Tokamak plasmas in MST with density up to ten times the Greenwald limit

N. C. Hurst, B. E. Chapman, A. F. Almagri, D. J. Den Hartog, J. B. Flahavan, C. B. Forest, K. J. McCollam, J. S. Sarff

UW–Madison Physics Department, Madison, WI, USA

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WiPPL

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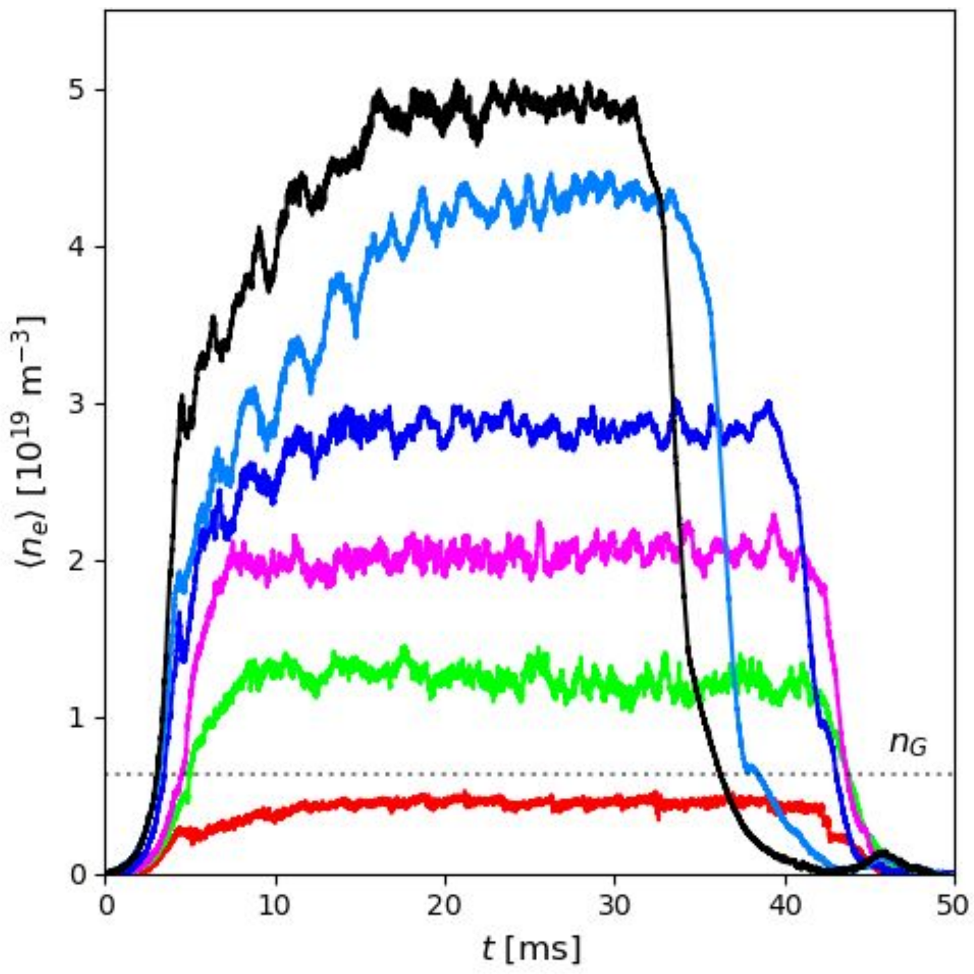
Interferometer measures density up to 10 nG in MST tokamak

$B_T = 0.13$ T

$I_p \sim 50$ kA



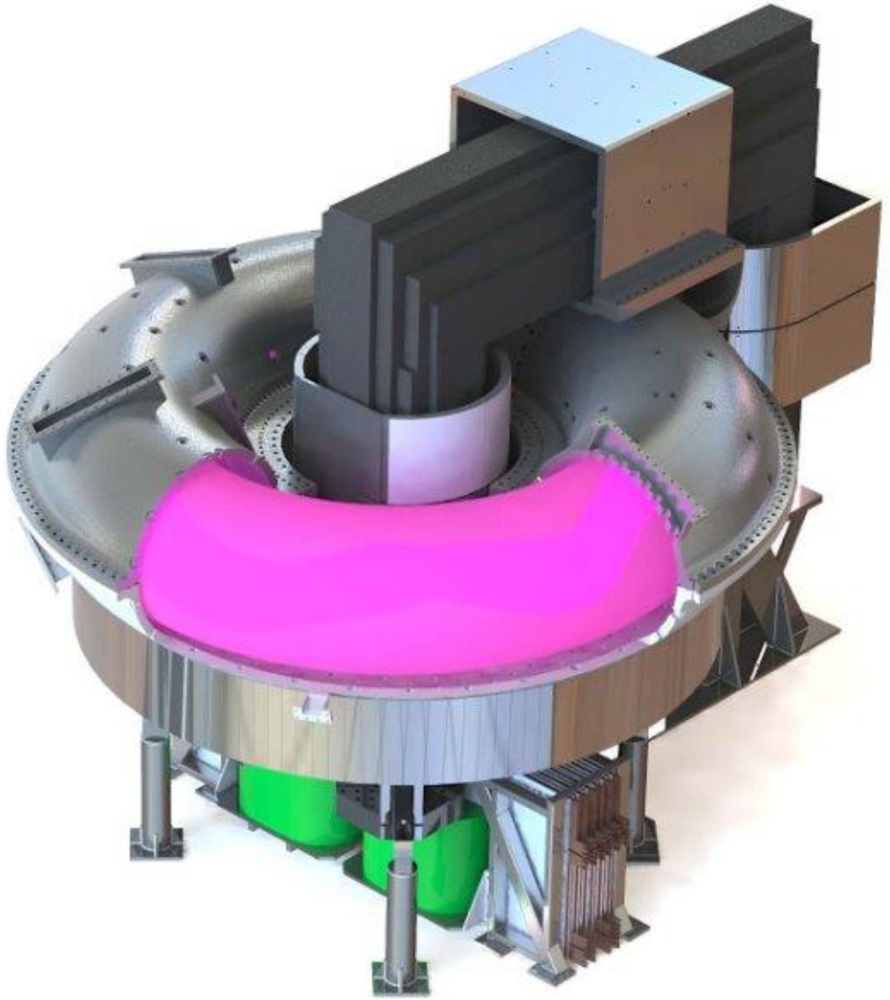
Hurst *et al.*, *PRL* **133**, 055101 (2024)

Talk outline

- Overview of Madison Symmetric Torus (MST) device
- Background on density limit physics
- Details of high-Greenwald-fraction plasmas
- Why is this possible in MST?
- How might these results translate to other devices?

