Perturbed Equilibria and ELM Suppression in DIII-D, and Implications for ITER

by

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Improved 3D Modeling and Pedestal Dynamics Models Allow Better Predictions of ELM Suppression

- Despite successfully mitigating ELMS with Resonant Magnetic Perturbations (RMPs) on many tokamaks, we still lack a good predictive model.

- In a set of DIII-D discharges, it was found that the Vacuum Island Overlap Width (VIOW) correlates with ELM suppression*

- Actual mechanism of ELM suppression is more complicated than VIOW
  - VIOW ignores plasma response (kinking, screening)
  - Pedestal is probably not stochastic, so “IOW” may not be physical

- We apply advances in modeling capabilities and understanding of pedestal dynamics to develop new correlation criteria for ELM suppression; apply to ITER

Plasma Response to RMP Significantly Alters the Magnetic Fields in H-Mode Edge

- **Plasma tries to exclude magnetic islands**
  - “Screening”; where $\omega_e$ is large (steep gradient region and core)

- **RMPs drive (stable) modes to finite amplitude**
  - “Kink response”
  - Driven reconnection; where $\omega_e$ is small (pedestal top)

- **Including plasma response is necessary to accurately model edge measurements**
  - $T_e, n_e$ profiles in edge strongly affected by “kink response” (Shafer NI2.00006, this morning)
  - Linear two-fluid modeling (M3D-C1) is successful in reproducing measured profiles
EPED Model Suggests ELM Suppression Requires Enhanced Transport Localized at Pedestal Top

- **EPED Model of pedestal structure:**
  - Gradient determined by local KBM stability
  - Width grows until global PB stability threshold is reached (ELM)

*P. Snyder UP8.00050, Thurs. afternoon*
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- **Implies model of ELM suppression:**
  - Something stops widening of pedestal before threshold
  - Requires enhanced transport at $\Psi \approx 96–97\%$

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**Diagram:**
- Stable!
- Enhanced Transport
- Width capped
- Maximum gradient is unchanged

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Predictive modeling needs model of RMP effect on transport
- Enhanced classical transport? (S. Smith, NI2.00005, earlier today)
- Change to KBM stability? (C. Hegna, PP8.00058, right now)
- Stochasticity? (D. Orlov, YI3.00006, Friday morning)
“Local Chirikov” Value Gives Indication of Localized Stochasticity

- Island width is estimated using pitch-resonant field at each mode-rational surface

\[ w(\Psi_m) = \frac{2}{\pi} \sqrt{\frac{\psi_{mn} q}{\psi' q'}} \]
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  \[ w(\Psi_m) = \frac{2}{\pi} \sqrt{\frac{\psi_{mn} q}{\psi' q'}} \]
- Chirikov value is defined for each pair of adjacent surfaces
  \[ \sigma\left(\frac{\Psi_{m+1} + \Psi_m}{2}\right) = \frac{1}{2} \frac{w(\Psi_{m+1}) + w(\Psi_m)}{\Psi_{m+1} - \Psi_m} \]
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- Plasma response reduces \( \sigma \) in the pedestal
Island width is estimated using pitch-resonant field at each mode-rational surface

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\[ \sigma_{ped} = \sigma(\Psi_{ped}) \]
IOW and $\sigma_{ped}$ Metrics Are Tested on a Set of DIII-D Discharges

• Considered set of 13 discharges at 162 times with $n=3$ RMP applied

• IOW and $\sigma_{ped}$ evaluated for each time, with and without plasma response
  – Plasma response is calculated with M3D-C1, using a linear two-fluid model (Spitzer resistivity, includes rotation)
  – Calculations include $n=3$ response, not $n=0$ transport changes

• Correlation with ELM Suppression is quantified by fitting tanh to “ELM Intensity” as a function of the metric
  – ELMing: ELM Intensity = 1
  – Suppressed: ELM Intensity = 0
**$\sigma_{\text{ped}}$ Correlates Better Than IOW; Plasma Response Doesn’t Always Improve Correlation**

- “Accuracy”: fraction of times correctly classified by the threshold from tanh fit

