Edge Localized Mode Control in DIII-D using Magnetic Perturbation-Induced Pedestal Transport Changes

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Presented at the
12th U.S.-E.U. Transport Task Force Meeting
San Diego, CA USA
April 17–20, 2007
**Edge resonant RMPs suppress Type I ELMs in DIII-D**

- **Pedestal becomes very quiet as imaged in CIII light (J. Yu, this mtg.).**

QuickTime™ and a decompressor are needed to see this picture.

126003, CIII
Paradox: why does RMP have large effect on pedestal density but little on pedestal $T_e$?

- **global particle balance change**
  - QL estimate $\rightarrow 3-4x$ increase in $D_{eff}$

- **$T_e$ profile flattens at top of pedestal**
  - qualitatively consistent with QL estimate
  - quantitatively consistent for $0.85 < \psi_n < 0.94$ with transport analysis by Stacey and Evans

- **$T_e$ increases for $0.98 < \psi_n < 1$**
Pellet perturbation experiments confirm that $\tau_p^*$ is reduced a factor of 2.

- Identical pellets injected into discharges with $v_e^* \sim 0.2$, $\delta \sim 0.7$, and similar recycling conditions → $\tau_p$ changes
  - $I$-coil = 0 kA, ELMing H-mode
  - $I$-coil = 4 kA, RMP-assisted ELM-free H-mode
Heat transport modeling of stochastic layer with E3D fluid Monte Carlo code predicts $T_e$ pedestal collapse

122342 at 4650 ms  BC’s: $T_e = 1.6$ keV, $T_i = 2.6$ keV at $\psi_n = 77$

- Constant temperature BC’s (more power into edge as I-coil current increases to maintain inner boundary $T_e$)
- Result is consistent with conventional expectations for electron thermal transport in a stochastic layer

Possible resolutions to the paradox of particle pumpout without increased electron thermal transport

- **Rotational screening of the RMP:**
  - Seen in MHD simulations with JORIK code (E. Nardon et al.) and preliminary NIMROD extended MHD code runs (V. Izzo and I. Joseph, Sherwood Theory mtg.)
  - If $\delta b_r$ doesn’t penetrate, then what changes the global particle balance?

- **Tokar model: combined impact of:**
  - Particle flows along perturbed $\mathbf{B}$
  - Reduction of neoclassical perpendicular transport with decreasing density
  - Nonlocality of parallel electron heat transport at low collisionality

- **Increased $E \times B$ convection across separatrix:**
  - Convection cells in MHD modeling (Nardon; Izzo) with enhanced resistivity, but weaken if resistivity is closer to experimental values
  - Leads to increased particle and electron thermal transport in fluid transport models without the heat flux limits
Tokar model [PRL 98 095001 (2007)] reproduces qualitative behavior of pedestal profiles:

- **combined impact of**
  - Il particle transport in stochastic field
  - neoclassical \( \kappa_\perp \sim n^2 \)
  - reduction of Il heat flux below free-streaming limit

\[
\kappa_\parallel = \frac{\kappa^{SH}_\parallel}{\left(1 + \frac{\xi_{SH}}{\xi_{FS}} \frac{L}{L_T}\right)}
\]

where \( \xi_{SH} \approx 3 \) and \( \xi_{FS} \leq 0.1 \)

\[
q_r \approx -\kappa_\perp + \frac{\kappa^{SH}_\parallel \alpha_r^2}{1 + \alpha_r \frac{\xi_{SH}}{\xi_{FS}} \frac{\lambda}{T} \frac{\partial T}{\partial r}} \frac{\partial T}{\partial r}
\]

where the stochastic field is described by

\[
\alpha_r = \sqrt{D_{FL}/L_K}
\]

with \( D_{FL} \) = field line diffusivity and \( L_K \) = Kolmogorov length

![Graph showing n_e, T_e, T_i profiles with separatrix indicating top of electron barrier]
Increased particle transport may be due to increased fluctuation-driven $E \times B$ convective transport.

- FIR scattering: $k_\theta = 1 \text{ cm}^{-1}$ not spatially localized

![Graph showing frequency (kHz) vs. amplitude (a.u.):](image)

- $\hat{n}(f)$ for different I-coil pulses and divertor $D_\alpha$ conditions.

![Overall $\hat{n}(f)$ for I-coil off and on:](image)
Increased particle transport may be due to increased fluctuation-driven $E \times B$ convective transport.

- **FIR scattering**: $k_\theta = 1 \text{ cm}^{-1}$ not spatially localized $\rightarrow$ increased coherent modes and broadband turbulence $\rightarrow$ 1.5x increase in $\bar{n}_{\text{rms}}$

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![Graph](image-url)

*Overall $\bar{n}(f)$*

- I-coil on
- I-coil off

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*Overall $\bar{n}_{\text{rms}}$ $k_\theta=1\pm1 \text{ cm}^{-1}$*
Increased particle transport may be due to increased fluctuation-driven $E \times B$ convective transport.

- **FIR scattering**: $k_{\theta} = 1 \text{ cm}^{-1}$ not spatially localized $\rightarrow$ increased coherent modes and broadband turbulence $\rightarrow$ 1.5x increase in $\bar{n}_{\text{rms}}$

- **Reflectometry**: localized to pedestal $\rightarrow$ increased turbulence $\rightarrow$ 2x increase in $\bar{n}_{\text{rms}}$

$D_{\alpha} \sim \bar{n}_{\text{rms}}^2 \rightarrow$ Deff increases 3-4x, consistent with change inferred from profiles.

