Alcator C-Mod
Highlights, Plans, Budget and Schedule
FY2006-FY2008

OFES Budget Planning Meeting
March 14, 2006

E. S. Marmar
for the Alcator Group
*Equilibrated electrons-ions, no core momentum/particle sources, RF $I_p$ drive*
Research Highlights 2005
All-Metal Plasma Facing Components

- Replaced all low-Z protection tiles (antennas)
- Removed boron build-up
- Extensive operation before first boronization
- Main results
  - Low z coating is required for high performance with high power ICRF
    - Mo radiation is main issue
  - Coatings last ~30 discharges (or 50 MJ RF input energy)
    - RF much more “efficient” than ohmic at removing boron
  - Localized areas appear to be critical

B. Lipschultz, et al., APS-DPP 2005 Invited, and PoP in press
Disruption Mitigation demonstrated with Massive Noble Gas Injection

- Higher pressure plasmas than previous experiments on other devices (~10x) (comparable to ITER)
- Halo current reduced ~50%
- More energy converted to (relatively) benign radiation
  - Close to 100% for higher Z gases
- Measurements show impurities do not penetrate to the core as neutrals
  - NIMROD modeling shows critical role of MHD

R. Granetz, et al., APS-DPP 2005 Invited
ELM regimes dependent on $\beta$, shape and collisionality

- Four regimes studied
  - ELM-free
  - EDA (quasi-coherent mode regulation)
  - EDA $\rightarrow$ ELMy
    - Small ELMs at higher $\beta_N$
  - Discrete ELMs
    - Lowest $\nu^*$, high $\delta$
    - High time resolution measurements show ballistic dynamics

J. Terry, et al., APS-DPP 2005
Error Field/Locked Mode Studies
Constraining Extrapolation to ITER

• Extended studies over wide B range on C-Mod (spanning ITER B)
  – Fixed \( n/n_G \) and q (ITER values)

• Dimensionless constraints imply favorable scaling to ITER
  \[ \propto R^{(.68 \pm .2)} \]

• Joint (ITPA) C-Mod-JET experiments
  – Fixed \( \rho^*, v^*, q, \beta \)
  – gives \( \alpha_B = -2.5 \pm 0.5 \)
    • Implies \( R^{-(1.38 \pm .25)} \)
Near-SOL $\nabla P$ Self-Organizes toward Critical $\nabla \beta_{\text{pol}} (\alpha_{\text{MHD}})$

- Evidence that Electromagnetic Fluid Drift Turbulence controls the edge\(^\dagger\)
  - Attainable $\alpha_{\text{MHD}}$ depends on collisionality
- New in 2005:
  - Depends on topology (LSN vs. USN)
  - $\nabla P$ near sep. $\propto I_P^2$
    - Higher $\alpha$ for LSN
- Suggests connection with edge flows and rotation
  - Contact with result of lower H-mode threshold for LSN

\[^{\dagger}\text{B. LaBombard, et al., Nuclear Fusion 45(2005)1658.}\]
C-Mod plays a major role in education of the next generation of fusion scientists

- Typically have ~25-30 graduate students doing full-time Ph.D. research on C-Mod
  - Nuclear Science & Engineering, Physics and EECS (MIT)
  - Collaborators also have students utilizing the facility (U. Tx, U.C. Davis, U. Wisc., Politecnico di Torino)
  - Current total is 29
- MIT undergraduates participate through UROP program
- Host National Undergraduate Fusion Fellows during the summer
## Budget Profiles (k$)

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<td>22,829 (15)</td>
<td>22,829 (13)</td>
<td>29,500 (25)</td>
<td>20,560 (8)</td>
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</table>

*Reduction in Force: 1.5 Scientists, 2 Students, 2 Engineers, 1 Technician*
Incremental Funds (~10%) Would Significantly Improve Progress

- Facility Operation: 6 additional run weeks
  - Only ~1/3 of priority runs can be accommodated in 14 weeks (FY06)
- Significantly earlier implementation of key upgrades
  - Tungsten tile outer divertor
    - ITER material and tile configuration
  - 4th MW Lower Hybrid Source Power
- Increased reliability, increased utilization
  - Real-time matching – final 3 ICRF transmitters
  - Spare LH Klystron
Collaborations are Significant in all Aspects of the Program

### Domestic Institutions

- Princeton Plasma Physics Lab
- U. Texas FRC
- U. Alaska
- UC-Davis
- UC-Los Angeles
- UC-San Diego
- CompX
- Dartmouth U.
- GA
- LLNL
- Lodestar
- LANL
- U. Maryland
- MIT-PSFC Theory
- ORNL
- SNLA
- U. Texas IFS
- U. Wisconsin

