Experimental identification of inter-ELM pedestal MTMs through edge current perturbations

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with
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We present a direct, time-dependent experimental identification of low-n microtearing modes in the H-mode pedestal on DIII-D.
Outline

• Introduction
  – Microtearing modes

• Experimental procedure and observations
  – Goal: Induce extra edge current to probe pedestal modes

• Mode identification
  – Comparison of experimental modes with MTM/KBM characteristics
    • Transport fingerprints
    • Propagation direction
    • Mode frequency

• Discussion/Conclusions/Future Work
  – Pedestal modes are consistent with MTM characteristics
  – More analysis coming on GENE; possible extension into pedestal model
Introduction
Inter-ELM instabilities ubiquitous, limit pedestal growth

• Instabilities at the plasma boundary observed on many machines
  – MHD-like modes expected to play a major role in regulating profile gradients
  – Microinstabilities are highly correlated with inter-ELM profile recovery phases
  – Consistent physical picture does not yet exist

• Kinetic Ballooning Mode (KBM) likely play a role as a pedestal-limiting mode

• Micro-Tearing Mode (MTM) also evident in pedestal region

[F.M. Laggner, et. al., NME 2019]
Microtearing Modes (MTMs)

- MTMs are small scale tearing modes that require finite collisionality
- Driven unstable by $\nabla T_e$ projected onto helically-resonant radial magnetic perturbations
  at rational $q = m/n$
  - $\nabla T_e$ drives a parallel current
  - reinforces $\delta B$ via Ampere’s law
- Multiple mechanisms:
  - Thermal drag force
  - Interaction between trapped/passing boundary layer
MTMs are more unstable when aligned with peak $\omega_{e^*}$

- MTMs are:
  - Localized on a rational $q = m/n$ surface
  - Unstable at a given $n$ when the rational surface aligns with the peak in the $\omega_{e^*}$ profile

- From gyrokinetics:
  - Evidence of MTMs on JET, AUG, DIII-D

- From RIP diagnostic:
  - Evidence of high-$f$ MTMs on DIII-D

[Chen PoP, 2020]
Test for modes: shift q-profile via current perturbation

- **Experimental strategy:** use vertical oscillations to probe edge modes
- **Hypothesis:**
  - Decreased edge current moves q-profile inwards
  - Modes trapped to q-profile also move inwards
VARYPED predicts frequency response in MTMs

- MTMs are localized on a rational $q=m/n$ surface

- As pedestal recovers post-ELM, MTM frequency predicted to rise...

\[ \omega_{dop} = \frac{nE_r}{RB_p} \]
\[ \omega_* = k_\theta \rho_S C_s \left( \frac{1}{L_{Te}} + \frac{1}{L_{ne}} \right) \]
VARYPED predicts frequency response in MTMs

- MTMs are localized on a rational $q=m/n$ surface

- As pedestal recovers **post-ELM**, **MTM frequency predicted to rise**…

- But as current rises **post-jog**, **expected MTM frequency may fall!**
Experimental Procedure
Experimental procedure – scan induced edge current

- Reference discharge with low 10Hz natural ELM frequency

- Explored jogging parameter space:
  - Jogging duration scan
  - Jogging height scan
  - Jogging direction scan

- During the largest and fastest jogging events (with the largest change in edge current):
  - Edge mode frequency change

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(a) Oscillation lengths on DIII-D

(b) Oscillation heights on DIII-D

(c) Oscillation directions on DIII-D
Largest jogs lead to inverted mode chirping!

- During the **largest and fastest** jogging events:
  - Edge mode frequency change
  - Inversion of chirping behavior

- Chirped modes identified as: $n = 3, 4, 5$

- Core modes (black) and modes inside the pedestal top (blue) unaffected
**Chirped mode only exists in edge BES channels**
- Amplitude peaks in pedestal region

**From magnetics, clear \( n \)-number identification**
- 60 kHz \( \rightarrow \) \( n = 3 \)
- 115 kHz \( \rightarrow \) \( n = 5 \)
- \( m \)-number unclear, but large!

