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

by **A. O. Nelson[1,2*]**

with

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Main takeaway

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

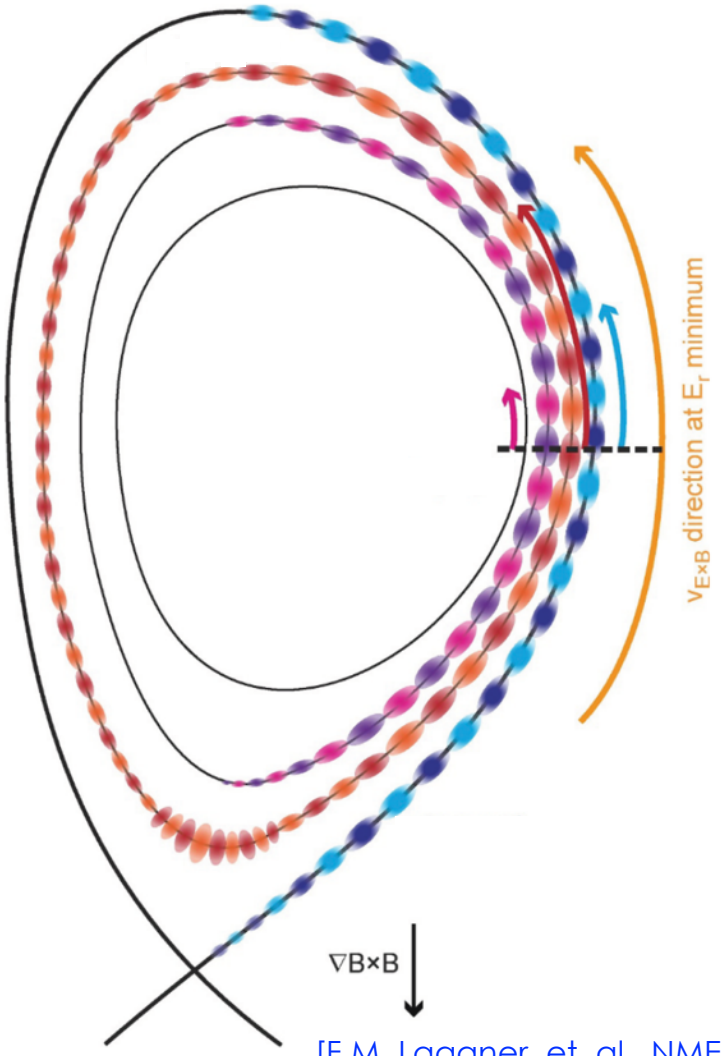
Outline

- **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

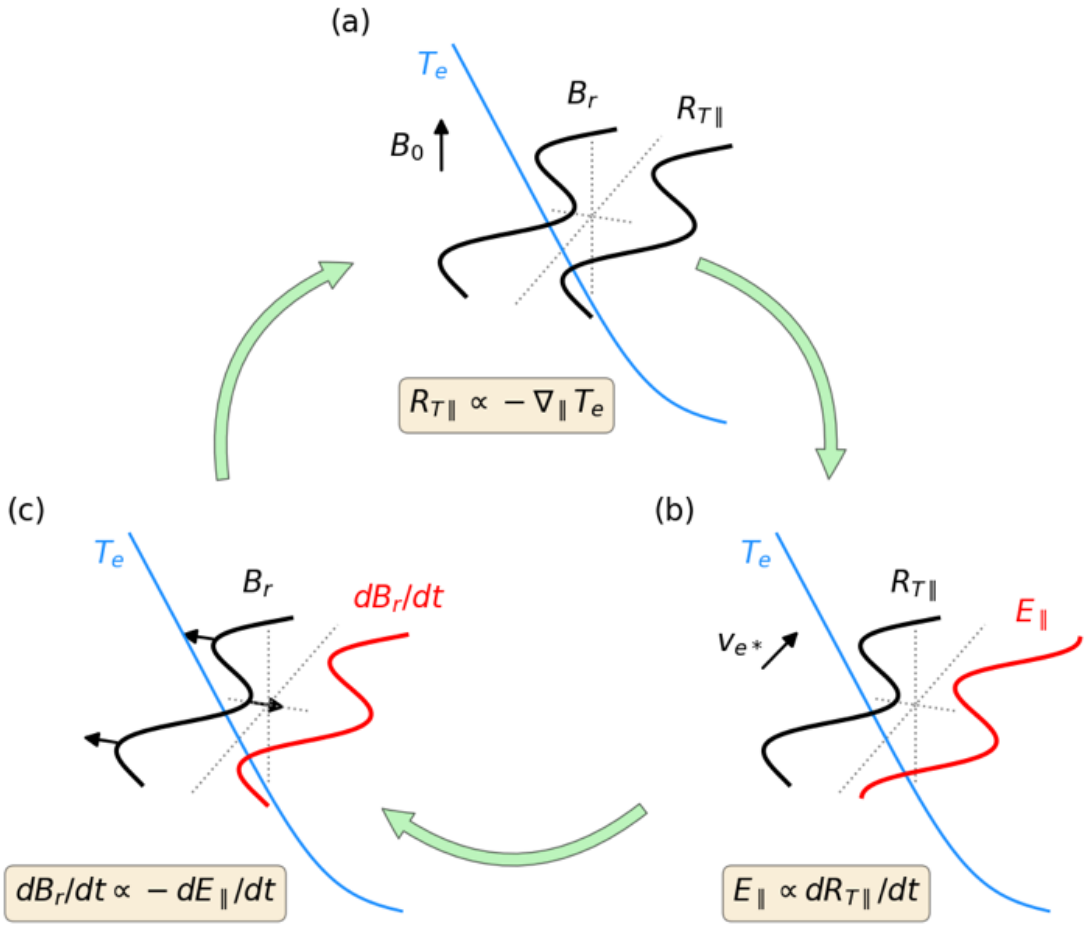
- **Instabilities at the plasma boundary observed on many machines**
  - MHD-like modes expected to play a major role in regulating profile gradients
  - Microinstabilities are highly correlated with inter-ELM profile recovery phases
  - Consistent physical picture does not yet exist
- **Kinetic Ballooning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

