# Scenario optimization and instability monitoring to reach the Q=10 ITER mission without disruptions

by

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with

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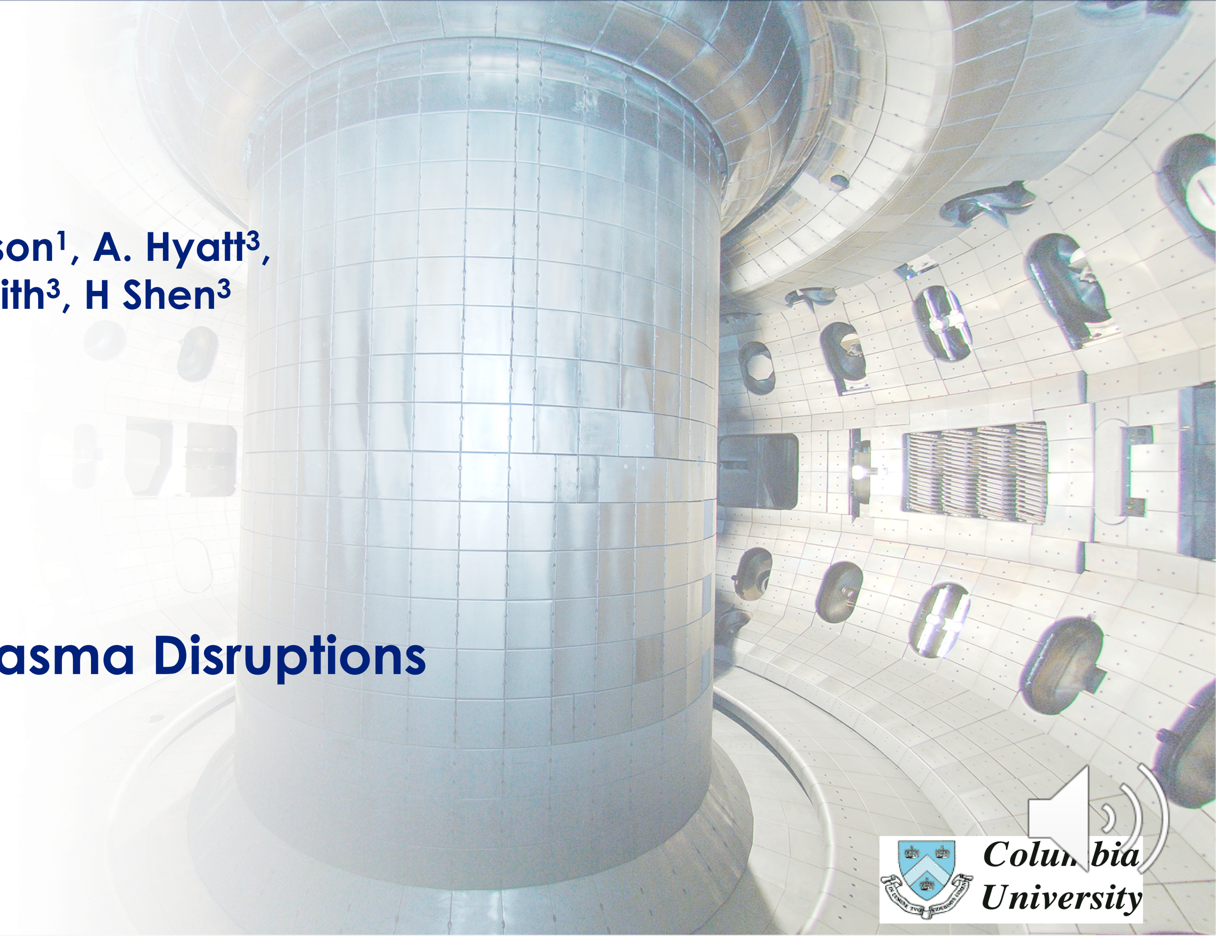


Presented at the

## Technical Meeting on Plasma Disruptions and their mitigation

July 20, 2020 (remote)

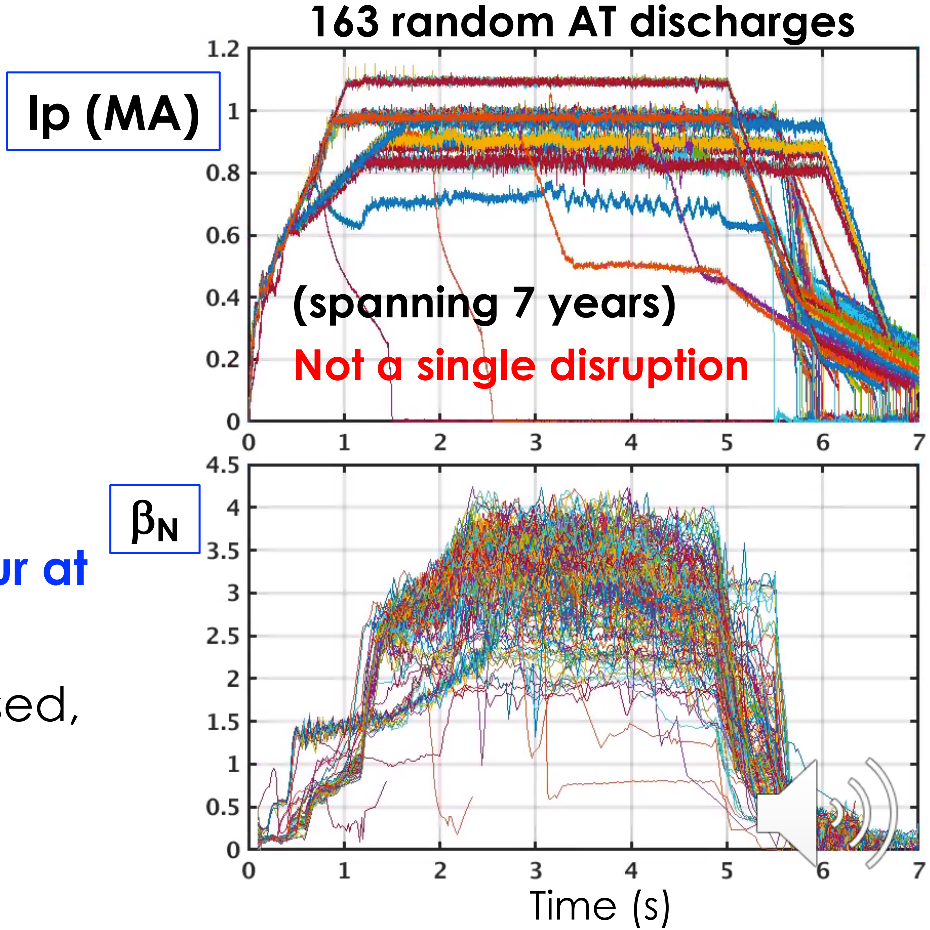
# Where do disruptions occur? (not where you think)

- Reactor relevant scenarios for steady-state power production are operated at $q_{95}$>=5

**NO disruptions at $q_{95}$>=5**
- At any $\beta$
- With any instability
- With any radiated fraction

- **Physics caused disruptions only occur at $q_{95}$<~3.8**

- Inductive scenario for high gain, pulsed, operation
- **Low $\beta_N$, very low $J_{NI}$, low input power**



**163 random AT discharges**

(spanning 7 years)

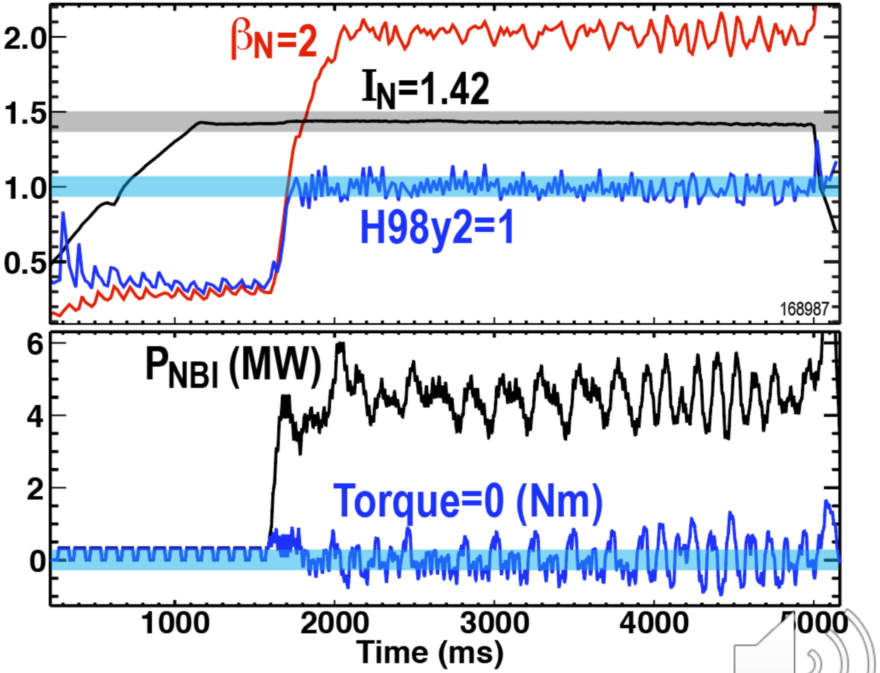
Not a single disruption

# I will focus on the low $q_{95}$ ITER Baseline Scenario, where disruptions occurr

ITER Baseline Scenario demonstrated in DIII-D matching most parameters

**Mission:**
- 500 MW for 400 s, Q = 10 (G=0.42)
- Full Bt, Ip=15 MA, $I_N$=1.415 → $q_{95}$=3
- Expected T<0.7 Nm, low rotation

