ITER/Burning Plasma Support Research Program on Alcator C-Mod

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Support for Burning Plasma Mission Continues to be a major theme of the C-Mod Program

C-Mod was designed for this mission support in the CIT/BPX era

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 Science Areas and the AT Program to Integrated Scenario Development
C-Mod ITER Research is carried out in all Topical Science Areas, Thrusts

- **Transport**
  - Pedestal Dynamics, Edge Relaxation
  - H-mode threshold physics
  - Rotation with no/low external torque

- **Edge/Divertor**
  - High Z-metallic PFC's
  - Plasma, neutral transport in SOL, divertor
  - Impurity lifecycle - co-deposition

- **MHD**
  - Disruption Mitigation
  - Nonaxisymmetric field effects
  - NTM Physics
  - Alfvén Eigenmode stability

- **RF**
  - ICRF Antenna Development
  - Weak single-pass absorption heating scenarios
  - Mode conversion Current and Flow Drive
  - Energetic particle driven modes

- **AT Physics - Lower Hybrid**
  - ITB Physics
  - LHCD for off-axis current drive, NTM stabilization
  - Hybrid Scenario studies
  - Advanced Scenario development

- **Burning Plasma**
  - Demonstration Discharges in relevant parameter regimes
  - Operational Scenario Development
MHD, Disruption and Control
- MHD stability analysis of H-mode edge transport barrier under Type 1 and tolerable ELM conditions
- NTM’s island onset threshold, stabilization of (3,2) and (2,1) NTM islands at high $\beta$ and $\beta$ recovery. Possible operation with benign NTMs (FIR, seed island control); identify requirements for reactor plasmas.
- RWM’s: analysis, experimental verification of control, role of plasma rotation and error fields, control system requirements for diagnostics.
- Construction of new disruption DB including conventional and advanced scenarios and heat loads on wall/targets
- Development of disruption mitigation techniques, particularly noble gas injection

Steady State Operation and Energetic Particles
- Steady state plasma operation: Investigate hybrid scenarios and full current drive plasmas with significant bootstrap current; assess beta limits.
- Use Heating and CD actuators for real time current profile control; assess predictability, in particular for off-axis CD
- Studies of fast particles collective modes in low and reversed magnetic shear configurations: Identify key parameters. Theory-data comparison on damping and stability, including non-linear mode dynamics and fast particle transport.
ITER High Priority Research Areas (cont.)

- **Transport Physics**
  - Improve experimental characterization and understanding of critical issues for reactor regimes with enhanced confinement, including:
    * Continue to optimize ITER hybrid and steady-state demonstration discharges and obtain physics documentation
    * Address reactor relevant conditions, *e.g.* electron heating, $T_e \sim T_i$, impurities, density, edge core interaction, low momentum input
  - Utilize international experimental ITPA database to test commonality of hybrid and steady state scenario transport physics across devices
  - Encourage tests of simulation predictions via comparisons of turbulence characteristics, code-to-code comparisons, and comparisons to transport scalings.

- **Confinement Database and Modeling**
  - Assemble and manage multi-machine databases, analysis tools, and physics models
  - Evaluate global and local models for plasma confinement by testing against the databases.
  - Use the models to predict the performance of Burning Plasma Experiments, including an estimate of the uncertainty of the predictions.
• Pedestal and Edge
  – Construction of Profile DB based on Inter machine exp.and Test of modeling using the profile DB as TG work.
  – Improve predictive capability of pedestal structure through profile modelling.
  – Construct physics-based and empirical scaling of pedestal parameters
  – Improve predictive capability for ELM size and frequency and assess accessibility to regimes with small or no ELMs.

• Divertor and SOL
  – Understand the effect of ELMs/disruptions on divertor and first wall structures.
  – Tritium retention & the processes that determine it.
  – Improve understanding of SOL plasma interaction with the main chamber.
C-Mod is actively participating in ITPA Joint Experiments

**CDB-4** Confinement scaling in ELMy H-modes: $\nu^*$ scans at fixed $n/n_G$ (C-Mod/JET)

**CDB-7** Ohmic Identity Experiments: test of scaling with dimensionless parameters

**TP-1** Investigation of transport properties of candidate hybrid scenarios

**TP-3** High performance operation with $T_e \sim T_i$

**TP-4** Enhanced confinement operation with low external momentum input

**PEP-7** Dimensionless identity experiments on C-Mod and JET

**PEP-11** Dimensionless comparison of L-H threshold and H-mode pedestals on C-Mod and ASDEX-Upgrade

**PEP-12** Comparison between C-Mod EDA and JFT-2M HRS regimes
ITPA Joint Experiments (cont.)

**DSOL-3** Scaling of radial transport

**DSOL-4** Disruptions and effect on materials choices

**DSOL-5** Role of Lyman absorption in the divertor (C-Mod, JET)

**DSOL-6** Parallel transport in the SOL

**DSOL-7** Multi-machine study on separatrix density and edge profiles

(DSOL-13) Deposition in tile gaps

**MDC-1** Pressure and size scaling of gas jet penetration for disruption mitigation

**MDC-3** Joint experiments on neoclassical tearing modes (including error field effects)

**MDC-6** Error field sideband effects for ITER (C-Mod, JET, DIII-D identity experiments)

**SSEP-1** Preparation of ITER steady-state scenario

**SSEP-2** Preparation of ITER hybrid scenario
C-Mod offers Unique Capabilities for Research in Support of Burning Plasma experiments

