade	50	Add second location: toroidal mode number control
ICRF real-time matching	350	Second antenna
Outer divertor upgrade	200	Power handling for >8MW, 5 seconds (complete in FY2006)
4 weeks additional run time	900	25 weeks total; full facility utilization

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

Item	Cost (k$)	Notes
6 weeks additional run time	1400	Total of 18 weeks research operation
4-strap ICRF antenna (complete and install)	400	Required to maintain full ICRF power capability when 2nd LHCD launcher installed
Spare 4.6 GHz Klystron	500	Prudent to have 3 spares
3 weeks additional run time	700	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	350	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 FY2007
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 10% budget decrement for FY2005.

Table 1.3: Major items cut under a 10% decrement in FY2005

Item	Cost (k$)	Notes
3 week decrease of run time	675	Total of 11 weeks research operation
Additional Personnel cuts	800	2 Engineer, 2 Techs, 1 Scientist, 1 Student
LHCD 2nd launcher deferred	300	At least 1 year delay
LHCD 4th MW deferred	300	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 decremental (10%) (D) cases.

Table 1.4: Research operation for guidance (04A-06A), increment (B) and decrement (D) budget cases

Fiscal Year	**04**	**05A**	**06A**	**05B**	**05D**	**06B**	**06D**
National Budget ($M)	22.22	21.50	21.50	26.26	19.35	28.17	19.35
Research Operation Weeks	19	14	12	25	11	25	10
Research Operation Hours	600	450	390	800	350	800	320

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 4.2 and 4.3 explicitly cover the contributions from Princeton and Texas respectively.

A summary of the planned facility schedule, assuming the guidance budget levels, is shown in Figure 1.4. Planned research weeks are shown in the operations blocks.

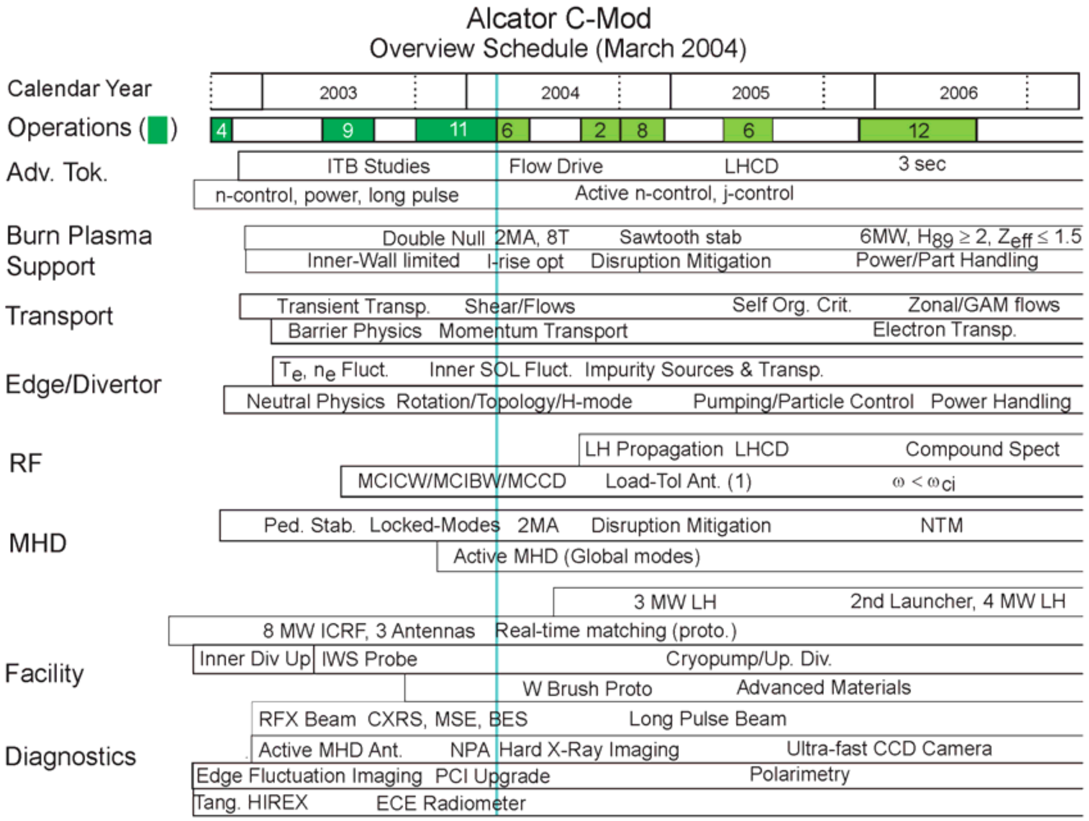


Figure 1.4. Schedule of Programmatic Emphasis and Major Installations (Guidance Budgets)

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.

Sensing approach to instability using active coils [Sep 04]

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.

Commissioning of the Microwave Current Drive System [Sep 04]

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 before the end of FY 2004.

Power and Particle Handling for Advanced Tokamak Plasmas [Sep 04]

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.

Current Profile Control with Microwaves [05]

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.

Plasma Flow control with Radio Waves [05]

A crucial part of control of transport is the control of the flow that helps to stabilize the responsible turbulence. Theoretical studies suggest that radio waves of the type used for heating Alcator C-Mod can control the plasma flow. We will complete the first experiments to verify, using our new diagnostics and the high power radio waves, what degree of control is possible, and how this can be used to optimize the plasma confinement.

Sustaining Plasma Current Without a Transformer [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 [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.

Goals Accomplished in FY2003

Higher Performance Plasmas

Produce high temperature plasmas with 5 Megawatts of radio frequency heating for pulse lengths of half a second. These plasmas should achieve conditions where the relative importance of plasma particle collisions is similar to what is expected for the burning plasma regime. The studies of the sucsceptibility of the plasma to instabilities *and the losses of plasma across the confining field under these conditions should therefore be applicable to predicting the performance of next-step experiments.*

Report:

The experiments to study these plasmas were completed in June, 2003, and the subsequent analysis was completed in September, 2003. A data set of 19 discharges was used for these evaluations. Representative traces from an example, shot 1030605030, are shown in Figure 1.5 The ICRF power was at 5 MW for a total of 0.53 seconds. All cases in this analysis had RF power in excess of 4 MW for at least 0.35 seconds. The dataset includes one shot with a total RF pulse duration exceeding 0.7 seconds with RF power greater than 4 MW. With the exception of the very lowest collisionality, values predicted for highest-temperature operation in ITER, the present C-Mod dataset covers the relevant

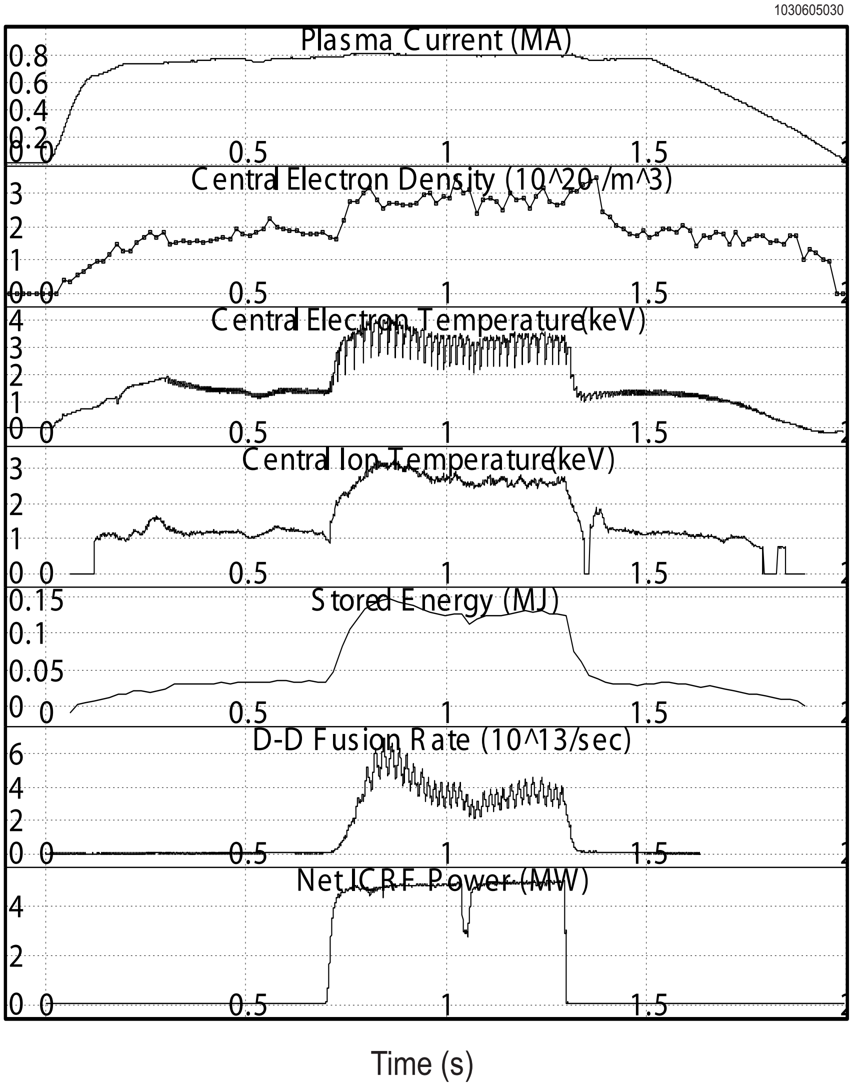


Figure 1.5 Time histories of representative plasma parameters for one of the discharges analyzed for this report.

range for burning plasmas. Access to even lower collisionality regimes is expected with the planned addition of the cryopump in FY 2005. All high power shots in this dataset made transitions into H-mode, exhibiting the usual phenomena of a steep edge pedestal and good global energy confinement, with H-factors (relative to the ITER 89-P scaling) up to 2.1 at the low end of the collisionality range. For higher collisionality plasmas (higher density, lower temperature), H-factors of 1.2 to 1.8 were more typical, and there is evidence that the ICRF power absorption efficiency decreases at the higher

collisionalities. Possible physics reasons for these effects are being investigated. These plasmas were all stable to global MHD modes, except for indications of benign tearing modes at the lowest collisionalities. All discharges were sawtoothing throughout the RF heating phase. The beneficial quasi-coherent edge mode, characteristic of the EDA H-mode, was observed in many discharges. In many cases at the lowest collisionalities, the mode was relatively weak, and regulation of impurity transport across the edge barrier was incomplete. As a result, global confinement usually decreased over time scales long compared to the energy confinement time.

Driving Electric Current with Radio Waves

For steady-state operation, which is attractive for a reactor, it is necessary to drive current in the plasma with waves, not just with DC electric fields. A new method of driving the current involves launching waves in such a way that they are converted by interaction with ion resonances inside the plasma from long wave-length to short wave-length. They then drive the electrons of the plasma, creating a current. The first round of C-Mod experiments on this scheme will be completed, establishing suitability for future experiments.

Report:

Initial experiments on mode-conversion current drive have been carried out using our 4-strap ICRF antenna, comparing co-current and counter-current phasing. Dramatic effects on the sawtooth period are observed when current is driven close to the q=1 surface. Figure 1.6 shows one such comparison. These experiments indicate that the techniques are very promising, and investigations will continue in coming campaigns. Another very significant result from these experiments is that impurity generation is not phase dependent, something which had been a problem in previous experiments. This latter result is attributed to the details of the antenna configuration, including the use of insulating (BN) protection tiles.

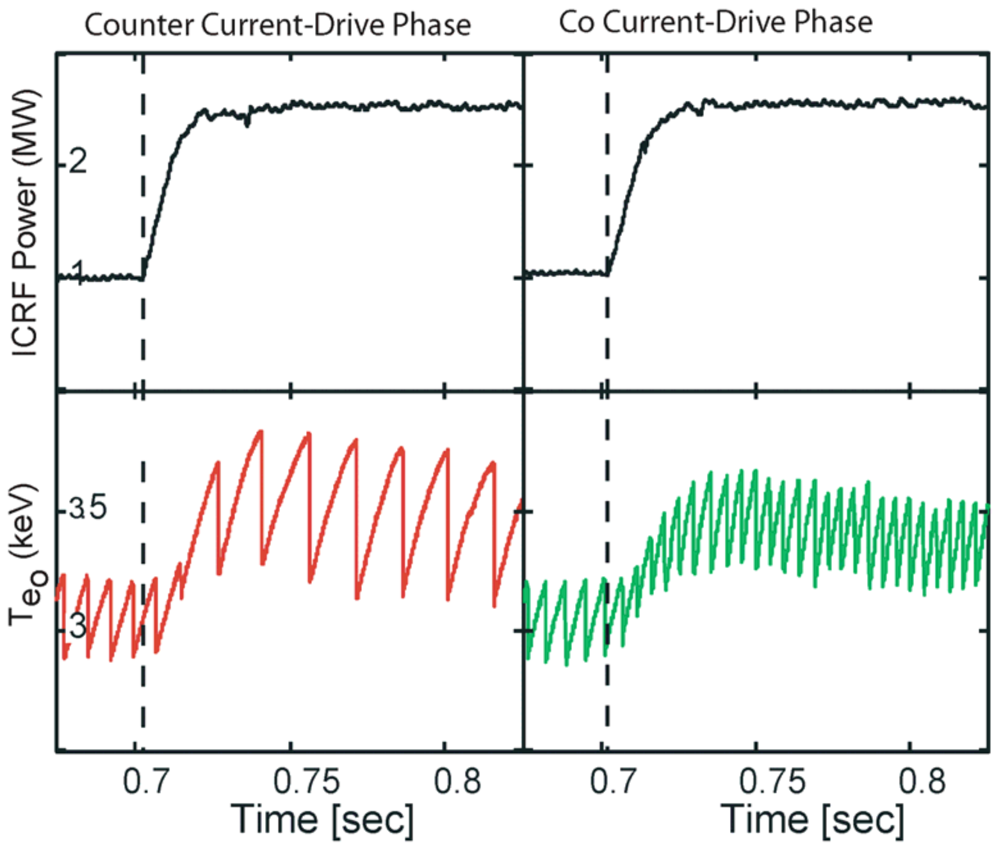


Figure 1.6 Comparison of the effects on sawtooth period of mode conversion current drive near the q=1 surface with co- and counter-current phasing.

Locked Mode Studies

Imperfections in the field structure of tokamaks are usually shielded from affecting the inner confinement regions provided the plasma rotates. However, if the imperfections are larger than a rather low threshold, they can themselves act as a brake on the plasma, bring its rotation to zero. The fields can then penetrate to the confinement region, causing substantial degradation of confinement. Such phenomena are called Locked Modes.

Report:

Locked modes and error field studies have become a major new topic of research on C-Mod in the last year, following the installation of a set of error field correction coils. These have been used to measure (see Figure 1.7) and reduce intrinsic errors, thereby allowing operation at lower densities (and soon higher currents). In addition, the scaling of locked mode thresholds in C-Mod is being studied, and an ITPA-coordinated joint collaboration with JET and DIII-D will investigate the implications for ITER. Current plans also include possible upgrade of the correction coils with an optimized coil set located closer to the plasma, as well as additional power supplies for added flexibility and increased field amplitude.

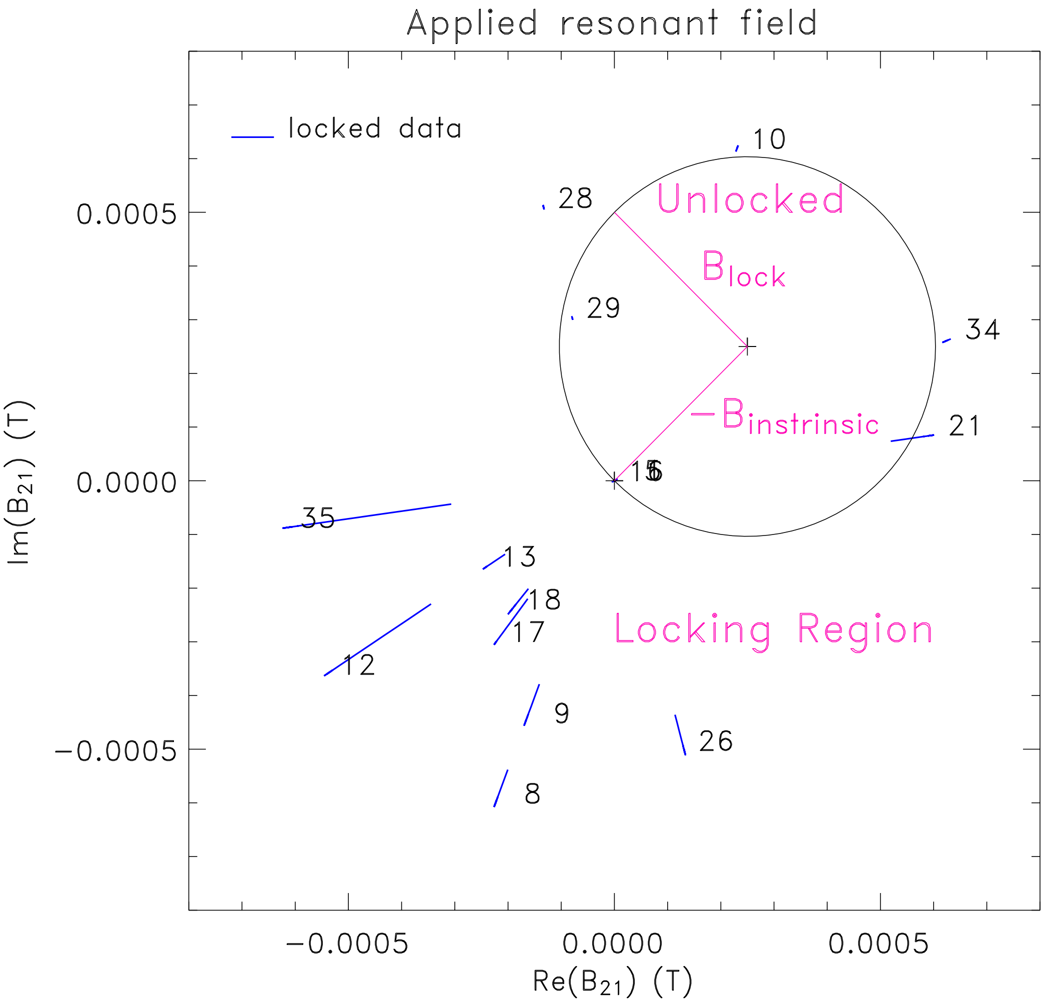


Figure 1.7 Effects on mode locking of varying toroidal phase and amplitude of the n=2, m=1 component of the applied resonant magnetic field. The center of the circle indicates the location where the intrinsic error field has been best compensated.

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, are:

1. *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.*
2. *Produce, understand and control core transport barriers in LH and ICRF driven regimes with strongly coupled electrons and ions.*
3. *Attain and optimize no-wall β limits, with β_n of at least 3, and explore means of achieving higher values.*

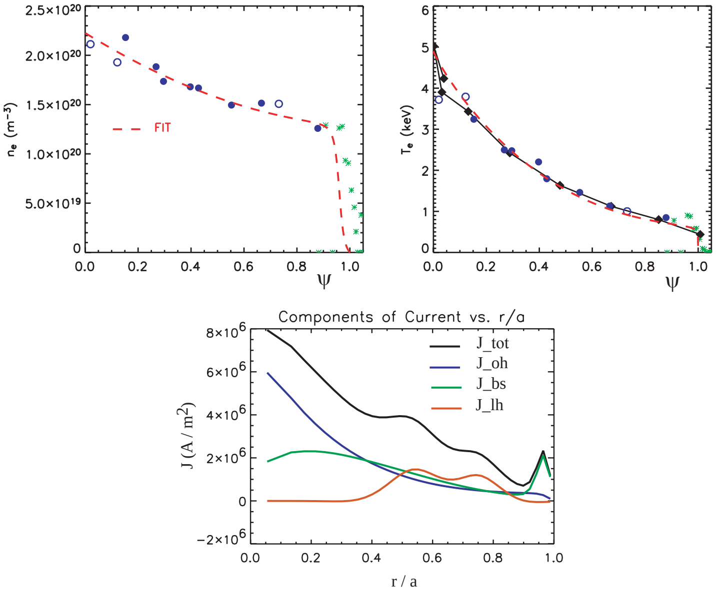


Figure 2.1.1: Experimental electron density (a) and temperature (b) profiles for a low density H-mode discharge developed as a potential LHCD target, with Ip=600 k_a and B_T=5.4 T and P_{RF}=3.5 MW. Profiles of various currents which would result from applying LHCD to this discharge were computed using ACCOME and are shown in (c).

During the past year we have focused primarily on the first two, nearer term, goals. Highlights of the progress made are as follows.

Since preparation and testing of the first lower hybrid launcher are nearly complete, experiments were carried out to develop and model target plasmas suitable for use in the first phase of LHCD experiments. A primary concern, since the cryopump will not be operational for the fall 2004 campaign, was controlling the density for good LH efficiency, while maintaining good energy confinement; H-modes on C-mod typically have pedestal densities in the range 2-4 10^{20} m^{-3}, which past modeling has shown can lead to low driven current. Using information from scaling studies of the pedestal density on C-Mod [1], we succeeded in developing high quality, high temperature H-modes with significantly lower density, $n_{e,ped}$ =1.4 x10^{20} m^{-3}. With only 3.5 MW ICRH, measured central electron temperatures reached 5 keV, as shown in Figure 2.1.1(a, b). High temperatures are important for good off-axis absorption of lower hybrid waves, as well as contributing to high pressures and bootstrap currents. These discharges proved also to have excellent confinement, with $H_{ITER89-P}$ up to 2.1, and low collisionality.

