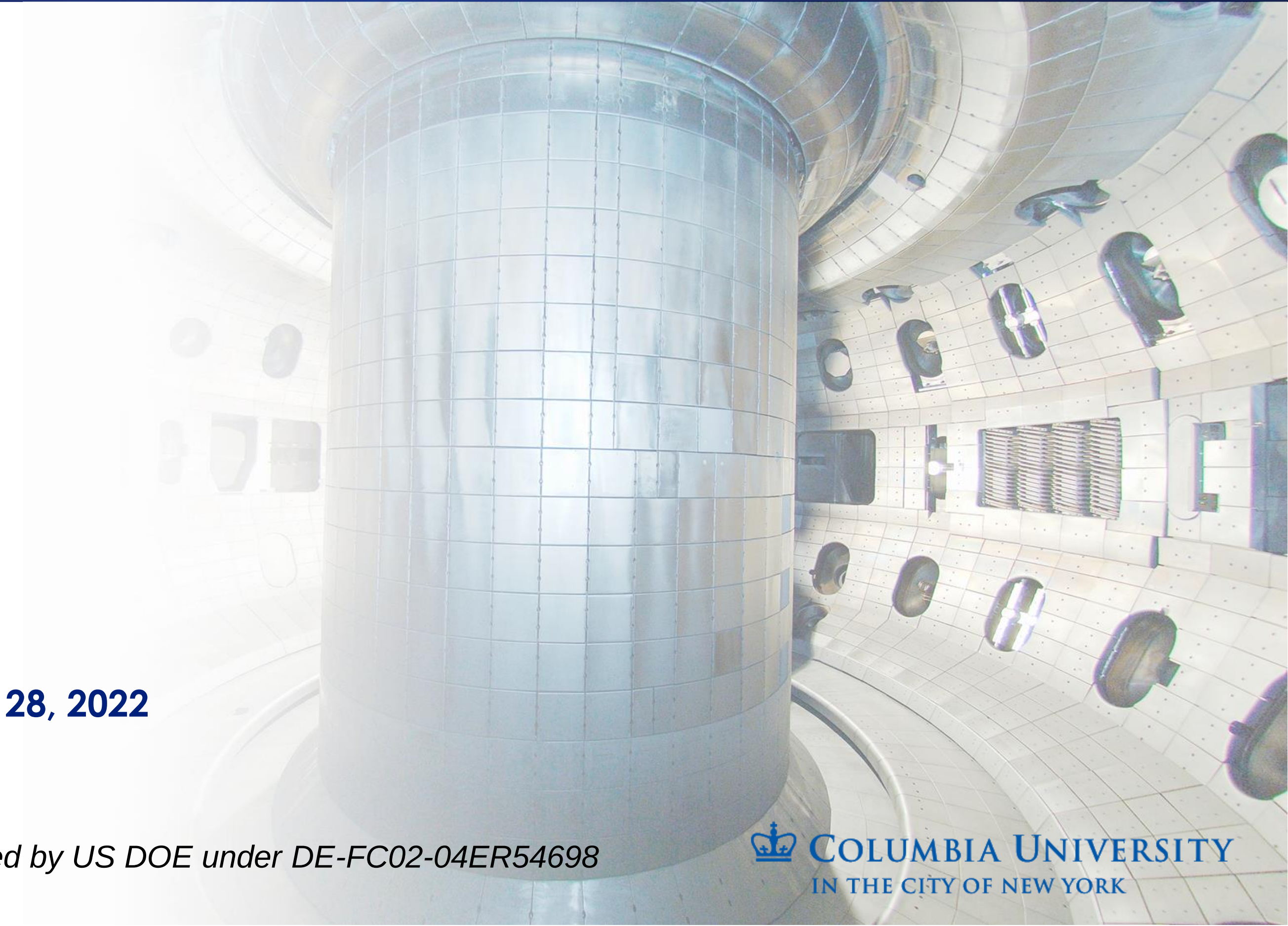
ITER Baseline Scenario – Q=10 operation



by

F. Turco

with

…many others

ITER International School; July 28, 2022

Work supported by US DOE under DE-FC02-04ER54698

What is a scenario

…, for our purpose today:

- **plasma goals**
  - **power output, gain, duration, …**
- **boundary conditions**
  - **heating mix, plasma formation, evolution, …**
- **constraints set by machine parameters**
  - **flux consumption, tolerable li, coil currents, divertor loads, …**

What is the ITER Baseline Scenario (affectionately, the IBS)

IBS Mission:

- **P_{fus}=500 MW** → $\beta_{T,therm}$=2.55%
  → β_N~1.8 (low β_N)
- **Q=10** =$P_{fus}/(P_{transp}+P_{loss}-P_{\alpha})$ → $\beta_T\tau_E$ or $G = \frac{\beta_N H}{q_{95}^2} \sim 0.4$ (proxy)
  → Minimise input power → **Need high confinement** → High Ip
- At full field B_t=5.3 T, **I_p=15 MA**
  → **q_{95}~3** (lower current alternatives require higher β_N or H_{98})

Constraints for demonstration discharges:

- ITER shape (affects MHD stability, pedestal)
- Zero injected torque (moderate rotation)
- H-mode on I_p flattop (heated ramps are possible)

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What we discuss today

1. Standard IBS pulse design
2. MHD stability and disruptions
   - Cause of the instabilities
   - Solution and new scenario
3. Confinement trends
4. Lower current and heated access options

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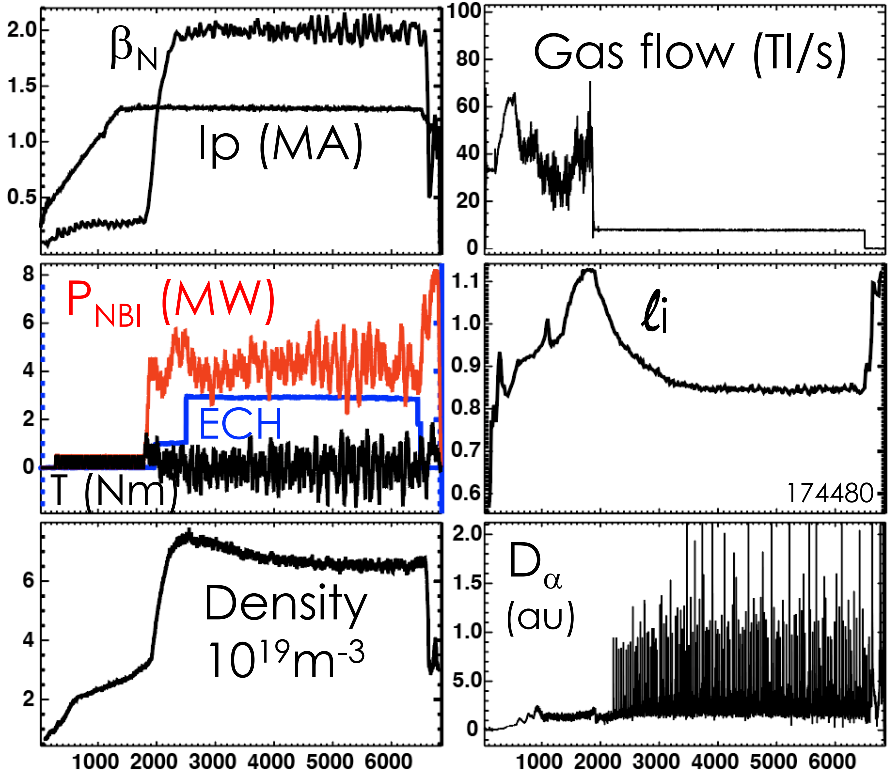
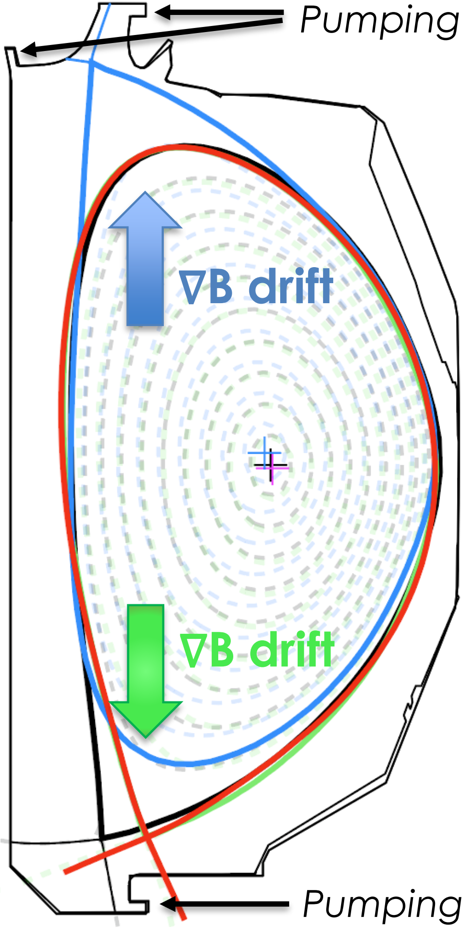
The IBS is Designed with an Ohmic Ramp-up, Zero Injected Torque Throughout and Low β_N





— **ITER** (x0.2778)

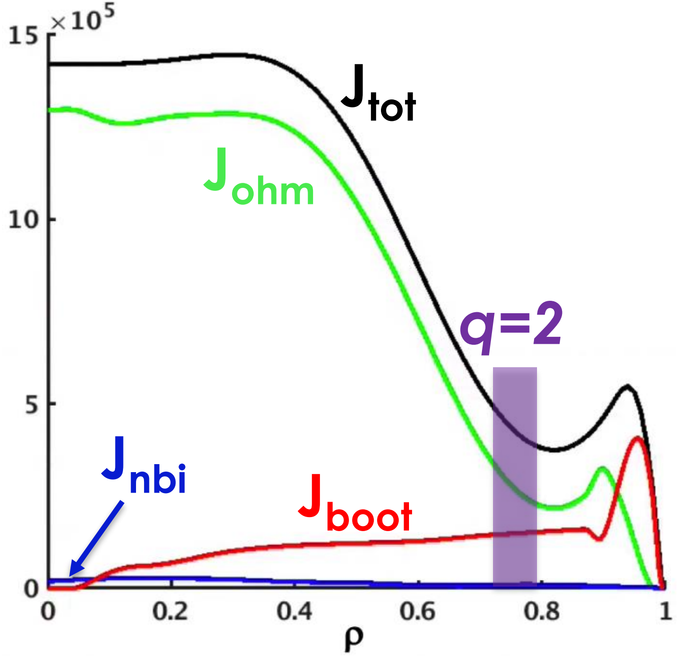
— **DIII-D pumped Std Bt**

— **DIII-D pumped Rev Bt**

— **DIII-D unpumped Std Bt**

Characteristics of the Equilibrium

- **The plasma current is mostly inductive**
  - → High I_p, low β_N for high gain
  - → Active current tailoring is not possible
- **J_{boot} dominates the pedestal**
- q_0~1 (sawteeth), q_{95}~3 → **q=2 at ρ~0.8** → Strong correlation between pedestal and core



For 15 Years, the IBS in DIII-D Was Often Terminated by a Fast Growing, Disrupting 2/1 Tearing Mode

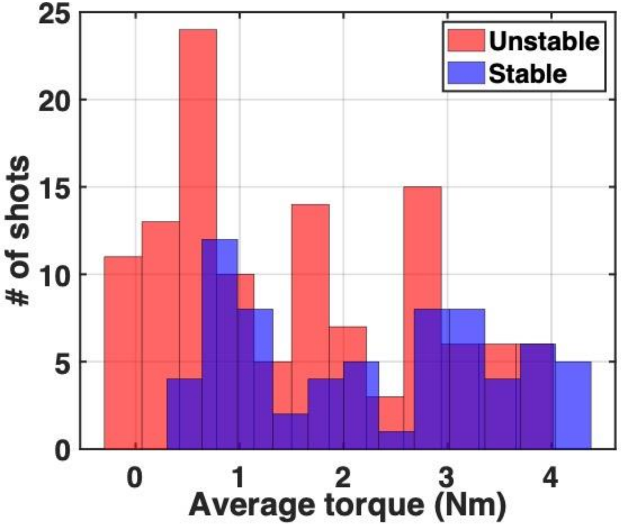
Before 2017

- Zero stable IBS at T<0.5 Nm
- Over 65% of full co-torque shots disrupt

There are no instabilities in the ramp-up (ohmic)
There can be some in the pre-programmed ramp-down

Today I will be discussing the instabilities that occur on the β_N flattop (burn phase)

IBS database <2017



Keep in mind! We are interested in the ONSET, not the growth (the modes collapse the pressure and disrupt in 10-200 ms)

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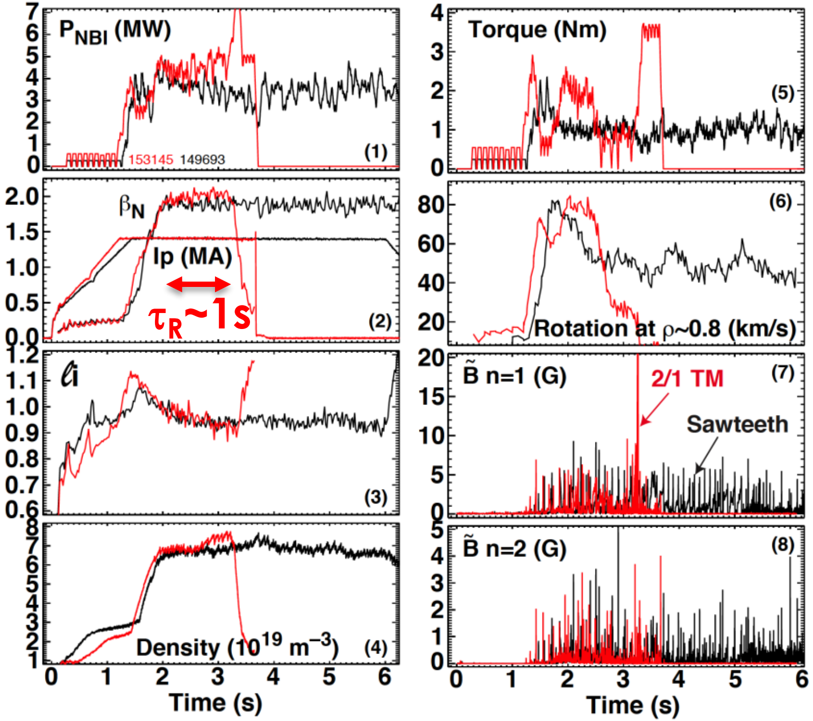
This 2/1 TM Is Not Your Garden Variety Pressure-Driven Instability

Characteristics of these modes:

- They occur at fixed β_N, pressure shape
- After several τ_Es (pressure equilibrated)
- After tens of sawteeth, hundreds of ELMs (not seeded)
- At all torque, rotation and $\nabla\Omega$ values
- Lower β_N is not better
- While the current profile J is evolving

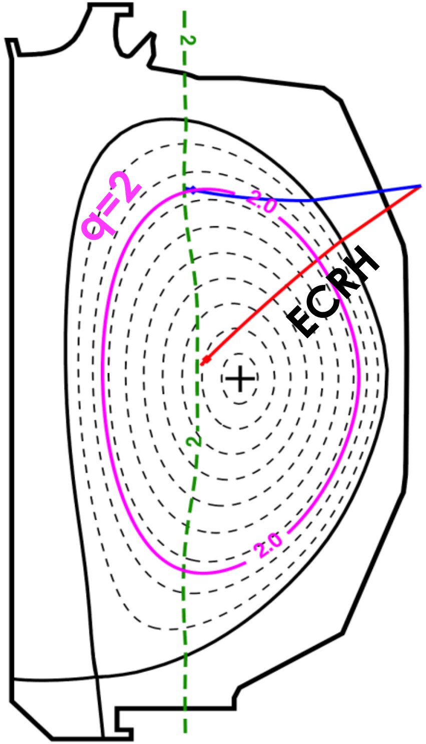
Studying the details of the TM drives led to a solution for robustly stable plasmas



Direct ECCD Stabilization is Not a Viable Option for This Scenario

- For this low-β_N scenario active stabilization of TMs has not been successful (and not for lack of trying)
- The TMs are likely *not* neoclassical in nature → replacing j_{Boot} does not eliminate the drive (Δ')
- q=2 is near the edge → ECCD at ρ~0.75 is very detrimental to the performance (shown later)

Different methods to achieve stability have to be investigated



Which Physics Mechanisms Can Affect the ONSET of Tearing modes?