- Reactor relevant B (5-8 tesla) and $n_e$ (to $10^{21} m^{-3}$)
- High power density and SOL power ($\lesssim 1 \text{ GW/m}^2$)
- Reactor-level absolute pressure ($P_0 \leq 1 \text{ MPa}$)
- High-Z metallic first wall and PFC’s
- Long pulse length compared to $\tau_{CR}$
- RF heating and current drive
- $T_e \approx T_i$, $\tau_e^e/i \ll \tau_E$ typical
C-Mod can operate with the ITER shape and $B_T$

\[ I_p = 15 MA \]

\[ I_p = 1.6 MA \]
Research Program in H-mode Pedestal Physics

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

A “local” solution, pertinent to the specific region of parameter space of a BPX, is a Reasonable Goal
The physics which sets the pedestal width is still not well established – but may be crucial for ITER

- Dimensionless identity (DIII-D, JET, ASDEX) – match with plasma parameters
- Expts. with for JET 2005 – will have better match to shape
- Pedestal scaling data to ITPA

If neutral physics dominated pedestal structure $L_n \propto a^2$

Neutral scale length is most sensitive to $\nabla n_e$ rather than $n_e$ (requires kinetic description - KN1D - LaBombard)

Experiments planned to look at effect of neutral source localization

Mapping a crucial issue - Plan to install H$\alpha$ array at TS position
Small/No ELM Regimes Highly Desirable

- Giant ELMs could compromise ITER divertor in small number of discharges
- Small/no ELM regimes with good energy confinement, particle regulation across barrier:
  - QH/QDB modes (DIII-D, also now on ASDEX-U, JET)
  - EDA H-Mode (C-Mod, also now seen on JFT2-M)
- Particle transport in EDA driven by mode just inside separatrix
  - Features consistent with resistive ballooning mode seen in modeling (Xu and Nevins)

Enhanced D_α (EDA) H-Mode

<table>
<thead>
<tr>
<th>Major Radius (mm)</th>
<th>Time (sec)</th>
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<tbody>
<tr>
<td>880</td>
<td>1.06</td>
</tr>
<tr>
<td>890</td>
<td>1.08</td>
</tr>
<tr>
<td>900</td>
<td>1.10</td>
</tr>
<tr>
<td>910</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Amp. peaks ~1-3 mm inside separatrix
At higher $\beta$, $T_e$ - small ELMs take over from QC mode

- Negligible heat and particle loads
- Continue regime mapping
- Shape, collisionality, pressure
- Enhance stability calculations
  - MSE – get j integral in edge, normalize BS calculation
  - CXR – edge Ti
Spontaneous rotation with no momentum input

Potentially important influence on
- Locked mode threshold
- RWM stability
- L-H threshold

Rotation is a transport effect, not due to RF or fast ions
- Momentum diffuses in from the edge
- SOL/edge flows may set boundary condition

Similar effects observed on JET, Tore Supra
- Masked by beam torque in most experiments
- Scaling to ITER needs to be determined

ICRF and Ohmic H-modes

\[ \Delta W/I_p \text{ (kJ/MA)} \]

0 20 40 60 80 100 120 140

0 2 4 6 8 10 12 14

1.2 MA
1.0 MA
0.8 MA
0.6 MA
Ohmic
NBI-free Plasmas Create an Ideal Laboratory to Investigate Self-Generated Flows and Momentum Confinement

- Rotation profiles are flat in EDA H-mode – momentum diffuses from edge – $D_\phi >> D_{NC}$
- Evolution in ELM-free plasma demonstrates inward momentum convection
- Further parameter scans
- Expand radial range of measurements – CXR
- Fluctuation measurements
- Reynolds stress – simulations with Gyro (Ernst)
- Ion orbit theory (Chang)
Remaining uncertainties in predicting ITER error field threshold are:-

- Toroidal Field scaling
- Size scaling

A very good match between JET and C-Mod applied error field spectra

B-field scan on C-mod help resolve TF scaling

Identity matches on error field threshold with JET to confirm validity of scale invariance approach and allow size scaling to be determined
Disruption Mitigation needs Testing in Higher Electron Pressure Plasmas