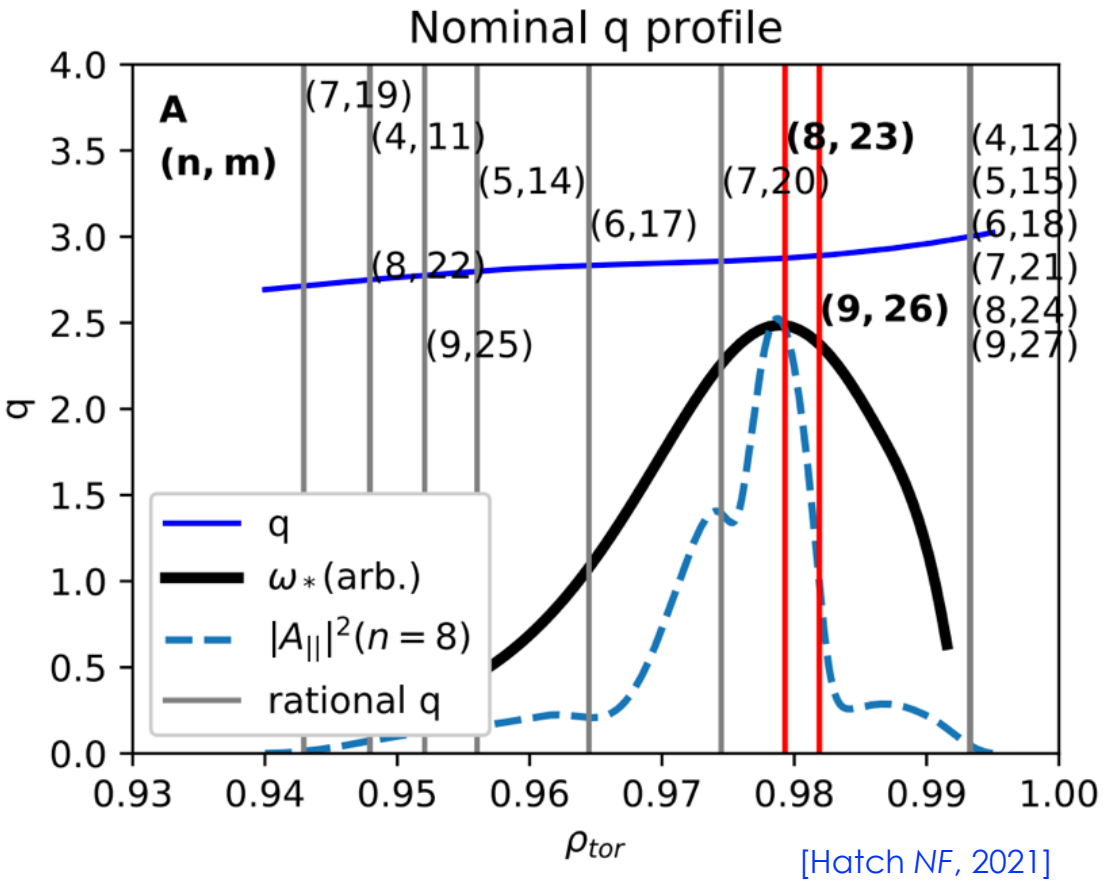
- **MTMs are small scale tearing modes that require finite collisionality**
- **Driven unstable by ∇T_e** projected onto helically-resonant radial magnetic perturbations **at rational $q = m/n$**
  - ∇T_e drives a parallel current
  - reinforces δB via Ampere's law
- **Multiple mechanisms:**
  - Thermal drag force
  - Interaction between trapped/passing boundary layer



MTMs are more unstable when aligned with peak ω_{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 ω_{e*} profile**
- From gyrokinetics:
  - Evidence of MTMs on **JET, AUG, DIII-D**
- From RIP diagnostic:
  - Evidence of high-f MTMs on **DIII-D**

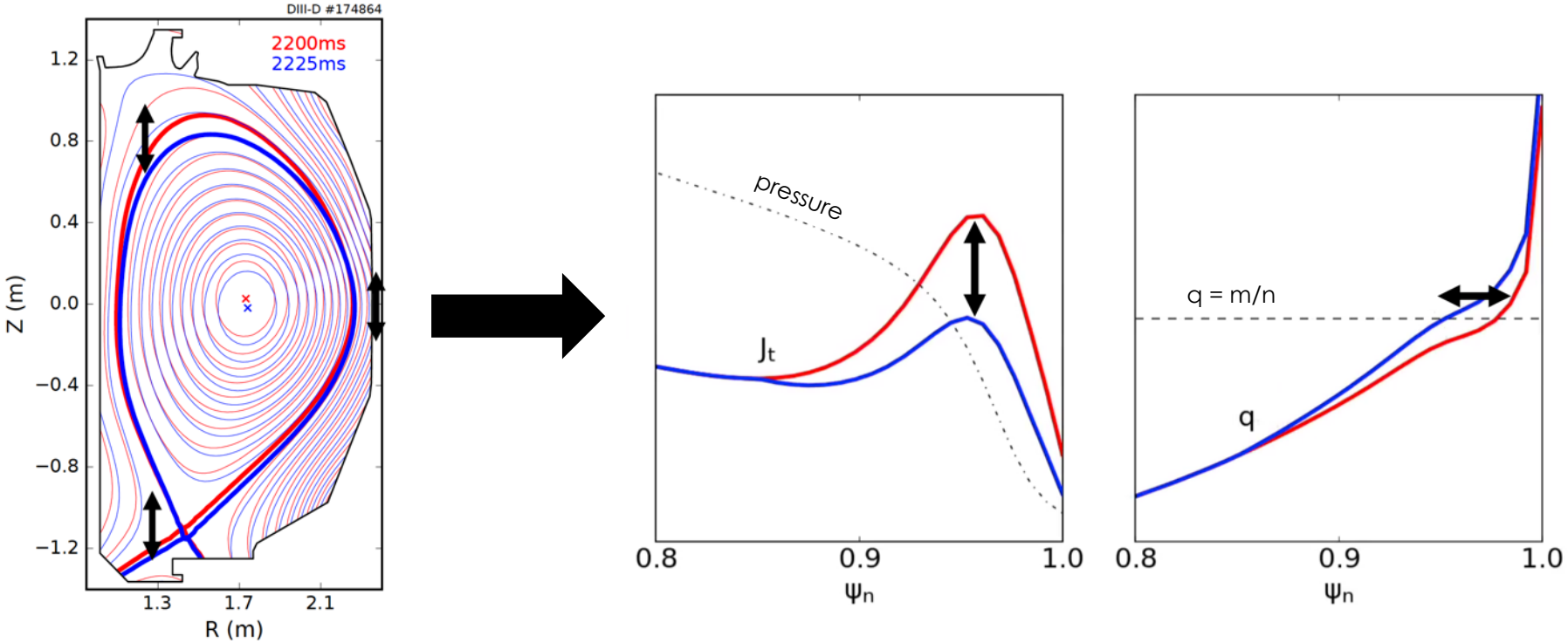
[Chen *PoP*, 2020]



[Hatch *NF*, 2021]

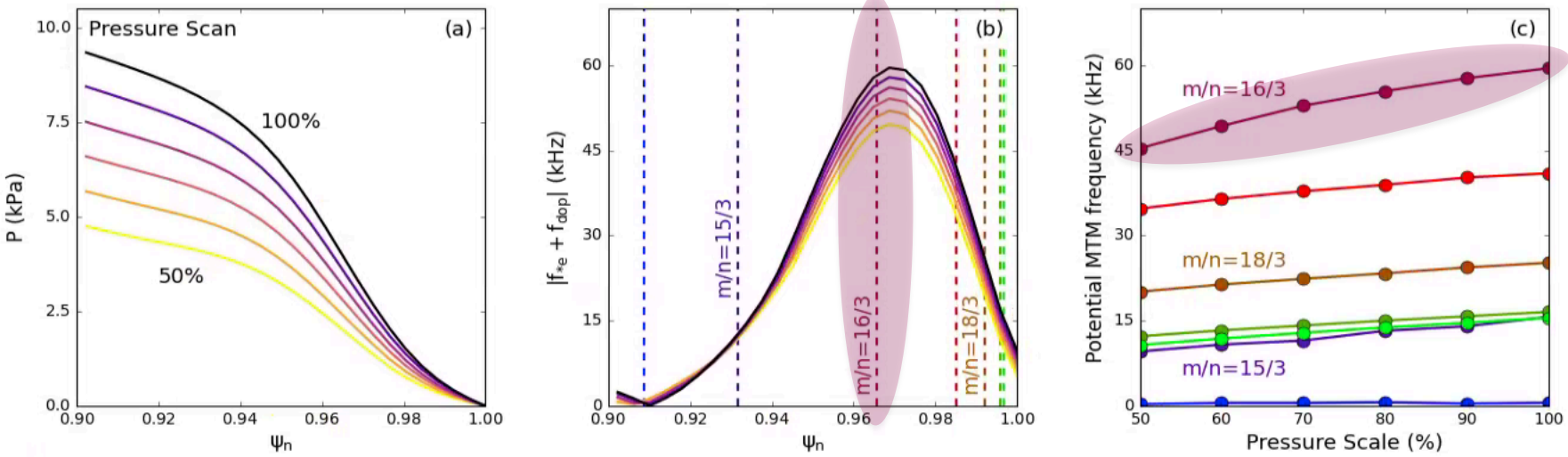
Test for modes: shift q-profile via current perturbation