- **Pressure *p* → it evolves on the τ_E time scale (~100 ms in DIII-D)**
- **Current profile *J* → it evolves on the τ_R time scale (~1 s in these plasmas)**
- **Rotation Ω and $\nabla\Omega$ → it evolves on the τ_E time scale**
- **Mode coupling → perturbed field from n>1 modes may resonate with 2/1 rational surface**
- **Seeding → it assumes the mode is classically stable, but "noise" produces SMALL islands at 2/1 surface (sawteeth, ELMs)**

The typical tearing time is τ_{tear}~5 ms $\ll$ τ_E, τ_R
If p, J, Ω, "seeds" are right, it MUST tear in $\leq$ 5 ms

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If p, J, Ω, "seeds" are right, ***it MUST tear in ≤ 5 ms***

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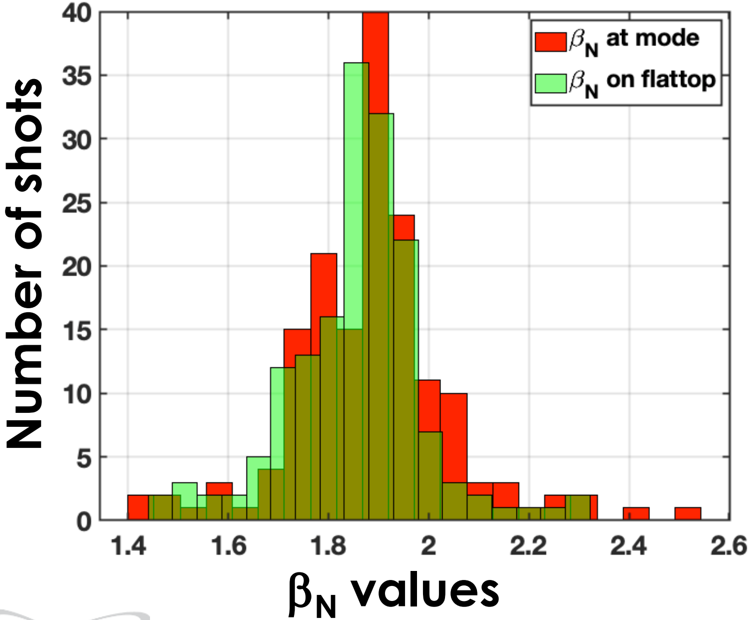
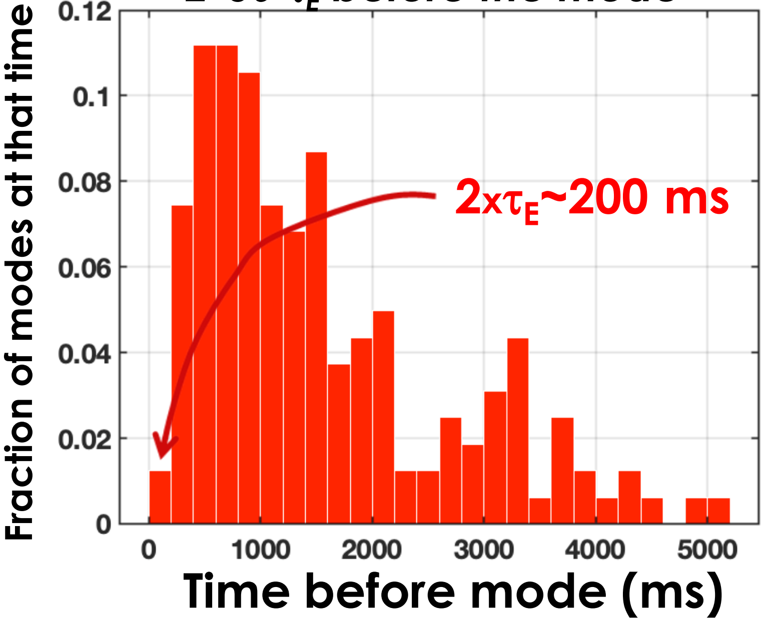
Pressure: The IBS Instabilities Are Not Due to a β_N Limit

- The modes appear after **>10 τ_E at constant pressure and pressure gradient**

β_N does not change from t=0 to mode



β_N has been constant for 2-50 τ_E before the mode



If it they were pressure-driven, it would tear in the first 100 ms

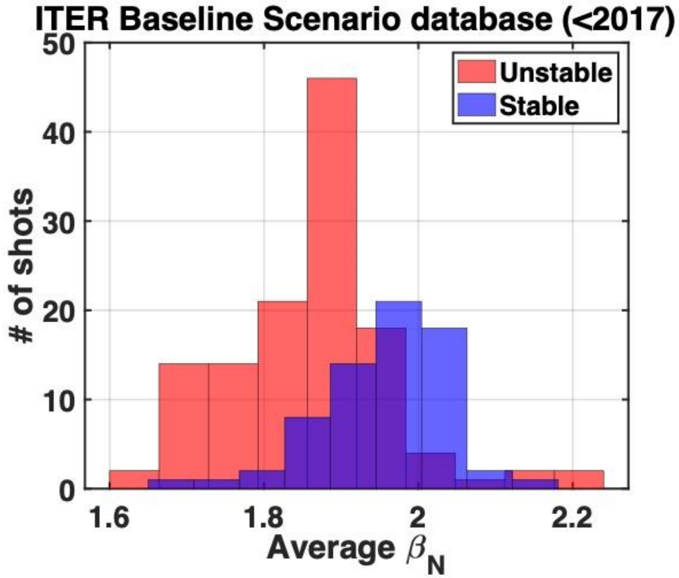
Pressure: The IBS Instabilities Are Not Due to a β_N Limit

- The modes appear after **>10 τ_E at constant pressure and pressure gradient**
- The **β_N is low** → $\beta_N \ll \beta_{N,\text{no-wall}}$ → not an ideal limit
- **Lower β_N** does not lead to better stability, **higher β_N** is not more unstable

↓

There is no β_N threshold for instability

The pressure is not the cause of the 2/1 modes in the IBS



Higher β Shots Are Stable for >10 τ_E → The Pressure is Relaxed, the Current is Not!

Timing of modes → type of drive

Still not a pressure limit:

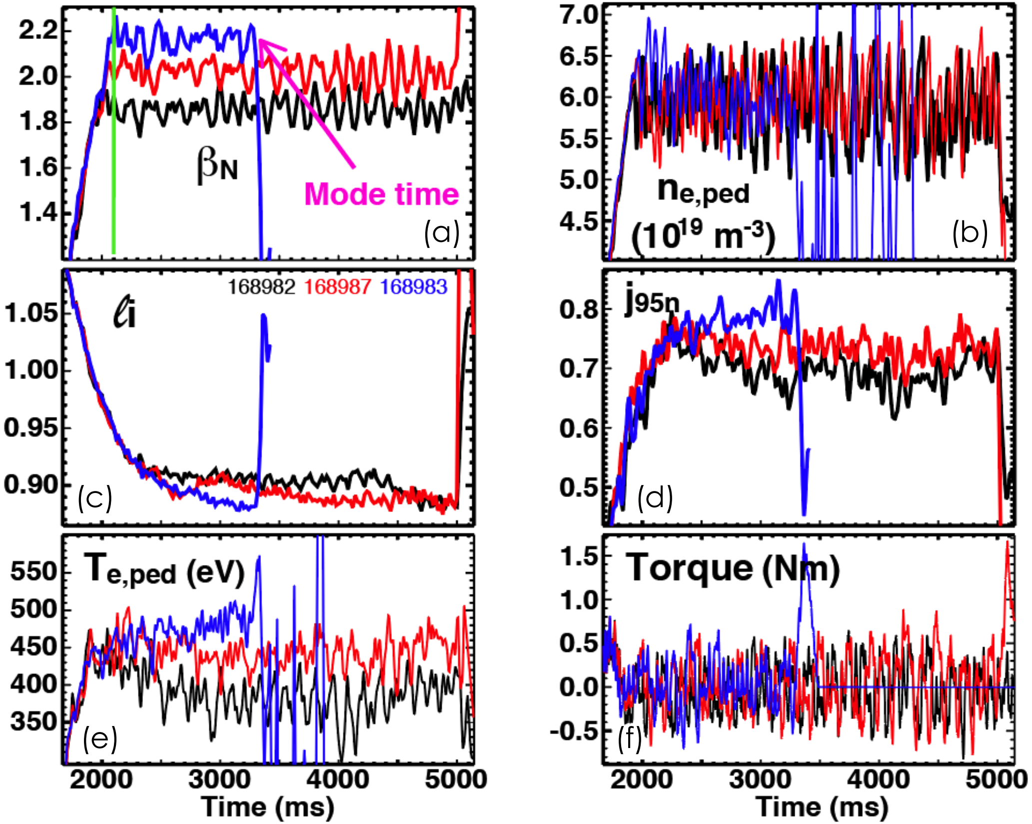
→ **p higher from the start**

→ **Mode hits >1 s later!**

→ **J_{ped} increases on τ_R~1 s**

More consistent explanation:

For a given J profile:
higher β_N =
→ higher pedestal (bootstrap)
→ more unstable



Which Physics Mechanisms Can Affect the ONSET of Tearing modes?

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- **Rotation Ω and $\nabla\Omega$ → it evolves on the τ_E time scale**
- Mode coupling → perturbed field from n>1 modes may resonate with 2/1 rational surface
- Seeding → it assumes the mode is classically stable, but "noise" produces SMALL islands at 2/1 surface (sawteeth, ELMs)

Correlation is NOT causation

The onset condition from $\nabla\Omega$ violates the onset time requirements → *Eliminated* (in backup slides if there is interest)

Which Physics Mechanisms Can Affect the ONSET of Tearing modes?

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- **Mode coupling → perturbed field from n>1 modes may resonate with 2/1 rational surface**
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All inconsistent with the mode onset timing and do not represent all the database → *Eliminated*
(in backup slides if there is interest)

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Which Physics Mechanisms Can Affect the ONSET of Tearing modes?

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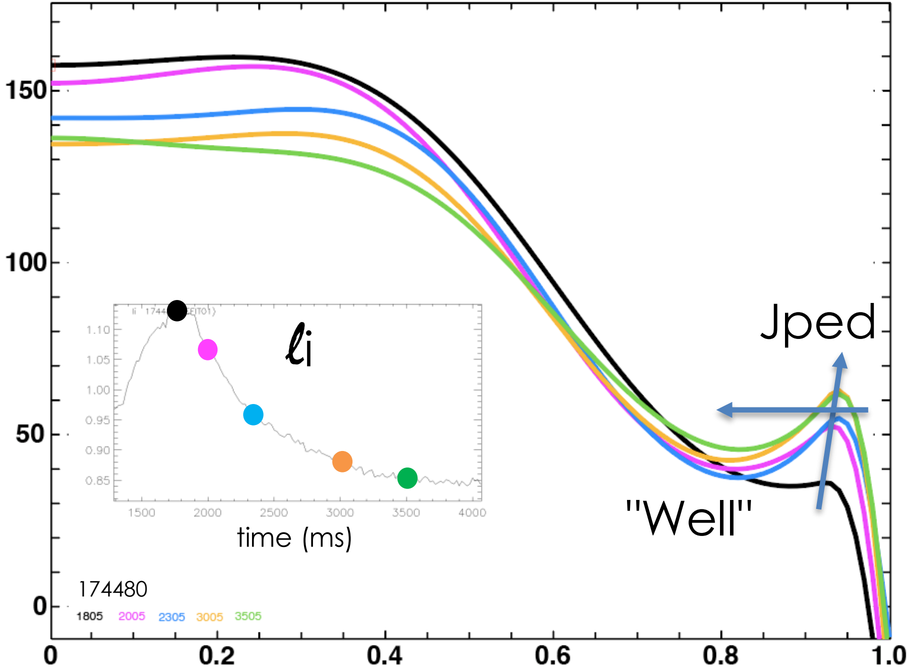
This actually worked…

Ohmic and Bootstrap Currents Create the Edge Peak and the Current "Well" That Evolves from the H-mode Transition

- **At the H-mode transition J_{boot} is formed**
  → peak at ρ~0.92

- **Ohmic current comes from the edge and diffuses inwards**
  → the "well" at ρ ~0.8 slowly fills

