Investigation of ELMs on Alcator C-Mod


MIT - Plasma Science and Fusion Center
*Univ. of Texas at Austin - Fusion Research Center
†General Atomics

American Physical Society - Div. of Plasma Physics
Philadelphia, PA Oct. 29 - Nov. 3
Motivation and Introduction

- Understanding ELMs is of crucial importance both because of they limit the pedestal pressure gradient and because of danger they pose to the first wall and divertor
  - Large, discrete ELMs are typically NOT present in C-Mod discharges
    - EDA H-mode with the "Quasi-Coherent Mode" as the pedestal relaxation mechanism is typical

- Recently, a new region of operational space has been accessed where discrete, relatively large ELMs are common
  - We present here results of an investigation of those ELMs:
    - "Global" characteristics: plasma parameters, ELM energetics, edge stability
    - ELM dynamics: precursor oscillation, pedestal/SOL perturbation, filament ejection, filament propagation, relative timing of ELM perturbations
Core Plasma Characteristics

- non-typical shape for C-Mod
  - lower > 0.75, upper~0.15

- Confinement can be good in these ELMing H-modes (H_{ITER98(y,2)} ≥1)

- these discharges exhibit other interesting transport properties, see M. Greenwald in C-Mod Oral Session Tues. afternoon

\[ n_e \text{ typically low with } n_{eo} \approx 2 \times 10^{20} \text{ m}^{-3} \]
non-typical shape for C-Mod
\[ n_{\text{lower}} > 0.75, \quad n_{\text{upper}} \sim 0.15 \]

- Confinement can be good in these ELMing H-modes (\( H_{\text{ITER98(y,2)} \geq 1} \))

- these discharges exhibit other interesting transport properties, see M. Greenwald in C-Mod Oral Session Tues. afternoon

- \( T_{\text{eo}} > 4 \text{ keV} \)
- \( P_{\text{rf}} (\text{MW}) \)
- \( n_{\text{eo}} (10^{20}/\text{m}^3) \)
- \( n_{\text{e}} \) typically low with \( n_{\text{eo}} \sim 2 \times 10^{20} \text{ m}^{-3} \)
- \( H_{\text{ITER98(y,2)}} \) factor
Edge Operational Space for Pedestal Relaxation in "Non-typical" Shape

- ELMs occur at relatively low $\nu^*$ ($0.2 < \nu^* < 1$)
  - discrete ELMs, variable size, probably Type I
  - small ELMs with EDA, at high power & pressure
- steady EDA, QC mode, no ELMs

for $q_{95} \sim 3.5$, $\nu_{lower} > 0.7$
$Z_{eff}$ taken to be 1
**ELM Pedestal Energetics**

- Energy loss per ELM typically 10-25% of $W_{\text{ped}}$
  
- 10% loss in $T_{\text{ped}}$

- $n_{\text{e}}^{\text{pedestal}}$ loss is less certain, but in range $0 < \Delta n_{\text{e}} < 15$

- Consistent with multi-machine observations for Type I ELMs

- Pedestal is not destroyed by ELM

---

**Graph:**
- Time series plot showing $T_{\text{e}}$ vs. $t-t_{\text{crash}}$
  
- Consistent with multi-machine observations for Type I ELMs from A. Loarte, et al., JNM 313-316 (2003)

---

**Figure:**
- Comparison of $W_{\text{ELM}}/W_{\text{ped}}$ for various devices:
  - JET
  - JT-60U
  - DIII-D
  - ASDEX-U

---

**Note:**
- Data from A. Loarte, et al., JNM 313-316 (2003)
ELM Dynamics Investigated using Magnetic-pickup-coils, D\(_\parallel\) Gas-Puff-Imaging, and ECE

- B\(_{\text{dot}}\) coils - very close to plasma edge (typically 2.5 cm from sepx.)
  - 6 different toroidal locations at 2 different poloidal angles

Top View

B\(_{\text{dot}}\) coils very close to plasma

limiter

Top View
ELM Dynamics Investigated using Magnetic-pickup-coils, DIII Gas-Puff-Imaging, and ECE

- GPI localizes emission toroidally
  - primarily sensitive to changes in $n_e$, with some sensitivity to changes in $T_e$
Fine Time-scale ELM Evolution

