C-Mod Pedestal Program

Alcator C-Mod Program Advisory Committee Meeting
March 2—4, 2011
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 a number of topical science areas and programmatic thrusts, and research contributes to FES, 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, but investigations will continue well 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:
- L-H thresholds and transition physics
- Pedestal structure and transport, edge relaxation mechanisms in H-modes and I-modes
- Pedestal control
- Theory and simulation
C-Mod exploits large range of operational space for pedestal studies

- Pedestal can be studied over extensive parameter space
  - $2.4 < B_T [T] < 8.0$
  - $0.4 < I_p [MA] < 1.7$
  - $<n_e> \sim 1 - \text{6} \times 10^{20} \text{m}^{-3}$
  - $1 < P_{in} [\text{MW}] < 7$
  - $1.4 < \kappa < 1.8$
  - $\delta_U, \delta_L$ from $\sim 0.2$ to $\sim 0.8$

- Operation with “alternate” magnetic topology
  - Unfavorable ion $\nabla B$ drift direction (in both normal and reversed $B_T$ direction)
  - Near double null

- Experiments generally compatible with cryopumping, low-Z impurity seeding
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- Experiments generally compatible with cryopumping, low-Z impurity seeding
- Several confinement regimes with edge pedestal are accessed
  - EDA H-mode (high density pedestal, $\nu^*_{ped} > 1$)
  - ELMy H-mode (reduced density pedestal, $\nu^*_{ped} < 1$)
  - I-mode (no significant density pedestal, $\nu^*_{ped} < 1$)
Pedestal diagnostic set is extensive, and continually improving

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

- **Thomson scattering** \( (T_e, n_e) \)
- **CXRS** \((T_I, v_{\theta I}, v_{\phi I})\)
  - LFS toroidal, poloidal views (passive, DNB-enhanced, gas-puff assisted poloidal view)
  - HFS toroidal, poloidal views (passive and gas-puff assisted)
- **Scanning Mach probes**, HFS+LFS \( (T_e, n_e, v) \)
  - Available probe heads include radially spaced LPs, magnetic pick-up coil
  - Fluctuation measurements possible, including \( T_e \)
- **Electron cyclotron emission** \( (T_e) \)
- **Visible bremsstrahlung** \( (n_e Z_{\text{eff}}^{1/2}) \)
- **Soft x-ray emission, bolometry** \( (n_I, \text{impurity radiation}) \)
- **Neutral emissivity**
- **Gas puff imaging** \( (n_e/T_e, \text{fluctuations}) \)
- **O-mode reflectometer** \( (n_e, \text{fluctuations}) \)
- **X-mode reflectometer** \( (n_e, \text{perturbations}) \)
- **Phase-contrast imaging** \( (n_e, \text{fluctuations}) \)
C-Mod participates in an ITPA task force on H-mode threshold physics

- Strong connection to ITER Baseline Scenario priorities [see talk by Wolfe]
- Research is focused on answering:
  - What are the edge conditions needed to trigger H-mode formation?
  - How does this relate to power threshold?
  - Can we improve extrapolation to ITER?

- Recent experimental work has examined the effects of potential “hidden variables”
  - Fueling location and the role of neutrals in suppressing L-H transition at high density
  - Reduced $P_{th}$ in near DN (PEP-6)
  - Dependence on X-point position and/or outer leg length (PEP-28)
  - Sensitivity to power deposition profile tested by moving ICRF resonance location

![Graph showing relationship between $P_{th}$ (MW) and Length of outer leg (cm)]
L-H threshold studies need to move beyond simple scaling laws

- Known issue of increased H-mode power threshold at low density is a concern for ITER
  - C-Mod, DIII-D, JET, AUG, TCV are analyzing data at varied I_p, B_T, R_maj (ITPA JEX TC-3)
  - Elevated edge T_e, and gradient observed prior to H-mode transition at low density; appearance of I-mode

