(Draft)
ALCATOR C-MOD
FY08-10 WORK PROPOSAL

March 2008

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

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

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

Organization of the program is through a combination of topical science areas supporting integrated thrusts. The topics relate to the generic fusion-plasma science, while the thrusts focus this science on integrated scenarios, particularly in support of ITER design and operation. The project is also aggressively investigating important issues on the MFE development path from ITER to DEMO. The program has five topical science areas: core transport; pedestal physics; plasma boundary; wave-plasma interactions; and macrostability. Integrated scenarios encompass the ITER baseline inductive H-modes, and Advanced Tokamak (AT) operation including partially inductive hybrid modes and fully non-inductive weak and reverse shear operation with active profile control. AT operation takes advantage of the unique long-pulse capability of the facility (relative to skin and L/R times), at $B \leq 5$ Tesla, combined with new current drive and density control tools, to investigate the approach to steady-state in fully non-inductive regimes at the no-wall beta limit; this is particularly relevant to the prospects for quasi-steady operation on ITER. All aspects of the research are intimately connected to a broad program of theory and modeling. The connections among the topical science areas and the integrated scenarios are illustrated in Figure 1.1.

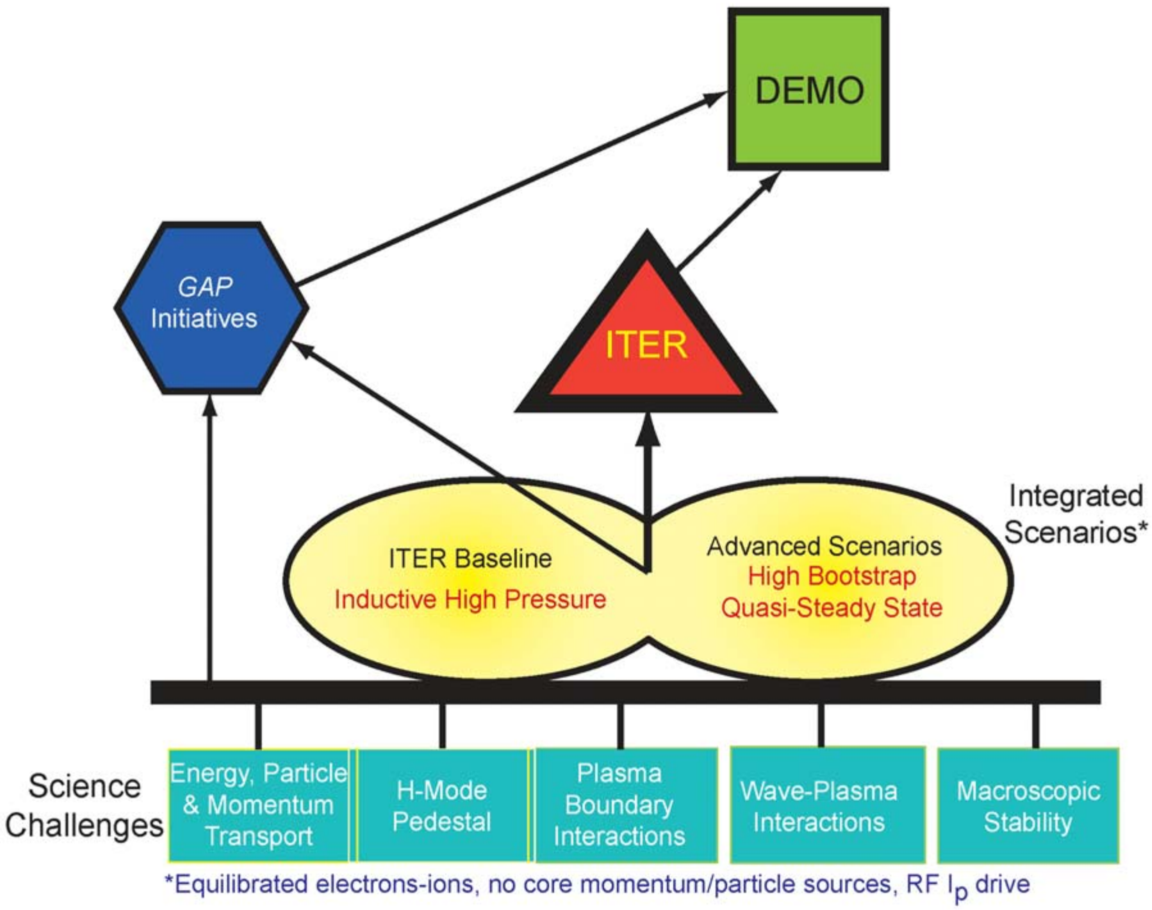

Figure 1.1 Integrated scenarios and topical science areas.

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

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

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

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

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

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

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

The C-Mod facility already has an impressive set of facility capabilities, control tools and diagnostics. During the next three year period, significant facility upgrades, particularly for ICRF and LHRF systems, and upgraded and new diagnostics will be implemented.

The C-Mod program is fully collaborative. In addition to MIT, which hosts the facility, major collaborations are ongoing with the Princeton Plasma Physics Laboratory and the University of Texas at Austin. Many smaller groups of collaborators at Universities and Laboratories, both domestic and international, are integral participants in the research.

Education is a very important aspect of the Alcator project mission, and the project has a large contingent of graduate students working toward their PhD degrees. They are drawn from four departments at MIT, as well as from collaborating Universities. At any time, about 30 graduate students are doing their PhD thesis 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 coming three year period. Many of the experiments are carried out jointly with other tokamak facilities, both in the US and around the world, with coordination through the ITPA. Major C-Mod contributions are as follows.

Integrated Scenarios, Baseline H-mode and Advanced Scenarios:

- Breakdown and current rise in ITER
- Reference set of ITER scenarios for baseline H-mode, steady-state and hybrid operation, for databases and modeling
- ITER hybrid scenarios: experimental development and understanding mechanisms for maintaining q_0>1
- Profile control methods: especially j(r) with combined LHCD and bootstrap

Transport

- Core transport regimes with equilibrated electrons/ions, no momentum input, dominant electron heating: regime for majority of C-Mod operation.
- Collisionality dependence of density peaking: addition of C-Mod data breaks the covariance between collisionality and n/n_G seen in other experiments; heating decoupled from core fueling.
- Develop and demonstrate turbulence stabilization mechanisms compatible with reactor conditions, such as magnetic shear stabilization, shear flow generation and q profile; compare these mechanisms to theory.
- Develop common technologies for integrated modeling (frameworks, code interfaces, data structures): MDSplus is a model.

Pedestal Physics

- Understand L-H power threshold at low density: C-Mod provides data at unique (ITER value) magnetic field; effects of neutrals/opacity.
- Role of rotation in the H-mode transition.
- Improve predictive and design capability for small ELM and quiescent H-mode regimes: small ELM regimes for β_N>1.3; effects of shaping.
- ELM control techniques: stochastic fields with external coils.

Plasma-Boundary Interactions

- Tritium retention and tritium removal: solid high Z PFCs; disruption cleaning; plasma and nuclear damage; erosion.
- Scaling present-day conditioning and operational techniques to future devices: boronization with high Z walls; ICRF induced impurity generation.
- Power handling and impurity control: SOL transport, radiative/detached divertor.

