SENSITIVITY OF TEARING MODE BETA LIMTIS TO ROTATION AND CURRENT PROFILE

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and DIII-D, JET and NSTX teams

Schematic layout of top and bottom banners (about 5 ft wide)

…being professionally drafted…

Abstract

GENERAL ATOMICS

Tearing mode beta limits depend on a complex balance between pressure gradient 'neoclassical' drives, small island threshold effects, external triggers and underlying classical tearing stability, Δ'.

In this study, the threshold physics is probed by:

- **deploying different types of *error fields* on NSTX & DIII-D to vary the plasma *rotation profile***
- **different forms of *current and heating ramp-up* on JET to vary the *current profile***

Results suggest changes in the intrinsic tearing stability play a major role in governing beta limits, and can be affected by variations in the current profile or the rotation shear at the q=2 surface

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Underlying Physics

Tearing drives & sinks described by modified Rutherford Equation:

$$\frac{\tau_r}{r}\frac{dw}{dt} = r\Delta' + r\beta_P\left[a_{bs}\frac{w}{w^2+w_d^2} - \frac{a_{pol}}{w^3}\right]$$

a_{pol} from ion polarisation currents

w_d from finite island transport leading to incomplete flattening of pressure

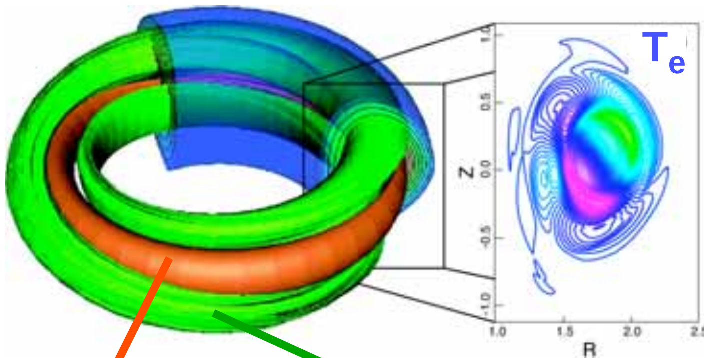
Classical tearing stability - usually negative and stabilizing for NTM

Bootstrap: main drive for the NTM

w_d, a_{pol} terms stabilise mode at small island size

Leads to trigger requirement (a seed) for mode

- **Current profile governs basic 'intrinsic' tearing stability**
- **Rotation can enter through several mechanisms:**
  - Shielding out trigger perturbation
  - Change intrinsic tearing stability
  - Small island effects e.g. a_{pol}



n=1 perturbed pressure

n=2 perturbed current

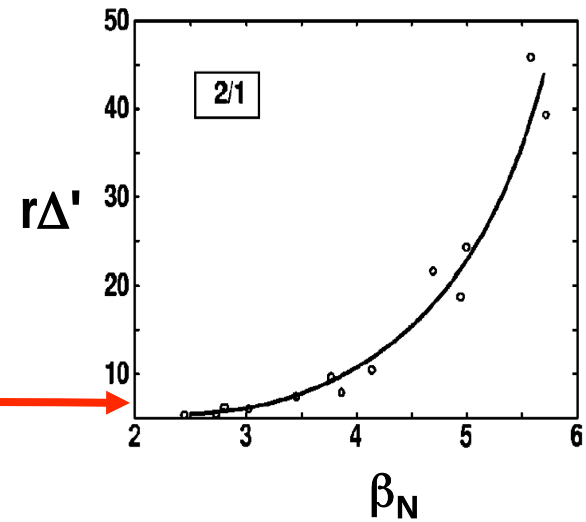
[NIMROD, Brennan]

Highest β Limits May Be Governed by Pole in Δ’
– *Introducing dependency on current and flow profiles*

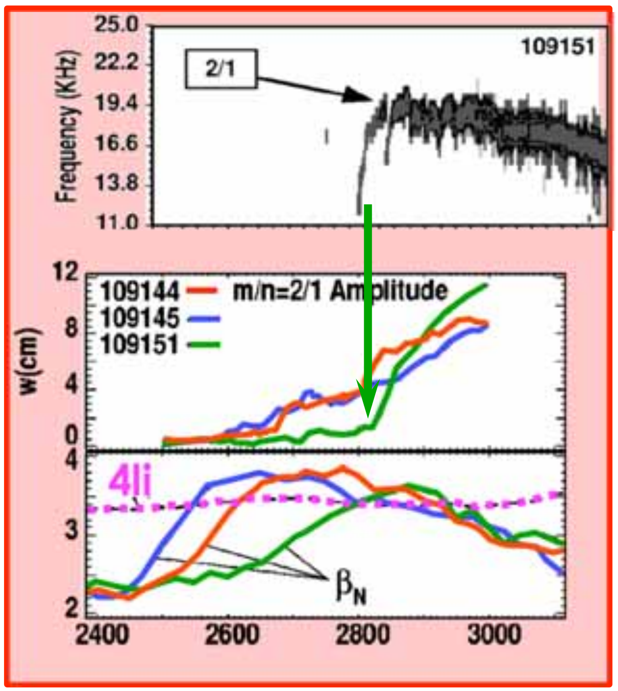
- **Calculations show Δ' rises as ideal β limit approached**

Seedless 2/1 modes observed as β_N crosses ideal no-wall limit

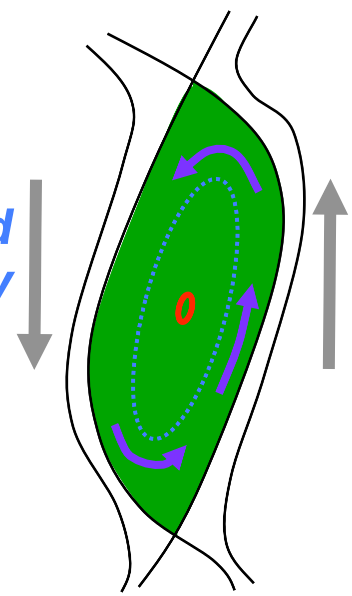
- ***Current profile governs baseline Δ’ & gives means to raise thresholds***



[Brennan et al, PP10, 1643]



- **Island stability may also be modified by flow shear:**
  - *Viscous coupling distorts island structure changing free energy*