**DIII-D demonstration discharges:**
- ITER shape+ϵ, $q_{95}$=2.9-3.3
- $H_{98}$=1, $\beta_N$=1.7-2.25 → G=0.38-0.43
- T=-0.5-5 Nm



# Contents

- **Finding the cause of the disruptive tearing modes in the IBS**
- **Modify the scenario to operate in a passively stable state**
- **Why the need for passive stability: negative aspects of off-axis ECCD**
- **A way to measure the approach to instability: Active MHD Spectroscopy**

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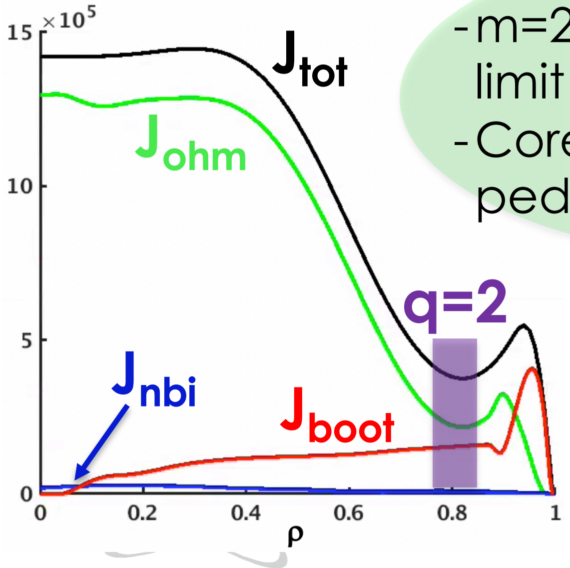
# IBS: Tension Between Stability and Confinement

- ITER Q=10 mission: $P_{fus}$=500 MW, high gain → **high I/B, low input power**
- $q_{95}$=3 + sawteeth → **q=2 near the edge**
- >2017: Passively stable **zero torque** IBS plasmas with NBI+ECH power

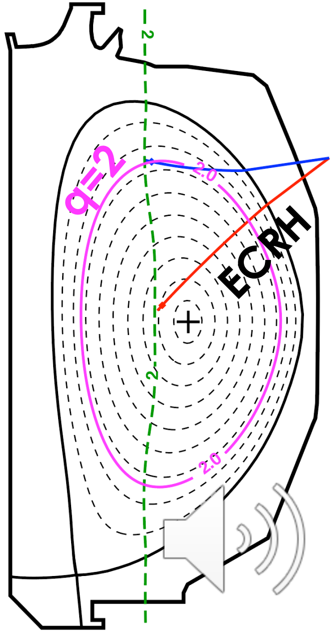


**STABILITY**

- m=2/n=1 rotating TMs can limit flattop duration
- Core stability determined by pedestal region

**CONFINEMENT**

- Direct ECCD stabilization requires far off-axis deposition
- Issue for fusion power and gain

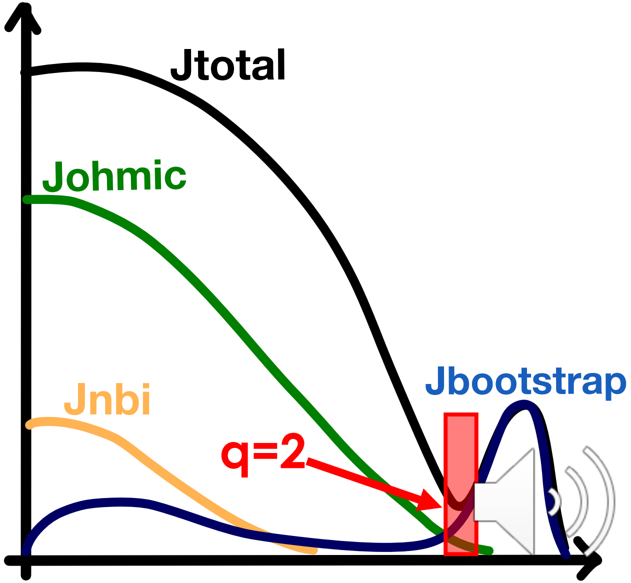


# "Unstable" Shots Are Terminated By an m=2/n=1 Tearing Mode

- **The plasma current is mostly inductive** → J profile tailoring by NI sources is ineffective (CD is not a viable actuator)

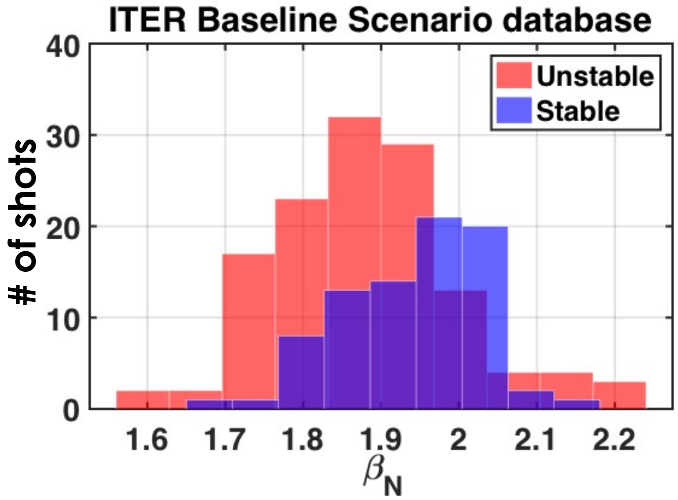
- $J_{boot}$ **dominates the pedestal, q=2 at ρ~0.8** → Strong correlation with pedestal/edge due to fixed Ip

- Many **shots are terminated by a 2/1 tearing mode**
  - At high and low torque
  - It locks and disrupts within 50-150 ms
  - ECCD stabilization isn't effective (low $T_e$, $j_{CD}$; fast growth, lock)



# The IBS Instabilities Are Not Due to a $\beta_N$ Limit

- The modes appear after **>10 $\tau_E$ at constant pressure**
- **Well below the no-wall MHD limit**
- **Lower $\beta_N$** does not lead to better stability



These are very likely classically unstable TMs,
**not NTMs:**

- Onset after 10s sawteeth, ELMs, 100s $\tau_{tear}$ at fixed pressure → on $\tau_R$ scale
- $J_{boot}$ is very small everywhere, and minimum at q=2 (inductive!)
- $J_{eccd}/J_{boot}>1\text{-}2$ does not stabilize ($\Delta'$ is the drive, not $J_{boot}$)