- Massive noble gas puff on DIII-D
  - Very encouraging results (D. Whyte, et al., PRL 2002)
- C-Mod investigations (collaboration with U. Wisconsin):
  - Higher Electron Pressure ($P_e$) plasmas (gas penetration)
  - Higher Energy Density plasmas (efficacy of radiation)
- C-Mod/DIII-D/JET comparisons valuable to test size scaling

<table>
<thead>
<tr>
<th>Device</th>
<th>$&lt;P_e&gt;$ (kPa)</th>
<th>$P_{e,0}$ (kPa)</th>
<th>a (m)</th>
<th>$P_{\text{gas-jet}}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIII-D</td>
<td>~8</td>
<td>30</td>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>C-Mod</td>
<td>10-150</td>
<td>40-400</td>
<td>0.22</td>
<td>300</td>
</tr>
<tr>
<td>JET</td>
<td>~15</td>
<td>~60</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>ITER</td>
<td>250</td>
<td>500</td>
<td>2</td>
<td>&gt;200?</td>
</tr>
<tr>
<td>FIRE</td>
<td>900</td>
<td>1800</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>IGNITOR</td>
<td>800</td>
<td>2500</td>
<td>0.47</td>
<td></td>
</tr>
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</table>
Stabilization of Neoclassical Tearing Modes is considered essential for ITER

ITPA Joint Experiment on NTM scaling (2004-5)

Investigate error-field effects on NTM (2004-5)

Evaluate suitability of MCCD and/or LHCD for stabilization (2005-6)

Test feedback stabilization in high performance H-mode (2007)
Active TAE Resonances in Diverted Plasmas

ITER relevant moderately high $n \sim 20$ antennas excite stable TAE’s.

Three TAE resonances as $f_{TAE}$ crosses the active frequency in a diverted plasma with outer gap $< 2.5$ mm have $|\gamma/\omega| \sim 1\%$
C-Mod continues to explore new concepts in particle and power control

- Vertical plate geometry is MIT concept
  - Part of DCT/CIT design development (1984)
  - Combines divertor plate and baffle
  - Directs impurities away from core
  - Lowers the separatrix Te (& sputtering)
  - Enables divertor detachment at lower ne
  - Considered standard for all divertor designs

- We are proposing a new concept
  - Near double-null operation
  - Heat load to primary divertor
  - Particle pumping to secondary divertor
  - Based on transport studies
  - To be implemented with new cryopump

- Use of advanced divertor target materials (high Z)
  - Prototype tungsten brush modules (near term)
Tungsten brush tile development and testing part of the C-Mod program

- Tungsten brush tiles have been proposed for BPXs
  - shown to handle up to 20 MW/m² steady state
  - resists melt layer formation
  - no tokamak experience

- C-Mod is working towards W-brush tile installation and testing
  - based on original Sandia design
  - collaboration with Sandia

- C-Mod design alternatives aimed at
  - simplified construction and manufacture
  - maximization of W/support interface

- Plans
  - 2 different tile designs being manufactured & tested
  - plan for installation of ~ 5-10 tiles next vacuum break
ITER plans for 50 MW ICRF

Heating and Current Drive for Control

- Bulk ion heating for burn control
- Sawtooth control
- On-axis current drive for advanced scenarios

Antenna is critical element

- Requires high voltage standoff in presence of plasma
- Load tolerant or robust matching

C-Mod ICRF system tests relevant configuration and matching concepts
C-Mod RF Physics Program addresses relevant heating, current drive scenarios

- Weak single-pass absorption heating scenarios (D He$^3$)

- Mode Conversion Current Drive (MCCD)

- Sawtooth control using localized current drive, fast particle pressure
C-Mod Advanced Tokamak Program supports ITER Advanced Scenarios

ITB Research supports ITPA Transport Physics Group top goal:

Improve experimental characterization and understanding of critical issues for reactor-relevant regimes with ITBs, specifically with $T_e \sim T_i$, low toroidal rotation speed, high density ($n/n_G=0.6-0.8$), flat density profile ($n(0)/\langle n \rangle < 1.5$), $Z_{eff} < 2$, and moderate safety factor ($q_{95}=3.5-5$), including:

- ITB formation and sustainment conditions.
- Impurity accumulation (low- and high-Z)
- Compatibility with divertor requirements ($n_{sep}/n_G > 0.3$)

(Access to) hybrid regime in C-Mod

- Proposed by A. Sips (IPP-Garching) as part of ITPA collaborations
- Using LHCD (1-2 MW) and ICRF (central and off-axis heating), $4 < q_{95} < 4.5$
- To be scheduled in FY05

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C-Mod AT Target Parameters address Enhanced Steady State operation

- Fully non-inductive (70% bootstrap)
- Far off-axis LHCD
- $\beta_N \approx 3$ at the no-wall limit
- $H_{89} > 2.5$
- Fully relaxed equilibrium $t >> \tau_{CR}$

