

(Draft)

FY04-FY05 WORK PROPOSAL

March 2003

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

Alcator Project

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ALCATOR C-MOD
FY04-05 WORK PROPOSAL

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Introduction

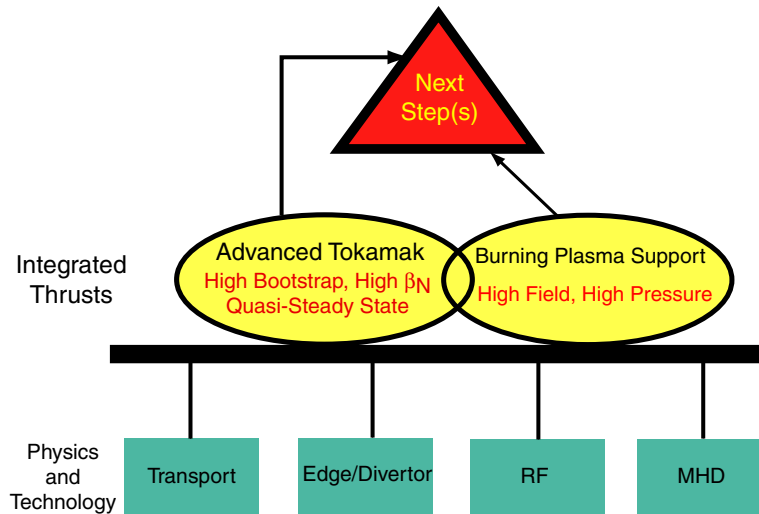
Alcator C-Mod is the high-field, high-density divertor tokamak in the world fusion program. The overall theme of the Alcator program is

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 takes advantage of the high-field high-pressure capability of the facility and also includes some critical research aimed at resolving performance questions related to next-step fusion experiments.

The connections among the topical science areas and the programmatic thrusts are illustrated in Figure 1.

Figure 1. Programmatic thrusts and topical science.



Since the Alcator project has recently (Feb 2003) submitted a full scale proposal and plan for the next five-year Grant, for review by OFES, this Field Work Proposal does not repeat that material. Details of the research proposed for the 2003-2005 period are given in that document (http://www.psfc.mit.edu/cmod/sciprogram/5yr_proposal.pdf), to which reference should be made.

This summary focuses on the material specifically requested for the Annual Budget Planning process.

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 2 gives a graphical representation of the mapping between specific C-Mod program elements, especially the Plain English objectives discussed later, and the 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.

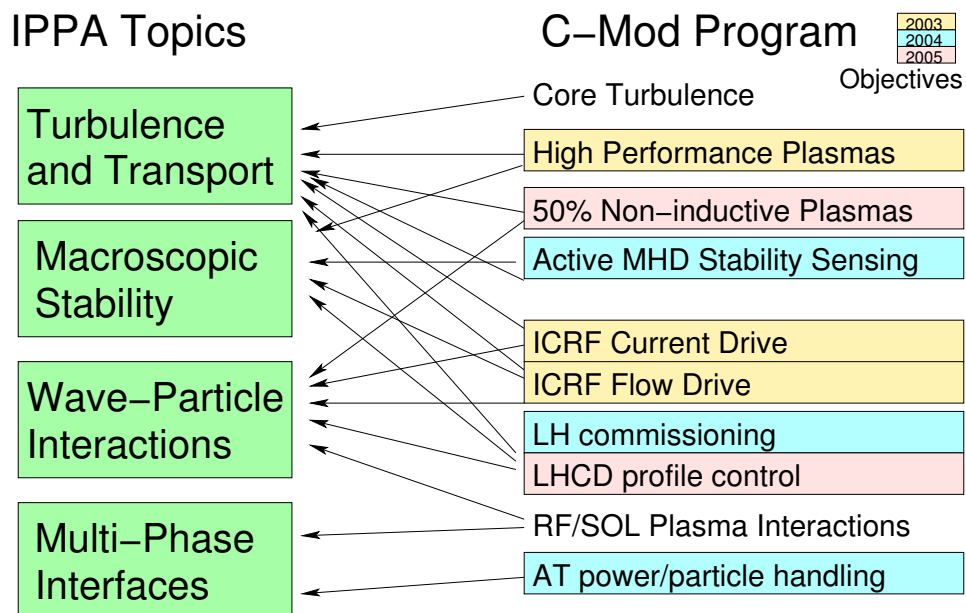


Figure 2. Mapping between Alcator program and IPPA Goal 1 objectives

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 focussed on addressing objectives related to Steady State, High Performance and Burning Plasma, as illustrated in Figure 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.