- **I-coil pulse**
  - **I-coil on**
    - Divertor $\bar{n}(f)$
    - Pedestal $\bar{n}_{\text{rms}}$
  - **I-coil off**
    - Overall $\bar{n}(f)$
    - Pedestal $\bar{n}_{\text{rms}}$

- **FIR REF LN**
  - I-coil on I-coil off overall $\bar{n}(f)$
  - Amplitude (a.u.)
    - Shot 123301
    - Time (msec)

- **Ampl. (a.u.)**
  - Frequency (kHz)
    - Overall $\bar{n}(f)$
    - Pedestal $\bar{n}(f)$

- **Ampl. (a.u.)**
  - Frequency (kHz)
    - Overall $\bar{n}_{\text{rms}}$ $k_{\theta} = 1 \pm 1 \text{ cm}^{-1}$
    - Pedestal $\bar{n}_{\text{rms}}$

- **I-coil**
  - Overall $\bar{n}_{\text{rms}}$ $k_{\theta} = 1 \pm 1 \text{ cm}^{-1}$
  - I-coil off
Increased particle transport may be due to increased fluctuation-driven $E \times B$ convective transport.

- **FIR scattering:** $k_\theta = 1 \text{ cm}^{-1}$ not spatially localized $\rightarrow$ increased coherent modes and broadband turbulence $\rightarrow$ 1.5x increase in $\tilde{n}_{\text{rms}}$
- **Reflectometry:** localized to pedestal $\rightarrow$ increased turbulence $\rightarrow$ 2x increase in $\tilde{n}_{\text{rms}}$
- $D_{\text{eff}} \sim \tilde{n}_{\text{rms}}^2$ $\rightarrow$ $D_{\text{eff}}$ increases 3-4x, consistent with change inferred from profiles.

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### Graphs

- **Overall $\tilde{n}(f)$**
- **Pedestal $\tilde{n}(f)$**
- **I-coil on**
- **I-coil off**

### Data

- **Pedestal $\tilde{n}_{\text{rms}}$**
- **FIR**
- **REFLN**

### Figures

- [Graphs showing data](image-url)
Pedestal toroidal rotation and $E_r$ change promptly when RMP is applied and edge $q$ resonant ($3.4 < q_{95} < 3.7$).

- **H-mode pedestal** $v_\phi$ spins up.

[Graph showing time vs. $v_\phi$ (km/s) with I-coil on at different times (1720 ms, 2520 ms, 2620 ms) and corresponding $v_\phi$ values.]
Pedestal toroidal rotation and $E_r$ change promptly when RMP is applied and edge $q$ resonant ($3.4 < q_{95} < 3.7$).

- **H-mode pedestal** $v_\phi$ spins up and $E_r$ well narrows.

![Graph showing changes in $v_\phi$ and $E_r$ over time](image)
**E_r** well formed by balance between X-pt ion orbit loss and rapid electron loss in stochastic field?

- **Outside of** E_r **well minimum, E_r becomes strongly positive all the way to the main chamber wall**
- **Persistence of E_r well**: X-point structure is stable during RMP
  - [Joseph] continued ion orbit loss [Park, Chang] on top of rapid electron loss

Some qualitative similarities to XGC simulations (Park et al., TTF 07)

![Graph](image)

- **Electron loss in stochastic field**
- **X-pt ion orbit loss**
$T_e$ rise near strike point and $V_{\text{float}} < 0$ during RMP are consistent with RMP penetration.

- Hot electrons and negative floating potential are consistent with connection of field lines from inside the pedestal with the divertor target plates
  - formation of a flux loss layer over at least the last few % inside the separatrix.

![Graphs and diagrams showing plasma parameters and heat flux over time.](image)
Xpt-TV experimental observations of “homoclinic tangle” confirm penetration of RMP at least into last few \% in \psi_n.

- Demonstrates stability of X-point in presence of RMP
- Intersecting manifolds allow field lines to “tunnel” out of pedestal without island overlap (\(\sigma_{CH} < 1\))
Summary and Conclusions

- **RMP ELM control experiments pose a paradox for pedestal transport**: how is the pedestal density reduced without any reduction in $T_e$?

- **Does toroidal rotation screen the RMP?**
  - Evidence for penetration at least to $\psi_n \sim 0.98$; NIMROD modeling underway to investigate $\delta b_r$(plasma).
  - If RMP is screened, what changes the particle balance?

- **Does RMP create $E \times B$ convection cells that enhance radial particle transport?**
  - Seen in high resistivity MHD simulations (JORIK & NIMROD) but the cells increase electron thermal transport as well (Izzo, NIMROD).
  - Cells become weaker at lower resistivity (Nardon, JORIK)

- **Do limits to the free-streaming parallel electron heat flux explain the low electron thermal transport?**
  - First suggested by S. Krasheninnikov; Tokar model is qualitatively consistent with experiment.

- **RMP promptly alters—but doesn’t destroy—H-mode $E_r$ well**
  - Similar to initial XGC results: balance between electron loss in stochastic field ($\phi \rightarrow$ positive) and X-point ion orbit loss ($\phi \rightarrow$ more negative).
  - ñ increases 2X & quasi-linear $D_{eff}$ increases 4x, consistent with measured pedestal density profile change.

- We need a transport model that self-consistently treats both the H-mode edge transport barrier and the stochastic layer transport.