Non-disruptive tokamak operation far beyond traditional safety factor and density limits

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**2023 DPP invited talk*

Background

- Introduced new OFES-funded MST project at TSDW 2019
- Aimed to produce disruptions in multiple ways
- Diagnose internally, couple to nonlinear MHD modeling

But MST tokamak plasmas do not behave as initially expected

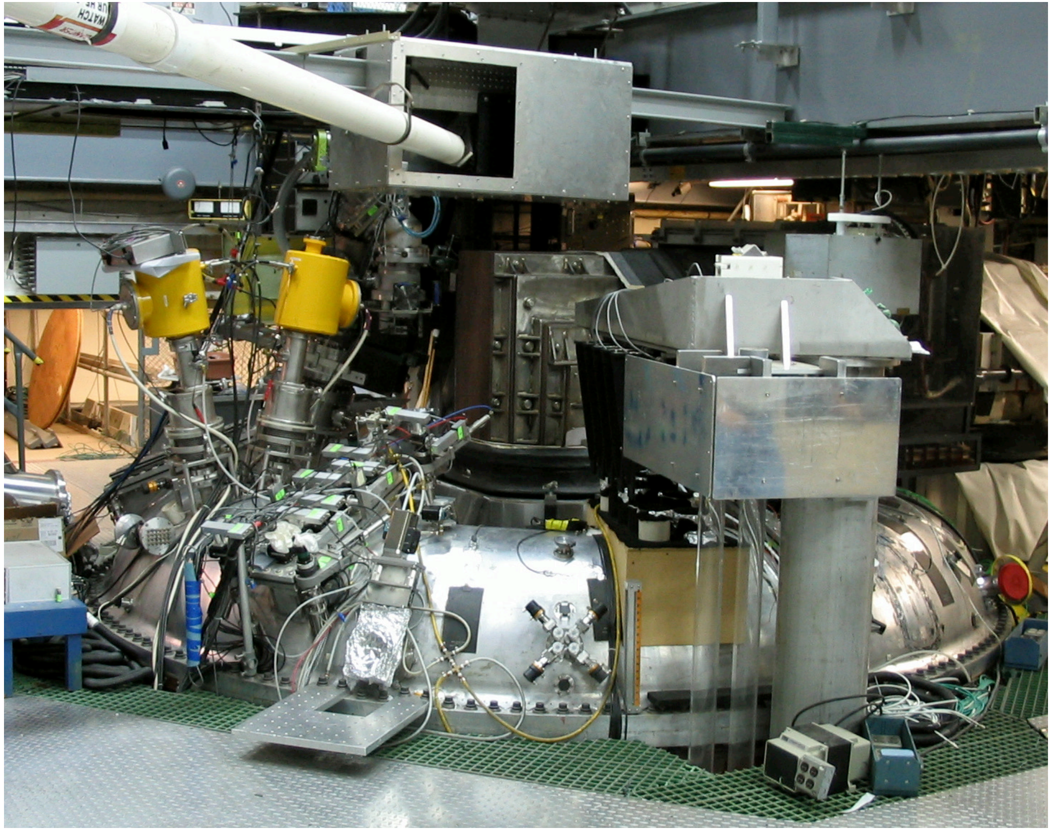
- Plasmas generally appeared commonplace
  - Exhibited sawteeth and other internally-resonant MHD activity
  - Energy confinement about as expected
- Had at least one type of disruption in hand already (more later)
- Further disruption production not expected to be a particular challenge

- But MST has proven to be disruption resistant

Outline

- MST introduction
- Non-disruptive plasmas with $q(a) < 2$ (not surprising, but interesting)
- Non-disruptive plasmas with $n_e \sim 10 n_G$ (surprising)

The MST (Madison Symmetric Torus)