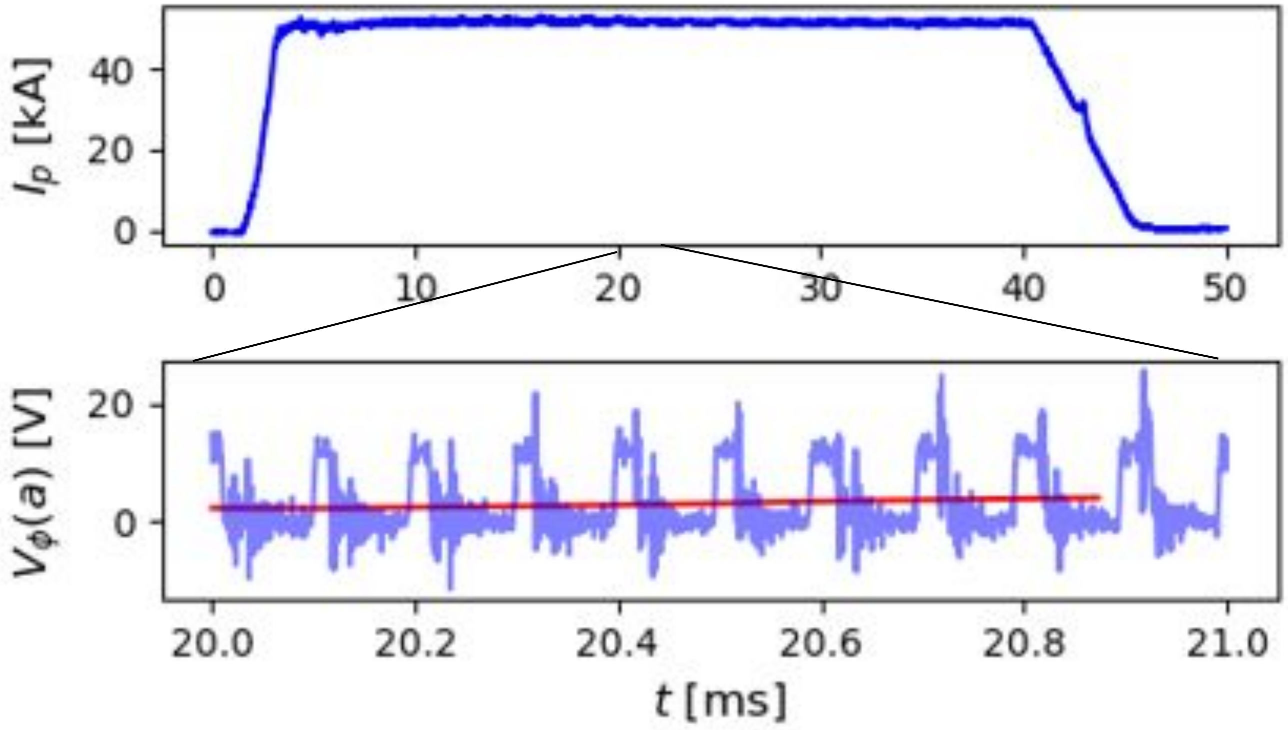
MST is a unique toroidal plasma device

- Operated primarily as RFP 1987-2017
- Since 2017 part of Wisconsin Plasma Physics Laboratory (WiPPL) where 50% of run-time offered to external groups
- R/a = 1.5/0.52 m, circular, graphite limiters
- Can be run as Ohmic, low-field tokamak with shell acting as single-turn B_T coil
- Thick, close-fitting shell with τ_w = 800 ms >> discharge duration ~ 50 ms



BT and Ip can be driven by programmable power supply system

- High-bandwidth, high-loop voltage (~ 100 V) feedback-controlled system meets arb demand
- Uses pulse-width modulation at 10 kHz



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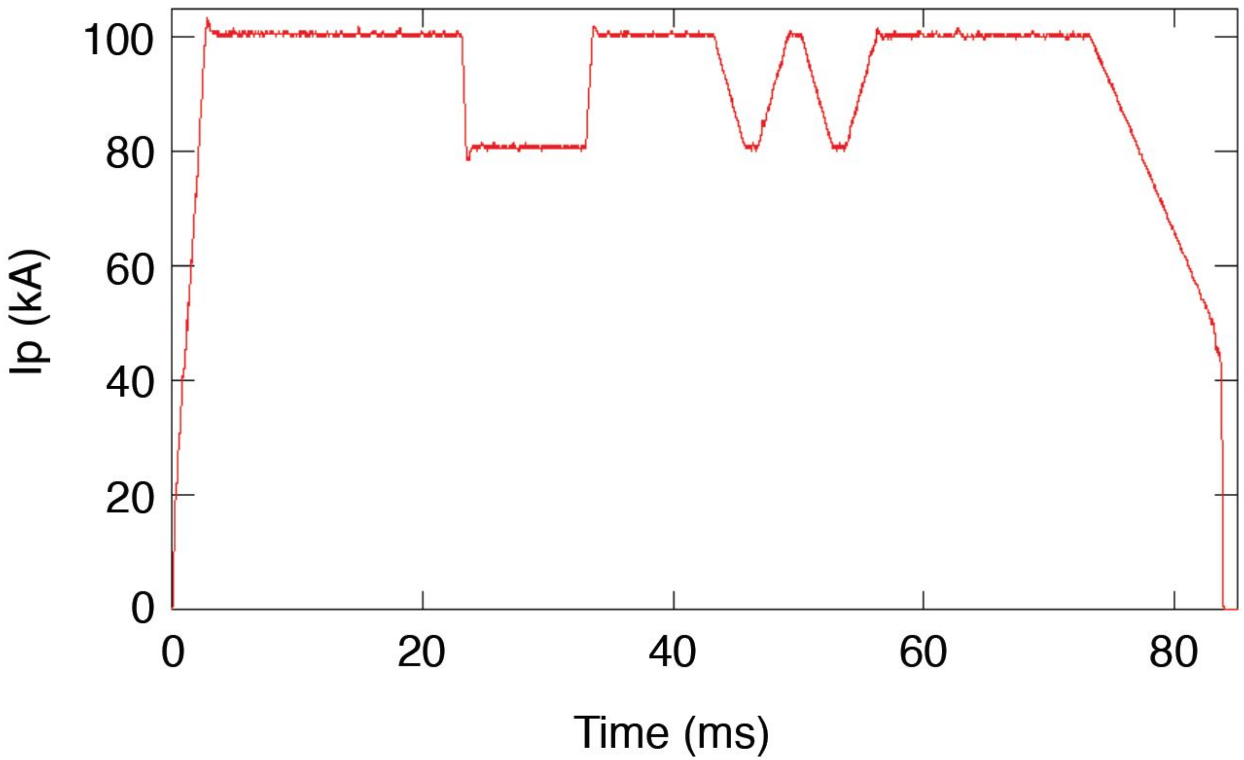
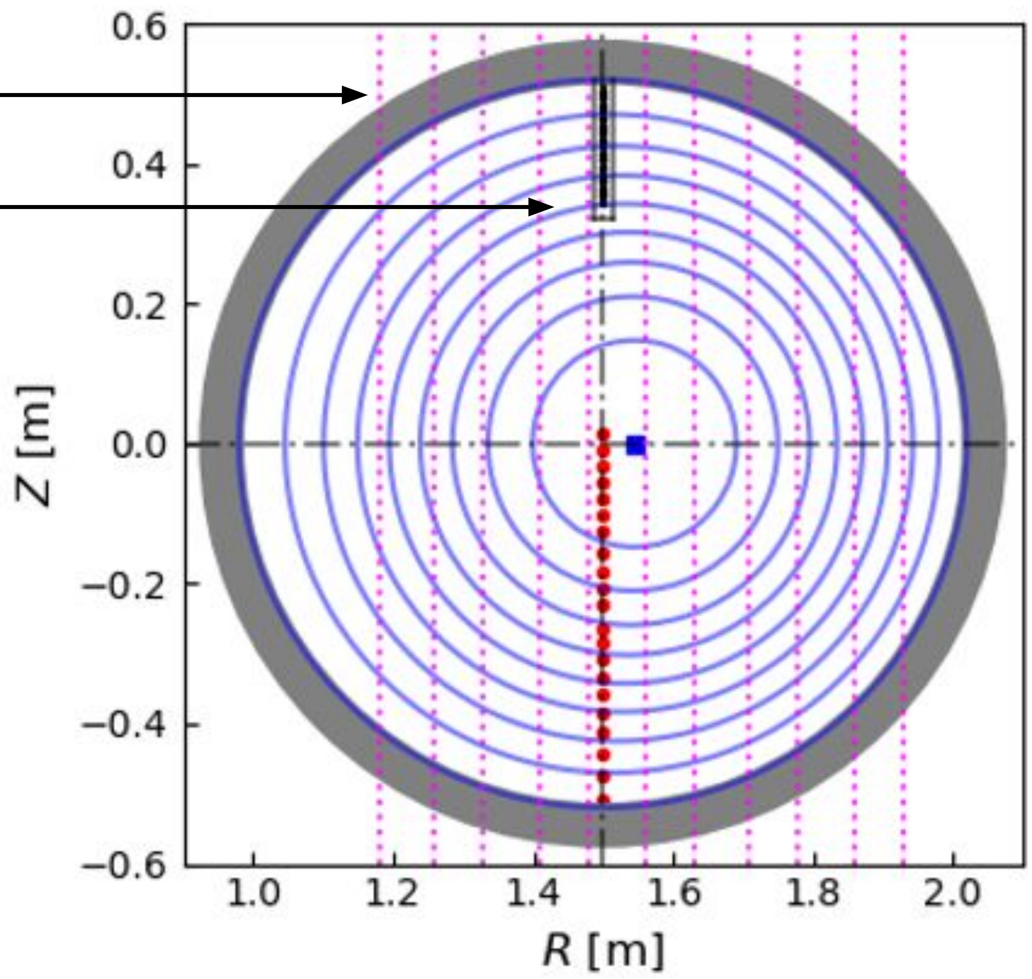