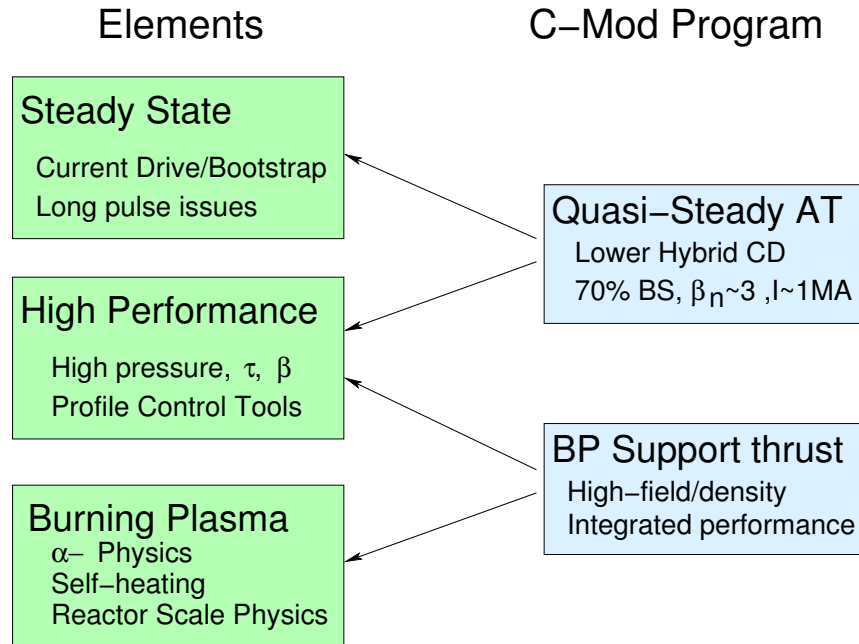


Figure 3. Mapping between Alcator program and IPPA Goal 3 objectives

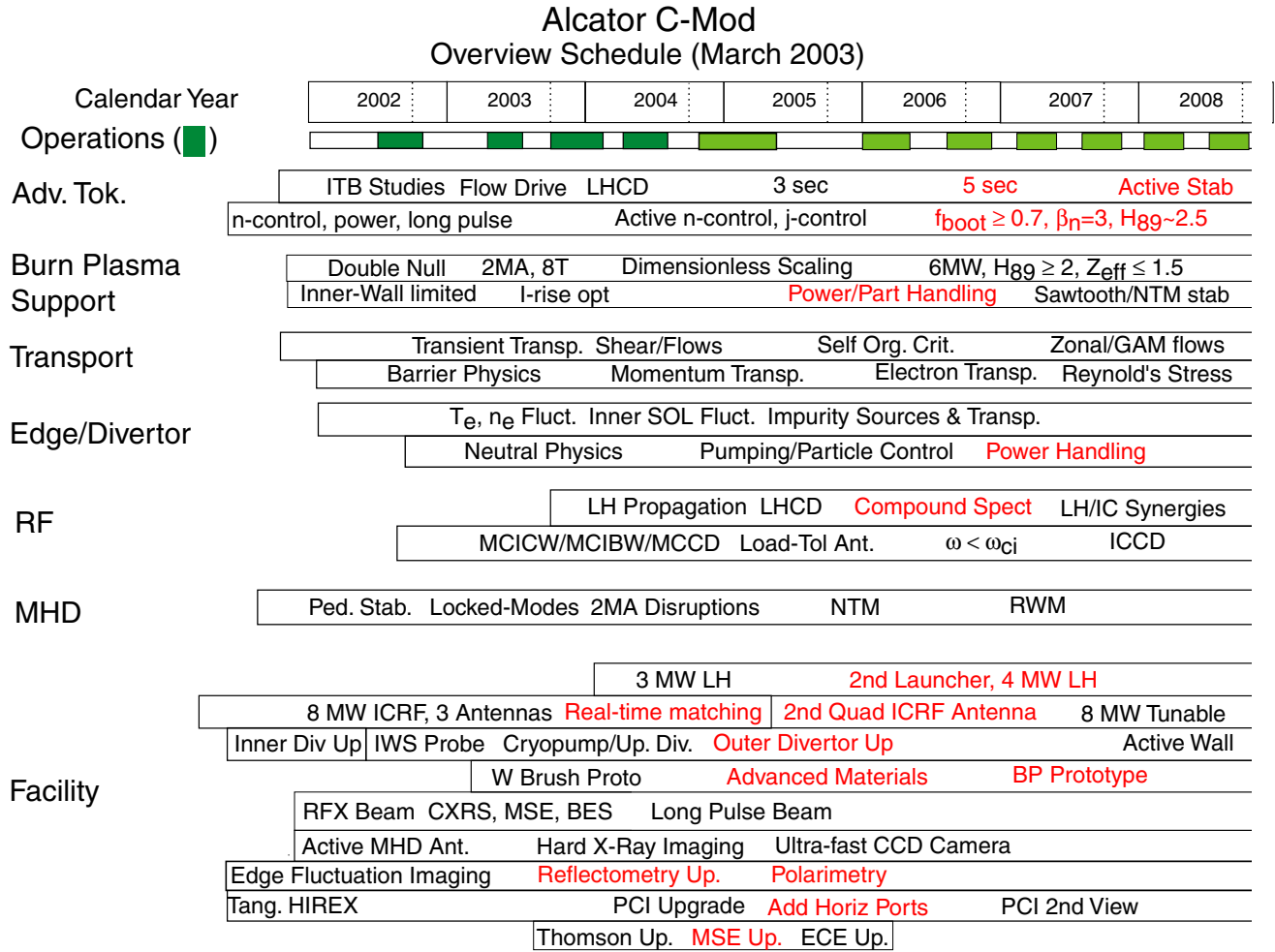
Concerning goal 4, the C-Mod program focuses attention in selected areas: ICRF and Lower Hybrid technologies, and high Z metal walls/divertors with reactor level heat flux. The Advanced Tokamak is an innovative concept that is a critical part of the broad range emphasized in goal 2.

Detailed discussion of how Alcator’s specific topical science plans address the key programmatic objectives are given in the respective sections of the five-year Grant proposal.

Budget and Schedule

The overall schedule for the C-Mod program is illustrated in Figure 4. The timing of various program elements assumes that the project will be funded at the guidance budget levels for FY04 and FY05. Upgrades that will be delayed and/or deferred under the 10% decrement cases are shown in red. Progress on all research topics will be slowed in the decrement cases. The strongest impact will be on the 5 year goals for the AT thrust; because of the delay in the Lower Hybrid upgrade, investigations of fully non-inductive discharges with high bootstrap fraction and fully relaxed current density profile will be delayed by at least 2 years in the lowest budget cases.

Figure 4. C-Mod Project Schedule.



A summary table of budgets, operations and staffing for the national program, including major collaborators, can be found in Appendix A.