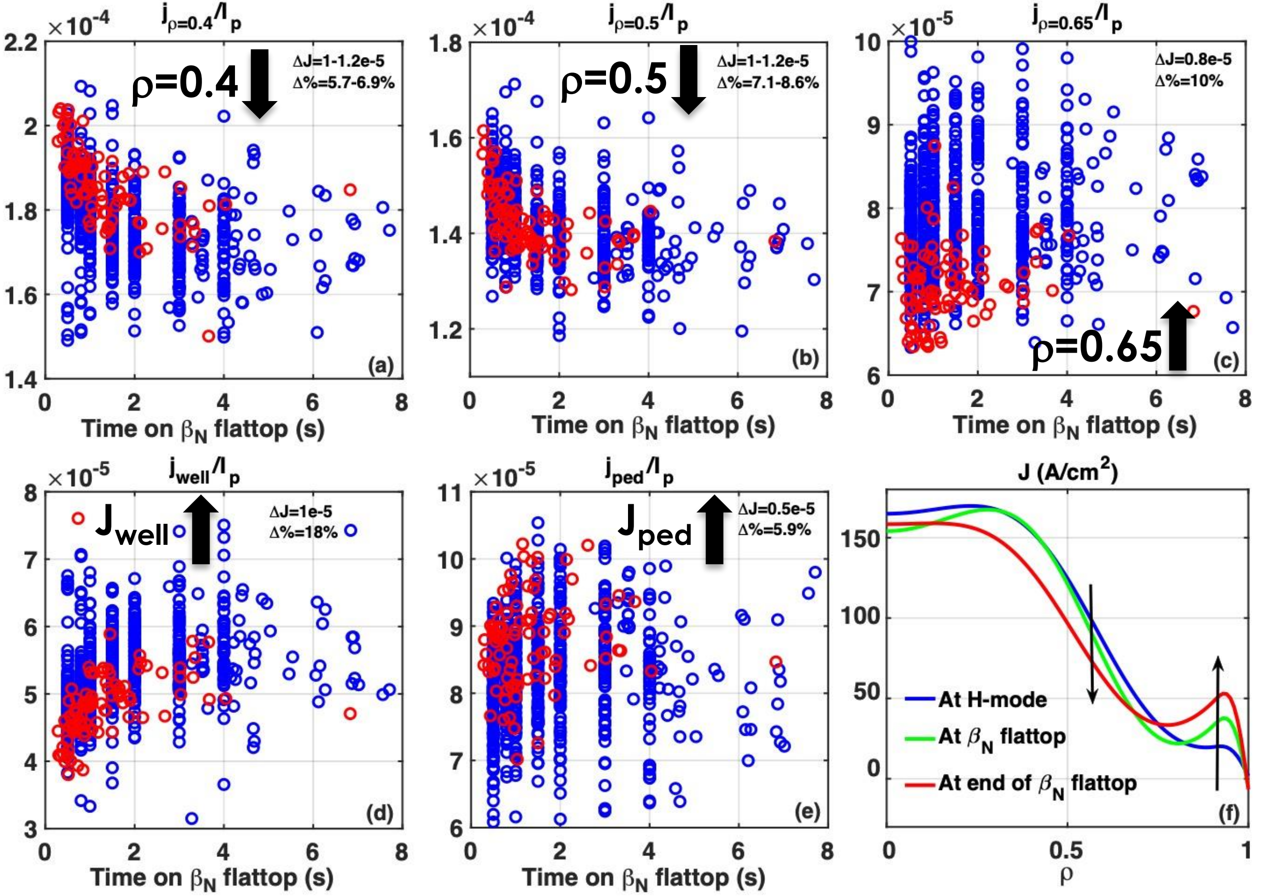
- **The core is fixed by sawteeth ρ <0.45 (q_{min}~0.9-1)**



The Current Profile Grows in the Outer Region and Reduces in the Core During the β_N flattop

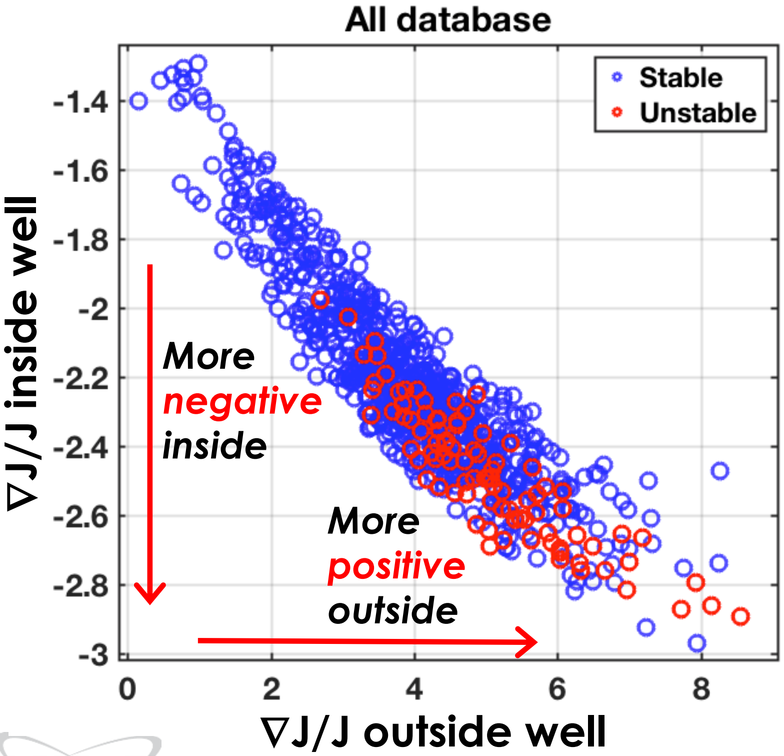
- Stable time slice
- Time of 2/1 mode

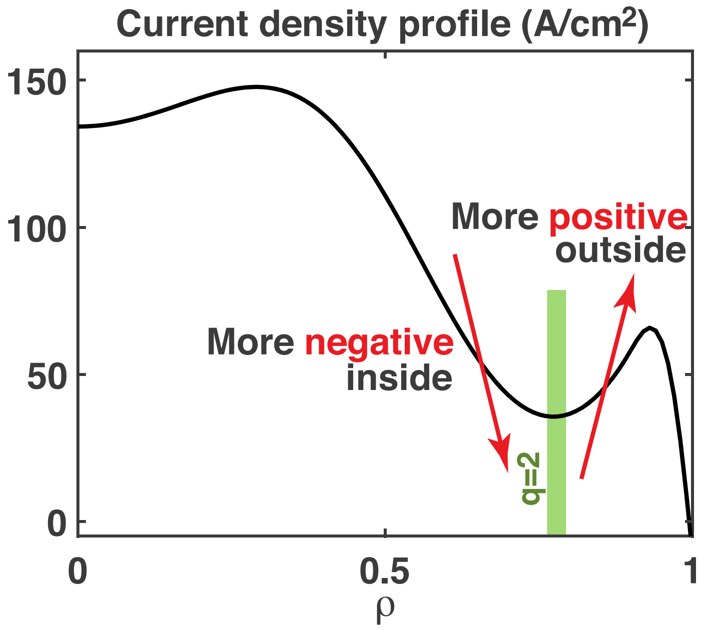
- J evolves for ~2 s after flattop
- **Stable** and **unstable** shots have a similar evolution
- …but the initial conditions are on average different



J at the Mode Onset has a Steeper Well Around the q=2 Surface

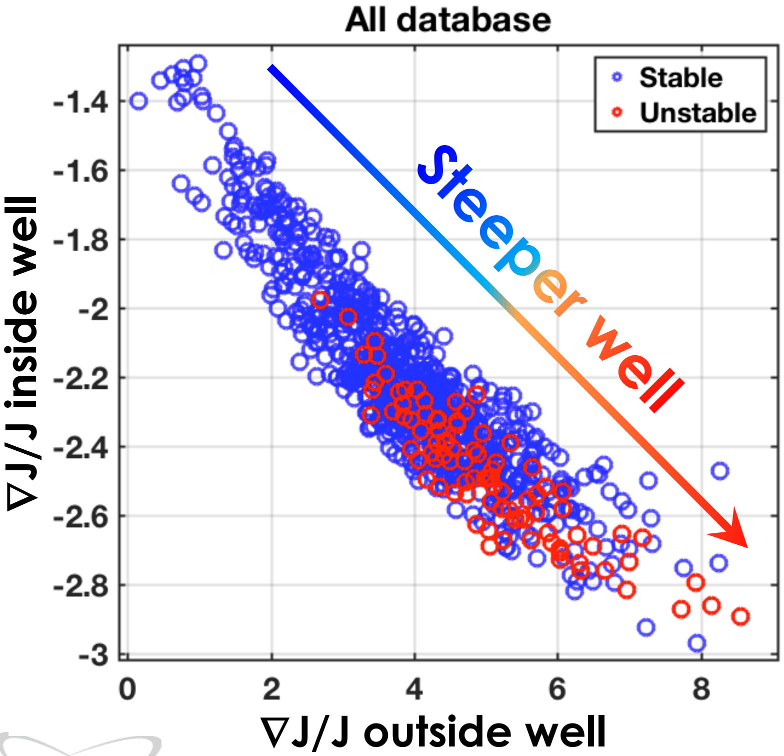
- **Both ∇J_s are larger in magnitude at the times of the mode onset**

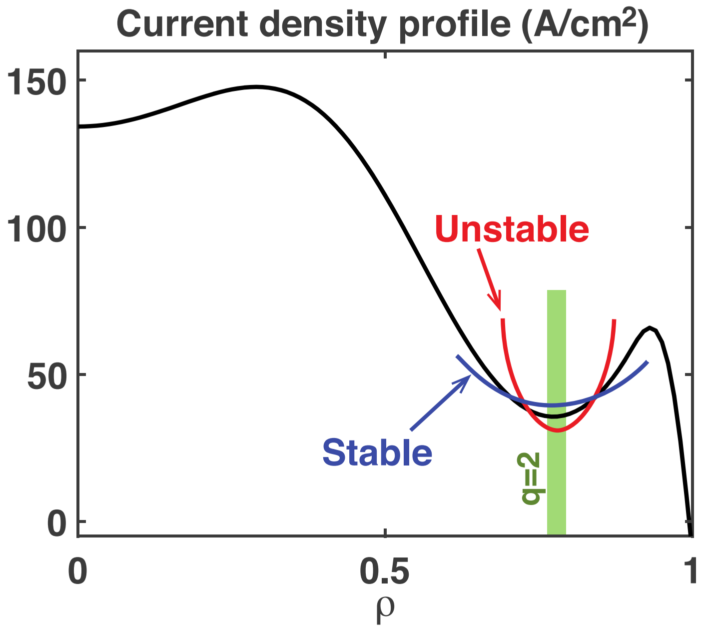




J at the Mode Onset has a Steeper Well Around the q=2 Surface

- **A steeper "well" in the current profile is likely the cause of the instabilities**

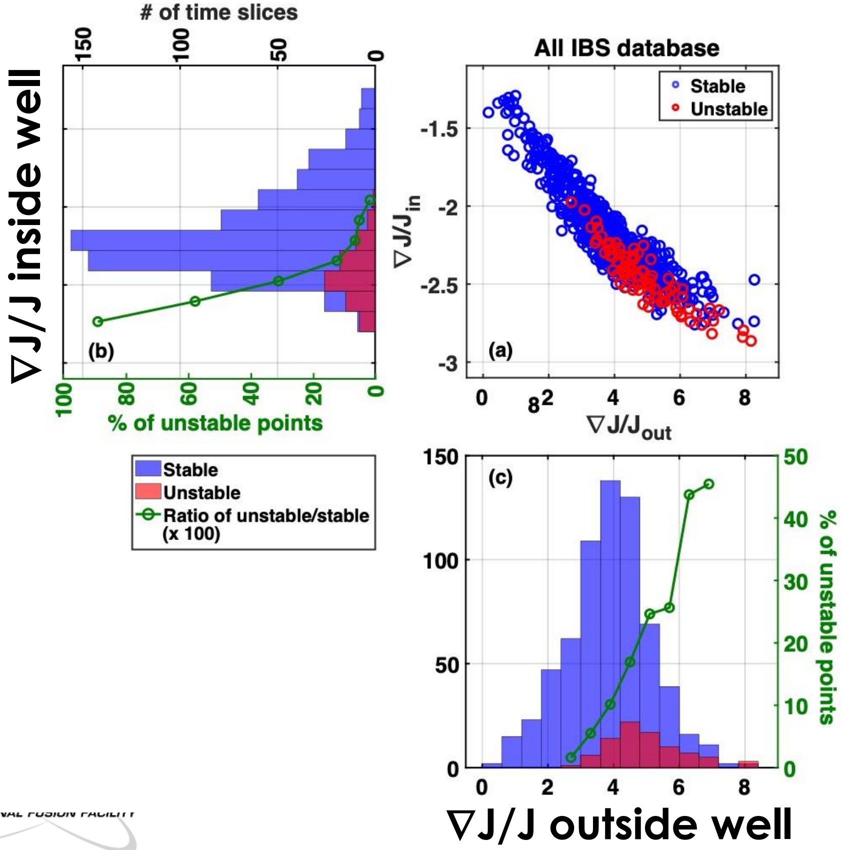




- Consistent with time scales τ_R
- Independent of seeding

Separating Stable vs Unstable TIMES Shows the Correlation Between the Current Profile and the Instability

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



- Histograms allow to see the **whole database** of time slices (10^4 hidden points)

- **Statistics** on the calculated ratios show this is meaningful (quantifiable)

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

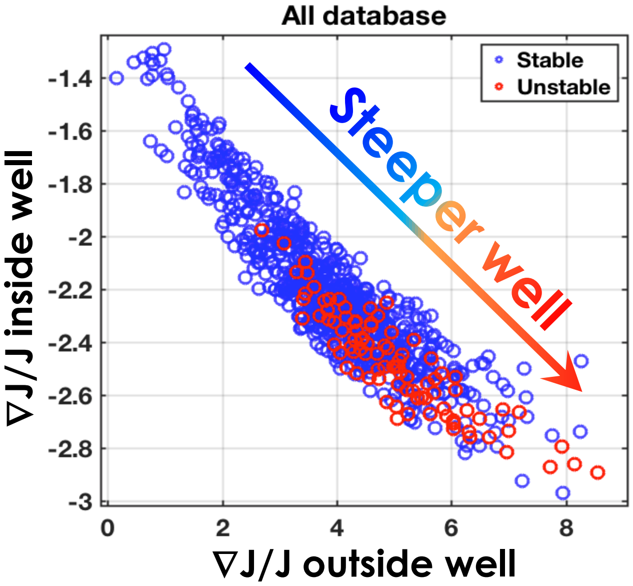
- **This suggests stable and unstable times have different Δ' : classical drive**

- **Δ' is a GLOBAL parameter, determined by all the current profile**

- **Δ'>0 is necessary, <u>not sufficient</u> for instability:**

  → Δ' trends determine if more/less stable

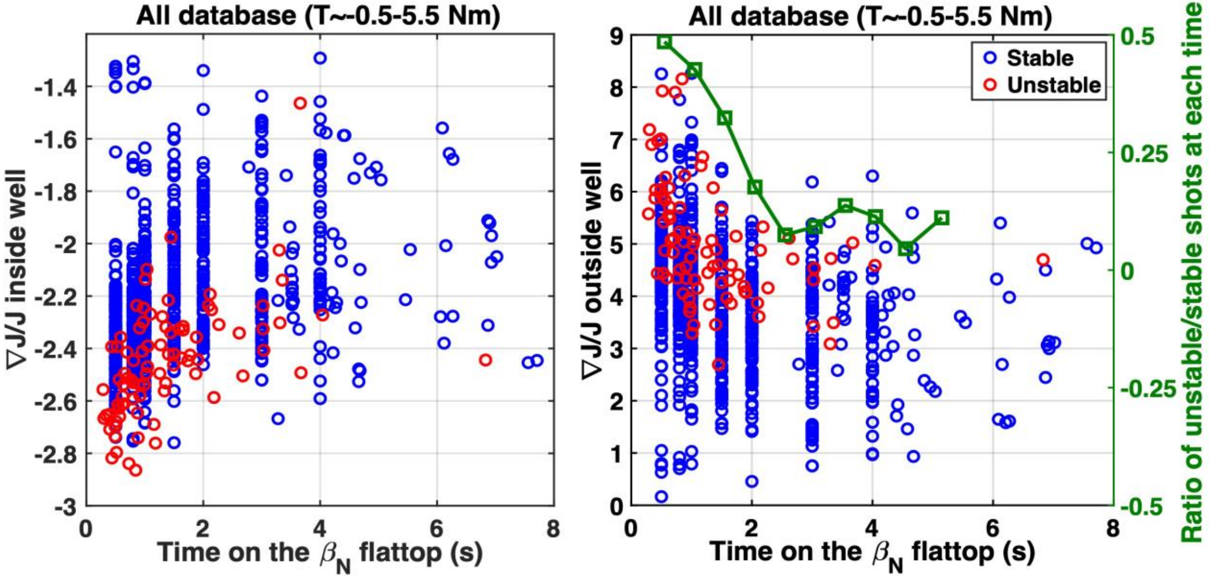
  → For instability, Δ'> Δ'$_{crit}$ (inner layer physics)



The critical Δ' for instability is likely the cause of the overlapping region of J (local T_e?)