Macrostability

- Disruption database (energy loss, halo current): excellent diagnostics for radiated power, surface heating, halo currents.
- ITER applicable disruption mitigation, validate 2 and 3-D MHD codes with radiation: pioneering studies with NIMROD/NIMRAD of C-Mod experiments; LHCD for controlling seed population of non-thermal electrons to study runaway amplification/suppression.
- Develop reliable disruption prediction methods: work started on robust algorithms; real-time automatic mitigation using Digital Plasma Control System planned.
- NTM physics: effects of rotation; LHCD control/stabilization
- Understand intermediate n Alfven Eigenmodes (AE's); Damping and stability of AE's: active MHD antennas couple to intermediate n modes.
- Redistribution of fast particles from AE's: ICRF ion tails drive AE's unstable, Compact Neutral Particle Analyzers (passive and active with Diagnostic Neutral Beam), plus new scintillator lost ion detector to measure effects of AE's on fast particles.

Fusion Science Priorities

Priorities from the April 2005 FESAC Priorities Report

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

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

- T13. How does the challenging fusion environment affect plasma chamber systems?
- T14. What are the operating limits for materials in the harsh fusion environment?
- T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

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

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

"Gap" issues on the path from ITER to DEMO

In its October, 2007 report, "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy", FESAC identified 15 science and technology gaps that need to be filled on the path to designing and building a successful MFE DEMO reactor. Complete resolution of most of these issues requires both a successful ITER program, and additional initiatives, including new facilities, primarily studying D-T burning fusion plasmas. However, many of the issues related to the gaps are amenable to research on existing experiments, coupled with advances in theory and modeling. Alcator C-Mod is working on a significant number of these issues, and substantial progress is expected in the next three years, which in turn will help to inform the design of new facilities that will be needed. The areas where C-Mod makes the strongest contributions are:

- Plasma facing components: high Z metals, ultra-high SOL power densities.
- Off-normal events: disruption avoidance, prediction and mitigation.
- Plasma-wall interactions: SOL and divertor transport, erosion and redeposition, hydrogen isotope retention.
- Integrated, high performance burning plasmas: focus of the Integrated Advanced Scenarios thrust.
- Theory and predictive modeling: code benchmarking, discovery of new phenomena, iteration of theory and comparison with experiment.
- Measurements: new and improved diagnostic techniques.
- RF antennas, launchers and other internal components: Advancing the understanding of coupler-edge plasma interactions, improvement of related theories and modeling.
- Plasma modification by auxiliary systems: RF systems (ICRF and LHRF) for current drive, flow drive, instability control; ELM control.
- Control: maintaining high performance advanced scenarios.

Summary of Achievements

Some of the key research achievements and discoveries of the Alcator program during the five year period between 2003 and 2008 are summarized in bullet form here.

- Transport Science
  - Pioneering studies of spontaneous core toroidal rotation in the absence of externally imposed momentum input.
  - Formation of ITB's on C-Mod with off-axis ICRF directly linked to reduction of ITG turbulence drive through gyrokinetic simulations using detailed experimental density and temperature profiles.
  - Identification of increased TEM drive as the controlling mechanism which limits pressure peaking in ITB discharges with the addition of stronger central heating.
  - Validation of gyrokinetic modeling through comparison with core fluctuation measurements.
  - Density peaking clearly linked to collisionality, not distance from the density limit.

- Pedestal Physics
  - Characterization of L-H threshold in terms of local variables, including explanation of grad-B asymmetry in L-H threshold based on topology dependent flows.
  - Extensive database developed mapping the dependence of pedestal characteristics on dimensional and dimensionless plasma parameters. Measurements of density, electron and ion temperature, rotation and radial electric field profiles are routinely available with ~mm spatial resolution in the pedestal region.
  - Dimensionless matched experiments comparing C-Mod with DIII-D indicate that plasma physics plays the dominant role in determining

pedestal width. Comparisons with JET show a similar result, but with hints that the density pedestal does broaden for very low densities, when the neutral mean free path is larger than the width.

- Pedestal pressure appears to be regulated by a critical gradient mechanism, similar to the dynamics seen in core transport.
- The quasi-coherent (QC) mode, which regulates pedestal density, and impurity outflow in the EDA regime, is consistent with a resistive ballooning drive. Detailed measurements of the QC mode characteristics have been made, and a theoretical picture is emerging. At the highest pedestal pressures on C-Mod, small ELMs appear on top of the QC mode.
- Access to the type I ELM regime on C-Mod has been achieved through increased shaping (in particular, high triangularity at the active X-point); good agreement is found between the threshold conditions for the type I ELMs, due to intermediate n peeling-ballooning modes, and modeling using the M3D resistive 3-D MHD code.

- Plasma Boundary Science
  - Evidence that electromagnetic turbulence sets the observed pressure gradients near the last-closed flux surface.
  - Identification of radial transport-driven edge plasma flows arising from ballooning-like transport asymmetries, which impact the toroidal rotation of the confined plasma and potentially explain the X-point dependence of the L-H power threshold.
  - Unprecedented detailed information on turbulent structures in the scrape-off layer, using a unique set of gas-puff turbulence imaging systems.
  - An enlightening dimensionless scaling study of cross-field particle convection in the far scrape-off layers of DIII-D, C-Mod and JET.
  - Increased understanding of the role of boronization with high-Z metallic plasma facing components.
  - Pioneering measurements of deuterium retention in bulk molybdenum PFCs, and an emerging explanation in terms of the plasma production and subsequent diffusion of defects in the metal which traps hydrogen isotopes.
- Wave-Plasma Interactions
  - World-record power flux levels (>10 MW/m^2) for plasma heating applied with C-Mod ICRF antennas.
  - Identification of ICRF sheaths as a primary mechanism for impurity generation.
  - Development and application of state-of-the-art antenna-plasma simulation code (TOPICA), and validation through detailed comparisons with experimental loading measurements across a range of edge plasma parameters.
  - Successful implementation of a Fast Ferrite Tuner active matching system, which keeps the ICRF system matched over a very wide range of plasma conditions; transient changes as fast as 1 msec can be tracked and accommodated, including L-H transitions and pellet injection.

— Physics mechanism responsible for antenna breakdown at high neutral pressure has been identified.
— For the first time, details of ICRF mode conversion processes have been directly observed, using the Phase Contrast Imaging diagnostic. All three plasma waves (fast, ion-Bernstein, and ion-cyclotron) are identified, and simulations with the TORIC code are in excellent agreement with the experiments.
— ICRF Mode Conversion Current drive used for sawtooth pacing.
— Greater than 800 kA of current driven non-inductively using Lower Hybrid Current Drive (LHCD), corresponding to 80% of the total current.
— Off-axis LHCD successfully used to broaden the current density profile.
— Variable phase control has been used to modify the radial deposition of Lower Hybrid wave, and change internal inductance.
— Sawtooth stabilization has been accomplished using LHCD.
— The Motional Stark Effect diagnostic is operational, and first measurements of changes in j(r) due to LHCD have been made.
— First studies of core plasma rotation changes induced by LHCD have started, and the formation of Internal Transport Barriers in these reduced shear discharges is evident.