The non-inductive current which would be expected if lower hybrid waves from the C-Mod LHCD system were applied to such a discharge was computed using the ACCOME code, developed by Paul Bonoli (MIT) and international colleagues. Magnetic parameters (shape, current, field) and profiles were taken from the above experiment. The $N_{//}$ spectrum was varied, as will be possible in the experiments. The profiles of the various inductive and non-inductive current contributions are shown in Figure 2.1.1(c), for a case using a spectrum with peaks at $N_{//}$=2.75 and 3.5, and a total power of 3 MW. All launched rays are well absorbed, mainly in the outer half of the plasma, as desired. The LH driven current is 131 kA, and 243 kA of bootstrap current are generated, for a total non-inductive current fraction of 62%. The resulting q profile is significantly modified from the case without lower hybrid, with q above 1.45 at all radii (experimental discharges were sawtoothing). These calculations are conservative in several respects. By using experimental profiles obtained without LHCD, we take no credit for additional heating and expected temperature increases. Likely improvements in core confinement resulting from shear modifications are also not considered. Recent benchmarking with the CQL3D code has shown that the adjoint calculation in the present version of ACCOME tends to underestimate the driven current by typically 30%. These experimentally demonstrated, low density, high confinement, ICRF H-mode plasmas are thus very promising as initial target plasmas for lower hybrid non-inductive AT scenarios. It should be noted that this near-term scenario does not represent the ultimate goal for C-Mod, as described above, for which we expect further density control via a cryopump, and additional bootstrap current from core barriers, will be necessary.

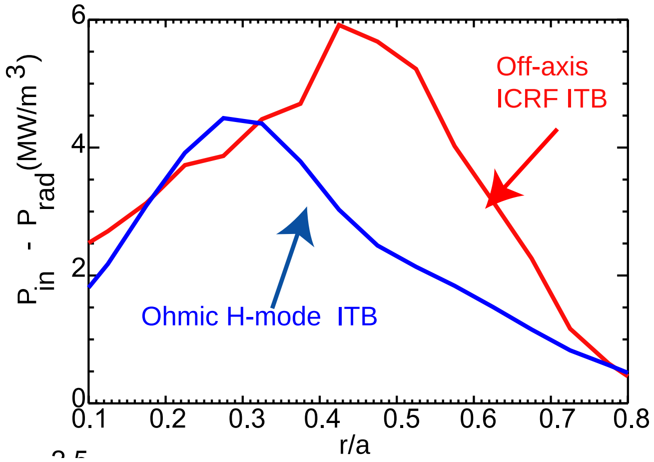


Figure 2.1.2: Profiles of net power P_{in}-P_{rad} for internal transport barriers discharges with off-axis RF heating (red) and ohmic heating (blue). From Fiore et al, to be

Experimental and modeling work has also been conducted to prepare ICRF-based tools for current profile control. As discussed more fully in the RF section (2.6), mode conversion heating and current drive were demonstrated in 2003 experiments which for the first time used current drive phasing of the J-port antenna. By tailoring the deposition location through adjusting B_T and the species mix, the sawtooth period could be lengthened or shortened. Such experiments give further confidence in TORIC calculations which predict up to 100 kA can be driven on axis. Preliminary and encouraging investigations of MC flow drive, which could be an exciting new transport control tool, were also begun. This work, and related modeling, was reported at APS in an invited talk by Y. Lin [2].

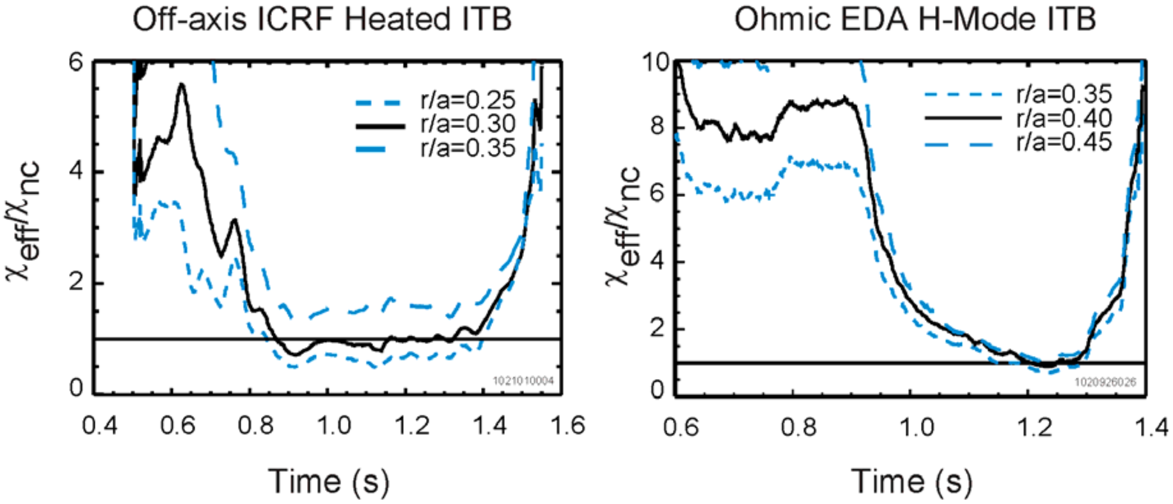


Figure 2.1.3: Effective thermal conductivity normalized to neoclassical level during evolution of internal transport barriers in cases with a) off-axis RF heating and b) ohmic heating. From Fiore, et al., to be published in Physics of Plasmas.

There has also been significant experimental and theoretical progress in understanding and controlling Internal Transport Barriers on C-Mod, as reported by Fiore in a 2003 APS invited talk [3]. Further experiments and analysis of ITBs arising from ohmic H-modes has clarified the common features between these barriers and those triggered by off-axis ICRH. In both cases, the net power profile $P_{net}=P_{in}-P_{rad}$ is hollow; $P_{net}(r)$ in the core is very similar in the two cases, as shown in Figure 2.1.2, and T_e profiles at the sawtooth peak are much flatter than with on-axis ICRH. Stability analysis by Redi (PPPL) and Ernst (MIT) shows that ITG modes are then stable in the core near the barrier formation time. In both cases, core χ_i decreases to the neoclassical level, as shown in Figure 2.1.3. We have further explored the scaling of the barrier location. r_{foot} increases with decreasing field, out to r/a = 0.53 at 4.5 T. There is also some dependence on I_p or q_{95}, though this is weaker and less clear. It is striking that for all fields the threshold for the ITB occurs when $r_{dep}/a=0.5$, on either the high or low field side; the barrier location can thus be inside or outside this location.

Extension of the ITB to 5.4 and 6.2 T, where ECE is not cut off, has allowed good quality T_e profile measurements. Some increase is seen in core T_e during the ITB, though there is not the dramatic peaking seen in n_e and p_e profiles. T_e increases further when on-axis ICRH is added to stabilize the barrier and arrest the particle transport. This controllability of core transport via the heating deposition profiles, which has been documented in both ohmic and RF triggered ITBs, is of great importance. Improved theoretical understanding of the phenomenon has come from recent linear and non-linear modeling with the GS2 code [4]. As the density peaks, the Trapped Electron Mode is destabilized and sets a new particle transport equilibrium which is dependent on the central input power via the local temperature.

Research Plans for FY05-FY06

The primary focus of Advanced Tokamak experimental work in FY05 will be the commissioning and exploitation of the new Lower Hybrid Current Drive system. Following installation and testing of the first launcher in late FY04, extensive scans will be carried out to measure and optimize 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 to optimize the size and location of the driven current. The MSE diagnostic and new a Hard X-ray camera and polarimeter, will provide important measurements for these studies.

Once LHCD has been demonstrated and understood, the program will progressively work 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. In late FY06 a second launcher will be added, bringing the total source power to 4 MW and allowing up to 3 MW launched power for long pulses of up to 5 seconds, which corresponds to many current relaxation times. 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 FY05 will be an important tool for density control, which is critical for maintaining good LHCD efficiency and deposition control in a variety of confinement regimes.

Optimization of the bootstrap current will be equally important for current profile control, and will require good confinement and kinetic profile control. To this end, the studies of internal transport barriers will be continued and extended to include investigations of the effects of current profile on barrier formation, location and control. It is anticipated that once shear is reduced or reversed via LHCD, it will be possible to form ITBs at a larger radius and with higher on-axis power. This would give a substantial increase in the bootstrap fraction. 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.

As the plasma β increases due to increased input power and improved confinement, issues of MHD stability will become more important. In the FY05-FY06 period, our plan is to modify shaping and plasma profiles so as to maximize the no-wall ideal stability limit. Active MHD antennas will be used to sense proximity to unstable regions and control algorithms will be developed to control profiles accordingly. 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. Overall, our 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.

References

[1] J.W. Hughes, D.A. Mossessian, A.E. Hubbard, B. LaBombard and E.S. Marmar, Physics of Plasmas 9 (7), 2002, 3019

[2] Y Lin, S. Wukitch et al, Investigation of ICRF Mode Conversion at the ion-ion Hybrid Layer in Alcator C-Mod, accepted for publication in Physics of Plasmas, 2004.

[3] C L Fiore, P T Bonoli, D R Ernst et al, Control of Internal Transport Barriers on Alcator C-Mod, accepted for publication in Physics of Plasmas, 2004.

[4] D R Ernst et al, Role of Trapped Electron Mode Turbulence in Internal Transport Barrier Control on Alcator C-Mod, submitted to Physics of Plasmas.

2.2 Burning Plasma Support 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 any 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 8T, 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 of β, β_N, β_p, f_{boot}, q and q_0, collisionality (ν^*,ν/ω_*, $\nu_{ei}\tau_E$), with $T_e \cong T_i$. Demonstration discharges which match the ITER 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 experiments on C-Mod, 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 $P/R \cong 10$MW/m would also be close to the ITER value, implying that many 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. This research is described in the relevant sections of this document, and is not repeated in detail here. A listing of ITPA Joint Experiments to be carried out on C-Mod in the next year is given in the following table.

Table 2.2.1:ITPA Joint Experiments on C-Mod (2004-05)

CDB-4	Confinement scaling in ELMy H-modes: ν^* scans at fixed n/nG (C-Mod/JET)
CDB-7	Ohmic Identity Experiments: test of scaling with dimensionless parameters
TP-1	Investigation of transport properties of candidate hybrid scenarios
TP-3	High Performance operation with $T_e \sim T_i$
TP-4	Enhanced confinement operation with low external momentum input
PEP-7	Dimensionless identity experiments on C-Mod and JET
PEP-11	Dimensionless comparison of L-H threshold and H-mode pedestals on C-Mod and ASDEX-Upgrade
PEP-12	Comparison between C-Mod EDA and JFT-2M HRS regime
DSOL-3	Scaling of radial transport
DSOL-4	Disruptions and effect on materials choices
DSOL-5	Role of Lyman α absorption in the divertor (C-Mod/JET)
DSOL-6	Parallel transport in the SOL
DSOL-7	Multi-machine study on separatrix density and edge profiles
DSOL-13	Deposition in tile gaps
MDC-1	Pressure and size scaling of gas jet penetration for disruption mitigation
MDC-3	Joint experiments on neoclassical tearing modes (including error field effects)
MDC-6	Error field sideband effects for ITER (C-Mod, JET, DIII-D identity experiments)
SSEP-1	Preparation of ITER steady-state scenario
SSEP-2	Preparation of ITER hybrid scenario

Recent Accomplishments

Recent activity in the Burning Plasma Thrust has included shaping and control development of ITER-like equilibria with high normalized current I_N, in preparation for ITER demonstration discharge experiments. An example of such an experimentally demonstrated equilibrium is shown in Figure 2.2.1. Some additional control optimization is required to improve vertical stability and eliminate locked modes for these discharges.

Other recent work in the burning plasma thrust has investigated global confinement properties in nearly balanced double null discharges, which have been compared with our standard single null configuration. These experiments were carried out as part of the research effort in support of the Level 1 (JOULE) milestone SC6-1b “Compare energy confinement, H-mode threshold and divertor particle dynamics in SN, DN and inner-wall limited discharges in Alcator C-Mod". In this series of experiments, which were carried out with a range of plasma currents and densities at $\beta_N < 1.6$, confinement times were found to be approximately 10% higher in the double null cases, relative to the single null configuration, relative to the single null configuration.

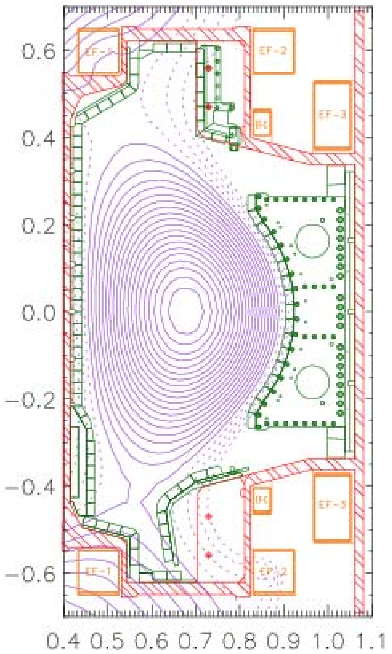


Figure 2.2.1: 1.6MA, 5.3 T C-Mod equilibrium in the ITER shape. $\kappa=1.85$, $\delta=0.49$, $q_{95}=3$, $I_N=1.4$

Proposed Research

The high level goals of the C-Mod Burning Plasma Support Thrust, and intermediate objectives are shown in Table 2.2.2. While these goals are applicable to a range of burning plasma experiments, we expect that the principal focus will be concentrated on ITER support, assuming a successful outcome of the site selection negotiations presently underway. In addition to the activities listed in Table 2.2.2, we expect to continue to actively support the ITPA effort through targeted research both in the Burning Plasma Thrust program and in the Topical Science groups.

Table 2.2.2

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_ψ	2004
	Determine effect of dissipative divertor techniques on pedestal parameters, stability	2004-05
	Determine compatibility of unbalanced DN particle control with EDA, Type II ELMs, or other edge relaxation	2005
	Assess RF coupling/heating efficiency with different edge relaxation phenomena	2004-05
	Determine divertor heat loads associated with relaxation phemomena	2005
Demonstrate high power operation with acceptable heat loads, steady-state density	Develop radiative/dissipative divertor techniques for high performance H-mode discharges	2004-05
	Test unbalanced DN pumping concept for density control	2005
	Test high heat flux components	2004-05
	Test high heat flux Advanced divertor	2007
	Demonstrate sustained high performance operation	2007-08
Demonstrate RF core heating in BPX relevant scenario	Evaluate D-He^3 heating scenario at relevant density, and field	2004
	Demonstrate real-time matching system to improve ICRF heating reliability	2005
Demonstrate control of neoclassical tearing modes using localized RF current drive	Confirm presence of NTM's in BPX parameter regime of β, ν_{eff} in C-Mod	2004-05
	Based on RF physics program results, evaluate suitability of LHCD and/or MCCD for NTM stabilization	2005-06
	Based on Stability physics program results, evaluate necessary current drive parameters for open-loop stabilization of NTM's	2005-06
	Develop[and test feedback stabilization of NTM in high-performance H-mode, demonstrating mode suppression and increased β, $nT\tau$	2007

Goal	Intermediate Objectives	
Develop and test high performance scenarios	Operate at ITER-scaled physics parameters, q_ψ, β, collisionality, shaping	2004-05
	Determine influence of pedestal parameters, edge relaxation on core performance	2004-05
	Investigate ITER hybrid scenario, using LHCD for current profile control	2005-06
	Apply AT/ITB techniques for current and density profile control, optimized reactivity	2006-07
	Demonstrate sustained high reactivity operational scenarios	2007-08

2.3 Transport

Recent Highlights

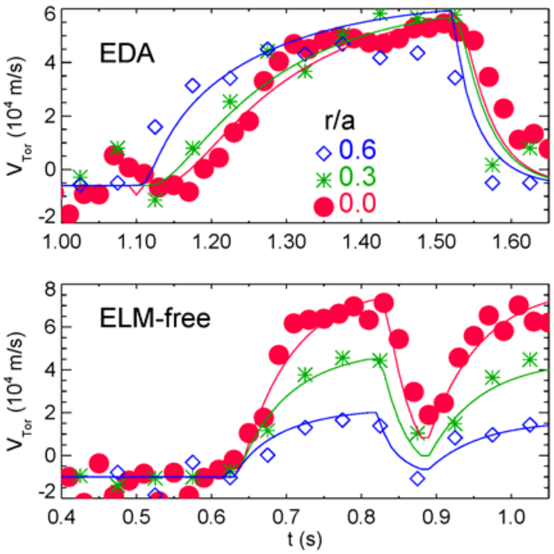


Figure 2.3.1: Momentum transport coefficients can be derived from the evolution of rotation profiles.

Previous observations of strong core plasma rotation, produced in the absence of external drive, have been extended by the measurement and analysis of rotation profile evolution. Transitions between L and H-mode, which correspond to changes in the edge boundary condition for rotation, produce a transient response from which the transport of angular momentum in the plasma core can be computed and compared among various operating regimes. Momentum is clearly seen diffusing from the plasma edge for EDA H-modes on a time scale similar to the energy confinement time. For ELM-free H-modes, a strong inward momentum pinch is observed along with diffusion. (see Figure 2.3.1) In both cases, transport coefficients are much greater than the neo-classical values. Experiments on self-generated flows and momentum transport in C-Mod have generated strong interest from the theory community. An important dependence on plasma topology was discovered with low-power upper single-null discharges ($B\times\nabla B$ down) tending to rotate much more strongly in the counter-current direction compared to lower single-null plasmas. In all cases, the rotation increases in the co-current direction as the plasma pressure is increased.

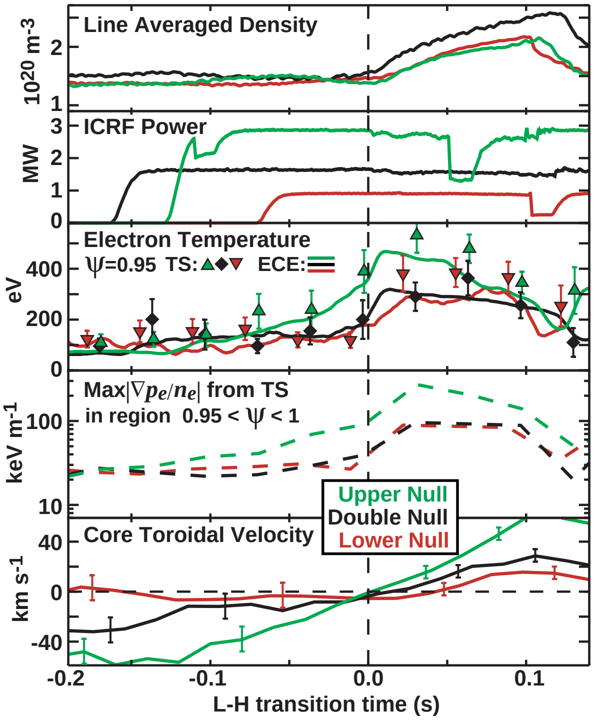


Figure 2.3.2: Topology dependent changes in the SOL and core flows may explain the dependence of the L-H threshold on the ∇B drift direction

There is clear evidence that flow in the SOL provides the boundary condition for core flows. The observation of momentum transport from the edge to the core in torque-free plasmas was described above. Further data come from the modification in flows as the plasma topology is modified from lower single null to upper single null in L-mode. Both the core and SOL rotations shift in the counter-current direction and by roughly the same magnitude. Most notable is the high degree of sensitivity for this change on the precise balance of the equilibrium. The change in SOL and core rotations is seen with a shift of only 5 mm in SSEP (the distance between the primary and secondary separatrices mapped to the outside midplane).

The correlation of self-generated plasma flows and topology has led to a novel explanation for the dependence of the H-mode power threshold on the ∇B drift direction. This 0^{th} order effect, which roughly doubles the required power to achieve H-mode, can be understood as the result of two effects, which add or subtract, depending on topology. The first are SOL flows which are driven by ballooning transport in a direction determined by topology and which couple across the separatrix to the core plasma. The second term is determined by momentum transport and increases monotonically in the co-current direction with plasma pressure. The H-mode threshold could then be understood as requiring a critical edge flow which requires very different input powers in the two cases. (see Figure 2.3.2)

Work on the H-mode threshold has included comparisons with a theoretical model [1] which attempted to capture physics revealed in non-linear gyro-fluid simulations. The result was a testable formula for a critical parameter at the L/H boundary: $\Theta \equiv \frac{T_e}{L_n^{1/2}} = 0.45 \frac{B_T^{2/3} Z_{eff}^{1/3}}{(RA_i)^{1/6}}$. A toroidal field scan performed on C-Mod found a similar dependence, but with experimental values about 40% below those predicted (see Figure 2.3.3). The influence of plasma topology described above, which is not in the model may account for some of the discrepancy.

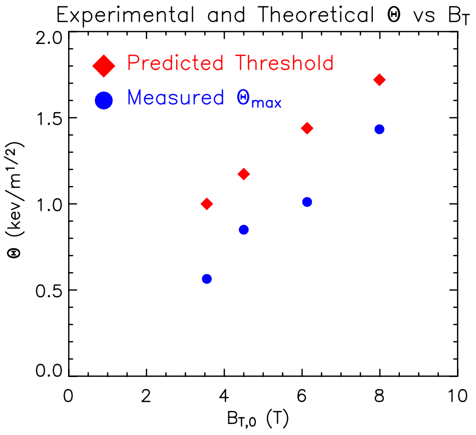


Figure 2.3.3. Comparison of the critical parameter derived by Guzdar with experimental data.

Investigations into the regulation of the H-mode pedestal by a quasi-coherent (QC) mode rather than ELMs were extended by new diagnostics and by detailed comparisons with the 3D non-linear fluid code BOUT. This code gave agreement in several important areas including fluctuation levels, mode frequency and wavenumber. The essential ballooning character of the mode was verified by comparing optical fluctuations from the low and high field sides of the plasma. The observed dependence of the EDA/ELM free boundary on edge safety factor which occurs in the range $3 < q_{95} < 4$, is seen in the code as well. Areas of disagreement remain however, including the prediction of a pair of high-frequency companion modes near 1.5 MHz, which have been ruled out experimentally by the PCI measurements, which has more than adequate frequency resolution and dynamic range (see Figure 2.3.4). The boundary for grassy ELMs, which occur at higher pressures and temperatures than EDA, can be understood in terms of coupled ballooning-peeling stability. Dimensionless identity experiments carried out among C-Mod and DIII-D, JET, and ASDEX-U confirm the dominance of plasma physics in determining the pedestal structure. Kinetic modeling of neutral transport finds that the pedestal width is not determined by neutral penetration in C-Mod.