- 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

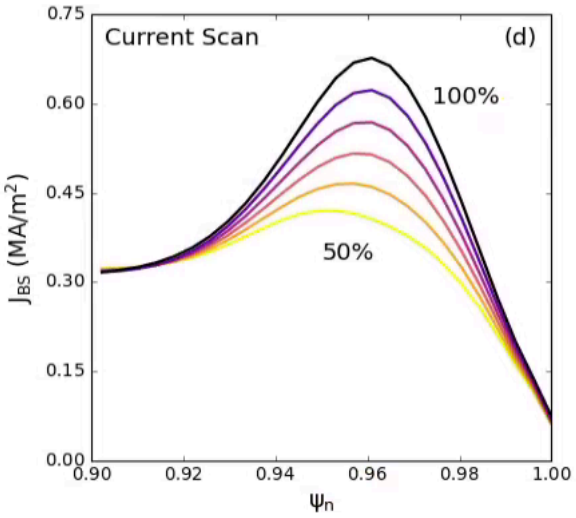
- MTMs are localized on a rational q=m/n surface
- As pedestal recovers **post-ELM, MTM frequency predicted to rise…**

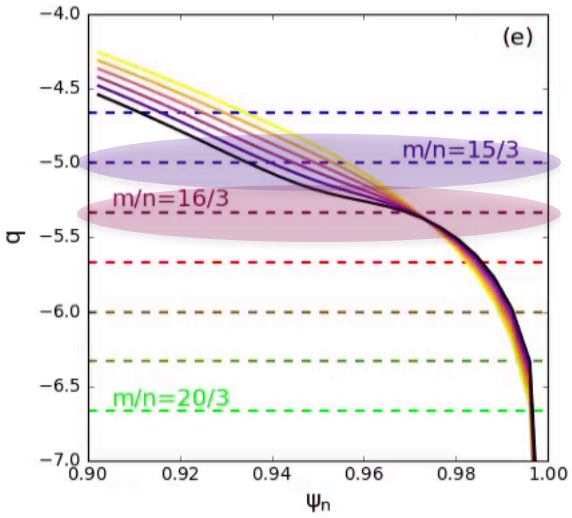


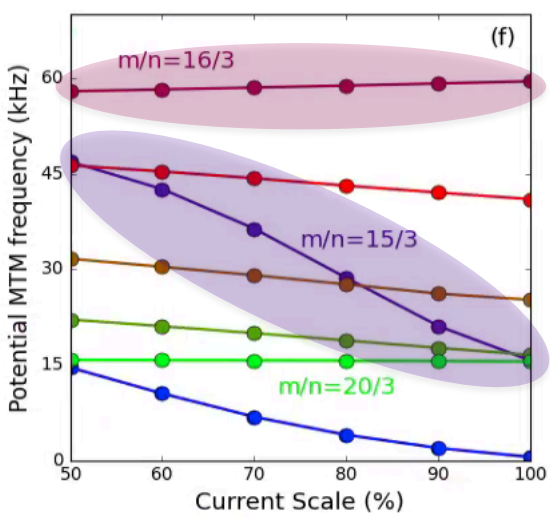
$$\omega_{dop} = \frac{nE_r}{RB_p} \qquad \omega_{*e} = k_\theta \rho_s c_s \left(\frac{1}{L_{Te}} + \frac{1}{L_{ne}}\right)$$