H-mode pedestal close to stability boundary

peeling/ballooning mode growth

"filaments" ejected

end with ~10% of $W_{\text{ped}}$ lost

 dB $\sqrt{q}$ /dt

t - t_{filament start} (s)

before filament image during ejection

Radial Vertical

1 cm
ELM Precursor

- frequencies: 200-400 kHz, slowing to 70-100 kHz
- toroidal mode number is around 10, constant during growth phase
- precursor oscillation begins growing - often with large growth rate
- osc. seen on outboard GPI emission with radial location in and at top of pedestal, radial structure seen
- at filament ejection, a higher freq. perturbation (0.5-1 MHz) is seen, the "hi-freq mag. osc."
  - use its onset as $t=0$ from now on
Pedestal Stability Analysis using MHD codes
ELITE (ideal MHD) and M3D (extended MHD)
2 atypically-shaped EFIT equilibria analyzed (meas. ped. press. profiles used)

ELITE:
large $\left| \frac{dP}{dr} \right|$ case
- $\square_{\text{MHD}}^{\text{ped}} = 8.8$
- $n > 15$ unstable

medium $\left| \frac{dP}{dr} \right|$ case
- $\square_{\text{MHD}}^{\text{ped}} = 3.9$
- all $n$ stable

M3D:
press. pert. ($n=12$)
both cases unstable to $n=6, 12, 20$ modes

prelim. conclusions:
- ELMing pedestals are close to and sometimes exceed peeling/ballooning instability boundary,
- for unstable case, modes are predominantly ballooning with weaker peeling component
- including previous ELITE analyses of equilibria of typical C-Mod shape, these atypical shapes are less stable for similar pedestal profiles

*see L. Sugiyama (Thurs. morn.)
ELM Dynamics in Radial Dimension - GPI D$^\alpha$ emission

2 frames from (6 s/fr) movie

before filament ejection

during filament ejection (12 ms after frame on left)

- much more complex time history with multiple ejections apparent from the radial array of views
- "primary" ejection occurs after ped. is perturbed
ELM Dynamics in Radial Dimension - GPI D\textsuperscript{\alpha} emission

time of "primary" ejection
onset of outboard perturbation

Alcator C-Mod

APS-2006 (12a)
ELM Dynamics in Radial Dimension - GPI D³ emission

- "primary" propagates rapidly outward with radial velocities ~0.5 to >6 km/s

![Graph showing distribution of ELM primary emissions and radial velocities](image)

- Time of "primary" ejection
- Onset of outboard perturbation

D³ monitor

Alcator C-Mod

APS-2006 (12b)
ELM Dynamics in Radial Dimension - GPI D$^\alpha$ emission

- characteristic radial size of "primary"
  $\sim$0.5-1 cm
- consistent with 2D movie images
ELM Dynamics in Radial Dimension - GPI D\textsuperscript{a} emission

- multiple "secondaries" occur after "primary"
- typically slower than "primary"

likely that not all secondaries are seen in limited view
The "Hi-Frequency Magnetic Oscillation"

- Onset of "hi-freq. mag. osc." is nearly simultaneous on coils separated toroidally and poloidally - with systematic differences of up to \( \sim 10 \) ms

- Onset of "hi-freq. mag. osc." nearly coincident with onset of filament ejection

Freq. spectrum of hi-pass-filtered dB/dt sig.

\[ f = 0, Z = 0.1 \text{m} \]

\[ f = -2^\circ \]

\[ f = -5^\circ \]

\[ f = 159^\circ \]

\[ f = 160^\circ \]

\[ f = 164^\circ \]
ECE Observations during ELM

- Onsets of $T_{e\text{ ped}}$ pert. and "hi-freq. mag. osc." are nearly coincident
- Non-thermal emission present during filament ejection since effective $T_{\text{rad}} > T_{e\text{ ped}}$
GPI Observations at Inboard Edge

- No mode observed on inboard edge
- No filaments observed in inboard SOL
- However, inboard edge is perturbed
  - Onset of pert. occurs during precursor growth phase, before outboard filament ejection
  - Perturbation propagates into the inboard SOL and appears to be a relaxation
Time-Sequence of ELM Perturbations

- t=0 taken to be onset of "hi-freq. magnetic oscillation"
- Onset of rapid growth of magnetic precursor amplitude: ~40 ms before
Time-Sequence of ELM Perturbations

- \( t=0 \) taken to be onset of "hi-freq. magnetic oscillation"
- Onset of rapid growth of magnetic precursor amplitude: \( \sim 40 \) s before
- Onset of density (GPI) perturbation on outboard edge: \( \sim 10-20 \) s before
Time-Sequence of ELM Perturbations

