C-Mod Pedestal Program

Alcator C-Mod Program Advisory Committee Meeting
January 27–29, 2010
Presented by Jerry Hughes
Pedestal physics: An integral component of the C-Mod research program

- *Edge barrier formation, profile structure* and *relaxation processes* all play critical roles in high-performance operation of tokamaks
- Issues permeate number of topical science areas and programmatic thrusts, and research contributes to FESAC, ITER priorities
- **Ultimate goal:** physics-based models for burning plasma which are scalable to ITER and beyond
- *Pedestal structure* is the focus of FY11 Joint Research Target
- C-Mod occupies a unique parameter space that complements studies on other devices (large $B/R$, $n_eL$, range of pedestal collisionality)

- Research highlights and plans covered in this presentation:
  - L-H thresholds and transition physics
  - Pedestal structure and transport
    - H-modes
    - Improved L-modes
  - Edge relaxation mechanisms
  - Pedestal control
  - Theory and simulation
C-Mod exploits large range of operational space for pedestal studies

- C-Mod pedestal studied over *extended range* of engineering parameters: e.g. $B_T$, $I_p$, $n_e$
- Increased studies of operation with "alternative" magnetic topology
  - Extremes in *shaping*
  - Unfavorable ion $\nabla B$ drift direction (in both normal and reversed $B_T$ direction)
  - Near double null
- Lower collisionality with above techniques, cryopumping
- Access a wide range of regimes
  - EDA, ELMy H-modes
  - Improved L-mode with T pedestal
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We are enabled by an extensive set of well-resolved edge diagnostics

Pedestal diagnostic set emphasizes *millimeter-resolution* profiles, fluctuations

- **Thomson scattering** \((T_e, n_e)\)
- **CXRS** \((T_i, v_{i\theta}, v_{i\phi})\)
  - Inner wall toroidal views (passive and gas-puff assisted)
  - Pedestal beam-based CXRS (*toroidal* and *poloidal* views)
- **Scanning Mach probes**, HFS+LFS \((T_e, n_e, v)\)
- Electron cyclotron emission \((T_e)\)
- Visible bremsstrahlung \((n_e Z_{\text{eff}}^{1/2})\)
- Soft x-rays \((n_i)\)
- **Neutral emissivity measurements** (passive, gas puff imaging)
- Reflectometer \((n_e\) fluctuations\)
- Phase-contrast imaging \((n_e\) fluctuation\)
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*Student involvement* in diagnostic development is high
L-H transition physics and H-mode access: Research supporting ITER

- C-Mod participates in an ITPA task force on H-mode threshold
  - Significant part of H-mode Integrated Scenarios thrust (S. Wolfe, tomorrow)
  - A research priority for next few years

- Recent progress:
  - Comparison of H-mode power threshold in He vs. D plasmas
    - Informs ITER non-activation phase (ITPA joint experiment TC-4)
    - Higher power thresholds in He
    - Consistent with experience on many other devices, but not all; need physics understanding

- Scalings of low-density limit for L-H transition is an ITER priority
  - ITPA joint experiment (TC-3) among C-Mod, DIII-D, JET, AUG, TCV is collecting data sets at varied $I_p$, $B_T$; entering data analysis phase

- Will participate in new ITPA joint experiments: ’10—’12+
  - Address thresholds in terms of local edge parameters (PEP-26)
  - X-point/strike point position/divertor leg length (PEP-28)

- Analysis of data will be aided by implementation of a multi-machine edge profile database, complementing the traditional scalar DB, both maintained at MIT: ’10—’12+
L-H transition physics and H-mode access: Highlights and Plans

- **Recent progress**
  - Exploring scaling of H-mode power threshold in unfavorable $\nabla B$ drift discharges
    - Partial suppression of energy transport precedes traditional L-H bifurcation
    - If L-H transition is suppressed, can lead to an improved L-mode (more later)

- **Plans**
  - Renewed focus on *local* edge parameters at threshold: ’10—’12
  - Understand role of SOL flows, edge rotation shear in ETB formation, through more routine diagnosis of pedestal rotation velocities, $E_r$: ’10—’12
  - Turbulence characteristics across L-H *(more in Boundary): ’10—’11
  - Is there a role for neutrals in suppressing L-H transition at high density? Does fueling location matter? $\Rightarrow$ experiment proposed: ’10
  - Follow up on evidence of reduced $P_{th}$ in near DN $\Rightarrow$ planning experiment (PEP-6): ’10