- Macrostability
  — Detailed studies of disruption mitigation with massive gas puffing, using combinations of noble gases, including significant reduction of halo currents and nearly 100% conversion of stored kinetic plus magnetic energy into radiation.
  — Advanced 3-D MHD modeling of mitigation dynamics, including radiated power.
  — Demonstrated real-time detection and mitigation of impending Vertical Disruption Events.
  — Important scalings of critical error field thresholds for mode-locking, including coordinated studies with JET and DIIID for size and field scalings to allow extrapolation to ITER.
  — Radial structure of Reverse Shear Alfven Eigenmodes, driven unstable by ICRF heating during the current ramp, measured with the PCI diagnostic; detailed comparisons with synthetic diagnostic developed for the NOVA code show excellent agreement for code verification.

- Integrated Scenarios – ITER H-mode Baseline
  — Development of demonstration discharges at world record tokamak plasma pressure ($\langle P \rangle$=1.8 atmosphere), with B_T=5.4 T and β_N=1.7, as planned for the ITER baseline.
  — Scaling to ITER of locked mode threshold, through ITPA coordinated joint experiments.
  — Showed that the low density limit for H-mode access does not scale with $n/n_{Greenwald}$.

- Integrated Scenarios – Advanced Scenarios
    - — Implementation of LHCD system and MSE diagnostic.
    - — Successful application of LHCD to modify j(r), including demonstration of nearly 100% non-inductive operation at 1 MA plasma current.
    - — Implementation of divertor cryopumping for particle/density control.
    - — Successfully combined LHRF and ICRF, and mapped out regimes of operation where good LH coupling can be maintained in the presence of high power ICRF.
    - — Coupling of LHRF into H-mode discharges demonstrated.
    - — Extension of pulse lengths to 4 seconds, with high power ICRF (>6 MJ total input energy).
    - — Significant advances in integrated scenario modeling, using state-of-the art codes.

Funding for the MIT portion of the C-Mod program is provided under the umbrella of a Cooperative Agreement with the Department of Energy, Office of Fusion Energy Sciences. The current five year agreement period ends on October 31, 2008. A formal proposal for the next five year period will be submitted during March, 2008. Since that proposal includes detailed descriptions of recent research highlights, and plans for FY09-FY13, reference should be made to the proposal document for the FY09-FY10 period; those details will not be repeated in this Work Proposal.

Budget and Schedule

The baseline (A) budget for the C-Mod project in FY2009 is based on guidance from the Office of Fusion Energy Sciences, with total national project funding of $23.3M, including $20.7M at MIT, and major collaborations totaling $2.6M. These budgets will accommodate 10 weeks of research operations in FY2009. In the event of a 10% cut from the FY09A guidance, research run time would be reduced to 8 weeks. For FY10A, we have taken a flat budget (relative to the FY09A guidance) with an assumed 2% increase. This results in a plan for 13 research weeks in FY2010. A 10% cut relative to FY10A leads to a plan for 8 research weeks in the FY2010D case.

Implications of the different budgets, along with prioritized increments, are listed in Appendix C. Areas of research emphasis are also listed there; more details can be found in the March 2008 proposal for the next 5 years of research on Alcator C-Mod, covering the grant period Nov 1, 2008 through Sept. 30, 2013.

Proposed facility research run time is given in table 1.1. In addition to the guidance cases, we show the 2009B and 2010B incremental cases, and the 2009D decremental case. Because of the planned tokamak core inspection, it will be possible to accommodate 13 weeks of research operation in FY2009 with the B budgets. The majority of the FY09B increments are applied to preparing the facility for optimized utilization in FY2010.

Table 1.1: Research operation for guidance (08-10A), incremental (09B-10B) and decremental (10D) budget cases

Fiscal Year	**08**	**09A**	**10A**	**09B**	**10B**	**10D**
National Budget ($M)	25.2	23.3	23.7	29.0	31.2	21.4
Research Operation Weeks	15	10	13	13	24	8
Research Operation Hours	480	320	416	416	768	256

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 assumes an integrated effort involving all of the collaborators.

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.

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

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

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

Hybrid Advanced Scenario investigation [Sept 2009]

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

Testing a model of the fuel retention process in first-wall tiles [September 2010]
Tritium fuel retention is an important issue for ITER and reactors, since the on-site inventory of tritium is restricted by safety considerations. In addition, the high neutron fluence environment of a reactor necessitates the use of tungsten as the first-wall tile material. Initial experiments have revealed a higher-than-expected level of fuel retention in C-Mod's molybdenum and tungsten tiles compared to laboratory studies. It has been proposed that when such tiles are exposed to C-Mod's high plasma particle fluxes, they experience damage deep within the material, forming ‘traps’ that can enhance fuel retention. Experiments will be performed to quantify the level of fuel retention in C-Mod's molybdenum and tungsten tiles and, with the help of parallel laboratory experiments, to develop and test a model for the trap formation and fuel migration that can explain the observations.

Study of runaway electron dynamics during disruptions [Sept 2010]
Disruption mitigation is a crucial issue for ITER. Viable techniques for reducing halo current forces and thermal loads to the ITER divertor have been successfully developed and tested on a number of tokamaks. However, avalanche growth of very high-energy (multi-MeV) populations of electrons (potentially carrying as much as 10 mega-amps of current) in ITER is a disruption-related critical issue that has not been experimentally studied in depth, and viable mitigation techniques have not yet been developed. We plan to investigate the use of the Alcator C-Mod lower hybrid current drive system to generate populations of non-thermal electrons as a seed for disruption runaways that can be studied using a number of specialized diagnostics on C-Mod, including an array of hard x-ray energy analyzers and synchrotron radiation detectors, with the goal of understanding runaway electron growth, confinement, and loss mechanisms. While not part of this goal, the results should be applicable to the eventual development of practical runaway electron mitigation techniques.

Characterize accessibility conditions for small edge-localized modes [Sept 2010]
Global tokamak energy confinement is determined largely by the level of transport suppression obtained in a barrier at the plasma edge. However, strong edge transport barriers often reach pressure limits that are manifested as large, intermittent losses of particles and energy from the edge. In ITER and reactors, these edge-localized modes, or ELMs, are expected to result in deleterious transient heat and particle loads on material surfaces, unless the ELMs can be made small or non-existent. C-Mod will explore accessibility conditions for small ELMs, with variations in magnetic geometry, density and input power serving as important experimental knobs. Local measurements of edge conditions, combined with edge magnetohydrodynamic stability calculations, will be

used to investigate the physical mechanisms responsible for reducing ELM size, and for supressing them altogether.

Goals Accomplished in FY2007

Achieve research operating time of 15 weeks (±10%) [September 07] (JOULE milestone).

Alcator C-Mod operates on an 8 hours/day, 4 days per week schedule. One research week corresponds to 32 hours of facility operation.

The FY07 campaign concluded on August 31, 2007, with 14.7 research weeks accomplished. Quarter by quarter run statistics can be found at http://www.psfc.mit.edu/research/alcator/facility/Operations/FY07_research_table.html and links to details about each run day can be found at http://www.psfc.mit.edu/research/alcator/program/cmod_runs.php.

