Research Highlights and Plans

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www.psfc.mit.edu/research/alcator

Work Supported by USDoE Office of Fusion Energy Sciences
C-Mod Unique in **World** and **US** Among High Performance Divertor Tokamaks

**Unique in the World:**
- High field, high performance divertor tokamak
- Particle and momentum source-free heating and current drive
- Equilibrated electron-ion coupling
- Bulk all metal high-Z plasma facing components
- ITER level Scrape-Off-Layer/Divertor Power Density
- Approach ITER neutral opacity, radiation trapping
- Highest pressure and energy density plasmas (ITER level)

**Exclusive in the US:**
- Lower Hybrid Current Drive
- ICRF minority heating
- Premier major US facility for graduate student training
C-Mod physics regime, machine capabilities and control tools are uniquely ITER-relevant

- **Edge and Divertor**: All metal walls. High divertor heat fluxes $\sim 0.5 \text{ GW/m}^2$. High SOL neutral opacity (*similar fuelling to ITER*). High Lyman opacity, radiation trapping (*closest to ITER*).

- **Core Transport**: Equilibrated ions and electrons. No core fuelling or momentum sources (*will be very low on ITER*).

- **Macro-stability**: Can access ITER $\beta$ range, as well as same $B_T$ and absolute pressures (*important for disruption mitigation*).

- **Wave Physics**: Similar tools (ICRF and LHCD) to ITER. Same $B$, $n \Rightarrow$ same
  $\omega_p$, $\omega_c$, similar $\omega$ (*key for waves, LH feasibility*).

- **Pulse length**: $\tau_{\text{pulse}} \gg \tau_{\text{CR}}$ (*exceeds ITER*). Adding non-inductive CD capability (*important for Steady State scenarios*).

Combination of these features is unique and enables integrated studies of many key questions.
C-Mod Plays Major Role in Education of Next Generation of Fusion Scientists

- Typically have ~25-30 graduate students doing their Ph.D. research on C-Mod (more students than scientists)
  - Nuclear Science & Engineering, Physics and EECS (MIT)
  - Collaborators also have students utilizing the facility (U. Texas, U.C. Davis, U. Wisc., ASIPP, China)
  - Current total is 31 (27 full-time on-site)
  - Fully involved in all aspects of our research, leading many of the experiments as session leaders

- MIT undergraduates participate through UROP program
- Host National Undergraduate Fusion Fellows during the summer
Lower Hybrid Current Drive: ~0.8 MA Driven with Phased Array Grill: Key Tool for AT Physics

• System commissioning went very well
  – Up to 2 MW source applied so far from 12 klystrons
    • No signs of power limits or significant arcing on couplers
• Close to 100% of current driven non-inductively in 1 MA plasma
  – Loop voltage 0 or reversed for more than 1 current relaxation time
  – Modeling indicates about .8 MA off-axis current drive from LH
Current Density Profile Control with Lower Hybrid Waves (LHCD)

MSE Diagnostic Measures
Changes in \( j(r) \)

Modelling in Very Good Agreement with Experiment

Porkolab_FPA_12/07/ORNL
Planned LHCD Upgrades (2009)

- Increased source power (from 3MW currently installed to 4 MW total)
- Advanced low-loss couplers/launchers
- More than doubling of net power to plasma (>2.5 MW)
- Improved j(r) diagnostics
  - Upgraded MSE (spatial channels)
  - Polarimeter array (ITER geometry)
- Goal: fully non-inductive, long pulse AT scenarios

![Diagram of LHCD system](image.png)

**TSC Time-Dependent Model**

\[
\begin{align*}
T_e(0) &= 6.1 \text{ keV} \\
T_i(0) &= 4.1 \text{ keV} \\
\langle n_e \rangle &= 1 \times 10^{20} \text{ m}^{-3} \\
P_{\text{LH}} &= 3 \text{ MW} \\
\langle n_\parallel \rangle &= 2.3 \\
I_{\text{Tot}} &= 0.6 \text{ MA}
\end{align*}
\]
Density Peaking at Low Collisionality: Good News for ITER

C-Mod Data Help Break Covariance Between $v$ and $n/n_G$ Makes Extrapolation to ITER More Certain

![Graphs showing the relationship between $n_e(0.2)/\langle n_e \rangle$ and $v_{\text{EFF}}$ and $n/n_G$.]
Tritium Retention is Major Challenge for ITER
Hydrogenic Retention in Refractory Metals (Mo, W) Surprisingly High