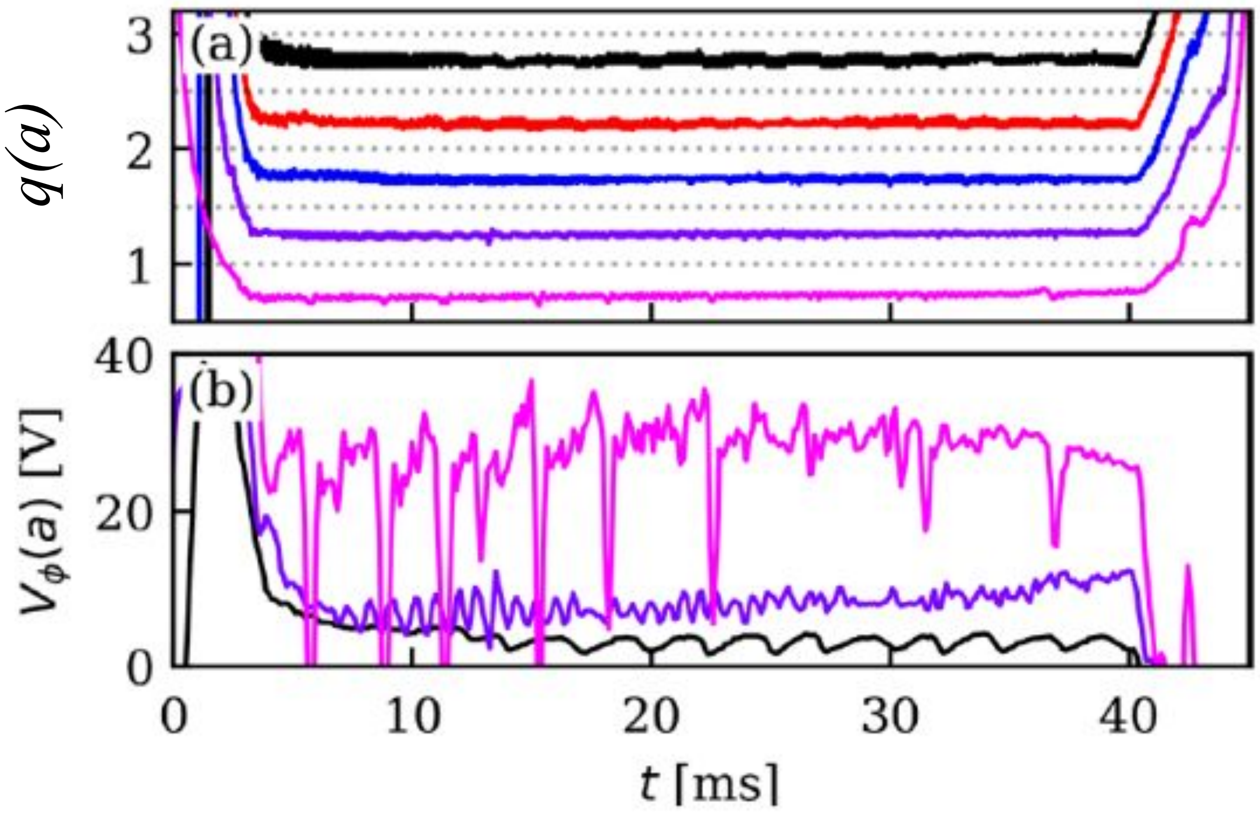
Several key diagnostics inform plasma behavior

- 11-chord far-infrared interferometer
- Deep-insertion magnetic probe
- Edge magnetic arrays
- Impurity monochromators
- Triple Langmuir probe
- Impurity ion spectrometer
- 21-point, 1 kHz Thomson scattering
- And more …



MST tokamak interestingly resistant to disruptions

- Can produce low safety factor plasmas with $0 < q(a) < 2$ ⟶
- Can produce $n >> n_G$ (this talk)
- No RWM due to thick shell, TM maybe also impacted (Strauss talk)
- Programmable power supply can sustain very resistive/dynamic plasma
- One type of disruption observed routinely: low density ~ 10^{17} m^{-3}



Hurst *et al.*, *Phys. Plasmas* **29**, 080704 (2022)