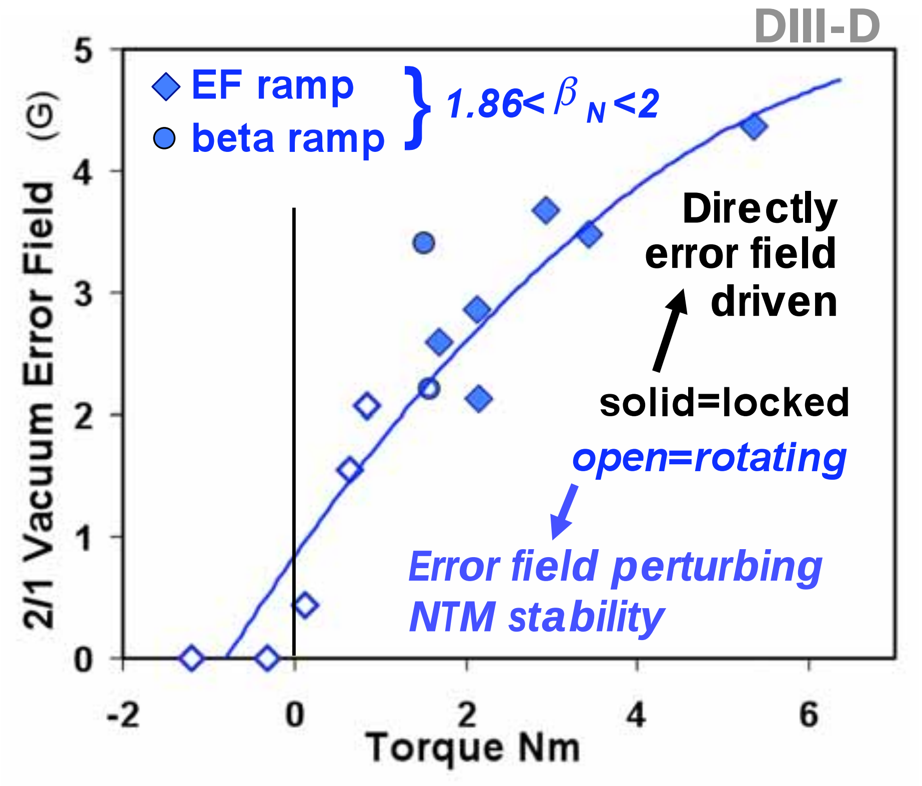


- **Error fields can perturb flows in the plasma**
  - *Response to error fields may depend on plasma stability ← β_N ,Δ'*

Role of Error Fields & Plasma Rotation

How do Error Fields Interact with Plasma?

DIII-D experiments show <u>resonant</u> error field can act through two mechanisms to drive modes in high β plasmas:



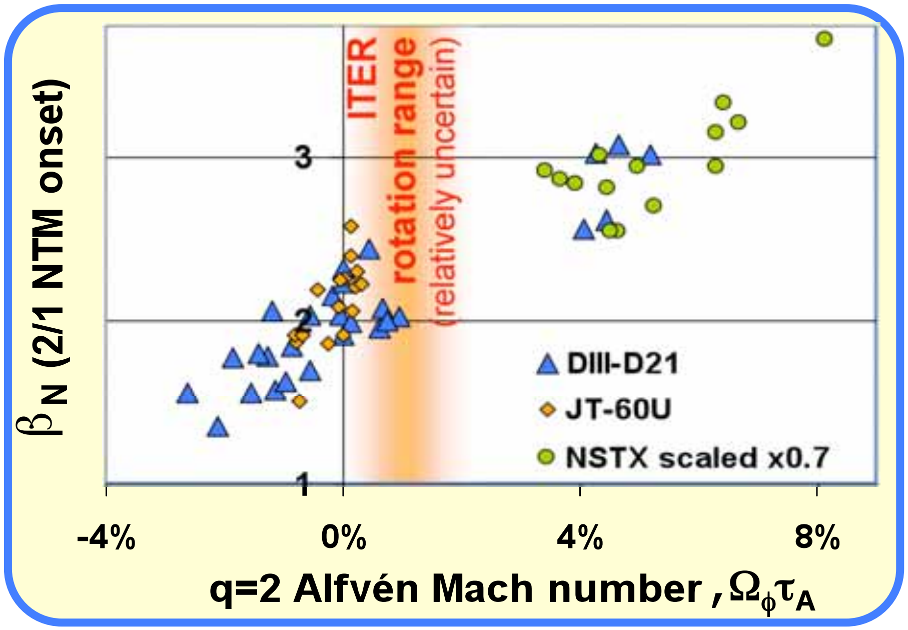
- **Locked modes:**
  - **Influenced by proximity to**
    - **ideal kink beta limit?**
    - **classical tearing limit?**
  - **Role of rotation?**
- **Rotating modes:**
  - **EF perturbing classical or neoclassical stability?**
    - **Action through rotation or rotation shear?**

→EFs can probe NTM physics

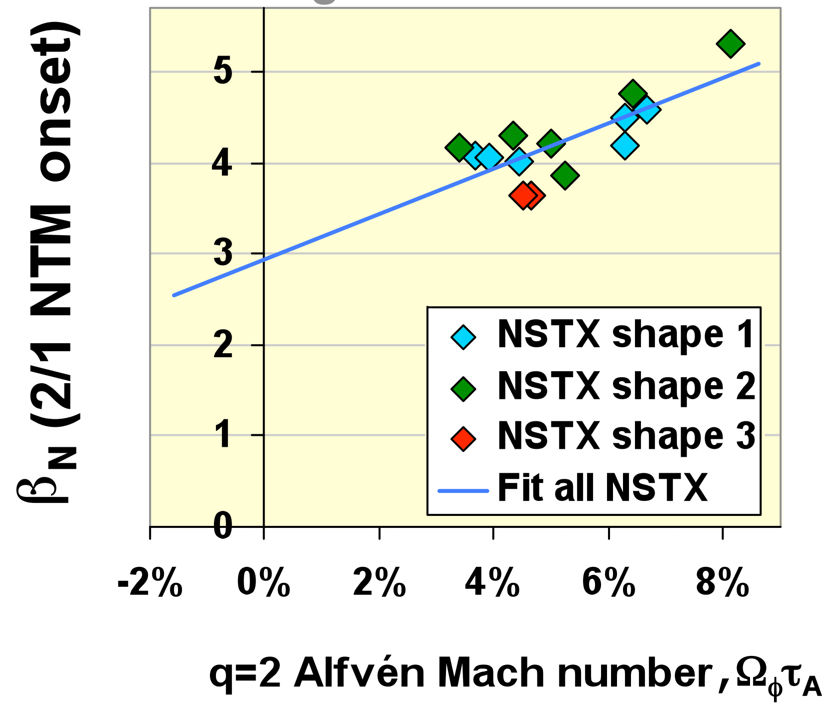
→Measure error field response & correction requirements…

NSTX Studies Have Shown a Rotation Effect in Error Field Interaction & Impact on NTM β limit

- **n=3 braking showed 2/1 NTM thresholds rise with rotation**
  - Consistent with rotation trends from beam mixing studies on DIII-D & JT-60U:



NSTX: n=3 braking perturbs rotating 2/1 NTM beta limit



→ ***How is rotation acting on NTM stability?***

→ ***What are practical error field limits?***

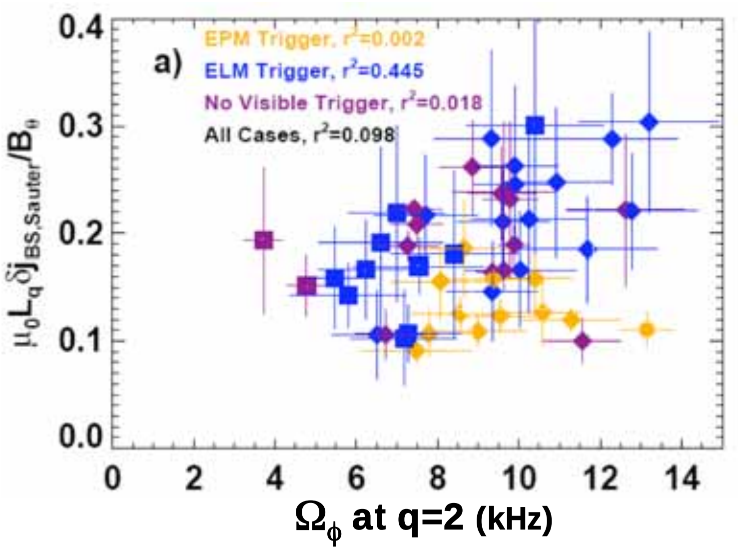
NSTX Database Study Suggested Rotation Acts Through the Local Rotation Shear at the Island

