Burning Plasma Support Research Program on Alcator C-Mod

Presented by:
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Alcator C-Mod Five Year Proposal Review
MIT Plasma Science & Fusion Center
Cambridge, MA
May 13, 2003
Mission Statement

The Burning Plasma Support Program on Alcator C-Mod emphasizes two complementary themes:

1. Development and validation of the **Physics Basis** underlying the key issues (transport, stability, heating, ...) in the relevant parameter ranges for a tokamak BPX (moderate beta, collisionality)

2. Development and demonstration of **Operational Scenarios and Techniques** for optimization of burning plasma experiments
The Mission of the Burning Plasma Experiment emphasizes the study of burning (self-heating) phenomena, “the next scientific frontier in the quest for magnetic fusion energy”.

In contrast to AT Regimes, the (baseline) BPX parameters are more conventional

- Modest (but substantial) $\beta$, $\beta_N$, $\beta_p$, $f_{\text{boot}}$
- Lower $q^* \sim 3$ and $q_0 \sim 1$, monotonic $q$ profile
- Somewhat higher collisionality $\nu^*$, $\nu/\omega^*$
- Typically higher edge density
- Pulse length comparable to current penetration, $t_p \sim 2\tau_{CR}$

Many features are uncommon in present experiments (except C-Mod)

- $T_e \approx T_i$, and strongly coupled $\tau^{e/i} << \tau_E$
- Inaccessible to positive NBI, may depend on RF Heating, current drive
- Small (or non-existent) external momentum or core particle sources
- High SOL power density
Burning Plasma Experiment Physics and Technology challenges

- MHD Instability
  - Operation at modest $\beta_N \sim 2$ reduces challenge in non-AT scenarios
  - Pedestal stability and edge relaxation a major issue
  - NTM may require active stabilization

- Power and Particle Control
  - High SOL power density, wall loading present materials challenge
  - Impurity control with metallic PFC’s (may be required due to tritium retention with C)
  - Fueling, ash removal, density profile control unproven

- RF Heating and Current Drive
  - Basic Physics well-known, but detailed modeling requires validation
  - Localized current drive needed for profile control, mode stabilization
  - Launcher technology/physics not routine
Burning Plasma Experiment Physics and Technology challenges (cont)

- **Core Transport**
  - Expect H-mode-like confinement
  - Rely on favorable $\rho_*$ scaling of ITG, etc.
  - Stiffness of Transport $\Rightarrow$ dependence on pedestal parameters
  - Strong electron-ion coupling, $\alpha$-heating may increase importance of electron transport
  - Rotation, momentum transport influence macro- and micro-stability

- **Disruptions**
  - Moderate $\beta_N$ at fusion pressures $\Rightarrow$ high $(B_T, I_p)$ $\Rightarrow$ high disruption loads
  - Disruption Heat Loads Challenge Divertor Materials
  - Early warning, mitigation and recovery techniques required

Major or Unique C-Mod capability or emphasis

Strong C-Mod contribution
C-Mod offers Unique Capabilities for Research in Support of Burning Plasma experiments

- High B (5-8 tesla) and $n_e$ (to $10^{21} m^{-3}$)
- High power density and SOL power ($\lesssim 1$ GW/m$^2$)
- Reactor-level absolute pressure ($P_0 \leq 1$ MPa)
- High-Z metallic first wall and PFC’s
- Long pulse length compared to $\tau_{CR}$
- RF heating and current drive
- $T_e \approx T_i$, $\tau_e/i \ll \tau_E$ typical
## The C-Mod Burning Plasma Support Program