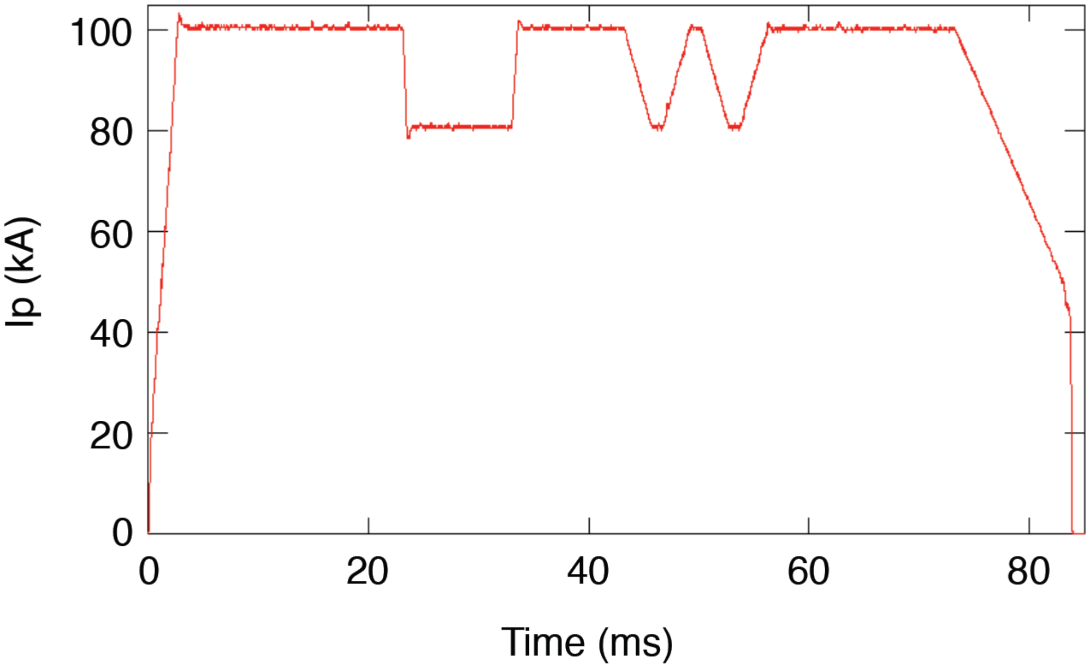


- R/a = 1.5 m/0.52 m
- Circular cross section
- Single-turn TF winding
- PF windings wrapped around iron-core transformer
- Close-fitting thick conducting shell (τ_{wall} ~ 800 ms)

Power and particle handling primitive, fueling standard

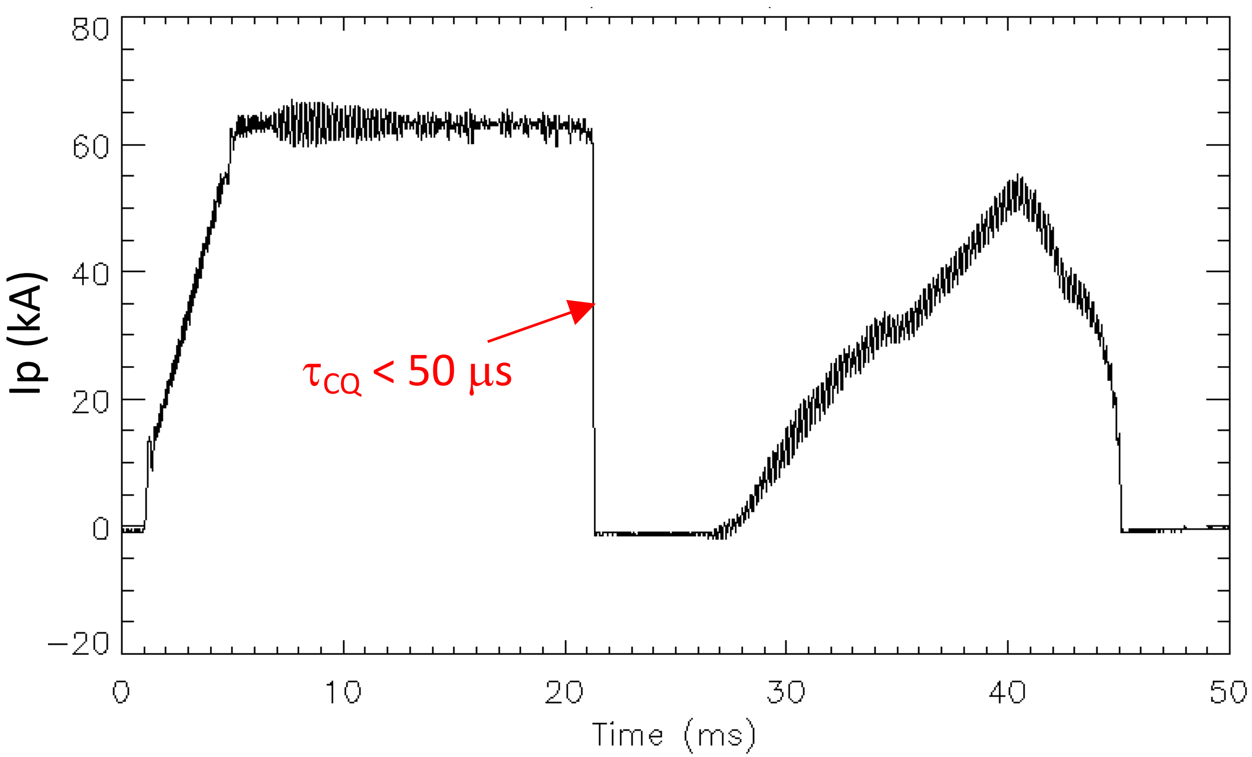
- Limited plasma
- Tiles cover ~ 10% of wall
- Pumping thru 193 holes in bottom of vessel
- Ohmic heating
- Fueling (D_2) via puff valves
- Recycling from graphite tiles