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*Figure: H-mode threshold power vs. $q_{95}$ showing two regions of interest: 5T < $B_T$ < 6T and 3.0T < $B_T$ < 3.4T.*

*Text: Power threshold in unfavorable grad-B drift direction.*
Pedestal structure and transport: Highlights

• Role of magnetic topology on pedestal and confinement properties has been investigated (PEP-6)
  – Natural H-mode density reduced for $\Delta R_{SEP}>0$, for sufficiently high power
  – Energy confinement time (absolute and normalized) significantly improved for $\Delta R_{SEP}<0$

• Obtained variation of $|\Delta R_{SEP}|$ within characteristic scale lengths near edge (i.e. 2—5mm)

• Suggests proximity to DN will not be a problem in ITER

• However, as $P_{\text{net}} = P_{\text{loss}} - P_{\text{rad}}$ decreases toward threshold for H-L back-transition, favorable energy confinement lost (TC-2)

• General observation of pedestal “stiffness” in EDA may require minimum $P_{in}/P_{th}$

• Useful supporting data for FY11 JRT

Scale ITER $\Delta R_{SEP}$ to C-Mod: ~-5mm
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- Useful supporting data for FY11 JRT
Pedestal structure: Progress toward predictive understanding (FY11 JRT)

- Pedestal width *nearly invariant* under typical C-Mod operating conditions (EDA/ELM-free)
  - Weak scalings with $\rho_\psi$, $\rho_\theta$, $\beta_{\text{pol}}$, neutral fueling depth
  - Indications that magnetic shear plays a role
- **Width scaling in Type I ELMy H-mode** is consistent with $\beta_{\text{pol}}^{1/2}$ scaling used in EPED1 predictive model
- EPED1-like predictions were made for comparison with $I_p$ scan in C-Mod
  - Time-averaged pedestal analysis shows ballpark agreement with prediction
- **Plans**
- Obtain more data, allowing complete ELM-synchronized analysis, benchmarking validation EPED1 and follow-on models: ’10-’11
- C-Mod data are invaluable for testing the diamagnetic stabilization physics in EPED

In collaboration with P. Snyder (GA)
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Pedestal structure and transport: Research goals

- Understand processes that limit pedestal gradients between or in the absence of ELMs
  - Important for FY11 JRT
- Are there correlations between turbulence and pedestal saturation?
  - Recent experiment in collaboration with R. Groebner (GA) to examine quasi-coherent mode onset in EDA H-mode
  - Related experiment on DIII-D to look for kinetic ballooning mode
- Plans
  - Linear stability analysis of evolving pedestal with GS2: ’10
  - Connect with attempts to simulate the QCM: ’10—11
  - Analyze dependence of pedestal structure (width, gradients) on magnetic topology and shape: ’10
  - Assess the role of magnetic shear in setting $\Delta$: ’11—12
  - How does this connect to L-mode critical gradient results in Ohmic plasmas?
Pedestal structure and transport: Particles, H-mode density control

- **Research goals and plans:**
  - Ongoing studies of profile stiffness, pedestal width, are being extended to lower collisionality
  - Impact of pumping on pedestal and performance continues to be a focus
  - Also, examine H-mode fueling of pedestal at ITER B_T, q as ITER neutral opacity is approached: ’11
  - Enhance the 2D picture of ionization source → inputs to modeling: ’11—12
    - Take advantage of neutral emissivity profiles at multiple poloidal locations
    - Modeling to facilitate interpretation of these measurements
  - Impurity transport: Exploit HFS/LFS CXRS diagnostics: ’10—11
    - Diagnose impurity transport coefficients in pedestal
    - Characterize in/out asymmetries in impurity profiles

Cryopumping partially ameliorates confinement degradation at marginal power
Improved L-modes: an alternative to traditional H-mode

• Suppression of traditional H-mode: Good for burning plasma operation?
• Obtained in high power discharges with unfavorable $\nabla B$ drift (high $P_{LH}$)
• Low particle confinement combined with high energy confinement ($H_{98}\sim1$)
• Temperature pedestals of $\sim1$keV have been obtained with benign impurity confinement
  – Experimental $\chi_{\text{eff}}$ in pedestal closer to that in H-mode than in L-mode
• Making progress in I-mode sustainment
  – Shaping, $I_P$ optimization
  – Cryopumping, impurity seeding
  – Staying out of H-mode
    • Operating with higher $P_{th}$
    • Reducing sawtooth size
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\[
\begin{array}{c}
\chi_{\text{eff}} \sim 1 - 2 \\
\chi_{\text{eff}} \sim 0.1 - 0.3 \\
\chi_{\text{eff}} \sim 0.05
\end{array}
\]
Improved L-modes: Plans

