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
- C-Mod occupies a unique parameter space that complements studies on other devices (large $B/R$, $n_e L$, range of pedestal collisionality)

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

- C-Mod pedestal scalings over *expanded 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
- ELMy regimes
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• ELMy regimes
We have developed an extensive set of well-resolved edge diagnostics

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

- **Thomson scattering** ($T_e, n_e$)
- **CXRS** ($T_\parallel, v_{\parallel\theta}, v_{\parallel\phi}$)
  - 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 ($n_e$ fluct.)
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Pedestal diagnostic set emphasizes \textit{millimeter-resolution} profiles, fluctuations

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Graph showing temperature and poloidal rotation versus distance from separatrix for different plasma modes.}
\end{figure}

\textbf{Student involvement} in diagnostic development is high
Pedestal structure and transport: Edge flows and radial electric field

- **CXRS** is a powerful new tool in our diagnostics set
  - $T_i \sim T_e$ over a wide range in collisionality
  - Strong $v_\theta$ shear in H-mode
  - Strongly negative $E_r$ well develops following L-H transition, typically dominated by $v_\theta$ contribution
  - Providing experimental data on flow coupling from SOL into core

- **Research plans:**
  - Relation of transport reduction, fluctuation suppression, confinement to level of $E_r$ shear in the pedestal region in various confinement regimes
  - **Student led work**: cross-machine comparison of $E_r$ well
    - Relative contributions of flow, diamagnetic components
    - Width – does it scale with machine size?
  - Momentum transport through pedestal
    - What is the source of toroidal rotation?
    - How are the core rotation and SOL flows coupled?
    - Critical for understanding intrinsic rotation in H-mode plasmas without external torque
Pedestal structure and transport: Pedestal width physics

- Pedestal width *nearly invariant* under typical C-Mod operating conditions
  - No apparent scalings with $\rho_\phi$, $\rho_\theta$, $\beta_{pol}$
  - Does not scale with neutral fueling depth
  - Indications that magnetic shear plays a role

- Substantial scaling of $n_e$, $T_e$ pedestal heights, gradients with engineering parameters, topology

- **Research goals**
  - Explore dependence of pedestal structure (width, gradients) on magnetic topology and shape
  - Assess the role of magnetic shear in setting $\Delta$
  - Assess impact of neutral fueling at reduced lower density (*i.e.*, reduced neutral opacity)
Pedestal structure and transport: Gradient limits in edge transport barriers

- Ballooning-like scaling observed in H-modes without ELMs
- Manifested as normalized pressure gradient $\alpha_{\text{MHD}} \sim \nabla p / I_p^2$ decreasing with increasing collisionality $\nu^*$
- Similarly, $\nabla p \sim I_p^2$ scaling seen in near SOL in L-mode, along with substantial evidence of gradient-driven radial flux (details in Boundary talk)
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**Research Plans:** Continued exploration of critical gradient behavior
- Does pressure gradient saturate at lower collisionality? (ELM-dominated?)
- Develop physical understanding of processes that set flux-gradient relationships in the absence of (or between) ELMs
- Examine the pedestal “phase-space” in alternate configurations (e.g. DN, reversed $B_T$, extreme triangularity)
- How does this connect to L-mode critical gradient results in Ohmic plasmas?
Pedestal structure and transport: Fueling

- Density pedestal height determined to leading order by plasma current
- Measured effective particle diffusivity reduced with increasing $I_p$
- Density gradients are stiff to changes in fueling (i.e., via aggressive gas puffing)

![Graph showing the effect of plasma current on density profile](image-url)
Pedestal structure and transport: Fueling

- Density pedestal height determined to leading order by plasma current
- Measured effective particle diffusivity reduced with increasing $I_P$
- Density gradients are stiff to changes in fueling (i.e., via aggressive gas puffing)
- Cryopump provides new tool for fueling modification, collisionality reduction

**Research goals and plans**
- Ongoing studies of profile stiffness, pedestal width, are being extended to lower collisionality
- Neutral emissivity profiles at multiple poloidal locations → enhance the 2D picture of ionization source; inputs to modeling
- Pedestal optimization and control (more later)
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?