- Plans
  - Renewed focus on local edge parameters at threshold (PEP-26): ’11—’13
  - Understand role of SOL flows, edge rotation shear in ETB formation, through more routine diagnosis of pedestal rotation velocities, E_r : ’12—’13
  - Characterize density, flow profiles preceding L-H with increased time resolution ’12—’13
  - Analysis of data aided by a multi-machine edge profile database, complementing the traditional scalar DB: ’11—’13+
C-Mod data are used to test models for pedestal structure

- **Recent progress**
  - Extensive ELMy H-mode data set has been obtained for testing EPED class of models (collaboration with GA)
    - 0.7—1.0MA, 5.4—8.0T; soon extend to 3.5T
    - $\kappa$ from 1.45 to 1.6
  - Strong diamagnetic effects on C-Mod motivated the addition of more accurate calculation of diamagnetic stabilization

- **Plans**
  - Mapping of peeling-ballooning stability boundary with ELITE, comparisons with BOUT++ ’11—’12
    - Include I-mode, ELM-free regimes in stability studies
    - Evaluate both conventional and modified models for bootstrap current
  - Validate EPED1.6 and follow-on models ’11—’13
  - Compare with neoclassical calculation of pedestal structure (XGC0) ’11—’12
  - Compare to paleoclassical predictions ’11—’12
  - Participate in joint experiments (including dimensionless matching where feasible) with DIII-D, JET, AUG (PEP-2) ’11—’12
Additional studies are planned in pedestal structure and transport

- Impurity transport: Exploit HFS/LFS CXRS diagnostics: ’11—12
  - Diagnose impurity transport coefficients in pedestal
  - Characterize in/out asymmetries in impurity profiles
  - Comparison of edge impurity flow velocities, $E_r$ with theory, simulation
- Study pedestal neutral and impurity transport for low-Z impurity seeded H-modes (Ne, N$_2$) ’13—’14
  - Investigate 2D radiation layer with increased radial and poloidal resolution
  - Measure 2D Ly$_\alpha$ emission to characterize CX neutral power loss
  - Impurity fluctuations and QCM response to large impurity fractions ($f_Z$~1-2%)
- Enhance the 2D picture of ionization source $\rightarrow$ inputs to modeling: ’12—13
  - Take advantage of neutral emissivity profiles at multiple poloidal locations
  - Modeling to facilitate interpretation of these measurements (B2-EIRENE, OEDGE)
  - High-power experiments at high neutral opacity to test limits of H-mode edge fueling, assess pinch
  - What happens to pedestal at ITER $B_T$, $q$ as ITER neutral opacity is approached?
Studying pedestal-limiting mechanisms 
*between or in the absence of ELMs*

- **Can we understand drive mechanisms and the confinement regulation?**
  - Q: Are small-ELM or no-ELM regimes compatible with a high-confinement ITER pedestal?
- Emphasis on two continuous relaxation regimes
  - EDA H-mode ($\nu^* > 1$), regulated by quasi-coherent mode
  - I-mode ($\nu^* > 1$), regulated by weakly coherent mode (*more later*)
- **EDA H-mode plans**
- Concerted effort to study the QCM in steady state with BOUT, M3D: '11—'12
- Renewed analysis of time-evolving data, correlations between turbulence and pedestal saturation ’12—’13
  - Linear stability analysis of evolving pedestal (e.g. GS2, TGLF)
  - New experiments will incorporate fast reflectometry, perhaps fast CXRS

### Multiple L-H transitions used to characterize pedestal evolution

- Maximum $p_e$ gradient in pedestal
- PCI fluctuations for Shot 1091210017
  - Channel = 17

### Time (s)

-0.02 0.00 0.02 0.04 0.06 0.08

-0.0 0.5 1.0 1.5 2.0 2.5

- $n_e$ [m$^{-3}$]
- $H_a$ [T]
- $\partial n_e / \partial r$ [mP$^{-1}$/m]
- Freq [kHz]
Edge modification by external means has potential for expanding pedestal studies