But the plasmas are produced with programmable power supplies



- Drive both TF and PF systems
- High voltage with nearly arbitrary waveforms
- "UW" easily programmed into Ip waveform

Very low density one route to disruption



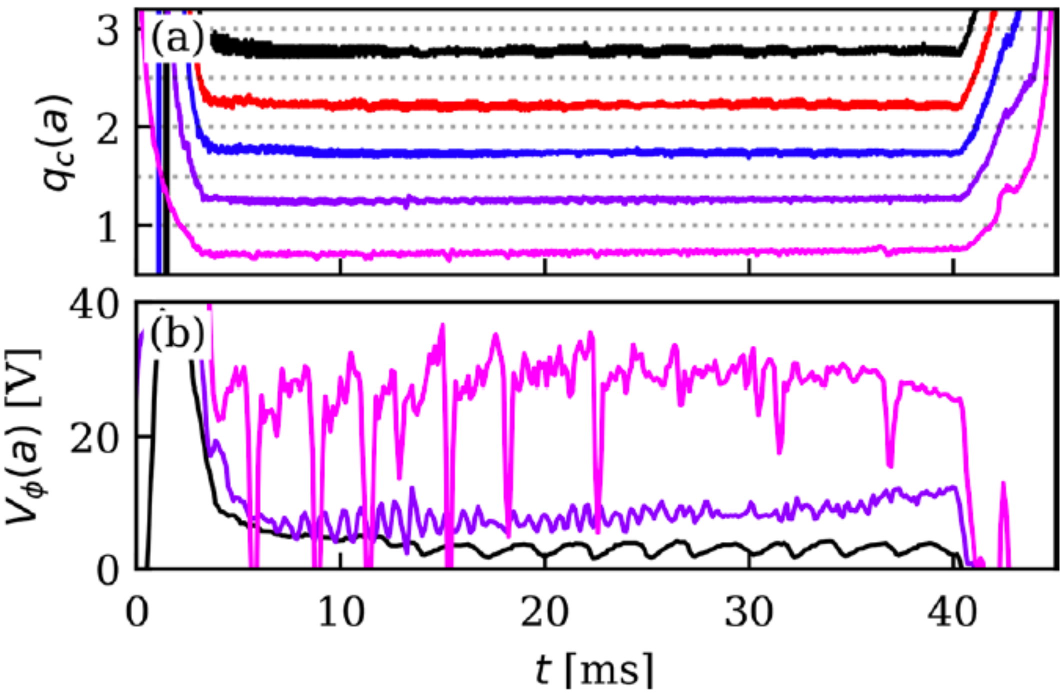
- $n_e < 5 \times 10^{17}$ m^{-3} with runaway electrons

Other approaches not as successful, so far

- Exceeding Greenwald limit (more later)
- RMP of various poloidal mode number
- Argon gas injection

Non-disruptive plasmas with $q(a) < 2$

MST can access broad range of q(a)



- Ip varied with fixed Bt ~ 0.135 T
- Parameter space had yet to be explored with steady equilibria and internal diagnosis