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!**



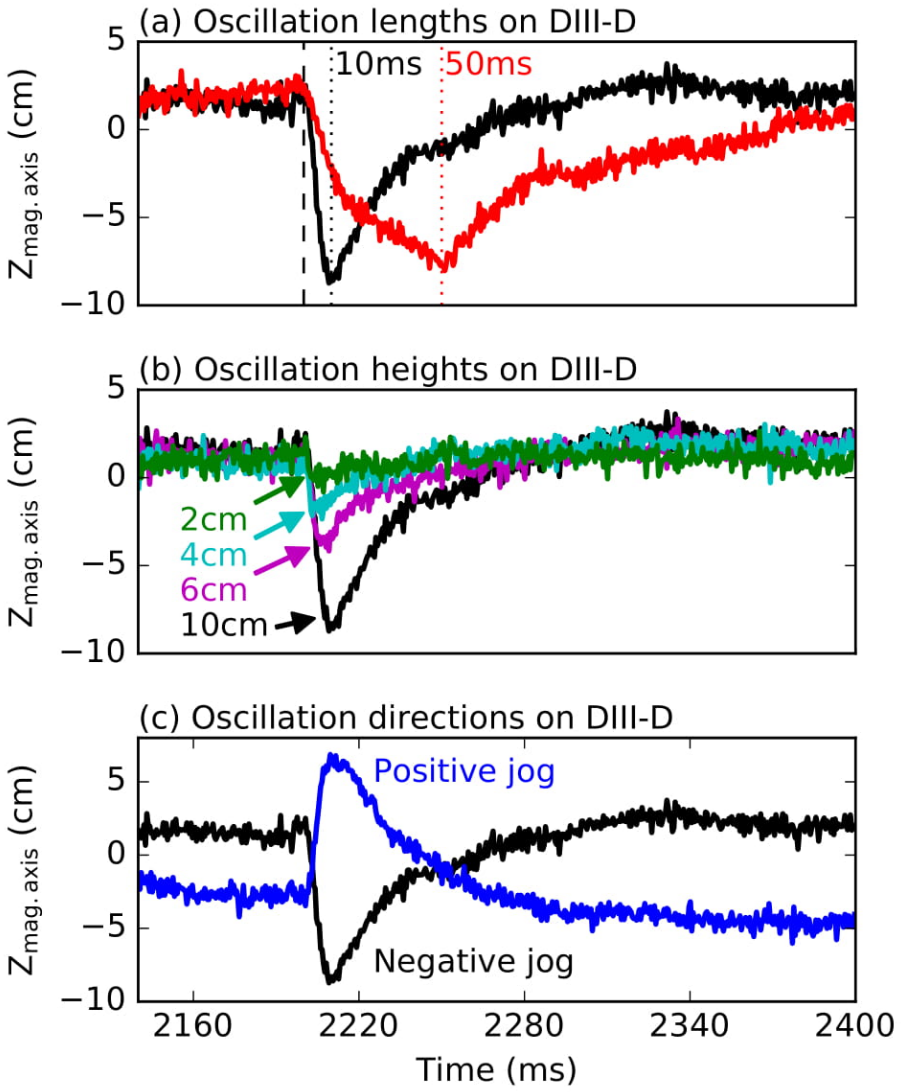




Experimental Procedure

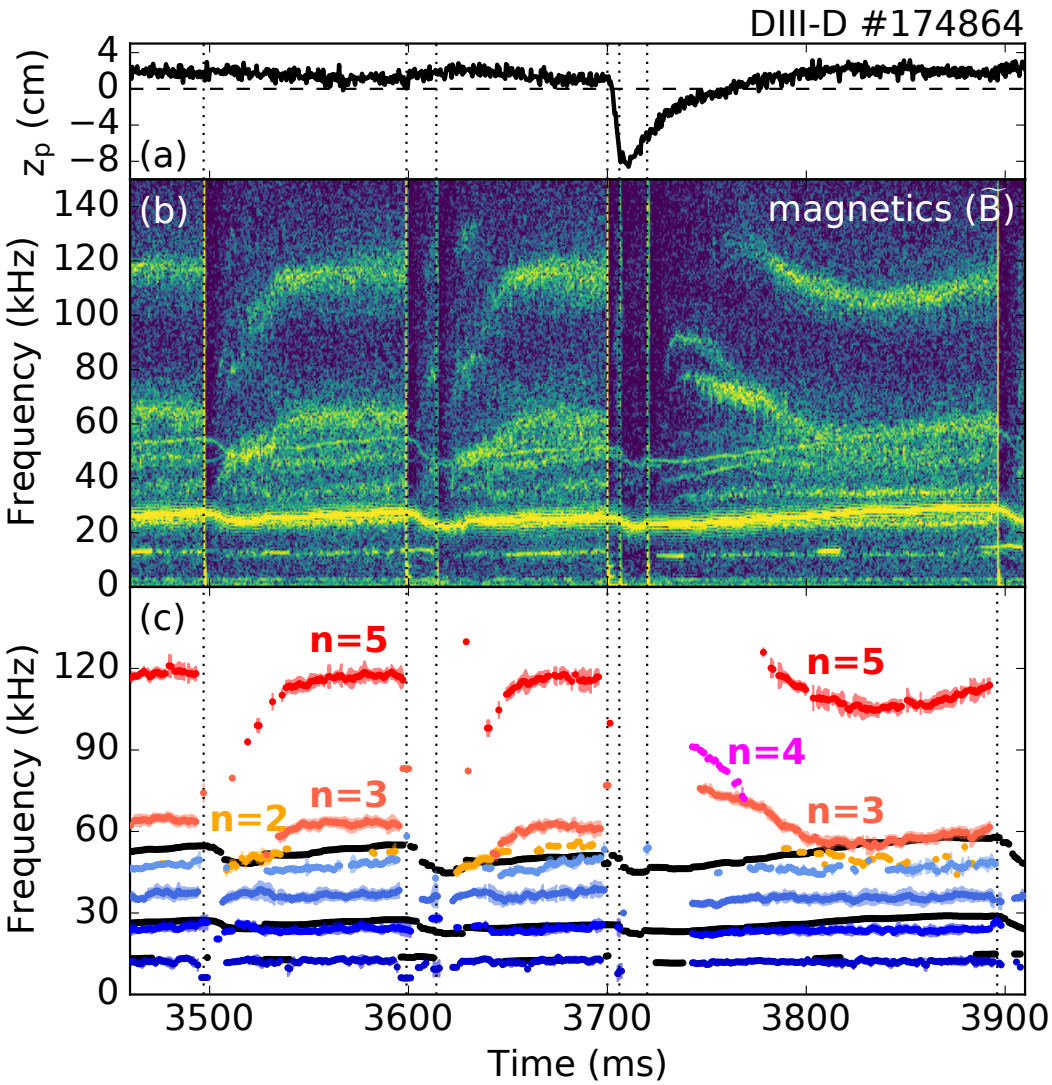
Experimental procedure – scan induced edge current

- 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



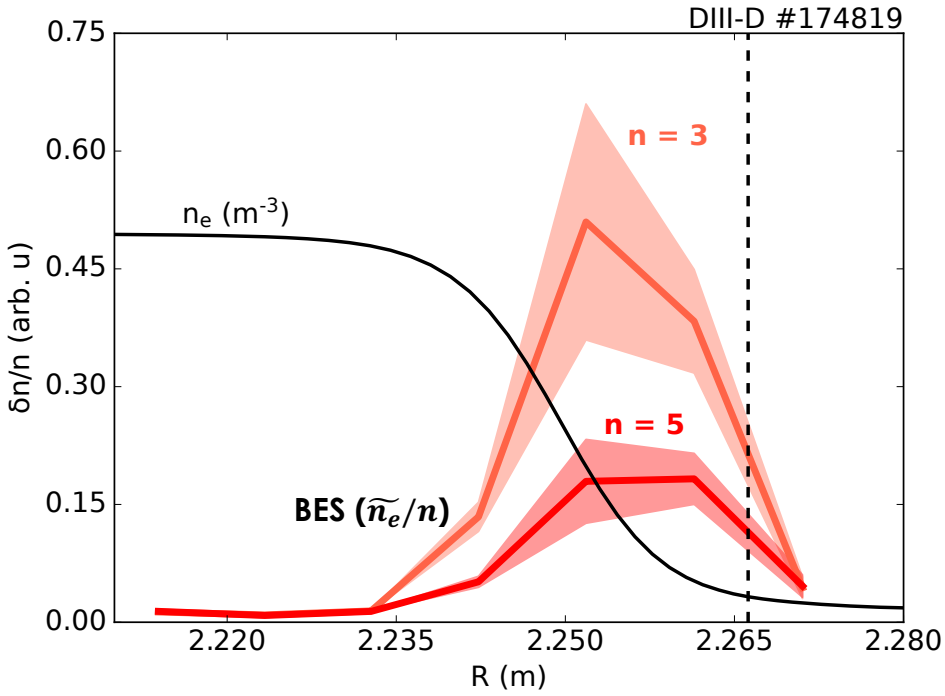
Largest jogs lead to inverted mode chirping!

- 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



BES localizes high f modes at the plasma edge

- 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 $\boldsymbol{q \geq 5}$



Mode Identification

Theoretical properties of pedestal MTMs

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
  $\omega_{e*} = k_y \rho_s c_s \left(\frac{1}{L_{n_e}} + \frac{1}{L_{T_e}} \right)$ [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]

Test these!