# Database of ~240 IBS Plasmas Analysed for Global and Local Quantities

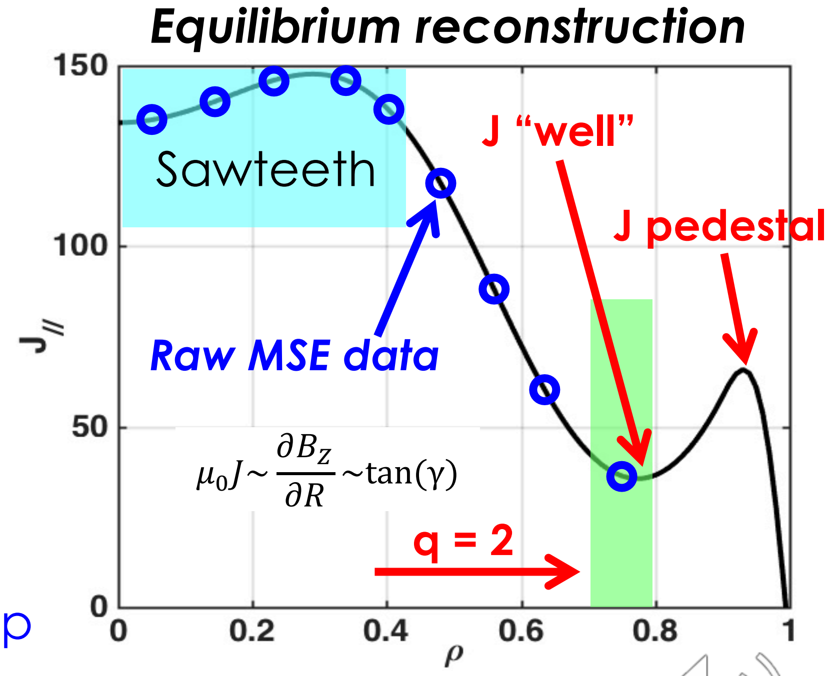
- **Local current density measured by raw MSE data**

- **“Enhanced” efits for q and J, with MSE+magnetics and a pedestal**

→ Magnetics + edge constraints describe the pedestal (similar to kinetic efit)

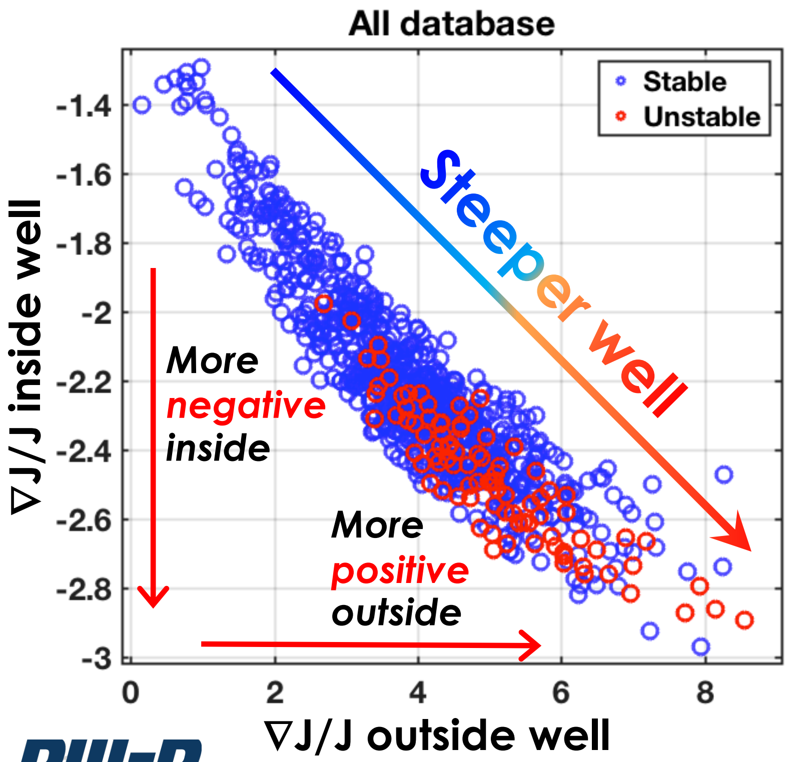
→ MSE constrains the core up to $\rho$~0.8

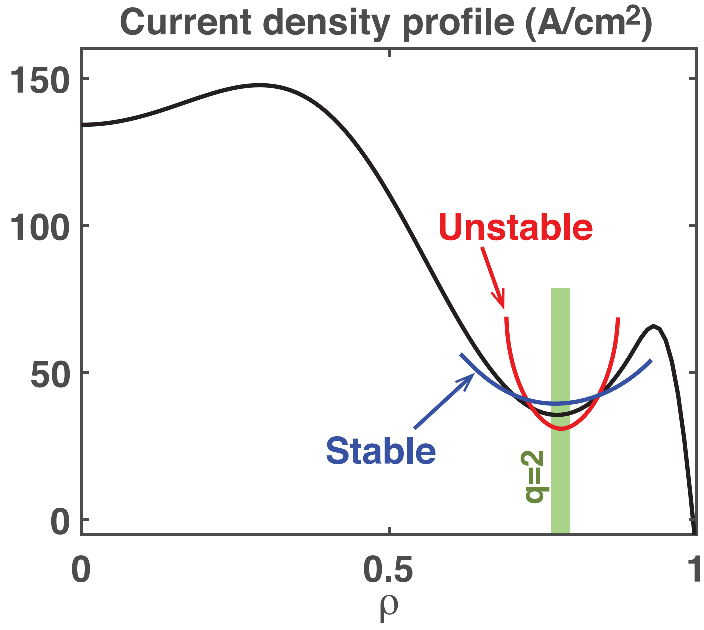
- Unstable = at time of 2/1 mode onset
- Stable = stable time slices on the $\beta_N$ flattop



# Changes in the Current Profile Are Correlated with Tearing Instability

- **Unstable points** fall predominantly in the lower right region (larger gradients)

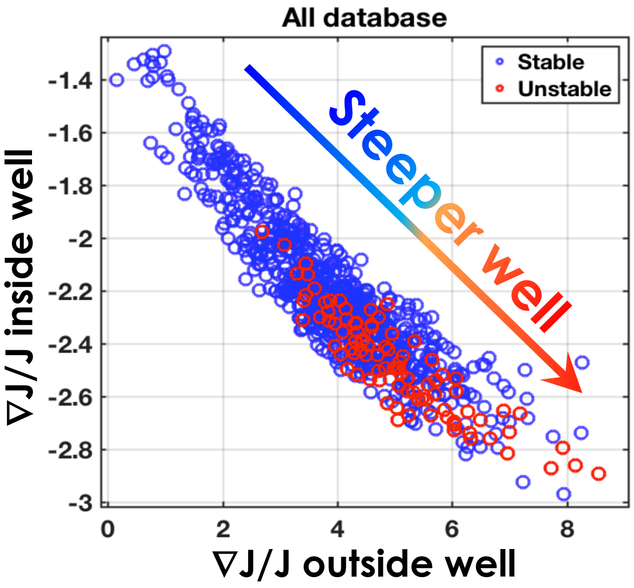




**Unstable points have steeper "current well" around the q=2 surface**

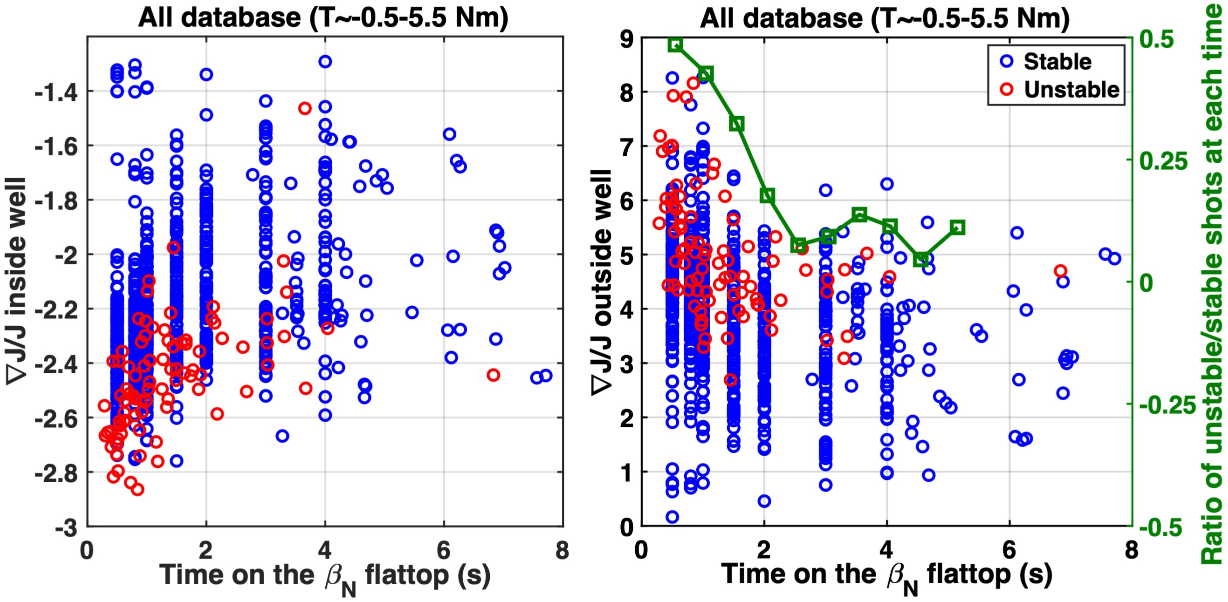
# Changes in the Current Profile Affect the Classical Tearing Index Δ'