Some disagreement on specifics of density limit mechanism

- **Phenomenology**
  - Empirical disruptive limit on $< n_e >$ across many machines: $n_G = I_p / \pi a^2$
  - Limitation on $P_{fus} \sim n^2$
  - Strong edge radiation/MARFE
  - 1.5-2 n_G possible with peaked $n_e(r)$ or negative triangularity (DIII-D)
  - Edge pressure/current profile collapse sets up unstable MHD

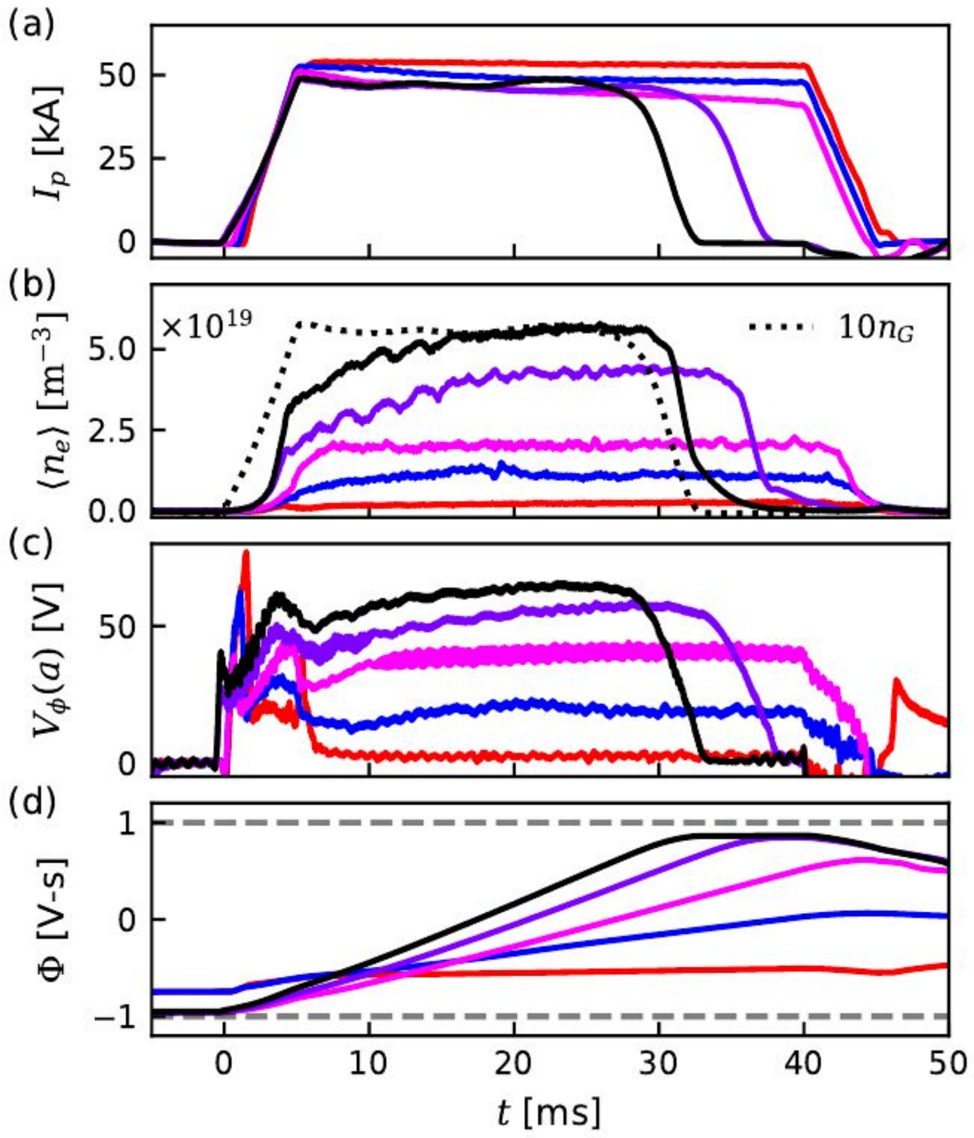
- **Models**
  - Edge radiative collapse
  - Radiation-destabilized TM
  - Ballooning turbulence onset at high collisionality
  - Shear-layer collapse

Greenwald, *PPCF* **44**, 201 (2002)

Manz *et al.*, *Nucl. Fusion* **63**, 076026 (2023)

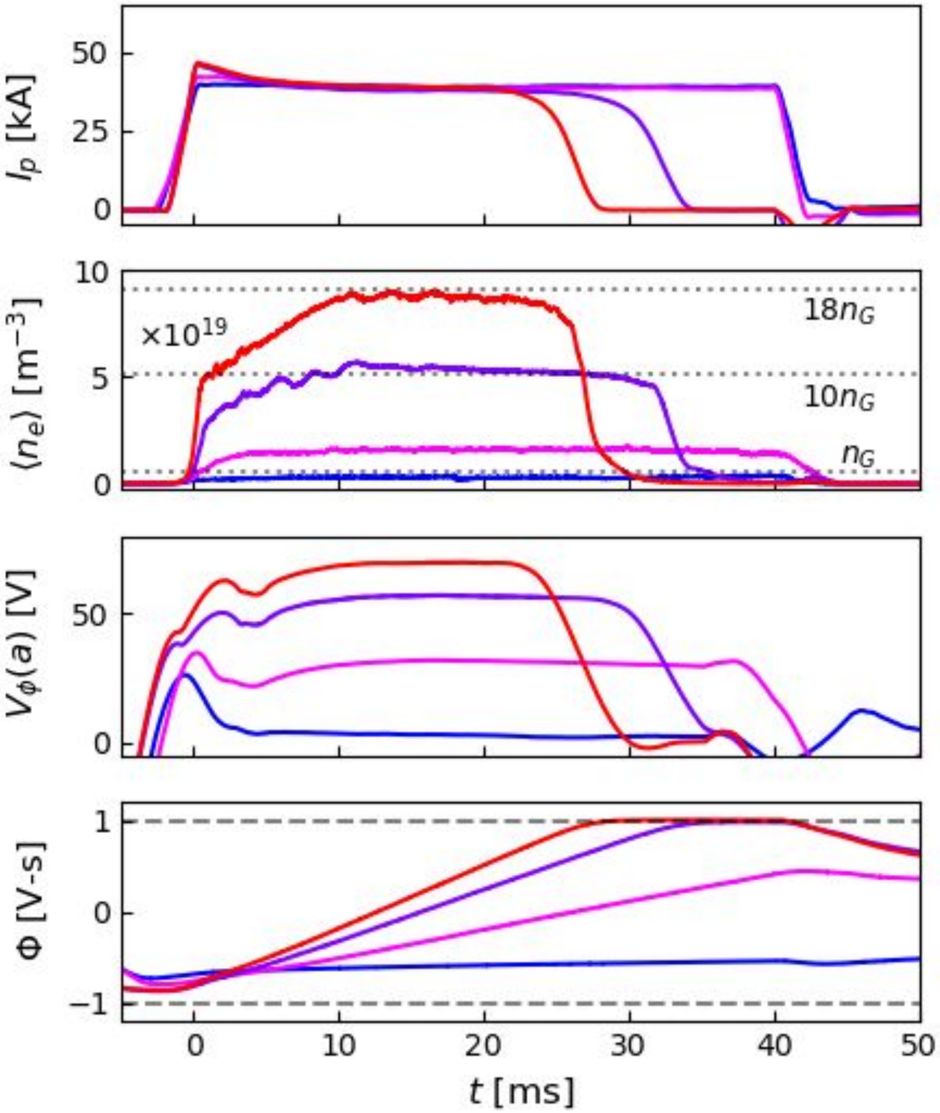
Transformer flux swing limits maximum density in MST tokamak