Timing of the Modes Helps Us Find a Solution: the Unstable Shots Are Separated in ∇J from the Start

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



67% of the Instabilities Occur Before 1.3 s on the β_N Flattop (1-1.5 τ_R)

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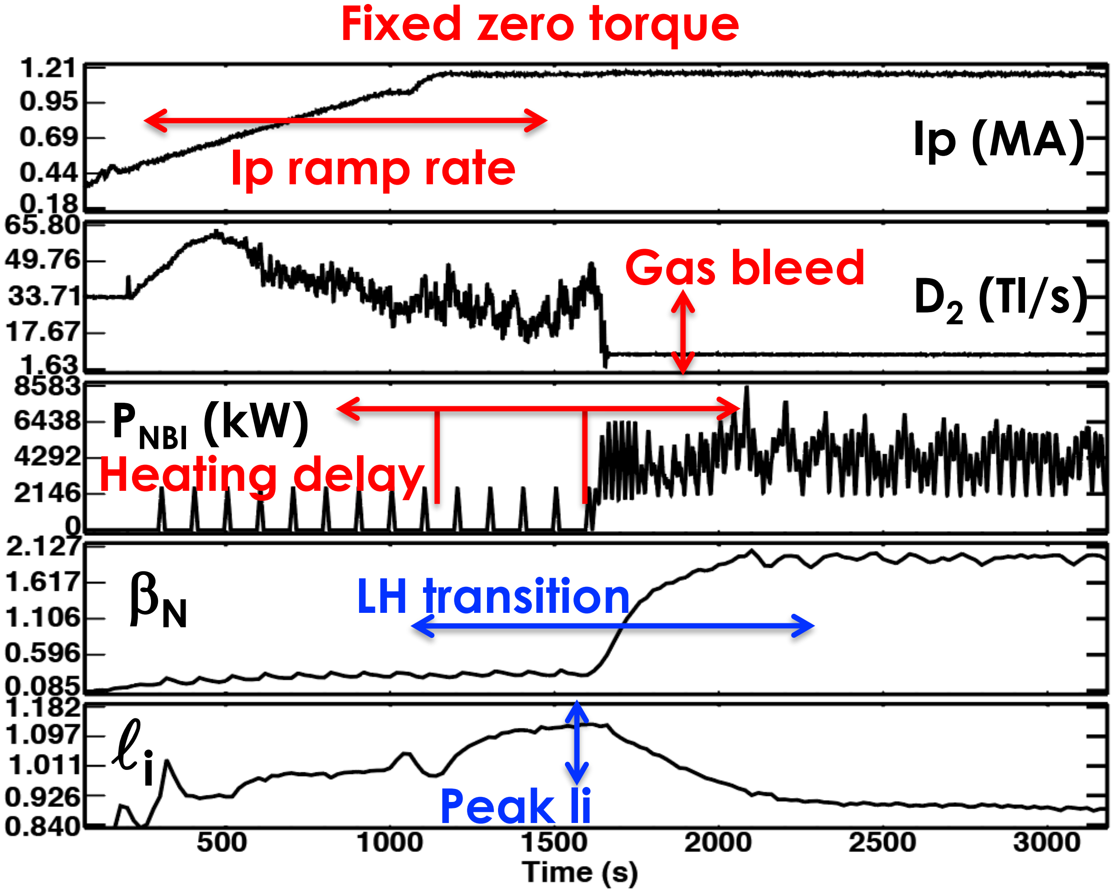
Methodology to Stabilize the IBS Modes Illustrates Actuators That Can be Used in All Scenarios to Change the Current Profile

Changes ℓ_i, current penetration

Changes ELM frequency, pedestal (not density)

Changes ℓ_i, current penetration

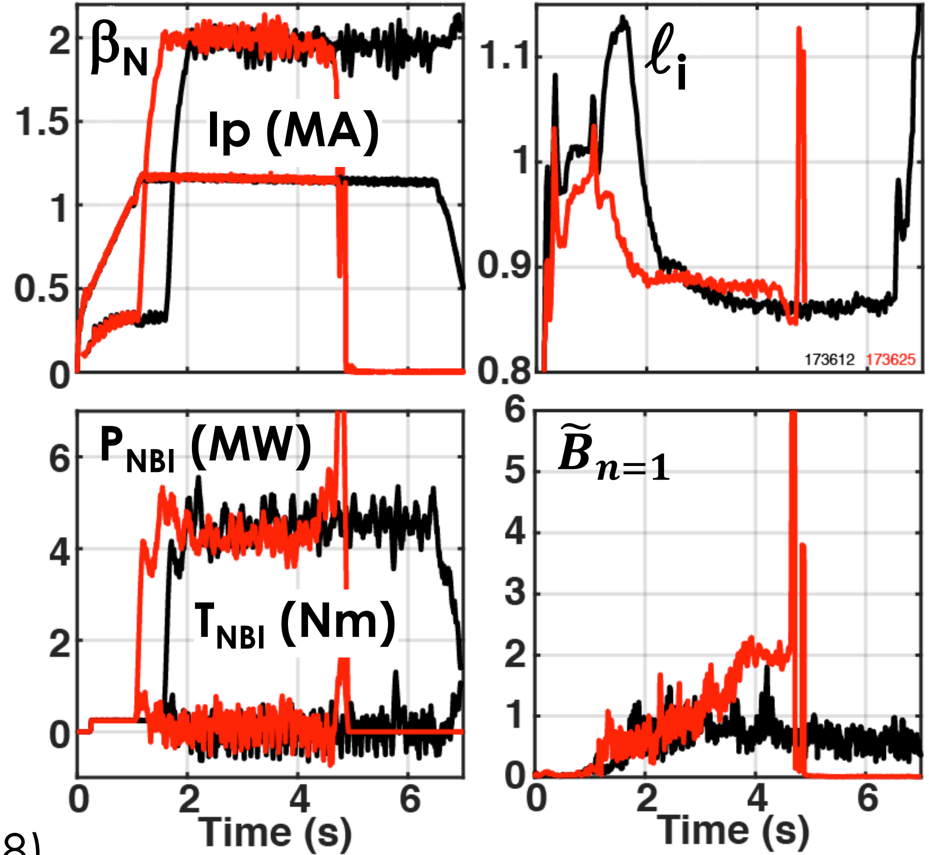
Allow J time to penetrate into the core → starts with lower pedestal



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**

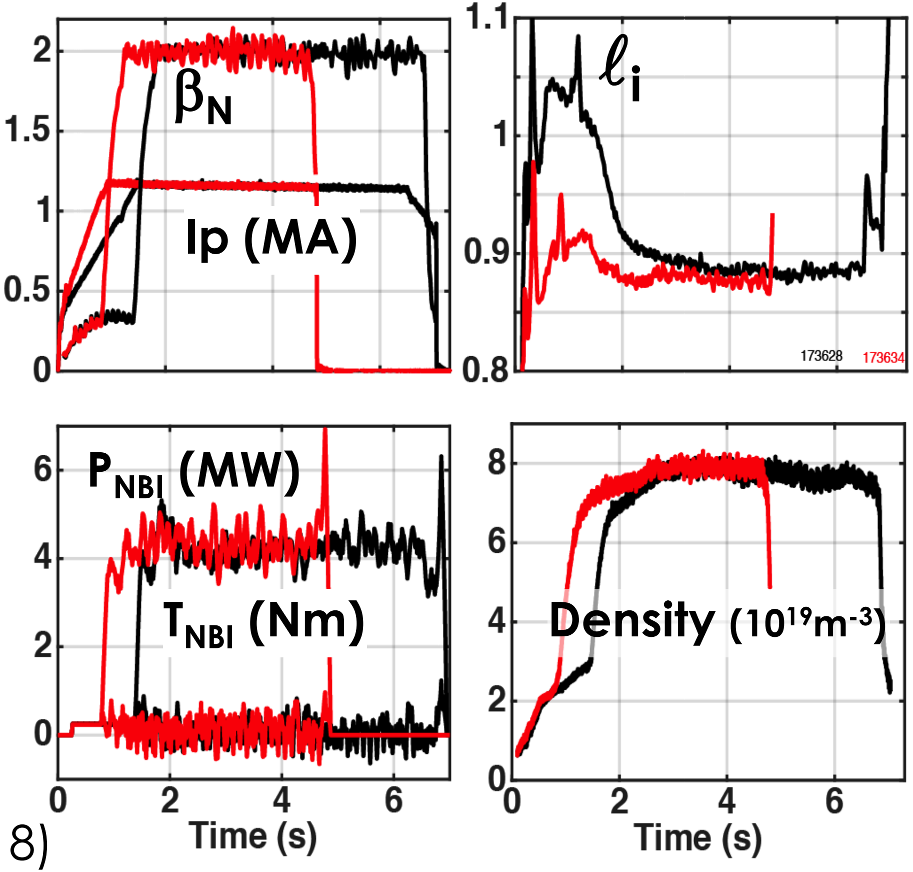
- **Trajectory of ℓ_i shows current profile evolution is different**
  - ℓ_i is not sufficient to predict stability



(T.C. Luce 2018)

Applied Modifications to Show Causality. (2) I_p ramp rate

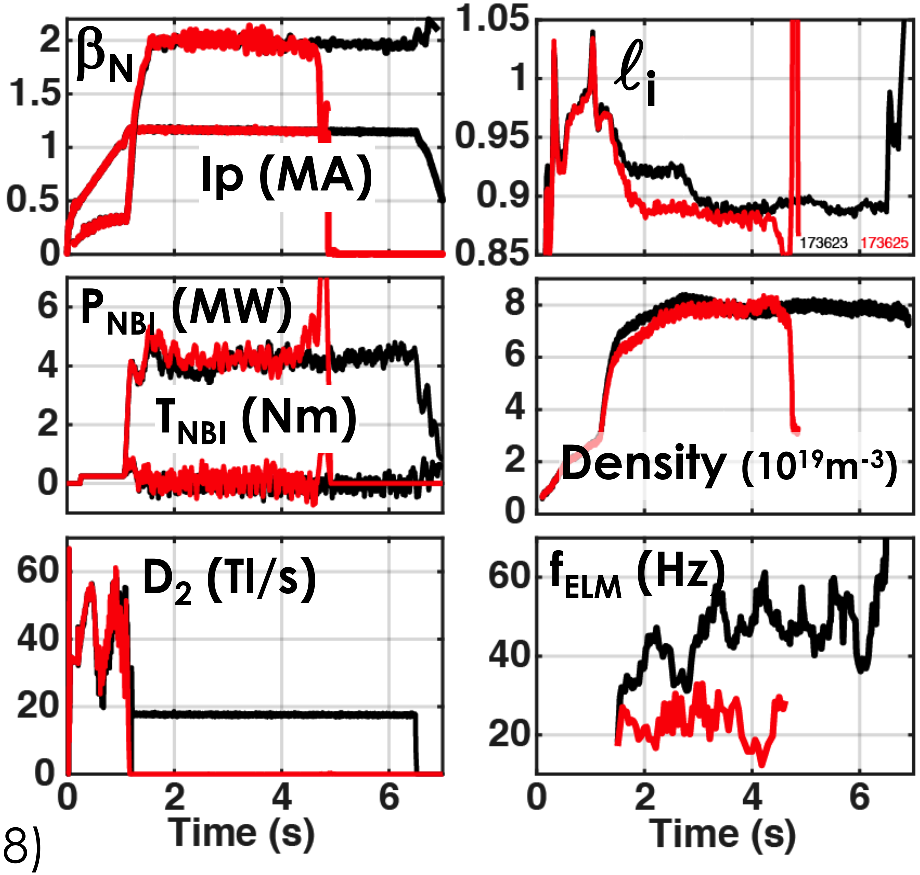
- **Slower Ip ramp rates are robustly stable – similar effect as heating delay**
- **Combination of Ip ramp and heating time changes can tailor the stability to the hardware requirements**



(T.C. Luce 2018)

Applied Modifications to Show Causality. (3) D_2 gas "bleed"

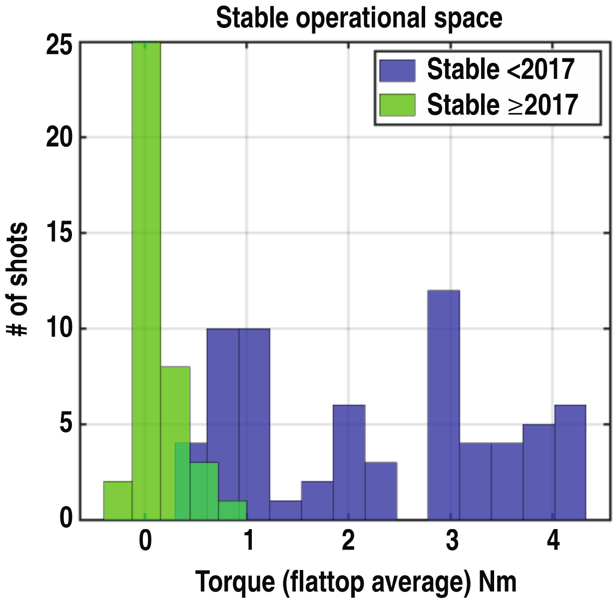
- **Modest gas "bleed" eliminates LATE modes**
- **Results in more regular and more frequent ELMs**
- **Smaller ELMs = lower pedestal!**
- **Little difference in density**

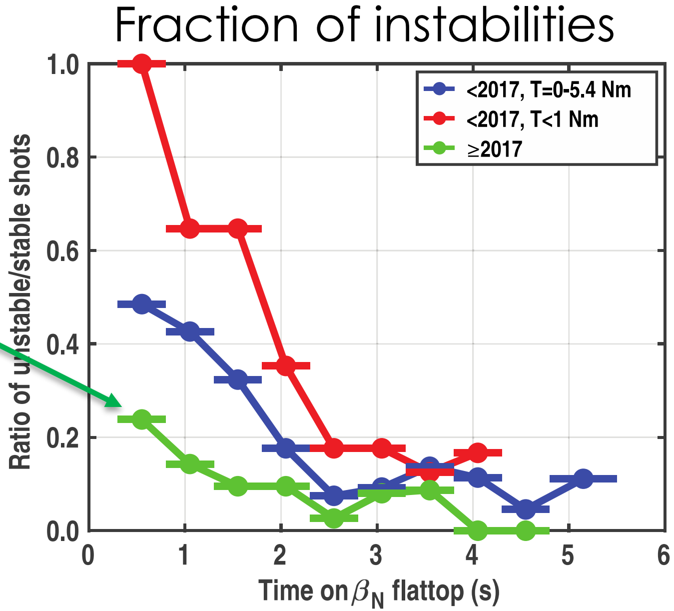


(T.C. Luce 2018)

The Recipe is Robust and Repeatable Under a Variety of Conditions

- **Different Ip, B_T, n_e, gas, impurities (Kr, Xe, C6, W)**
- **Heating mix (ECH, NBI)**
- **Open/closed divertor (USN, LSN)**
- **It did not go to a different density, Ω, ΔΩ regime**





This is NOT the intrinsic instability!