- **Long term dependence on J suggests stable and unstable times have different Δ' : classical drive**
- **Δ' is a GLOBAL parameter, determined by all the current profile**
- **Δ'>0 is necessary, not sufficient for instability:**
  - **→ Δ' trends determine if more/less stable**
  - **→ For instability, Δ'> $\Delta'_{crit}$** (inner layer physics)



# 67% of the Instabilities Occur Before 1.3 s on the $\beta_N$ Flattop (1-1.5 $\tau_R$ in DIII-D)

- More stable current profile late, fewer unstable shots after ~1 s
  → if we solve the access problem, high probability of remaining stable



∇J separation is independent from torque, sawteeth, ELMs, higher m/n modes

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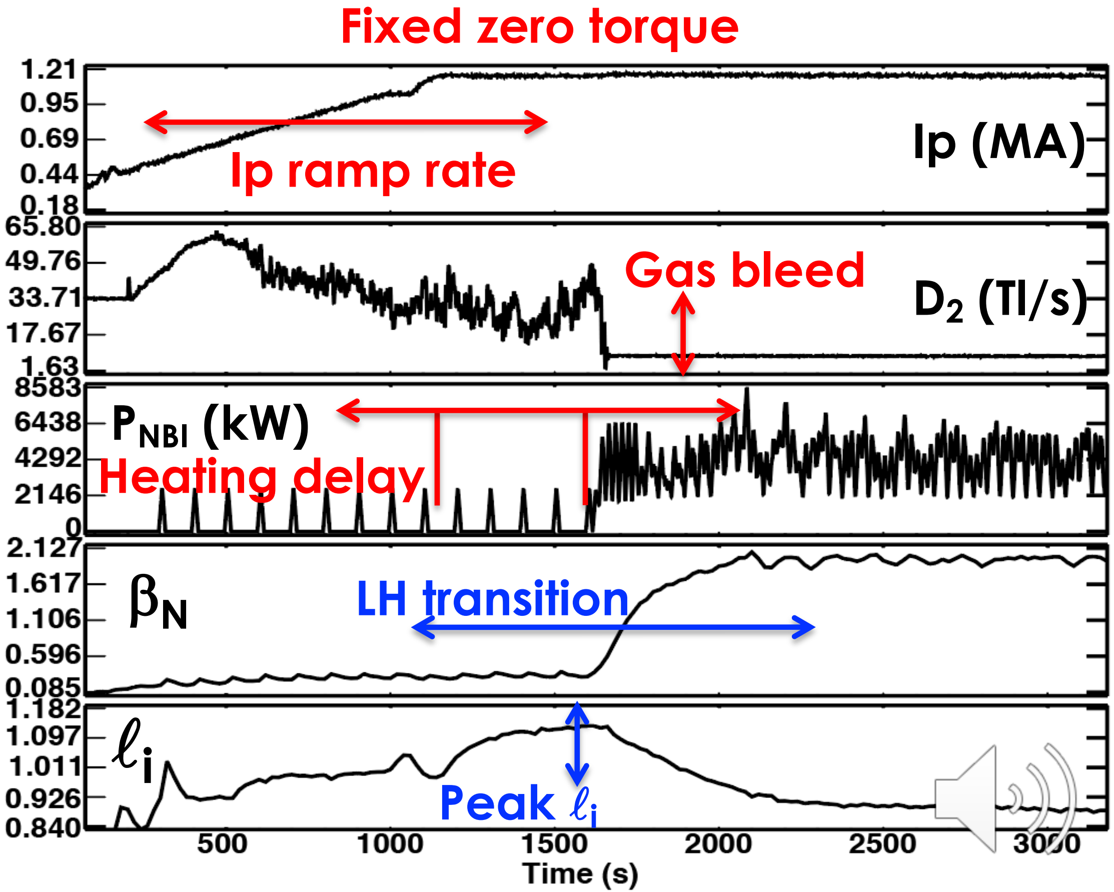
# Database study indicates that the early current evolution is crucial for stability → created new $\beta_N$ ramp up recipe

Changes $\ell_i$, current penetration

Changes ELM frequency, pedestal (not density)

Changes $\ell_i$, current penetration

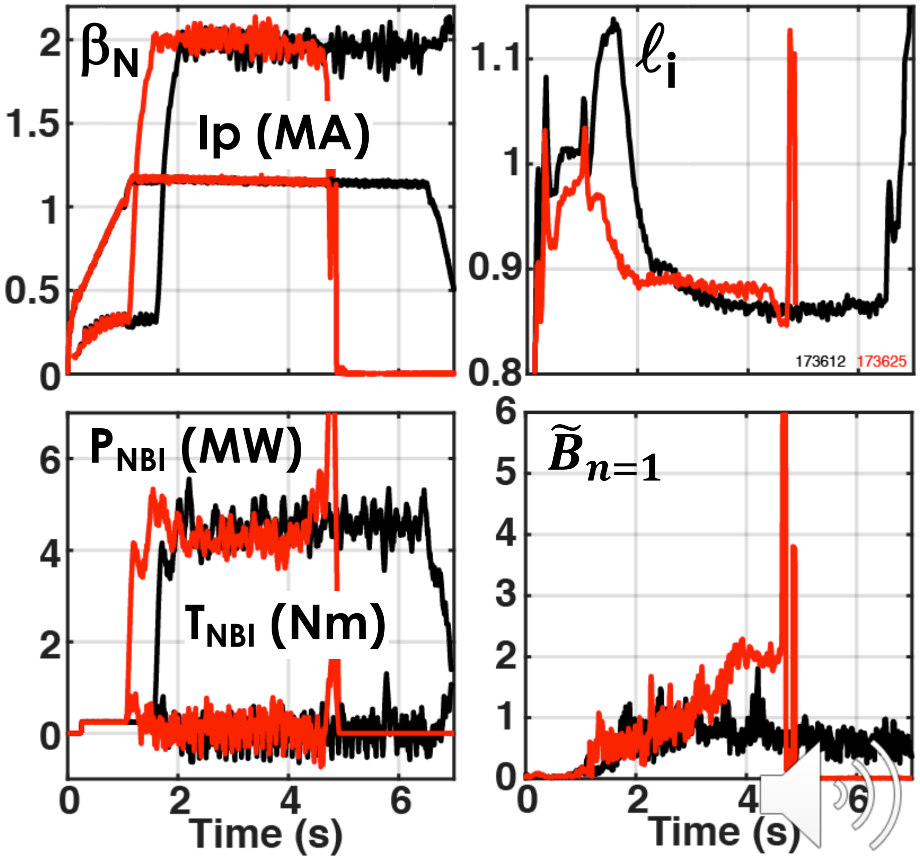
*No time to scan the L-mode density/gas*



# Applied modifications to show causality. (1) Heating delay

- **Database of pulses with only change to the H-mode transition time shows the late timing is robustly stable**

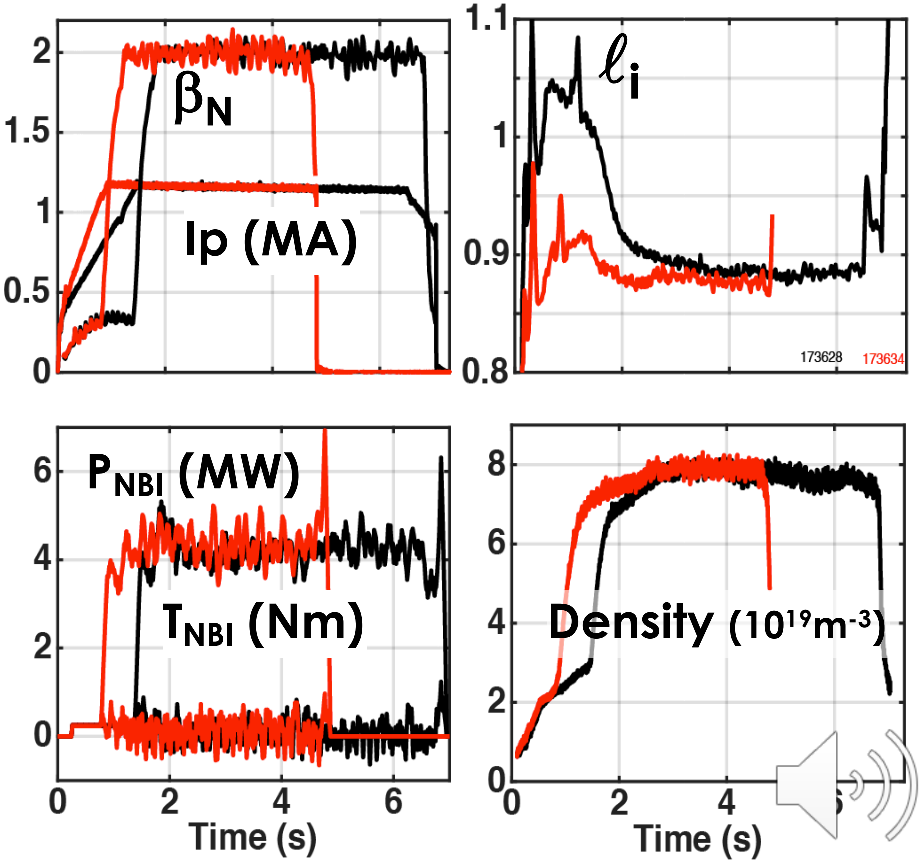
- **Trajectory of $\ell_i$ shows current profile evolution is different**
  - $\ell_i$ is not sufficient to predict stability