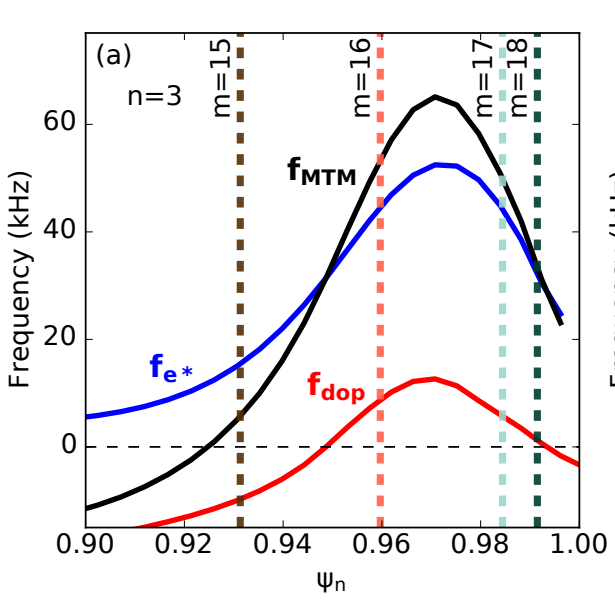
- Requires finite collisionality/resistivity [Drake 1980] −
- Growth rate depends non-monotonically on collisions [Chen 2020] −
- Saturates as $|\delta B_r/B| \sim \rho_e/L_{T_e}$ [Chen 2020] −
- Mode can peak anywhere (top/bottom in [Hatch 2021]) −

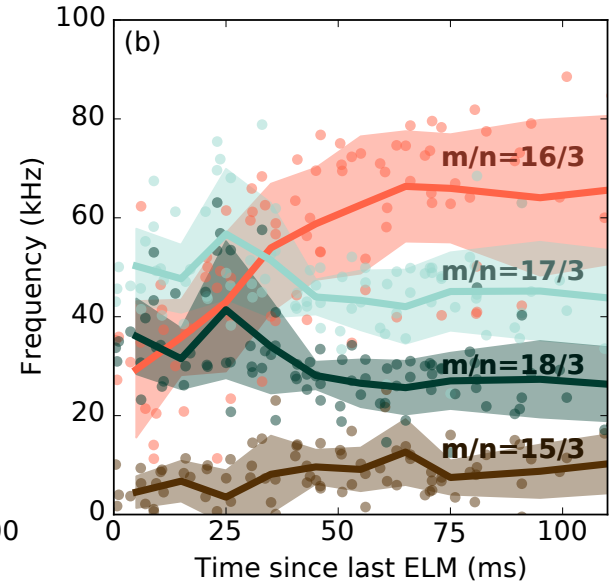
Mode frequency consistent with MTM predictions

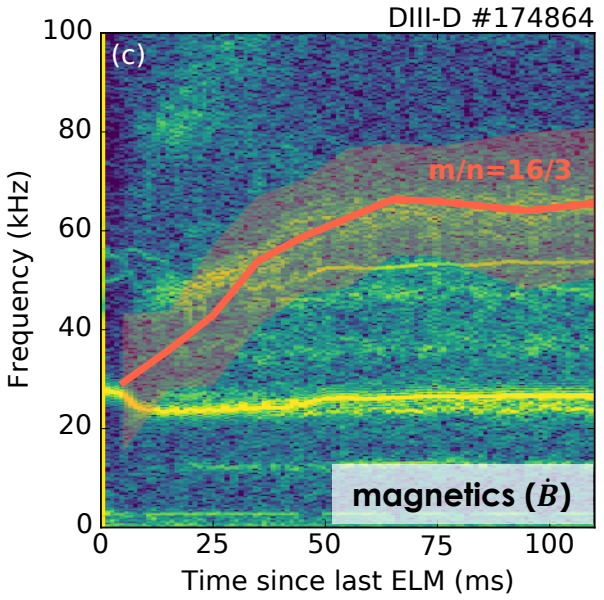
- **Normal ELM:**
  - Up-chirp in $n = 3$ and $n = 5$ modes due to inter-ELM gradient recovery

$$\boldsymbol{\omega_{MTM}(\psi_n) = \omega_{dop}(\psi_n) + \omega_{*e}(\psi_n)}$$

- **Qualitative and quantitative agreement with magnetics!**



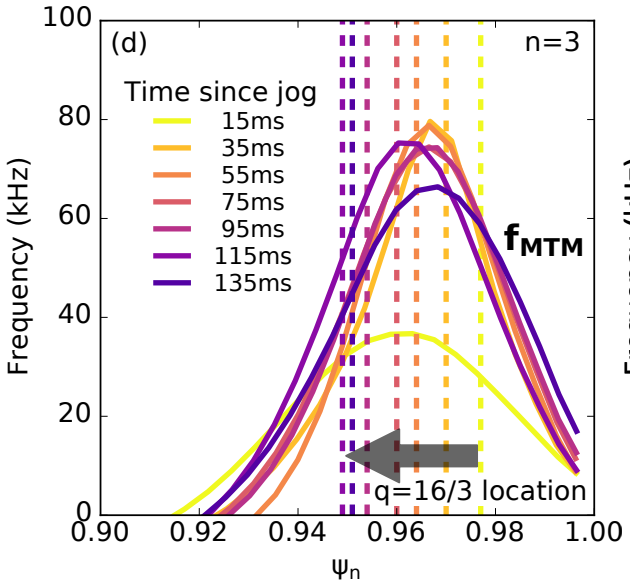


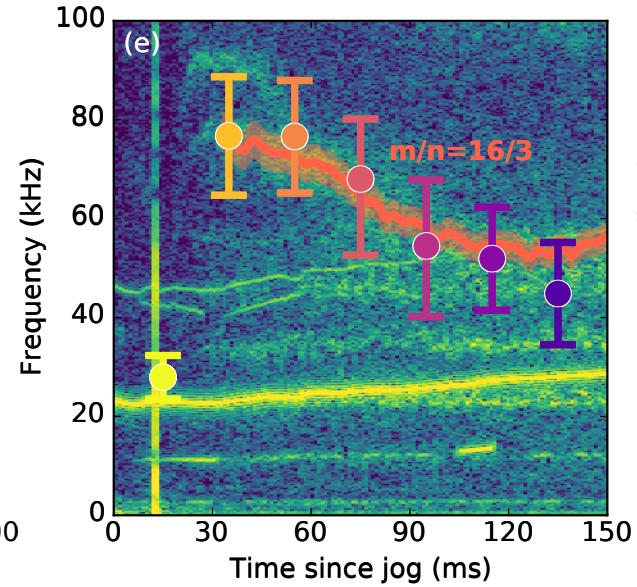


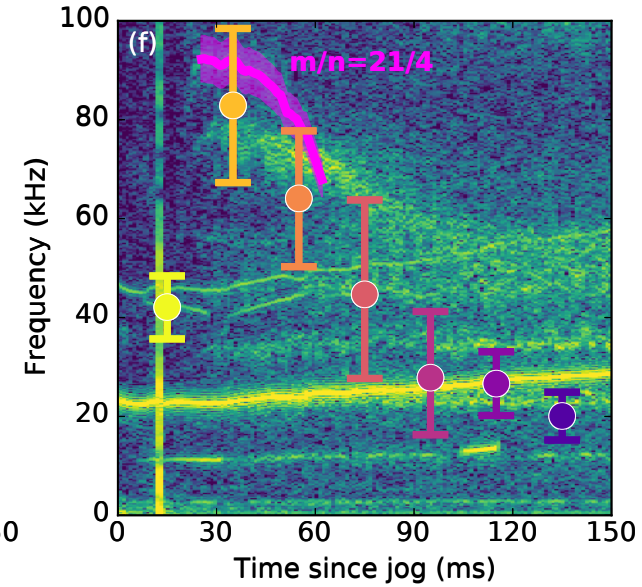
Mode frequency consistent with MTM predictions