### International Institutions

- Budker Institute, Novosibirsk
- C.E.A. Cadarache
- C.R.P.P. Lausanne
- Culham Lab
- ENEA/Frascati
- IGI Padua
- IPP Garching
- IPP Greifswald
- JET/EFDA
- JT60-U, JFT2-M/JAEA
- KFA Jülich
- KFKI-RMI Budapest
- LHD/NIFS
- Politecnico di Torino
- Risø National Laboratory
- U. Toronto
C-Mod Fusion Science and Technology Priorities

Understand matter in the high temperature state
Develop the science and technology to enable fusion energy

- Plasma Boundary
  - Turbulence and EDGE/SOL transport
  - Edge flows and coupling to core rotation
  - Hydrogenic isotope retention and recycling
  - High-Z PFC operational experience, including tungsten tile development

- Transport
  - Self-generated flows and momentum transport
  - Role of magnetic shear (enabled by LHCD)
  - Role of collisionality (enabled by cryopump)
  - Fluctuations and Electron transport
  - Particle and Impurity transport

Inter-machine comparisons of spontaneous toroidal rotation beginning to bear fruit
• Macroscopic Stability
  – Disruption mitigation (massive gas puff); Disruption database (ITPA)
  – Locked modes (joint experiments)
  – Alfven modes, cascades
  – Sawtooth Stabilization

• Waves
  – Lower Hybrid
    • Coupling/Phase studies
    • Current drive, heating
  – Ion Cyclotron
    • Mode conversion current drive
    • Antenna-Plasma interactions
      – RF coupling
    • Minority $^3$He heating

Higher Z gases better at reducing halo currents during mitigated disruptions
C-Mod well positioned to help solve challenges for ITER

Create a star on earth

- **Unique regimes**
  - ITER B field, density, power density, plasma pressure
    - Disruption mitigation
    - Neutral opacity, Radiation Transport
  - High leverage database contributions
    - Dimensionally unique
    - Non-dimensional match to larger, lower field tokamaks
- **ITER heating and current drive tools**
  - Lower Hybrid Off-Axis CD
  - ICRF minority heating, MCCD
  - Torque and particle source free
    - Transport-driven rotation
- **All-metal high-Z Plasma Facing Components**
  - Molybdenum → Tungsten
    - Tritium retention, Impurity dynamics, Detachment
  - Low-Z wall coatings

\[
\begin{align*}
B_T &= 5.3T, \quad I_p = 1.6MA \\
B &\leq 8.1T, \quad I \leq 2.0\ MA \\
\beta_N &\leq 1.8, \quad Z_{eff} \sim 1.5 \\
0.1 \times 10^{20} &< n_e < 10 \times 10^{20} \\
P_{\parallel}(SOL) &\leq 0.5\ GW/m^2 \\
\beta_N &= 1.75, \quad Z_{eff} < 1.6 \\
n_e &= 1 \times 10^{20}\ m^{-3} \\
P_{\parallel}(SOL) &\approx 1\ GW/m^2
\end{align*}
\]
Research strongly motivated by, aligned with, high priority ITPA/ITER research tasks

- **Boundary Science**
  - SOL plasma interaction with main chamber
  - H isotope (tritium) retention, removal
  - Inter-ELM transport, \( \perp \) SOL transport
  - Dimensionless cross machine comparisons for SOL physics
- **Pedestal**
  - Small ELM regimes
  - Structure: transport and atomic physics
  - Contributions to pedestal database
- **Transport physics**
  - Reactor relevant conditions (electron heating, equilibrated e-i, low momentum input)
  - Commonality of transport physics in hybrid, s.s. scenarios with reactor relevant conditions
  - Comparisons of turbulence measurements with simulations
- **Macrostability**
  - Disruption mitigation and disruption database
  - Intermediate-n Alfven Eigenmodes (active antennas)
  - NTM stabilization, Sawtooth stabilization
- **Confinement database and modeling**
  - Effects of \( \nu^* \) vs \( n/n_G \), \( \beta \) scaling, \( \rho^* \) scaling, analysis of ITER reference scenarios
  - Density peaking
- **Steady State Operation**
  - Real-time control of advanced scenarios
- **Diagnostics**
  - Dust measurement, erosion
Strong Participation in Joint Experiments
Coordinated through ITPA