***Current Profile Control with Microwaves* [September 07]**

These experiments are aimed at developing efficient steady-state tokamak operation by launching microwaves into Alcator C-Mod plasmas. The location of current driven by the "Lower Hybrid" waves we will use depends on their wavelength as measured parallel to the magnetic field. We will vary this wavelength and measure the location and amplitude of the driven current, with the intention of demonstrating an improvement of the plasma confinement through current-profile control. By adding independent plasma heating, the plasma pressure will be raised, and by varying the location of the RF-driven current, we can begin to investigate the stability limit of the plasma, i.e. the maximum pressure the plasma can sustain without developing global instabilities.

The target was completed in September, 2007. When the LH power is applied to an inductively-formed discharge the loop voltage decreases in order to maintain the current at its feedback-controlled level. On C-Mod, the loop-voltage has been transiently reversed by 800 kW of LHCD power applied to a 1 MA discharge with central density of ~ 5x1019 m-3. As the Ohmic power is replaced by RF power, the central temperature in this discharge increases to ~ 4 keV, indicating that the RF power is at least as efficient as the Ohmic power regarding its global heating effectiveness. By varying RF power density and current, we find that the fractional change in loop voltage is, over a wide range, roughly proportional to the parameter $P_{LH} / n_{19} I_P R_0$. As is well known, in addition to the direct current drive by RF, there is a synergistic effect with the residual electric field due to the RF-produced non-thermal tail in the electron distribution function. When this is taken into account the specific RF current drive efficiency is found to be $n_{19} I_{LH} R_0 / P_{LH} \approx 0.3\, MA/m^2 MW$. This efficiency is consistent with the value derived from the simulations leading to the development of advanced steady-state regimes in Alcator C-Mod. Evidence that the LH driven current in Alcator C-Mod is peaked off-axis stems from a number of independent observations, including indirect indications such as a decrease in the internal inductance deduced from EFIT and sawtooth stabilization, as well as more direct measurements such as the spatial profiles of the hard X-Ray emission associated with the RF-driven tails in the electron distribution function, and preliminary

MSE measurements of the current density profile. A more direct indication that the LH current is mainly driven off-axis comes from measurement of bremsstrahlung emitted by the fast electrons created by interaction with the LH waves. In C-Mod LHCD experiments, Bremsstrahlung profiles are routinely monitored by a 32 spatial channel X-Ray camera that spectrally resolves the photon emission over the range 20-200 keV in each channel. Since the absorption of LH waves depends on $n_{||}$, varying the launched $n_{||}$ should affect the profile of bremsstrahlung emission, and this is directly seen in the experiments. Increasing the launched shifts the radial peak of the photon emission, and thus the region of LH wave absorption, outward as expected.

Active Density Control [September 07]

A new divertor cryopump will be installed in C-Mod and pumping properties will be tested during FY06. Beginning in FY07 the configuration will be evaluated for density control, particularly for target plasmas suitable for Advanced Tokamak regimes with efficient lower hybrid current drive combined with high bootstrap fraction.

The target was completed in September, 2007. A new upper divertor cryopump system has been successfully installed and operated in Alcator C-Mod. The system is a fully integrated divertor and cryopump design that employs a number of unique features including a 'pumping-slot' style divertor target and a full toroidal cryogenic loop that acts as a liquid helium 'pot'. The system is found to function as intended, providing C-Mod with a new high-throughput particle exhaust tool (exceeding 9,000 liters/s for room temperature D_2 gas) while minimizing helium consumption and avoiding a complex external cryogenic system. Dedicated experiments were performed during the FY07 run campaign to explore the capability of the pump for particle exhaust and plasma density control as a function of magnetic topology, plasma density and confinement regime. These experiments have provided valuable information, demonstrating the pump's utility for future physics experiments and for expanding the research capabilities of Alcator C-Mod.

Appendix A

Alcator C-Mod Publications –2007 to present

Papers Published in Refereed Journals:

Basse, N.P., Dominguez, A., Edlund, E.M., Hutchinson, I.H., et al., "Diagnostic Systems on Alcator C-Mod", *Fusion Science and Technology,* **51**, 476 (2007).

Bonoli, P. T., Parker, R., Wukitch, S. J. *et al*, "Wave-particle studies in the ion cyclotron and lower hybrid ranges of frequencies in Alcator C-Mod", *Fusion Science and Technology*, **51** (2007) 401-436.

Bonoli, P. T., Batchelor, D. B., Berry, L. A. *et al*, "Evolution of nonthermal particle distributions in radio frequency heating of fusion plasmas", *Journal of Physics,* **78** (2007) 012006.

Callen, J. D., Anderson, J. K., …, , Greenwald, M., et al., "Experimental tests of paleoclassical transport" *Nuclear Fusion* **47** (2007) 1449-1457.

Cohen, R.H., LaBombard, B., Ryutov, D.D., Terry, J.L., Umansky, M.V., Xu, X.Q., and Zweben, S., "Theory and fluid simulations of boundary-plasma fluctuations," *Nuclear Fusion* **47** (2007) 612.

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Conferences:

1st Workshop on Diagnostic Developments for Burning Plasmas, General Atomics, San Diego, CA, USA, Feb. 2007

Talks
M. Bitter, K. W. Hill, S. D. Scott, A. Ince-Cushman, J. E. Rice, P. Beiersdorfer, M. –F. Gu, J. Dunn, S. G. Lee, C. Broennimann, E. F. Eikenberry, “ITER-relevant developments of X-ray imaging crystal spectrometers on NSTX and Alcator C-Mod”

22nd IEEE/NPSS Symposium on Fusion Engineering, Albuquerque, NM, Proceedings, 2007

Invited Talk

Granetz, R.S., Irby, J., Labombard, B., Lin, Y., Lipschultz, B., Zaks, J., "Alcator C-Mod status, recent accomplishments, and future plans"

Posters

Burke, W., Terry, D.T., Kennedy, H., Stillerman, J., Milne, P., McLean, J., "The coupler protection system upgrade for lower hybrid current drive on Alcator C-Mod"

Koert, P., MacGibbon, P., Beck, W., Doody, J., Gwinn, D., "High power water load for lower hybrid current drive at 4.6 GHz on Alcator C-Mod"

Terry, D.R., Burke, W., Kanojia, A., MacGibbon, P., Johnson, D., Parker, R.R., Vieira, R.F., Wallace, G., Beck, W., Koert, P., Irby, J., Wilson, Greenough, N., Gwinn, D., "Lower Hybrid Current Drive on Alcator C-Mod: System Design, Implementation, Protection, Calibration and Performance"

Beals, D.F.; Granetz, R.; Cochran, W.; Byford, W.; Rowan, W.L.; Ivanov, A.A.; Deichuli, P.P.; Kolmogorov, V.V.; Shulzhenko, G., "Installation and operation of new long pulse DNB on Alcator C-Mod"

International Sherwood Fusion Theory Conference
Annapolis, MD April, 2007

Talks

Ernst, D.R., Basse, N. Dorland, W., Fiore, C.L., …, et al., "Observation of TEM Turbulence and New Effects of Collisions."

Bonoli, P.T., Porkolab, M. Wright, J.C., …, et l., "Comparison of Lower Hybrid Current Drive Predictions from Different Simulation Models in Reactor Relevant Regimes."

Catto, P.J. Simakov, A.N., LaBombard, B., "Magnetic Topology Effects on Alcator C-Mod Flows."

Para, F.I., Catto, P.J., "Extension of Electrostatic Gyrokinetics to Retain Long Wavelength Effects".