**Modes localized at the edge of the plasma, at \( q \geq 5 \)**
Mode Identification
Micro-tearing modes have many properties:

- Electromagnetic [Hazeltine 1975] ✓
- Long-wavelength modes \( k_\theta \rho_s < 1 \) [Doerk 2012] ✓
- Frequency close to electron diamagnetic frequency
  \[ \omega_{e*} = k_\gamma \rho_s c_s \left( \frac{1}{L_{ne}} + \frac{1}{L_{Te}} \right) \] [Hatch 2021]
- Frequencies in the electron diamagnetic direction [Hatch 2021]
- Driven by electron temperature gradient [Gladd 1980]
- Causes almost exclusively electron thermal transport
  \( (D_e/\chi_e \approx 1/10) \) [Kotschenreuther 2019]
- Requires finite collisionality/resistivity [Drake 1980] ✗
- Growth rate depends non-monotonically on collisions [Chen 2020] ✗
- Saturates as \( |\delta B_r/B| \sim \rho_e/L_{Te} \) [Chen 2020] ✗
- Mode can peak anywhere (top/bottom in [Hatch 2021]) ✗
Mode frequency consistent with MTM predictions

- **Normal ELM:**
  - Up-chirp in $n = 3$ and $n = 5$ modes due to inter-ELM gradient recovery
    
    \[ \omega_{MTM}(\psi_n) = \omega_{dop}(\psi_n) + \omega_{*e}(\psi_n) \]

- **Qualitative and quantitative agreement with magnetics!**
Mode frequency consistent with MTM predictions

- Jogging ELM:
  - Down-chirp in $m/n = 16/3$ MTM due to motion of $q$-profile during gradient recovery

- Qualitative and quantitative agreement with magnetics!
Mode frequency fully consistent with MTM predictions

![Graph showing mode frequency comparison with predictions](image-url)
Micro-tearing modes have many properties:

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- Frequency close to electron diamagnetic frequency
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Frequencies in the **electron diamagnetic direction** in plasma frame
- Confirmed with BES

Maximum $n=3$ doppler shift

**magnetics ($\vec{B}$)**
Mode saturation with $\nabla T_e$ and $\nabla P_e$

- Amplitude of magnetic fluctuations consistent with $\nabla T_e$ (MTM-like)

- Due to fast density recovery timescale, also consistent with $\nabla P_e$ (KBM-like)

- MTM amplitude also dependent on offset between $\omega_*$ peak and rational surface
  - Amplitude change after saturation
GYROKINETIC FINGERPRINTS: [Kotschenreuther, et. al., NF, 2019]

MTM-like: \( D_e / \chi_e \approx 1/10 \)

KBM-like: \( D_e / \chi_e \approx 2/3 \)

UEDGE and TRANSP simulations:

- Transport is **predominantly MTM-like near separatrix!**
- Significant uncertainty from unknown neutral profile – scanned
Micro-tearing modes have many properties:

- Electromagnetic [Hazeltine 1975]
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- Saturates as $|\delta B_r / B| \sim \rho_e / L_{Te}$ [Chen 2020]
- Mode can peak anywhere (top/bottom in [Hatch 2021])
Conclusions
Low-\(n\) inter-ELM pedestal modes observed on DIII-D

- Low-\(n\) magnetic modes observed near the edge in a series of DIII-D discharges
- Similar to:
  - Category 1 modes from [Laggner NME 2019]
  - Washboard modes on JET [Perez PPCF 2004]
  - Other QCFs on DIII-D [Diallo PoP 2015]
  - Pedestal MTMs on JET [Hatch NF 2021]
  - 60kHz modes on AUG [Neuhauser NF 2008]
  - 100kHz modes on EAST [Gao PST 2013]
Low-\(n\) inter-ELM modes on DIII-D consistent with MTMs

- Modes are experimentally consistent with MTM characteristics!
  - Propagation in the electron diamagnetic direction
  - Cause almost exclusively electron thermal transport \((\chi_e \gg D_e)\)
  - **Dynamical evolution of mode frequency** agrees with predicted MTM frequency \((f_{NTM} \sim f_{dop} + f_{e})\) at rational \(q\)-surface in pedestal.