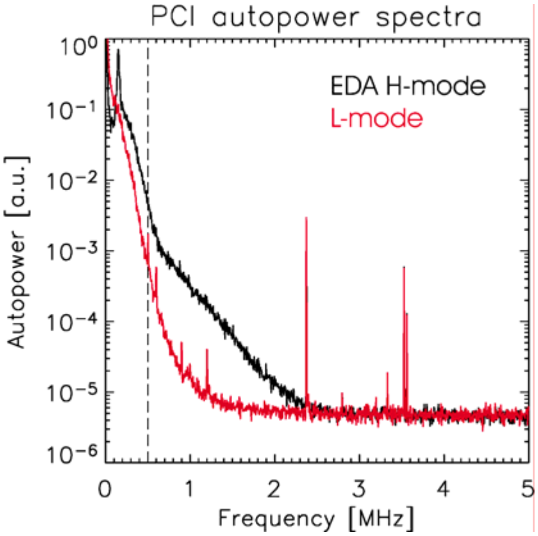


Figure 2.3.4: Comparison of fluctuation spectra in L and H-mode plasmas. Note the absence of the high-frequency companion modes which were predicted to accompany the QC mode in the EDA regime.

Research into internal transport barriers (ITB) has focused on control of the barrier strength, and location. The foot of the barrier could be moved to larger minor radius by lowering B_T. It is not clear yet whether this is an effect of q, q′ or B_T itself. The barriers, which are produced in C-Mod by off-axis RF heating, can be weakened by the application of on-axis power. The dynamics of barrier creation and control has been investigated with the non-linear gyrokinetic code GS2. Simulations find that modification of the temperature profile by off-axis heating helps stabilize ITG turbulence, lowering anomalous transport and leading through the Ware pinch to more peaked density profiles. These in turn further stabilize the ITG modes. The process continues until the steepened density profiles destabilize TEM modes. On-axis heating increases transport caused by the TEMs, providing the control mechanism.

Research Plans

C-Mod experiments will emphasize the study of particle, momentum and electron thermal transport channels, which have not received as much attention as ion thermal transport. The exclusive use of RF power for auxiliary heating and current drive leads to significant differences 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. Core barriers in C-Mod 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.

The importance of plasma flows in regulating stability and transport has been demonstrated, however the observation of strong toroidal rotation in plasmas without an explicit momentum source remains unexplained. Since flow shear can be a critical element in transport reduction and because NBI flow drive is unlikely to scale to reactor grade devices, self generated flows are of obvious interest. The search for alternate explanations has focused on transport mechanisms, and at least theoretically, on Reynold's stress where toroidal velocity is advected by the turbulence. The PSFC theory group is planning to begin gyrokinetic simulations using the GYRO code in support of this effort. Measurement of the full velocity profiles made possible by the deployment of beam assisted diagnostics and observations of core fluctuations will be essential in studying this phenomenon. Transient transport experiments to measure momentum transport coefficients will be continued, perhaps in conjunction with mode-conversion IBW/ICW flow drive experiments. While still speculative and computationally uncertain, this last technique, if successful, would also provide a powerful tool for studies of flow-shear turbulence reduction and profile control. The possibility of direct and effective intervention in a transport suppression mechanism would be a development of tremendous potential.

A large number of experiments are planned to study the relationship of flows in the SOL and core and their influence on the L/H threshold. These include investigations into: the role of neutrals in coupling flows, particularly near the low density limit where the power threshold tends to rise sharply; the nature and role of flows in limiter H-modes; and the connection to important scaling variables like density, field and plasma current. Improvements, particularly the CXR rotation profiles and modification to the scanning probes will be carried out to improve diagnostic coverage. Connection to theory based models, particularly the BOUT code are planned in collaboration with the LLNL group. We will continue studies of the threshold based on local measurements of profiles and fluctuations. New capabilities for plasma shaping and heating will be exploited, along with the ability to modify the edge collisionality by lowering density with the planned cryopump. General studies of the transport bifurcation and transition dynamics will be continued in collaboration with the ORNL theory group and may yield important information about the underlying physics.

Studies of EDA H-mode will focus on the QC mode, and particularly on apparent discrepancies between experimental measurements and simulations with BOUT with an aim toward improving the physics in the code. While the code was successful in predicting several features of the mode, the high-frequency companions, a geodesic-acoustic wave and an Alfvenic mode have clearly not been observed. Improvements to the optical arrays and to the scanning probe, to allow non-perturbative measurement of the radial extent of the mode will be carried out and the results compared to the simulations. Reliable extrapolation of favorable operating regimes like EDA can only be achieved through a more complete understanding of the underlying phenomena. To that end, a significant effort will be devoted to mapping out the 'phase space' of the observed edge regimes. These regimes include L-mode, H-modes with type I, II, and III ELMs, as well as ELMfree and EDA H-modes. In these experiments, we will exploit the higher input power and increased shaping capabilities that are now available. In order to make closer contact to the underlying physics, the emphasis in these studies will be on local variables and profiles rather than global parameters. The operating space to be examined will include scans of input power, plasma current, triangularity, and density - with the aim of independently varying the plasma gradients and collisionality as well as those variables that affect micro and macro stability. The results of these studies will be compared directly to the output of microstability codes like GS2 and macrostability codes like ELITE.

Pedestal scaling experiments will be continued including the similarity experiments carried out with JET and DIII-D and will exploit the new shaping capabilities (of both C-Mod and JET) and increased RF power available. A focus of these latter experiments will be on resolving the debate over the relative importance of plasma physics compared to atomic physics in determining the pedestal profiles. The approach of these studies will be to alter the neutral interactions independently of the bulk plasma parameters. Techniques which will be used include: inner and outer gap scans, which can localize the plasma wall interactions and the fueling source; density scans, which change both the magnitude and the location of the neutral source; and comparison of helium and deuterium discharges. This last case relies on the difference in neutral penetration and recycling for the two species. A new H_α array is planned which will view the same volume in the plasma as the Thomson scattering system and which can be geometrically cross calibrated, eliminating mapping as a source of error for these studies. Plans are also in place for a set of dimensionless identity studies with the ASDEX Upgrade device. These will include both threshold and pedestal scaling experiments and should provide useful information on the role of neutrals as well.

A major effort to upgrade core fluctuation measurements on C-Mod has begun. The PCI diagnostic now has better spatial coverage and improved data acquisition allowing measurement of 32 channels at 10 MHz for the full discharge. Later this year, a phase plate will be added which will provide some degree of spatial localization to what is otherwise a line integral measurement. For low k fluctuations (ion scale) the localization will be coarse, allowing us to distinguish between edge and core. However, for high k fluctuations, spatial resolution on the order of 2 cm should be possible. Future upgrades will expand the accessible wave number resolution to about 30 cm^{-1} which should encompass electron scale fluctuations like ETG modes. Combined with the spatial localization, this should allow measurement of both k_r and k_θ and may help resolve a critical issue for electron transport – that is whether extended radial structures are present. Without these structures, short wavelength modes like ETG are incapable of causing significant transport. It is worth noting that recent measurements of high frequency fluctuations in C-Mod (see Figure 2.3.4) show features which are consistent with short wavelength modes Doppler shifted by the measured plasma rotation. The reflectometry diagnostic will also be upgraded for fluctuation measurements with improvements in signal to noise obtained by eliminating the amplitude modulation of the probe wave and by upgrades to its data acquisition. Reflectometry is particularly well suited to probe fluctuations localized in the steep density gradients associated with transport barriers.

Work on internal transport barriers (ITB) will continue to focus on access conditions, dynamics and control. The improved core fluctuation measurements discussed above will allow us to study the role of TEM turbulence in barrier control. With the deployment of LHCD, it will be possible to directly manipulate magnetic shear, an important parameter in determination of the critical gradient for ITG, TEM and ETG modes. This may allow investigations of "electron" vs "ion" barriers and better understanding of the relationship of particle and energy transport. With the MSE diagnostic to measure current profiles, studies of core micro-stability can be carried out with greater precision. The anticipated accuracy of the measurement will make a quantitative difference on the comparison between theory and experiment. Barrier dynamics will be studied in a series of hysteresis experiments involving the ratio of on and off-axis power and toroidal magnetic field. Finally, various RF flow drive scenarios will be tested, with emphasis on mode conversion experiments and the barrier creation through direct control of ExB stabilization.

It is widely believed that particle transport is driven by ion-scale fluctuations, but detailed calculations and measurements are generally lacking. Since density profiles evidently play an important role in the C-Mod internal transport barriers through the stabilization of ITG modes, and since in the absence of external fueling, peaked profiles can only be produced through modification of particle transport, the understanding of this transport channel is essential. More generally, the lack of core fueling can provide a test bed for the study of off-diagonal terms in the transport matrix, since only such terms can be responsible for pushing particles up the density gradient into the plasma core. With LHCD replacing inductively driven current, C-Mod will be able to perform particle transport experiments without a core particle source and without a Ware pinch, thus isolating any anomalous pinch. In the EDA H-mode, impurity confinement is reduced dramatically, but there is no obvious change in the edge density or temperature profiles. (In the presence of the observed large amplitude mode, the change in impurity transport is perhaps less surprising than the only minor modification of energy transport in the pedestal.) Experimental and theoretical studies of the quasi-coherent mode will focus on the role of the mode in the transport of particles, energy, and impurities.

Connection to IPPA

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 IPPAsection 3.1.1 and appendix III 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, described in section 2.4, 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.

References

[1] Guzdar, P.N., et al., “Zonal flow and zonal magnetic field generation by finite beta drift waves: a theory for low to high transitions in tokamaks,” Phys. Rev. Lett **87** No. 1, 2, (2001) 015001.

2.4 Edge and Divertor Physics

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. Our research in transport is based on a two-pronged approach: On long time scales we study the time-averaged transport and profiles to extract an empirical understanding of how transport scales and what affects it. Such an understanding allows scaling to other tokamaks and potentially points out the underlying physics. Our second approach to the understanding of transport is to understand the underlying turbulence and how it leads to the time-averaged profiles.

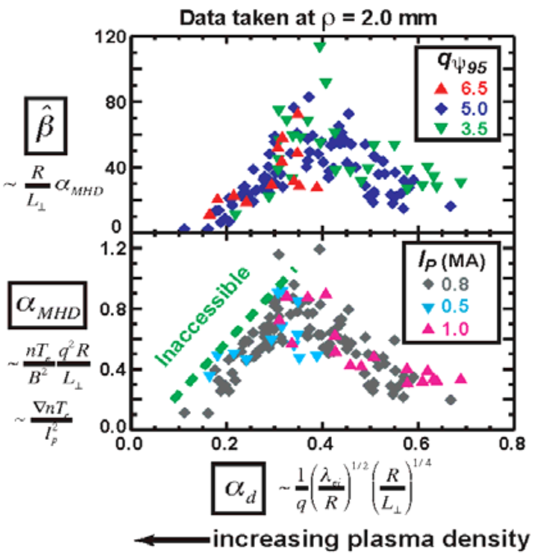


Figure 2.4.1: The normalized parameters for pressing radient (α_{MHD} and $\hat{\beta}$) are plotted vs the collisionality ($\hat{\alpha}$) for 3 different plasma currents.

The development of a radial transport analysis technique ('window frame' technique) based on particle balance was made several years ago here at C-Mod [1] allowing for studies of the C-Mod SOL. We have taken this technique and worked with DIII-D and JET collaborators to create dimensionlessly similar discharges on those tokamaks (and C-Mod) in order to compare the SOL transport across tokamaks. From these experiments we have learned that the radial transport in the far SOL increases with distance from the separatrix, with transport defined as a D_{eff} or v_{eff}. The dependences on ρ^*, ν^*, β and minor radius, *a*, are weak, providing a robust scaling law to other tokamaks [2][3]. As a result of the C-Mod to JET comparison we have tentatively hypothesized that neutrals are also playing an important role in the sense that as the SOL becomes more opaque to neutrals (C-Mod, ITER) the profiles are more likely to develop a flat region (in density) due to a radial high-recycling condition. We have identified this as a potential issue for ITER, particularly its impact on the upper divertor and main chamber PFCs. We plan to continue this research in the coming two years. A mini-proposal has been accepted for DIII-D to expand the use of the window-frame technique to H-mode ELMing discharges. We also plan to continue experiments on JET when it starts up again. Lastly we will work with the ITER physics group (Kukushkin) in the modeling of ITER to understand better the implications for that device.

Recent analysis of plasma pressure gradients near the separatrix and their dependence on plasma conditions suggest that electromagnetic fluid drift (EMFD) turbulence, as contained in non-linear plasma turbulence models [7], controls the level of transport in this region [6]. These models identify two key parameters, pressure gradient and collisionality, as controlling the level of plasma transport. Natural normalizations for these quantities (e.g., α_{MHD} and α_d) are suggested by the system of equations which describe EMFD physics. It has been recently found that the edge plasma state near the separatrix in C-Mod lies on a well defined curve in this 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 (see Figure 2.4.1). We plan on completing the recent data analysis and publishing the results. Follow-up experiments are planned to explore the EMFD parameter space over a wider range of plasma currents and magnetic fields including reversed magnetic fields.

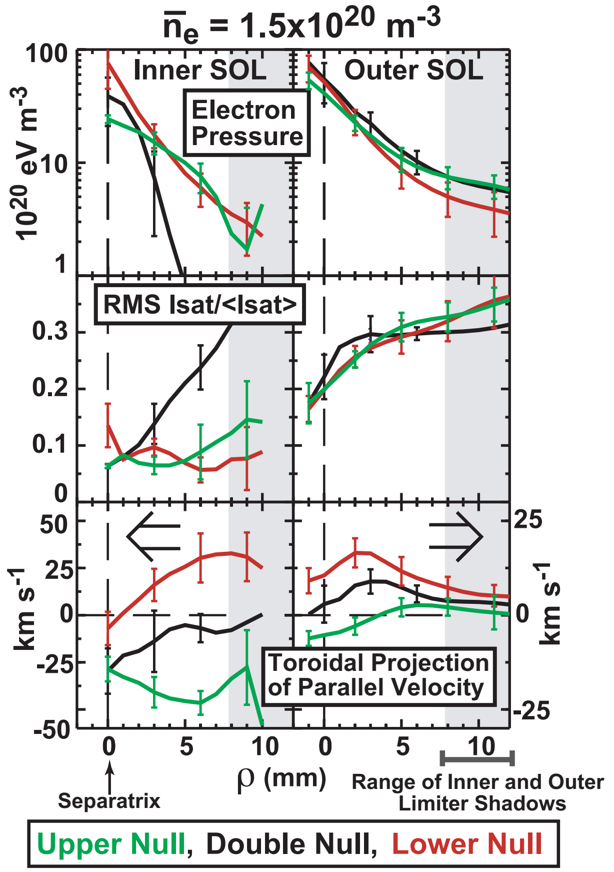


Figure 2.4.2: The SOL flow profiles at the Inner and outer SOL regions are shown for three magnetic topologies: Upper single-null (green), Lower single-null (red), and double-null (black.)

Experiments over the past year have revealed an interesting interplay between ballooning-like transport asymmetries, scrape-off layer flows and magnetic topology. Moreover, near-sonic plasma flows in the high-field SOL appear to be connected to differences in the L-H power threshold for upper versus lower single-null topologies (see Figure 2.4.2) [8]. Over the next two years we plan on exploring this physics in detail as it may provide a fundamental breakthrough in the understanding of the L-H threshold. Working with our 2-D edge plasma transport collaborators (X. Bonnin – IPP Greifswald, A. Pigarov – UCSD, M. Umansky – LLNL), we hope to identify the physics which is presently lacking in the 2-D transport codes and does not allow the measured and computed plasma flow fields in the SOL to agree. We also plan on upgrading our measurement capabilities for flows in the high-field SOL with the development of a multiple electrode inner wall scanning probe and the use of charge-exchange recombination spectroscopy (likely involving intrinsic boron) for Doppler flow measurements.

The physics which underlies the observed time-averaged plasma transport is plasma turbulence, with fluctuation ‘events’ of duration under the 50 μs timescale. Over the past year we, in collaboration with S. Zweben of PPPL, have expanded our pioneering use of optical measurements (Gas-Puff Imaging - GPI) and probes, both to visualize the turbulent structures and their dynamics as well as to examine statistics of the turbulent fluctuations which include large-amplitude “events” responsible for non-diffusive, convective, and “bursty” transport [12]. The GPI technique [11] measures the local n_e and T_e turbulence as manifested in local neutral emission from puffed gas. This emission is observed in 2D (radial and poloidal) in 300-frame, 250 kHz movies and as ~1Mhz signals from multi-channel diode arrays, viewing both inboard and outboard edges. These measurements have yielded, among other things, k_{pol} spectra [9], velocity fields of the structures, and fluctuation statistics [10]. Over the next two years, we will further exploit the use of the movies and improve the spatial resolution of the system to < 1mm. We also plan to purchase of a state-of-the-art camera (which was used previously as part of an SBIR). A poloidally-resolving multi-channel array will be added to the diagnostic complement, and the spatial resolution of the existing radial array will also be improved (to ~2mm). Our collaboration with D. Stotler (PPPL) on the interpretation of the emission will also be continued.

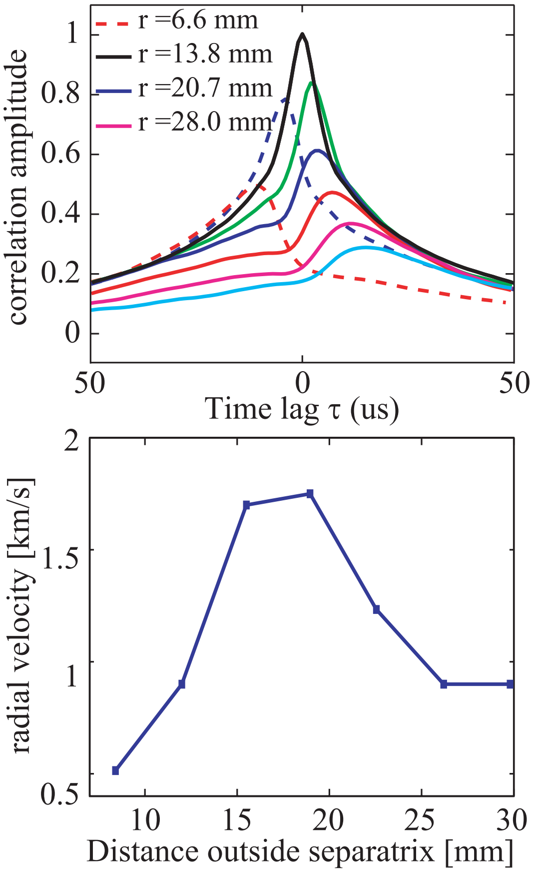


Figure 2.4.3: Correlation analysis of a set of radially spaced (3 mm) diodes to determine the radial propagation velocity of large fluctations.

An area where these techniques have been particularly useful and important is in the study of density limits. Probe measurement on C-Mod have previously revealed that, as the density limit is approached, the characteristics of the large magnitude transport found in the far-SOL move inside the separatrix, thereby creating a plausible explanation [14] for the universally-observed limit. Recent turbulence movies have confirmed and expanded upon investigations made with probes, with observations of turbulent structures generated inside the separatrix and propagating outward radially.

Using one of the probes and one of the GPI optical arrays, we have also made simultaneous measurements of turbulence at different locations along the same field line. These experiments test the correlation of fluctuations *along* the field and reveal details of the relative structure of the potential and density fluctuations.

We have utilized the long-duration, high-time-resolution measurements of the radial GPI diode array for "conditional averaging" and cross-correlation analyses of the large amplitude fluctuations. We find that the large turbulent structures propagate radially outward with velocities varying between 0.5 to 1.5 km/s. (see Figure 2.4.3) These experiments, done in collaboration with O. Grulke (IPP-Griefswald), will be continued with emphasis not only on the large "events", but also the "holes" in the fluctuations to determine if they move inward, perhaps allowing for enhanced penetration by impurities.

In order to investigate the turbulence drive and ultimately to link quantitatively the turbulence to the transport, we use 3D fluid simulations [16] of the C-Mod edge turbulence in which the time-averaged profiles have been prescribed based on measurements. We plan on continuing and expanding our collaboration with LLNL (Umansky, Xu, Nevins) in the use of the BOUT code [15]. The code will be set up to simulate specific C-Mod plasmas and its output will be made available to C-Mod personnel. This will allow for detailed investigation of a number of edge issues, including further study of the QC mode (see section 2.3 on Transport). As the measurements become more extensive and accurate and the codes become more inclusive, we seek ultimately to obtain a self-consistent simulation - with simulated turbulence self-consistently relaxing the time-averaged profiles and both turbulence and profiles matching the experimental observations.

Over the next two years we plan to continue our fruitful collaborations with Ben Carreras (ORNL) and Ghassan Antar (UCSD) in looking at statistical descriptions of the nonlinear dynamics which underlies edge plasma turbulence [18]. Recent analysis using 'quiet-time statistics' suggest that the near SOL exhibits self-organized critical dynamics while the far SOL does not [10]. We hope to extend these kinds of analyses to long-time probe data samples taken over a range of plasma conditions, including different plasma densities and radial locations in the SOL. A new inner-wall scanning probe should allow long-time samples to be recorded at this location as well.