A detailed bulleted list of plans and consequences for the various budget levels is in Appendix C.

Highlights for each fiscal year are summarized here.

FY2003

A total of 13 weeks of operation are planned in FY2003. Of these, 6 have already been completed, in September and October of 2002. Areas of research emphasis this year are:

- High power ICRF (up to 6 MW) to study lower collisionality plasmas, mode conversion flow and current drive, and the assessment of MHD stability at increased β
- Development of optimized target plasmas for future LHCD experiments
- High current operations, 2 MA (1.7 MA already achieved)
- Locked-mode studies using newly installed non-axisymmetric control coils
- Pedestal and core transport studies
- Coordinated studies with DIII-D, JET, ASDEX-U, and JT60-U
- SOL and divertor studies

The Lower Hybrid MIE upgrade will be completed in the spring of 2003 with the delivery of the waveguide launcher from PPPL. Twelve klystrons, with total source power of 3 MW, are installed in the test-cell.

FY2004

Under the FY04 guidance budget, the facility will have 21 weeks of research operations. The highest priority upgrades are included within this budget envelope, including replacement of the borrowed DNB with a long-pulse beam, design and start of construction of the cryopump for density control, commissioning and first operation of the LHCD system, design and start of construction of the second phase of LHCD (second launcher, increased source power to 4 MW total), upgrades to existing diagnostics and new diagnostics.