- Plasma current drops slightly from 55 to 45 kA as power supply tries to meet demand
  - Relatively low $q(a) \sim 2.3$
- Highest density shown here 10 n_G for about 10 ms >> $\tau_E \sim 0.1$ ms
- V_{loop} up to 60 V, discharges shortened due to consumption of 2 V-s flux swing
- T_e drops from 60-80 eV at $f_G = n/n_G < 1$ to estimated 5-10 eV at $f_G \sim 10$



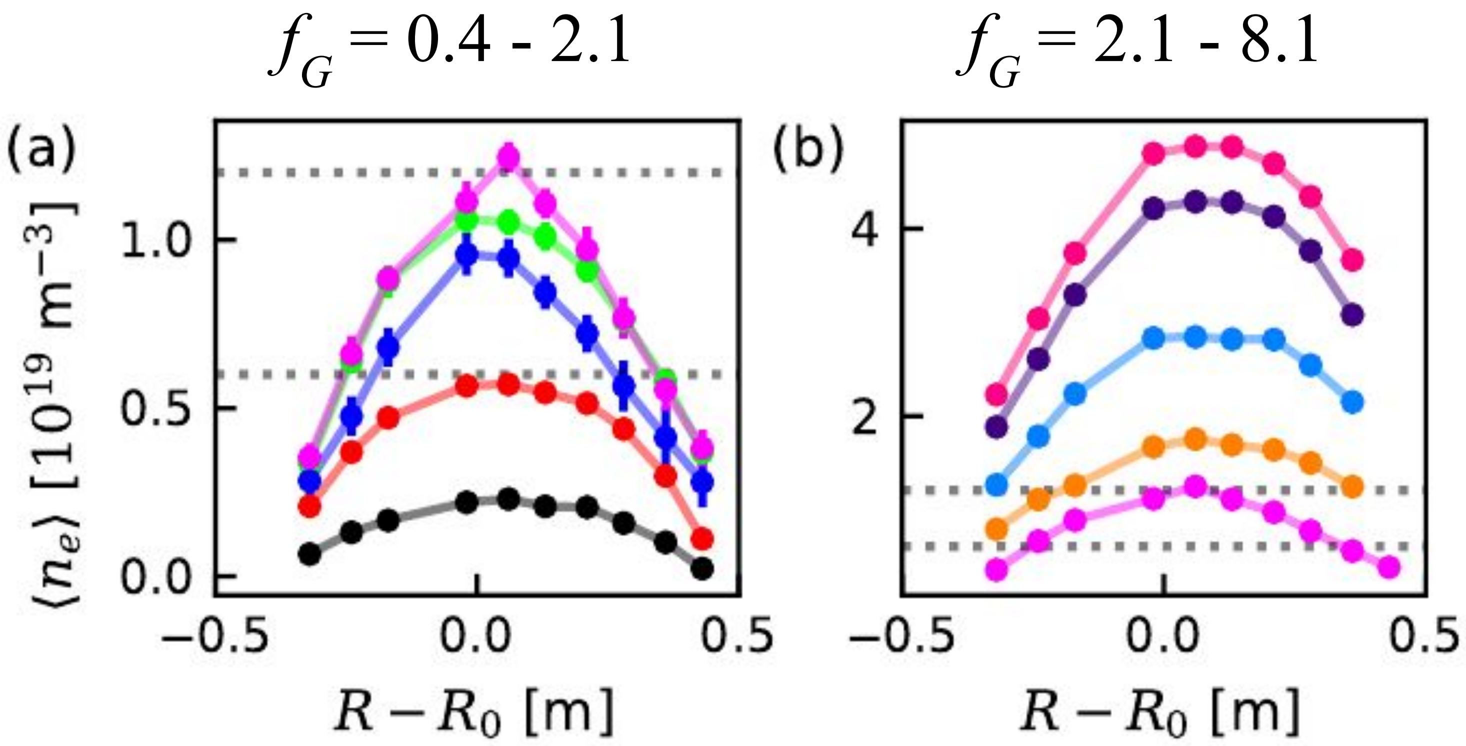
Recently produced plasma with f_G = 18 at lower current

- Preliminary results from WiPPL grad student Joe Flahavan (right)
- *q(a)* ~ 3 similar to other tokamaks
- Lower V_{loop} required for given f_G
- Shorter discharges at f_G = 18, but probably still considered steady



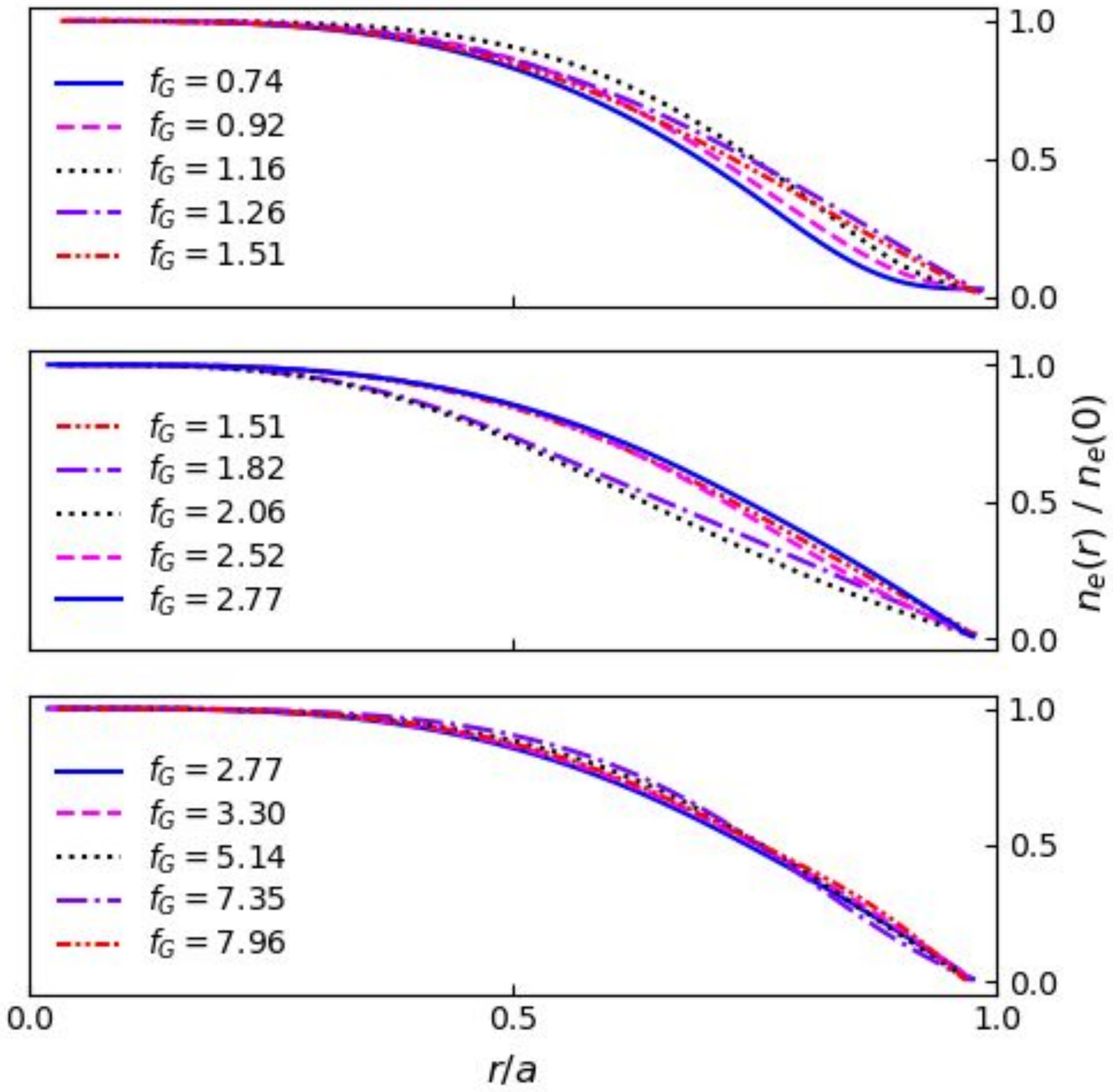
11-chord interferometer yields density profile information