Closing pump valves during and after shot: accurate accounting for total particle inventory

Sequence of disruption-free shots shows continual, constant uptake of D by the walls

![Graph showing D retention per shot and D retained/incident percentage over discharge sequence.]
ICRF Sheaths Cause Impurity Sputtering: Depend on Wall Conditions and Plasma Transport

$V_{\text{sheath}}$ Smaller after Boronization

$V_{\text{sheath}}$ Larger for H-Mode than for L-Mode

For 2009: Designing new antenna to minimize radial RF fields, minimize sheath potential
NIMROD Modeling of Massive Gas Disruption Mitigation: Excellent Agreement with Experiment

- Flux surfaces promptly destroyed by MHD
  - Rapid core cooling without the need for deep impurity particle penetration
- Good news for ITER
  - Next challenge:
    - runaway electrons (use LHCD to investigate)

Simulation includes impurity radiation; 
$S_{\text{exp}}/S_{\text{sim}} = 400$
Facility Plans and Major Enhancements

(Blue colored items require additional funds not in base program)

- Inspections (2008-09) – insure facility reliability for at least the next 5 years
- Lower Hybrid upgrades
  - Add 1 MW source (to 4 MW); refurbish first launcher (reduced losses, simplified splitting/phase control, increased voltage/power handling); add second launcher/coupler (2009); spare klystrons (2008-2010)
  - Gas puff system at each coupler (improved plasma matching)
  - Add 5’th MW (if required, 2013)
- ICRF upgrades
  - New 4-strap antenna (consolidate 2 antennas into 1 port, 2009)
  - Fast-Ferrite Tuners for all 4 transmitters (real time adaptive tuning, 2009-10)
  - Power supply/control upgrades (improved reliability, 2011)
  - Convert transmitters 1 and 2 from fixed frequency to tunable (2012)
- Outer divertor upgrade (2012)
  - Continuous vertical plate (higher power/energy handling)
  - Tungsten in highest-heat-flux regions
Major Diagnostic Enhancements/Upgrades
Planned 2009-2013

(Blue colored items require additional funds not in base program)

- Polarimetry \([j(r), n_e(r), \text{magnetic fluctuations}]\) (2009)
- DNB aperture [improved spatial resolution for beam-based diagnostics] (2010)
- MSE upgrade (PPPL) [more radial channels] (2010)
- Doppler reflectometry (U. N.M.) [fluctuations, flows] (2010)
- Heterodyne ECE upgrade (U. Texas) [improved views] (2012)
- SOL Thomson scattering (2010)
- Compact Neutral Particle Analyzer [multiple chords] (2009)
- \(\text{CO}_2\) scattering [fluctuations, waves] (2010)
- ICRF antenna reflectometer (2009)
- In-situ accelerator [first wall analysis] (2010)
- SPRED survey spectrometer (2009)
- Fast-ion loss detector (ASDEX) (2010)
- IR camera upgrade [divertor heat loading] (2009)
- Gas puff imaging upgrades (PPPL) [edge fluctuations] (2010)
C-Mod is Well Positioned to Continue Major Progress for Fusion Science and Fusion Energy

- Flexible, Capable, Cost Effective Facility
- Excellent Tools and Diagnostics
- Key Upgrades to Facility and Diagnostics
- Unique and Complementary Contributions to Joint (National and International) Experiments
- Model Validation across Broad Range of Dimensional and Dimensionless parameters
- Key Contributions to solution of challenges for ITER and Beyond
Collaborators are key participants 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.
- General Atomics
- 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-RMKI Budapest
- LHD/NIFS
- Politecnico di Torino
- Risø National Laboratory
- U. Toronto

### Coordination: USBPO, TTF, ITPA
**Levitated Dipole Experiment**

**Research Staff:** 1 scientists (Dr. Garnier), 1 engineer, 2 graduate students, PI's (Kesner & Mauel), + 2-3 undergrad students

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### FY07/08 Campaign

- Perform initial experiments in levitated plasma heated with ECRH; Floating coil: 0.7(1.2) MA, 1200 lbs
- Damaged upper support HT, L-Coil: Replaced with Cu levitation coil
- Investigate stability of ECRH plasma confined by levitated dipole

### FY09 Campaign

- Expanded diagnostics for detailed physics studies and increased run time
- Investigate the unique capability for high beta, high energy confinement, and adiabatic convective flows.
- Answer critical questions to evaluate the potential for advanced (non D-T) fuels.