(intentional disruptions)

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Metrics for Evaluation of the Performance

- **Fusion power in DT plasmas of interest in ITER will have:**

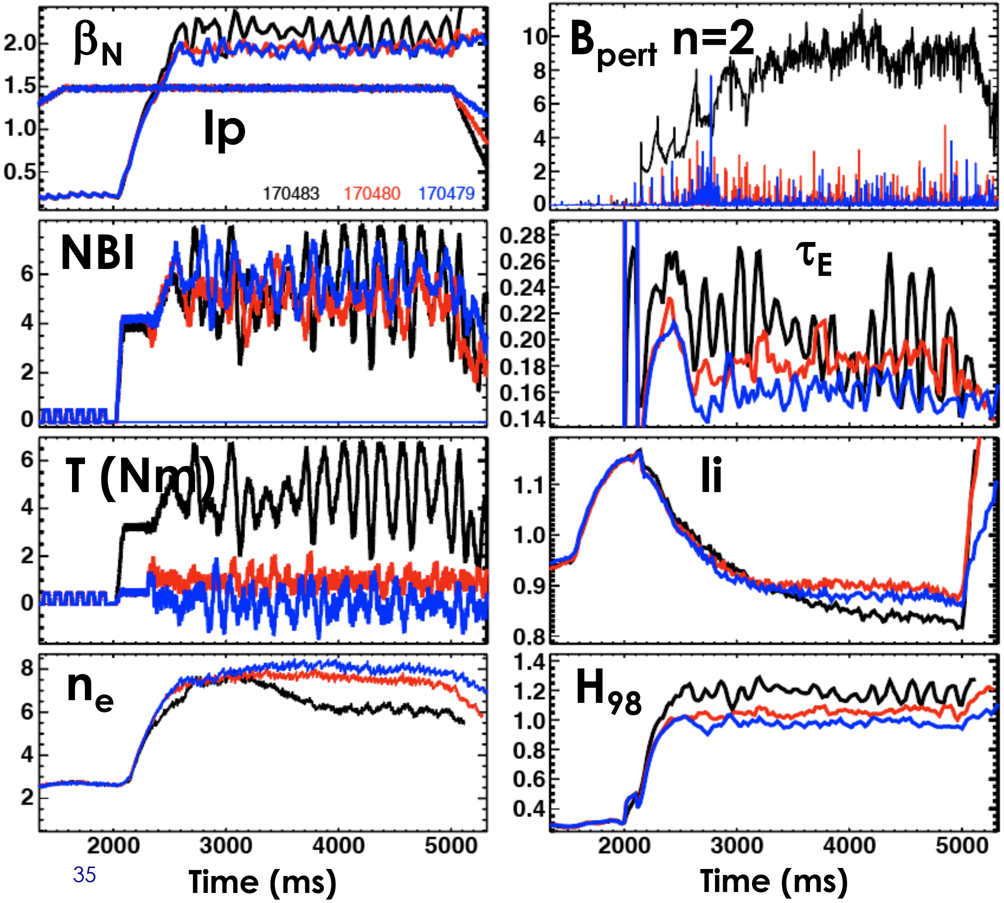
  $P_{fus} \propto \langle p^2 \rangle \propto \beta_T^2(\%)$ at fixed B (makes P_{fus} dimensionless)

  - In ITER, P_{fus} = 500 MW at B=5.3 T requires **β_T=2.55%**

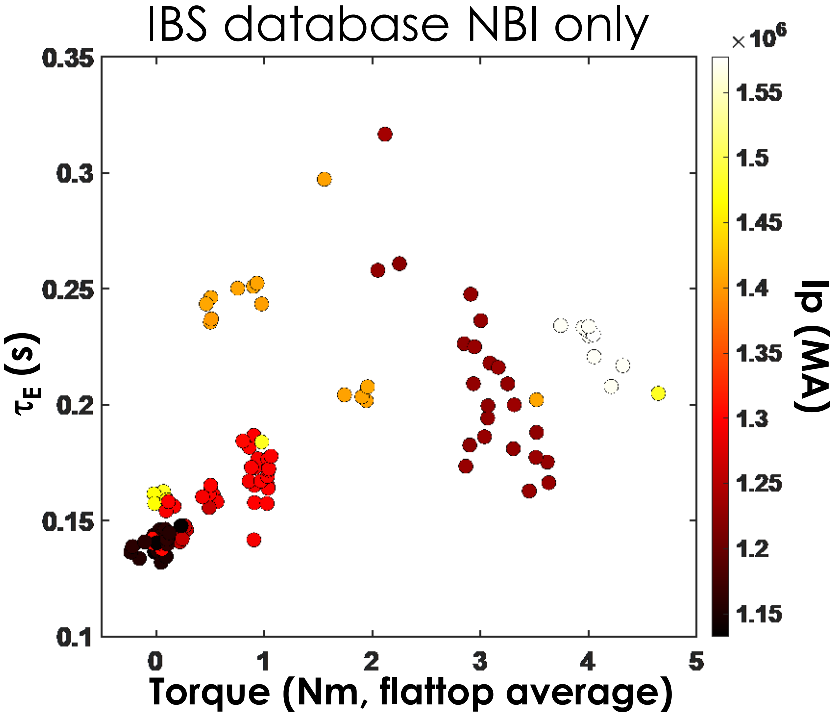
- **$Q_{fus} \propto \langle nT \rangle \tau \Rightarrow$ use $\beta_T \tau$ as a proxy for gain (not dimensionless)**
  - Can also use $G \equiv \beta_N H_{89} / q_{95}^2$ as a proxy for gain, but the accuracy of a confinement scaling is assumed
  - ITER Q=10 requires **G=0.38-0.42** (depends on precise value assumed for q_{95} at 15 MA)

- **Will also show the standard stability and confinement metrics (β_N, H_{98y2})**

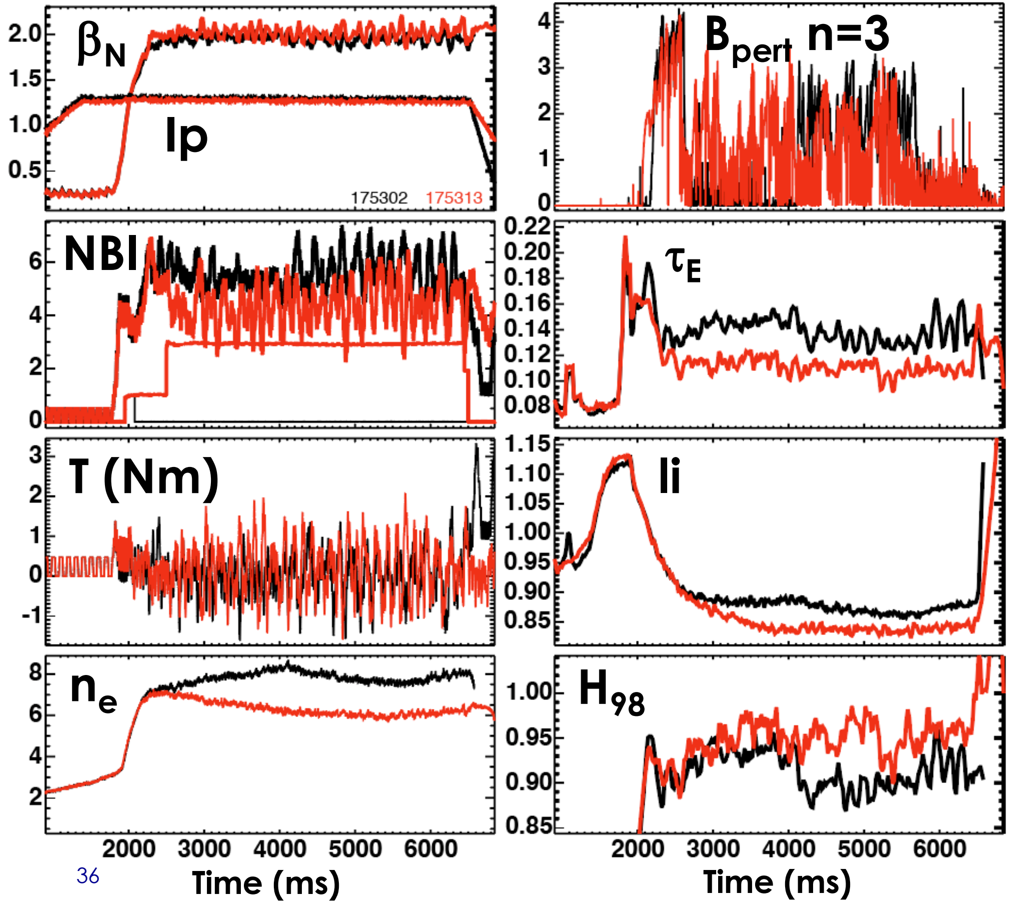
Confinement Gets Worse at Lower Torque



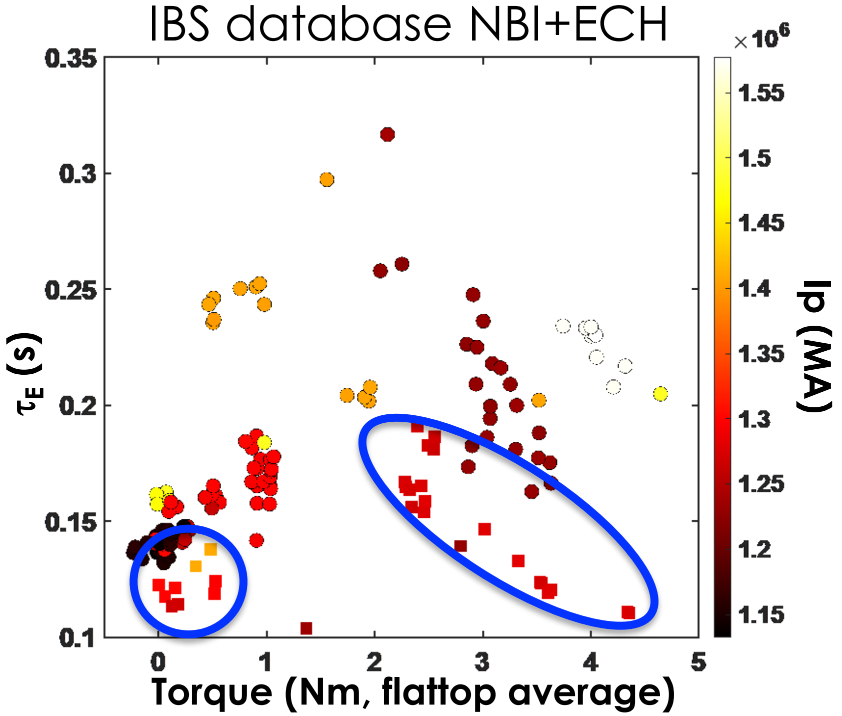
- **But other factors apply (Ip, density, etc…)**



ECH in Dominant NBI Heated Plasmas Reduces Confinement



- **ECH degrades both heat and particle confinement**



The ECH Location Also Strongly Affects the Confinement

Heating efficiency drops dramatically with off-axis heating

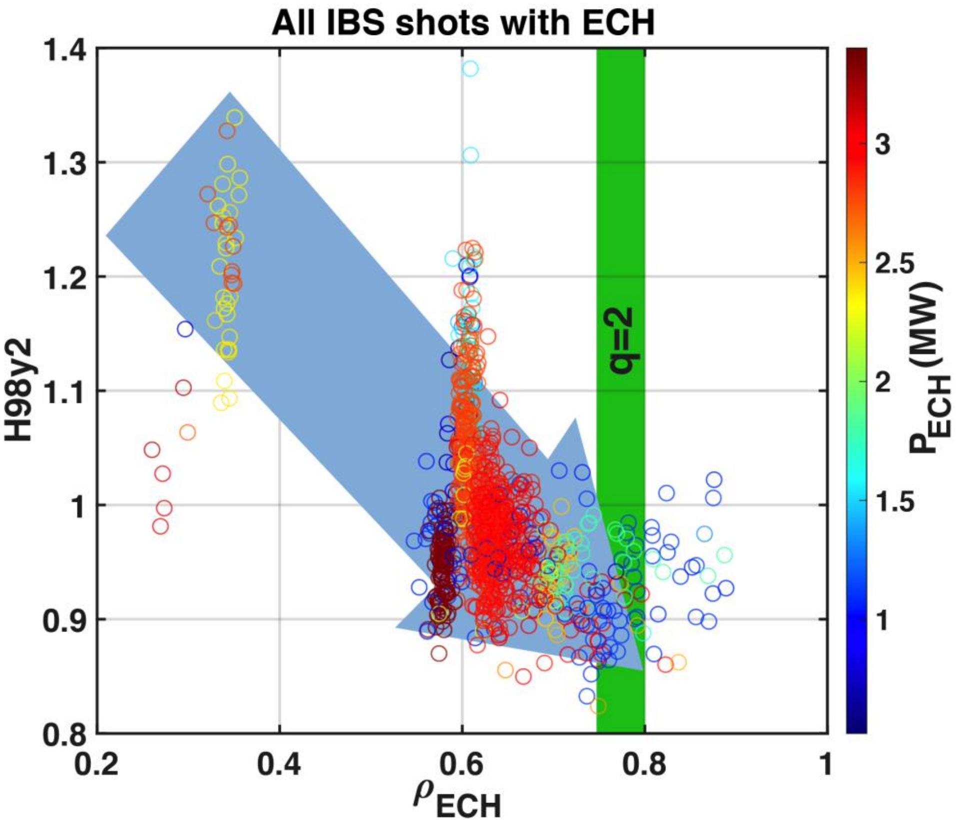
$\eta_H \sim 1-\rho^2$

Regardless of I_p, torque: ρ_{ECH}>0.75

- Reduces confinement below standard H-mode levels

(Not a power degradation effect)