- Farthest outboard chords tangent to $r/a \sim 0.69, 0.83$
- Density profile narrows around $f_G = 2$, shifts outboard for $f_G > 2$
- High f_G not associated with strongly peaked profiles



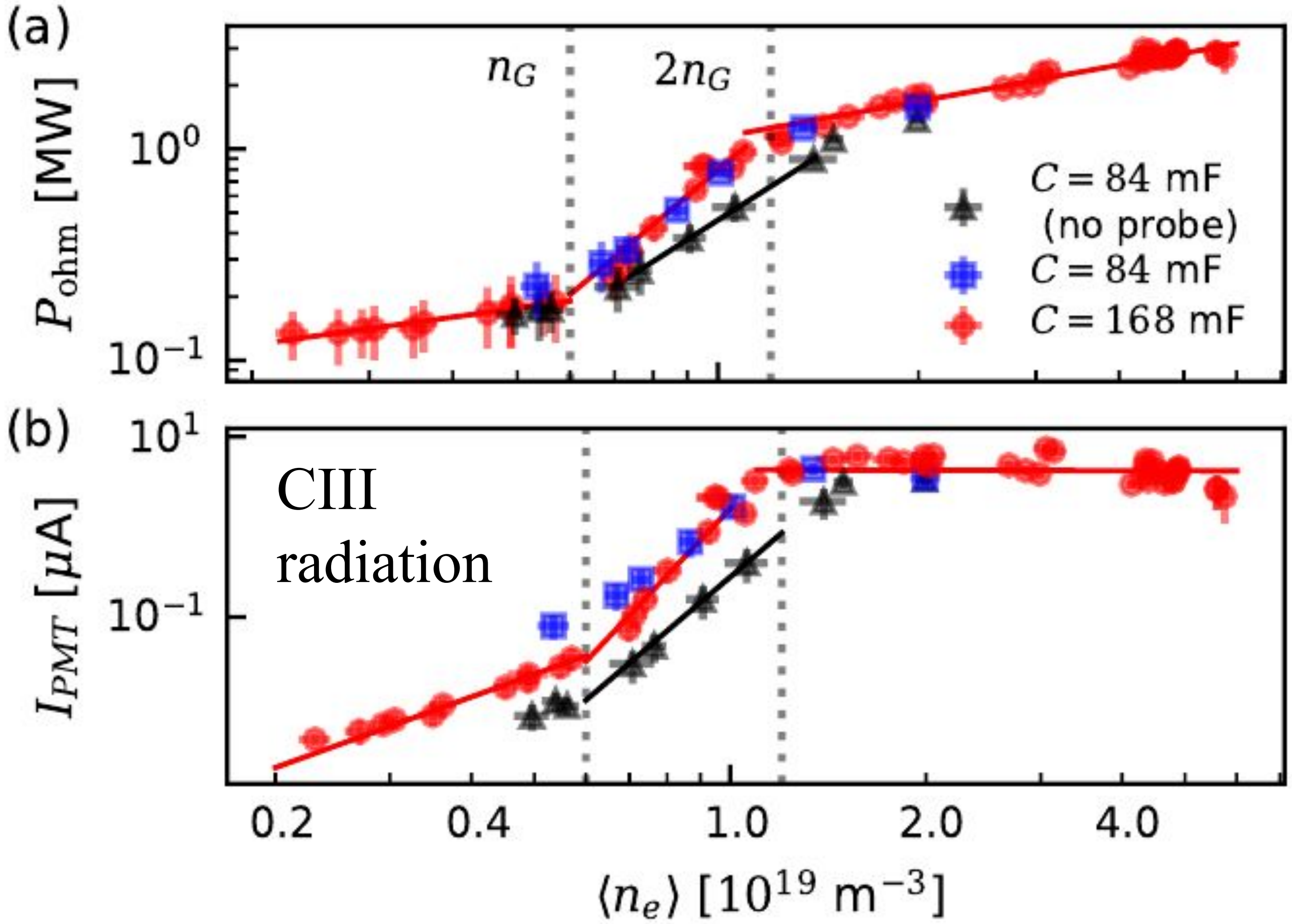
11-chord interferometer yields density profile information

- Toroidal equilibrium reconstructions using MSTFit code give inverted density profiles $n_e(r)$
  - Assume $n_e(a) / n_e(0)$ fixed
- Profile broadens above $f_G = 1$, narrows at $f_G \sim 2$, then broadens again at higher density