Neutrals

The C-Mod divertor typically operates in a regime with short neutral mean free paths compared to the divertor dimensions and with significant opacity to Ly_α radiation – a unique regime among presently operating tokamaks yet prototypical of the conditions which will be found in ITER. Until recently, modeling of neutral pressures in the C-Mod divertor could not achieve a match with experimental measurements, being a factor of ~10 too low. Over the past year work has progressed towards resolving reasons for the discrepancy (described below). In parallel, efforts were directed toward developing a practical understanding of the neutral pressures in the upper chamber in preparation for the upper divertor cryopump.

Recently, Lisgo (U. Toronto) was able to model divertor pressures in C-Mod within a factor of 2 using OSM-Eirene. Key new physics ingredients were the inclusion of neutral-neutral and neutral-plasma collisions which could only be tested in C-Mod. 3-D geometry and prescribing a plasma 'background' that matched detailed measurements of divertor conditions from a variety of diagnostics [17] were important steps as well. These efforts have pushed the state-of-the-art in divertor neutral modeling. Plans for continuation of this work include radiation transport benchmarking using advanced algorithm computations with Eirene (D. Reiter).

In parallel, a series of experiments was performed to directly measure neutral conductances through divertor and port structures in C-Mod with and without plasma present [13]. These results have demonstrated the dominant role of plasma-neutral interaction ('plasma plugging') in C-Mod. Effective neutral conductances out of the open, upper divertor chamber where found to be reduced by a factor of 5 by the presence of plasma in an upper null configuration. A comparison of these results with that of the lower divertor indicate that a simple upper neutral baffle structure should enhance the upper divertor neutral pressures by about a factor of ~2. Over the next year, we plan to install a version of that baffle in the upper chamber to assess this predicted effect on the neutral pressures and to give more confidence in the upper cryopump baffle design. D. Stotler will also model neutral conductances in C-Mod with DEGAS2 using a detailed 3-D model of the divertor and vacuum vessel structures. The aim is to benchmark neutral conductances against those obtained from direct measurement in the C-Mod vacuum vessel [13].

Several years ago we investigated the D retention in C-Mod in collaboration with Wampler [5]. This work showed that C-Mod, with high-Z surfaces, had 10-100 times lower D retention than carbon PFC tokamaks. The highest levels were in areas of B covering the Mo (boronization) while the lowest D retention was on bare Mo surfaces. We intend to continue this work in the coming two years with analysis of tiles taken out during a vent, (both on the front and sides of tiles) as well as specific experiments to characterize the D retention (globally) in a single discharge. These efforts are highly relevant to ITER.

Impurities

Because of the high-Z walls in C-Mod we contribute important data to the operational experience that will be used in predicting ITER performance 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. Questions that need to be addressed are the levels of Mo in the core for different operating regimes, the level of melting and melt-layer dynamics, and the consequences for main plasma operation after high-Z surfaces are damaged.

Several important experimental results are being modeled at C-Mod in an attempt to determine the underlying physical mechanisms (compression, enrichment, screening). We utilize the DIVIMP code (supported by U. Toronto collaboration) for this purpose. The past year has been spent expanding the code's capability to track the flow of different ionization states around the grid and across the separatrix. This has allowed us to synthesize the penetration factor (# of impurities reaching the core/# launched). We have shown that the divertor penetration factor is much lower than from the main chamber, as seen in experiment [4]. The scaling with plasma density and impurity species/mass was also reproduced. The next step is to add experimentally measured flows and radial convection to evaluate the effect of the background plasma.

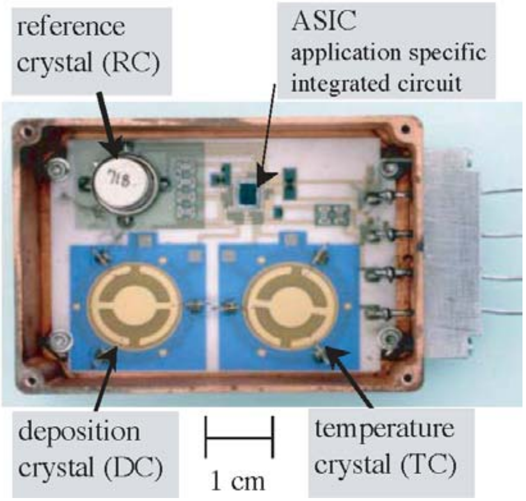


Figure 2.4.4: QMB installed in JET. A modified version has been ordered for C-Mod.

As part of the same tile-analysis work by Wampler described above, we have found that the outer divertor is a strong erosion region while the rest of the PFC surfaces, in general, are not. We would like to expand the characterization of the impurity transport to the deposition of Mo & B around the chamber in an effort to determine if high-Z impurity transport is somehow different than for low-Z. This will involve two efforts: Tiles will be removed after the current run period and analyzed for small amounts of Mo deposited on boronized main chamber surfaces. This will be compared with spectroscopic measurements of Mo influx from those same surfaces. Secondly we are purchasing quartz-crystal microbalances (QMB) for deposition measurements at several points poloidally, which will allow in-situ, between shot analysis (see Figure 2.4.4).

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. We are presently developing tungsten brush tiles to improve our heat-flux handling capability. Prototype tiles will be installed during the next vacuum break with the intent that a full outer divertor module will be designed for the following year. A second project is the development of the divertor cryopump. On the basis of the plasma plugging experiments discussed above and strong radial transport in the far SOL we have determined that the upper divertor can be used for pumping. This separates the heat and particle handling functions between the two divertors. It also allows for greater variation in the upper triangularity of C-Mod plasmas. As mentioned above, a baffle will be installed in the upper divertor during the next vacuum break to test our understanding of the effect on neutral pressures for the cryopump.

References

[1] LaBombard, B., et al., Nucl. Fusion **40**, 2041 (2000).

[2] 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.

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

[4] Chung, T., et al., "DIVIMP modeling of impurity flows and screening in Alcator C-Mod," to be presented at the 16th Conference on Plasma Surface Interactions, Portland Maine, May 24-28, 2004.

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

[6] LaBombard, B., et al., "Evidence for Electromagnetic Fluid Drift Turbulence Controlling the Edge Plasma State in Alcator C-Mod," APS 2003, paper CO1.002.

[7] 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.

[8] LaBombard, B., Rice, J.E., Hubbard, A.E., et al., "Scrape-off layer flows, magnetic topology and influence on the L-H threshold in a tokamak," submitted to PRL.

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

[10] Carreras, B.A., et al., Phys. Plasmas **8** (2001).

[11] Terry, J.L., Maqueda, R., Pitcher, C.S., Zweben, S.J., LaBombard, B., Marmar, E.S., Pigarov, A.Y., and Wurden, G., J .Nucl. Mater. **290** (2001) 757., Zweben, S.J., et al., Phys. Plasmas **9** (2002) 1981.

[12] LaBombard, B., et al., Phys. Plasmas **8**, 2107 (2001), J. L. Terry et al., Phys. Plasmas **10**, 1739 (2003)

[13] LaBombard, B., and Boswell, C., "In-Situ Gas Conductance and Flow Measurements Through Alcator C-Mod Divertor Structures With and Without Plasma Present," M.I.T. PSFC Report PSFC/RR-03-6.

[14] Greenwald, M., Plasma Phys Cont Fusion **44** (2002) R27, B. LABOMBARD et al., Proceedings of the 19^{th} IAEA Fusion Energy Conference, Lyon, France, 2002, B. LaBombard et al., Phys. Plasmas **8**, 2107 (2001)]

[15] Xu, X.Q., et al., Phys. Plasmas **7** (2000) 1951, Xu, X.Q., *et al.*, New Journal of Physics **4** (2002) 53.

[16] Rogers, B.N., et al., PRL **81** (1998) 4396., Zeiler, A., Biskamp, D., Drake, J.F., and Rogers, B.N., Phys. Plasmas **5** (1998) 2654., Xu, X.Q., *et al.*, New Journal of Physics **4** (2002) 53.

[17] Lisgo, S. "Interpretive Modeling of the Alcator C-Mod Divertor," University of Toronto Doctoral Thesis, May, 2003.

[18] Antar, G.Y., et al., Phys. Plasmas **10**, 419 (2003).

2.5 MHD

The Alcator C-Mod MHD research program addresses issues of macroscopic stability 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 relvant to ITER and future reactors. The C-Mod MHD program also has excellent connections to theory and modelling.

Locked Modes and Error Fields

Locked modes and error field studies have become a major new topic of research on C-Mod, following the realization that locked modes are responsible for disruptions at high plasma currents and also at very low densities. This was rather unexpected, based upon a widely-held view that small tokamak plasmas were less susceptible to error fields. A set of error field correction coils ("A-coils") was installed on the outside of the C-Mod igloo last year. These have been used both to study locked mode thresholds and scalings in C-Mod over a range of operating-space parameters, and to reduce instrinsic errors, thereby allowing operation at lower densities (and soon at higher currents). The threshold studies in C-Mod bode well for ITER, as shown in Figure 2.5.1. The exploration of these preliminary scaling results will be expanded significantly in an ITPA joint collaboration with JET and DIII-D in the near future. Dimensionless identity experiments (including matched plasma shape) will be performed on the three machines with error field correction coils programmed to generate non-axisymmetric fields having similar harmonic content at the 2/1 surface. Since the intrinsic error fields in these machines cannot be matched, these discharges will be run at high densities, where the required applied fields will dominate over any intrinsic error fields. Future plans also include the possible upgrade of the A-coils with an optimized coilset located nearer to the plasma, as well as additional power supplies for added flexibility and field amplitude.

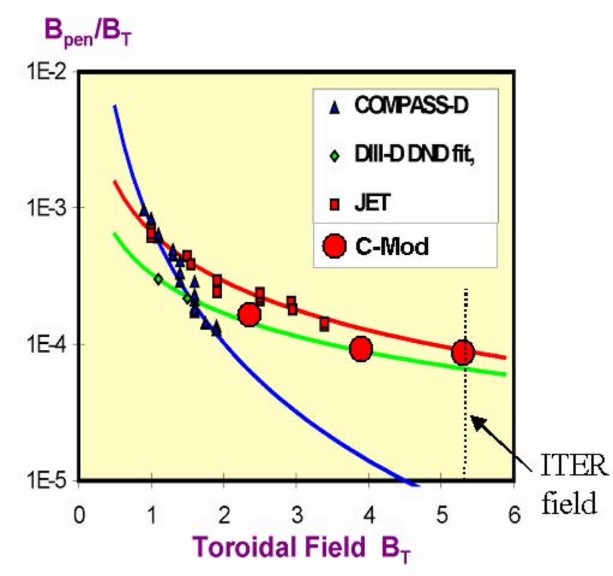


Figure 2.5.1: Toroidal field scaling of locked mode threshold field, including preliminary data from C-Mod

Disruption mitigation

Disruption mitigation continues to be a very active area of MHD research on C-Mod. 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 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 challenging test due to its order-of-magnitude higher plasma pressure, energy density, and current density. In a collaboration with D. Whyte (U.Wisc), a gas jet experiment is being planned on Alcator C-Mod. During the next vacuum break, a gas tube will be installed on an outboard limiter, with its outlet nozzle near the plasma midplane. A fast valve, mounted externally, will control the injection of high-pressure (700 kPa) jets of neon, argon, helium, or deuterium. C-Mod has a fast framing CCD camera (up to 300 images captured as frequently as every 4 μs) which currently looks in the vicinity of the nozzle location, but the viewing optics will be modified to give a wide-angle field-of-view of the entire plasma cross-section. This 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 should help improve understanding of expected halo current reduction.

High β instabilities and NTM's

Recently, a new collaboration with D. Brennan (GA) has been initiated to use the Nimrod MHD code to study examples of β-limiting instabilities observed in C-Mod to date. With the installation of additional RF power in the near future, the occurrence of such phenomena may become a much more important issue. A key question is whether or not the observed instability, shown in Figure 2.5.2, is a neo-classical tearing mode (NTM). Initial results from Nimrod non-linear stability calculations (Figure MHD-3) show that the 2/1 mode at the q=2 surface is Δ′ unstable, but its growth is greatly enhanced by non-linear coupling with the 1/1 mode, which is always present, since the discharge is sawtoothing throughout this period. Thus the instability starts as a classical resistive tearing mode, but then develops some of the characteristics of an NTM. Much work remains to be done with the Nimrod modelling, including enabling the neoclassical drive terms. The Alcator MHD group expects to add a post-

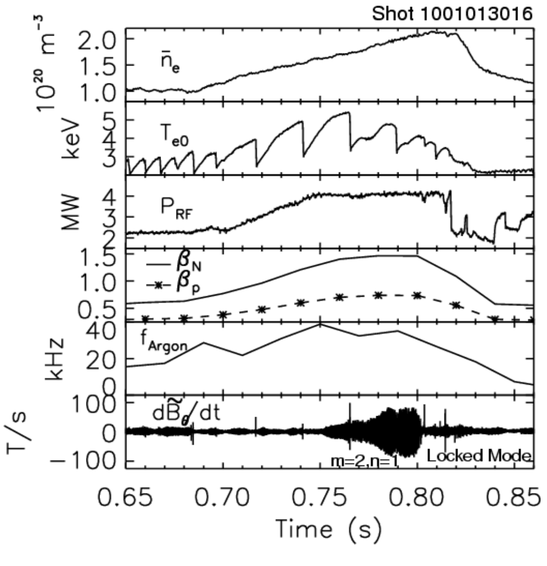


Figure 2.5.2: Example of m/n=2/1 β-limiting MHD in C-Mod. The instability grows to large amplitude and then locks at t=0.80 s

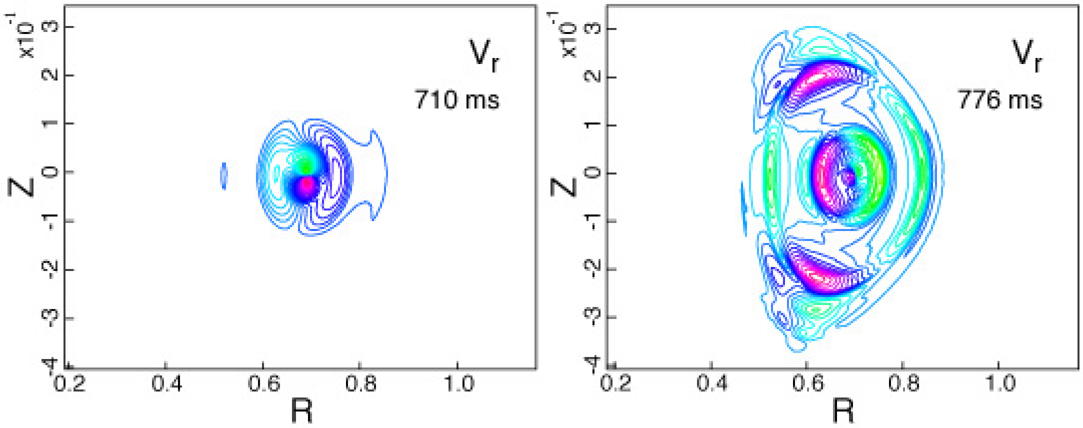


Figure 2.5.3: Nimrod calculations of MHD modes at two times during high-β discharge (see Fig. MHD-2). The 2/1 mode appearing at the latter time is non-linearly driven by the 1/1.

doc next year with extensive expertise on using Nimrod and other codes to study MHD phenomena such as NTM's, disruption halo current mitigation, etc.

NTM's are the focus of another planned ITPA collaboration with DIII-D and JET to determine the β_N threshold in discharges with matched dimensionless parameters (ρ_*,ν_*, 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 current 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 for C-Mod 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 RF chapter.

Active MHD and TAE Cascades

Unstable TAE modes have been observed in C-Mod discharges when high-power ICRF is turned on early in the current rise. Information on RF-generated fast particle distributions can be extracted from the detailed characteristics of the TAE modes. Furthermore, the temporal behavior of TAE cascades directly reflects the evolution of the internal current profile. In a collaboration with JET, the MISHKA code is being used to determine the shape of the q-

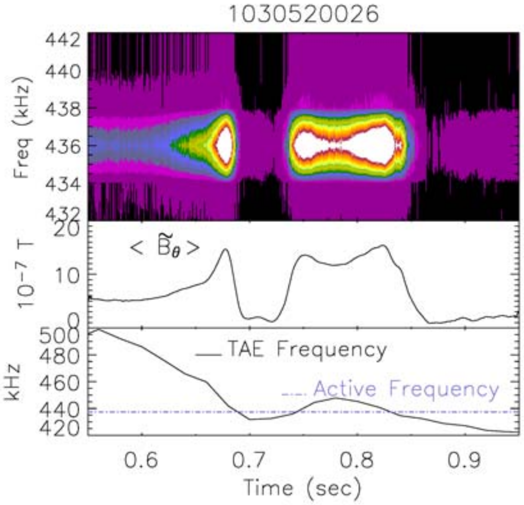


Figure 2.5.4: Active excitation of a TAE mode. The three resonances confirm the accuracy of the calculated TAE frequency evolution.

profile as the plasma current diffuses in. Each cascade is initiated when q_{min} passes through an integer or half-integer value, and the spectrum of n-values depends on the shear at the resonant surface. Initial results indicate that the q-profile in C-Mod is very flat or slightly reversed during the time that q_{min} drops from 3.0 to 2.5. This technique is expected to prove very useful as a complement to other current profile diagnostics during the lower hybrid current drive experiments.

Stable TAE modes can also be generated during the current flattop using the C-Mod active MHD coils. At present, there are two coils located at the same toroidal position in the torus, which can excite ITER-relevant moderately high n-number modes. The coils can be run in two different frequency modes: (1) at fixed frequency (typically 400-500 kHz for TAE studies), while varying B_T and/or n_e to sweep the Alfvén frequency through the resonance, or (2) with frequency sweeps across a relatively constant Alfvén frequency. An example of the former is shown in Figure 2.5.4. The rationale for installing the active MHD system is that it can be used to determine the damping rate of stable modes, or conversely, the proximity to marginal stability, by measuring the frequency width of the resonance. For the TAE seen in Figure 2.5.4, the resonance is quite narrow (1-2 %), indicating that the mode is nearly unstable.

In principle, the active MHD coils can also be used to excite low-frequency, global MHD modes, which normally have much more significance in terms of overall plasma performance than TAE's. Ideally, one would like to monitor the proximity to marginal stability of global modes to provide an early warning of impending instabilities. Open or closed loop feedback of heating power, for example, could then be invoked to avoid a global MHD instability, and perhaps, an ensuing disruption. However, active MHD excitation of low-frequency (10's of kHz), global MHD modes requires larger amplitude magnetic fields and reasonable control of the driven spatial harmonic content. Initial tests, using the present pair of coils in C-Mod have been done, as shown in Figure 2.5.5. So far, no resonant responses have been observed. Intrinsic, benign MHD instabilities do not seem be affected by the active fields either. But several upgrades are planned to enhance the system. A new audio stereo amplifier will provide more power (6 kW), and an additional set of 2 to 4 drive coils, to be installed 180° away toroidally, will provide a better match to the desired toroidal mode spectrum.

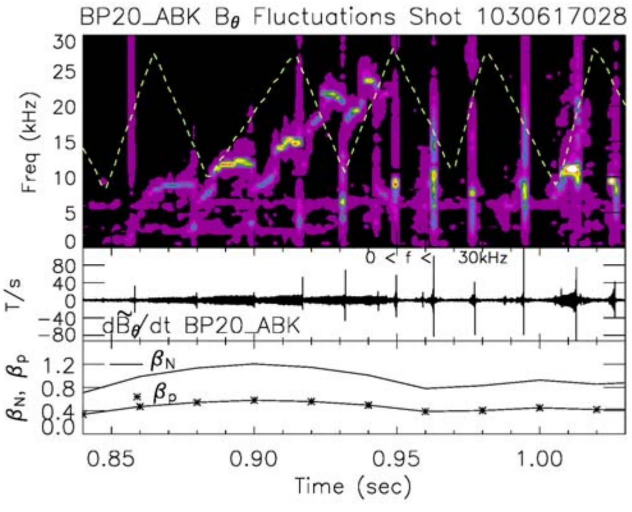


Figure 2.5.5: No MHD resonances are seen during a low-frequency sweep. A naturally-occurring n=3 mode is unaffected by the drive.

Digital Plasma Control System (DPCS)

The Alcator C-Mod tokamak has been using a ‘Hybrid’ analog/digital computer for real-time plasma control since the start of C-Mod operation. The Hybrid can only implement linear control algorithms; 16 plasma quantities are estimated from linear combinations of 96 inputs, and then 16 outputs (to power supplies and gas valves) are generated from linear combinations of PID-weighted errors. In addition, the analog signals (inputs, errors, outputs) are subject to baseline offsets and saturation problems. Furthermore, the Hybrid consists of relatively old hardware, including a μVAX and a bitbus communication highway. So the Hybrid is presently being replaced with a new all-digital system. The DPCS provides significant hardware improvements, including twice as many output channels (32), more input channels (128), and faster response time. But even more important is the capability to implement non-linear control algorithms, possibly including real-time EFIT’s. During the next few years the MHD group will be developing, implementing, and testing new control algorithms in support of the C-Mod research program.

2.6 RF Heating and Current Drive

C-Mod exclusively uses RF for auxiliary heating (predominantly ion cyclotron range of frequency – ICRF) and uses 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.