- CDB-4 Confinement scaling in ELMy H-Modes: $\nu^*$ scaling at fixed $n/n_G$
- CDB-8 $\rho^*$ scaling along ITER relevant path
- CDB-9 Density profiles at low collisionality
- TP-4.1 Similarity experiments with off-axis ICRF and density peaking
- TP-6.1 Scaling of spontaneous rotation with no external momentum input
- TP-8.2 Investigation of rational q effects on ITB formation and expansion
- PEP-7 Pedestal width analysis by dimensionless edge identity experiments
- PEP-10 Radial efflux at the mid-plane and ELM structure
- PEP-16 C-Mod/NSTX/MAST small ELM regime comparison
- PEP-17 Small ELM regimes at low pedestal collisionality
- DSOL-3 Scaling of radial SOL transport
- DSOL-4 Comparison of disruption energy balance and heat flux profile
- DSOL-5 Role of Lyman absorption in the divertor
- DSOL-11 Disruption mitigation experiments
- DSOL-13 Deuterium codeposition in gaps of plasma facing components
- DSOL-15 Inter-machine comparison of blob characteristics
- MDC-1 Disruption mitigation by massive gas jet
- MDC-5 Comparison of sawtooth control methods for NTM suppression
- MDC-6 Low $\beta$ error field experiments
- MDC-10 Damping rates of intermediate n Alfven Eigenmodes
- SSO-2.3 $\rho^*$ dependence on confinement, transport and stability in hybrid scenarios
1. RWM Control

2. Disruption Mitigation
   • Dennis Whyte (Participant Team Leader), Bob Granetz (co-PI)

3. Fast Particle Confinement
   • Joe Snipes (C-Mod data and NOVA-K simulations)

4. Effects of Radiation Transfer on Divertor Plasma
   • Bruce Lipschultz (P.T. Leader), Steve Lisgo (co-PI), Jim Terry (C-Mod data)

5. ICRF Heating and Current Drive – Benchmarking of ICRF Codes
   • Paul Bonoli (co-PI), Steve Wukitch (C-Mod data)
• Integrated Scenarios
  – Lower Hybrid Current Drive for Advanced Tokamak scenarios
    • Hybrid scenarios
    • Quasi-steady-state, fully non-inductive
  – Compatibility of high-Z Plasma Facing Components
  – H-Mode pedestal physics
  – Small ELM regimes
  – H-Mode threshold physics
C-Mod Contributions to Priority ITER Science

• Boundary
  – Erosion, Deposition
  – Tritium retention and removal
  – Radiation transfer in the divertor and effects on detachment
  – Divertor viscosity, atomic and molecular collisions (high neutral density)
  – Cross-field SOL transport, filamentary turbulence
• Macrostability
  – Disruption mitigation (including MHD and radiation physics)
  – Error field/locked mode physics
  – Intermediate toroidal mode number Alfven Eigenmodes
• Transport
  – Torque-free rotation, momentum transport
  – Density peaking, particle transport, impurity transport
• Wave-Plasma
  – Fast wave minority heating (including low single-pass absorption regimes)
  – Mode-conversion heating and current drive
  – ICRF code benchmarking
  – ICRF coupling (experiment and modeling)
  – Lower Hybrid: propagation, absorption and far off-axis current drive
  – Sawtooth stabilization
C-Mod Contributions to Priority ITER Technology

- Disruption mitigation (massive gas)
- Tungsten Plasma Facing Components
- Real-time ICRF matching
- Data system tools
- Remote participation tools
- Wall conditioning/coating (including during-shot)
- Dust detection

- ITER style laminar plate tungsten tiles being tested for power handling (Sandia and Jülich)
- Installation and testing in C-Mod (FY06-07)
AT Operation likely needed for Successful ITER Quasi-Steady-State

• C-Mod has entered key new phase of AT program: demonstrate RF tools for current profile control
  – LHCD system commissioned
  – Current drive experiments beginning
    • About 0.5 MW coupled to plasma in first week of FY06 LH operations
• Good progress in understanding and optimizing core transport barriers with localized ICRF
  – Higher power, central n and T
  – As j(r) control becomes available, explore influence of shear on transport and barriers
• Move toward integration of tools to produce high bootstrap fraction, non-inductive, long-pulse
  – Modeling, incorporating latest wave-plasma and transport understanding is key
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C-Mod Well Aligned with US Fusion Science Priorities

FESAC Priorities Panel 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?
C-Mod **Contributes Strongly** to 5 of 6 Identified Areas of “Opportunities for Enhanced Progress”

- Top 6 priorities for incremental resources:
  - Support ITER construction and operation, including diagnostic R&D.
  - Predict the formation, structure, and transient evolution of the H-mode edge pedestal with high confidence.
  - Support the TTF initiative with emphasis on extended understanding of electron-scale transport.
  - Develop an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas.
  - Understand electron transport and laser-plasma interactions for Fast-Ignition high-energy density plasmas.
  - Extend understanding and capability to control and manipulate plasmas with external waves.
### Alcator C-Mod
#### Overview Schedule (March 2006)