- C-Mod H-modes traditionally in **steady-state EDA regime**
- *Continuous transport process* driven by fully electromagnetic **quasi-coherent mode** in pedestal, usually with no ELMs
  - Ballooning-like drive, though discharges ideal-MHD stable
  - Existence favored by higher $q$, $\nu^* \rightarrow$ likely resistive mode
  - Similar fluctuations reported in BOUT simulations (Nevins, Xu, IAEA02)
- Compatible with the appearance of small ELMs at sufficiently high power

- **Research Goal and plans**: Understand the natural QCM drive via additional experimental diagnosis and theory/modeling
  - Extensive measurements available: PCI, magnetics, reflectometry, fast $D_\alpha$
  - Test consistency with resistive ballooning using BOUT code (Umansky)
  - Evaluate other candidate mechanisms (e.g. K-H instability, saturated kink/ballooning mode)
Edge relaxation mechanisms: Edge-Localized Modes

- Large Type I ELMs studied in atypically shaped discharges \((\delta_{\text{lower}}>0.75, \delta_{\text{upper}}\sim0.15)\)
- Smooth transition from EDA to ELMy as edge \(v^*\) is lowered
- Detailed studies made of filamentary structures
- MHD stability of C-Mod discharges analyzed with ELITE
  - Marginal instability to peeling-ballooning modes when large ELMs present
  - Same is true for small ELMs sometimes observed at high power
  - Consistent results found with resistive MHD code M3D
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- **Goals and plans:**
  - Study structure and dynamics of edge filaments in ELMs of varying size
  - Resolve boundaries of relaxation regimes in operational space
  - **Focus on role of shape:** How does shape affect underlying pedestal transport, ELM stability?
  - More efficient stability analysis through importation of data handling codes (T. Osborne, DIII-D)
  - Use stability codes to aid in ELMy discharge development
L-H transition physics: Highlights

- Results suggest a considerable role for *transport-driven edge flows* in determining *L-H power threshold*
  - Strong parallel flows in SOL couple into core across separatrix
  - Provides a co- or counter-current increment to $V_{\phi}$, depending on magnetic topology
  - Points to a possible explanation of the large topology-dependent variation in H-mode power threshold (USN vs. LSN)
  - Threshold extremely sensitive to magnetic balance near DN → potential impact for ITER
- Recent improvements to probes, CXRS diagnostics are connecting SOL flow measurements with core rotation
- Work in progress to refine empirical power thresholds for H-mode access, gain deeper physical understanding of mechanisms that trigger L-H transition
L-H transition physics: Ongoing and future contributions to ITER

- Auxiliary power required for H-mode access a critical issue for ITER mission
- Scaling of low-density limit for L-H transition is an ITER priority
  - C-Mod $n_{LH,\text{min}}$ almost 2x higher than planned ITER target density
  - Dedicated C-Mod experiment demonstrates that $n_{LH,\text{min}}$ does not scale with current
  - Recent experiments exploring the $B_T$ dependence of low-density limit
  - Further work among C-Mod and other devices needed to resolve scaling of limit with $B_T, R$
- ITER considering a He phase for system commissioning
  - Assess H-modes in He plasmas (L-H transition power, confinement properties, comparison of edge relaxation)
- More threshold work near DN (PEP-6)
  - Is there a minimum $P_{LH}$ at exact magnetic balance?

![H-mode Threshold Power](image)

$P_{\text{scaling}} = 3.44 n^{0.47} B_T^{0.65} R^{0.26} \rho^{1.37}$

Standard shape, LSN
$B_T = 5.4$ T
L-H transition physics: Plans

- Understand role of SOL flows, edge rotation shear in ETB formation, through more routine diagnosis of pedestal rotation velocities, $E_r$
- Continue study of unfavorable $\nabla B$ drift discharges
  - 2-phase transitions to H-mode, showing gradual suppression of fluctuations, $T_e$ evolution, followed by L-H bifurcation
  - Slow evolution of edge profiles, flows favorable for resolving L-H transition trigger
- “Improved L-mode”
  - Low particle confinement combined with high energy confinement ($H_{98} \sim 1$)
  - Temperature pedestals of 1keV or greater obtained with benign impurity confinement, steady
  - Suppression of traditional H-mode: Good for burning plasma operation?
Pedestal optimization and control is a developing priority for C-Mod

- H-mode density control challenging due to stiff pedestal transport
- Developing shapes favorable to low-$\nu^*$, high confinement H-modes, in near steady state
  - How is edge relaxation affected by details of shape?
  - Will continue to explore near DN operation

![Graph showing relationship between SSEP (cm) and ne_PED (10^20 m^-3)](image)
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**Other Plans:** Explore external pedestal relaxation, ELM modification
- Lower hybrid in H-mode (more in Adv. Scenarios presentation)
  - Understand density pedestal reduction observed in H-mode with LH
  - Can LHCD control pedestal through magnetic shear modification?
- Magnetic perturbations from external coils
- Triggering continuous edge modes via ICRF
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[Graph showing edge pedestal with LH off and LH on]
Theory and simulation: Plans