- Will continue extending studies of lower hybrid wave effects on the pedestal ’11—’12
  - LHRF injected into H-modes can give up to 30% reduction in pedestal density, while maintaining similar energy confinement
  - Recently achieved effects at low LH power levels, with inaccessible core plasmas
- Plans for LHRF as a control tool
  - Extend operational range of density pedestal regulation ’12
  - Attempt to change, perhaps control ELM quality (PEP-22): ’12
  - Examine connections to the physics of the low-density limit for wave penetration [see LH talks]
- Explore tools for external stimulation of continuous modes in pedestal: ’11—’13
  - ICRF modulation
  - Attempt direct stimulation of QCM, WCM modes with a dedicated antenna [more in Boundary talk]
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Operation in I-mode decouples transport of particles and energy in the pedestal

- High energy confinement ($H_{98} \sim 1$) obtained with particle/impurity transport of L-mode
- More readily obtained when H-mode threshold is high
  - Often seen with unfavorable $\nabla B$ drift
  - In favorable drift cases at low density, atypical shaping
- Distinct temperature pedestals of (~1keV in some cases) are obtained with flat density profiles
- Edge fluctuations differ from those in L-mode
  - Reduced broadband turbulence at ~50-150kHz
  - Weakly coherent mode (WCM) at ~250kHz
- Recent focus on operational optimization and utilization of the regime [see Alt. Scenarios talk]

Hubbard, APS '10
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Hubbard, APS ’10
Pedestal and H-mode threshold research is enhanced by I-mode studies

Two key I-mode physics questions:
(1) What is preventing transition into H-mode?
(2) Why are edge particle and energy transport so well decoupled?

- Perform profile, stability analyses for comparison with H-modes: ’11—’12
- Examine conditions for existence of WCM. Thresholds in local gradients? ’11—’12
- Fluctuations and transport: is the WCM responsible for enhanced particle/impurity transport (analogous to QCM in EDA H-mode)? ’11—’13
  - Effective particle transport inferred from measurement, coupled with fluctuation characterization
  - Cross-correlate $T_e$, $n_e$ fluctuations in I- and H-mode

- Study physics of H-mode suppression ’11—’13
  - Edge flow shear, $E_r$ measurements
- New ITPA joint experiments ’11—’12
  - Dimensionless comparison between C-Mod and AUG

Hubbard, APS ’10
C-Mod data are used to test pedestal models and for edge code validation

- Test theoretical predictions of edge $E_r$, flows, pedestal impurity asymmetries
- Analyze roles of pedestal/SOL flows, neutral particles, and the quasi-coherent mode on pedestal structure using fluid transport and turbulence codes UEDGE and BOUT (LLNL)
- Evaluate neoclassical transport from NEO and XGC0 (GA, CPES)
- Ongoing comparisons to the EPED model for pedestal structure (GA)
- Continue ELM stability studies (GA, LLNL, MIT, CPES)
  - Characterization of peeling-ballooning mode stability boundary with ELITE, BOUT++, using variation in edge current/pressure gradient; What is the impact of varying model for pedestal bootstrap current?
  - Evaluate effects of extended and two-fluid MHD terms with M3D code
  - Quantitatively assess impact of dissipation, rotation, and diamagnetic stabilization
- Explore use of GYRO, TGLF in pedestal region (GA, LLNL)
  - Linear growth rates for ETG, TEM, KBM
  - Assess feasibility of nonlinear gyrokinetic simulations and comparison to turbulence measurements
- Validation of full-f guiding center simulation with EM turbulence: XGC1 (CPES)
- Compare profile scale lengths, transport coefficients to paleoclassical theory

Collaborators are an essential resource in this effort! FY11 JRT has helped with this.
Expectations for research priorities through FY13