Three distinct regimes observed in density scalings

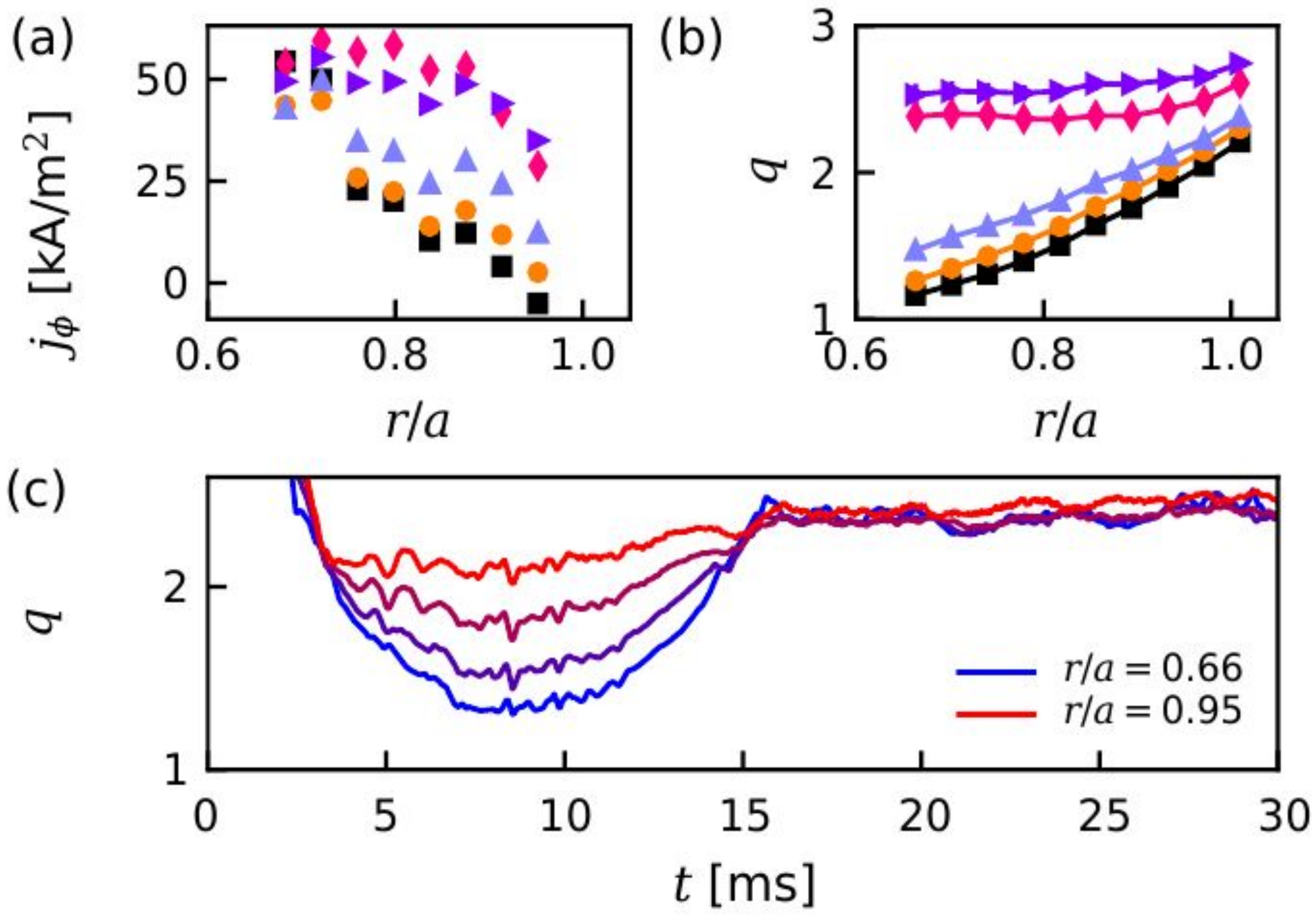
- Three datasets with different power supply capacity, probe usage
- Sharp increase in P_{ohm} and CIII radiation at $f_G = 1$
- Scaling changes again around $f_G = 2$
- $P_{ohm} \sim n_e^2$ for f_G = 1-2



Global flattening of current profile around f_G = 2

- Internal magnetic probe measurements
- $j_\varphi \sim 50$ kA/m^2 similar to $I_p / \pi a^2$
  - Steep edge current gradient near conducting wall
  - No low-order rational surfaces
- Probably global radiative collapse event

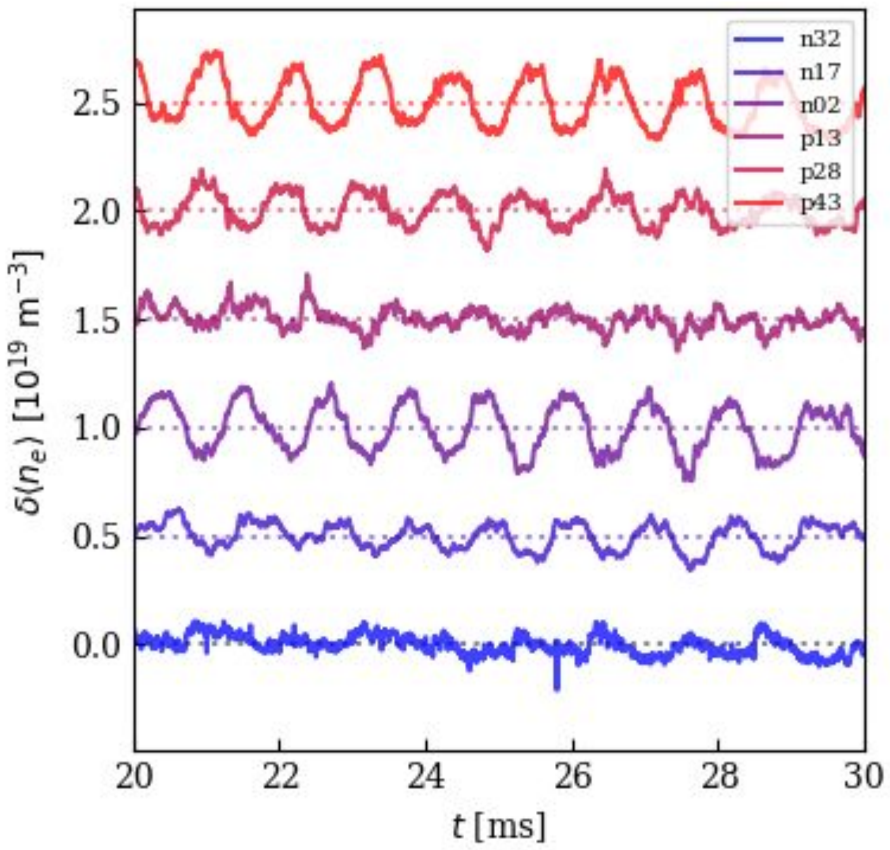
f_G = 0.9, 1.5, 1.7, 3.5, 3.9 (black to purple)



