Suppression of large edge localized modes with a stochastic magnetic boundary in high confinement DIII-D plasmas

Presented by

T. E. Evans
General Atomics, San Diego, CA, USA

With contributions from:
R. A. Moyer, J. A. Boedo, D. L. Rudakov - UCSD, La Jolla, CA, USA
J. G. Watkins - Sandia National Laboratories, USA
M. Becoulet, P. R. Thomas - CEA Cadarache, France
M. E. Fenstermacher, M. Groth, C. J. Lasnier - LLNL, CA, USA
K. H. Finken - FZ-Jülich, Germany
J. H. Harris, D. G. Pretty - Australian National University, Australia
E. J. Doyle, T. L. Rhodes, G. Wang, L. Zeng - UCLA, Los Angeles, CA, USA
S. Masuzaki, N. Ohyabu - National Institute for Fusion Science, Gifu-ken, Japan
H. Reimerdes - Columbia University, New York, NY, USA
M. R. Wade - ORNL, Oak Ridge, TN, USA

20th IAEA Fusion Energy Conference
1-6 November 2004, Vilamoura, Portugal
DIII-D has made substantial progress toward developing an ELM control solution for ITER

Evans EX2-5Ra

- Type-I ELMs are suppressed with resonant magnetic perturbations
  - no confinement degradation
  - good suppression for $\Delta t \sim 9\tau_E$ (some isolated ELMs remain)
- A new type of dynamical state replaces Type-I ELMs
  - transport dominated by small, high frequency fluctuations
    » Magnetic fluctuations increase at higher frequencies and shift to higher toroidal mode numbers ($n = 1-3$ core modes shift to $n = -2$ to $-5$ edge modes)
  - divertor surface temperature spikes reduced by at least a factor of 5
  - divertor particle flux impulses reduced by at least a factor of 8
  - stored energy impulses from the pedestal reduced by a factor of 3
- Suppression is resonant in: $q_{95}$, shape, I-coil configuration, etc.
  - field errors have a significant impact on ELM character
- Good suppression is obtained in high triangularity ($\delta=0.76$), ITER scenario $2$ ($\delta=0.60$) and lower single null ($\delta=0.37$) shapes
- Looks promising for ITER ELM control
MOTIVATION AND APPROACH
ELM control is a high priority ITER issue

- $T_{\text{ped}}^{\text{ped}} \geq \sim 4$ keV for $Q \geq 10$ in ITER

- Normalized ELM energy ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) increases with $T_{\text{ped}}^{\text{ped}}$

- In ITER $\Delta W_{\text{ELM}}/W_{\text{ped}} > 20\%$
  - exceeds carbon ablation limit by a factor of 2-4
The DIII-D I-coil provides a flexible system for n=3 ELM control experiments

- n=3 used to minimize core perturbations

MHD control I-coil (inside vacuum)

n=3 (odd up-down parity)
DIVERTOR IMPULSES ARE SIGNIFICANTLY REDUCED DURING I-COIL ELM SUPPRESSION
ELMs are suppressed without degrading confinement

- Several isolated ELM-like events remain
- ELMs return after I-coil pulse turns off
Peaks in the divertor surface temperature due to ELMs are reduced by at least a factor of 5 with the I-coil.
Langmuir probes show a factor of 8 reduction in the impulsive particle flux to the divertor.