- Pedestal pressure, *collisionality* similar to that of ELMy H-mode
  - Sporadic ELMs are observed, sawtooth-triggered
  - Transport appears to be regulated by edge mode evocative of the EDA QCM, though favored by reduced $\nu^*$
- Perform comparative stability analyses: '10—11
- Examine conditions for existence of continuous modes → is there a connection to edge harmonic oscillations on DIII-D?: '10—11
- Get at relevant physics keeping H-mode suppressed at higher power
  - Edge flow shear, $E_r$ measurements: '10—11
  - Explore possible role of magnetic shear: '11—12
- *Improved L-modes are attractive targets for research requiring low density, good confinement*
  - Potentially important discharges for core transport studies, LHCD, advanced scenarios integration (more in later talks)
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Pedestal structure and transport: Flows and radial electric field

- **Research plans:**
  - Relate transport reduction, fluctuation suppression, confinement to level of ExB shear in the pedestal region *in various confinement regimes* ’11—12
    - Explore decoupling of particle and thermal transport suppression (*improved L-modes*)
  - Cross-machine comparisons of $E_r$ well
    - Relative contributions of flow, diamagnetic components
    - Revisit non-dimensional pedestal matching experiment between C-Mod/DIII-D
  - Deploy Doppler reflectometry as edge velocity measurement: ’11—12
  - Comparison of edge impurity flow velocities, $E_r$ with edge codes (i.e. XGC0/1): ’11
  - *Momentum transport through pedestal* → understanding intrinsic rotation without external torque: ’11—12
    - What is the source of large H-mode toroidal rotation?
    - How are the core rotation and SOL flows coupled?
Edge relaxation mechanisms: Continuous pedestal regulation

- **Objective**: Understand the physical processes determining the operational space of edge relaxation mechanisms in H-mode
  - Are small-ELM or no-ELM regimes compatible with a high-confinement ITER pedestal?
- **EDA H-mode**: Continuous transport process driven by fully electromagnetic quasi-coherent mode (QCM) in pedestal
  - Usually with no ELMs
  - Compatible with the appearance of small ELMs at sufficiently high power
- **I-mode**: Likely regulated by an relatively broadband edge mode (Q^2CM?) which is favored by low collisionality

**Research goals and plans**: Understand mode drive via additional experimental diagnosis and theory/modeling: ’10—12
- Extensive measurements available: PCI, magnetics, reflectometry (static and scannable frequency), fast \( D_\alpha \)
- Use probe with radially spaced elements to determine radial extent and position of the QCM
- Simulations of C-Mod EDA edge
  - BOUT, BOUT++ are candidates
  - M3D (L. Sugiyama)
- Evaluate other candidate mechanisms (e.g. K-H instability, saturated kink/ballooning mode)
Edge relaxation mechanisms: Edge-Localized Modes

- Small ELMs often appear at sufficiently high $\beta$ in EDA H-modes
- Large Type I ELMs studied in atypically shaped discharges ($dlower>0.75$, $dupper\sim0.15$)
- **Goals and plans:**
  - Continue studying structure and dynamics of edge filaments in ELMs of varying size
  - Resolve boundaries of relaxation regimes in operational space (FY10 facility milestone)
  - Attempt to induce ELMs with vertical jogs: ’10
  - Theoretical understanding of the ELM stabilization obtained naturally on C-Mod (P. Snyder, GA): ’10—11
  - Model C-Mod ELM cycle with XGC0/ELITE (A. Pankin, Lehigh): ’10
  - **Focus on role of shape:** How does shape affect underlying pedestal transport, ELM stability?: ’10—11
  - More efficient stability analysis through importation of data handling codes (T. Osborne, GA): ’10
  - Use stability codes to aid in ELMy discharge development: ’11—12
External pedestal modification

- Combining LHCD with low-density H-modes gives up to 30% reduction in pedestal density, with similar energy confinement.
- Transient behavior of edge, core plasma suggest transport is being altered in stages, possibly at different radial locations.
  - Experiment and modeling indicate enhanced absorption of LHRF in SOL plays an important role.

