Progress in characterizing pedestal structure and stability on Alcator C-Mod

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53rd Meeting of the APS Division of Plasma Physics
Salt Lake City
15 November 2011
JO4.00002
Goal: Better understanding of the edge pedestal through combined experiment and modeling

- Developing *predictive capability for the edge pedestal* in tokamaks is highly desirable to projecting performance on ITER
  - Focus of the FY11 FES Joint Research Target among US facilities, modeling groups

- Pedestal structure and relaxation mechanisms (ELMs, continuous modes) characterized in C-Mod high-performance plasmas

- Models for pedestal structure, stability are evaluated

- This talk will contrast:
  - (a) *ELMy H-mode*
  - (b) *Enhanced D-alpha (EDA) H-mode*

  - I-mode will be discussed in separate presentations
    - Dominguez, JO4.00004 (this session)
    - Whyte, NO4.00011 (Wed AM)
    - Marmar, YI2.00003 (Fri AM)
Modified shaping promotes transition from *EDA* to *ELMy* H-mode on Alcator C-Mod

\[ B_T = 5.4 \text{T} \]
\[ I_p = 0.9 \text{MA} \]

Both *EDA* and *ELMy* H-modes relatively stationary

Edge relaxation very different

\[ \delta_{\text{upper}} \sim 0.2 \]
\[ \delta_{\text{upper}} \sim 0.3 \]

\[ \delta_{\text{lower}} \sim 0.45 \]
\[ \delta_{\text{lower}} \sim 0.8 \]
Transition from EDA to ELMs associated with collisionality reduction + wider pedestal

- H-modes with similar performance compared
- Modeled current profile similar in peak value, but with greater radial extent in ELMy case

\[ n_e \left(10^{20} \text{m}^{-3}\right) \]

\[ B_T = 5.4 \text{T} \]
\[ I_p = 0.9 \text{MA} \]
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

- Prior studies mostly restricted to 5.4T, 0.9MA, low elongation
- New data:
  - $0.45 < I_p [\text{MA}] < 1.05$
  - $3.5 < B_T [\text{T}] < 8.0$
  - $1.42 < \kappa < 1.56$

- Width data consistent with $\beta_p^{1/2}$ scaling, with little or no trend on other parameters
  - Consistent with trends observed on DIII-D, JET, NSTX, MAST
  - Consistent with a pedestal limited by kinetic ballooning mode (KBM) stability

- Need additional physical mechanism to limit total pedestal pressure
ELITE: C-Mod ELMs associated with peeling-ballooning instability

- Coupled pressure gradient and edge current driven instabilities, seen to be linearly unstable before Type-I ELMs on a number of devices
- Proximity to stability boundary now demonstrated in C-Mod ELMy H-mode
Stability calculation confirmed with similar \textit{ELMy H-modes} on DIII-D

- Recent experiment on DIII-D to match C-Mod non-dimensional parameters at pedestal top: $\beta$, $v^*$, $\rho^*$
- Similarities observed in experimental ELM signatures, inter-ELM fluctuations
- Stability diagrams, edge mode structure, and experimental operating point all similar
EPED model reproduces ELMy H-mode pedestal structure on C-Mod

- EPED model simultaneously solves:
  
  (a) Pedestal width constrained by kinetic ballooning modes \( \Delta \sim p_{ped}^{1/2} \)
  
  (b) Pedestal height limited by PBMs \( p_{ped} \sim \Delta^{3/4} \)

- (a), (b) appear well satisfied in C-Mod, as on other devices

- Height/width predictions agree over a wide range of experimental conditions

C-Mod significantly extends the range of validation of EPED predictive capability
EDA H-mode is a naturally ELM-suppressed regime with continuous pedestal regulation

- Pedestal saturation and stationary H-mode established typically in <100ms

- Enhanced $D_\alpha$; no ELMs needed to regulate particles/impurities

- Pressure pedestal saturation accompanied by onset and growth of ~100kHz fluctuation in edge density, magnetic field --- quasi-coherent mode (QCM)

- Small ELMs are observed in EDA H-modes at sufficiently high power, but these cases are not considered here
EDA H-mode tends to operate in a region stable to peeling-ballooning modes.
Stability window significantly reduced in differently shaped ELMy target

Note: Wider ELMy pedestal means similar plasma $\beta$ accessed despite smaller pedestal $\alpha$. 
BOUT++ simulation finds edge resistivity important for stability in *EDA H-mode*

- BOUT++ is an initial value code capable of calculating non-linear fluid edge turbulence → can investigate effects of resistivity, diamagnetism on pedestal stability
  - EDA H-mode found ideally stable, but increased $\eta$ increases linear growth rates
  - Diamagnetism stabilizes higher $n$ modes

\[
S = \frac{\mu_0 a v_A}{\eta}
\]

$n=15$ Growth Rate vs. Pedestal Resistivity

Growth Rate vs. Toroidal Mode Number

Davis, UP9.00008 (Thurs PM)
Additional effort needed to understand turbulence and transport in EDA pedestal

- BOUT++ results suggestive of resistive ballooning modes with $5 < n < 25$ being a dominant pedestal relaxation mechanism in the EDA H-mode
- Would be consistent with empirical observations
  - QCM activity favored by higher $n^*, q, m_i$
  - EDA can sometimes be “burned through” at high power to yield ELMs $\rightarrow$ transition to ideal instability
- Analysis of fully non-linear calculations needed to study fully developed turbulence

- Improved understanding of pedestal stability, turbulence-driven transport $\rightarrow$ an EPED-like model for pedestal structure in ELM-suppressed H-mode?

- Simulations of EDA H-modes with additional codes (SOLT, 2DX, M3D) are being pursued
  - Russell, JO4.00007; Myra, JO4.00008; this session
  - Sugiyama, JP9.00094 (Tues PM)
Key results and near term plans

• ELMy H-mode
  – Pedestal scalings agree with expectations from height, width limits imposed by a mix of KBMs, PBM)s
  – Linear peeling-balloonning mode calculations with ELITE show proximity to stability boundary
  – Tests of EPED model successfully extended using C-Mod data
  – *New experiments are proposed to seek signatures of KBM in fluctuations*

• EDA H-mode
  – Calculations with ELITE and BOUT++ show EDA pedestal is ideal MHD stable
  – BOUT++ resistive calculation with diamagnetic stabilization yields finite linear growth rates and shows promising consistency with experimental QCM
  – *Analysis of non-linear simulations should predict turbulence driven transport*
  – Higher v* H-modes favor EDA, even in atypical shape; *will allow comparison of pedestal structure and stability of EDA and ELMy H-modes for fixed shaping*
  – *Attempts to stimulate continuous edge fluctuations – “QCM antenna”*
    • LaBombard, Golfinopoulos: UP9.00016,17