Impacts of a 10% decrement in FY04 include reduction of run-time to 18 weeks, and deferral of the lower hybrid and ICRF upgrades. FTE reductions in personnel will total 1 engineer, 1.5 technicians and 1 scientist.

The FY04B program planning budget (11% increment over FY04A) allows for full utilization of the facility, with 25 weeks of research operation, increased science effort, earlier implementation of the full ICRF real-time matching systems (increased reliability at high power), and targeted upgrades of diagnostics, data acquisition hardware and computing facilities.

FY2005

Under the FY05A flat budget, the facility will have 19 weeks of research operations. The second LH launcher will be completed, and the outer divertor upgrade will be on schedule for completion in FY06. Advanced tungsten divertor modules will be installed and tested. The cryopump system will be completed and installed.

Impacts of a 10% decrement in FY05 include a reduction of research operations to 16 weeks, and substantial delay in several upgrades. The second lower hybrid launcher will be delayed by at least 6 months. If the FY04 budget was also reduced from the guidance level, the total delay in the LHCD upgrades will be close to 2 years. The polarimeter system ($j(r)$ at high density) will be deferred, as will the tungsten divertor modules. Real-time ICRF matching systems will be delayed by at least 1 year and the outer divertor upgrade will be deferred. We will also have to defer the purchase of a spare ICRF final power amplifier tube, leading to significant risk to the schedule in the event of a tube failure. FTE personnel reductions will total 1.5 engineers, 2 technicians, and 1.5 scientists.

The FY05B program planning budget (9% increment over FY04B) allows for full utilization of the facility, with 25 weeks of research operation. It also accommodates the purchase of 1 additional LHCD klystron, reducing schedule risks. The polarimeter system will be enhanced with extra channels for a 50% increase in spatial resolving power. A lithium beam polarimeter system will be added for edge/pedestal current density profile measurements.

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.

Plasma Flow Control with Radio Waves [Sep 03]

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 RF, what degree of control is possible, and how this can be used to optimize the plasma confinement.

Higher Performance Plasmas [Sep 03]

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 susceptibility 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.

Driving Electric Current with Radio Waves [Sep 03]

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 its efficiency and suitability for the future.

Commissioning of the Microwave Current Drive System [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 Advanced Tokamak experiments before the end of FY 2003.

Power and Particle Handling for Advanced Tokamak Plasmas [04]

Techniques for safely radiating away the extremely large parallel 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.

Sensing approach to instability using active coils [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.

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.

Sustaining Plasma Current Without a Transformer [05]

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.

Goals Accomplished in FY2002

Plasma Probing with Energetic Neutral Particles: Critical Measurements

By injecting energetic neutrals into the plasma, a wealth of new information will be gathered on (a) the profiles of ion temperature and ion flow which are important for plasma confinement, (b) the plasma current profile which determines the macroscopic stability of

the plasma, particularly at high pressure, and (c) plasma density fluctuations, which are responsible for the turbulent transport that ultimately determines the quality of confinement.

Report:

The project entered into a collaboration with the University of Padova, Italy, borrowing a neutral beam designed for their experiment. It was installed on Alcator and operated successfully during FY02. Current-profile information was obtained with acceptable signal to noise. Fluctuations associated with edge plasma turbulence were measured by University of Texas collaborators using the beam. Ion temperatures were also obtained in the outer plasma regions. Ion flow measurements were obtained but with insufficient accuracy; they require improved spectroscopy and detection techniques and possibly a higher current beam for full utility.

Exploiting Divertor Upgrades

Significant modifications and upgrades to the inner divertor structures in Alcator C-Mod are being implemented in Fiscal Year 2002. The hardware is being strengthened to permit full plasma current operation and the previous highly shaped inner wall structure is being replaced with a flatter, more open design, which will allow for the investigation of a broader range of plasma shapes, especially those with increased plasma triangularity. These upgrades expand the range of current and shape that can be studied and are expected to open up new plasma regimes on Alcator C-Mod.