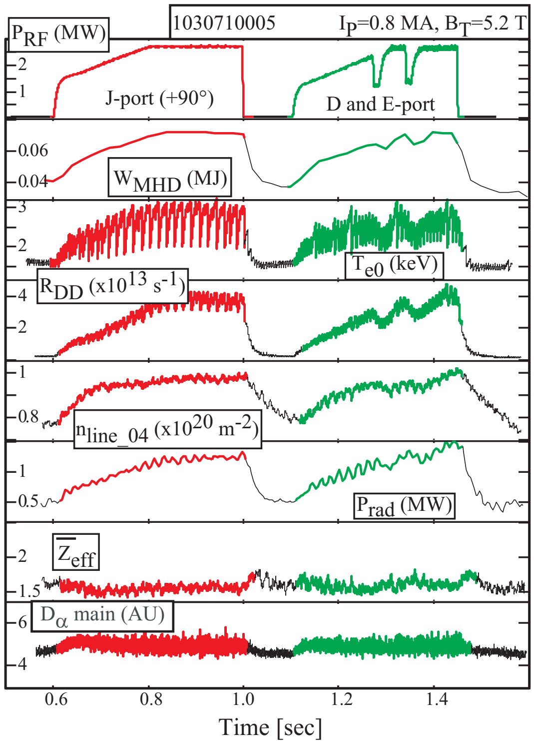


Figure 2.6.1: Plasma response to J antenna with co-current phase is similar to D and E antennas in a D(H), L-mode discharge.

ICRF

Antenna coupling and Antenna/Plasma interactions

One of the primary concerns regarding the planned ICRF system on ITER is the antenna operation. An ideal ICRF system would have minimum negative impact on the plasma edge, have the generator isolated from the load and/or the match resilient to load variations, and efficiently couple power to the plasma. We have successfully demonstrated phased, high power operation with a compact 4-strap ICRF antenna on C-Mod. As shown in Figure 2.6.1., the plasma response for J antenna with co-current drive phase is similar to the D and E antennas including low impurity and density production. Similar results were obtained for counter current drive and heating phases. In contrast to other experiments where the impurity generation increased for current drive phase and was a maximum for so-called monopole phase, these encourage results suggest the impurity generation can be minimized for current drive phase. We plan to study the underlying cause of this phase independent performance by characterizing the RF sheaths and local density. In addition we plan to collaborate with U. of Torino on the development of an electromagnetic solver that has a realistic ICRF antenna geometry coupled to a 1-D plasma field solver (’04 -’06).

Plasma load variations are commonly encountered during L/H transitions and edge localized mode activity (ELM's). One potential solution is a load tolerant antenna design and fast matching technologies. A load tolerant matching network is one where the two ports of the antenna are paired together in such a fashion as to minimize the load variation seen by the transmitter. Initial experiments with the E dipole antenna showed that excessive coupling from one port to the other spoils the load tolerant character. This coupling was higher in plasma operation compared to vacuum conditions. In FY04, we plan to continue these investigations into load tolerant matching configurations on J-port where the coupling is lower between the paired ports. The outcome of these experiments could have an impact on a future 4-strap ICRF antenna for C-Mod and also on the ITER antenna design and the implementation of the JET-EP antenna. We also plan to investigate the integration of fast matching technologies. We have received 2 fast ferrite stubs previously tested on Asdex Upgrade and we to plan to perform similar tests using a double stub matching network on the E-port antenna in C-Mod discharges in FY05. In preparation for a new 4-strap antenna, we plan to investigate the impact of shorter vacuum transmission lines (VTL) on the J antenna performance in FY05. Currently the antenna has a neutral pressure limitation that is ~20% lower than D and E antennas, which have significantly shorter VTL. If the J antenna can operate to higher neutral pressures with shorter VTL, VTL length and operational pressure will need to be accounted for in antenna designs. In FY06, the J antenna will be operated without a Faraday screen to test how the antenna coupling, impurity and density production, and voltage handling are affected. If a screen is unnecessary for antenna operation, a major simplification can be made to the future C-Mod 4-strap antenna. 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.

Propagation, Absorption and Mode Conversion Physics

C-Mod provides a unique platform 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, and the availability of advanced diagnostics for RF wave measurements. We have increased the spatial coverage, digitizing rate, and memory of the Phase Contrast Imaging (PCI) diagnostic (DoE Diagnostic Initiative) which has been used in the past to detect mode converted ion cyclotron wave. In FY04-FY05, we propose to test the use of Faraday rotation of the scattered signal to provide localization information along the measurement chord. Furthermore, we plan to upgrade the optics to resolve higher k which may be important for detecting the mode converted ion Bernstein wave. Taking advantage of this unique capability, studies will initially focus on D(^{3}He) and D(H), the primary species mixes used in C-Mod. An important aspect of these studies is comparing the measured spectrum with TORIC simulations. In collaboration with the RF Sci-DAC initiative, we have local access to the MARSHALL Beowulf cluster to perform simulations with up to at least 511 poloidal modes routinely. To achieve this capability the TORIC code was modified to use highly efficient out-of-core matrix inversion methods and massively parallel computing algorithms.

Realizing high heating efficiencies in D(^{3}He) discharges, where the single pass absorption is weak, is important for planned 2 MA, 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 FY04, 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. Further experiments in FY05 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.

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 ponderomotive 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 begun in FY03 suggest the measured poloidal flow was proportional to the RF power and sensitive to the antenna phase. Further experiments in FY04-FY05 are planned to perform more detailed measurements. The emphasis here will be to assess the magnitude of the poloidal flow, its profile, and its relation to the RF power, its 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.

Mode Conversion Current Drive (ICRF)

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. Initial experiments in FY03 undertaken to identify candidate MCCD scenarios have provided initial data through sawtooth variation, that the driven current is localized. In these experiments, the period of the sawtooth was sensitive to the phase of the antenna as shown in Figure 2.6.2 for power deposition near the q=1 surface. For situations where the deposition was away from q=1, 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(^{3}He) 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 the motional stark effect (MSE) diagnostic. Depending on diagnostic capability, the driven current profile will be measured with some combination of the MSE and planned Faraday rotation diagnostic. The driven current profile is critical for understanding the RF physics. For the central current drive case, the predicted driven current is similar to 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 is 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 driven modes through local current profile modification.

Physics of Energetic Ions

The physics of energetic ions is of obvious importance to burning plasma experiments. 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.

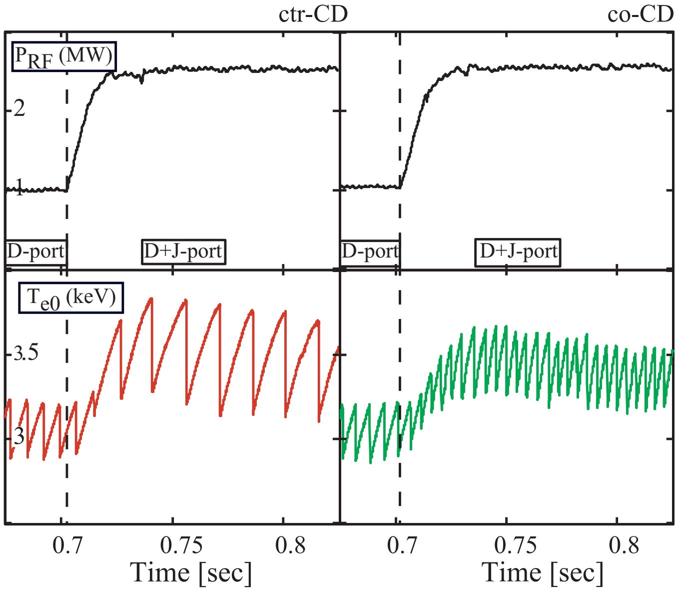


Figure 2.6.2: For deposition near and inside q=1, the sawtooth period increases for ctr-CD and is shortened for co-CD.

In C-Mod, energetic ion affects have until now been limited to experiments at 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 indicating a new ability to monitor the energy and perhaps spatial distribution of the ICRF minority tail ions. Initial J antenna phasing experiments in D(H) minority experiments found the sawtooth period was sensitive to antenna phase for on axis deposition. This sensitivity is believed to be a result of resonant ion orbit sensitivity to the antenna phase. Further experiments are planned to investigate these initial observations and the results will be compared with a new finite banana width Fokker-Planck code with self consistent RF fields, through the RF Sci-DAC initiative.

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 FY03 have found so-called Alfvén cascades during current ramps with high power ICRF, see Figure 2.6.3. Both global modes (measured by the edge B-dot probes) and core localized modes (measured by PCI) were 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. Additional current probes are planned to be installed in FY04 on the antenna limiters and an inner wall set is planned for FY05. Additional experiments will investigate the impact of deposition location and antenna phase on the excited modes. The recently acquired CASTOR will be implemented on the PSFC theory cluster MARSHALL, and used to model the results.

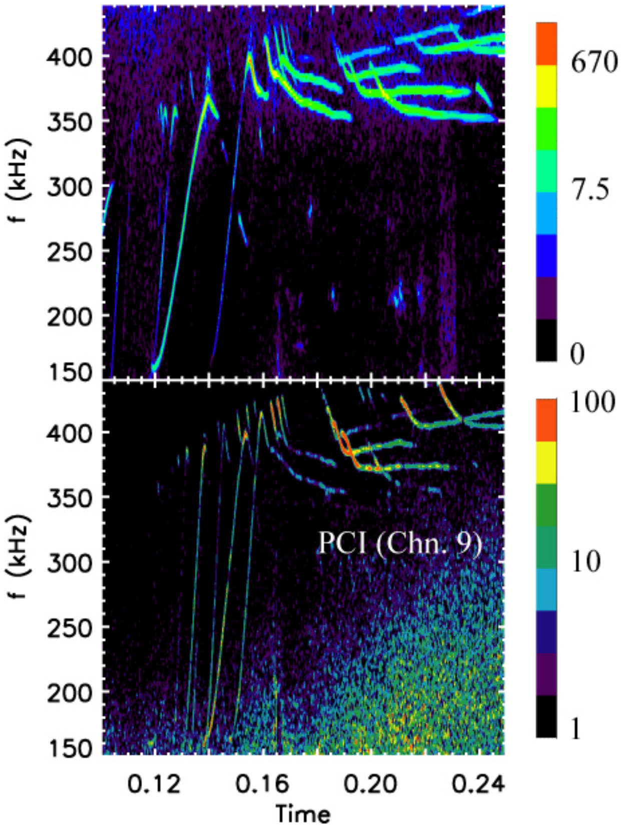


Figure 2.6.3: Alfvén cascades measured during early ICRF power in initial current ramp.

LH

A major upgrade to the C-Mod facility, to provide current drive capability using lower hybrid waves, is underway. This system is optimized for 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, 3 MW of source power at 4.6 GHz will be coupled through a single 96 waveguide launcher array and is to begin operation in FY04. To improve current drive efficiency, increase the system flexibility, and reduce the power density at the launcher a second launcher and additional 1 MW of source power will complete the system in 2006.

Wave and Fast electron physics, Current Drive

The primary 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. Along with current density measurements from the MSE, the driven current profile can be determined. The effects of plasma density, plasma temperature, and launcher phasing on the driven current and current profile will 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 FY06, 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. Another principle measure is the coupling efficiency. The particular advanced RF computational tools will be developed in conjunction with the Sci-Dac Initiative. In FY03, a comparison of the predicted current between ray tracing combined with 2-D velocity space Fokker Planck module (exact solution) and an adjoint solution to Fokker-Planck equation (computationally fast) in the ACCOME code was undertaken. The results indicate the exact solution consistently predicts 30-50% more driven current than the adjoint method. The reasons for this discrepancy are as follows: Although the current drive efficiency can be computed quite accurately from an adjoint approach, it is necessary to know the local wave absorption to convert the efficiency into a current density. The model approximation for wave absorption typically used with the adjoint method does not properly account for 2-D velocity space effects in the damping such as pitch angle scattering. This was found to result in an underestimate of the final driven current density, especially in devices such as C-Mod and ITER, where the quasi-linear plateau is relatively narrow. More recently the full-wave solver TORIC was modified so that its dielectric operator is valid in the lower hybrid range of frequencies, where ions can be treated as unmagnetized and electrons as strongly magnetized. Model calculations have been performed with the modified full-wave solver in which fast LH waves were coupled to a typical C-Mod plasma and the solutions were shown to be converged. Full-wave electric field solutions in the LHRF will be extremely useful as they will elucidate the effects of focusing and diffraction on LH wave propagation and damping. These types of physical effects cannot be easily studied within the geometrical optic framework.

Launcher/Plasma Interactions

Initial experiments will focus on power handling and coupling efficiency versus launcher position. In contrast to previous experiments on other devices, the coupler will use BN protection tiles. Furthermore, reduced coupling and power handling have been observed elsewhere when ICRF antennas on the same field line are operated in conjunction with LH couplers. The reason cited is a decrease in the density on the field lines resulting from ICRF induced ExB drifts. The insulating limiters on the ICRF antennas may reduce this potential conflict between the ICRF antennas and the LH coupler. A camera to monitor the coupler-plasma edge interaction is planned 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.

Synergies

Synergistic effects between ICRF and Lower Hybrid waves will be studied and simulated using the advanced modeling codes developed by 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 β, and the slowing down of the tail ions is influenced by electron temperature.

3. Operations

3.1 Facilities

Introduction

Over the last twelve months, approximately 2,000 plasma discharges have been produced in C-Mod with a startup reliability of 77% (including cleanup periods). Startup reliability once physics operation began has been more typically 85%. We have maintained a shot rate of over 30 shots/day. Thus far over 10 weeks of physics operation out of the promised 19 weeks have been completed. We have worked to improve reliability of ICRF systems, continued development of lower hybrid systems, done major inspections of the flywheel and alternator, and begun development of new diagnostics, as well as upgraded old ones. Data acquisition and analysis hardware and software continue to be upgraded.

Figure 3.1.1: Detailed UT tests of critical alternator rotorlocations have been performed.

Major Inspections

The flywheel inspection was completed successfully in April of 2003. Extensive tomographic ultrasonic (UT) and dye penetrant tests were conducted on the flywheel. UT tests of the bearings and rotor were also made. All tests indicated the flywheel and associated components were in excellent condition.

A very successful inspection of the alternator was also done this year, with the alternator returned to service mid September of 2003. A novel UT test of the rotor, developed jointly by GE and MIT, indicated that high stress regions in the dovetail section of the rotor are in very good condition (see Figure 3.1.1). Hi-Pot tests of the rotor also indicated that the rotor was in excellent electrical condition. The initial Hi-Pot tests of the stator gave anomalous results. After analysis, we concluded that these results were unphysical and the test had been improperly performed by the vendor.

When the tests were then repeated by GE with new equipment and personnel, and the results indicated the stator was in excellent electrical condition. Because of lingering concerns over the 1st Hi-Pot results, the DC Hi-Pot was performed to a higher voltage than in the past. An AC Hi-Pot, which had never before been performed on our alternator, was done to 1.5 times the alternator's rated voltage. The AC test is the most severe off-line electrical test that can be performed on the stator, and very closely matches actual machine operation.

ICRF Systems

Improvements to the antennas, transmission systems, and instrumentation have allowed record rf powers to be coupled into C-Mod. Very successful current drive experiments have been run with little impurity generation. We have begun to investigate load tolerant configurations and fast ferrite tuning (FFT) systems. Design of a new 4-strap antenna has been proceeding rapidly in collaboration with ORNL. This new antenna will eventually replace the two 2-strap antennas at D- and E-Port, freeing up one horizontal port for diagnostics without reducing the rf power available for experiments. The initial tests of the FFT prototype system will begin near the end of FY04. The new 4-strap antenna design will also be completed on a similar time scale. Current plans call for fabrication of the antenna during FY06 with installation during FY07. We will continue work on the design and implementation of load tolerant transmission systems.

Upper Divertor Cryopump

We have continued development of the upper divertor cyropump. This pump will provide up to 25,000 l/s of pumping speed for density control for C-Mod (Figure 3.1.2). Its operation will be of particular importance during AT operation. The pump will consist of a toroidally extended liquid helium filled stainless steel tube surrounded by a liquid nitrogen cooled heat shield. The pump design is well underway (Figure 3.1.3). The pump has been designed with three sections connected by bellows so that it can be built and tested outside the vacuum vessel and then passed through a horizontal port for installation. To protect the pump, new upper divertor hardware will also be installed. Extensive simulations of the pump and the new divertor hardware indicate these new components will survive worst case disruptions (both upward and downward going). Pumping speed calculations, benchmarked against DIIID measurements, have also been performed.

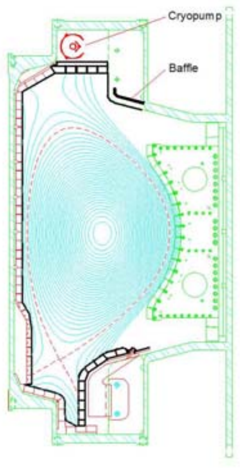


Figure 3.1.2: Conceptual layout of the new upper divertor cryopump.

Components are in-house for fabrication of a 1/10 sector prototype that will be operated in our vacuum test stand during July/August 2004. The prototype will be used to check pumping speed calculations, but more importantly it will verify our ability to control LHe flow into the pump. The cryopump will be installed during the up-to-air following the initial plasma operation of the lower hybrid launcher, probably mid FY05.

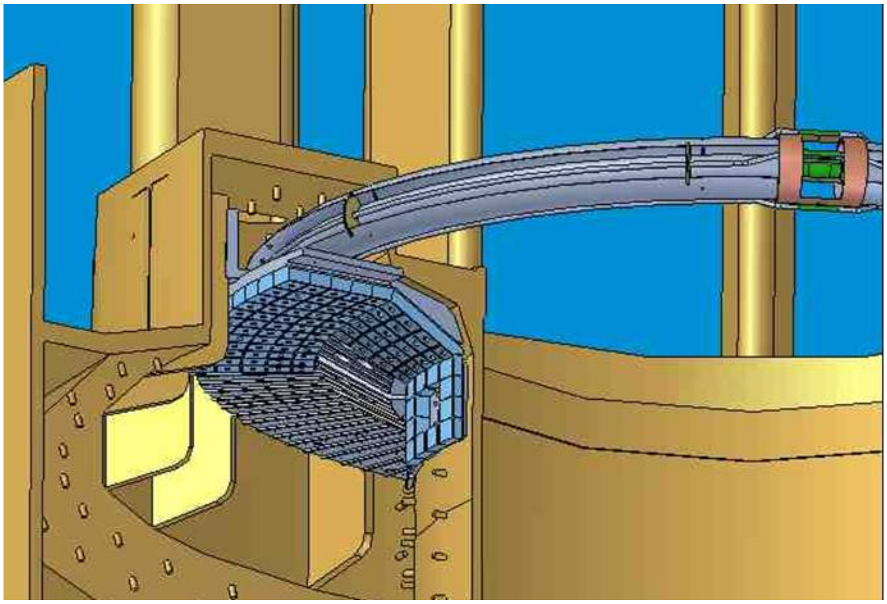


Figure 3.1.3: Solid model of the cryopump, showing the LN_2 heat shield, LHe filled pumping tube, and the new upper divertor hardware.

Figure 3.1.4: Prototype tungsten brush tile is shown together with three of the tungsten rods.

Tungsten Brush Tile Development

In collaboration with Sandia (SNLA), we are developing a set of tungsten brush tiles for installation in C-Mod (Figure 3.1.4). They will 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 hydraulically press fit into the holes and/or pinned with stainless steel rods (Figure 3.1.5). Similar tiles have been tested to approximately 20 MW/m^2 at Sandia. C-Mod will provide the first test of these tiles in a tokamak. Four to five tiles at two toroidal locations will be installed in the C-Mod outer divertor. Results from tungsten brush tile tests on C-Mod will have important implications for ITER. We will also consider using them in the C-Mod advanced divertor.

The tungsten tile prototypes will be installed in an outer divertor module during the next up-to-air period, and initial data from these tiles will be available late FY04 and extending well into FY05. The tiles will be placed where they can be viewed by both visible and infrared cameras. Following the first operational period they will be removed, sectioned, and analyzed for damage and gas retention (important for determining tritium retention in a reactor environment such as ITER).

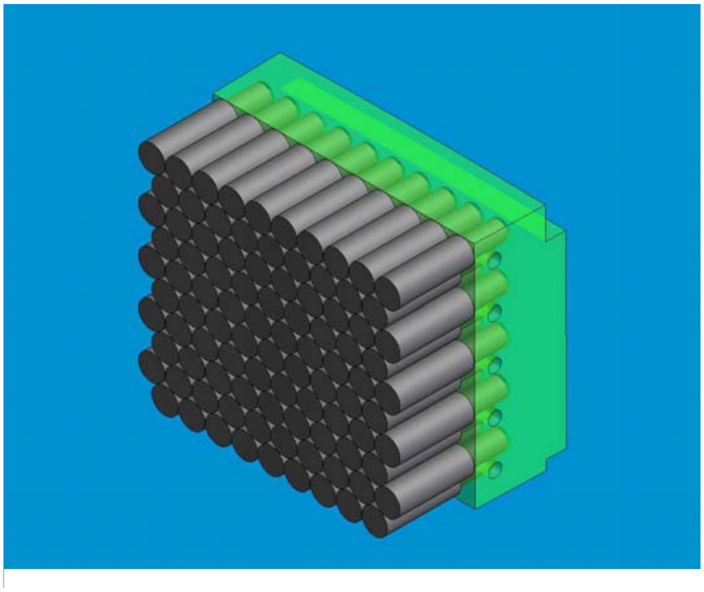


Figure 3.1.5: Solid model on tungsten brush tile showing tungsten rods, inconel support plate.

Lower Hybrid Project

A great deal of progress was made on lower hybrid systems over the last year. After issues arose with the plating of both the forward wave guide assembly (FWG) and the lower hybrid couplers that contain the vacuum windows, a major effort was mounted at both MIT and PPPL to resolve these problems. The FWG was completely dissassembled and the plates successfully replated. Following extensive tests of the plating at MIT, the FWG was reassembled at PPPL. Successful high power tests were then performed at MIT to qualify operation of the FWG (Figure 3.1.6). The FWG is now undergoing vacuum testing at MIT. The rear wave guide assembly has also been delivered to MIT from PPPL and has also passed high power tests (Figure 3.1.7). To assure that high quality brazes can be produced on all 96 coupler windows, a large R&D effort has been mounted at MIT to qualify braze materials and techniques. A new set of couplers have been fabricated and the vacuum windows will soon be brazed.