Wright, J.C., Bonoli, P.T., Brambilla, M., "Three Dimensional Calculations of Plasma Admittance in the Ion Cyclotron."

17th Topical Conference on Radio Frequency Power in Plasmas, Clearwater, FL, USA, May 2007

Invited talks

Wukitch, S., Lin, Y., Lipschultz, B., Parisot, A,, Reinke, M., Bonoli, P.T., Porkolab, M., Hutchinson, I.H., Marmar, E.S. and the Alcator C-Mod team, “ICRF Performance with Metallic Plasma Facing Components in Alcator C-Mod”

Bonoli, P.T., Batchelor, D.B., Berry, L.A., Choi, M., D’Ippolito, D.A., Harvey, R.W., Jaeger, E.F., Myra, J.R., Phillips, C.K., Smithe, D.N., Valeo, E., Wright, J.C., Brambilla, M., Bilato, R., Lancellotti, V., Maggiora, R., “Physics Research in the SciDac Center for Wave-Plasma Interactions”

Porkolab, M., “ RF Heating and Current Drive in Magnetically Confined Plasma: A Historical Perspective”

Posters
LinY., Binus, A., Parisot, A. and Wukitch, S., "Fast Ferrite ICRF Matching System on Alcator C-Mod"

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

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

Wilson, J.R., Hosea, J., Phillips, C. K., Parker, R., Bonoli, P.T., Hubbard, A.E., Porkolab, M., Schmidt, A.E., Wallace, G., “Lower Hybrid Current Drive on Alcator C-MOD”

Fifth IAEA Technical Meeting on Steady State Operation of Magnetic Fusion Devices
Daejeon, Republic of Korea, May 2007

Talk
Wright, J.C., “Lower Hybrid Current Drive Experiments in Alcator C-Mod”

Sixth IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, Inuyama, Japan, June 2007

Talks
Stillerman, J.A., “Digital real-time control for an ICRF fast-ferrite-tuning system on Alcator C-Mod”

Fredian, T.W., “MDS Plus Extensions for Long Pulse Experiments”

Poster
Lin, Y. Stillerman, J., Binus, A. et al. “Digital real-time control for an ICRF fast ferrite tuning system on Alcator C-Mod”

11th IAEA Technical Meeting on Hmode Physics and Transport Barriers, Tsukuba, Japan, Sept. 2007

Poster
A. E. Hubbard, I. O. Bespamyatnov*, A. Dominguez, J. W. Hughes, A. Ince-Cushman, B. LaBombard, B. Lipschultz, L. Lin, K. Marr, R. McDermott, P. Phillips*, M. Porkolab, M. L. Reinke, J. E. Rice, W. L. Rowan*, J. A. Snipes, "Evolution of edge profiles and fluctuations in two-phase L-H transitions in unfavorable magnetic configurations in Alcator C-Mod"

34thrd European Physical Society Conference on Plasma Physics. Warsaw, Poland, July 2007

Contributed Talk
Hubbard, A.E., Hughes, J.W., Greenwald, M., LaBombard, B., Lin, Y., Terry, J.L. and Wukitch, S., "H-mode experiments at reduced collisionality on Alcator C-Mod", Oral Paper Apr. 1, 2007

Posters
R.R.Parker, R.R., Wilson, R., Bonoli, P.T., Harvey, R.W., Hubbard, A.E., Porkolab, M., Schmidt, A.E., Wallace, G.M., "Lower Hybrid Experiments in C-Mod"

Parisot, A., Wukitch, S.J., Bonoli, P.T., Greenwald, M., Hubbard, A.E., Lin, Y., Parker, R.R., Porkolab, M., Ram, A.K., Wright, J.C., "Sawtooth pacing with mode conversion current drive on Alcator C-Mod"

2007 Transport Task Force Meeting, San Diego, CA, USA, April 2007

Talk
Porkolab, M., "Observations of Alfvén Cascades During ICRF Heating in Alcator C-Mod"

Snipes, J., "A Comparison of Alfvén Eigenmode Stability in L- and H-Mode"

Hubbard, A., "Two-phase LH Transitions in Unfavorable Configurations in Alcator C-Mod"

Greenwald, M., "Particle Transport at Low Collisionality on Alcator C-Mod"

Posters
Fiore, C.L., "ITB Transport Studies in Alcator C-Mod"

Lin, L., "Experimental Studies of Turbulence with the Phase Contrast Imaging Diagnostic in the Alcator C-Mod Tokamak"

11th International Conference on Accelerator and Large Experimental Physics Control Systems, Knoxville, TN, US, Oct. 2007

Talk
J.W. Farthing, A. Capel, N. Cook, M. Edwards, E. Jones, R. Layne, D. McDonald, M. Wheatley, J. Lister, M. Greenwald, "Data Management at JET with a Look Forward to ITER"

Schissel, D.P., Abla, G., Greenwald, M., Fredian, T., Stillerman, J., “Remote Operation Of Large-Scale Fusion Experiments”

49th Annual Meeting of the APS Division of Plasma Physics,
Orlando, FL, USA, October 2007

Invited Talks
Bonoli, P., “Lower Hybrid Current Drive Experiments on Alcator C-Mod: Comparison Bewtween Theory and Simulation”

LaBombard, B., “Critical Gradients and Plasma Flows in the Edge Plasma of Alcator C-Mod”

Wukitch, S., “ICRF Performance with Metallic Plasma Facing Components: Revenge of the Sheath”

Izzo, V., “MHD Simulations of Disruption Mitigation on Alcator C-Mod and DIII-D”

Contributed Orals
Marmar, E., “Overview of Alcator C-Mod Research”

Wilson, R., “Experiments with Lower Hybrid Current Drive on Alcator C-Mod”

Hughes, J., “H-mode Performance and Pedestal Studies with Enhanced Particle Control on Alcator C-Mod”

Greenwald, M., “Particle Transport and Density Peaking at Low Collisionality on Alcator-C-Mod”

Fiore, C., “Internal Transport Barriers in Alcator C-Mod”

Terry, J., “Observations of the Spatial and Temporal Structure of Edge Turbulence near the X-Point of Alcator C-Mod”

Zweben, S., “Interpretation of Edge Turbulence Images Near the X-Point of Alcator C-Mod”

Cziegler, I., “Structure of the Broadband Edge Turbulence in L-Mode and pre-H-mode Plasmas in Alcator C-Mod”

Whyte, D., “Hydrogenic Fuel Retention in Molybdenum”

Pigarov, A. Y., “Plasma Flows Due to Blobs and Drifts in Alcator C-Mod Scrape-off Layer”

Smick, N., “First Measurements of Total Flow Vector in the C-Mod High-Field Side SOL”

Snipes, J., “Fast Electron Driven Alfvén Eigenmodes in in Alcator C-Mod”

Ince-Cushman, A., “First Results From The New High Resolution Imaging X-ray Crystal Spectrometer On Alcator C-Mod”

Maddison, G., “Kinetic modeling of ionisation sources within C-Mod/JET pedestals suggests decay-lengths in proportion to their widths”

Posters

Angelini, S., “Real-time Detection of Locked Modes”

Bader, A. “Dust Studies in Alcator C-Mod”

Bespamyatnov, I. “CXRS Measurements and Study of Impurity Poloidal Rotation for $0.1 < \rho < 1.0$ in Alcator C-Mod Plasmas”