Report: (see Figure 5)

The new divertor was installed and utilized successfully. The hardware performed extremely well, and the additional shaping flexibility was obtained. Plasma currents up to 1.7 MA were run. In addition, important observations were made on changes in the halo currents produced during disruptions. These halo currents are major design challenges for next-step experiments, because of the large forces involved. We found that the change in divertor shape substantially lowered the currents. Our interpretation is that this decrease is associated with the details of the plasma geometry and the connection to the plates during the disruption. This work suggests that by appropriate geometric design, halo currents in a next-step experiment might be substantially reduced, and disruption effects thereby mitigated.

Test the merits of Power Handling options for Next Step Designs

Burning plasma experiment designs incorporate different options for the challenging task of taking away safely the heat escaping from the confined plasma. One choice is whether to use an edge magnetic configuration that is up-down mirror symmetric or an asymmetric configuration where the bottom divertor handles all the heat. Another choice is between using magnetic topology or a material surface to define the confined plasma boundary.

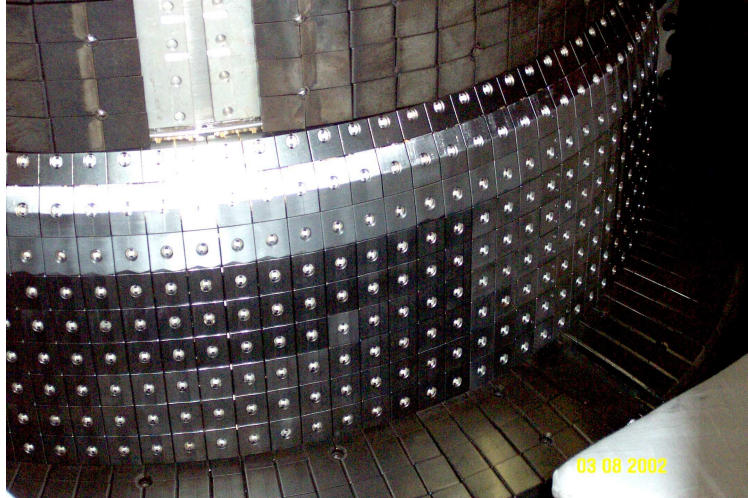


Figure 5. Alcator's new inner divertor

Since Alcator is able to operate under all these conditions and has edge power densities comparable to future burning plasma experiments, we will study how the different options affect the plasma performance.

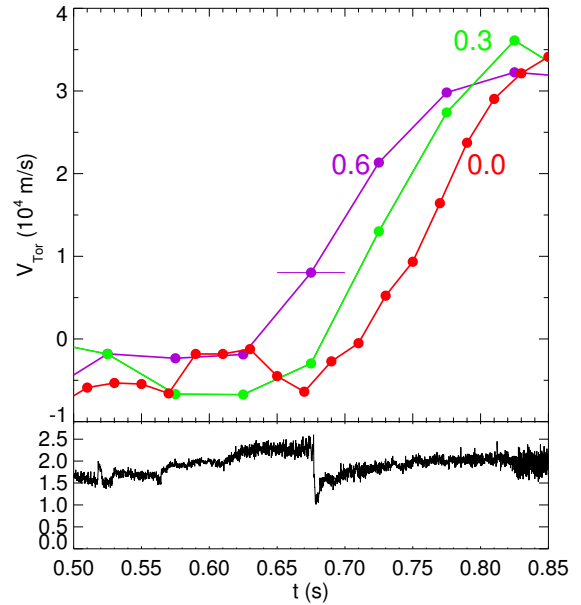
New observations have shed light on the differences between symmetric and asymmetric plasma divertor configurations. In symmetric, or near-symmetric configurations we observe in Alcator a very narrow scrape-off-layer on field-lines that are restricted to the inboard side. We have measured the turbulent fluctuations there and found that they are far smaller than on the outboard. These results prove unequivocally that the scrape-off-layer plasma transport is far greater on the outboard side of the plasma and point to the underlying instability physics. Moreover the thin inboard layer gives an opportunity for fuelling with greater efficiency. We have also shown that the plasma can be operated in a slightly asymmetric configuration that allows the heat to be conducted to the lower divertor, while the particles flow sufficiently to the upper chamber to be pumped there. High confinement performance can be sustained in the symmetric configuration once initiated, but it is harder to initiate. By contrast, non-divertor plasmas, limited by field-lines intersecting the inner wall, revert immediately to low confinement even in plasmas that are started in high confinement by using the divertor.