- Reduction in particle flux impulses due primarily to amplitude reduction not $\delta t$.
Radial extent of ELM driven lower divertor particle flux is significantly reduced inside resonant $q_{95}$ window

- Inside the I-coil resonance window $3.7 \leq q_{95} \leq 3.5$:
  - the amplitude of large particle flux impulses are reduced
  - the spatial extent of large particle flux impulses are reduced
- Large particle flux impulses return (amplitude and spatial extent) below the resonant window $q_{95} < 3.5$
- Particle flux and $D_\alpha$ recycling impulses are reduced by a factor of 3-6 during the I-coil pulse
SUBSTANTIAL CHANGES IN PEDESTAL DYNAMICS SEEN DURING ELM SUPPRESSION

Evans EX2-5Ra
Dynamical state of pedestal changes globally

- Suppression seen on:
  - all $D_\alpha$ arrays (outer midplane, upper and lower divertor, inner wall)
  - particle flux and heat flux to the primary (lower) divertor

- ELM transport is replaced by an increase in edge magnetic field and density fluctuations
  - modulated by a 130 Hz coherent oscillation
Stored energy drops are smaller and slower with the I-coil reducing the impulses by > 3X.

Evans EX2-5Ra

115472 (I-coil off)

\[ \langle \Delta W_{ELM} \rangle = 14.1 \, \text{kJ} \]

115472 (I-coil on)

\[ \langle \Delta W_{OSC} \rangle = 5.5 \, \text{kJ} \]
**I-coil pulse suppresses the convective loss channel along B field**

- **ELM suppression** obtained at high density with small $\Delta T_e$ and little conductive energy loss

- **I-coil pulse modifies** ELMs at lower density with a more significant conductive loss
  - limited run time allotted in 2004 for low $n_e$ ELM suppression work
  - I-coil current limit (4.4 kA) expected to increase to 7 kA in 2005
I-coil reduces ELM density impulses to the wall

- High frequency fluctuations replace ELM transport
  - bursty, intermittent and less impulsive
MODEST PEDESTAL PROFILE CHANGES ARE CONSISTENT WITH UNALTERED CONFINEMENT
Time averaged pedestal profiles do not show edge flattening due to strong stochasticity.

Thomson pedestal data show modest increase in electron pressure with I-coil.

\[ n_e \times 10^{13} / \text{cm}^3 \]

\[ T_e \, (\text{eV}) \]

\[ T_i \, (\text{eV}) \]
CVI ion measurements show a broadening of $T_i$ and $P_{CVI}$ across the pedestal but $E_r$ and $v_\theta$ are preserved.

- Toroidal rotation drops through 0 and reverses in edge!
- H-mode transport barrier is preserved
  - $v_\theta$ & $E_r$ well don’t change
  - Increased $\nabla P_i$ offsets change in $V_\phi$ in single ion force balance
- $T_i$ and $\nabla P_i^{CVI}$ changes may be important for $j_{BS}$ and stability
I-coil pulse delays variation of total pedestal pressure relative to ELM cycles without I-coil

- Time between ELMs = **13 ms on average without the I-coil**
- Time between isolated events/ELMs = **64 ms with I-coil**.

Unstable phases

ELM spacing increases:
- 13 ms -> 64 ms
- ELITE linearly unstable
time increases:
- 5 ms -> 28 ms

![Graph showing the effect of I-coil on ELM spacing and pressure](image-url)
ROTATION DROPS AND MAGNETICS SHOW POWER REDISTRIBUTION FROM LARGE ELMS TO SMALL SCALE, HIGH FREQUENCY FLUCTUATIONS

Evans EX2-5Ra
Strong toroidal rotation damping seen during ELM suppression

- Modeling indicates small islands on 4/3, 3/2, and 2/1 surfaces
- Sawteeth lost on soft X-ray signal as rotation drops

Evans EX2-5Ra

H. Reimerdes Columbia U

- with $n=3$ perturbation

CERNEUR - 115467

- $t=2800-3000\text{ms (405 samples)}$
- $t=3300-3500\text{ms (135 samples)}$

CERNEUR - 115468

- $t=2800-3000\text{ms (405 samples)}$
- $t=3300-3500\text{ms (135 samples)}$

- NBI 30 deg
- NBI 330 deg
Loss of edge toroidal momentum takes about 50 ms and reverses direction after ~ 130 ms