complements work being done around the world

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>Other tokamaks</th>
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<tbody>
<tr>
<td><strong>Plasma Facing Components</strong></td>
<td>Molybdenum (W testing planned)</td>
<td>DIII-D, JT60U: Carbon</td>
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<tr>
<td></td>
<td></td>
<td>ASDEX-U: Carbon/W</td>
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<tr>
<td></td>
<td></td>
<td>JET: Carbon/Be</td>
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<tr>
<td><strong>Heating</strong></td>
<td>ICRF (minority ion)</td>
<td>All Mostly NBI, plus:</td>
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<td></td>
<td>LH (electron)</td>
<td>DIII-D: ECH, FW (el.)</td>
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<tr>
<td></td>
<td></td>
<td>ASDEX-U: ECH, ICRF</td>
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<tr>
<td></td>
<td></td>
<td>JT60U: LH, Neg. NBI, EC</td>
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<td></td>
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<td>JET: ICRF</td>
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<td><strong>Current Drive</strong></td>
<td>Lower Hybrid, MCCD, FWCD</td>
<td>ASDEX-U: ECCD, NBI</td>
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<td></td>
<td></td>
<td>DIII-D: ECCD, NBI, (FW)</td>
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<td></td>
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<td>JET: NBI, LH, FW</td>
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<td></td>
<td></td>
<td>JT60U: NBI, EC, LH</td>
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<td></td>
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<td>NSTX: HHFW, (EBW)</td>
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<tr>
<td><strong>Pedestal Physics</strong></td>
<td>EDA, small ELM regimes</td>
<td>JET, JT-60U: TYPE-I, II ELM</td>
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<td></td>
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<td>DIII-D, (ASDEX-U): QH/EHO regime</td>
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<td><strong>Shaping</strong></td>
<td>SN, Unbalanced DN</td>
<td>DIII-D: flexible, emphasizing hi-δ DN</td>
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<tr>
<td></td>
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<td>ASDEX-U: SN</td>
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<tr>
<td></td>
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<td>JT60U: SN, lo-δ</td>
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<td></td>
<td></td>
<td>NSTX: SN, low A</td>
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<tr>
<td><strong>Special Features</strong></td>
<td>High $B_T$ (=ITER), pressure, density $\tau^{e/i} \ll \tau_E$, $T_e \approx T_i$</td>
<td>JET: DT Physics</td>
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<td></td>
<td>Dissipative Divertor</td>
<td>DIII-D: AT Physics $\beta &gt; \beta_{no-wall}$, I-coils</td>
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<td>No-torque ITB</td>
<td>ASDEX-U: Hybrid Scenarios, ITER coil config.</td>
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<td>JT60U: High performance, High bootstrap</td>
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The C-Mod Program has made substantial contributions

- Contributions to International Confinement, Pedestal Databases
- H-mode threshold studies at high $B$, $n$
- Pioneering of high-Z (Molybdenum) first wall and divertor with $P_{\text{\| SOL}} \sim 0.5 \text{GW/m}^2$
- Pioneering of vertical plate divertor geometry; demonstration of dissipative/radiative divertor
- ICRF Heating/antenna technology at high power density and high $B$
- Identification of “EDA H-mode” and role of quasi-coherent mode
- Contributions to Disruption Database, halo current scaling, disruption mitigation techniques
C-Mod Burning Plasma Support Research
Emphasizes Unique Features and Capabilities

Principal Research Foci

- Pedestal physics
- Power/particle handling at high plasma and power densities
- Use of RF (ICRF, LH) for Heating, Current Drive, and Plasma Control

Additional BP Research Topics

- Rotation effects with low/no external torque
- Disruption Effects, Mitigation and Avoidance
- Density Limit Physics
- Fueling and density profile control

Integrated Scenarios Demonstrate Consistent Solutions in Relevant Parameter Regimes
C-Mod Can Match Non-Dimensional Parameters of Burning Plasma (except $\rho_*$)

- Demonstration Discharges on different tokamaks with the same shaping, $\beta$, $q_\psi$, collisionality, . . . , as proposed burning plasma can clarify scaling with remaining parameter $\rho_*$.

- Because $\rho_*$ is not matched, a single measure of collisionality is not adequate to characterize different physical processes
  - Some transport effects may be characterized by the neoclassical $\nu_{*}^{\text{neo}} = \epsilon^{-3/2} \nu_{ii} q R / v_{thi}$
  - Others, along with tearing mode effects, will depend on $\nu / \omega_*$, which is larger by a factor $\sim \rho_*$
  - Electron-ion equilibration depends on $\nu_{ei} / \tau_E$

- It is not in general possible to model all the relevant physical processes in the same demonstration discharge

- Profiles at different $\rho_*$ are not guaranteed to be self-similar, complicating the extrapolation to the Burning Plasma
C-Mod accesses relevant non-dimensional and dimensional parameters for ITER

Standard operation at $B_T = 5.3$ T, same as ITER-FEAT

Matches $\beta$ and absolute pressure

Gyrosizes:

$$4 \leq \left( \frac{\rho_*}{\rho_*^{ITER}} \right) \leq 6.5$$

$$n_e \leq 0.5 \, n_{Greenwald}$$
To focus the high-performance program, we have adopted **Integrated Performance Targets**

- $B_T = 5.3, 8 \ T$
- $I_p = 1.4, 2 \ MA$
- Confinement $H_{89} \geq 2$
- Heating Power $6 \ MW$
- $Z_{eff} \leq 1.5$
- $\langle P \rangle \approx 2.5, 4 \ atm$

Extrapolation of Present Performance

Assume $\tau_E = 2 \tau_{89}$

Development of these challenging targets requires simultaneous demonstration of confinement, heating, control, power handling, and impurity control techniques suitable for a burning plasma experiment.
**Integrated Scenario Development**