# Applied modifications to show causality. (2) $I_p$ ramp rate

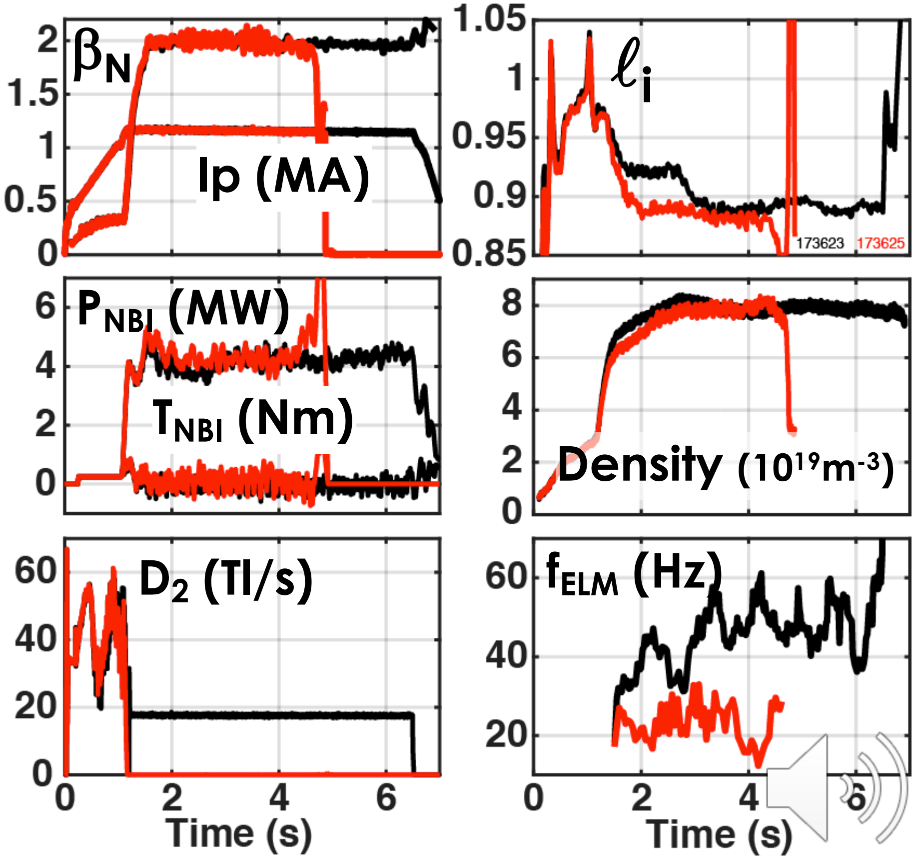
- **Slower Ip ramp rates are robustly stable – similar effect as heating delay**

- **Combination of Ip ramp and heating time changes can tailor the stability to the hardware requirements**



# Applied modifications to show causality. (3) $D_2$ gas "bleed"

- **Modest gas "bleed" eliminates LATE modes**
- **Results in more regular and more frequent ELMs**
- **Little difference in density**
- **No difference in energy confinement**



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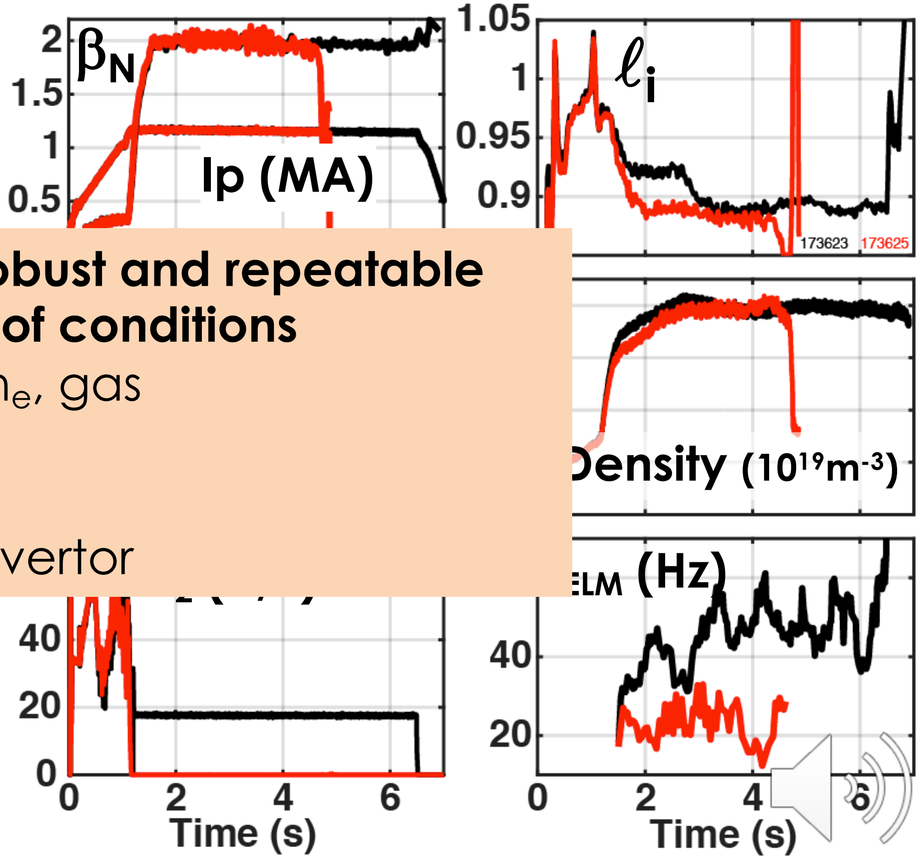
- **No differ**
  **confiner**

**The passive stability is robust and repeatable under a variety of conditions**

- Different Ip, $B_T$, $n_e$, gas
- Wall conditions
- Heating mix
- Open/closed divertor



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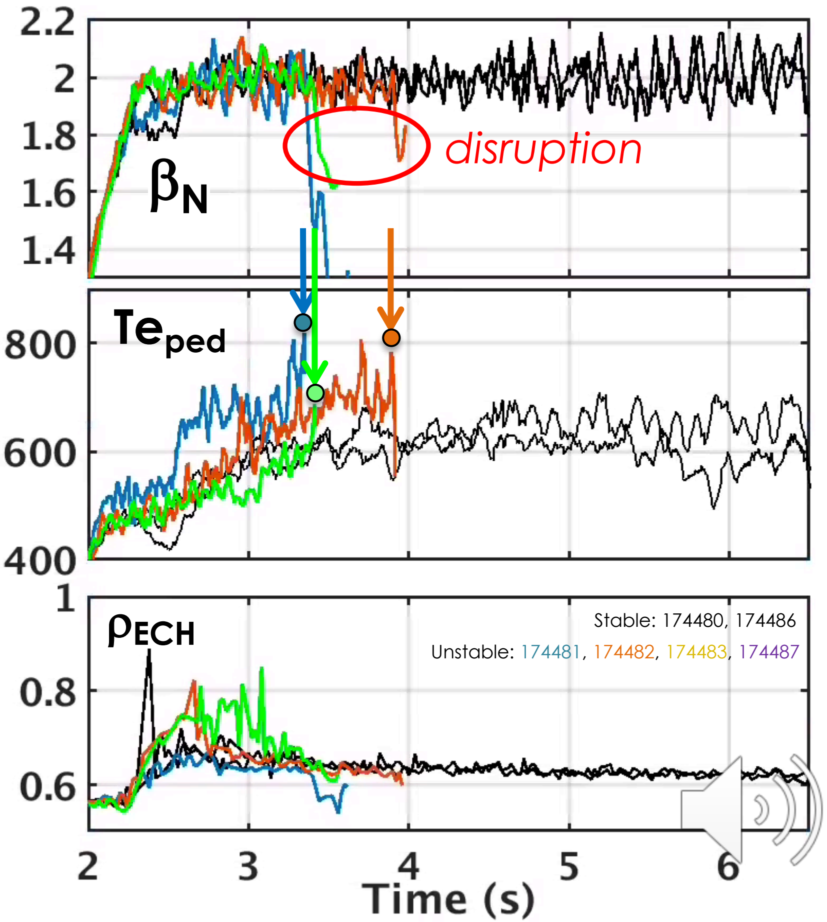
# Effect of e- Heating: Early ECH Deposition Location Can *Negatively* Affect the TM Stability