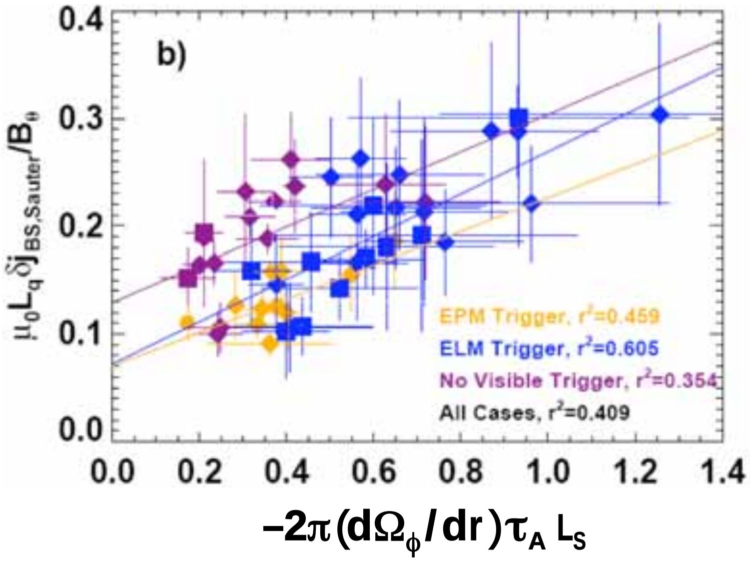
- **Gerhardt analysis[1] compared trends for different types of NTM trigger across NSTX 2007 campaign**
  - no n=1 braking in this data set

Goal 2009: Controlled study of error field effect in constant conditions:

- Decouple rotation roles further with n=1 and n=3 fields
- Learn about error field interaction

- ***Achieved reproducible scans by tuning H mode:***
  - shape, gas, lithium





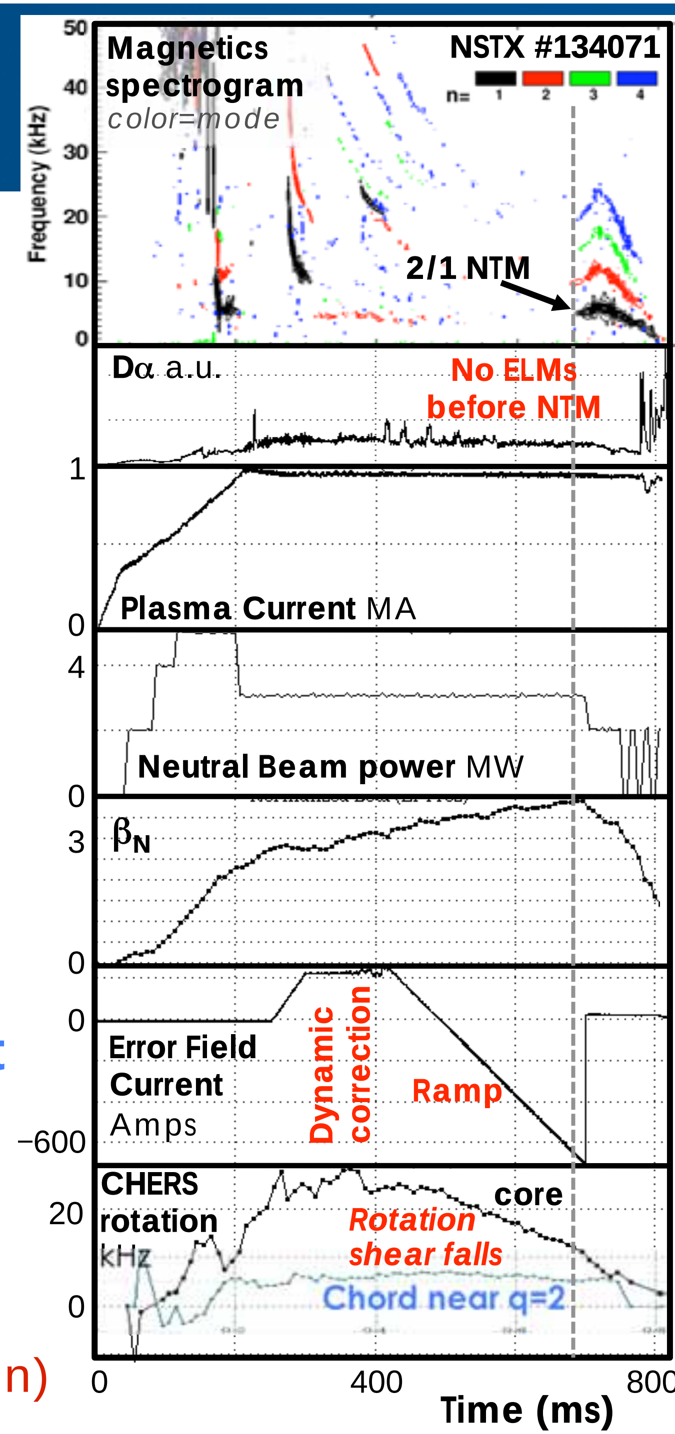
[1S.P. Gerhardt, NF (2009) 032003.]

New NSTX Experiment:
Ramp Error Fields to Make Mode

- **Vary ratio n=1:n=3 fields shot to shot**
- **Typically ELMs are small (due to lithium)**
- **No clear NTM trigger in most shots**
  - **'Seedless' – must be Δ' triggered**

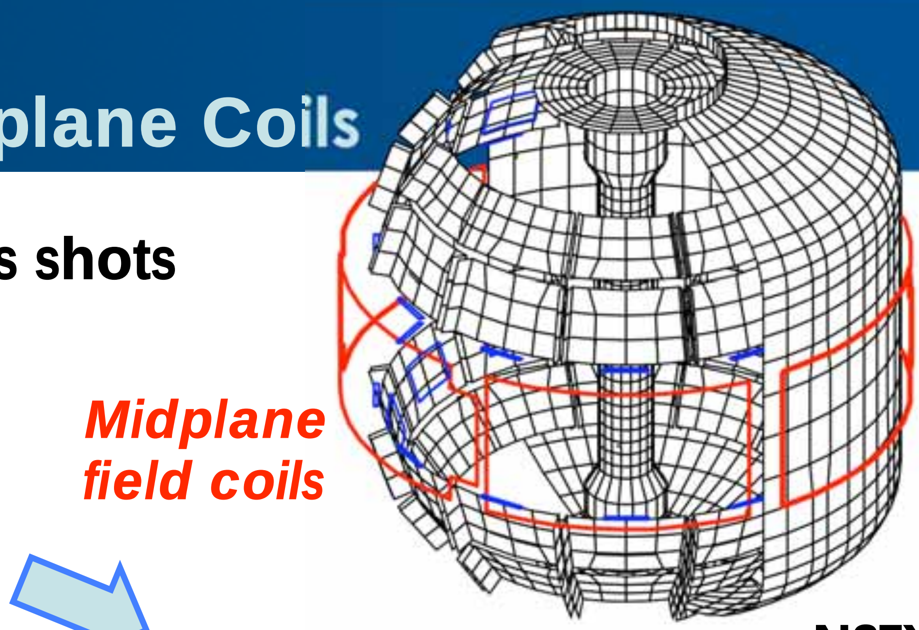
Other shot details:

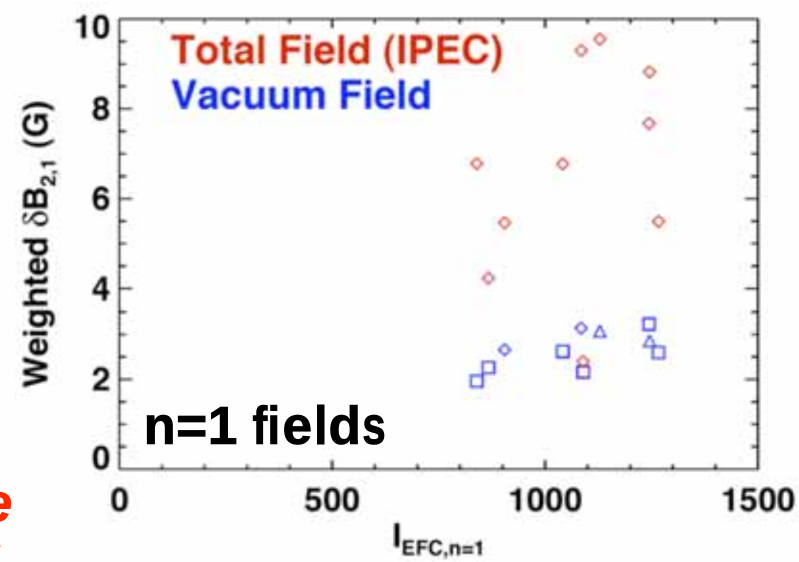
- **Early strong heating for H mode**
- **MHD at 300ms when q=2 appears**
- **Reproducible conditions & front end to eliminate q profile changes shot-shot**
  - From evaporating lithium each shot
- **But note q relaxing towards q=1 (when bad MHD would occur)**
  - (Role of q_{min}=1 with EF under investigation)



Applied Error Fields
Mix of n=1 & n=3 from Midplane Coils

- **n=1 field computed for various shots across the scan:**
  - **Vacuum field** is ~2.5G/kA (m=2 n=1 at q=2 surface)
  - Including plasma response from other surfaces (**IPEC**) raises **total field** at q=2

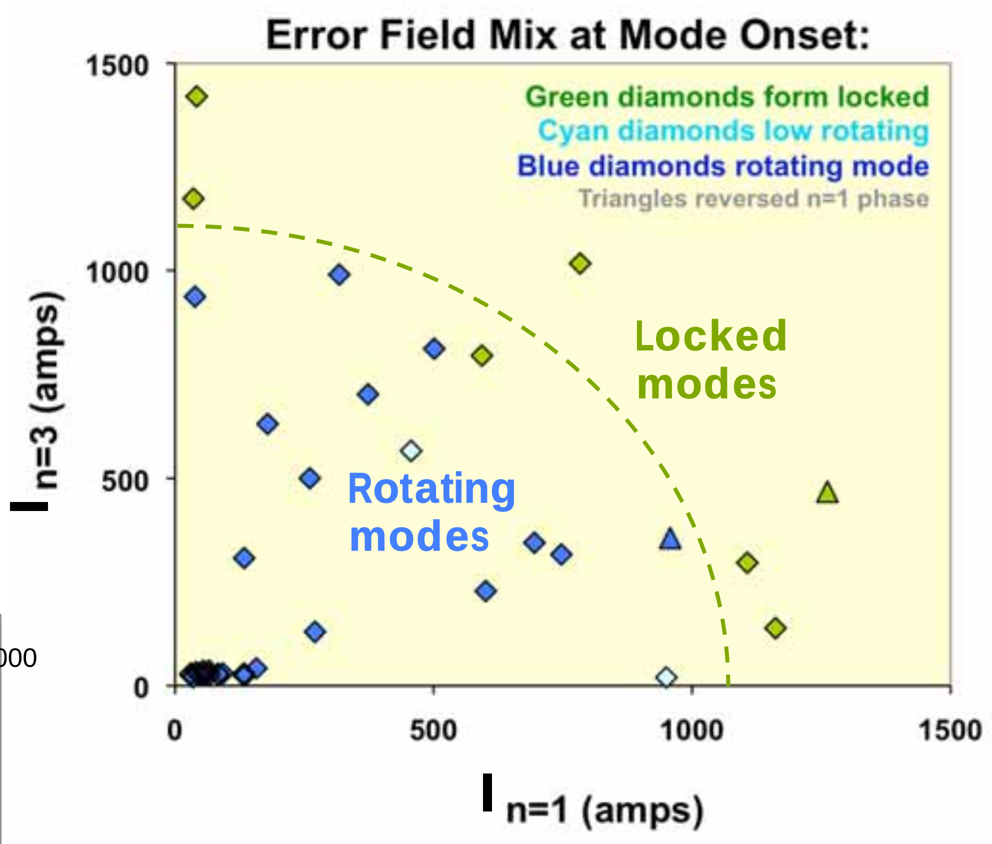


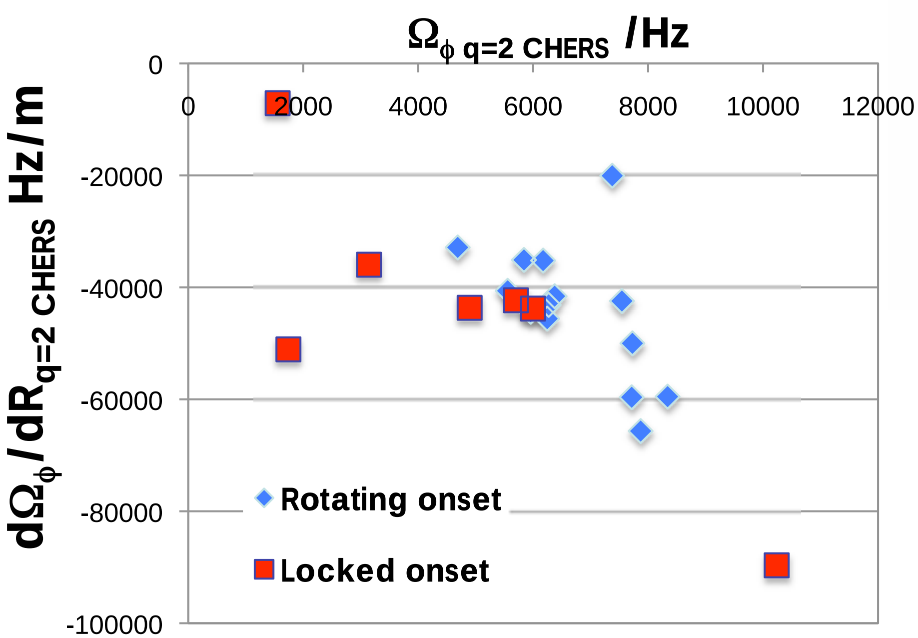


- **n=3: no similar formalism to compare size (as non-resonant)**
  - Typical surface averaged |B| is a few Gauss
  - ***But may be best to compare relative magnitudes in terms of coil currents!***
    - *Gives better idea of relative field strengths*

New Experiments Perturbed β Limit with Wide Range of Resonant n=1 & Non-resonant n=3 Fields

- **n=1 and n=3 fields varied up to locked mode limits (◆)**
  - Locked mode threshold with roughly equal levels of n=1 and n=3 field current
  - Wide variation in rotation profile achieved:

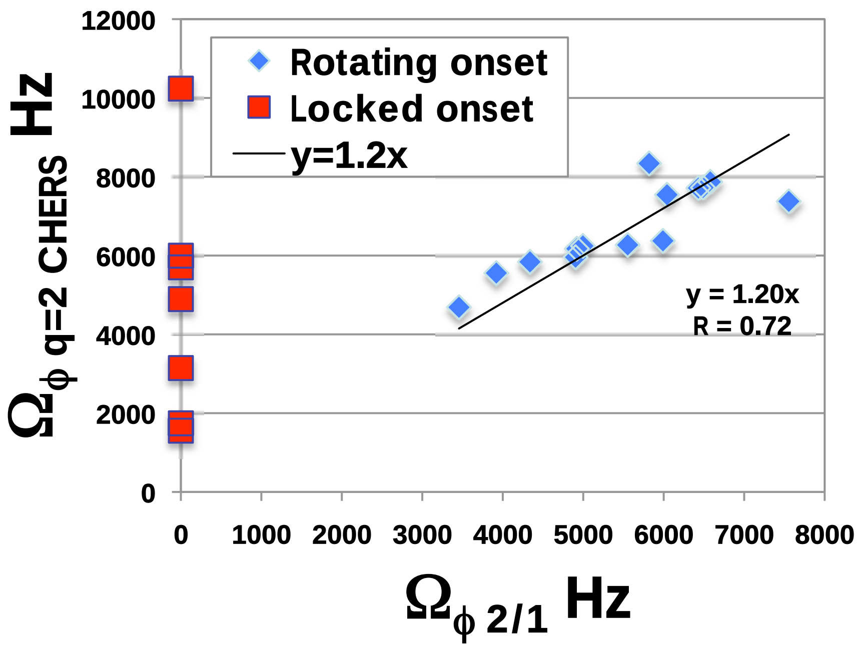


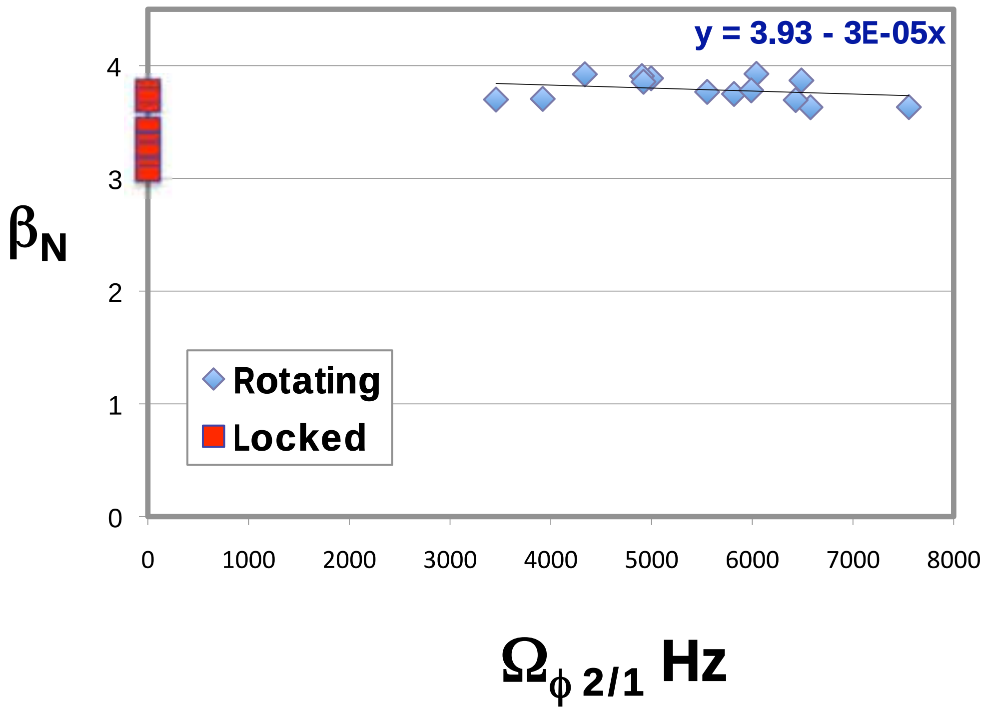


  - Locked modes much slower on CER but not at zero rotation

Differences in CHERS q=2 and 2/1 mode rotation

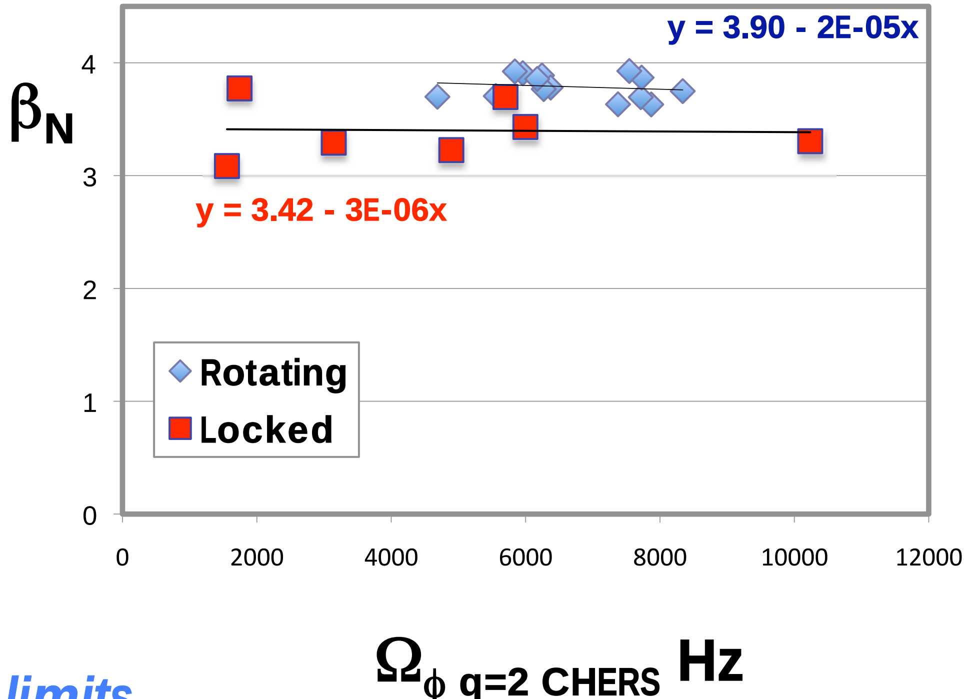
- **Mode forms locked while CHERS shows plasma rotating**
  - **Actual mode onset rotation is lower than CHERS**
    - Coupling to ELMs?
  - **Locked mode stops MHD fluid while plasma still flows**





Mode Forms at Lower β_N when Locked

- **Locked mode threshold is 0.5 lower in β_N**
  - May be partly confinement reduction
  - stripped out for rest of this analysis (J-KP analyzing locked mode physics[1])