**Goal:** Develop and test High-Performance Scenarios

<table>
<thead>
<tr>
<th>Research Activity – Objective</th>
<th>Date</th>
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<tbody>
<tr>
<td>Operate at BPX-scaled physics parameters, $q_{\psi}$, $\beta$, collisionality, shaping, geometry (SN/DN/lim)</td>
<td>2004-05</td>
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<tr>
<td>Determine influence of pedestal parameters, edge relaxation phenomena on core performance</td>
<td>2004-05</td>
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<tr>
<td>Apply AT/ITB techniques for current and density control, optimized reactivity</td>
<td>2006-07</td>
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<tr>
<td>Demonstrate sustained high reactivity operational scenario(s)</td>
<td>2007-08</td>
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Prediction and Control of the Pedestal is potentially the highest leverage Issue for an H-mode Burning Plasma Experiment

This subject has perhaps the highest ratio of Importance to Understanding

- Height and Width of the Pedestal strongly influence core performance through Profile Stiffness
- Edge Relaxation phenomena can dominate power and particle exhaust, as well as impacting RF coupling
- No applicable first-principles Transport model available
- MHD Stability theory, including non-ideal, non-linear effects, also incomplete
- Both problems may require consideration of open field lines
- Role of neutrals, atomic physics still uncertain
Edge Pedestal Height and Width Determine Boundary Condition for Core Transport

- Continue dimensionless identity experiments (DIII-D, ASDEX, JET)
- Experiments to decouple atomic and plasma physics effects
- Detailed measurements and scaling of profile parameters
- Dependence on ion mass, temperature, plasma shape, current
- Comparisons with theory and modeling (MHD, turbulence, neutrals)

Excellent match across entire pedestal for dimensionless identity experiments
H-mode Pedestal Gradient Relaxation

- Find and Exploit regimes with good core confinement (large pedestals), moderate particle transport, no large ELMs
- Pedestal pressure gradient approximately consistent with ideal MHD stability
- Relaxation mechanisms vary (ELMS: I, II, III; EDA/QC; EHO, etc.)
- Need to understand what mechanisms are consistent with regimes of interest to Burning Plasma

At higher pressure and lower collisionality EDA ⇒ type II ELMs
**BP Research Program in H-mode Pedestal Physics**

**Goal:** Identify Optimized Edge Relaxation Mechanism with respect to core confinement, particle control, power exhaust

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<th>Research Activity – Objective</th>
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<tr>
<td>Characterize pedestal parameters, transport and stability as function of shaping, $q_{\psi}$, collisionality</td>
<td>2004</td>
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<tr>
<td>Determine effect of dissipative divertor techniques on pedestal parameters, stability</td>
<td>2004-05</td>
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<tr>
<td>Determine compatibility of unbalanced DN particle control with EDA, type II Elms, other edge relaxation phenomena</td>
<td>2005</td>
</tr>
<tr>
<td>Assess RF coupling, heating, current drive efficiency with different edge relaxation phenomena</td>
<td>2004-05</td>
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<tr>
<td>Determine divertor heat loads associated with edge relaxation phenomena</td>
<td>2005</td>
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<tr>
<td>Incorporate into Integrated Operational Scenarios</td>
<td>2006-2008</td>
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</table>
High heat flux and density control is crucial for Burning Plasma Experiment, Reactor

- Extend Power Dissipation Techniques (sweeping, impurity puff)
- Test Metallic High Heat Flux Components (w/Sandia)
- Optimize particle exhaust in SN, near DN equilibria
- Evaluate density profile control by AT control of transport

W-Brush Tile (SNL)
**Goal:** Demonstrate high power operation with acceptable divertor heat loads and steady-state density

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<th>Research Activity – Objective</th>
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<tr>
<td>Develop radiative/dissipative divertor techniques for high-performance H-mode discharges</td>
<td>2004-05</td>
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<tr>
<td>Test unbalanced DN pumping concept for particle control using new cryopump</td>
<td>2005</td>
</tr>
<tr>
<td>Test of high heat flux components, modules <em>e.g.</em> <em>Tungsten Brush tiles</em></td>
<td>2005-06</td>
</tr>
<tr>
<td>Test high heat flux advanced divertor prototype</td>
<td>2007</td>
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<tr>
<td>Demonstrate <em>Sustained</em> high-performance operation</td>
<td>2007-2008</td>
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Plasma Control Techniques Using RF

- Real Time Impedance Matching and Load-tolerant antenna
- ICRF Minority Heating with D-He$^3$
  - Absorption Physics, Model validation in low single-pass absorption regime
  - Assess Parasitic edge absorption
- MCCD Physics and Mode Conversion Flow Drive for profile control
- LH coupling, CD efficiency at moderate edge density
- FWCD Physics with $\omega < \omega_{ci}$ for all species
- Feedback stabilization of NTM with LHCD and/or MCCD
- Sawtooth control using Current Drive techniques
**Goal:** Demonstrate RF Core heating in BPX-relevant scenario