<table>
<thead>
<tr>
<th>Metric</th>
<th>Threshold</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum IOW</td>
<td>12.7%</td>
<td>63%</td>
</tr>
<tr>
<td>Plasma IOW</td>
<td>6.4%</td>
<td>70%</td>
</tr>
<tr>
<td>Vacuum $\sigma_{\text{ped}}$</td>
<td>1.55</td>
<td>89%</td>
</tr>
<tr>
<td>Plasma $\sigma_{\text{ped}}$</td>
<td>0.90</td>
<td>73%</td>
</tr>
</tbody>
</table>
New Metrics are Better, But Still Imperfect

- Plasma response is sensitive to the equilibrium

- Plasma response conflates cause / effect of suppression

- Only the $n=3$ component is considered here
  - Strong evidence that sidebands can be important (Orlov)
  - Fenstermacher (2008) VIOW definition includes sidebands

- Linear response misses some important physics
  - Amplification of islands implies nonlinear effects important
  - IOW and $\sigma_{ped}$ are imperfect indicators of enhanced transport
Suppression Correlation Metrics Have Been Applied To Several ITER Scenarios

- Metrics have been calculated for 8 ITER scenarios, n=1–4
  - 15 MA \( Q_{DT} = 10 \) \( T_{ped} = 3.8, 4.4, 5.0, \) and 6.3 keV
  - 12 MA Hybrid
  - 10 MA Ramp-Up
  - 9 MA
  - 7.5 MA

- IOW and \( \sigma_{ped} \) calculated as a function of the phase of the upper and lower coil rows (relative to center row)
Suppression Threshold of Three of Four Metrics Can Be Achieved for All ITER Scenarios

- **Thresholds for three of four metrics can be satisfied for all scenarios**
  - Plasma IOW cannot be satisfied for 2/8 scenarios

- **Metrics tend to agree on optimal coil phases; generally find easier suppression at higher $n$**

*only $n=4$ considered for 9 MA scenario*
Applying new understanding of pedestal evolution and perturbed 3D equilibria yields improved ELM suppression metrics

- Local measure of stochasticity at pedestal top \( \sigma_{\text{ped}} \) appears to correlate better than vacuum island overlap width
- Still imperfect (don’t recover \( q_{95} \) window)

Three of four metrics can be satisfied for all ITER scenarios

- Encouraging, but not definitive

For truly predictive models, better understanding of transport in 3D geometry is needed
ELM Suppression is a Top DIII-D Priority

- **R. Nazikian, GO4.00004**: Pedestal Response to Resonant Magnetic Perturbations in DIII-D H-mode Plasmas
- **A. Wingen, GO4.00005**: A Possible Connection of Plasma Response to RMP ELM Suppression in DIII-D
- **S. Smith, NI2.00005**: Magnetic Flutter Plasma Transport Induced by 3D Fields in DIII-D
- **M. Shafer, NI2.00006**: Plasma Response Measurements of Non-Axisymmetric Magnetic Perturbations on DIII-D
- **C. Hegna, PP8.00058**: The effects of weakly 3-D equilibrium on MHD stability of tokamak pedestals
- **T. Evans, UP8.00025**: 3D Magnetic Perturbation Effects on Transport in Tokamaks
- **P. Snyder, UP8.00050**: Optimizing Pedestal Performance with the EPED Model
- **A. Leonard, XR1.00001**: Edge Localized Modes (ELMs) in Tokamaks
- **D. Orlov, YI3.00006**: Suppression of Type-I ELMs with a Reduced I-coil Set in DIII-D
Reduced two-fluid nonlinear calculations show significant effect on pedestal from RMPs with just 11.25 kA in control coils.

RMP causes PB to mode to rapidly achieve “nonlinear” amplitude.
"Accuracy" defined as fraction of cases that are correctly classified using the best-fit "threshold".
Local Chirikov Parameter Correlates With Suppression Better than IOW

- Best correlation is found when $\sigma(\Psi)$ is evaluated at the pedestal top ($\sigma_{\text{ped}}$, usually $\Psi \approx 96–97\%$)

- Including plasma response reduces correlation!

Accuracy = 89%

Accuracy = 73%