**Plans:**
- Improve modeling of LH wave propagation: '10—11
- Understand SOL/core deposition and also determine balance of heating/CD: '10—11
- Compare results with the application of ECH/ECCD on other devices (PEP-22): '11—12
- Explore LHRF as a tool for controlling pedestal structure, ELM quality: '11—12
- Explore possibility of using LHRF and ICRF tools for enhancing or inducing continuous modes in pedestal: '10—12

![Density pedestal relaxation with LHRF](image)
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**Theory and simulation: Plans**

- *Use computational tools to enhance our physical understanding, and contribute data for validation of newest edge codes*
- Use measurements to test theoretical predictions of edge $E_r$ and its role in pedestal formation
- Continue ELM/EDA studies with ELITE, M3D (Snyder, Sugiyama)
- Utilize XGC0 for pedestal transport calculations, with 3D EM turbulence calculated by XGC1 (C.-S. Chang, NYU)
- ELM cycle simulation with coupled XGC0/ELITE (A. Pankin, Lehigh)
- Work closely with Center for Plasma Edge Simulation (near term) and Edge Simulation Laboratory (longer term)
  - Code validation
  - Integrated work flow for simulating complex time-dependent edge phenomena (ELM cycle, L-H transition)
- With DIII-D, NSTX, we will work to test models for pedestal structure for the 2011 FES Joint Research Target
Research priorities and approximate timeline for achieving key goals

- **Pedestal themes:**
  - Pedestal structure (and its impact on core confinement) and scalability to future devices
  - Physical processes determining the operational space of edge relaxation mechanisms in H-mode
  - Critical local parameters needed to trigger L-H transition and relationship to global threshold conditions
  - Methods for controlling pedestal structure and edge relaxation mechanisms that are compatible with high confinement
  - Validation of edge simulation tools currently in development using experimental data

- **FY10—11**
  - Examine flux-gradient relationships in the ETB in various configurations and operational regimes; resolve boundaries for edge relaxation mechanisms
  - Expand Type I ELMy data set with full diagnostic coverage for comparisons with modeling
  - Study trigger conditions for L-H transitions (including all edge profile information)

- **FY11—12**
  - Compare pedestal structure with available models, code predictions
  - Study role of edge magnetic shear in determining pedestal width
  - Explore suppression of pedestal density and possible ELM modification with LHRF

- **FY12—13**
  - Examine role of pedestal in spontaneous flow generation
  - Relation of particle, thermal transport to fluctuations, ExB shear suppression in ELMy, EDA H-mode, improved L-mode

Green = Direct contribution to FY11 JRT
We are positioned to contribute to a number of ITER priority tasks

- Improve predictive capability of pedestal structure
  - Cross machine comparisons to isolate physics setting pedestal width
  - Utilize profile database for integrated modeling of pedestal structure and transport comparison to experiment
  - Establish pedestal profile database for hybrid and advanced regimes
  - Assess impact of ELM control techniques on pedestal structure
- Improve predictive and design capability for small ELM and quiescent H-mode regimes and ELM control techniques
  - Assess applicability of low collisionality small ELM regimes
  - Test nonlinear MHD and turbulence models of ELM evolution
- Re-examine L-H power threshold at low density
- Assess H-mode access, pedestal and confinement properties in He plasmas
- Examine core fueling efficiency at neutral opacity approaching that of ITER
We participate in (and lead*) inter-machine collaborations through ITPA

<table>
<thead>
<tr>
<th>Description</th>
<th>ITPA designation</th>
<th>Notes on C-Mod contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestal structure and ELM stability in double null</td>
<td>PEP-6</td>
<td>H-modes in near DN and SN configurations are compared in terms of profile structure and ELM stability.</td>
</tr>
<tr>
<td>Small ELM regime comparison on C-Mod, NSTX and MAST</td>
<td>PEP-16</td>
<td>High-power ELMy regimes accessed in double and single null configurations</td>
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<td>Controllability of pedestal and ELM characteristics by edge ECH/ECCD/LHCD</td>
<td>PEP-22</td>
<td>Modifications to pedestal observed with application of LHRF. Will examine effects of edge CD, electron heating on pedestal transport, ELM stability</td>
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<td>Critical edge parameters for achieving L-H transition</td>
<td>PEP-26*</td>
<td>Will assemble data sets of edge profiles in density scans and analyze for radially localized L-H triggers. Other devices will provide complementary data</td>
</tr>
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<td>Pedestal profile evolution following L-H transition</td>
<td>PEP-27*</td>
<td>Multiple L-H transitions used to generate time-dependent data on pedestal profile and turbulence evolution</td>
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<td>Physics of H-mode access with different X-point height</td>
<td>PEP-28</td>
<td>Comparisons of H-mode threshold power (and edge conditions) as X-point/strike point positions are varied. Will attempt to compare USN discharges to older USN cases prior to closure of upper divertor.</td>
</tr>
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<td>Power ratio – Hysteresis and access to H-mode with H~1</td>
<td>TC-2</td>
<td>Incidental data obtained in the course of EDA H-mode studies. Further controlled experiments are possible.</td>
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<td>Scaling of the Low-Density Limit of the H-mode Threshold</td>
<td>TC-3*</td>
<td>Provided high-field data on current and field scaling of low-density limit. Evaluating impact of wall conditions, character of edge fueling</td>
</tr>
<tr>
<td>H-mode transition and confinement dependence on ionic species</td>
<td>TC-4</td>
<td>H-mode threshold power found to be significantly higher in He. Work to evaluate He H-mode confinement, ELM access is planned.</td>
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Pedestal research contributes to issues in 2007 FESAC “Priorities” Report*