The lower hybrid project also saw great progress in the development of the hardware and software required to control the phase and amplitude of the klystrons so that the proper lower hybrid current drive spectrum could be produced at the plasma. The software required to link MDSplus to the control software has also been developed. A new set of analog optical link transmitters and receivers have been designed, fabricated, and are now being tested. These links provide the communication between the vector modulators and I/Q detectors and the control computers.

Figure 3.1.6: The forward wave guide assembly ready to be installed into the vacuum test stand.

As mentioned above, we have also carried out an extensive program of high power testing of the forward and rear waveguides, coupler prototypes, circulators, dummy loads, and transmission line components. We have continued commissioning of the twelve klystrons required for the initial lower hybrid program, and tested and had refurbished our spare klystrons. A recent picture of the klystron mezzanine is shown in Figure 3.1.8.

We have also completed design of the wave guide run from the mezzanine to the launcher. All wave guide components for this run are in house.

Major plans for the lower hybrid system include installation of the launcher into C-Mod during the next up-to-air period (Spring 2004). We expect first plasma operation with lower hybrid power near the end of FY04 and extending into mid FY05.

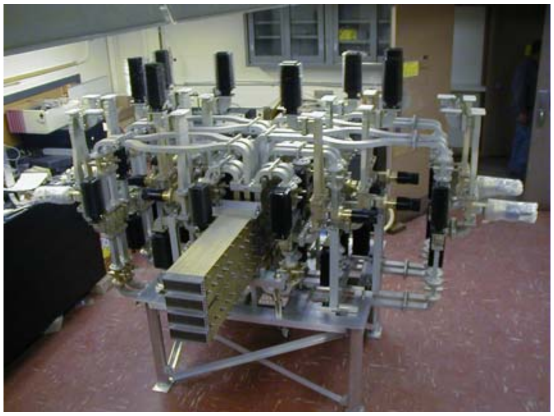


Figure 3.1.7: The rear wave guide assembly following high power testing.

Upgrades to the lower hybrid project will involve the fabrication of a second launcher and an increase in source power from 3 to 4 MW. The second launcher will enable both a lower power density at the plasma and the ability to generate compound spectra that could improve current drive efficiency and deposition control. With the second launcher, the increase in total source power should be easily handled. We plan complete these additions in FY06.

03 02 2004

Figure 3.1.8: Klystron mezzanine showing klystrons and the circulators now undergoing high power testing.

Long Pulse DNB

Our current 50 ms pulse width diagnostic neutral beam will be replaced in September 2004 with a new 1.5 s pulse width beam. The installation will be performed by a team of Russian engineers dispatched with the beam. We will provide technical support to the Russian team and make all necessary changes to our power distribution system in the cell to operate the beam.

Data Acquisition and Control

Alcator C-Mod is now taking approximately 1 GByte of data per shot with a doubling time of 2.2 years (Figure 3.1.9). To accommodate this rapid growth in data a carefully coordinated effort to upgrade data acquisition, storage, and processing hardware is ongoing.

We have continued the deployment and support of new high speed CPCI digitizers. These new components provide both higher capacity and reliability compared to CAMAC equipment. We have also begun testing a new CPCI timing module to replace our current encoder/decoder CAMAC modules. These new modules will provide trigger, gate, and event generation for the data system.

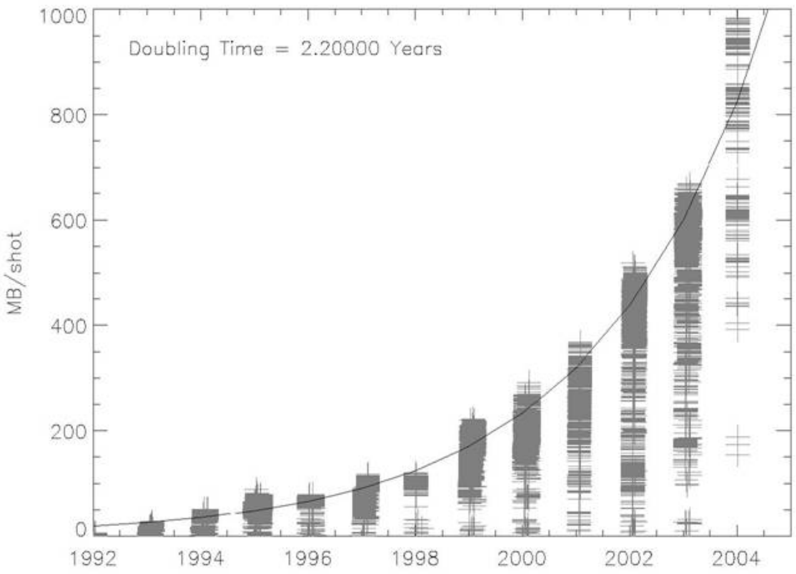


Figure 3.1.9: Growth of the amount of data per shot over the lifetime of the C-Mod project.

Nearly all data system applications have migrated from VMS to Linux, and we have installed 15 new Linux workstations (now a total of 35). Two new Linux Xeon servers have also been installed. One server is being used for data acquisition and data archiving, the other as a user file server. To improve communications among all these new systems the control room network has been upgraded to a1 GBit switch.

During the remainder of FY04 into early FY05 we will deploy our new all digital plasma control system. The new system will replace the hybrid control system. It will allow a large increase in the number of control lines while also allowing non-linear control algorithms to be implemented. We will also complete migration to Linux during this time.

During FY04 and FY05 we will continue deployment of CPCI and the replacement of CAMAC systems. We will upgrade our database and account management servers. We will also deploy a comprehensive web based system to link shot cycle info, electronic logbook, experimental proposals, run reports, and summary physics data.

Ongoing projects will include expanding the size of data archive and backup systems, continuing the expansion of our Linux workstation pool, maintenance and upgrades to MDSplus software, and continued support for on and off-site MDSplus users.

Diagnostics

We continue to improve existing diagnostics and develop new ones. Improvements have been made to the MSE and CXRS systems. The MHD antenna broadband transmitter has been upgraded and a new low frequency 6 kW amplifier is being installed. As part of the data system improvements mentioned earlier, the capability of our fluctuation diagnostics has been greatly improved in both the amount of data acquired and the bandwidth of the digitizers. We continue to improve our ability to image the plasma edge fluctuations with more capable fast framing cameras, and upgrades to diode arrays, reflectometry, and probes.

New diagnostics and upgrades being developed include a poloidially viewing interferometer/polarimeter, a 32 channel hard x-ray camera to view the lower hybrid generated hot electron population, improvements to the range and sensitivity of the reflectometer, increased spatial coverage of the PCI diagnostic, erosion/deposition divertor diagnostics, and and a new compact neutral particle analyzer. Additional active MHD antennas and new magnetic probes are also planned to investigate Alfvén cascades and global modes.

4. Alcator C-Mod Collaborations

4.1 Introduction

Collaborations are significant in all aspects of the C-Mod program. Collaborators from 17 domestic and 16 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 the 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 4.4.

The vast majority of theory and modeling efforts for C-Mod are accomplished through collaborations. Sorted by topic, ongoing collaborations in these areas include:

- **Transport, Turbulence and MHD**
  - Xu, Nevins, Rognlien, Umansky, R. Cohen: EDA H-mode QCM, Edge Fluctuations (BOUT simulations)
  - Carreras, Antar : SOL turbulence analysis, L-H dynamics
  - Guzdar: L-H threshold theory
  - Hallatschek and Rogers: Theory and modeling
  - Diamond: Theory
  - Mikkelsen, Dorland: Critical gradient – Non-linear stability
  - Redi, Ernst, Bravenec, Dorland: GS2 microturbulence modeling
  - Bateman and Kritz: Baldur transport simulations
  - McCune, C.K. Phillips: TRANSP
  - Chang, Chan, Coppi, Perkins, Shaing, White: Transport, RF induced rotation
  - Huysmans, Wright: TAE modeling (CASTOR)
  - Boswell, Sharapov, Breizman, Berk: Alfven cascades
- **Impurity and particle dynamics**
  - Stangeby, Lisgo, Elder: OSM-Eirene divertor plasma and neutral modeling
  - Stotler: DEGAS II neutral transport
  - Pigarov, Krasheninnikov: Edge atomic processes, 2-D edge transport modeling (UEDGE), Edge turbulence/structures
  - Catto, Helander, Fulop: Neutral effects on rotation
  - Parks: Pellet ablation dynamics
  - Fournier: Atomic physics modeling
- **ICRF**
  - Jaeger, Myra and D’Ippolito: ICRF Flow Drive
  - Brambilla, Jaeger, D’Azevedo, Batchelor, J. Wright: Fast wave and Bernstein waves in toroidal geometry
  - McCune, C.K. Phillips, Okuda, Brambilla, J. Wright: Full-wave/Fokker Planck minority heating simulations
  - R. Maggiora (Torino): TOPICA modeling of antenna-plasma system

- **Lower Hybrid**
  - — C.K. Phillips, Okuda, J. Wright: 2D full wave simulations
  - — Peysson, Bers: Fokker Planck LHCD efficiency and distribution functions
  - — Harvey, Imbeaux: 2D LHCD Fokker Planck simulations
  - — Bernabei: Scenario development
  - — Bernabei: Launcher design and coupling simulations
  - — McCune, C.K. Phillips: Integration of ACCOME into TRANSP

In addition to the PPPL and U. Tx. contributions, the main ongoing experimental collaborations include:

- Locked modes (LaHaye, GA; Hender, JET; Buttery, Culham)
- NTM Dimensionless Scaling with DIII-D (R. LaHaye, GA)
- Pedestal studies (Groebner, Osborne, GA; Suttrop, IPP Garching; Madison, Saibene, JET)
- EDA H-Mode (Madison, Saibene, JET; Oyama, JFT2-M; Suttrop, IPP Garching)
- Alfven Eigenmode studies (Fasoli, CRPP; Boswell, MIT/JET)
- ITB Physics (Stober, IPP Garching)
- ITER Hybrid Scenarios (Sips, IPP Garching)
- SOL Radial Transport (Kallenbach, IPP Garching; Whyte, U. Wisc.; Matthews, JET; Nakano, JT60-U)
- Fluctuation Studies (Grulke, Endler, IPP Greifswald; Zoletnik, KFKI-RMKI Budapest)
- Disruption Mitigation (Whyte, U. Wisc.)
- IR Imaging (Wurden, Furno, LANL)
- X-Ray Imaging (Peysson, CEA-Cadarache)
- Polarimetry (Brower, Peebles, UCLA)
- Spectroscopy (May, LLNL; Graf, UC-Davis; Griem, U. Md.; Howard, ANU; Kondo, NIFS)
- ICRF Technology (Goulding, Ryan, Rasmussen, ORNL)
- Tungsten Plasma Facing Components (Ulrickson, SNLA)
- Diagnostic Neutral Beam (Valisa, IGI Padua; Ivanov, Budker Institute)
- Tritium co-deposition (Whyte, U. Wisc.; Neu, IPP Garching)

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 off-axis current drive via Lower Hybrid current drive and its effect on plasma performance (including design and fabrication of the launcher and participation in the associated research);
- the joint experimental/theoretical 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, off-axis current drive for PEP/ITB mode studies, and low frequency ($\omega<\Omega_{ci}$) current drive for reactor application via ICRF heating and mode conversion current drive; and
- the study of core confinement, and H-mode behavior including pedestal characteristics and fluctuations.

Recent and proposed hardware upgrades include both plasma control and diagnostic components:

- ICRF antenna for plasma heating and current drive;
- a LHCD launcher and coupling hardware for control of the plasma current profile;
- current profile diagnostics to increase understanding of current drive and plasma behavior (in conjunction with the diagnostic neutral beam);
- 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, which is key to the prediction of the performance of future burning plasma devices.

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 current-drive system as part of the Lower Hybrid project.

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 research opportunities for PPPL scientists. PPPL works as a strong team-player.

APPROACH

Members of the PPPL research staff continue to 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.

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

- increase the understanding of the physics of ICRF heating and current drive at high power, and
- 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.

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 spectroscopy to measure H/(H+D) ratios, impurity behavior, and plasma rotation.

The heating and current-drive upgrade allows an extension of the C-Mod operating parameters. Doubling the available auxiliary heating power allows us to:

- heat the core of internal transport barrier confinement modes,
- 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 H-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.

Improving the directed wave launch allows us to drive plasma current by FWCD (core) and 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,
- explorethe capabilities to control the radial electric field through toroidal rotation, and
- extend the pellet enhanced performance mode.

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 calibrations and analysis are in progress in order to derive accurate current distributions from them.

The study of plasma edge physics has been enhanced through the upgrading of the C-Mod reflectometer for edge density and fluctuation measurements further up the edge pedestal and the addition of a new fast camera to obtain 2-D imaging of edge turbulence.

A considerable further expansion of the C-Mod operating space into the advanced tokamak regime will be achieved through the addition of off-axis lower hybrid current drive (LHCD). This will provide information for the extension of the already successful tokamak concept toward an attractive reactor. This should allow us to:

- achieve quasi-steady state operation at the no-wall β limit ($\beta_N \sim 3 - 3.5$),
- increase the β limit due to plasma current profile modification,
- achieve non-inductive current drive with high bootstrap fraction and current profile control,
- 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 is based on 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 will assist 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.

TECHNICAL PROGRESS

In FY2003 and early FY2004, PPPL made the following technical progress.

- The 4-strap ICRF antenna's remaining voltage (and power) limitation had been largely addressed by modeling and redesigning the antenna current strap crossover, the site of remaining arcing. The antenna's performance at higher power levels has been demonstrated in heating phasing, with minimal arcing up to 3 MW. Current drive phasing tests have been performed up to 2.7 MW so far, and the overall plasma response is found to be identical to heating phasing operation.

- The ICRF modeling has been extended to include recent improvements in the TORIC code in order to obtain a closer agreement with C-Mod experiments and improve the code's predictive capability. The 1-D integral wave code METS was parallelized for use on computer clusters. The resulting performance improvement has allowed extension of this code to the Lower Hybrid frequency domain and permits the numerical investigation of Lower Hybrid wave propagation and absorption in C-Mod.

- Mounts for the optical components of the MSE diagnostic have been further improved to reduce damage from disruption-induced mechanical shocks; these improvements appear to have been successful. Measurements of magnetic pitch angle have now been performed under a variety of plasma conditions. Extensive calibrations and analysis are in progress in order to validate the usefulness of this diagnostic with the new beam.

- The C-Mod reflectometer has been upgraded with the addition of 130 and 140 GHz channels to provide the capability to measure fluctuations closer to the plasma core as well as higher up the pedestal at the edge. Initial measurements have been obtained at the plasma edge.

- The 28-frame high speed imaging system that was installed to allow the edge turbulence imaging diagnostic to capture "movies" rather than snapshots of the turbulent structures now displays their growth and motion. The observed structure was compared with several theoretical models of edge turbulence, and good agreement is seen with drift ballooning modes. The 2-D turbulence imaging diagnostic was improved by modifying the gas nozzle design to produce a more uniform gas source, resulting in a more uniform illuminating medium for the turbulence images. The number of edge-viewing transient digitizer sightlines was also increased.

- Nonlinear modeling of the effect of turbulence on transport in the plasma core has continued. Theoretical transport predictions have been compared with experimental data to determine whether drift-type instabilities could be predicted to be responsible for transport in the core of typical H-mode plasmas in C-Mod. A number of nonlinear gyrokinetic simulations of turbulent transport due to long wavelength electrostatic drift-type instabilities have been performed. Simulations of core turbulent transport in an Alcator C-Mod EDA H-mode plasma have been extended to higher wave numbers and finer resolution. A number of very long simulations (with lower resolution) have provided test data used to develop an algorithm for estimating the uncertainty in the predicted fluxes.

- Gyrokinetic simulations of plasma turbulence with the GS2 code were carried out to examine H-mode RF heated plasmas which exhibit internal transport barriers (ITB). Simulations are focused on the trigger time shortly before the ITB is established. Linear calculations show stable long wavelength turbulence at the barrier, without invoking suppression by ExB shear. At the ITB no strongly growing TEM nor ITG is found, although ETG is present. Outside the ITB the calculations indicate the presence of toroidal ITG and ETG modes. In the plasma core, no drift modes are found unstable in the TEM, ITG, nor ETG range of frequencies. Reduced instability growth rates predicted at the barrier are consistent with the observed reduced transport. Nonlinear simulations have been performed, reproduce the linear results, and agree with the experiments at the trigger time.

- PPPL continued to utilize the provided array of plasma control and diagnostic tools to study plasma confinement and stability.

- The Lower Hybrid launcher project was completed in April, 2003, but coupler and launcher repairs resulting from defective electroplating on the launcher and improper commercial stripping of defective electroplating on the coupler are expected to delay the installation on C-Mod until April 2004.

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

- PPPL scientists published 5 first author papers on the C-Mod work in FY 2003, and were included as co-authors on 14 papers by the C-Mod group.

FUTURE ACCOMPLISHMENTS

FY2004

Physics studies will continue on C-Mod making maximum use of the upgraded ICRF system and the new or upgraded diagnostics. The LHCD launcher will be installed in the machine and commissioned.

- The upgraded ICRF system and improvements in codes will continue to be used for basic ICRF physics investigations, to attempt current profile control, to study transport barriers, and to extend the C-Mod plasma parameter space. Antenna behavior will continue to be explored over the full range of plasma parameters and power and phase levels in order to validate the modifications.

- 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.

- Studies of plasma heating in general will be extended to higher power levels and under a greater variety of plasma conditions. The resumption of C-Mod operation at 8 Tesla toroidal field in 2002 will allow additional ICRF heating scenarios to be included in FY2004. These studies will investigate both the basic plasma-wave interactions in an extended plasma parameter space as well as allowing the study of confined plasma behavior at the extended parameters.

- The physics of mode conversion of a launched fast wave into an ion Bernstein wave and the associated poloidal flow drive will be studied. 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.

- Attempts to modify plasma turbulence through the application of off-axis ICRF heating will be continued.

- Both transport and ICRF modeling will continue strongly in order to assist a deeper understanding of C-Mod's plasma behavior and the understanding of plasma-wave interactions at extended plasma parameters. The transport modeling will obtain experimental data from the edge reflectometer fluctuation measurements, while the 2-dimensional edge turbulence imaging diagnostic will reveal enhanced edge information. The full-radius gyrokinetic turbulence simulation code GYRO will be applied to C-Mod plasmas, and benchmarked against the previous work with the flux-tube code GS2. The ICRF modeling should receive additional experimental input from the current profile measurements as well as the full set of C-Mod plasma diagnostics.

- Repair of the first Lower Hybrid launcher will be completed, and it will be 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.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs. They will also assist in all phases of the Lower Hybrid startup.

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.

- Continue physics studies on C-Mod with the ICRF heating and current-drive system, using the full set of C-Mod diagnostics and plasma controls. Investigate the physics of particle-wave interactions and plasma heating processes at high power levels, and investigate the behavior of plasmas subjected to high power heating.

- Continue to extend and improve C-Mod-relevant transport and ICRF modeling capability. Compare the advances in modeling with C-Mod experiments on an ongoing basis.

- Evaluate and optimize the coupling efficiency and power handling capability of the first Lower Hybrid launcher.

- Initiate current drive in the plasma with the first Lower Hybrid launcher.

- Investigate the physics of coupling Lower Hybrid waves to high density plasmas.

- Attempt to modify plasma turbulence through the application of off-axis LH heating or off-axis current drive.

- Perform further experiments to understand the physics responsible for the modification of turbulence with ICRF and attempt to control the turbulence, if the initial attempts to modify plasma turbulence with ICRF are successful.

- Assist MIT with ICRF transmitter operation, retuning, and repairs. PPPL staff will also assist with the Lower Hybrid launcher operation.

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.

- Continue high power ICRF physics studies. Extend the study of basic particle-wave interactions experimentally and in conjunction with increasingly refined ICRF modeling.

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

- Continue the study of high power LH wave propagation and absorption both experimentally and through the use of improved LH modeling.
- Drive current in the plasma through off-axis application of phased Lower Hybrid power, document the current profile change with MSE.

- If the initial attempts to modify plasma turbulence with LH are successful, perform further experiments to understand the physics responsible for the modification and attempt to control the turbulence with LH.

- 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.

FUTURE ACCOMPLISHMENTS - INCREMENTAL

FY2005I

Incremental funding could be used to return the PPPL/C-Mod collaboration manpower to near the FY2002 level in order to increase our physics yield. The financial burden of the LHCD launcher repair resulted in the shedding of scientific manpower from the PPPL/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 a return of ~0.5 FTE toward the FY2002 level. This incremental budget request allows return of the rest of this manpower to the collaboration before FY 06, with a corresponding increase in the collaboration's scientific productivity.

- Increase the collaboration scientific manpower by ~0.5 FTE to return manpower to near the FY2002 level.

FY2006I

Incremental funding could be used to upgrade the Motional Stark Effect (MSE) diagnostic (possibly fabricate and install second sightline), upgrade the Gas Puff Imaging (GPI) diagnostic, or start an upgrade to the reflectometer diagnostic.

- Upgrade the Motional Stark Effect (MSE) diagnostic, possibly with the addition of a second sightline.

  and

- Upgrade the Gas Puff Imaging (GPI) diagnostic by completing the purchase of a new PSI-5 camera with 280-frame capability or sightline improvements.

  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.

4.3 U. Texas Collaborations

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.

An ECE radiometer, FRCECE, with high spatial and temporal resolution is used to provide electron temperature profiles and is being developed as a fluctuation diagnostic. Plans for the diagnostic include improvement in high frequency response to detect fluctuations above 100 kHz and a data acquisition extension to allow full temporal coverage of the plasma discharge.

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 1) an increase in the available plasma views and 2) application of the results to inference of the local radial electric field.

The BES diagnostic has been used for measurement of poloidal wavenumber and location of the quasi-coherent mode. The plans for this diagnostic include investigation of new optical and electronics schemes to improve the ability of the diagnostic to measure broadband fluctuations.