- Core rotation decays in 300 ms; edge has a fast drop (~50 ms) followed by a slower decay
  - Mirnov coils see slowing down in the downshift of internal MHD modes (here, q=1 & 2)
- ELMs suppressed within 1 ELM cycle ≈ 15 ms

Initial fast drop in edge
Amplitude of magnetic fluctuations increase at higher frequencies and mode numbers

- Power in edge $B_\theta$ fluctuations increases up to $f_N = 50$ kHz
- Quiet intervals between ELMs fill in with higher $n$ edge modes
  - $n = 1$–3 core modes shift to $n = -2$ to -5 edge modes
MODELING CONFIRMS IMPORTANCE OF SMALL SCALE MAGNETIC ISLANDS

Evans EX2-5Ra
Field line integration modeling indicates that small islands may be linked to ELM suppression mechanism.

- Small scale, high $k_\theta$, remnant islands formed across the pedestal with $\phi_{\text{tor}} = 0^\circ$
  - due to mixing of I-coil and field-error spectrum

TRIP3D modeling (no plasma response included)
Resonant character of ELM suppression verified during q-scans

Plasma current was ramped during the I-coil pulse in a series of discharges to determine the optimum range of \( q_{95} \) for the ELM suppression.

- Strong suppression of Type I ELMs for \( 3.5 \leq q_{95} \leq 4.0 \)
Islands change size and shape during q scan - local stochastic minimum at $q_{95} = 3.7$

- Suppression when (9,3) island is at/near top of pedestal
- Density of small scale states due to I-coil and field-error mixing is a maximum at $q_{95} = 3.7$
  - But edge stochastic loss region is minimized
ELM SUPPRESSION IS SEEN WITH VARIOUS SHAPES AND I-COIL CONFIGURATIONS

Evans EX2-5Ra
Good ELM suppression is obtained in LSN, high triangularity and ITER scenario 2 shapes.

Evans EX2-5Ra

Δt = 8.6T_E

High Triangularity
δ = 0.76

ITER scenario 2
δ = 0.60

Lower Single Null
δ = 0.37
Changing the toroidal phase of the I-coil significantly increases the midplane $D_\alpha$.

- More stochastic with $\phi_{\text{tor}} = 60^\circ$ than with $\phi_{\text{tor}} = 0^\circ$
With $\phi_{\text{tor}} = 60^\circ$ the ELM frequency and amplitude is reduced in the divertors - more I-coil current needed?

- Odd parity, $\phi_{\text{tor}} = 60^\circ$ perturbations reduce ELMs in divertor
- Midplane $D_\alpha$ increases:
  - baseline covers remaining ELMs
  - Has classic stochastic character
  - Similar to EDA mode
The pedestal ion and electron channels have a more stochastic character with $\phi_{\text{tor}} = 60^\circ$.

- Foot of CVI ion pressure moves inward.
- $E_r$ well shifts in by about 5% in poloidal flux.
Summary and Conclusions

Evans EX2-5Ra

- Type-I ELMs are suppressed with resonant magnetic perturbations
  - no confinement degradation
  - good suppression for $\Delta t \sim 9\tau_E$ (some isolated ELMs remain)
- A new type of dynamical state replaces Type-I ELMs
  - transport dominated by small, high frequency fluctuations
    » Magnetic fluctuations increase at higher frequencies and shift to higher toroidal mode numbers ($n = 1-3$ core modes shift to $n = -2$ to $-5$ edge modes)
  - divertor surface temperature spikes reduced by at least a factor of 5
  - divertor particle flux impulses reduced by at least a factor of 8
  - stored energy impulses from the pedestal reduced by a factor of 3
- Suppression is resonant in: $q_{95}$, shape, I-coil configuration, etc.
  - field errors have a significant impact on ELM character
- Good suppression is obtained in high triangularity ($\delta=0.76$), ITER scenario 2 ($\delta=0.60$) and lower single null ($\delta=0.37$) shapes
- Looks promising for ITER ELM control