Example of an AT target scenario meeting performance target.
One of many optimized scenarios modelled with ACCOME.
- $I_p = 860 \text{ kA}$, non-inductive.
- $I_{lh} = 240 \text{ kA}$
- $I_{BS} = 600 \text{ kA}$ (70%)
- $\beta_N = 2.9$ J (MA / m$^2$)

Safety Factor - $q(r)$
- $q(0) = 5.08$
- $q_{min} = 3.30$
- $q(95) = 5.98$

Double transport barrier
- $B_T = 4 \text{ T}$
- ICRH: 5 MW
- LHCD: 3 MW, $N//0 = 3$
- $n_e(0) = 1.8 \times 10^{20} \text{ m}^{-3}$
- $T_e(0) = 6.5 \text{ keV}$ (H=2.5)

Scenarios without barrier, or only an ITB, have similar performance.


AT Program is relevant to ITER and to Reactor Scenario
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 $\nu^{neo}_* = \epsilon^{-3/2} \nu_{ii} qR / \nu_{thi}$
  - Others, along with tearing mode effects, will depend on $\nu / \omega_*$, which is larger by a factor $\sim \rho_*$
  - Electron-ion equilibration depends on $\nu^{e/i} / \tau_E$

- 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 the range of collisionalities

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

Matches $\beta$ and absolute pressure

Gyrosizes:

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

$$n_e \leq 0.5 \ n_{\text{Greenwald}}$$

ITER-FEAT Demonstration Discharges

$\beta_N = 1.8$

$B = 5.3$ T

$P_{\text{CMOD}}(\text{MW})$

$[H_{89} = 2]$

$n_{\text{CMOD}} / n_G$
Dimensionless Similarity Scaling to Next Steps

Example matching $\beta$ and $v_i/\omega_e$ for $\rho^*$ scaling of NTM physics

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>C-Mod</th>
<th>DIII-D</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_0$ (T)</td>
<td>5.3</td>
<td>5.3</td>
<td>2.1</td>
<td>3</td>
</tr>
<tr>
<td>$a$ (m)</td>
<td>2.0</td>
<td>0.22</td>
<td>0.54</td>
<td>0.91</td>
</tr>
<tr>
<td>$I$ (MA)</td>
<td>15</td>
<td>1.6</td>
<td>1.6</td>
<td>3.9</td>
</tr>
<tr>
<td>$n$ ($10^{20}$ m$^{-3}$)</td>
<td>1</td>
<td>3.5</td>
<td>0.73</td>
<td>0.82</td>
</tr>
<tr>
<td>$n/n_g$</td>
<td>0.85</td>
<td>0.33</td>
<td>0.42</td>
<td>0.54</td>
</tr>
<tr>
<td>$T$ (keV)</td>
<td>17</td>
<td>4.8</td>
<td>3.7</td>
<td>6.7</td>
</tr>
<tr>
<td>$\tau_H$ (s)</td>
<td>3.5</td>
<td>.067</td>
<td>.236</td>
<td>.80</td>
</tr>
<tr>
<td>$2\tau_{89}$ (s)</td>
<td>3.2</td>
<td>.075</td>
<td>.247</td>
<td>.74</td>
</tr>
<tr>
<td>$P$ (MW)</td>
<td>100</td>
<td>5.7</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>$\rho^*$ factor</td>
<td>1</td>
<td>4.8</td>
<td>4.3</td>
<td>2.4</td>
</tr>
</tbody>
</table>
To focus the high-performance program, we have adopted Integrated Performance Targets

- Toroidal Field: 8T
- Plasma Current: 2MA
- Confinement: $H_{89} \geq 2$
- Heating Power: 6 MW
- $Z_{eff}$: $\leq 1.5$
- $\langle P \rangle$: 4 atm

Extrapolation of Present Performance

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

Development of this challenging target requires simultaneous demonstration of confinement, heating, control, power handling, and impurity control techniques suitable for a burning plasma experiment.
C-Mod can study plasmas at the same $\beta$ and magnetic field as ITER.
C-Mod Research addresses key issues for Next Step Burning Plasma Experiments

- **Unique dimensional parameters**
  - Provide strong constraints on database scalings
  - High leverage through dimensionless identity and similarity experiments
- **Equilibrated electrons and ions**
- **High SOL power density, all metal Plasma Facing Components**
  - ITER/Reactor relevant
  - Unique recycling properties, D/T retention
- **Reactor-like normalized neutral mean free path**
- **Prototypical disruption forces**
- **Exclusively RF driven**
  - Heating/Current Drive decoupled from particle, momentum sources
  - Efficient off-axis current drive (Lower Hybrid)
- **Long pulse length relative to skin, L/R times**