- **A2. Integration of high-performance, steady-state, burning plasmas:** Create and conduct research, on a routine basis, of high performance core, edge and SOL plasmas in steady-state with the combined performance characteristics required for Demo.
  - Focus on high-performance regimes with ELMs either benign or suppressed altogether.
  - Both naturally occurring small- or no-ELM regimes and operation with externally determined relaxation of the pedestal will be explored.
  - A research focus will be to compare with the results of other devices and determine the capability of extrapolating to ITER and Demo.
- **A3. Validated Theory and Predictive Modeling:** Through developments in theory and modeling and careful comparison with experiments, develop a set of computational models that are capable of predicting all important plasma behavior in the regimes and geometries relevant for practical fusion energy.
  - Assist in the validation/de-validation of developing edge/pedestal codes.
  - Specific predictions of models which can be tested include flux-gradient relationships, ELM stability, edge flows and the coupling of momentum across the pedestal, and L-H transition triggers.
- **A6. Plasma Modification by Auxiliary Systems:** Establish the physics and engineering science of auxiliary systems that can provide power, particles, current and rotation at the appropriate locations in the plasma at the appropriate intensity.
  - Explore pedestal transport/structure modification using phenomena such as electron heating or non-inductively driven current from RF waves.

*“Priorities, Gaps and Opportunities: Towards a Long Range Strategic Plan for Magnetic Fusion Energy”*
Specific pedestal research contributions
to ReNeW thrusts

- **Thrust 2**: Control transient events
  - Edge plasma transport and stability, emphasizing ELM-free regimes

- **Thrust 4.** H-mode access and dependence on ion species.
  - Heating power required for attaining several regimes
    - L-H and H-L
    - Type III ELMy H-mode
    - H_{98}\sim 1 H-mode
  - Isotope mass and species scaling (i.e., hydrogen and helium plasmas) of the above regimes
  - Develop strategies for minimizing the power requirements
  - Excellent edge diagnostics
    - Density, temperature and flows
    - Edge fluctuations
  - Assess different heating schemes (ICRF vs. Ohmic vs. LHRF)

- **Thrust 4.** H-mode pedestals
  - *What is the physics of the edge pressure pedestal in high-confinement mode (H-mode) plasmas and how does it integrate with core models of heat and momentum transport?*
  - Comparison of pedestal structure with modeling
  - Test models of the H-mode pedestal structure and of the complete ELM cycle (including low torque)
  - Impact on the H-mode pedestal of
    - Helium or hydrogen operation
    - P_{in}/P_{th}\sim 1
    - Near DN
    - High neutral opacity

- **Thrust 6**: Develop predictive models
  - Strong connection to theory/modeling
  - Essential contributions of data for model validation
In conclusion

- C-Mod makes valuable contributions to pedestal physics relevant to burning plasmas and ITER development
  - L-H transition physics
  - Barrier structure (width, gradient scalings)
  - Edge relaxation mechanisms
- Pedestal program priorities
  - Improving experimental diagnosis of pedestal profiles, fluctuations, edge flows
  - Pedestal studies in an extended range of machine parameters, equilibrium configurations
  - Seeking better understanding of transport, edge stability through modeling, simulation
  - Collaboration with other facilities to develop multi-machine scalings
  - Optimization and control of pedestal in various confinement regimes
  - Support of integrated scenario development
- Poised to make critical contributions to ITER/ITPA goals and FES research targets
End of talk