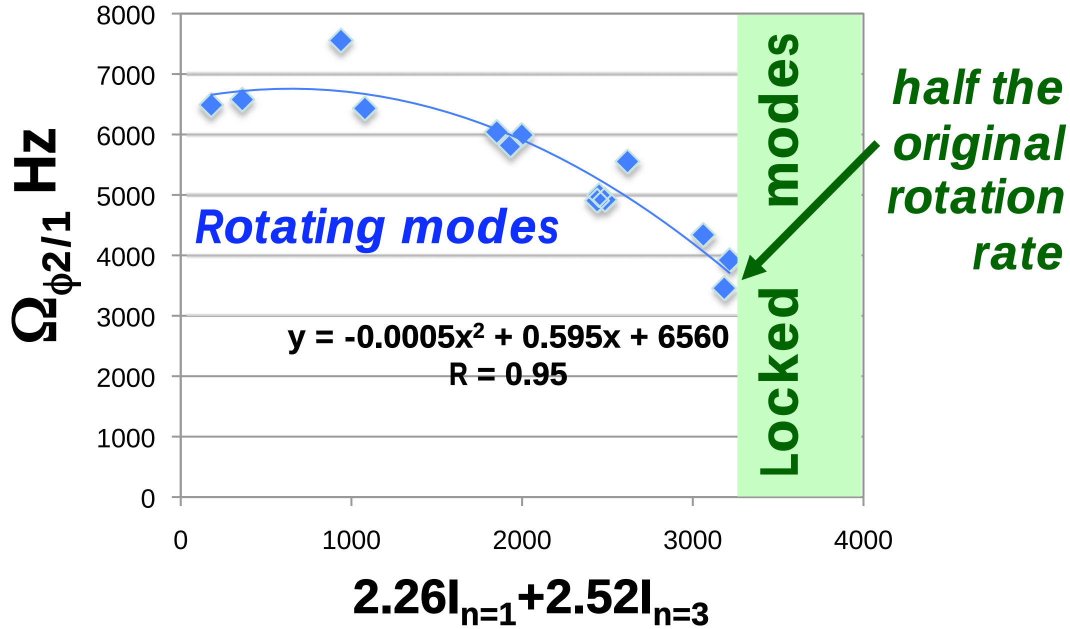


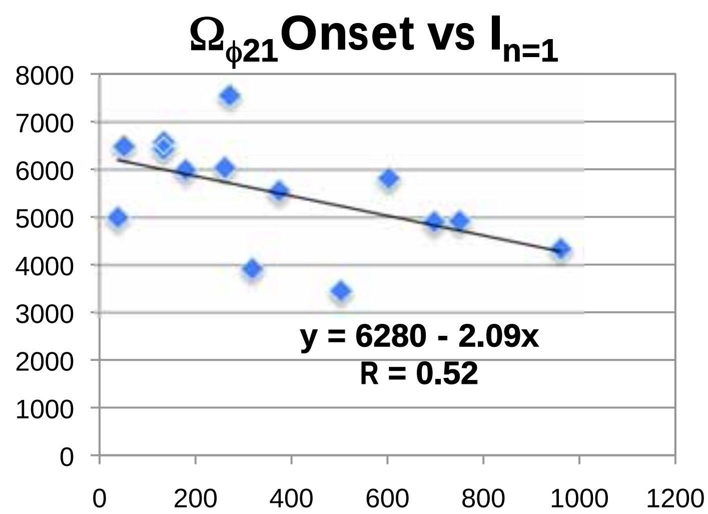
- **Rotating mode shows no rotation dependence!**
  - *Generally below no-wall β_N limits*
  - ***But need to look at drives in local parameters & understand what we really varied***
    - ***How does braking impact rotation and mode drives?***

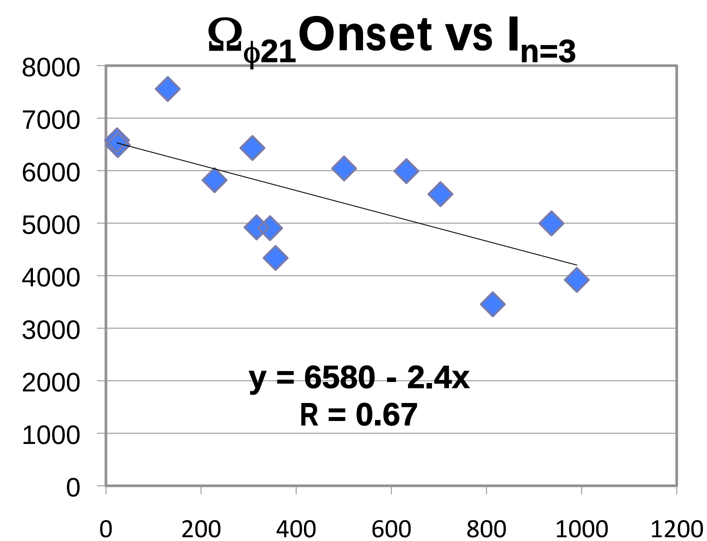
[1Poster: PP8.00051, Jong-Kyu Park]

Braking Effect:
n=1 & n=3 Contribute Similarly to Braking

- **Both n=1 and n=3 brake plasma**
- **Best fit is combination of similar levels of n=1 and n=3 currents:**
    - $\Omega_{\phi 21} = 7500 - (2.26 I_{n=1} + 2.52 I_{n=3})$
  - *Good correlation for braking:*