- **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

- **FY11—12**
  - Compare pedestal structure with available models, code predictions
  - Pursue simulations of continuous relaxation mechanisms to understand physical drive
  - Relation of particle, thermal transport to fluctuations, ExB shear suppression in ELMy, EDA H-mode, I-mode
  - Explore possible ELM modification with LHRF
  - Study trigger conditions for H-mode transitions, relating edge profile characteristics to power thresholds

- **FY12—13**
  - Evaluate impact of edge fueling on pedestal transport/structure, with improved neutral measurements/modeling
  - Examine role of pedestal in spontaneous flow generation
  - Detailed examination of edge radiation effects on pedestal in high-performance seeded discharges
We are positioned to contribute to a number of ITER/ITPA priority tasks

• Improve predictive capability of pedestal structure
  – Cross machine comparisons to isolate physics setting pedestal width
  – Comparison with theoretical predictions
  – Dependence of pedestal quality on heating source
  – Characteristics of the H-mode when the power is marginally above threshold
  – Dependence on ion species
  – Examine core fueling efficiency at neutral opacity approaching that of ITER
  – Improve predictive and design capability for small ELM and quiescent H-mode regimes and ELM control techniques

• L-H transitions and power threshold
  – Impact of radiated power
  – Impact of plasma heating mechanism and the impact of momentum injection.
  – Back-transition thresholds to reduced performance (e.g. Type III or dithering H-mode, L-mode)
  – Effect of current ramps
  – Plasma ion species
  – Power threshold at low density
We participate in (and lead*) inter-machine collaborations through ITPA

<table>
<thead>
<tr>
<th>Description</th>
<th>JEX</th>
<th>C-Mod contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestal gradients and ELM energy losses in dimensionally similar discharges and their dimensionless scaling</td>
<td>PEP-2</td>
<td>Augment ongoing pedestal width scaling studies in ELMy H-mode; designing compatible dimensionless matched discharges for comparison to DIII-D, JET and AUG</td>
</tr>
<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. H-mode power threshold reduction near DN evaluated</td>
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<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>
</tr>
<tr>
<td>Controllability of pedestal and ELM characteristics by edge ECH/ECCD/LHCD</td>
<td>PEP-22</td>
<td>Examine effects of edge CD, electron heating on pedestal transport, ELM stability</td>
</tr>
<tr>
<td>Critical edge parameters for achieving L-H transition</td>
<td>PEP-26*</td>
<td>Assemble data sets of edge profiles in density scans and analyze for radially localized L-H triggers</td>
</tr>
<tr>
<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>
</tr>
<tr>
<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</td>
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<tr>
<td>Vertical jolts/kicks for ELM triggering and control</td>
<td>PEP-29</td>
<td>Experiments to trigger and/or pace ELMs</td>
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* Pink = Successfully closed in 2010
* Cyan = New for 2011
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<td>Pedestal structure and edge relaxation mechanisms in I-mode</td>
<td>PEP-31*</td>
<td>Characterize edge profiles, including flows, and fluctuation induced transport over a range of operational space</td>
</tr>
<tr>
<td>Effect of current ramps on the L-H transition and on the stability and confinement of H-modes at low power above the threshold</td>
<td>PEP-33</td>
<td>Utilize prior experience with H-mode formation and sustainment in ITER-relevant discharges to develop further experiments</td>
</tr>
<tr>
<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>
</tr>
<tr>
<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>
</tr>
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<td>Dimensionless Identity Experiments in I-Mode</td>
<td>TC-18</td>
<td>Provide target I-modes with well-characterized edge profiles/fluctuations for AUG, and possibly DIII-D, to match</td>
</tr>
<tr>
<td>Characteristics of I-mode plasmas</td>
<td>TC-19*</td>
<td>Document access conditions, power scaling with target density, plasma current and shape; compare with H-mode</td>
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Cyan = New for 2011
In conclusion

• C-Mod makes key 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 results
  – 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