- **Rising $Te_{ped}$ → 2/1 mode**
- **Sometimes correlated with $\rho_{ECH}$>0.85,** but other factors apply
- **Some cases are at the marginal point:** small perturbations can cross the threshold

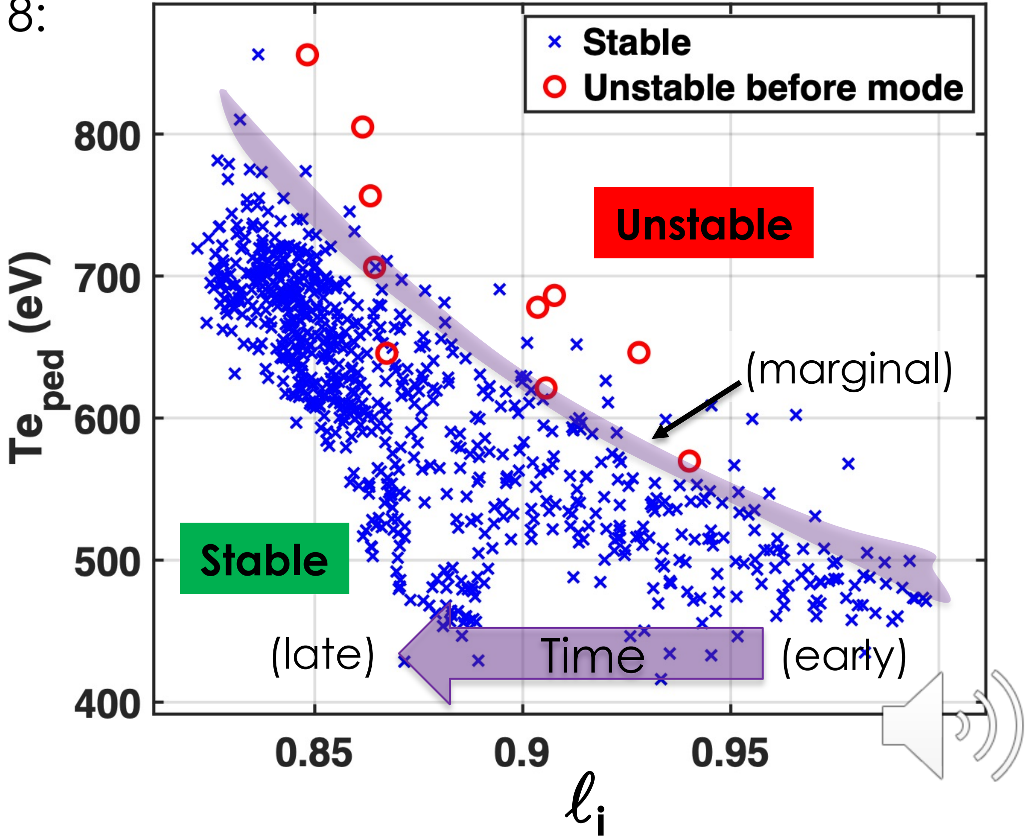


# $\ell_i$ Sets the $Te_{ped}$ Threshold: Global Classical Δ' Effect

Expanded database of all 2017-2018:

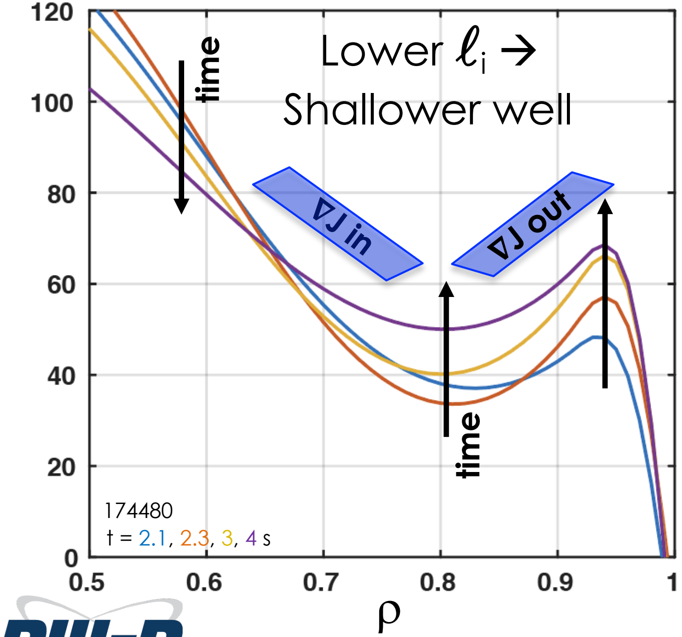
- Timing matters: **higher $Te_{ped}$ late can be stable**
- $\ell_i$ decreases → the well is shallower → **equilibrium can survive a higher pedestal**
- **Effect of $T_e$ on $J_{pedestal}$ is the limiting factor** (not absolute $T_e$!)

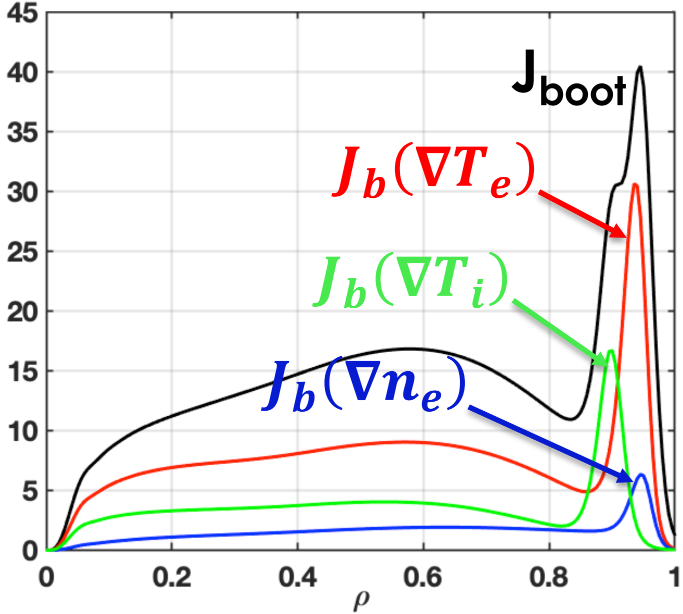
**IBS database with ECH and Torque = 0 Nm**



# $T_e$ Has a Much Larger Impact on $J_{boot}$ than $n_e$, $T_i$ in These Plasmas

- **J profile responds to local $J_{boot}$ changes due to fixed total plasma current**
- **Classical tearing index Δ' changes as a function of global J profile**