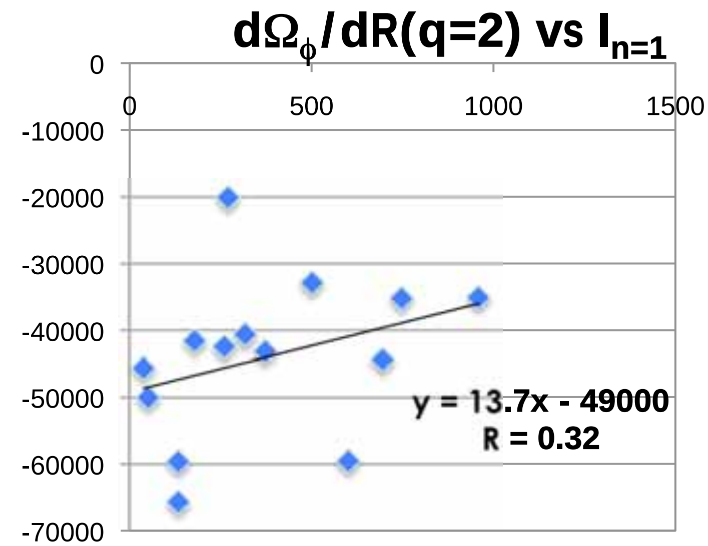


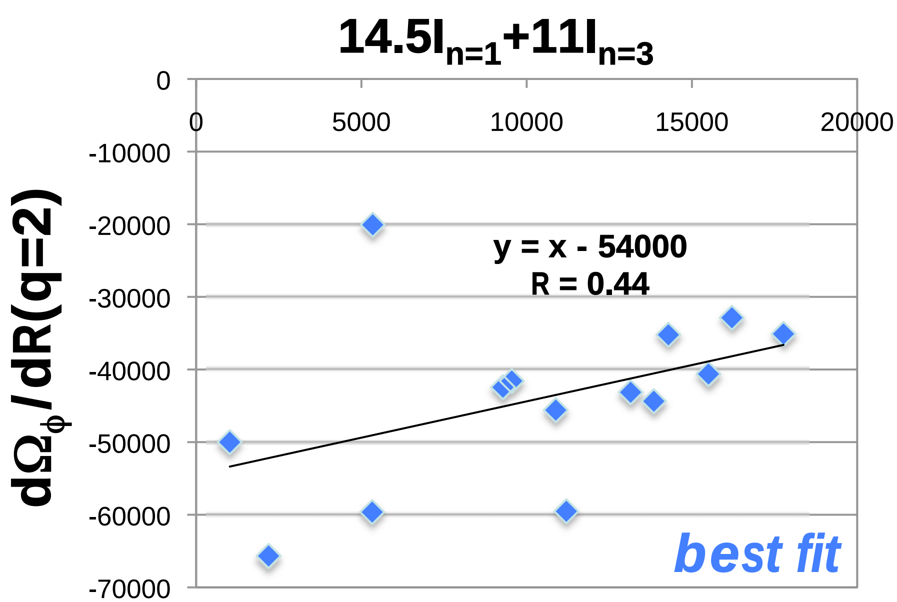


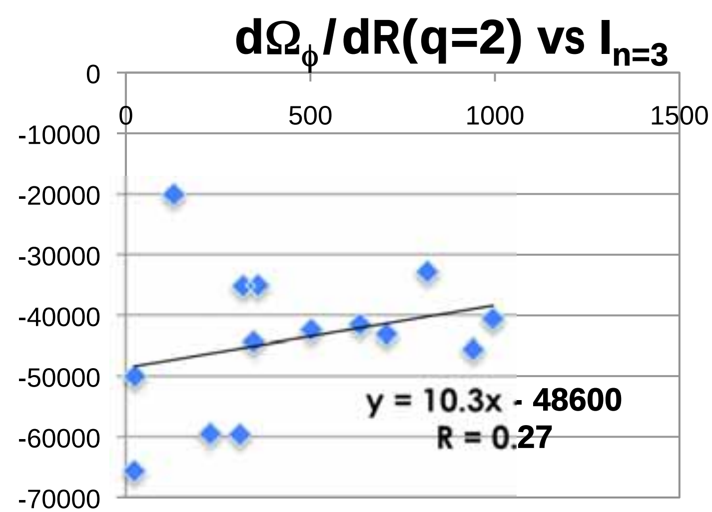
✓ ***Matches Fitzpatrick theory: Penetration at half natural rotation rate.***

Rotation Shear Much More Variable Over The Scan
– provides opportunity to decouple from rotation trend

- **Rotation shear more scattered than simple dependence on n=1 & n=3**
  - **Although both forms of braking reduce rotation shear – *best fit:***
    - $d\Omega_{\phi 21}/dR = -54000 - (14.5 I_{n=1} + 11 I_{n=3})$
  - **Can decouple rotation shear from rotation effects – *which governs NTM?***







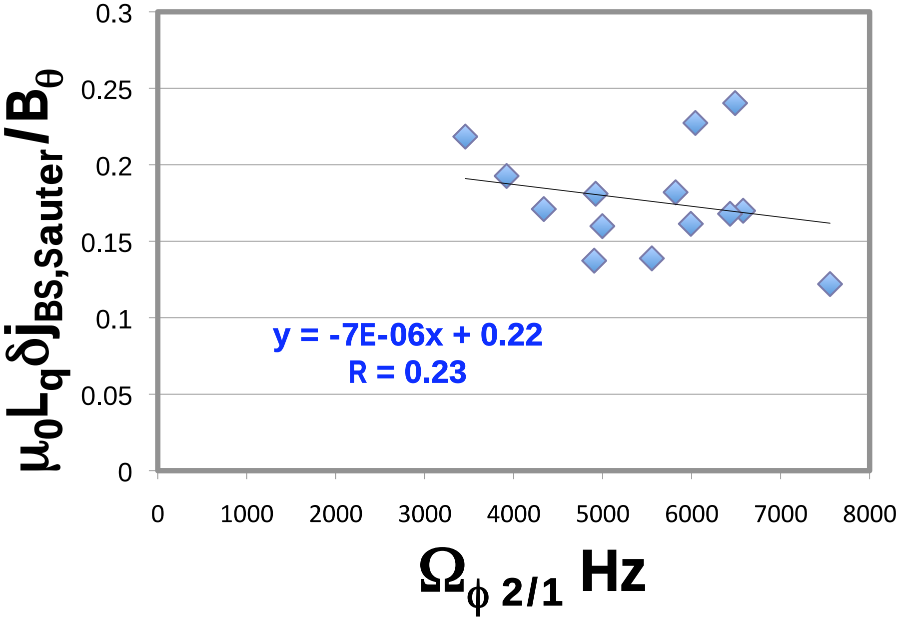
Bootstrap Drive Measure of NTM Threshold Suggests Dependence Through Rotation Shear

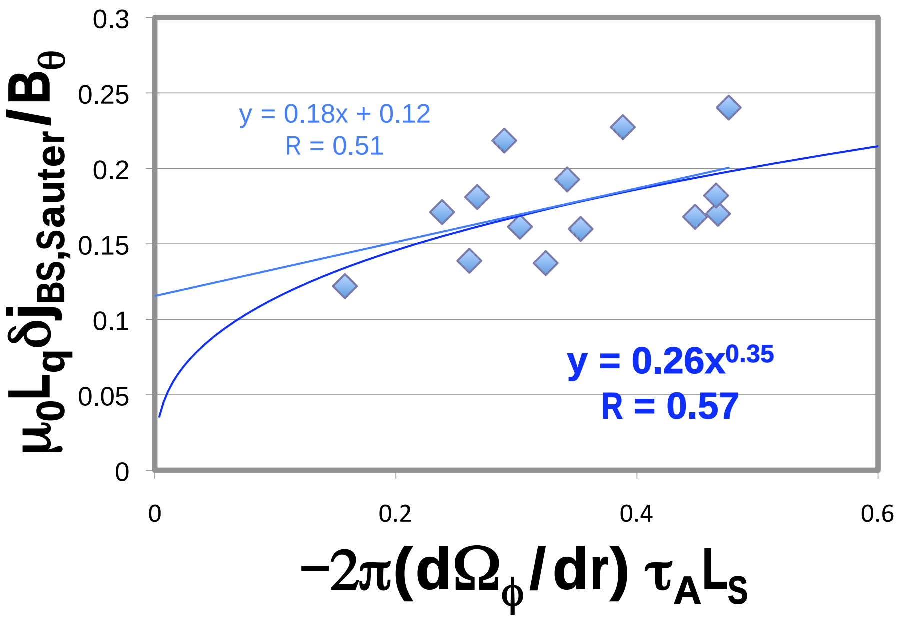
- **No measurable trend with rotation!**
- **Weak positive correlation with normalized rotation shear**
  - **Lowest thresholds at low rotation shear**
  - **Highest thresholds at high rotation shear**
  - **Best 'fit' is power law**

This correlation in the 'most noisy' parameters suggest physics is right:

  - ***Rotation impact is through shear changing Δ'***

- **No correlation if fit β_N instead**
- **Fit vs rotation & rotation shear offers little improvement**





Conclusions on Rotation & Error Fields

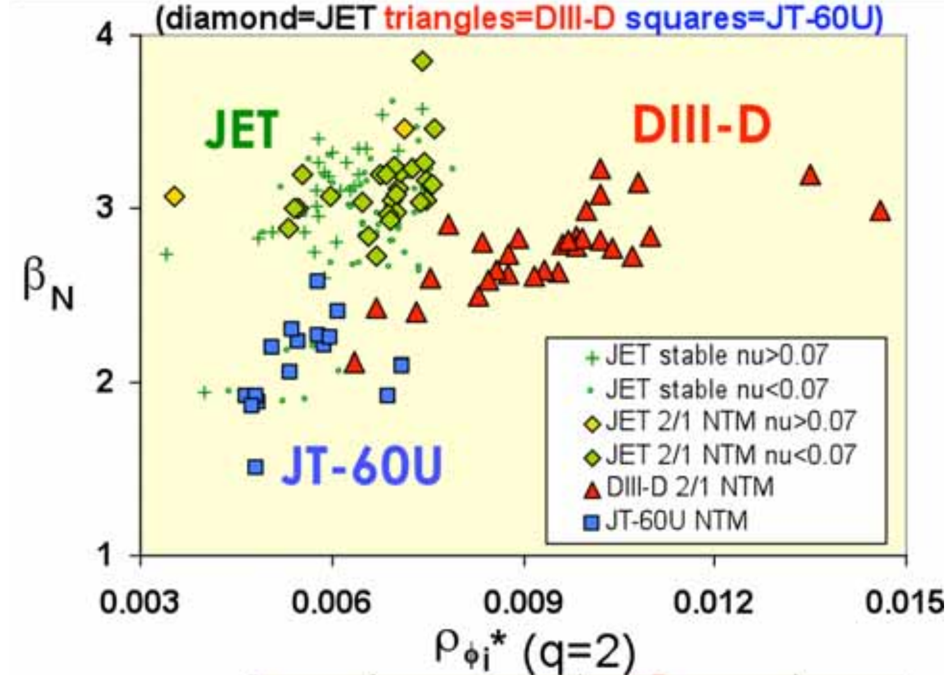
- **NTM threshold dependence on rotation comes through flow shear impact at the rational surface**
  - Confirms previous database study in controlled conditions
  - Correlations with rotation completely stripped out!
    - *Suggests changes to inherent plasma stability at the tearing resonant surface play an important role in determining mode onset*
- **Threshold between rotating & locked mode regime at half natural plasma rotation**
  - β limit for rotating modes reduced below this
  - Locked modes above this (à la Fitzpatrick)
- **Locked mode cases exhibit confinement degradation *before* mode onset, and have a lower β_N limit**
- **Both n=1 resonant braking and n=3 non-resonant braking have similar effects on plasma and mode**