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

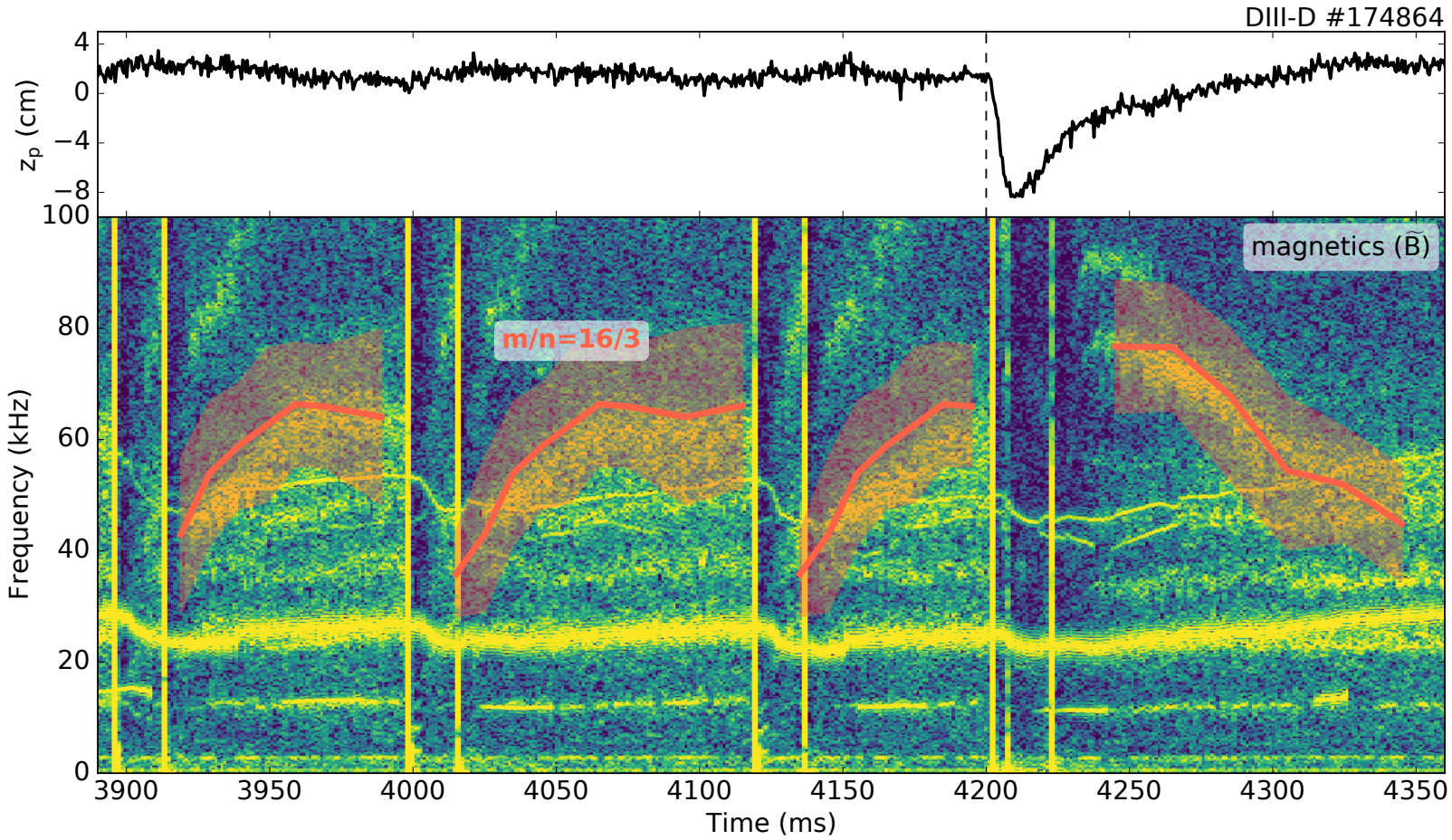
- **Qualitative and quantitative agreement with magnetics!**