**Calculated $J_{boot}$ contributions (Sauter model)**

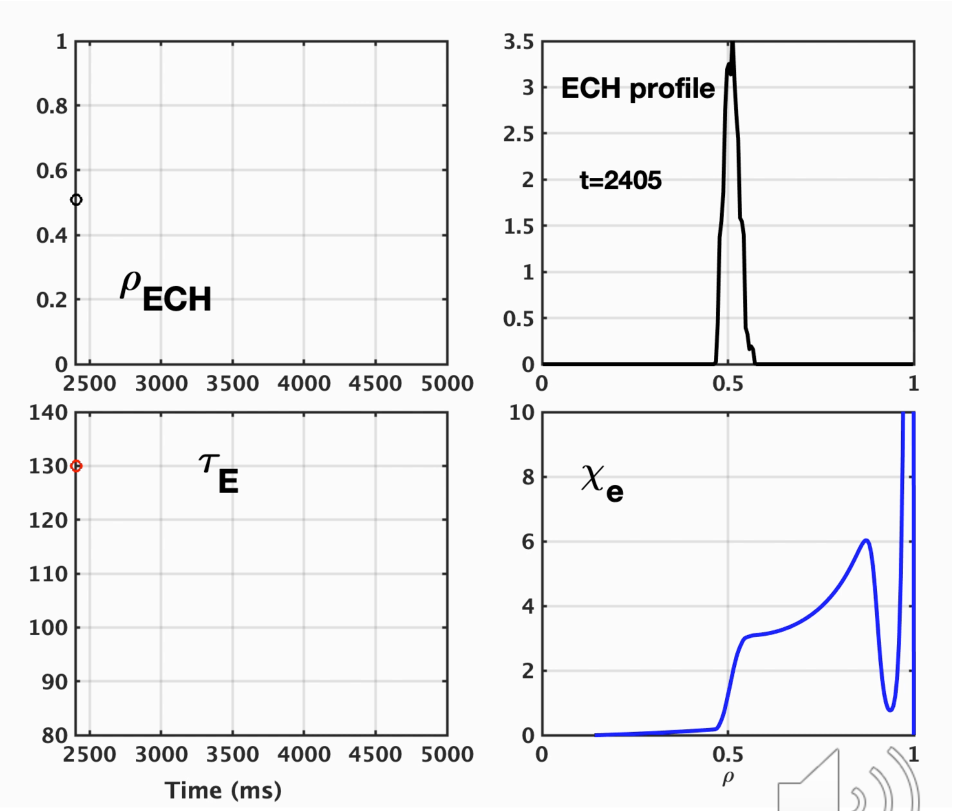
# ECH Power Near q=2 is Significantly Detrimental to Performance

- **Moving 3 MW of ECH from ρ=0.5 to ρ=0.8 decreases $\tau_E$ by 25-30%, $H_{98y2}$ by 15-18%**

$$\boxed{\eta_{heating} \approx 1 - \rho_{ECH}^2}$$

Expect 50% drop in $\tau_E$, observe 25%

Loss of heating efficiency compensated by transport improvement



**This is also observed clearly in the full database (220 shots)**

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# MHD Spectroscopy Measurements Shows the Approach to a Stability Limit

- Reduced IBS database at T=0-1 Nm
- n=1 external field rotating at 20 Hz
- Magnetic probes measure the plasma response of the external kink

- **Signals: response amplitude & phase vs external field**
- **Phase shows a "jump" when approaching a limit**

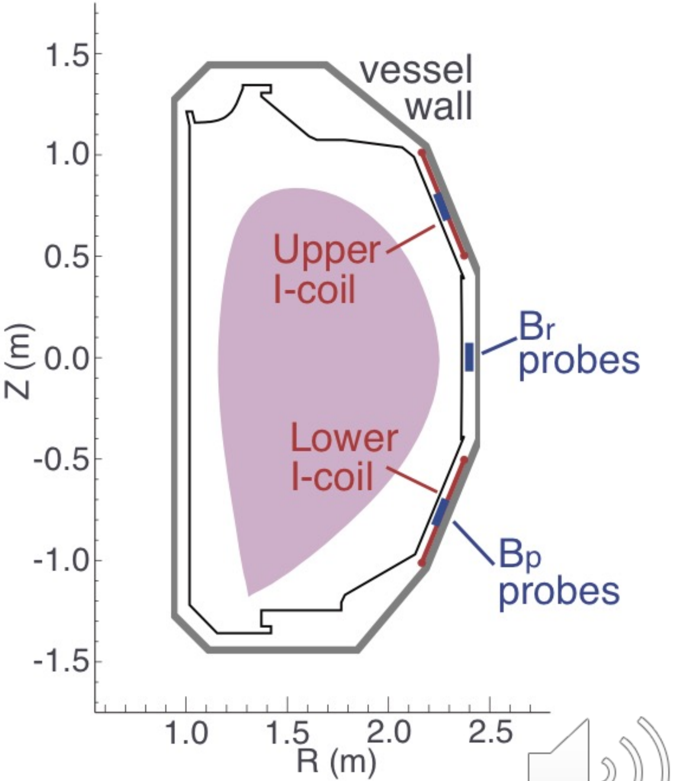
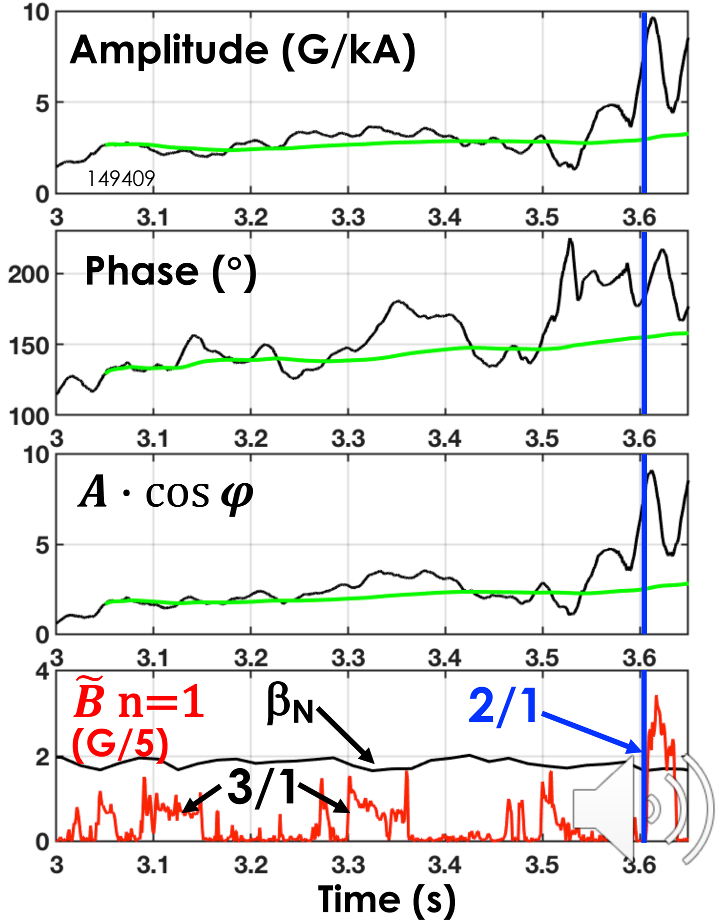


Figure courtesy of J. Hanson

# Realtime AMS Signals May Become a Stability Sensor

- IBS plasmas have intermittent 3/1 bursts and 1/1 sawtooth precursors
- **Spectroscopy amplitude and phase changes are largest with large 2/1 component**
- **Relative measures help discard false positives – intrinsic dependence on $\beta_N$, $\ell_i$**

Use A, φ, $\boldsymbol{A} \cdot \cos \boldsymbol{\varphi}$ – shot average

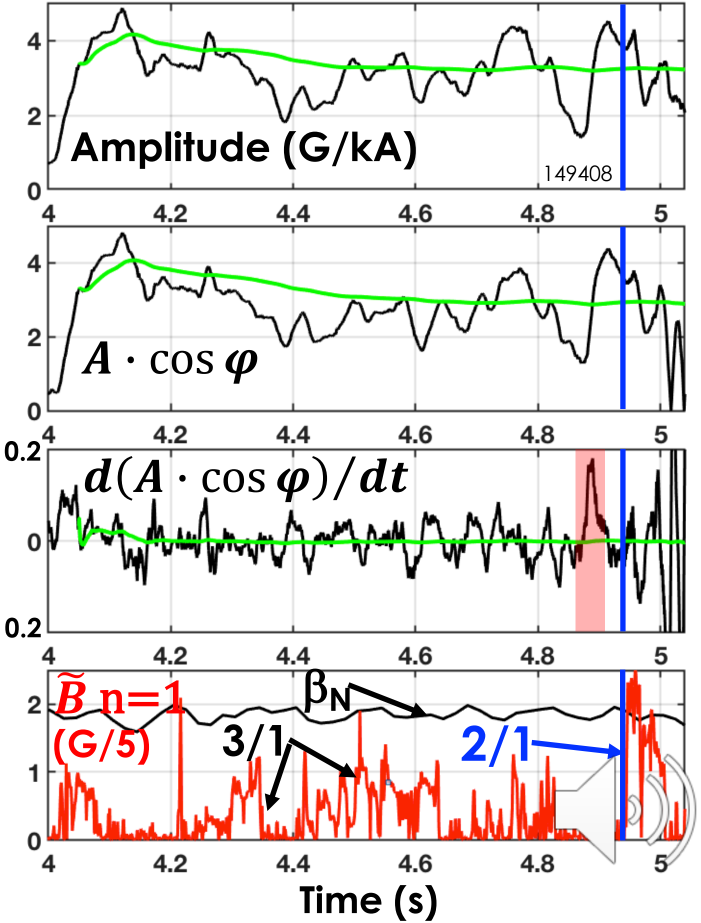


# Realtime AMS Signals May Become a Stability Sensor

- When the 3/1 activity is stronger and continuous, **the derivative of the signals is a good indicator of the 2/1 mode**