Beam parameter measurements are also included in our collaboration primarily to support the beam diagnostics.

At a significantly lower level, some turbulence simulation work is pursued in association with the SciDac Plasma Microturbulence Project. Our primary interest here is to support the BES and ECE diagnostics through the development of synthetic diagnostics; that is, software that will convert the "infinitely-detailed" output of gyro-kinetic turbulence codes into the "signal" that would be produced by a real-world diagnostic.

ECE Highlights

Calibrated, high resolution measurement of T_e are made and used generally within the C-Mod group.

The capability for making accurate, precise measurements of the electron temperature gradient scale length L_{Te} was demonstrated in a simple, direct application and it has potential as a powerful research tool.

Electron density and temperature fluctuations were measured during ITB and EDA discharges. The density fluctuations can be measured due to refractive effects. This is a novel, new application which actually tends to amplify the effect of density fluctuations and thus much improves the natural limits of the radiometer. The analysis technique for this application of ECE emission is still under development. Thus far, these measurements have resulted in the identification of a new mode at 80 kHz during ITB's and observation of broadband T_e fluctuations.

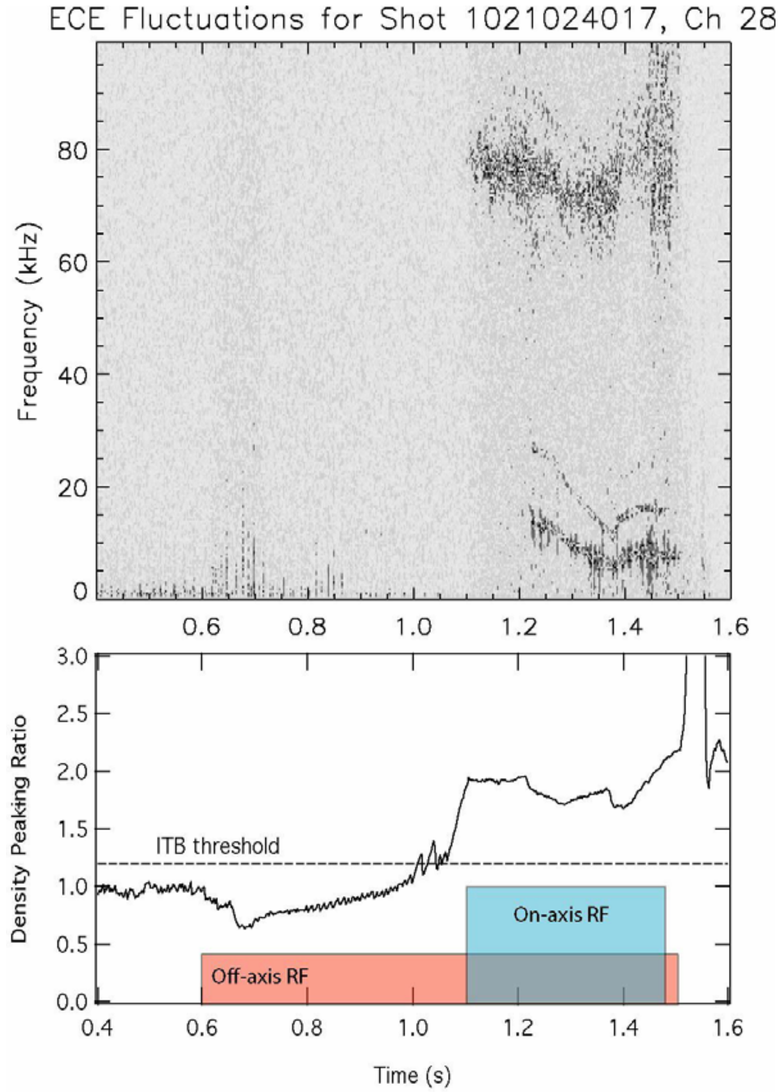


Figure 4.3.1. The fluctuation detected by one of the core channels of the ECE diagnostic are shown as a function of time for an ITB discharge. Note that an 80 kHz mode is enhanced with the application of on-axis RF and is accompanied by suppression of the density profile peaking.

ECE Plans

FY2004

Develop the ECE radiometer's novel measurement of density fluctuations. This will be a useful diagnostic for C-Mod and may turn out to be a complement for the core PCI diagnostic. The diagnostic development will center on acquiring additional data under the most advantageous conditions and development of analysis through simulation.

Using the diagnostic, we will investigate fluctuations:
ITB and EDA: 80 kHz core mode,

Broadband fluctuations in both density and temperature during ITB's at 4.5 T and high density pellet discharges

A student thesis will be completed: "Heterodyne Electron Cyclotron Emission Measurements of Coherent Modes and Broadband Fluctuations in the Alcator C-Mod Tokamak," by Alan G. Lynn

FY2005

Using the diagnostic, we will investigate L_{Te} in ITB discharges and pellet discharges.
Like other gradients, the temperature gradient is an energy source for turbulence and 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 χ_e for a discharge.

Add better temperature control in the IF and RF sections of the radiometer.
We have observed changes in calibration associated with changes in the ambient air temperature near the diagnostic. This requires frequent recalibration. Our experience is that temperature control can significantly reduce this diagnostic maintenance.

FY2006

Increase the number of high frequency channels from 10 to 26.
Broadband fluctuations and the EDA mode are often above 100 kHz which is the limit in the existing system. With more channels with the higher frequency limit, we can observe fluctuations in n_e and T_e over more of the plasma and throughout the C-Mod shot. We plan to replace the existing CAMAC channels with PCI data acquisition to expand the number of channels and to allow full temporal coverage of the plasma discharge which will be 2+ sec.

CXRS Highlights

A multichannel upgrade was completed which allows simultaneous measurements of T_i, rotation, and background emission over the outer third of the plasma radius.

T_i profiles and rotation profiles have been measured

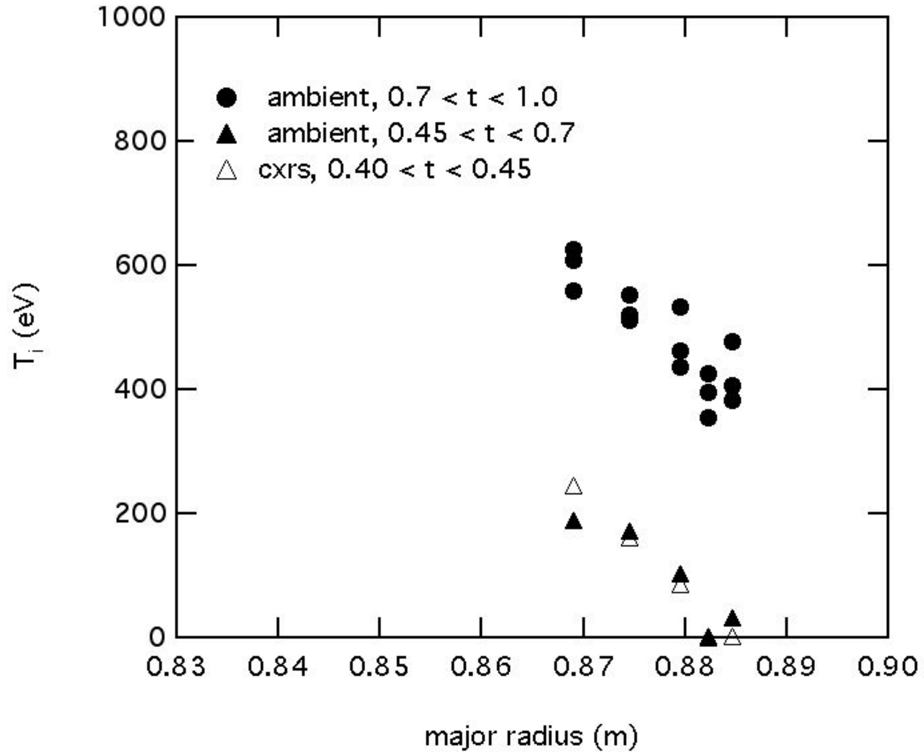


Figure 4.3.2: Temporal dependence of the ion temperature profile during an RF heated discharge in which the RF is turned on at 0.7s Note that temperatures are derived from both ambient and CXRS data to make maximum use of the available data and to compensate for the limited beam pulse.

CXRS Plans

FY2004

Complete measurements of EDA H-Mode and other interesting discharges as they are developed and to support C-Mod research. These measurements will include T_i, rotation, and n_z. All three are needed for inference of the radial electric field.

FY2005

Make detailed rotation measurements in the outer third of the plasma.
Present experiments indicate that rotation may be induced by RF in the plasma edge and then propagate inward to the core. The weakness of this conclusion is that it is not tested in the outer third of the plasma radius.

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.

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.

FY 2006
Add another detector/spectrometer to further increase the number of simultaneous views.

BES Highlights

The quasi-coherent (QC) mode was localized using a combination of ambient and beam-assisted measurements. The localization leads to the conclusion that the mode straddles the separatrix and can therefore lead to significant diffusion.

The average poloidal wavenumber and phase velocity for the QC mode was measured.

Comparisons of the BES, Langmuir probe, and PCI wavenumbers with an EFIT calculation confirms the flux expansion effect on the mode.

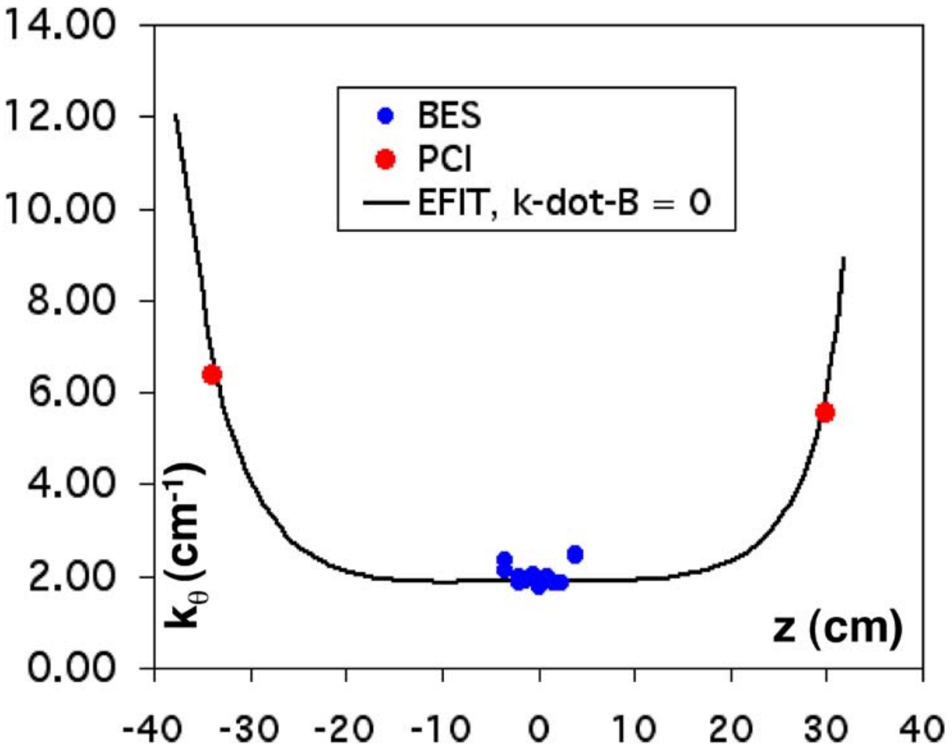


Figure 4.3.3: The BES turbulence measurements are compared to those from PCI for the quasi-coherent mode. The data imply that the measurements are consistent over a large poloidal extent in the plasma.

BES Plans

FY2004

Conditional on other fluctuation diagnostics' locations, participate in field-line cross-correlations with other diagnostics.

Investigate new BES optics design independent of the MSE optics with the motivation to create a more densely packed array of views, sharper spot sizes in edge, and improved coverage of the plasma core.

FY2005

Apply cooling to a few of the BES channels to determine whether signal to noise is improved significantly.

QC Mode: Use improved signal-to-noise and resolution to improve measurement of location, poloidal wavenumber and velocity and amplitude of the QC.

Survey broadband fluctuations.

FY2006

Move from CAMAC to CPCI data system to handle new long-pulse operation.

Beam Parameter Measurement Highlights

Beam characteristics (other than basic parameters such as acceleration voltage, extraction current, *etc*.) have been measured to i) optimize operation of the beam, and ii) benchmark models of the beam emission and therefore performance of the beam-dependent diagnostics. These include beam mix (percentage full-, half-, third-, and eighteenth-energy (water)), beam width (1/e), and neutralization fraction (with help of modeling).

Beam Parameter Measurement Plans

FY2005

A dedicated beam-mix diagnostic which will allow shot-by-shot monitoring of the beam component mix.

Turbulence Simulation Highlights

Participated in community-wide GS2/GYRO benchmarking as part of a voluntary participation in SciDac Plasma Microturbulence Project. With this, we acquired sufficient support from the Project members to pursue our limited simulation plans for C-Mod.

Turbulence Simulation Plans

FY2004

Write, with help of diagnosticians, "synthetic diagnostic" software for gyro-kinetic codes to model fluctuation diagnostics.

FY2005

Perform GS2/GYRO simulations of C-Mod plasmas, in particular at the top of the pedestal of EDA H-mode plasmas, where an upgraded BES system has a chance to measure turbulence. Use CXRS measurements of T_i, v_{tor}, v_{pol}, n_z, (and thus E_r) and MSE measurements of q as input. Compare computed and measured fluxes (and hopefully, turbulence).

4.4 MDSplus

Recent Highlights

MDSplus software maintenance and ongoing support for off-site installations continues to be a major activity for the MDSplus development group. 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. To ensure coordination, a workshop for MDSplus users was organized in San Diego with attendance from more than a dozen countries. MDSplus documentation has been improved, though this work is still incomplete.

Completion of the software ports to Linux/UNIX and Win32 platforms has been demonstrated by deployment of complete data systems based on these platforms. These implementations make full use of the distributed dispatching capabilities now in MDSplus. The distributed client implementation has replaced the “thick” client for Linux. The deployments revealed a number of minor bugs which have been fixed. The code has been made “thread-safe” and tested on processors enabled with Intel’s hyper-threading architecture. MDSplus I/O has been enhanced with support for large data blocks which improves performance - especially for remote connections with significant network latency. (Additional I/O and security enhancements have been carried out as part of the National Fusion Collaboratory.) Device support has been extended, particularly for compact PCI (CPCI) based data acquisition modules. This activity is crucial as most sites are actively migrating away from older CAMAC based equipment.

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 the MDSplus users meetings on an annual basis. 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

Appendix A

Alcator C-Mod Publications — 2003

Papers Published in Refereed Journals

Antar, G.Y., LaBombard, B., et al., "Universality of intermittent convective transport in the scrape off-layer of magnetically confined devices," Phys. Plasmas **10** (2003) 419.

Basse, N.P., et al., "Characterization of turbulence in L- and ELM-free H-mode Wendelstein 7-AS plasmas," Plasma Phys. Control. Fusion **45** No. 4 (2003) 439.

Basse, N.P., et al., "Turbulence at the transition to the high density H-mode in Wendelstein 7-AS plasmas," Nuc. Fusion **43** No. 1 (2003) 40.

Bernabei, S., Parker, R.R., Porkolab, M., et al., "Design of a compact lower hybrid coupler for Alcator C-Mod," Fusion Science and Technology **43** No. 2 (2003) 145.

Boswell, C.J., LaBombard, B., Lipschultz, B., Pitcher, C.S., Terry, J.L., et al., "EIRENE neutral code modeling of the C-mod divertor," J. Nucl Materials **313-316** (2003) 1089.

Chung, T., Pitcher, C.S., LaBombard, B., Lipschultz, B., Terry, J.L., Rice, J.E., et al., "Recycling impurity compression in Alcator C-mod divertor," J. Nucl. Materials **313-316** SUPPL., (2003) 990.

Gangadhara, S., LaBombard, B., "Flow measurements in the scrape-off layer of Alcator C-Mod using impurity plumes," J. Nucl. Materials **313-316** (2003) 1167.

Ghosh, J., Terry, J., Marmar, E., Lipschultz, B., LaBombard, B., Rice, J.E., et al., "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.

Gohil, P., Rice, J., et al., "Increased Understanding of the dynamics and transport in ITB plasmas from multi-machine comparisons," Nucl. Fusion **43** No. 8 (2003) 708.

Greenwald, M., et al., "EU-US transport task force workshop on transport in fusion plasmas: transport near operational limits," Plasma Phys. Control. Fusion **45** No. 4 (2003) 445.

Greenwald, M., "Transitions of Turbulence in plasma density limits," Phys. Plasmas **10**, 2003, p. 1773.

Hughes, J.W., Mossessian, D., Zhurovich, K., Hubbard, A., et al., "Thomson scattering upgrades on alcator C-mod," Rev. Sci Instrum., **74** No. 3 (2003) 1667.

Hutchinson, I.H., “Ion Collection by a Sphere in a Flowing Plasma: 2. Non-zero Debye Length,” Plasma Phys. Control. Fusion **45** (2003) 1477.

LaBombard, B., Gangadhara, S., Lipschultz, B., Pitcher, C.S., “Toroidal rotation as an explanation for plasma flow observations in the Alcator C-Mod scrape-off layer,” J. Nucl Materials **313-316** (2003) 995.

Lee, W.D., Boivin, R.L., Bonoli, P.T., Fiore, C.L., Hubbard, A., Irby, J., Porkolab, M., Wukitch, S.J., “Neutral particle analysis of ICRF heated discharges on Alcator C-Mod,” Plasma Phys. Control. Fusion **45** No. 8 (2003) 1465.

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,” Phys. Rev. Lett. **91** No. 20 (2003) 205003/1-4

Lin, Y., Wukitch, S.J., Bonoli, P.T., Marmar, E., Mossessian, D., Phillips, P., Porkolab, M., Schilling, G., Wolfe, S., et al., “Ion cyclotron range of frequencies mode conversion electron heating in deuterium-hydrogen plasmas in the Alcator C-Mod tokamak,” Plasma Phys. Control. Fusion **45** No. 6 (2003) 1013.

Maqueda, R.J., Wurden, G.A., Zweben, S.J., LaBombard, B., Terry, J.L., et al., “Gas puff imaging of edge turbulence,” Rev. Sci Instrum., **74** No. 3 (2003) 2020.

Marmar, E.S., Hutchinson, I., Parker, R., Porkolab, M., et al., “Overview of recent alcator C-Mod research,” Nucl. Fusion **43** No. 12 (2003) 1610. Nuclear Fusion, **43**, No. 12 December, 2003, p 1610-1618

Marmar, E., et al., “Thin foil Faraday collectors as a radiation hard fast lost-ion diagnostic,” Rev. Sci. Instrum. **74** No. 3 (2003) 1747.

Mossessian, D.A., Groebner, R.J., Hughes, J.W., Greenwald, M., Hubbard, A., et al., “Edge dimensionless identity experiment on DIII-D and Alcator C-Mod,” Phys. Plasmas **10** No. 3 (2003) 689.

Mossessian, D.A., Hubbard, A., Hughes, J.W., Greenwald, M., LaBombard, B., Snipes, J.A., Wolfe, S., et al., “High-confinement-mode edge stability of Alcator C-mod plasmas,” Phys. Plasmas **10** No. 5 (2003) 1720.

Nelson-Melby, E., Porkolab, M., Bonoli, P.T., Lin, Y., Wukitch, S.J., et al., “Experimental observations of mode-converted ion cyclotron waves in a tokamak plasma by phase contrast imaging,” Phys. Rev. Lett. **90** No. 15 (2003) 1555004/1-4.

Rice, J.E., Bonoli, P.T., Fiore, C.L., Lee, W.D., Marmar, E.S., Wukitch, S.J., Granetz, R.S., Hubbard, A.E., Hughes, J.W., Irby, J.H., Lin, Y., Mossessian, D., Wolfe, S.M., Zhurovich, K., Greenwald, M.J., Hutchinson, I.H., Porkolab, M., Snipes, J.A., et al., "Pressure profile modification of internal transport barrier plasmas in Alcator C-Mod," Nucl. Fusion **43** No. 8 (2003) 781.

LaBombard, B., Terry, J.L., Zweben, S.J., et al., "Neutral transport simulations of gas puff imaging experiments," J. Nucl. Mat. **313-316** SUPPL. (2003) 1066

Terry, J.L., LaBombard, B., Bai, B., Greenwald, M., et al., "Observations of the turbulence in the scrape-off-layer of Alcator C-Mod and comparisons with simulation," Phys. Plasmas **10** No. 5 II (2003) 1739.

Papers Submitted for Publication

Basse, N.P., et al., "Study of intermittent small-scale turbulence in Wendelstein 7-AS plasmas during controlled confinement transitions," *Phys. Plasmas*.

Boswell, C.J., Terry, J.L., LaBombard, B., Lipschultz, B., Pitcher, C.S., "High-field side scrape-off layer density profiles inferred from D_α emission on Alcator C-Mod," *Plasma Phys. Control. Fusion*.

Ernst, D.R., et al, "Role of Trapped Electron Mode Turbulence in Internal Transport Barrier Control on Alcator C-Mod," *Phys. Plasmas*.

Fiore, C.L., Bonoli, P.T., Ernst, D.R., Hubbard, A.E., Greenwald, M.J., Lynn, A., Marmar, E.S., Redi, M.H., Rice, J.E., Wolfe, S.M., Wukitch, S.J, Zhurovich, K., et al., "Control of Internal Transport Barriers on Alcator C-Mod," *Phys. Plasmas*.

Gangadhara, S., LaBombard, B., "Impurity Plume Experiments in the Edge Plasma of the Alcator C-Mod Tokamak," *Nuc. Fusion*.