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<tr>
<td>Evaluate D-He(^3) heating scenario at relevant density, field, and current, including effects of parasitic edge absorption</td>
<td>2004</td>
</tr>
<tr>
<td>Demonstrate use of real-time matching system to improve ICRF heating reliability, efficiency</td>
<td>2004-05</td>
</tr>
<tr>
<td>Evaluate Lower Hybrid electron heating at BPX-relevant density, field</td>
<td>2005-06</td>
</tr>
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</table>
**Goal:** Demonstrate Control of Neoclassical Tearing Modes using localized RF current drive

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<th>Research Activity – Objective</th>
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<tr>
<td>Confirm presence of NTM in BPX parameter range of $\beta$, $\nu_{eff}$ in C-Mod discharges</td>
<td>2004-05</td>
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<tr>
<td>Based on RF Physics Program results, evaluate suitability of LHCD and/or MCCD for stabilization</td>
<td>2005-06</td>
</tr>
<tr>
<td>Based on MHD Stability Physics Program results, evaluate necessary current drive parameters for open-loop stabilization of NTM under best-chance conditions</td>
<td>2005-06</td>
</tr>
<tr>
<td>Develop and Test feedback stabilization of NTM in high-performance H-mode, demonstrating mode suppression and increased $\beta$, $nT\tau$, for multiple $\tau_E$</td>
<td>2007</td>
</tr>
</tbody>
</table>
Disruption Mitigation (or Avoidance) is Crucial for ITER

- Study physics of high pressure gas jet penetration into high-pressure core, as well as thermal quench (Collab. with D. Whyte, U.Wisc.)

- Use Active MHD Spectroscopy real-time measurements of growth rates to avoid unstable regimes

- Use non-axisymmetric coils to control static error-field effects

MHD Stability Limit

\[ \beta_N \]

\[ \beta_0 < \beta > \]

large damping: no danger

small damping: danger

\[ \beta_N \]

\[ \beta_0 < \beta > \]
C-Mod Burning Plasma Program Reflects FESAC/IPPA Science Goals

3.1.1 Turbulence and Transport
   3.1.1.1 Predictive Capability
   3.1.1.2 Understanding Transport Barriers
   3.1.1.3 Integrated Models of Core and Edge Physics

3.1.2 Macroscopic Stability
   3.1.2.1 Understanding Observed Macroscopic Stability Limits
   3.1.2.2 Understanding Physics Underlying External Stability Control
   3.1.2.3 Extending MHD Description

3.1.3 Wave-Particle
   3.1.3.1 Plasma Heating and Current Drive
   3.1.3.2 Energetic Particle Effects on Radial Profiles and Confinement
   3.1.3.3 Instabilities Affected by Energetic Particles

3.1.4 Multiphase Interfaces (Plasma Boundary Physics)
   3.1.4.1 Plasma Edge Physics
   3.1.4.2 Coupling between Edge and Core Plasmas
   3.1.4.3 Plasma-Wall Interaction
C-Mod Burning Plasma Program Reflects FESAC/IPPA Burning Plasma Goals

3.3.1 Profile Control
   3.3.1.1 Plasma Current Profile
   3.3.1.2 Plasma Pressure Profile
   3.3.1.3 Plasma Flow Profile
   3.3.1.4 Plasma Transport Profile
   3.3.1.5 Low Density Divertor Operation

3.3.2 High $\beta$ Stability and Disruption Mitigation
   3.3.2.1 Resistive Wall Mode Control
   3.3.2.2 Current Drive Inside Magnetic Islands
   3.3.2.3 Active Profile control to avoid unstable boundaries
   3.3.2.4 Disruption Control and mitigation

3.3.3 Burning Plasma
   3.3.3.1 Coordinated and Joint Experiments
   3.3.3.2 Prepare for DT experiments to be carried out on the enhanced JET
   3.3.3.3 Continue conceptual design work and trade-off studies for next step devices
3.4.1 Plasma Technologies
   3.4.1.1 Plasma Heating and Current Drive
   3.4.1.2 Fueling Technologies
   3.4.1.3 Plasma facing components
   3.4.1.4 Magnets

3.4.2 Advanced Design
   3.4.2.1 Carry out engineering design work and system optimization studies for next step burning plasma devices: Identify and understand key issues that need to be addressed, resolve technical issues and be ready to move forward with participation in a next step burning plasma experiment

3.4.3 Fusion (chamber) technologies
   3.4.3.5 Evaluate the performance and reliability of advanced solid and liquid wall concepts
Support for Burning Plasma Mission remains a major theme of the C-Mod Program

C-Mod was designed for this mission support

C-Mod's unique parameters are highly appropriate to this task

The Burning Plasma Support Program applies the Scientific Understanding arising from fundamental physics research in all of the topical areas to Integrated Scenario Development

AT Research at C-Mod and elsewhere incorporated into the BP Research Program