- Direct ECCD stabilization is not compatible with Q=10 performance



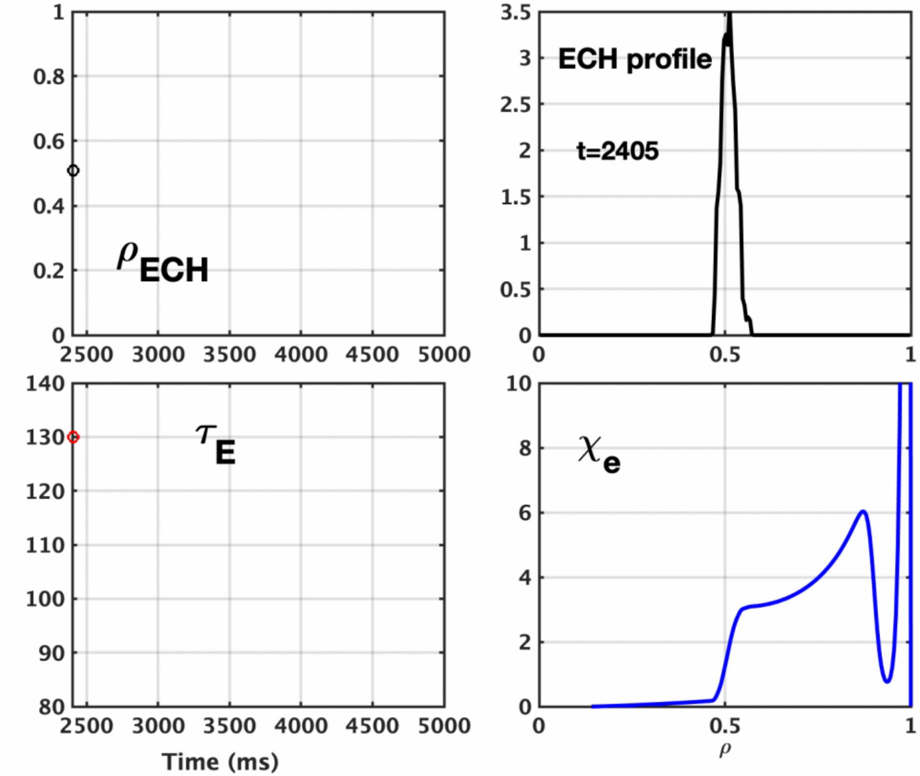
Drop in Confinement With Off-Axis Heating Can Be Seen Also Dynamically With RT Mirror Steering of the Gyrotrons

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

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

Expect 50% drop in τ_E, observe 25%

Loss of heating efficiency compensated by transport improvement



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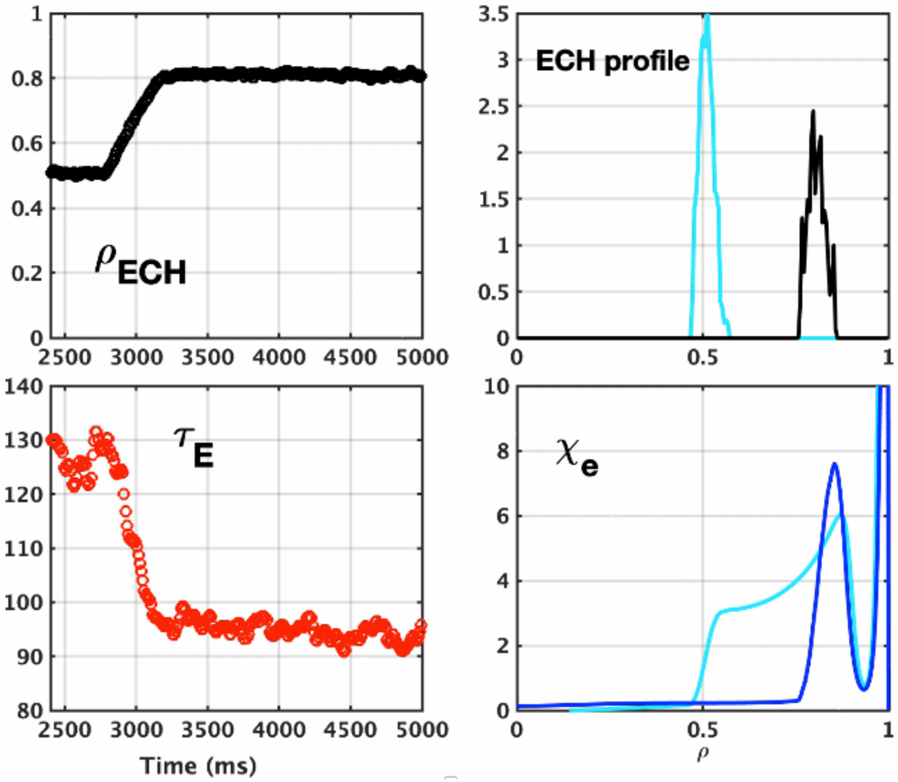

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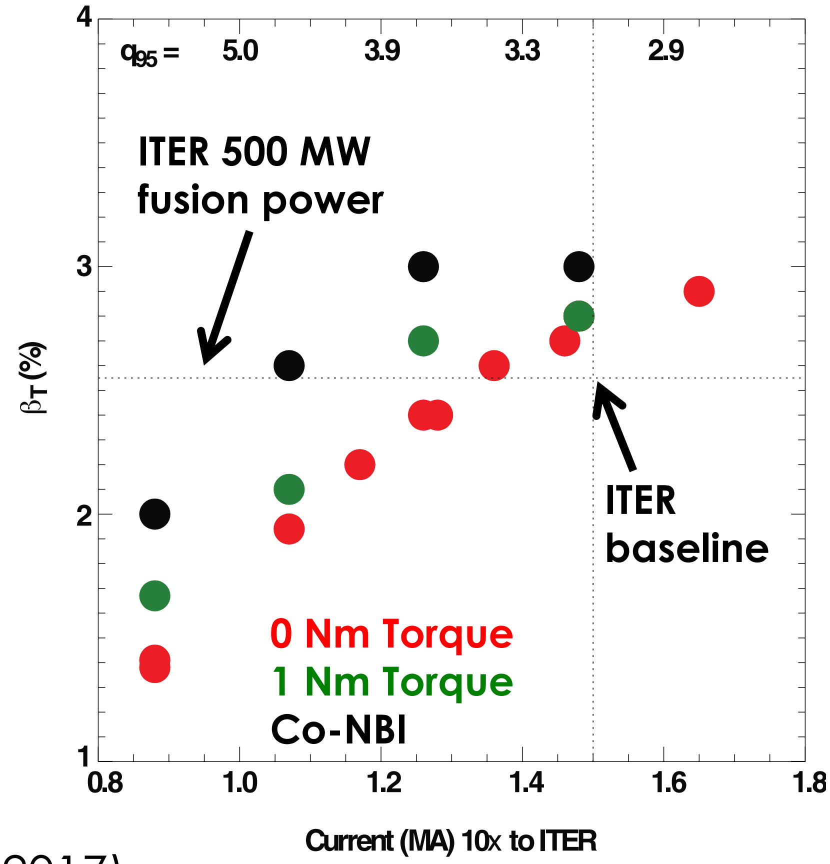
Performance to Reach 500 MW of Fusion Power in ITER Achieved at All Torque Levels and Lower Current

- **With co-NBI, the goal is reached by 11 MA equivalent**
- **With 0 Nm torque, 13.5 MA may be sufficient**
- **For co-NBI, the achieved β does not increase above 12.5 MA**

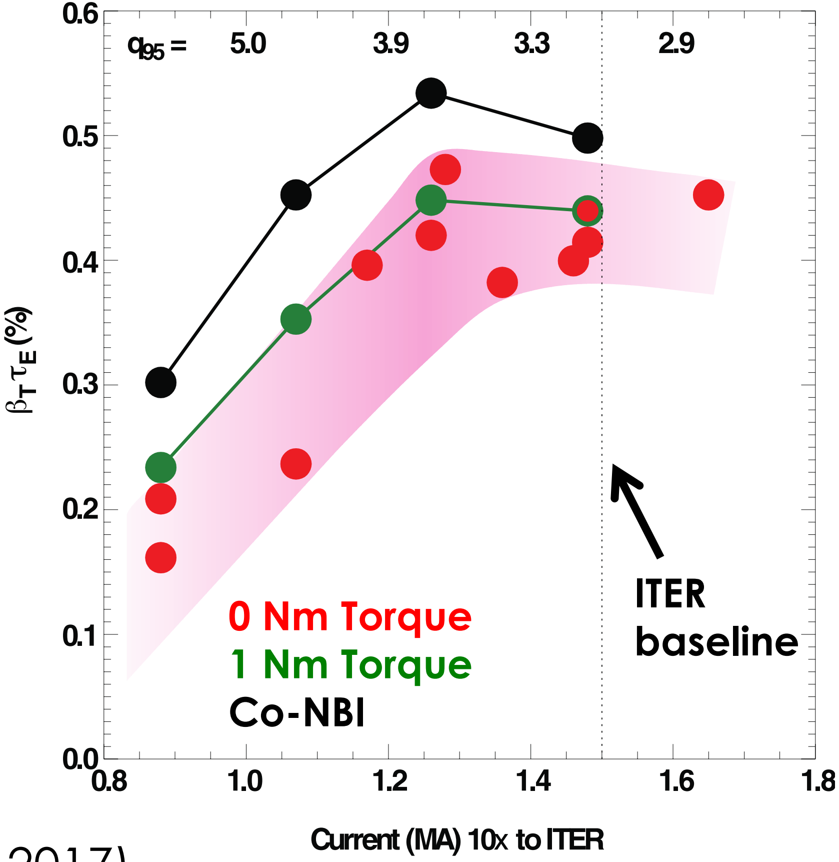


(T.C. Luce 2017)

Gain Metric (βτ) Does Not Improve Above 13 MA Equivalent Current

- **Curves at all torque levels have similar shapes**
  - Effect is not likely due to ExB shear

- **Increase in gain seems to saturate around 13 MA**
  - Corresponds to q_{95}≈3.7
  - Previously seen on DIII-D, but not explained [Schissel, et al., NF 32, 107 (1992)]



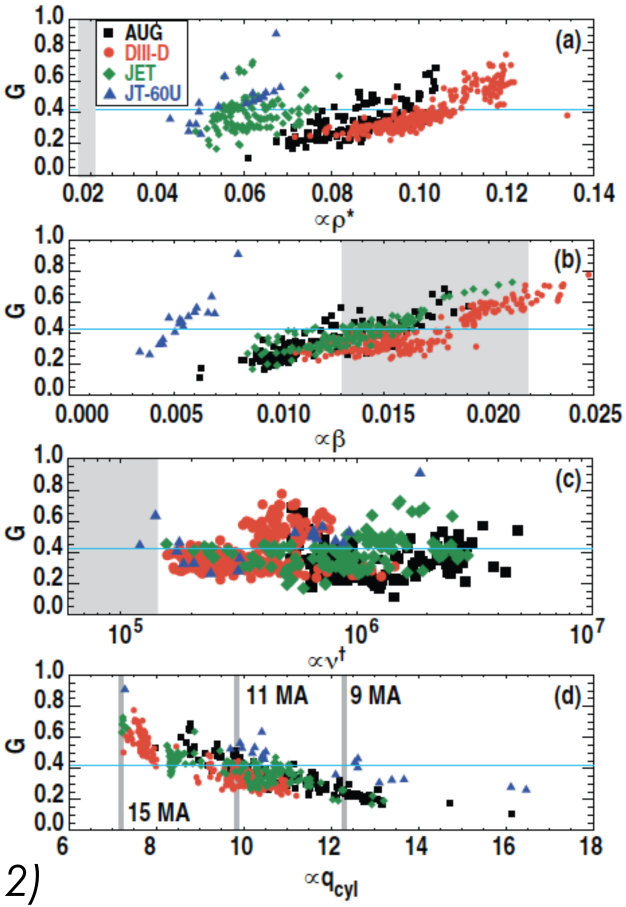
(T.C. Luce 2017)

The Advanced Inductive Scenario Constitutes a Promising Alternative for ITER's Q=10 Mission at Lower Current

- **Advanced Inductive** (A.I.) scenario has demonstrated good performance projecting to Q=10:
    - H_{98y2}~1.2-1.5, β_N=2.4-3.0 → G~0.4
    - At q_{95}~3.8-4.8 and T_i/T_e~1-1.6
    - In DIII-D, AUG, JT-60U and JET

- **This scenario has a different access to H-mode: heated ramp**

- **Needs to be extended to SN shape and low T**



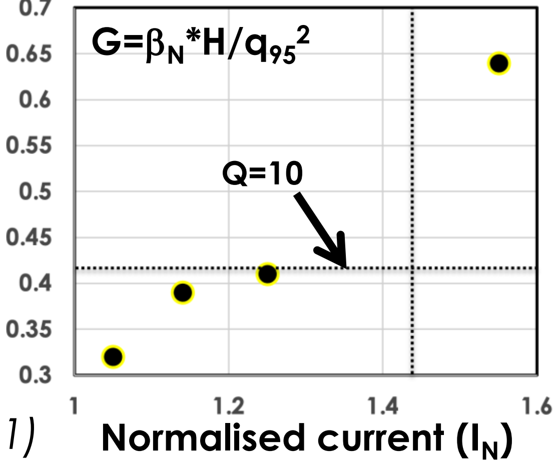
(Luce 2012)

Ohmic vs A.I. Heated Access Has Significant Impact on the Stability and Performance of the Burn Phase

- **Heating in the Ip ramp usually gives access to higher stable flattop β_N**
- **A.I. scenario can operate at reduced q_{95}~4.5 because of higher MHD limits**
- **G is maintained thanks to higher β_N and high H_{98}**

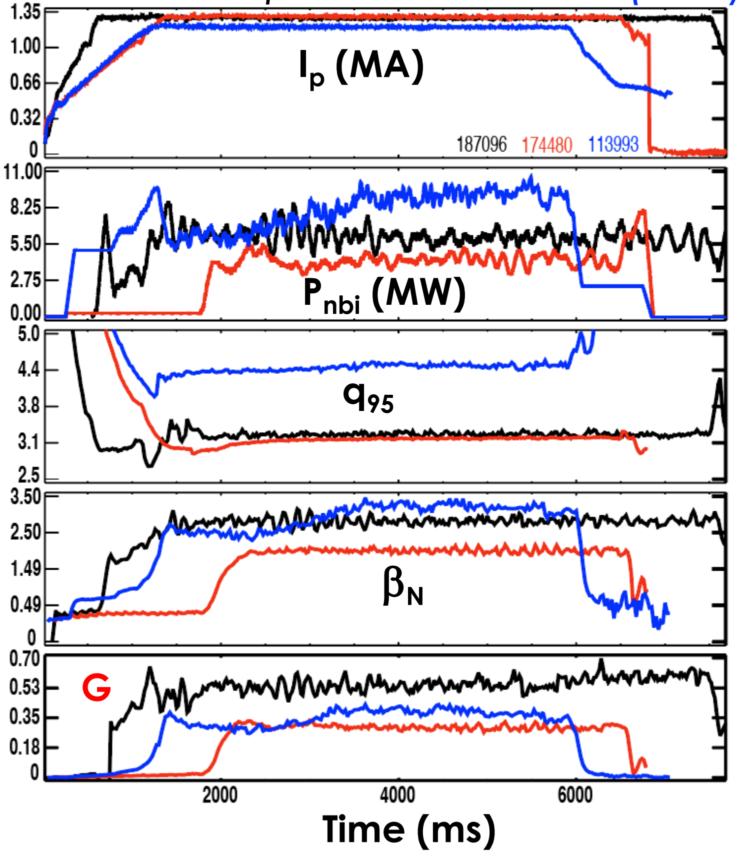
JET hybrid scenario results in next talk!