Measurements of Rotation Profile Evolution

Report: (see Figure 6)

This achievement, not previously called out as a major objective, has great importance because the plasma rotation or flow is intimately connected with its confinement. Alcator has previously observed strong rotation even without direct momentum input, the situation that is likely to obtain in a reactor. But till last year's upgrade, our diagnostics were able only to give a central rotation value. Now with profile information we have been able to establish that in many situations the plasma momentum mostly diffuses in from the plasma

Figure 6. Measurements of toroidal rotation at different radii (indicated as fraction of minor radius) are plotted vs time. Rotation in the outermost channel increases immediately after the L/H transition (seen by the drop in H_α) followed in sequence by channels closer to the center.



edge, where most of it is generated by anomalous processes still under investigation. Our results give us the momentum diffusion coefficients. In other strongly RF heated cases, however, a central peaking of the velocity is observed, which indicates that there are mechanisms other than pure diffusion occurring even in the core of the plasma.

Appendix A: Alcator C-Mod Summary National Budgets, Run Time and Staffing

	FY03 Approp	FY04 Request	FY04 Prog Plan	FY04 -10%	FY05 -10%*	FY05 Level	FY05 Prog Plan	
Funding (\$ Thousands)								
Research	5,123	5,889	6,340	5,300	5,224	5,804	6,739	
Facility Operations	10,483	12,496	13,986	12,298	11,959	12,586	15,287	
Lower Hybrid MIE (MIT)	124	0	0	0	0	0	0	
Lower Hybrid upgrades	0	1,485	1,485	285	700	1,480	1,995	
Capital Equipment	98	96	96	86	86	96	116	
PPPL Collaborations	2,442	2,072	2,500	1,865	1,865	2,072	2,600	
UTx Collaborations	425	427	540	384	384	427	560	
LANL Collaborations	99	96	110	86	86	96	120	
International Activities	47	47	47	42	42	47	47	
MDSplus	145	146	146	131	131	146	146	
Total	18,986	22,754	25,250	20,479	20,479	22,754	27,610	
Staff Levels (FTEs)								
Scientists & Engineers	48.32	52.29	57.14		48.89	52.06	58.88	
Technicians	28.84	29.30	34.20		27.10	28.20	34.75	
Admin/Support/Clerical/OH	15.08	14.37	15.22		13.20	14.27	16.05	
Professors	0.54	0.54	0.54		0.54	0.54	0.54	
Postdocs	2.70	3.00	3.00		2.00	3.00	4.00	
Graduate Students	21.71	20.71	21.71		20.71	20.71	21.71	
Industrial Subcontractors	1.00	1.00	1.00		1.00	1.00	1.00	
Total	118.19	121.21	132.81		113.44	119.78	136.93	
*Assumes FY04 was at request level								
	FY02 Actual	FY03 Approp	FY04 Request	FY04 Prog Plan	FY04 -10%	FY05 -10%	FY05 Level	FY05 Prog Plan
Facility Run Schedule								
Scheduled Run Weeks	8	13	21	25	18	16	19	25
Users (Annual)								
Host	54	54	59	60		57	58	60
Non-host (US)	85	90	100	110		90	100	110
Non-host (foreign)	8	10	15	18		10	15	18
Graduate students	24	24	27	29		25	27	29
	147	154	174	188		157	173	188
Operations Staff (Annual)								
Host	64	69	75	80		72	74	80
Non-host	4	4	5	5		5	5	5
	68	73	80	85		77	79	85

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

FY03

Plans

13 weeks total research operations (6 already accomplished)

Areas of Emphasis:

- High power ICRF
 - lower collisionality plasmas
 - MC flow and current drive
 - Increased β , assess MHD stability
- Develop optimized target plasmas for future LHCD AT scenarios
- High current ops, to 2 MA
- Non axisymmetric control coils
 - Locked-mode studies
- Pedestal and core transport studies
 - momentum transport, ITBs
 - turbulence and marginal stability
 - particle and energy transport comparisons
 - ICRF edge heating, effects on H-mode
- Coordinated studies with DIII-D, JET, ASDEX-U, JT60-U
- SOL and Divertor studies
 - turbulence and particle/energy transport
 - deuterium co-deposition, erosion studies
 - strike-point sweeping for power handling
- Completion of Lower Hybrid MIE (3 MW source, 1 launcher)