- $t=0$ taken to be onset of "hi-freq. magnetic oscillation"
- Onset of rapid growth of magnetic precursor amplitude: $\sim 40$ ms before
- Onset of density (GPI) perturbation on outboard edge: $\sim 10-20$ ms before
- Onset of density (GPI) perturbation on inboard edge: $\sim 10$ ms before
Time-Sequence of ELM Perturbations

- t=0 taken to be onset of "hi-freq. magnetic oscillation"
- Onset of rapid growth of magnetic precursor amplitude: ~40 ms before
- Onset of density (GPI) perturbation on outboard edge: ~10-20 ms before
- Onset of density (GPI) perturbation on inboard edge: ~10 ms before
- Onset of (outboard) $T_e$ perturbation: ~coincident
Time-Sequence of ELM Perturbations

- t=0 taken to be onset of "hi-freq. magnetic oscillation"
- Onset of rapid growth of magnetic precursor amplitude: ~40 ms before
- Onset of density (GPI) perturbation on outboard edge: ~10-20 ms before
- Onset of density (GPI) perturbation on inboard edge: ~10 ms before
- Onset of (outboard) Te perturbation: ~coincident
- Onset of (outboard) filament ejection: ~coincident
- often two "primaries" are seen (~10 ms separation) → there is not a single "primary" filament
ELM Dynamics in Poloidal Dimension - GPI Dα emission

- often two "primaries" are seen (∼10 ms separation) → there is not a single "primary" filament
- poloidal size of "primary" is > the 4.5 cm field-of-view
- often two "primaries" are seen (~10 ms separation) → there is not a single "primary" filament
- poloidal size of "primary" is > the 4.5 cm field-of-view
- over this poloidal f-o-v, "primary" moves out radially (consistent with movie)
- upper part precedes lower
Speculations about ELM Filament Ejection
- clearly a 3D non-linear phenomenon

- Strong evidence against ejection as an ideal MHD phenomenon, with field "frozen into" plasma filament, since \( \frac{V_{rad}}{C_s} \approx 1 \) is clearly not observed

- Evidence for ejection as electrostatic ExB convection
  - Similar to "blob" radial convection (likely electrostatic ExB)
  - \( \frac{V_{rad}}{C_s} \approx 1\% \)
  - Observe poloidal variation in outboard filament ejection
  - ELITE & M3D simulations show unstable modes with poloidal variation within flux surface

* acknowledgement to A. Boozer - Columbia Univ. and V. Naulin - JET for helpful discussions
Speculations about ELM Filament Ejection
- clearly a 3D non-linear phenomenon

Possible Evidence for Magnetic Reconnection (MR)
- ECE shows "filament" with non-thermal emission yielding effective $T_{\text{rad}} > 1$ keV in SOL, a result of MR causing parallel electron acceleration
- "filament" ejection coincident with onset of "hi-freq. magnetic oscillation", with the oscillation showing a broadly peaked 0.5-1 MHz spectrum

- MR near X-point causes Alfven wavepacket to bounce back and forth between high-shear X-pt regions, i.e. along field line of length=$2\frac{R}{q_{95}}$

  $\text{bounce freq} = \frac{V_{\text{Alfven}}}{2\frac{R}{q_{95}}} = 0.5 \text{ MHz for C-Mod}$

* acknowledgement to A. Boozer - Columbia Univ. and V. Naulin - JET for helpful discussions
ELM Evolution Paradigm - Summary

- Precursor oscillation, \( n \sim 10 \), cntr-\( l_p \) rotation, localized in outboard ped., grows rapidly before filament ejection
- Rapid mode growth precedes filament ejection by \( \sim 40 \) s
- No mode evident at inboard SOL - yet inboard SOL responds to perturbation before ejection
- Modeling with ELITE and M3D yield unstable modes for \( n > 15 \) (ELITE), for \( n = 6, 12, 20 \) (M3D)
  Implication: non-typical shape unfavorable for ped stability

- Complex structure of filaments observed in single ELM event
- "Primary" filaments propagate radially thru outboard SOL with \( V_r \) of 0.5-7 km/s; radial size \( \sim 1 \) cm; poloidal size >4.5 cm
- Multiple "secondary" filaments follow
- "Primary" ejection coincident with 0.5-1MHz hi-freq magnetic oscillation & onset of \( T_{e\text{ped}} \) decrease
- Non-thermal ECE emission observed in outboard SOL coincident with "primary"