- Thick shell plays important role (pulse duration << wall time)
- Power supplies also important

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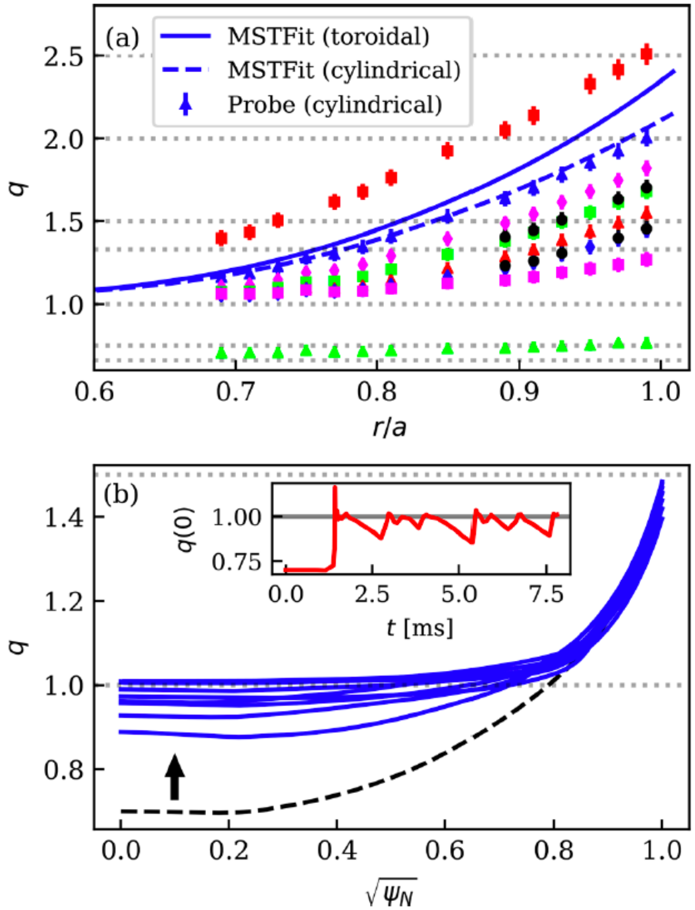
q(0) appears clamped near unity as q(a) is decreased

Data from MST

Data from NIMROD



- Experimental data from steady equilibria, deep insertion probe
- NIMROD nonlinear modeling over several sawtooth cycles, dependent on initial conditions

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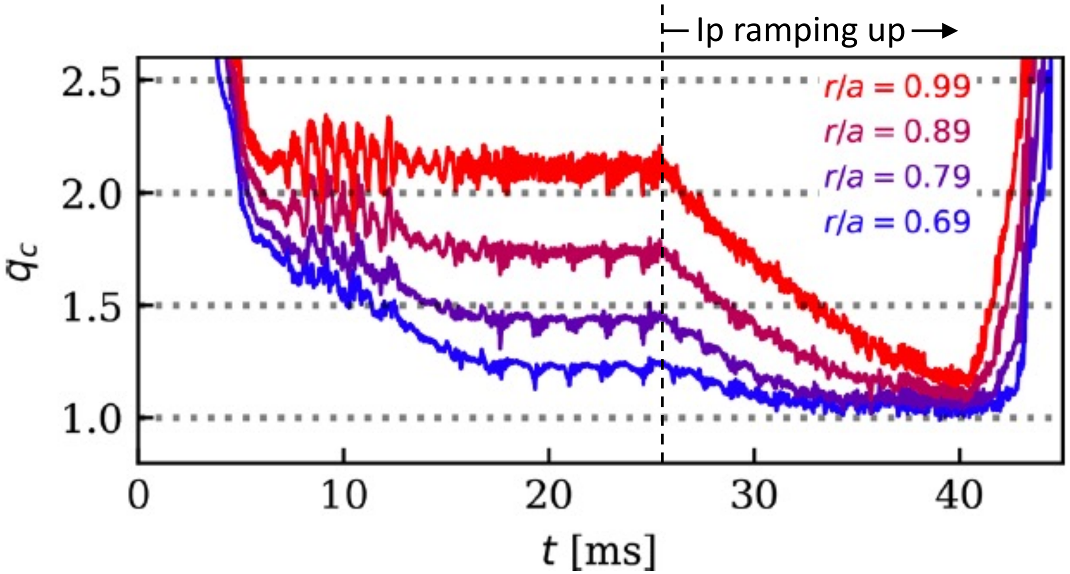
Clamping occurs when q(a) ramped down in single shot