Plain English Goals

- Higher performance plasmas
- Plasma flow with radio waves (ICRF)
- Driving electric current with radio waves (ICRF)

Physical infrastructure

- Flywheel / alternator inspection
 - Required approx every 5 years
 - will be completed in FY03
 - payment spread over 03 (440k) and 04 (320k)

Awards

- Bruce Lipschultz named Fellow of APS

FY04 10% Decrement

Plans

- 18 weeks of research operation
- first operation with lower hybrid system (up to 3 MW source)
- Proceed with long-pulse DNB purchase, cryopump

Impacts

- Research operations reduced by 3 weeks
- deferral of LHCD upgrade to 4 MW source, second launcher
 - needed to reach 5 year AT goals (Fully non-inductive, 0.85MA, $f_{boot} > 0.7$)
- deferral of advanced 4-strap ICRF antenna
- Reductions in force:
 - 1 Engineer
 - 1.5 Technician
 - 1 Scientist

FY04 Level Budget case

Prioritized increments:

- Add 3 weeks research operation, to 21 weeks total (600k)
- Proceed on schedule with LHCD upgrades and advanced ICRF antenna
 - completion in FY05
 - 1300k\$ in FY04

Detailed research plans

- In Five Year proposal

Plain English Goals

- Commissioning of microwave current drive system
- Power and particle handling for advanced tokamak plasmas
- Sensing approach to instability using active coils

FY04 Program planning budget

Prioritized increments:

- 4 weeks additional operations, to 25 total, full utilization (1200k)
- Increased science effort [1.5 scientist, 1 student] (300k)
- Increased Engineering and Technical support (350k)
- Earlier implementation of full ICRF real-time matching systems (125k)
 - more reliable operations at high power
- Additonal polarimeter channels (120k in 04)
- Faster replacement of obsolete CAMAC and computers (100k)
- Instrumentation upgrades (150k)

FY05 Decrement case 1 (10% below 04 guidance for BOTH 04 and 05)

- 16 weeks of research operation
- 2 year cumulative delay in Lower Hybrid phase II
 - earliest possible implementation of full LHCD power delayed to FY08
- Diagnostics deferred/delayed
 - Polarimeter delayed
 - IR cameras deferred
- Advanced tungsten divertor test modules deferred

FY05 Decrement case 2 (guidance budget in 04, 10% decrement in 05)

- 16 weeks of research operation
- Does not make sense to stop Lower Hybrid phase II entirely (started in 04)
 - Finish delayed at least 6 months into FY06
- Bigger impact on other systems
 - Polarimeter deferred
 - IR cameras deferred
 - tungsten test modules deferred
 - Real-time ICRF matching delayed
 - Outer divertor upgrade deferred
 - Vessel upgrade deferred
 - Spare ICRF FPA tube deferred (schedule risk without spares)

FY05 Level budget case (assumes guidance budget in 04)

- add 3 weeks of research operation, to 19 total (700k)
- Complete Lower Hybrid phase II launcher (900k)
- Complete advanced 4 strap ICRF antenna (380k)
- Outer divertor upgrade on schedule (FY06 completion) (100k)
- Complete polarimeter (150k)
- Tungsten test modules installed (50k)
- Purchase spare ICRF FPA tube (100k)
- Complete IR cameras (50k)
- Vessel upgrade proceeds on schedule for FY06 implementation (50k)

Plain English Goals

- Current profile control with microwaves
- Sustaining plasma current without a transformer (50% non-inductive)

FY05 project planning case

- Add 6 weeks of research operation, to 25 total (full utilization) (1500k)
- Increased science effort [2.5 scientist, 1 student] (500k)
- Increased Engineering and Technical support (950k)
- Complete phase II Lower Hybrid (550k)
- Complete ICRF real-time matching (245k)
- MSE 2nd view (E_r) (240k)
- Increased participation in scientific meetings (including ITPA) (50k)
- Complete polarimeter with extra channels (100k)
- Lithium beam polarimeter (edge $j(r)$) (160k in 05)
- Outer divertor upgrade on schedule for 06 completion (50k)
- Faster replacement of obsolete CAMAC and computers (200k)