Bose, B. “Results From Stereoscopic Imaging of the Ablation of Injected Li Pellets in the Alcator C-Mod Tokamak”

Hubbard, A. “Progress and Prospects of Advanced Scenarios using LHCD on C-Mod”

Dominguez, A. “Density Fluctuation Studies Using the Upgraded C-Mod Reflectometry System”

Edlund, E. “Structure and Stability Analysis of Reversed Shear Alfvén Eigenmodes with NOVA-K”

Ferrara, M. “Kalman Filter for the Real Time Estimation of the Vertical Position of Tokamak Plasmas”

Mikkelsen, D. “Collisionality Dependence of Density Peaking in H-mode Plasmas in Alcator C-Mod”

Graf, A. “Spectroscopic Diagnostics with a Visible Transmission Grating Spectrometer at Alcator C-Mod”

Rowan, W. “Ohmic ITBs in Alcator C-Mod”

Zhurovich, K. “The Role of Turbulent Suppression in the Triggering ITBs on C-Mod”

Gierse, N. “Application of New Fitting Routines on Edge Thomson Scattering Profiles from Alcator C-Mod”

Lin, L. “Drift Wave Turbulence Studies with the Phase Contrast Imaging Diagnostic in the Alcator C-Mod Tokamak”

Lin, Y., “Recent ICRF Results in Alcator C-Mod”

Scott, S. “Effect of Secondary Beam Neutrals on MSE: Theory”

Hill, K. “Inference of Ion-Temperature and Rotation-Velocity Profiles from a Spatially Resolving X-Ray Crystal Spectrometer on Alcator C-Mod”

Marr, K. “Results from Pedestal Viewing, CXRS Diagnostics Using GPI and DNB Injection on Alcator C-Mod”

McDermott, K. “Initial Results from the Edge Charge Exchange Diagnostic on Alcator C-Mod”

Parker, R. “Current Profile Modification By Lower Hybrid Waves in Alcator C-Mod”

LaBombard, B. “Design and Operation of a Novel Divertor Cryopumping System in Alcator C-Mod”

Lau, C. “Design of a New X-mode Edge Reflectometer for Alcator C-Mod”

Tsujii, N. “Development of Absolute Calibration of the Phase Contrast Imaging Diagnostic and Experimental Tests in Alcator C-Mod”

Ma, Y. “Continued Upgrades to Thomson Scattering Diagnostics on Alcator C-mod for Improved Core Spatial Resolution”

Sears, J. “Influence of ICRF Heating on the Stability of TAEs”

Ko, J. “Effect of Secondary Beam Neutrals on MSE: Experiment”

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

Bitter, M. “The Instrumental Function of the New X-ray Imaging Crystal Spectrometer on Alcator C-Mod”

Ochoukov, R. “Surface Science Station: A Real-time Diagnostic of Boronization in Alcator
C-Mod”

Kessel, C. “Simulations and Experiments on Modifying the q-profile for Advanced Tokamak Discharges on Alcator C-Mod”

13th Meeting of the ITPA Topical Group on Diagnostics, Chengdu, China Oct 29-Nov 2, 2007

Talks
B. Stratton, M. Bitter, K. W. Hill, S. Scott, A. Ince-Cushman, M. Reinke, J. E. Rice, P. Beiersdorfer, M. F. Gu, S. G. Lee, Ch. Borennimann, E. F. Eikenberry, R. Barnsley, “Progress on Imaging x-ray crystal spectroscopy”

IAEA International Workshop “Challenges in Plasma Spectroscopy for Future Fusion Research Machines”, Jaipur, India, Feb. 2008

Talks
M. Bitter, K. W. Hill, S. Scott, A. Ince-Cushman, M. Reinke, J. E. Rice, P. Beiersdorfer, M. F. Gu, S. G. Lee, Ch. Broennimann, and E. F. Eikenberry, “A novel x-ray imaging crystal spectrometer for Doppler measurements of ion temperature and plasma rotation velocity profiles”

Invited Talks

Lin, Y., “Ion Cyclotron Range of Frequencies Heating and Current Drive in Tokamaks”, Plasma Physics Winter School, ASIPP, Hefei, China, Jan. 11, 2008

C-Mod Related Science Talks, Presented to Audiences Primarily Composed of Fusion Science Researchers

Lipschultz, B., FOM Colloquim: “Divertor physics under ITER-like conditions in Alcator C-Mod”, Rijnhuizen, The Netherlands, March 1, 2007

Lipschultz, B., JET Colloquim: “Characteristics of D retention in a high-Z\ tokamak: A new retention process?”,Culham, UK November 28, 2007

Lipschultz, B., Joint ASDEX Upgrade and Materials Research division colloquium: “Characteristics of D retention in a high-Z tokamak”,Max Planck Institut fur PlasmaPhysik, Garching, Germany - January 11, 2008

Lipschultz, B., MIT PSFC weekly seminar: “Characteristics of D retention in a high-Z tokamak”, MIT/PSFC, Cambridge, MA, USA, February 29, 2008

Parker, R., “Initial Results of Lower Hybrid Current Drive Experiments in Alcator C-Mod”, Columbia University, New York City, NY, USA, March 2, 2007

Whyte, D. “Magnetic fusion energy: Requirements for Plasma-Facing Materials” BES Materials under Extreme Environments Workshop, Washington, D.C., June 11, 2007

Whyte, D. “Measuring and controlling plasma-surface interactions of low-Z elements in a tokamak fusion device,” Joint meetings of 17th International Vacuum Conference and 13th International Conference on Surface Science, Stockholm, Sweden, July 6, 2007

Outreach Plasma Presentations for Non Fusion Audiences

Fiore, C., Presentation to Girl Scout Troop 1656: “Meeting the challenge: global energy needs, global warming, and our future.”, Jan. 11, 2007

Fiore, C., IAP Talk: “A Hitchhiker's Guide to Fusion Plasmas.”, MIT/PSFC, Cambridge, MA, USA, Jan. 23, 2008

Hubbard, A., MIT “Independent Activities Period” seminar: “Advanced Scenario research on Alcator C-Mod: Towards a better tokamak reactor”, MIT/PSFC, Cambridge, MA, USA, January 22, 2008

Irby, J., “Alcator C-Mod", Talk and Tour for the Boston Chapter of the IEEE, MIT/PSFC, Cambridge, MA, USA, Apr. 2, 2007

Irby, J., “Fusion, ITER, and Alcator C-Mod”, Talk and Tour for TOTAL Executives (French Energy Company), MIT/PSFC, Cambridge, MA, USA, Nov. 12, 2007

Porkolab, M. “Recent Progress in Fusion Research”, Hungarian Nuclear Society Annual Meeting, Budapest , Hungary, November 29th, 2007

Awards and Prizes

Miklos Porkolab- Received the Hungarian Nuclear Society “Simonyi Karoly Prize for Outstanding Contributions to Plasma Physics and Fusion Research” in Nov. 2007.