Heated ramp



(Luce 2011)

IBS co-torque, IBS T=0, A.I. (DN!)



What we have not covered (a lot)

- Tungsten and the impact of intrinsic radiation
- ITER-like controls: slower, fewer?
- Projections (no time today…)
- Differences with ITER parameters:
  - Higher temperature (Ip, power)
  - Lower collisionality
  - Rotation is relatively unknown → confinement?
  - Core-edge integration (divertor impurities and detachment)
  - RMP ELM suppression
  - Fuelling: less core, more pellets?

Extras

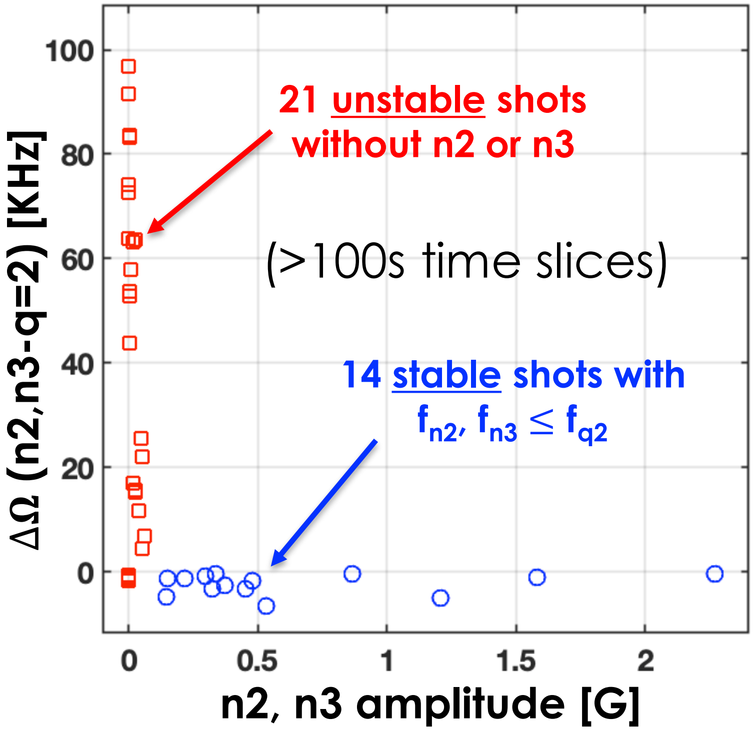
Stability: seeds (not)

Experience, and DB analysis, show that the presence of other n>1 modes does not separate stable/unstable plasmas

- Many of the 2/1 modes are **not coincident** with any other n>1 mode
- Many of the stable shots have zero rotation differential between n2,n3 islands and the q=2 surface - but **no 2/1 mode**

Higher n modes cannot be a general cause of the instabilities in the IBS

2011-2020 full IBS database



21 unstable shots without n2 or n3

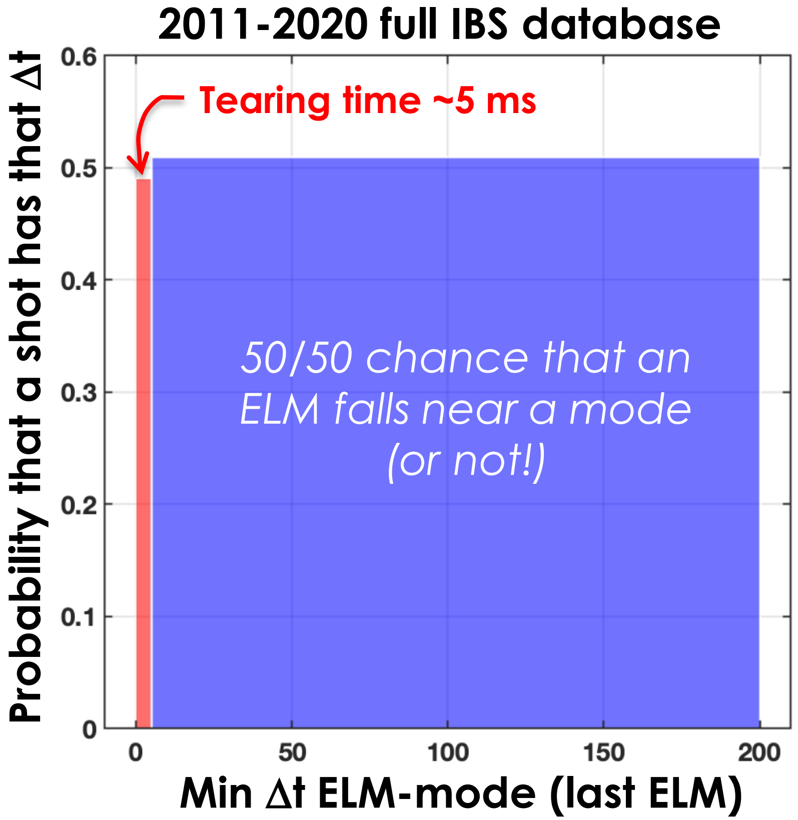
(>100s time slices)

14 stable shots with $f_{n2}, f_{n3} \leq f_{q2}$

Millions of seeds… and very few modes → seeding is not the main cause of the 2/1 instabilities

- There are 18054 ELMs in 273 shots – only 162 modes □
- Stable shots have the same ELMs and sawteeth as the shots with a mode
- There are hundreds of ELMs and tens of sawteeth before a mode

Focussing on the last lone ELM or sawtooth will not solve the problem



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Stability: rotation (not)

J, p represent the equilibrium, Ω may affect mode coupling or locking

Sources of free energy

- → **Pressure, current** (and their profile shapes)
- → **Δ'** is a global parameter **function of p and J** = free energy for tearing
  - **Δ' > 0** *Necessary but not sufficient*:
- → Instability threshold **Δ'_{crit}>0** in toroidal geometry: function of inner layer physics → $T_e,\ n_e, \nabla T_e$, etc

Rotation and its gradient:

- → **Ω not a source of free energy**
- → **at rational surface**, large *Ω gradient* destabilizing → need very large island (not our case)
- → **between rational surfaces**, large *Ω gradient* believed to decouple equal n surfaces → only 1/1 and 3/1 surfaces can couple

(Refs: Wesson, GGJ, Pletzer)

Unlike J, Ω and ΔΩ Evolve Fast, or Are Fixed at Low Torque

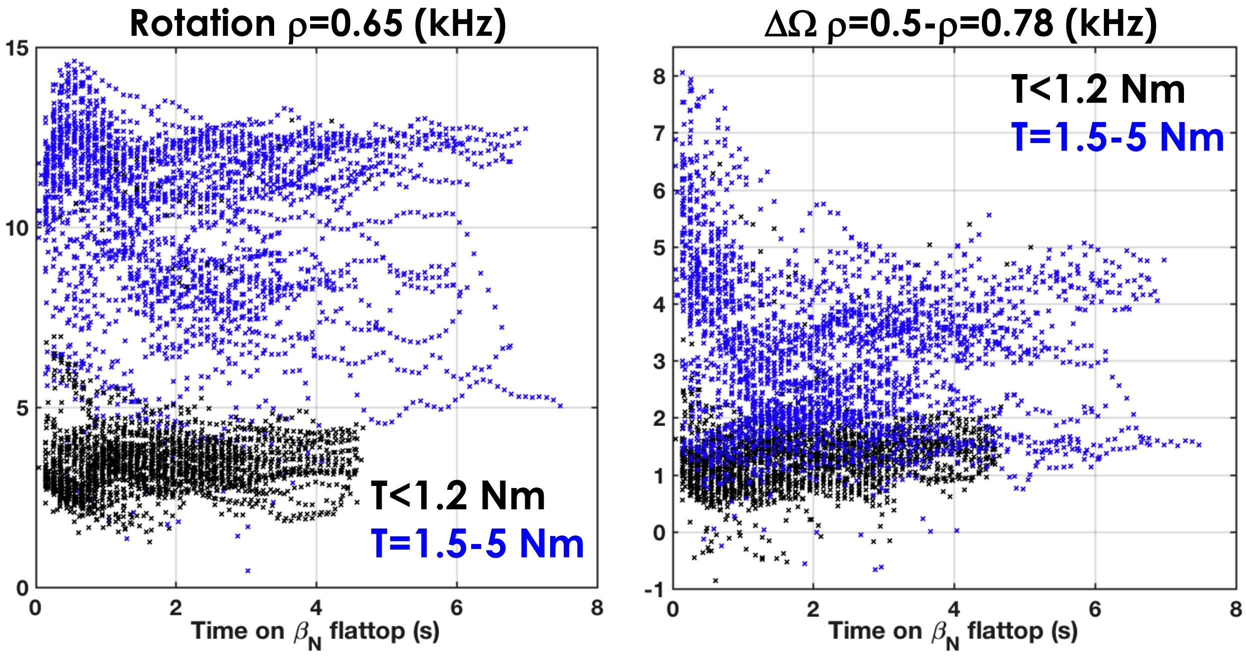
- **Time-of-mode plot shows that stability gets better in time (fewer modes late)**

Ω and ΔΩ either decrease (worse) or stay the same

The equilibrium becomes more stable, Ω does not

↓

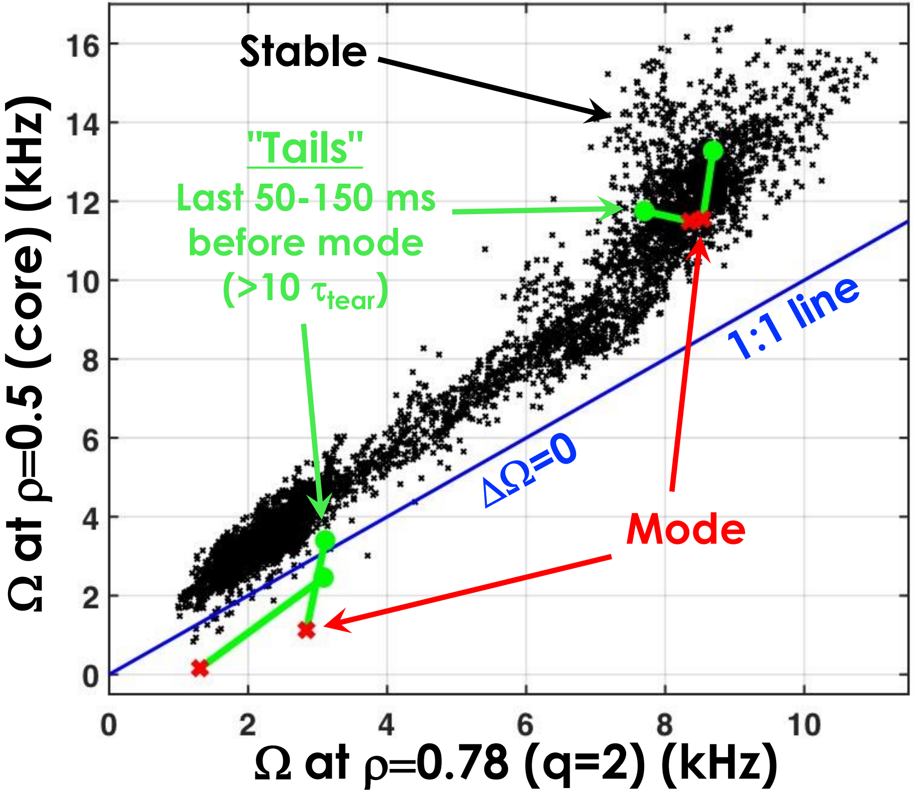
Hypothesis of destabilization by ΔΩ inconsistent with sparser modes late



Time Scales of ΔΩ Evolution to Instability Are Too Long to Explain the Mode Onset by Surface Coupling

- Differential rotation between core and edge appears lower for many unstable times
- "Tails" show that ΔΩ is low for $t > 10\text{-}30\ \tau_{tearing}$! ($\tau_{tear} \sim 5$ ms)

All database, 100 ms average



Lack of ΔΩ is Not Likely To Be the Cause of the Instabilities

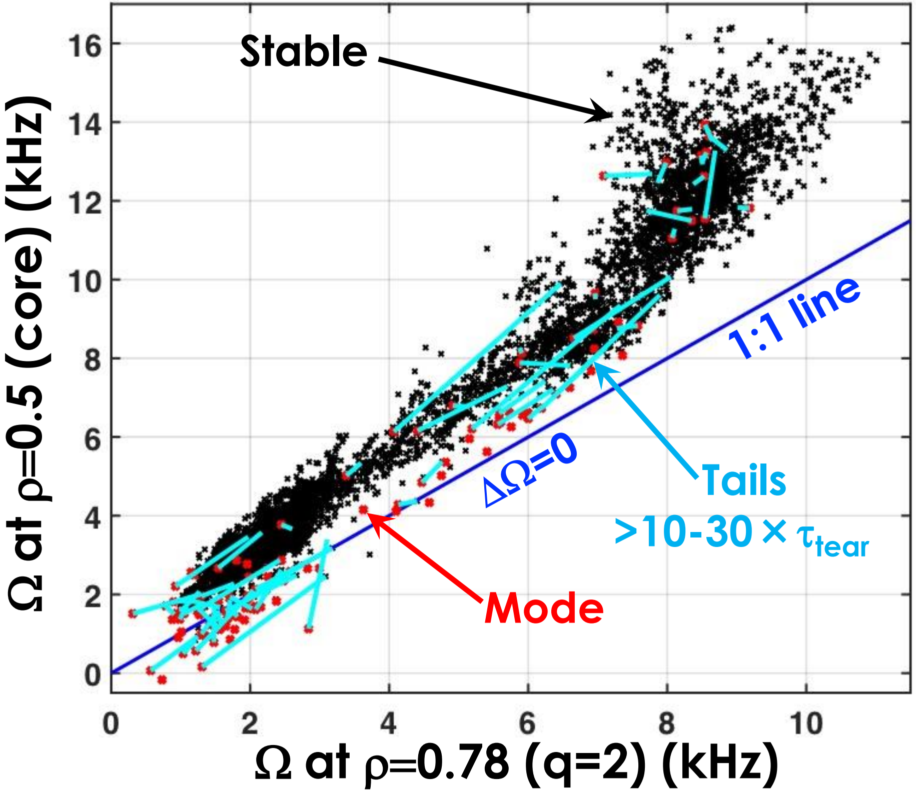
50% of the modes have

- Large ΔΩ (in "stable" region)
- Constant ΔΩ ("tail" // to 1:1)
- Low/zero ΔΩ for >10-30 τ_{tear}

⇩

Mode "triggering" by lack of ΔΩ is inconsistent with the onset time scale

All database, 100 ms average



Stability: rotation is coupled to current profile

In the Pedestal, the Time Scales are Shorter

Current → Energy, Rotation → Tearing:

- **Global resistive diffusion time τ_R ~ 800-1200 ms, $\tau_R \sim \Delta\rho^2$**

  → Local J changes at ρ~0.70-0.95 can be on $\Delta\tau_R$~100 ms

- **Energy confinement time (pressure, rotation) τ_E ~ 100-200 ms**

  → if torque is stepped up, Ω and $J_{pedestal}$ change in ~200 ms

- **Tearing time τ_T ~ 5 ms**

Rotation and current profile can be coupled locally

Fixed Ip Forces the Correlation Between "Well" and Pedestal

At lower rotation/rotation shear:

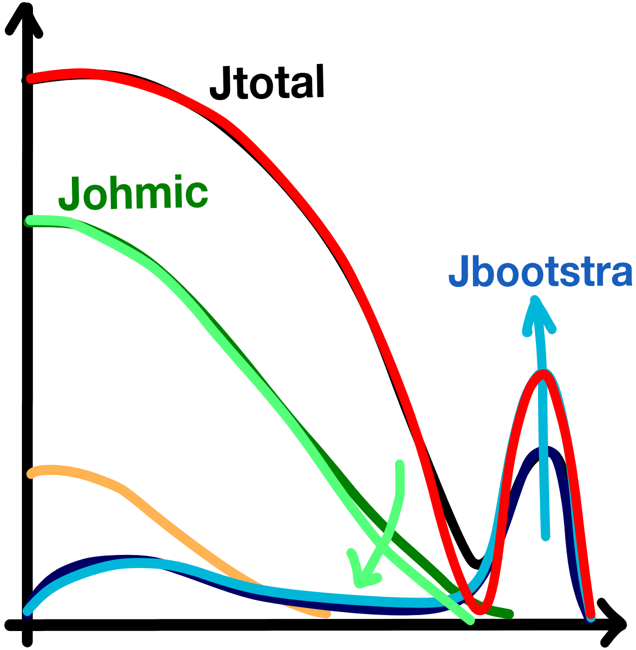
→ **The pedestal increases (transport)**

→ **More J_{boot}**

→ **The Ohmic drive has to reduce (fixed Ip)**

⇩

Steeper "well" around q=2



When the Rotation Changes, the Current Profile Changes too!