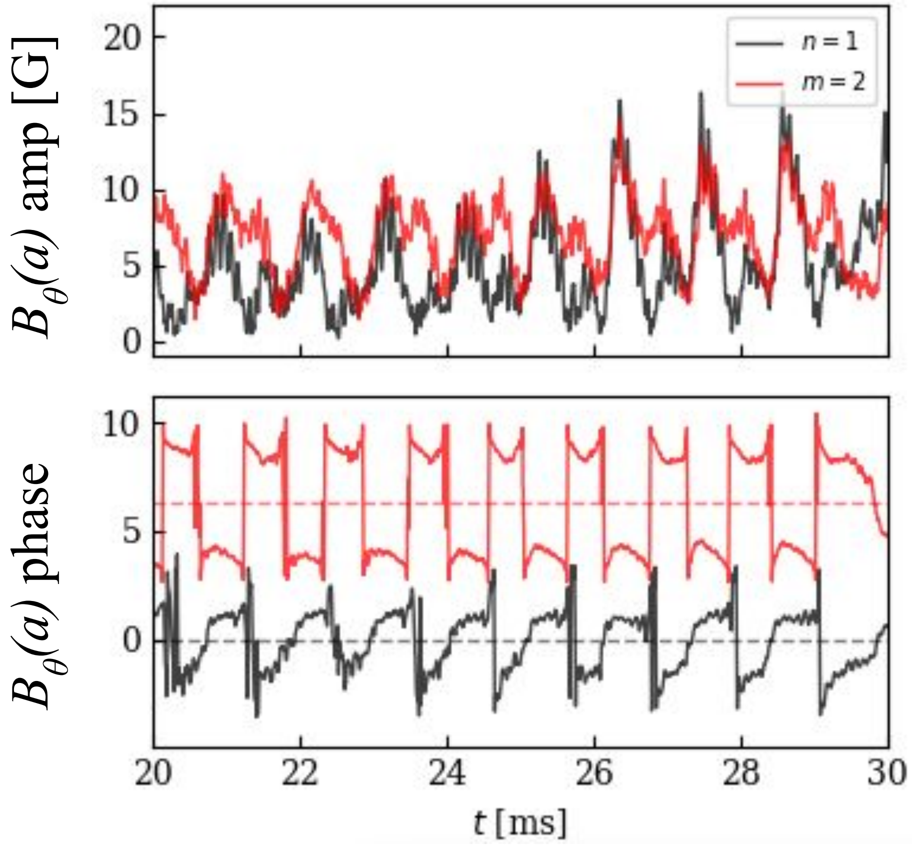
Sometimes observe strong m/n = 2/1 TM around f_G = 1-2

- Present in < 50% of discharges with f_G = 1-2 … Related to profile collapse?

Interferometer

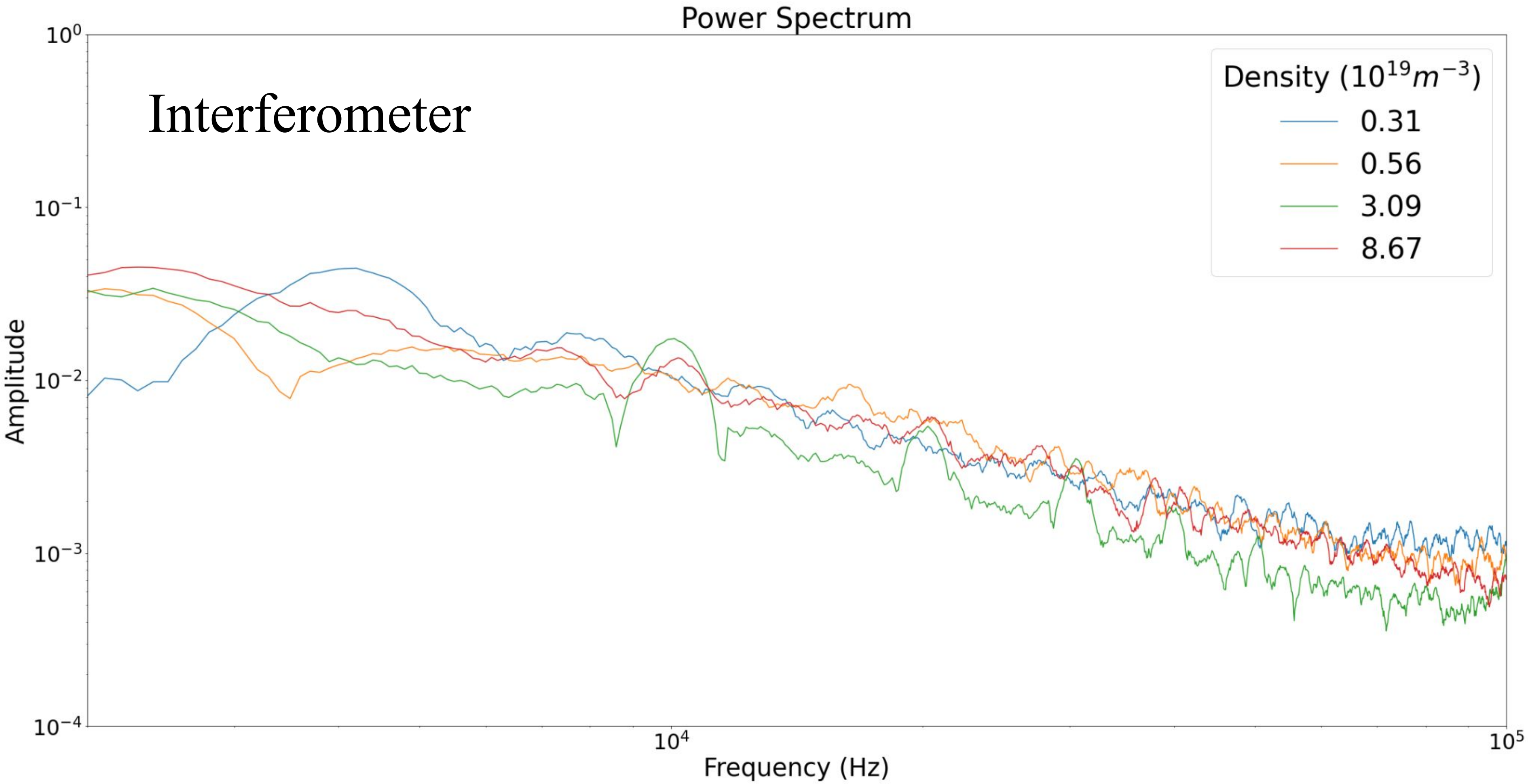


Edge magnetics



No clear evidence of changing turbulence in density fluctuations

- Try to test transport models
- Work by undergraduate Emi Bell



Why can MST run with $f_G >> 1$??

- Hard to say without clear model of density limit mechanism
- Probably related to thick wall and high-loop-voltage power supply
- Some evidence of changes to MHD & TM activity above n_G
- Need more data/analysis to evaluate turbulence
- Possible explanation: MHD mostly suppressed by wall, radiation/turbulence drives TQ, but high-loop-voltage power supply prevents CQ
- Role of edge voltage switching?

How might these results be useful to other fusion devices?

- Possible that RWM/TM stabilization and/or strong edge current drive or heating could help avoid edge pressure collapse central to density limit models in higher-performance devices
- 10-20 n_G not a great fusion scenario, but anywhere above n_G would be a win
- Preventing density limit disruption during density transient also a win
- If disruption happens, long wall time could slow TQ, reduce heat fluxes, give control systems more time to deal with consequences

Summary and conclusions

- MST can run non-disruptive, steady plasmas with Greenwald fraction f_G up to 10 (recent PRL) and up to 18 (preliminary result)
- Probably related to thick, conducting wall and high-voltage feedback power supply
- Opens a new regime of high-normalized-density tokamak plasmas for study
- May inform density limit physics models, help avoid disruptions
- MST open to externally-led projects, proposals due probably in Dec 2024
- Contact me: nhurst@wisc.edu