James L. Terry - Awarded the APS Fellowship in 2007: *For significant contributions in the areas of volume recombination in plasmas, plasma impurity transport, wall-conditioning with lithium, plasma transport, and plasma turbulence in magnetic fusion confinement devices.*

Appendix B. Summary National Budgets, Run Time and Staffing

		FY08	FY09A	FY10D	FY10A	FY10B
			Request	Reduced	Guidance	Full
Funding ($ Thousands)						
Research		7,222	6,700	6,320	6,870	8,600
Facility Operations		14,694	13,377	12,500	14,015	18,500
Capital Equipment		416	400	0	0	0
PPPL Collaborations		2,090	2,070	1,900	2,110	3,240
UTx Collaborations		415	400	367	408	440
LANL Collaborations		103	103	95	106	127
MDSplus		155	155	140	155	170
International Activities		80	80	40	80	100
Total (inc. International)		25,175	23,285	21,362	23,744	31,177
Staff Levels (FTEs)						
Scientists & Engineers		55.01	51.96	42.22	51.34	61.84
Technicians		26.64	26.63	24.99	26.73	30.37
Admin/Support/Clerical/OH		15.53	15.07	14.35	15.27	17.07
Professors		0.34	0.35	0.35	0.41	0.41
Postdocs		1.83	3.00	2.00	3.00	4.00
Graduate Students		28.15	27.03	25.03	28.03	29.28
Industrial Subcontractors		1.90	1.70	1.00	1.50	2.10
Total		129.40	125.74	109.94	126.28	145.43
	FY07 Actual	FY08	FY09A	FY10D	FY10A	FY10B
			Request	Reduced	Guidance	Full
Facility Run Schedule						
Research Run Weeks	14.7	15	10	8	13	24
Users (Annual)						
Host	40	41	39	35	39	45
Non-host (US)	67	67	65	58	66	80
Non-host (foreign)	48	50	45	40	48	60
Graduate students	30	30	29	27	29	33
Undergraduate students	5	5	4	3	5	10
Total Users	190	193	182	163	187	228
Operations Staff (Annual)						
Host	68	70	67	61	66	76
Non-host	4	4	4	3	4	5
Total	72	74	71	64	70	81

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

FY08: 15 weeks total research operations (1 week = 4 days, 8 hrs/day)

Areas of Research Emphasis

- Inductive H-mode scenarios (ITER baseline)
    - ITER-related startup and rampup studies
    - ELM mitigation/control using A-coils
    - Low density/collisionality H-modes
    - ITER-related rampdown studies
    - High performance H-modes at I_p>1.2 MA
- Hybrid and steady state operation (ITER-AT)
    - Investigations of hybrid scenarios with LHCD
    - Optimizing non-inductive current drive in improved L-mode scenarios
    - Extended pulse length operation at moderate density with increased ICRF and LHCD
    - Internal Transport Barrier plasmas: modulation and interaction with LHCD
    - Diverted AT target plasmas with ICRF, LHCD and current ramps
    - Mode conversion heating in the current ramp phase for AT target plasmas
- Core transport studies
    - Intrinsic rotation profile evolution
    - Momentum transport
    - Particle transport in low collisionality H-modes
    - Radial electric field studies
    - Influence of sawteeth on rotation profiles
    - Fluctuations and evolution of ITB discharges
    - L to H threshold, including ohmic only heating
    - Relationship of T_i profile and ITB formation
    - 2-d impurity transport
- Pedestal studies
    - Magnetic shear and relationship to pedestal width
    - Pedestal optimization with combination of topology variation and pumping
    - ELM dependence on shape and collisionality
    - Small ELM regimes
- Plasma Boundary Physics and Technology
    - Improve understanding of tritium retention in metal walls and the processes that determine it
    - Edge flows (topology, current, field, density, puff/pump)
    - Poloidal & toroidal structure of SOL filaments
    - Dust studies
- Wave-Plasma Interactions
    - Ion Cyclotron RF
        - ICRF induced sheaths and plasma-wall interactions

    - Realtime matching with Fast-Ferrite technology
    - Sawtooth control with Mode Conversion Current Drive
    - Synergies between minority ICRF heating and Lower Hybrid coupling
    - Synergies between Mode Conversion Electron Heating and Lower Hybrid Current Drive
    - Mode conversion flow and current drive (ICRF)
  - Lower Hybrid RF
    - Increased LH power (>1 MW coupled)
    - Manipulating the q profile with LHCD
    - Low internal inductance startup with LHCD assist and implications for ITER
    - Rotation in LHCD plasmas
    - Current drive in H-mode regimes
- Macroscopic Stability
  - Maximum tolerable vertical excursions and implications for ITER control
  - Tests of Kalman filter algorithms for control system noise immunity
  - Disruption runaway physics, using LHCD to provide non-thermal seed electrons
  - Effects of externally applied n=1 resonant error fields on transport and rotation
  - Non-resonant n=2 fields to study magnetic braking
  - Fast electron-driven Alfvenic activity
  - Gas quantity/mix optimization for disruption control

Plain English Goals

- Confinement at high plasma current
- Active control of ICRF antenna

FY09D *10% below FY09A Guidance (*7 weeks research operations)

Plans

- Complete the inspection of the tokamak core
- Install and commission advanced Lower Hybrid Coupler
  - Lower loss system for better utilization of source power
    - LHCD efficiency
    - Edge pedestal stability and ELM studies
- Exploitation of Lower Hybrid system at powers exceeding 1 MW
  - Far off-axis current drive for AT regimes
  - Phase control – variation of radial deposition and driven current

Implications

- Personnel reductions: 2.5 scientists, 3.5 engineers, 1 technician; do not replace 2 graduate students
- Reduced research runtime

    - Even fewer of high priority runs can be completed (to less than ¼)
- Defer new 4-strap ICRF antenna
- Remove first Lower Hybrid launcher to preserve diagnostics and ICRF dipole antenna
    - No net increase in total LH coupled power (1.2 MW)
- Delay completion of polarimetry diagnostic to measure j(r)
    - At least 1 year delay
    - Adjunct to MSE; only current profile measurement for highest density plasmas; overlaps with MSE in optimal density range for LHCD
    - Geometry, density and field the same as on ITER
        - Valuable prototyping lost
- Defer data acquisition and computing infrastructure upgrades
    - Hardware becomes obsolete on time scale of about 3 years

FY09A Guidance Budgets: 10 weeks research operations

Prioritized increments:

- Add 3 weeks research operation (to 10 total), and restore some of the personnel cuts (still reduced from FY08 by 1 scientist, 1.5 engineers)
    - Increased productivity across all topical areas
        - Particularly important to take advantage of new tools (LH, cryopump, diagnostics) developed in FY07
    - Student training maintained
- New 4-strap ICRF antenna on schedule
    - Preserve first LH launcher, install new LH launcher, maintain diagnostics
        - Increase in net LH power (to 2 MW)
        - compound spectrum for increased flexibility of deposition (and thus current profile control)
- Polarimetry development on schedule
    - Current profile measurements are critical to understanding of LH experiments
    - Enhanced understanding of all regimes, particularly for high density conventional H-mode (ITER baseline)
- Data acquisition upgrade pace maintained
    - Improving reliability and productivity

Areas of Research Emphasis

- Inductive H-mode scenarios (ITER baseline)
    - Approach to nominal ITER H-mode operating point (shape, β, l_i, n_e, …)
    - ELM pacing studies
    - Influence of pedestal parameters and relaxation mechanisms on core performance
- Hybrid and steady state operation (ITER-AT)
    - Hybrid scenario feasibility with LHCD
    - ITBs with LHCD only
    - AT Integrated scenario modeling (TSC+LSC+TRANSP)
- Core transport studies