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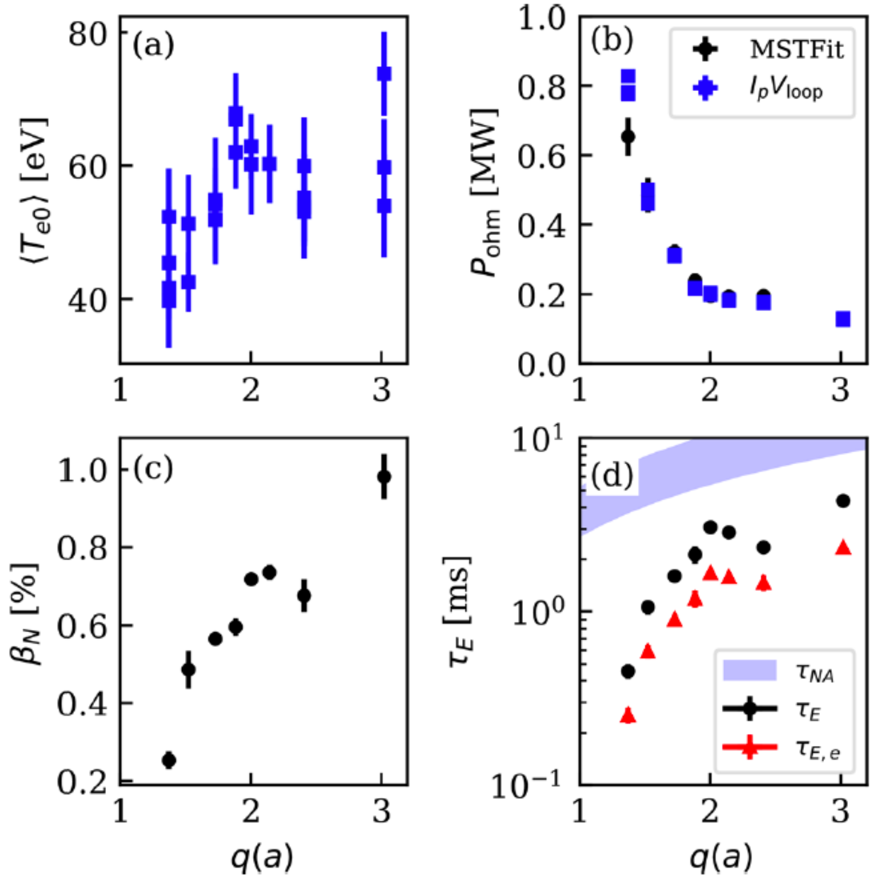
Energy confinement drops with q(a) for q(a) < 2



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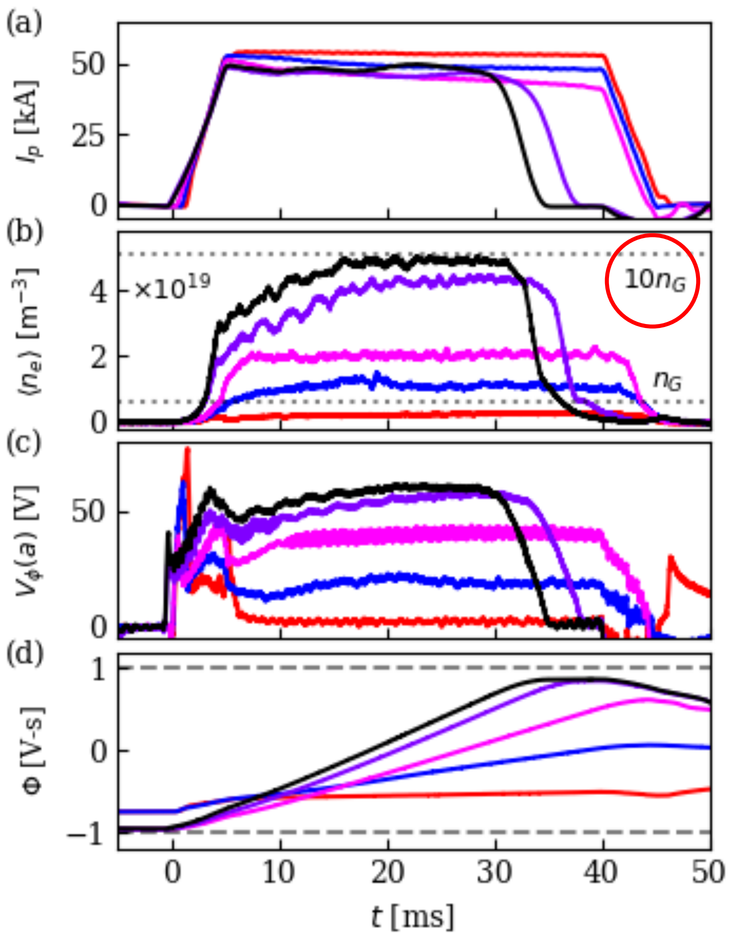
Non-disruptive plasmas with $n_e \sim 10n_G$