• Use measurements to test theoretical predictions of edge $E_r$ and its role in pedestal formation
• Use computational tools to enhance our physical understanding, and contribute data for validation of newest edge codes
• Simulate edge turbulence using BOUT (M. Umansky)
• Continue ELM/EDA studies with ELITE, M3D
• Utilize XGC0 for pedestal transport calculations, with 3D EM turbulence calculated by XGC1 (C.-S. Chang)
• Work closely with Center for Plasma Edge Simulation
  – Code validation
  – Integrated work flow for simulating complex time-dependent edge phenomena (ELM cycle, L-H transition)
## Summary of research goals, objectives and enabling tools

<table>
<thead>
<tr>
<th>Thematic Research Goal</th>
<th>Intermediate Objectives</th>
<th>Enabling Tools</th>
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<tbody>
<tr>
<td>Characterize <strong>pedestal structure</strong> (and its impact on core confinement) in a manner scalable to future devices, through a physics-based understanding of edge plasma and neutral transport</td>
<td>Examine flux-gradient relationships in the ETB in various configurations and operational regimes</td>
<td>SOL TS, CXRS, Ly\textsubscript{a} arrays (Upgrades in 2009—10) Pedestal database enhancements</td>
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<td>Study impact of neutral fueling on pedestal at reduced density/collisionality</td>
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<td>Determine impact of edge magnetic shear on pedestal width</td>
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<td>Characterize momentum transport through the ETB</td>
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<td>Understand the physical processes determining the operational space of <strong>edge relaxation mechanisms</strong> in H-mode</td>
<td>Refine map of edge operational space of ELMs and other transport-regulating modes in experiment</td>
<td>Fast H\textsubscript{α} diode array upgrade (2009); Doppler reflectometry (2011) ELITE, M3D, BOUT, GA toolkit</td>
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<td>Extend the use of MHD stability codes in the identification of edge relaxation mechanisms</td>
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<td>Compare characteristics of QCM with theoretical predictions</td>
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<tr>
<td>Identify critical local parameters needed to trigger <strong>L-H transition</strong>; understand how they relate to global threshold conditions</td>
<td>Diagnose profiles of edge flows, pressure profiles with improved temporal resolution</td>
<td>SOL TS, CXRS, Ly\textsubscript{α} arrays (Upgrades in 2009—10)</td>
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<td>Investigate the evolution of radial electric field shear across the L-H transition, and in slow transitions; explore improved L-mode as a useful operating regime</td>
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<td>Map L-H transition trigger conditions onto non-dimensional phase space; compare with theory</td>
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<td>Identify scaling of low-density limit for H-mode access</td>
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<td>Develop methods for controlling pedestal structure and edge relaxation mechanisms that are compatible with high confinement</td>
<td>Regulate pedestals and confinement via shaping, topology</td>
<td>Correction coil upgrades (2013); Lower hybrid powerlauncher upgrades (2009—10)</td>
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<td>Explore use of externally applied fields to relax pedestals, regulate ELMs</td>
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<td>Utilize LHCD for pedestal/ELM modification</td>
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<td>Investigate RF drive for continuous edge relaxation modes</td>
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<td>Validate edge <strong>simulation</strong> tools currently in development using experimental data</td>
<td>Compare pedestal structure and scalings with edge transport code predictions</td>
<td>XGC0, XGC1, ELITE, M3D; Kepler workflow as developed by CPES</td>
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<td>Validate simulation of dynamic events such as ELM cycle</td>
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## Approximate timetable for pedestal research, 2008—2013

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<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tbody>
<tr>
<td><strong>Pedestal structure and transport</strong></td>
<td>Shape, magnetic shear effects</td>
<td>Neutral fueling, ionization distribution</td>
<td>Flux-gradient relationships</td>
<td>Momentum transport</td>
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<td><strong>Edge relaxation mechanisms</strong></td>
<td>Empirical operational space mapping</td>
<td>ELM and continuous mode characterization with codes</td>
<td>QCM comparison with theory</td>
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<td>Pedestal control</td>
<td>Shaping, topology-based pedestal regulation</td>
<td>External fields</td>
<td>Large r/a LHCD</td>
<td>RF drive for edge modes</td>
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<td>L-H transition</td>
<td>Time-resolved measurements of critical edge parameters</td>
<td>Slow transitions</td>
<td>Non-dimensional mapping of critical edge L-H transition</td>
<td>Low-density limit scaling</td>
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<tr>
<td>Simulation</td>
<td>Pedestal structure, scalings</td>
<td>ELM cycle and other transients</td>
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</table>
Planned research is in alignment with topical questions of 2005 FESAC Report*

- **T1.** How does magnetic field structure impact fusion plasma confinement?
  - Examine H-mode pedestal behavior as a function of shaping, magnetic topology.
  - Study the effects of error fields, resonant perturbations on pedestal structure and edge relaxation mechanisms.