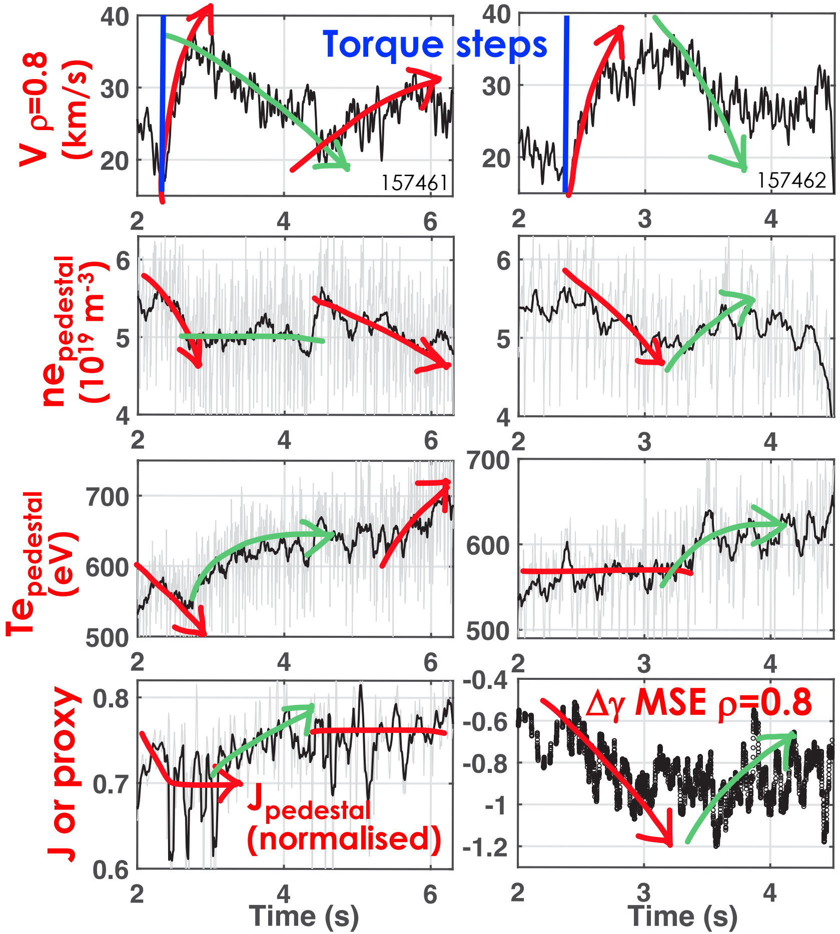
- **Rotation keeps evolving after the torque step!**
- **Rotation and pedestal J are anti-correlated**

Rotation ↗

n_e, pedestal ↘

MSE J at “well” ↗

$J_{pedestal}$ ↘



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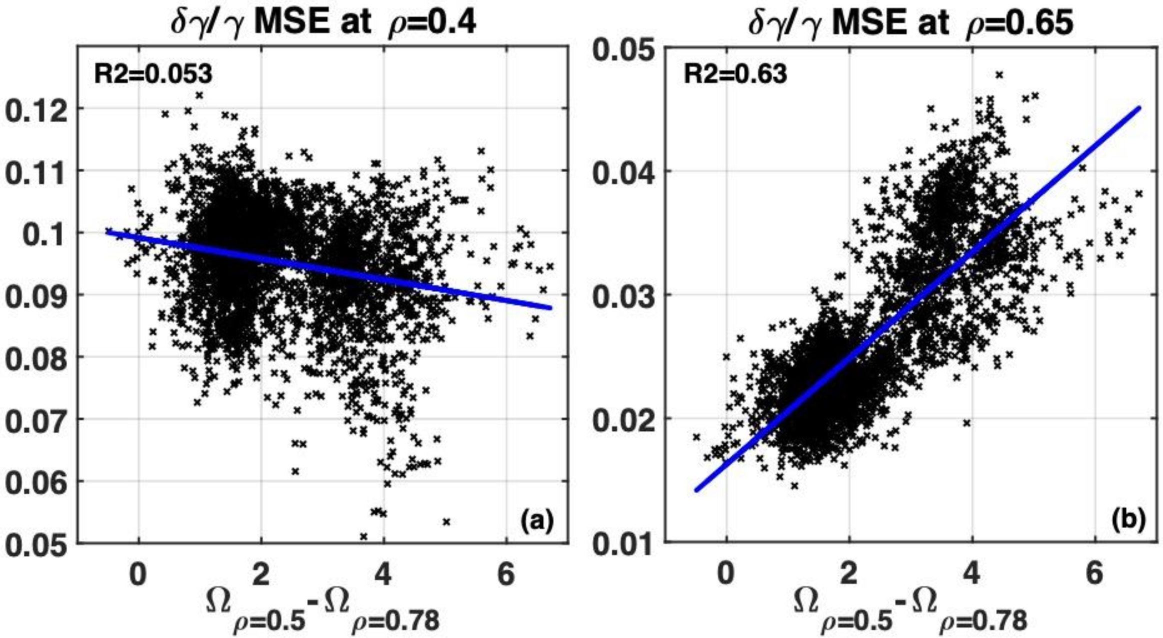
Current and Rotation Are Also Correlated in the Global Database – raw data

- **If you don't see an effect in the raw data, it does not exist**

- **Raw MSE data show that Ω and $\Delta\Omega$ are correlated in the IBS database**



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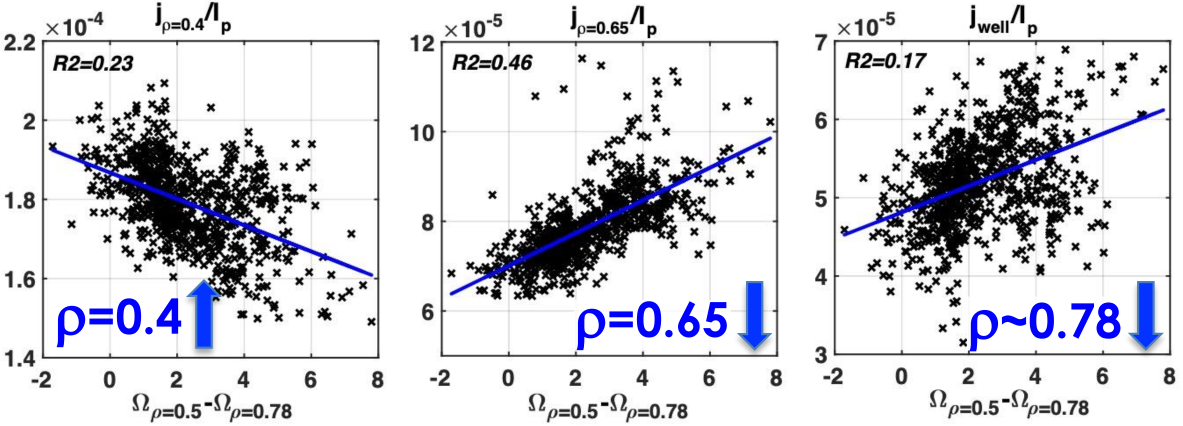
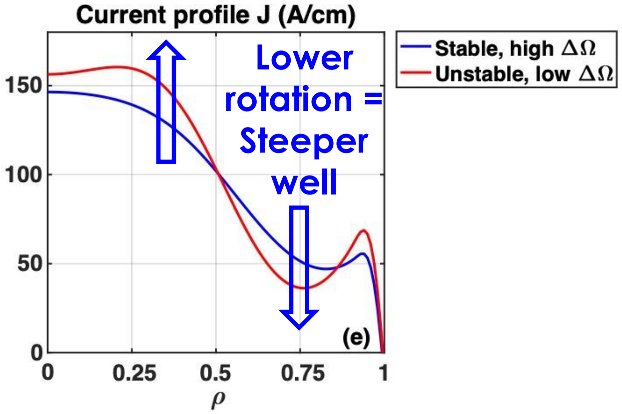
Current and Rotation Are Also Correlated in the Global Database – raw data and J (efit) reconstructions

- ***MSE constrains the core, magnetics the pedestal***

- ***The total plasma current Ip is fixed → lower J in the "well" requires higher J in the core***





Stability: more on current profile

The Current Profile of the ~330 IBS Shots can be Reconstructed and Correlated with Stability and Global Quantities

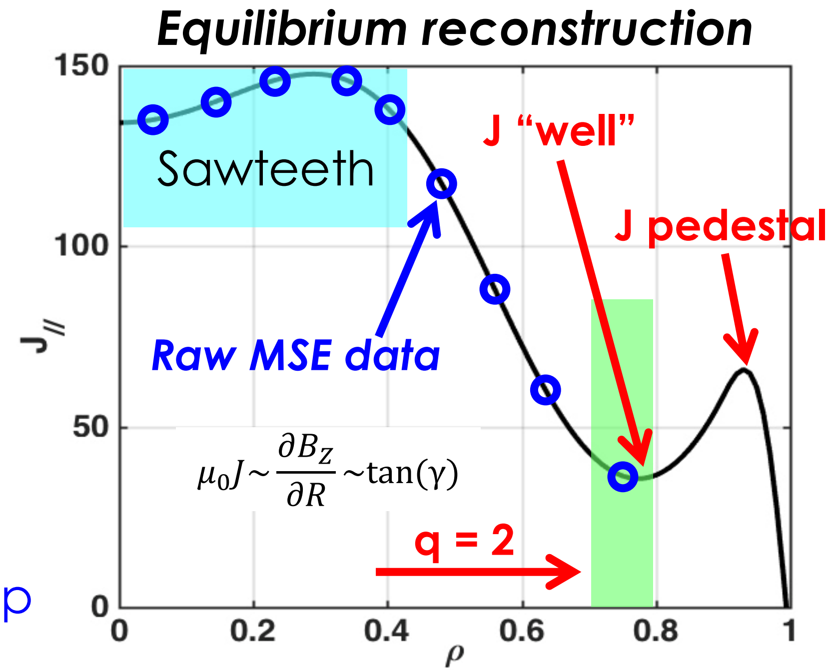
- **Local current density measured by raw MSE data**

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

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

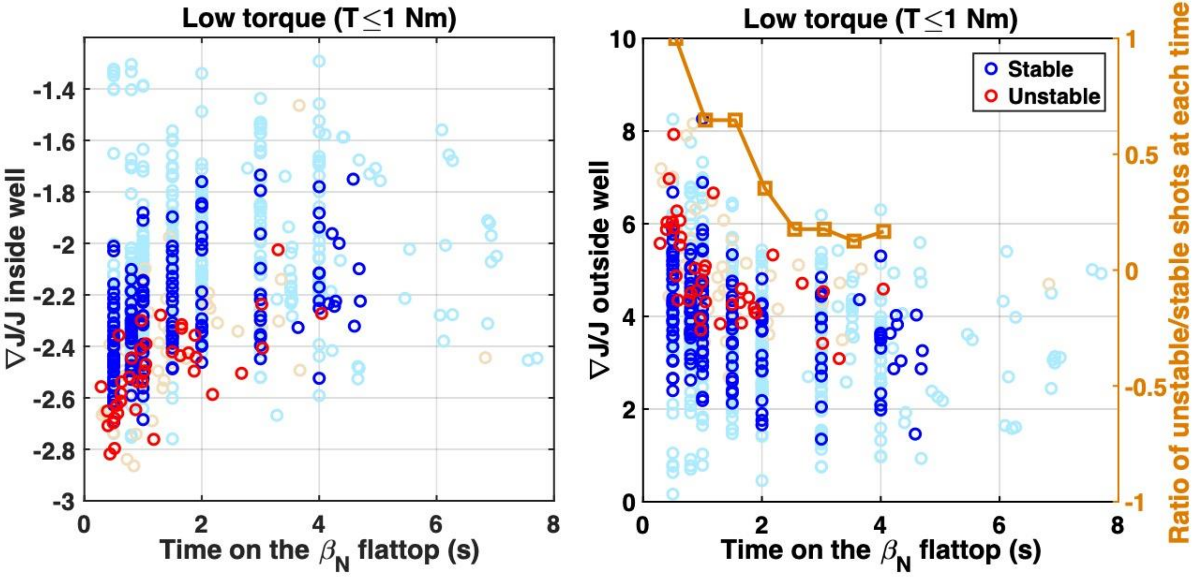
→ MSE constrains the core up to ρ~0.8

- Unstable = at time of 2/1 mode onset
- Stable = stable time slices on the β_N flattop (stable + unstable before mode!)



Separation and Its Evolution Are Independent from the Applied Torque

- **Low torque shots tend to be more unstable**
- **They start, and stay, predominantly in the higher ∇J regions**



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

Represent the Evolution with Gradients Inside and Outside the J "well"

- It takes 1.5-2 s for the current profile to reach equilibrium
- Both J_{ped} and J_{well} grow, but they evolve toward a shallower "well"