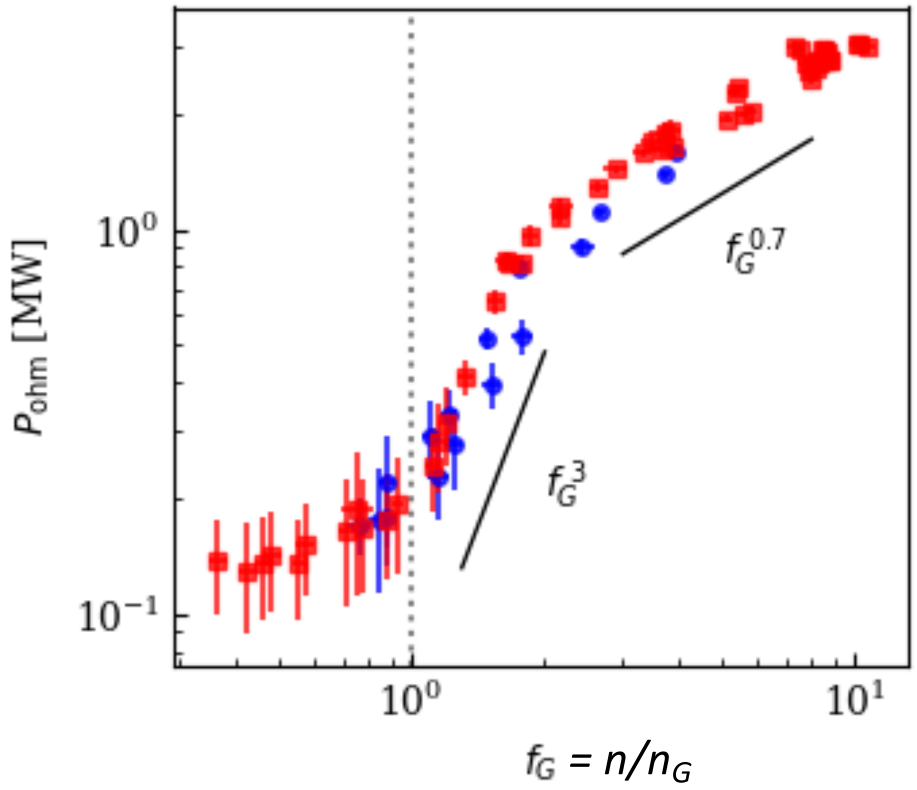
Plasmas achieved with density up to 10X Greenwald limit



- Fixed Bt ~ 0.135 T, q(a) > 2
- Density appears to be limited by hardware rather than instability

Courtesy N. Hurst

Behavioral transitions occur at 1X and 2X Greenwald limit



- At the limit, sawtoothing ceases
- At 2X the limit, density and current profiles broaden, magnetic fluctuations weaken

Courtesy N. Hurst

Conclusions and some of the questions outstanding

- In some cases, MST tokamak plasmas hard to kill
- Low q(a) generally understood, but not high density

- For high density, power supplies certainly play a role
- How about the conducting shell?
- How do Prad and τ_E evolve as density increases?
- Does same behavior occur at higher Bt, Ip, Te…?