- Slowly growing 2/1 modes are harder to detect, but in that case **spectroscopy picks up imminent locking**

**→ Deploy disruption mitigation systems**



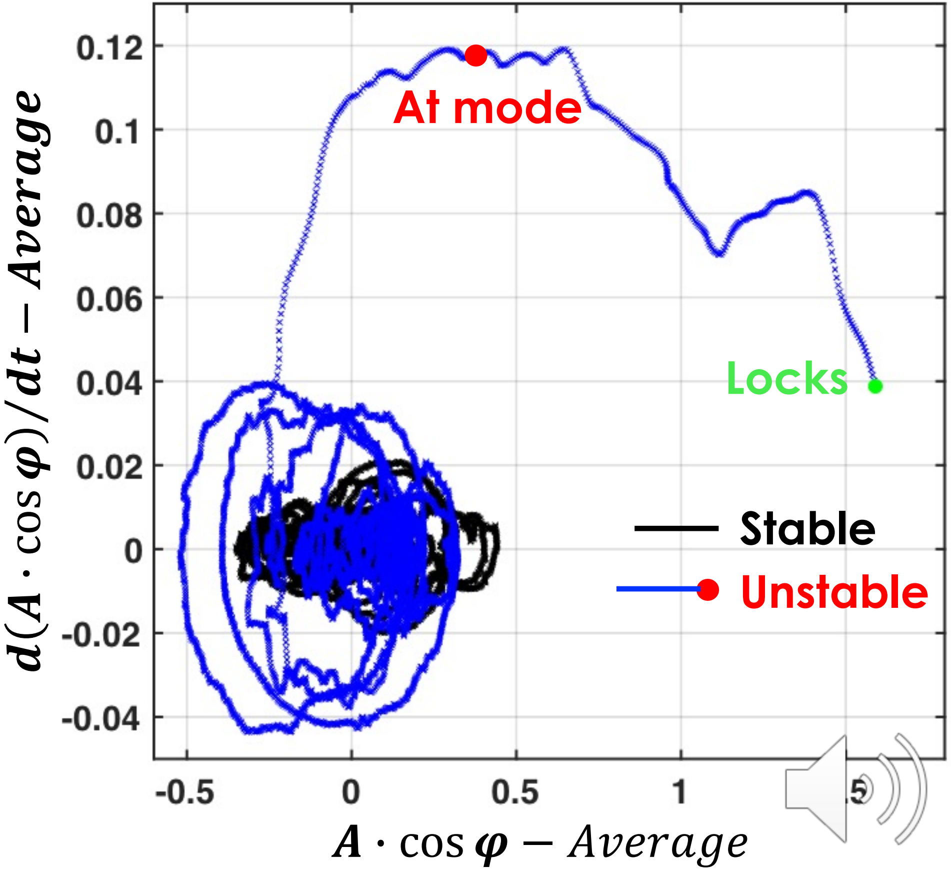
# In Stable Shots, A and φ Show Little Excursion from Average

- To generalise and quantify, chose evolution of

  $$A \cdot \cos\varphi,\ d(A \cdot \cos\varphi)/dt$$

- Compare to shot average (plasma response typical of that shot ← $\beta_N$, $\ell_i$ dependent)

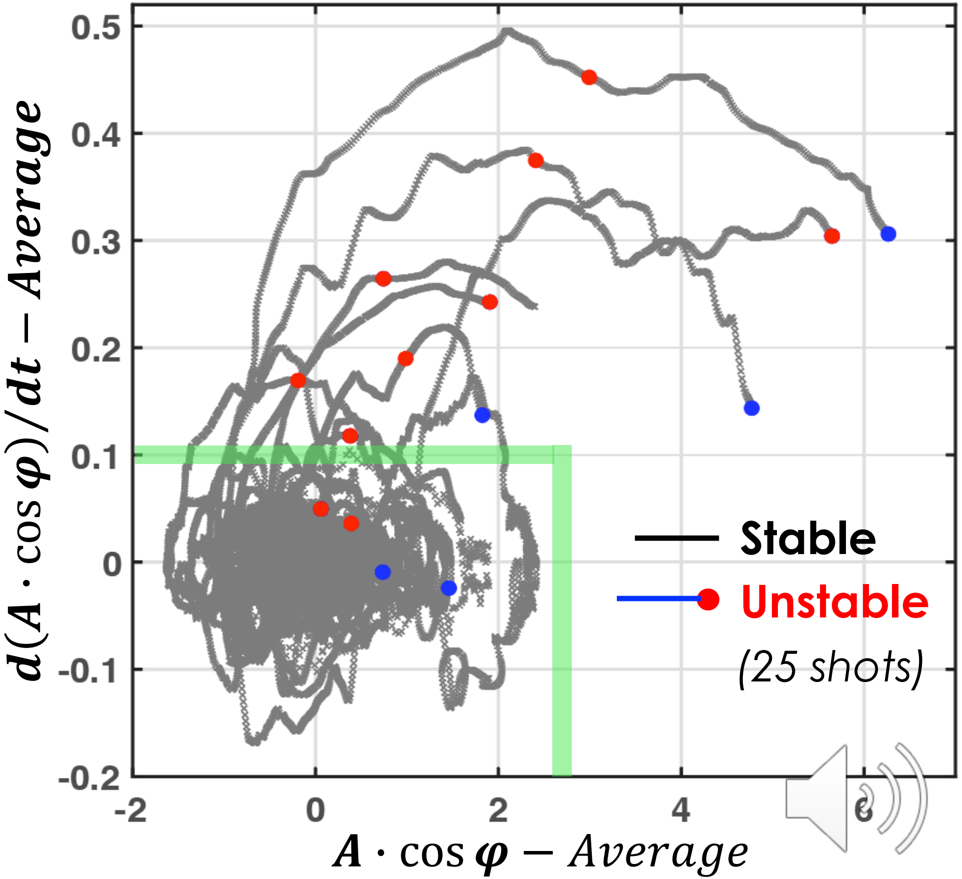
- Unstable shots shoot out of stable envelope at time of mode



# Careful Choice of Limits can Lead to a Real-Time Sensor

- **Limits of stable envelope can be used to define sensor trigger values**

- **Other choices of signals are possible, depending on the scenario parameters**



# Conclusions

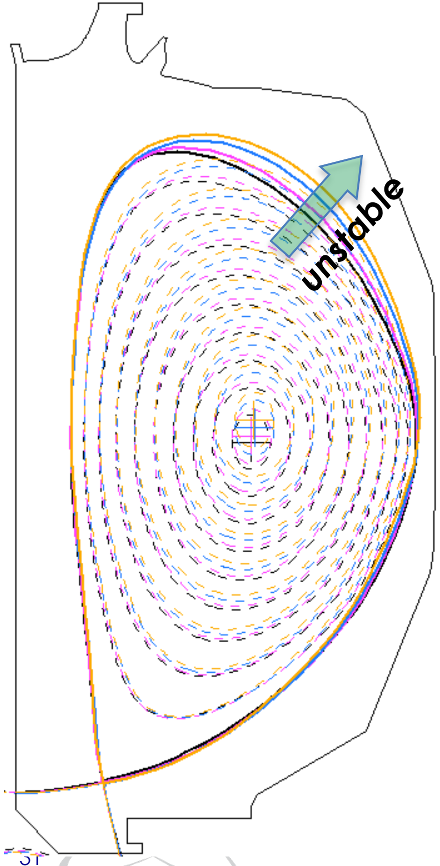
- "Physics driven" disruptions are only relevant to low q95 (pulsed) inductive scenarios

- In the IBS there are no good actuators to rein in the instabilities (no JNI, JECCD fails to stabilize the modes, off-axis power prevents to reach the goals)

- Passive stability is the best option, and it has been demonstrated

- Indirect actuators may be an option if the conditions evolve on the flattop: squareness and triangularity changes

# Preview on effect of shape on current density and stability



Small shape changes can change the pedestal during the flattop