Hubbard, A.E., Carreras, B.A., Basse, N.P., Hughes, J.W. Marmar, E.S., Mossessian, D., Wukitch, S., et al., "Local Threshold Conditions and Fast Transition Dynamics of the L-H Transition on Alcator C-Mod," *Plasma Phys Control. Fusion*.

Hutchinson, I.H., "Spin Stability of Aysmmetrically Charged Plasma Dust," *New J. Phys*.

LaBombard, B., Lipschultz, B., et al., "Multi-fluid code simulations including anomalous non-diffusive transport of plasma and impurities in the toakmak SOL," *Plasma Phys*.

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., Smick, N., Wolfe, S.M., Wukitch, S.J., "Scrape off layer-flows, magnetic toplogy and influence on the L-H threshold in a tokamak," *Phys. Rev. Lett*.

Lin, Y., Wukitch, S.J., Bonoli, Nelson-Melby, E., P.T., 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., et al, "Investigation of ICRF Mode Conversion at the Ion-ion Hybrid Layer in Alcator C-Mod" *Phys. Plasmas*.

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

Redi, M.H., Fiore, C.L., Dorland, W., Mikkelsen, D.R., Rewoldt, G., Bonoli, P.T., Ernst, D.R., Rice, J.E., Wukitch, S.J., "Stability of Microturbulent Drift Modes during Internal Transport Barrier Formation in the Alcator C-Mod Radio Frequence Heated H-Mode," *Phys. Plas*.

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. Plas.*

Rice, J.E., Fournier, K.B. (LLNL), Marmar, E.S., Terry, J.L., Safronova, U.I. (Notre Dame University), "X-Ray Spectroscopy of High n Transitions of He- and Ne-like Ions in Alcator C-Mod Plasmas, *Nuc. Fusion*.

Snipes, J.A., Schmittdiel, D., Granetz, R.S., Parker, R.R., et al., "Initial Active MHD Spectroscopy Experiments Exciting Stable Alfvén Eigenmodes in Alcator C-Mod," *Plasma Phys Control. Fusion*.

Watts, C., In, Y., Heard, J., Phillips, P., Lynn, A., Hubbard, A., Gandy, R., "Upper limit on turbulent electron temperature fluctuations in the core of Alcator C-Mod," *Plasma Phys*.

MIT Plasma Fusion Center Research Reports (including theses)

Boswell, C.J., "Visible Imaging Spectroscopy on the Alcator C-Mod Tokamak," PSFC/RR-03-1, March 2003.

Feng, J., "Probabilistic Analysis of Fatigue Life for ITER CS Conduit," PSFC/RR-03-7, October 2003.

Gangadhara, S., "Physics and Application of Impurity Plume Dispersal as an Edge Plasma Flow Diagnostic on the Alcator C-Mod Tokamak," PSFC/RR-03-2, March 2003.

LaBombard, B., and Boswell, C., "In-Situ Gas Conductance and Flow Measurements Through Alcator C-Mod Divertor Structures With and Without Plasma Present," PSFC/RR-03-6, September 2003.

LaBombard, B., Lipschultz, B., "Cross-Field Particle Transport in the Edge Plasma of Tokamak Experiments and Implications for ITER," PSFC/RR-03-8, December, 2003.

Lee, W.D., "Experimental Investigation of Toroidal Rotation Profiles in the Alcator C-Mod Tokamak," PSFC/RR-03-3, June 2003.

Schmittdiel, D., "Investigation of Alfvén Eigenmodes in Alcator C-Mod Using Active MHD Spectroscopy," PSFC/RR-03-5, June 2003.

Shadman, K., "The Gridded Electromagnet Probe," PSFC/RR-03-4, June 2003.

Conferences

APS 2003
Philadelphia, PA
April 5 — 8, 2003

Hubbard, A.E., "Physics Issues of Edge Transport Barriers in Magnetically Confined Fusion Experiments" (Invited).

Redi, M., "Gyrokinetic Calculations of Microturbulence and Transport for NSTX and Alcator C-Mod H-modes."

15th Topical Conference on Radio Frequency Power in Plasmas
Moran, Wyoming
May 19 — 21, 2003

Basse, N.P., et al., "Control and data acquisition system for lower hybrid current drive in Alcator C-Mod."

Bonoli, P.T., et al., "Lower Hybrid Current Drive: an Overview of Simulation Models, Benchmarking with Experiment and predictions for Future Devices."

Decker, J., "ECCD for Advanced Tokamak Operations Fisch-Boozer versus Ohkawa Methods."

Lin, Y., Wukitch, S., et al., "Study of Ion Cyclotron Range of Frequencies Mode Conversion in the Alcator C-Mod Tokamak" (Invited).

Parisot, A., Wukitch, S., et al., "Investigation of ICRF Coupling Resistance in Alcator C-Mod tokamak."

Porkolab, M., et al., "Optimized AT target plasma Studies in Alcator C-Mod with lp ramp and intense ICRH."

Schilling, G., Wukitch, S., et al., "Analysis of 4-strap ICRF Antenna Performance in Alcator C-Mod."

Wright, J.C., Bonoli, P.T., et al., "Ultrahigh Resolution Simulation of Mode Converted ICRF and LH Waves with a Spectral Full Wave Code."

Wukitch, S., et al., "Overview of Alcator C-Mod ICRF experiments."

30th EPS Conference on Controlled Fusion and Plasma Physics
St Petersburg, Russia
July 7 — 11, 2003

Decker, J., et al., "Electron Cyclotron Current Drive by the Ohkawa Method in the Presence of Bootstrap Current."

Decker, J., Bers, A., et al., "Relativistic Effects in Heating and Current Drive by Electron Bernstein Waves."

Hutchinson, I.H., "Sphere in Flowing Plasma with non-zero Debye length: the unmagnetized Mach Probe part 2."

Krasheninnikov, S.I., . . . LaBombard, B., Lipschultz, B., et al., "Edge plasma structures and transport."

Lipschultz, B., Andrew, P., Coad, J., et al., "A Study of JET SOL Radial Transport Based on Particle Balance," ECA Vol. **27A**, P-3.197.

Maddison, G.P., Mossessian, D., . . . Snipes, J.A., et al., "EDA H-mode pedestal identity studies on JET and Alcator C-Mod."

Mossessian, D. et al., "H-mode pedestal physics studies in local dimensionless identity experiments."

Mossessian, D.A., . . . Hughes, J.W., Greenwald, M., LaBombard, B., et al, "Local dimensionless identity experiments as a tool for studying H-mode pedestal physics."

Pigarov, A.Yu., Krasheninnikov, S.I., LaBombard, B., Lipschultz, B., et al., "Analysis of non-diffusive transport and SOL recycling with fluid plasma code UEDGE."

Redi, M.H., Bell, R., Bonoli, P., . . . Fiore, C., Rice, J., Wukitch, S., et al., "Gyrokinetic Calculations of Microturbulence and Transport on NSTX and Alcator-CMOD H-modes."

Snipes, J.A., . . . Burke, W., Granetz, R.S., Parker, R.R., Vieira, R., Wolfe, S.M., "Initial Active MHD Spectroscopy Results on Alcator C-Mod."

IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research
San Diego, CA
July 21 — 23, 2003

Fredian, T., et al., "Migration of Alcator C-Mod Computer Infrastructure to Linux."

18th International Conference on Numerical Simulations in Plasmas
September, 2003

Greenwald, M., "Beyond Benchmarking: How Experiments and Simulations can work together in Plasma Phsyics," presented at the ICNSP, September 2003, and to be published in *Computer Physics Communications*, 2004

IAEA Conference on H-mode Physics and Transport Barriers
San Diego, CA
September 24 —26, 2003

Hubbard, A.E., Marmar, E.S., et al., "Local Threshold Conditions and Fast Transition Dynamics of the L-H Transition on Alcator C-Mod."

Hughes, J.W., Mossessian, D., LaBombard, B., "Investigations of plasma and neutral transport in the Alcator C-Mod edge pedestal."

Lynn, A.G., Phillips, P.E., Hubbard, A.E., Wukitch, S.J., Redi, M.H., "Observations of core modes during RF-generated internal transport barriers in Alcator C-Mod."

Sampsell, M.B., Bravenec, R.V., Lynn, A.G., Phillips, P.E., Rowan, W.L., et al., "Measurements of the Quasi-Coherent Mode on Alcator C-Mod."

9th International Conference on Accelerator and Large Experimental Physics Control Systems
Gyeongju, Korea
October 13 — 17, 2003

Lister, J., Costley, A., Duval, B., Fredian, T., Greenwald, M., Lauren, F.-S., Spears, W., Stillerman, J., "The ITER Project and its Data Handling Requirements."

20th Symposium on Fusion Engineering
San Diego, CA
October 14 — 17, 2003

Burke, W., Cochran, W., Schmittdiel, D., Snipes, J., Zhong, X., “Broadband Amplifiers for the Active MHD Diagnostic on Alcator C-Mod.”

Burke, W., “Serial Fiber Optic Links for the Lower Hybrid Current Drive Control System on Alcator C-Mod.”

Terry, D., Burke, W., Grimes, M., Parker, R., Basse, N., Bosco, J., Rokhman, Y., Stillerman, J., “Lower Hybrid Low Power Microwave Active Control System Design, Installation and Testing on Alcator C-Mod.”

Zaks, J., Vieira, R., Savelli, H., LaBombard, B., Irby, J., Childs, R., Lipschultz, B., et al., “C-Mod Cryo-pump Design Evaluation.”

44th Annual Meeting - Division of Plasma Physics of the American Physical Society
Abstracts Published in Bull. Am. Phys. Soc., **48**, 2003
Albuquerque, New Mexico
October 27 — 31, 2003

APS Invited

Ernst, D., “Role of Trapped Electron Mode Turbulence in Internal Transport Barrier Control in Alcator C-Mod.”

Fiore, C., “Control of Internal Transport Barriers on Alcator C-Mod” (Slides).

Lin, Y., “Investigation of ICRF Mode Conversion at the Ion-ion Hybrid Layer in Alcator C-Mod.”

Rice, J., “Toroidal Rotation and Anomalous Momentum Transport in Alcator C-Mod Plasmas with No Momentum Input”

Wright, J., “Full Wave Simulations of Fast Wave Mode Conversion and Lower Hybrid Wave Propagation

<u>APS Orals</u>

Basse, N.P., “Reflectometry measurements of turbulence in Alcator C-Mod plasmas.”

Bonoli, P., “Comparison of Simulation Models for Lower Hybrid Current Drive: With Application to ITER and Alcator C-Mod.”

Greenwald, M., “Recent Highlights from C-Mod Program.”

LaBombard, B., “Evidence for Electromagnetic Fluid Drift Turbulence Controlling the Edge Plasma State in Alcator C-Mod.”

Grulke, O., “Spatiotemporal Characterization of turbulent Fluctuations in the SOL of Ohmic Discharges in Alcator C-Mod.”

Redi, M., “Gyrokinetic Calcuations of C-Mod and NSTX H-mode Plasmas.”

Sampsell, M., “Multi-Diagnostic Study of the QC Mode on Alcator C-Mod.”

Snipes, J., “Active MHD Spectroscopy on Alcator C-Mod.”

Terry, J., “The Radial Location of the Quasi-coherent Mode in Alcator C-Mod EDA H-mode Discharges.”

Wukitch, S., “Recent Advances in ICRF Experiments on C-Mod.”

Zweben, S., “Edge Minority Heating Experiment in Alcator C-Mod.”

<u>APS Posters</u>

Böse, B., “Poloidal Drift of Striations in Li+ Pellet Ablation Clouds.”

Graf, A., “Toroidal Rotation Measurements of Tokamak Plasmas with Fast Time Resolution.”

Granetz, R.S.. “A Long-pulse Diagnostic Neutral Beam for Alcator C-Mod.”

Graves, T., “Investigation of Radio Frequency Breakdown in Fusion Experiments.”

Hill, K., “Profiles of Helium-like Argon Spectra from Alcator C-Mod with High Spatial and Spectral Resolution.”

Hughes, Jr., J.W., “Experimental studies of plasma and neutral particle transport in the Alcator C-Mod plasma edge.”

Irby, J., “Elemental Boron Injector for Wall Conditioning on the Alcator C-Mod Tokamak.”

Lin, L., “Phase Contrast Imaging Studies of Turbulent Density Fluctuations and RF Waves in Alcator C-Mod.”

Liptac, J., “Hard Xray Diagnostic for Lower Hybrid Current Drive on Alcator C-Mod.”

Lynn, A., “Heterodyne ECE Observations of Coherent Modes in Alcator C-Mod.”

Parisot, A., “Design of an ICRF fast matching system for the Alcator C-Mod tokamak.”

Phillips, P., “Broadband Fluctuations Observed in the Heterodyne ECE Radiometer on Alcator C-Mod During ITB's.”

Schilling, G., “Results from ICRF Heating and Current Drive on C-Mod.”

Scott, S., “Evaluation of Anomalous Fast-Ion Losses in Alcator C-Mod.”

Smick, N., “Plasma Profiles and Flows in the High-Field Scrape-off Layer in Alcator C-Mod.”

Tang, V., “Characterization of Alcator C-Mod ICRF Minority Tails via Neutral Particle Detection.”

Watts, C., “Upper limit on turbulent electron temperature fluctuations on Alcator C-Mod.”

Wolfe, S.M., “Non-axisymmetric Field Effects on Alcator C-Mod.”

Yuh, H., “Calibration of and Measurements from the C-Mod MSE Diagnostic.”

Zhurovich, K., “Core Thomson Scattering Diagnostic.”

Workshop Presentations

Transport Task Force Workshop
Madison, WI
April 2 — 5, 2003

Contributed Orals

Fiore, C.L., “Progress in Alcator C-Mod Internal Transort Barrier Studies.”

Mossessian, D., “Local Dimensionless Identity Method as a Tool for Studying H-mode Pedestal.”

Redi, M., “Gyrokinetic Calculations of Microturbulence and Transport on NSTX and Alcator C-Mod H-modes.”
Rice, J.E., “Observations of Momentum Transport in Alcator C-Mod Plasma with No Momentum Input.”

Posters

Greenwald, M., Schissel, D., “The National Fusion Collaboratory.”

Phillips, P., “Temperature Scale Lengths and ETG Models for C-Mod.”

Sampsell, M., “BES and ECE Measurements of the Quasi-Coherent Mode on Alcator C-Mod.”

Terry, J.L., “Turbulence in the Outboard and Inboard Scrape-Off-Layers of Alcator C-Mod.”

Other Presentations

Basse, N.P., et al., “Reflectometry on Alcator C-Mod: Status and future upgrades,” 6th intl. reflectometry workshop (2003)

Greenwald, M., "Turbulence, Transport and the Tokamak Density Limit", Invited Talk, Dartmouth College Physics Colloquium, May 2003

Hubbard, A., “Advanced Tokamak Research on Alcator C-Mod: Towards Profile control and Long Pulses,” Plasma Physics Colloquium, Columbia University, Nov 21, 2003.

Marmar, E.S., “Status of Tokamak Research: Alcator C-Mod and the Path to ITER and Beyond,” presented at the FPA Annual Meeting and Symposium, Nov, 20, 2003.

Porkolab, M., “High Field Approach to Demo,” presented at the FESAC Meeting at GA, San Diego, CA, Jan. 13, 2003.

Appendix B

Summary National Budgets, Run Time and Staffing

		FY04 Approp	FY05 Guidance	FY05 Prog Plan	FY05 -10%	FY06 -10%	FY06 Flat	FY06 Prog Plan
Funding ($ Thousands)								
Research		5,950	5,969	6,631	5,622	5,622	5,969	7,278
Facility Operations		13,344	12,500	16,234	11,000	11,000	12,500	17,486
Research Capital Equipment		190	207	299	186	186	207	307
Operations Capital Equipment		0	100	100	90	90	100	100
PPPL Collaborations		2,070	2,050	2,250	1,845	1,845	2,050	2,250
UTx Collaborations		425	425	480	383	383	425	480
LANL Collaborations		97	100	120	90	90	100	120
International Activities		47	47	47	42	42	47	47
MDSplus		146	149	149	134	134	149	149
Total (inc. International)		22,269	21,547	26,310	19,392	19,392	21,547	28,217
Staff Levels (FTEs)								
Scientists & Engineers		49.38	48.93	54.43	45.73	44.73	48.43	52.64
Technicians		30.28	28.28	32.28	26.08	24.28	26.28	32.58
Admin/Support/Clerical/OH		16.27	15.46	17.08	13.91	13.82	15.33	17.24
Professors		0.25	0.25	0.25	0.25	0.25	0.25	0.25
Postdocs		2.00	3.00	3.00	3.00	2.00	3.00	3.00
Graduate Students		22.05	22.05	22.05	20.05	19.00	22.05	22.05
Industrial Subcontractors		1.20	1.00	1.00	1.00	1.00	1.00	1.00
Total		121.44	118.98	130.10	110.03	105.09	116.35	128.77

	FY03 Actual	FY04 Approp	FY05 Guidance	FY05 Prog Plan	FY05 -10%	FY06 -10%	FY06 Flat	FY06 Prog Plan
Facility Run Schedule								
Scheduled Run Weeks	13	19	14	25	11	10	12	25
Users (Annual)								
Host	53	56	54	60	53	51	53	60
Non-host (US)	90	95	93	110	90	85	90	95
Non-host (foreign)	10	12	10	18	10	10	10	18
Graduate students	24	25	24	26	23	21	24	26
	153	163	157	188	176	167	153	173
Operations Staff (Annual)								
Host	68	71	69	80	66	65	67	80
Non-host	4	4	4	5	4	3	4	5
	72	75	73	85	70	68	71	85

Appendix C

Alcator C-Mod Program Detail in Bullet Form

FY04

Plans

19 weeks total research operations (11 already accomplished)
    1 week = 4 days, 8 hours/day

Areas of Emphasis

- Pedestal and core transport studies
  - Rotation, momentum transport
  - Topology and H-Mode dynamics
  - Edge pedestal, small/no ELM regimes, QC mode
- Edge and divertor physics
  - SOL transport (energy and particles)
  - Neutral dynamics
  - Edge turbulence (imaging, profiles, theory and modeling)
  - High-Z first wall (Mo – tungsten comparisons)
    - Hydrogen retention
- MHD/Stability
  - Error fields and locked modes
  - Active MHD (global and Alfven modes)
- RF heating and current drive
  - Current and flow drive (ICRF)
  - Mode conversion physics
  - Load tolerance (ICRF)
  - Installation of first LH coupler; initial experiments
- Advanced Tokamak thrust
  - Low density H-Mode target development
  - Multiple frequency ICRF ITB studies (experiments and modeling)
- Burning Plasma support thrust
  - Comparisons of single-null, double-null and limited configurations
  - Lower collisionality plasmas
  - ITER-like equilibria
  - D-^{3}He heating scenarios at relevant density and field

Plain English Goals

- Plasma flow control with radio waves (ICRF)
- Commissioning of the microwave current drive system (LHRF)
- Power and particle handling for advanced tokamak plasmas

Awards

- Amanda Hubbard named Fellow of APS

FY05 10% Decrement

Plans

- 11 weeks research operation
- Lower Hybrid Current Drive/AT physics
- Disruption mitigation
- Implement long pulse Diagnostic Neutral Beam

Impacts

- Research operation reduce by 3 weeks
- Deferral of LHCD upgrade to 2 launchers, 4 MW
- Reductions in force
    - 1 Scientist, 1 Student, 2 Engineers, 2 Technicians
- Delay in implementation of load tolerant antenna modifications
- Delay in implementation of key diagnostics, including polarimeter/interferometer

FY05 Guidance Budget

Prioritized increments:

- Add 3 weeks research operation (675k)
- Restore additional personnel cuts (800k)
- 2nd LHCD launcher on schedule (300k)
- LHCD 4th MW on schedule (300k)

Detailed Research Plans

- See work proposal

Plain English Goals

- Current profile control with microwaves

FY05 Program planning budget

Prioritized increments:

- 7 weeks additional research operation, to 21 weeks (1500k)
- Development of 4-strap ICRF antenna to maintain full capability (350k)
- Spare 4.6 GHz klystron (500k)
    - Currently 1 spare for 16 tube system
- Key diagnostic upgrades
    - Core Thomson scattering: add core channels (150k)
    - Active MHD upgrade: 2nd toroidal location for n control (50k)
- ICRF real-time matching: 2nd antenna (350k)
- Outer divertor upgrade
    - Power handling for >8MW, 5 seconds (200k)
- 4 weeks additional research operation, to 25 weeks (900k)

FY06 10% Decrement

Plans
- 10 weeks research operation
- 50% non-inductive AT plasma investigations

Impacts
- Research operation reduce by 2 weeks
- Deferral of LHCD upgrade to 2 launchers, 4 MW
- Reductions in force
    - 1.5 Scientist, 1 Post-Doc, 1 Student, 2 Engineers, 2 Technicians

FY06 Guidance Budget

Prioritized increments:
- Add 2 weeks research operation (450k)
- Restore additional personnel cuts (1000k)
- 2nd LHCD launcher on schedule (300k)
- LHCD 4th MW on schedule (300k)

Detailed Research Plans
- See work proposal

Plain English Goals
- Sustaining plasma current without a transformer (50% non-inductive)

FY06 Program planning budget

Prioritized increments:
- 6 weeks additional research operation, to 18 weeks (1400k)
- Implementation of 4-strap ICRF antenna to maintain full capability (400k)
- Spare 4.6 GHz klystron (500k)
- 3 weeks additional research operation, to 21 weeks (700k)
- Additional tangential views: high res. x-ray for rotation, T_I, profiles (100k)
- Outer divertor upgrade
    - Power handling for >8MW, 5 seconds (300k)
- ICRF real-time matching: all antennas (350k)
- MSE second view
    - Direct E_R measurement (400k)
- ICRF cavity conversions: transmitters 1 & 2 to tunable (350k)
- Advanced material divertor (500k)
- Develop laser scattering fluctuation diagnostic (300k)
- 4 weeks additional research operation, to 25 weeks (900k)