Mode frequency fully consistent with MTM predictions



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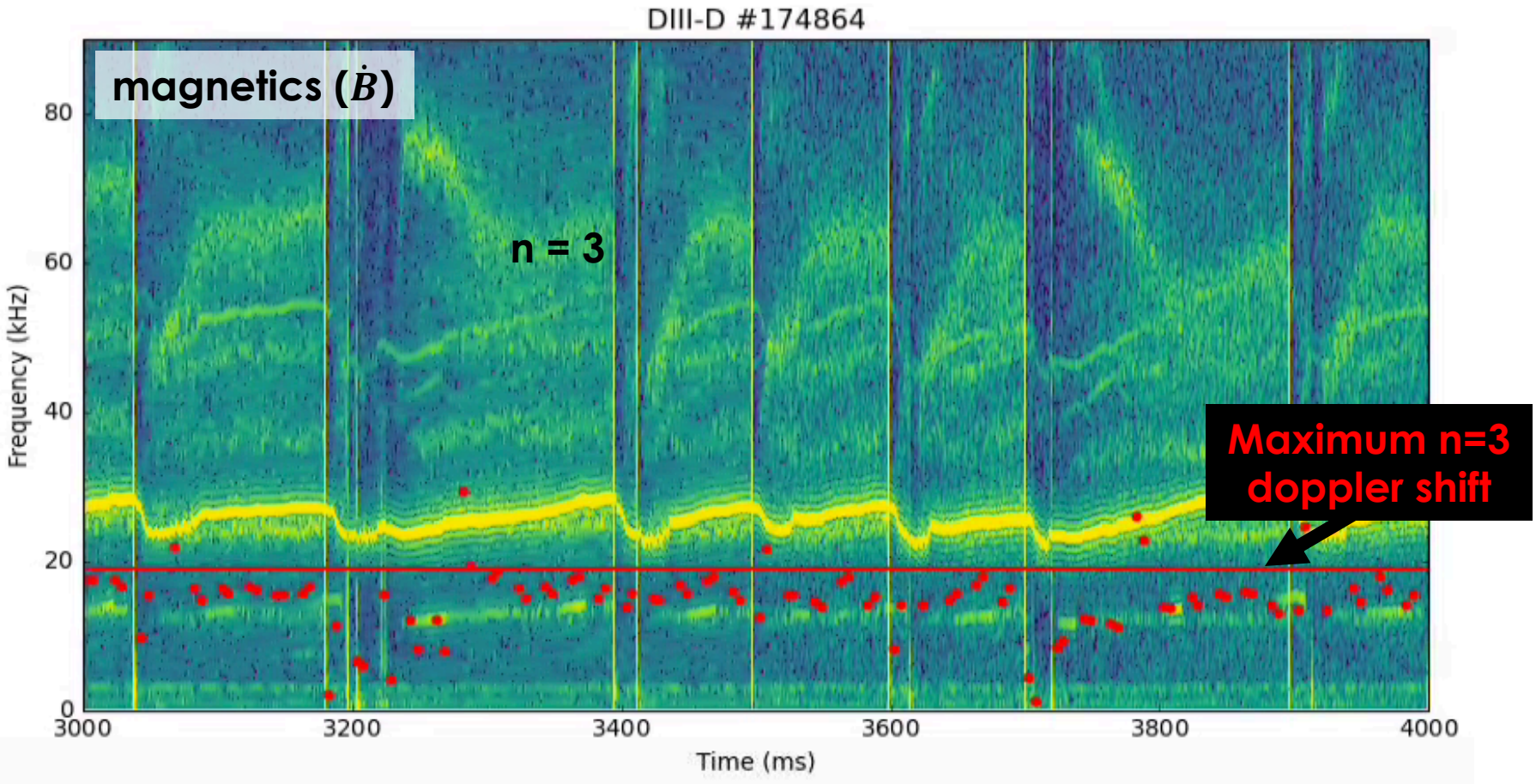
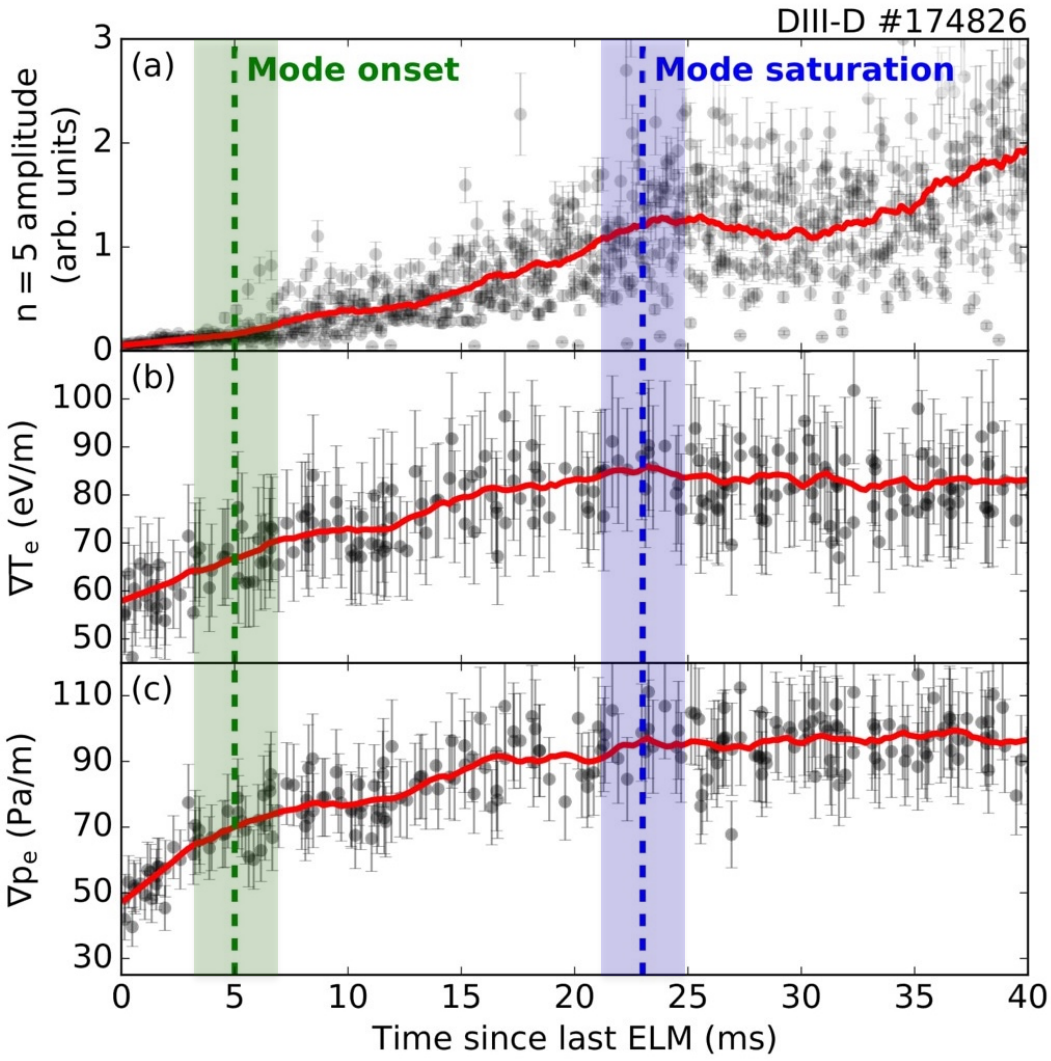
Propagation direction consistent with MTMs

- Frequencies in the **electron diamagnetic direction** in plasma frame
  - Confirmed with BES



Mode saturation with ∇T_e and ∇P_e

- Amplitude of magnetic fluctuations consistent with $\boldsymbol{\nabla T_e}$ (MTM-like)
- Due to fast density recovery timescale, also consistent with $\boldsymbol{\nabla P_e}$ (KBM-like)
- MTM amplitude also dependent on offset between ω_{*e} peak and rational surface
  - Amplitude change after saturation

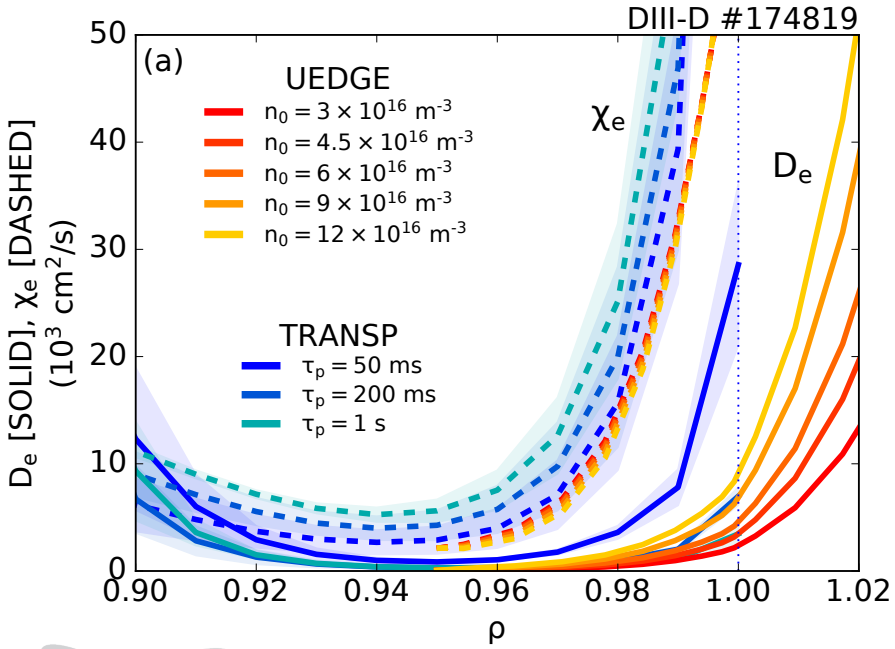


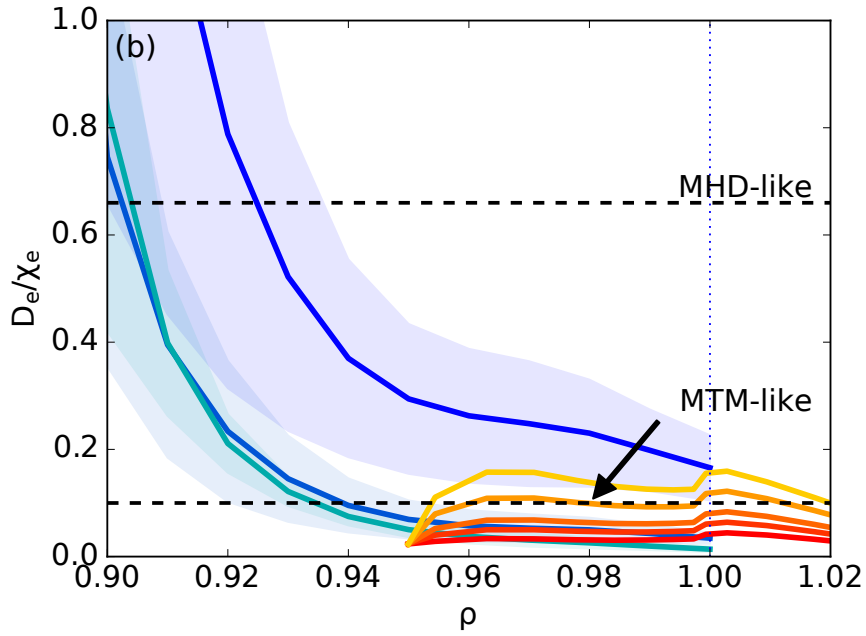
UEDGE + TRANSP calcs consistent with MTM fingerprints