- **T2.** What limits the maximum pressure that can be achieved in laboratory plasmas?
  - Examine edge relaxation mechanisms in various confinement regimes to determine maximum pedestal pressure gradients in each.
  - Characterize pedestal transport both with and without ELMs.
  - Perform linear and non-linear MHD analysis of ELMs and study/simulate inter-ELM transport.

- **T3.** How can external control and plasma self-organization be used to improve fusion performance?
  - Explore techniques for pedestal modification via magnetic field perturbations, and with lower hybrid or ICRF waves.
  - Characterize momentum transport induced in H-mode, and the associated intrinsic rotation.

- **T4.** How does turbulence cause heat, particles, and momentum to escape from plasmas?
  - Relate measured density, magnetic fluctuations to transport in the edge.
  - Study confinement regimes with differing levels of particle and thermal edge transport (H-modes, L-modes, improved L-modes, etc.).
  - Characterize flux-gradient relationships for particle and heat transport across a number of regimes.
  - Explore slow L-H transitions and associated edge flow changes and fluctuation reductions in order to identify critical triggers for L-H bifurcation.

*“Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program”*
Planned research is in alignment with topical questions of 2005 FESAC Report*

- **T5.** How are electromagnetic fields and mass flows generated in plasmas?
  - Exploit high-resolution impurity flow measurements, in concert with background plasma characterization, to understand source of plasma spin-up and intrinsic rotation (Rice scaling)
  - Assess coupling of SOL flows into core
- **T6.** How do magnetic fields in plasmas reconnect and dissipate their energy?
  - Provide experimental data for validation of MHD codes (ELITE, M3D) that will be used to simulate ELM cycle
- **T10.** How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?
  - Characterize upstream decay lengths of pedestal temperature profiles in various confinement regimes, in order to understand power transmission mechanisms in SOL.
  - Refine prediction of power e-folding width for ITER and beyond
- **T11.** How do electromagnetic waves interact with plasma?
  - Explore differences in H-mode power threshold, pedestal parameters with variations in power in ion vs. electron channels

* “Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program”
C-Mod research aligns with specific activities called for in FESAC Report*

- The edge pedestal thrust addresses a highlighted priority issue for ITER: *Predict the formation, structure, and transient evolution of edge transport barriers*

- “Measure steady-state and transient H-mode pedestal profiles over a wide range of operating conditions and geometries, with sufficient resolution to guide theory development.”
- Further develop profile measurements of “parameters, such as ion temperature, flows and $E_r$ . . . to allow more routine operation and inter-machine comparisons.”
- “Measurements of particle sources are needed at several poloidal and toroidal locations.”
- “Multiple experiments spanning a range of dimensional as well as dimensionless parameters are essential,” utilizing “collaboration with international facilities”
- “Compare computer simulations and experimental data over a wide range of plasma parameters to confirm physics understanding.”
- “Investigate promising H-mode regimes and/or edge-localized mode control methodologies that feature reduced transients and improved confinement. . . . Understanding of the access conditions and confinement properties of the various “small” edge-localized mode (ELM) regimes is well behind that of the standard Type I ELMy H-mode. . . . an active means to control [ELM] size, without decreasing confinement, may be required.”

* “Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program”
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”*
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
  - Define magnetic field structure and magnitude required for ELM control, accounting for plasma response and field penetration
  - 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 will continue our fruitful inter-machine collaborations through ITPA.

<table>
<thead>
<tr>
<th>Description</th>
<th>ITPA designation</th>
<th>Notes on C-Mod contributions</th>
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<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 will be compared in terms of profile structure and ELM stability. We will examine whether a local minimum in L-H threshold power exists at exactly DN.</td>
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<tr>
<td>Pedestal width analysis by dimensionless edge identity experiments</td>
<td>PEP-7</td>
<td>Discharges were designed to match non-dimensionally complementary JET discharges, with results being prepared for publication. Additional devices may add similarly matched discharges.</td>
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<tr>
<td>Comparison of small ELM regimes</td>
<td>PEP-13</td>
<td>q and n* scans with high input power to map out boundaries of small ELM regimes</td>
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<tr>
<td>Small ELM regime comparison on C-Mod, NSTX and MAST</td>
<td>PEP-16</td>
<td>Experiments have accessed high power H-modes in double and single null configurations, achieving ELMy regimes for further study</td>
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<td>Low density limit for L-H transitions</td>
<td>CDB-11</td>
<td>Providing data at high field, and evaluating impact of wall conditions, character of edge fueling</td>
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</table>
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