    - Role of electron heating and LHCD on self-generated flows
    - Impurity particle transport
    - Gyro-kinetic modeling of fluctuations and fluxes in ITB regimes
- Pedestal studies
    - Shaping and pedestal regulation
    - Non-dimensional mapping of the edge L-H transition
    - Low density limit physics
- Plasma Boundary Physics and Technology
    - Connections between critical gradients in near SOL and plasma flows
    - Relationship between SOL $\Gamma_{\perp}$ and pressure/collisionality
    - Statistical database and modeling of SOL blobs
    - Dust dynamics
    - Lyman-a opacity, comparisons with B2-Eirene modeling
    - Deuterium retention
- Wave-Plasma Interactions
    - Ion Cyclotron RF
        - Commission and test advanced 4-strap antenna
        - ICRF sheath physics
        - Compare measured antenna characteristics with TOPICA modeling
    - Lower Hybrid RF
        - Current profile control with Lower Hybrid
            - Maximize power through two launchers
            - Utilize compound phasing
        - Modeling of hard x-ray profiles during LHCD using CQL3D with synthetic diagnostic
        - Effects of plasma parameters and local gas puffing on LH coupling
    - ICRF-LH interactions: compatibility, coupling
- Macroscopic Stability
    - Disruption mitigation
        - real-time detection and mitigation
        - NIMROD/KPRAD modeling
    - Magnetic rotation braking, comparisons with NTV theory
    - Safe scenario control development for axisymmetric stability of ITER-like equilibria
    - Alfven Eigenmode stability (joint expts with JET, MAST, JT60-U)

Plain English Goals

- Self-generated plasma rotation
- Hybrid Advanced Scenario investigation

FY09B Incremental budget: 14 weeks research operation

Prioritized increments:

- 4 weeks additional research operation, to 14 weeks
- upgrade DNB power supplies for more flexible and reliable operation

    - Upgrade will allow better time resolution and synchronization for MSE and CXRS diagnostics
- Add 3 klystrons, required as spares to accommodate increased operations both in FY09 and FY10
- ICRF power supply upgrades implemented 2 years earlier
    - Should yield improved reliability and significant increase in tube lifetime
- Faster change-over of divertor tiles from molybdenum to tungsten
- Install helium recovery system
    - Reduced costs and improved availability of liquid helium for DNB and divertor cryopump operations

Research Highlights

- Substantial increased progress across all topical science areas and integrated thrusts, with particular emphasis on high priority ITER R&D and ITPA joint research, both in FY09 and subsequent years

FY10D: 10% Decrement from FY10A (8 weeks research operation)

Plans

- Continue highest priority studies, but at significantly reduced pace

Implications:

- Personnel reductions: 3 scientists, 3.5 engineers, 1 technician; do not replace 3 graduate students
- Reduced runtime (5 weeks)
    - Even fewer of priority runs can be completed (to less than ¼)
- Defer 2nd advanced LH launcher
- Delay installation of DEMO-like high temperature divertor (at least 1 year)
- Defer installation of second advanced 4-strap ICRF antenna
    - At least 1 additional year of reduced ICRF power (only 6 out of 8 MW source available for plasma experiments)
- Delay/defer implementation of key diagnostic upgrades (Polarimetry, In-situ surface analysis system, fast ion loss diagnostic, GPI edge fluctuation upgrades)

FY10A Guidance Budgets: 13 weeks research operation

Prioritized increments:

- Add 5 weeks research operation and restore some of the personnel cuts
- 2nd advanced LH launcher on-schedule (install FY11)
- DEMO-like high temperature tungsten divertor on-schedule (install FY11)
- Complete and install 2nd advanced 4-strap ICRF antenna, returning to full system capability (8 MW source, at least 6 MW coupled)
- Key diagnostics on-shedule

Areas of Research Emphasis

- Inductive H-mode scenarios (ITER baseline)
  - Simulated burn control experiments
  - Operate at ITER-scaled physics parameters q_{95}, β, collisionality, shaping and geometry
  - Develop control algorithms which mimic the ITER configuration
- Hybrid and steady state operation (ITER-AT)
  - Combine LHCD with high power ICRF, compare with predictions of CQL3D and TORIC
  - Study effects of shear modification by LHCD on core barriers formed with off-axis ICRF
  - Assess pedestal and ELM properties in advanced scenarios, and contribute to international studies
- Core transport studies
  - Test RF flow drive scenarios
  - Compare ion, particle and momentum transport
  - Investigate portion of k-space responsible for electron energy transport in low density regimes
- Pedestal studies
  - Neutral fueling/ionization influence
  - Modeling of EDA H-mode quasi-coherent modes
  - Slow L-H transitions
  - Simulations of pedestal structure
- Plasma Boundary Physics and Technology
  - Deuterium retention in first wall tiles
  - Quantify poloidal field fluctuations in near SOL, validation tests of electromagnetic turbulence codes
  - Assess role of neutral recycling on the inner divertor
  - In-situ analysis of tile surface erosion, including limiters
  - Sheath rectification and erosion enhancement
  - Comparisons of molybdenum and tungsten in high heat-flux regions of the divertor
- Wave-Plasma Interactions
  - Ion Cyclotron RF
    - Characterize RF sheaths with RF power, phasing and single pass absorption
    - Investigate mode-conversion regimes with PCI, compare with TORIC simulations
    - Evaluate low field side mode conversion flow drive
  - Lower Hybrid RF
    - Measure 4.6 GHz wave fields in plasma; correlate with parametric decay instabilities
- Macroscopic Stability
  - Disruption mitigation
    - Runaway electron growth, losses and mitigation
  - NIMROD/KPRAD modeling

Plain English Goals

- Testing a model of the fuel retention process in first-wall tiles
- Runaway electron dynamics during disruptions
- Characterize accessibility conditions for small edge-localized modes

Physical Infrastructure Needs

- Following the completion of the FY08 run campaign, the C-Mod alternator will undergo a periodic inspection.

Prizes and Awards

- James L. Terry was awarded APS Fellowship in 2007. His citation reads: *For significant contributions in the areas of volume recombination in plasmas, plasma impurity transport, wall-conditioning with lithium, plasma transport, and plasma turbulence in magnetic fusion confinement devices.*

- Miklos Porkolab was awarded the Hungarian Nuclear Society "Simonyi Karoly Prize for Outstanding Contributions to Plasma Physics and Fusion Research" in Nov. 2007.

FY10B Incremental budget: 24 weeks research operation (assuming guidance budget in FY09)

Prioritized increments:

- 5 weeks additional research operation, to 18 weeks
- Upgrade to fast vertical control power systems for improved stability at high elongation
- Upgrade to correction coil power supplies for increased capabilities to study effects of applied non-axisymmetric fields
- 3 weeks additional research operation, to 21 weeks
- additional LH klystron and ICRF FPA to accommodate increased operations (finite tube lifetime)
- LH transmitter protection upgrade for improved operational flexibility
- CO_2 scattering diagnostic, for core fluctuation studies, including LH waves
- 3 weeks additional research operation, to 24 weeks

Research Highlights (see 5 year proposal, dated March 2008, for details)

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