- **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





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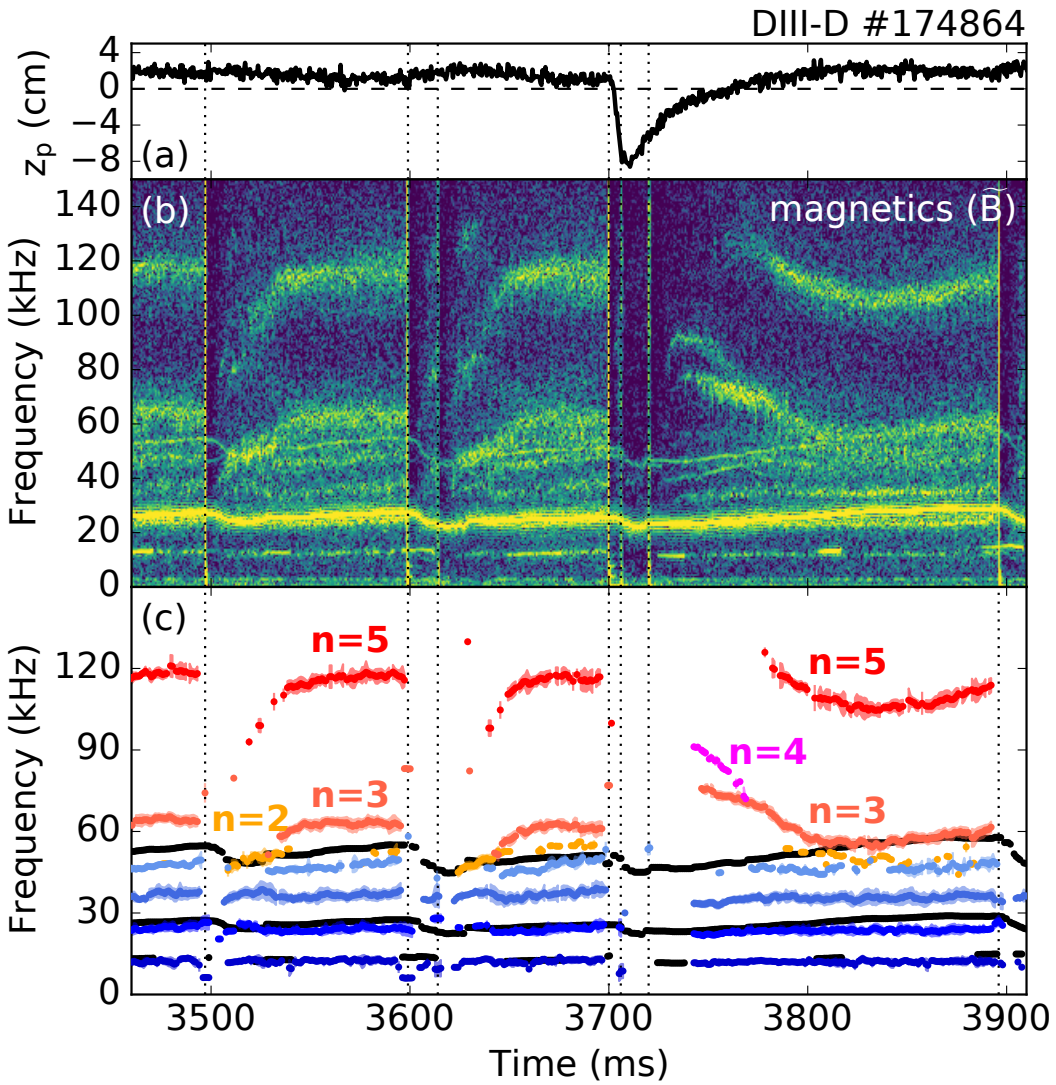
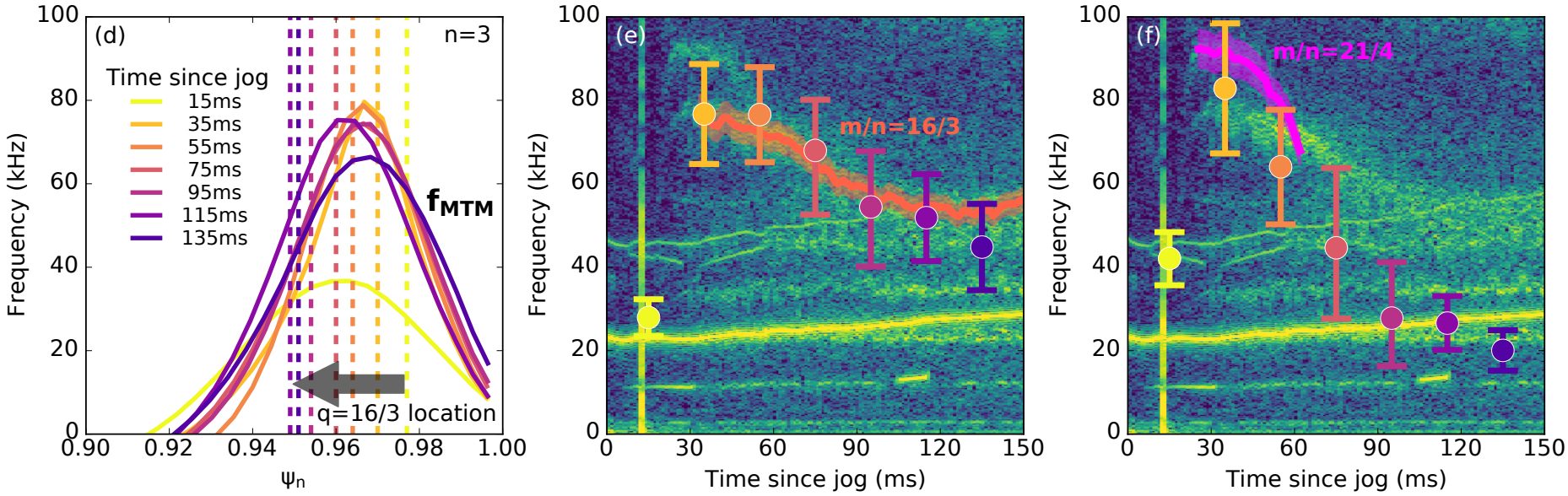
Conclusions

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.