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
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<tr>
<td>Operations (■)</td>
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<td>4</td>
<td>10</td>
<td>15</td>
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<tr>
<td>ITER Baseline Scenarios</td>
<td>All Metal PFCs Sawtooth stab 6MW, $H_{99} \geq 2$, $Z_{\text{eff}} \leq 1.5$ $I_p \geq 1.6$MA/High Perf. Disruption Mitigation Power/Part/ELM Handling Tungsten PFC</td>
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<tr>
<td>Advanced Scenarios</td>
<td>ITB Studies MCCD LHCD 50% non-inductive 3 sec Density control, power, long pulse j-control Active density control</td>
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<tr>
<td>Plasma Boundary</td>
<td>Impurity Sources &amp; Transp. Active Boronization Pumping/Particle Control Rotation/Topology/H-mode Power Handling Tungsten PFC</td>
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<td>Waves</td>
<td>LH Propagation LHCD LH/ICRF synergy Compound Spectrum Mode Conversion Screenless Ant. Load-Tol Ant. (1) $\omega &lt; \omega_c$</td>
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<td>Macro-Stability</td>
<td>Locked-Modes Disruption Mitigation NTM Adaptive disruption mitigation Active MHD: Global modes; real-time control; feedback control</td>
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## Research Goals (FY06-FY08)

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<th>Goal</th>
<th>Year</th>
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<td>Disruption mitigation of high pressure plasma</td>
<td>FY 2006</td>
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<tr>
<td>Sustaining plasma current without a transformer (50% non-inductive)</td>
<td>FY 2007</td>
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<td>Current profile control with microwaves</td>
<td>FY 2007</td>
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<tr>
<td>Active density control</td>
<td>FY 2007</td>
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<td>Confinement at high plasma current</td>
<td>FY 2008</td>
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<tr>
<td>Active control of ICRF antenna</td>
<td>FY 2008</td>
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Targets and Milestones

• Disruption mitigation of high absolute pressure plasma (FY06)
  – Successful experiments and modeling well underway

• Non-inductive sustainment of plasma current (FY07)
  – Intermediate goal: 50% non-inductive

• Current profile control with microwaves (FY06-07)
  – Far off-axis current drive
• Active Density Control (FY07)
  – Install divertor cryopump (summer 2006)
  – Low density H-modes for AT regimes with efficient LH current-drive
• Confinement at high plasma current (FY06-08)
  – $I_p \geq 1.5$ MA
• Active control of ICRF antenna (FY07-08)
  – Maintain coupling across L/H transitions and ELMs
Incremental Funds for C-Mod in FY07-08 would Enable Significantly Extended Scientific Progress*

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<th>Transport Science</th>
<th>Momentum transport in torque-free discharges</th>
<th>Electron thermal transport</th>
<th>Compare near marginal stability fluctuations with non-linear GK models</th>
<th>Role of equilibrium and fluctuating flows in L/H threshold</th>
<th>Nature of momentum coupling at edge</th>
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<td>SOL turbulence and transport</td>
<td>ITER prototype tungsten divertor module studies</td>
<td>High-Z first wall studies</td>
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<td>Wave-Plasma</td>
<td>Lower Hybrid j-profile control</td>
<td>Real-time ICRF matching</td>
<td>ICRF/LHCD synergies</td>
<td>LHCD with compound spectrum (2 launchers)</td>
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<td>Macro-Stability</td>
<td>Adaptive disruption mitigation</td>
<td>NTM Threshold at increased $\beta$</td>
<td>Fast-particle-driven collective modes in low/reversed shear</td>
<td>Test feedback stabilization of NTMs</td>
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<td>Conventional H-Modes</td>
<td>H-mode pedestal scaling</td>
<td>Confinement at high $I_p$</td>
<td>Exploit sustained high reactivity scenarios</td>
<td>Characterize and exploit small ELM regimes</td>
<td>High power handling of tungsten divertor</td>
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<td>Advanced Scenarios</td>
<td>Active density control</td>
<td>50% non-inductive scenarios</td>
<td>Optimize hybrid scenarios with equilibrated electrons/ions</td>
<td>Generation and control of ITBs via manipulation of $B$ shear</td>
<td>Fully non-inductive, quasi-steady-state</td>
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*Progress expected in most topics (red indicates incremental funds required for hardware upgrades and/or increased run time)
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<td><strong>Facility Run Schedule</strong></td>
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<td><strong>Scheduled Research Run Weeks</strong></td>
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<td>Undergraduate students</td>
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<td><strong>Total Users</strong></td>
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<td>164</td>
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<td><strong>Operations Staff (Annual)</strong></td>
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<td><strong>Total</strong></td>
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C-Mod is Major Contributor to Fusion Science and Preparations for ITER Burning Plasma

- Unique dimensional regimes
- ITER relevant heating and current drive tools, metal PFCs
- Increasingly strong collaborations
- Strong, broad contributions to high priority ITPA/ITER research
- Tight coupling to theory and modeling
- Exciting prospects in coming 3 years with new tools and diagnostics
  - LHCD; cryopump
  - Disruption mitigation
  - Turbulence measurements
  - CNPA, Hard X, long-pulse DNB
  - Polarimeter \([j(r)]\)
  - All digital plasma control system