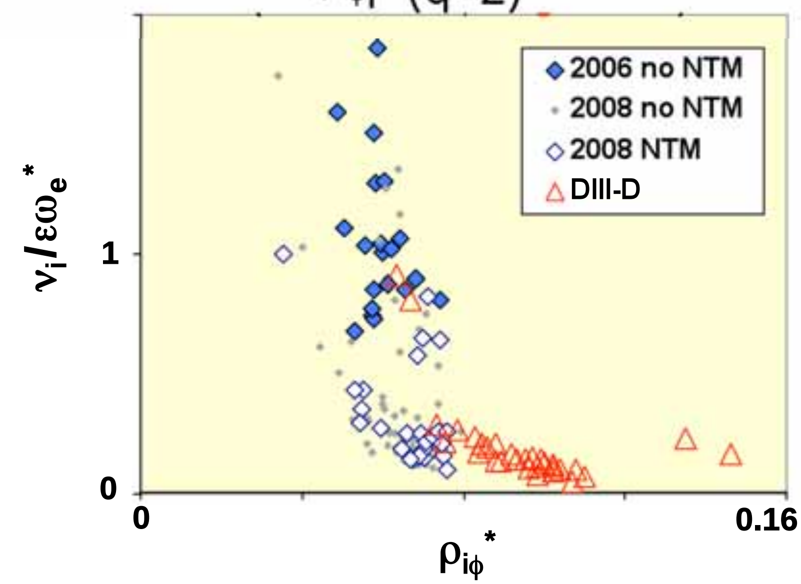
Role of the Current Profile

JET Hybrid Plasma Sit Above β Limit of Other Devices:
Other parameters coming into play – q profile?

- **JET sits above DIII-D and JT-60U trends**
  - **JT-60U lower rotation** →lower β_N
  - **But DIII-D high rotation**
- **Possible collisionality role? <u>No</u>:**
  - **JET unstable at ◆low ν^***
  - **But stable at +high and ∘ low ν^***

→**Collisionality provides 'access condition' for NTM**
  - **Enables q profile modification**
  - **Can change Δ'**
  - ***q profile is the parameter to test…***

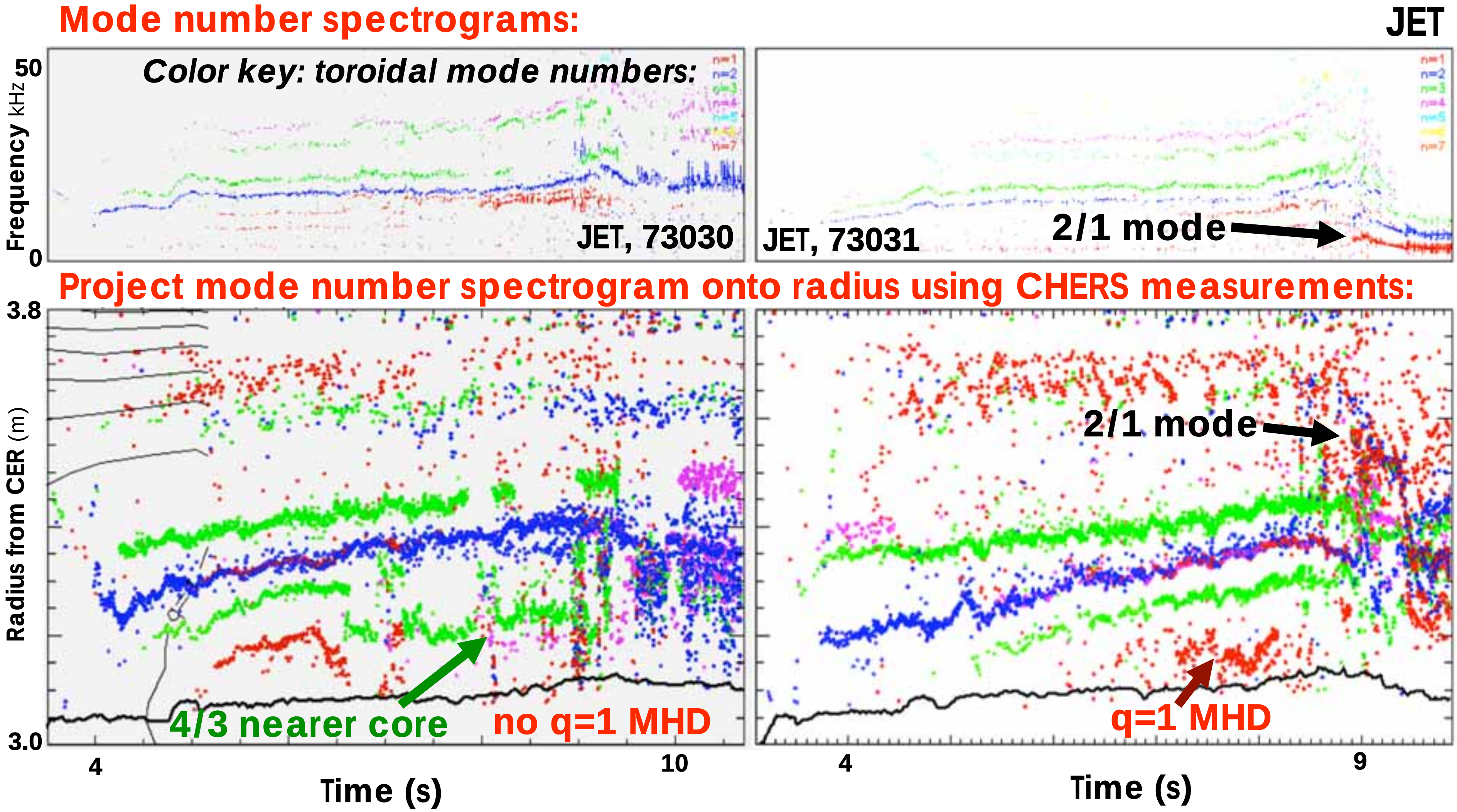




Difference in MHD Markers Indicates q Profile Change Correlating with NTM Stability Change

Mode number spectrograms:

Project mode number spectrogram onto radius using CHERS measurements:



➔ q_0 lower in 2/1 case NTM

Exploring q profile role in controlled scans

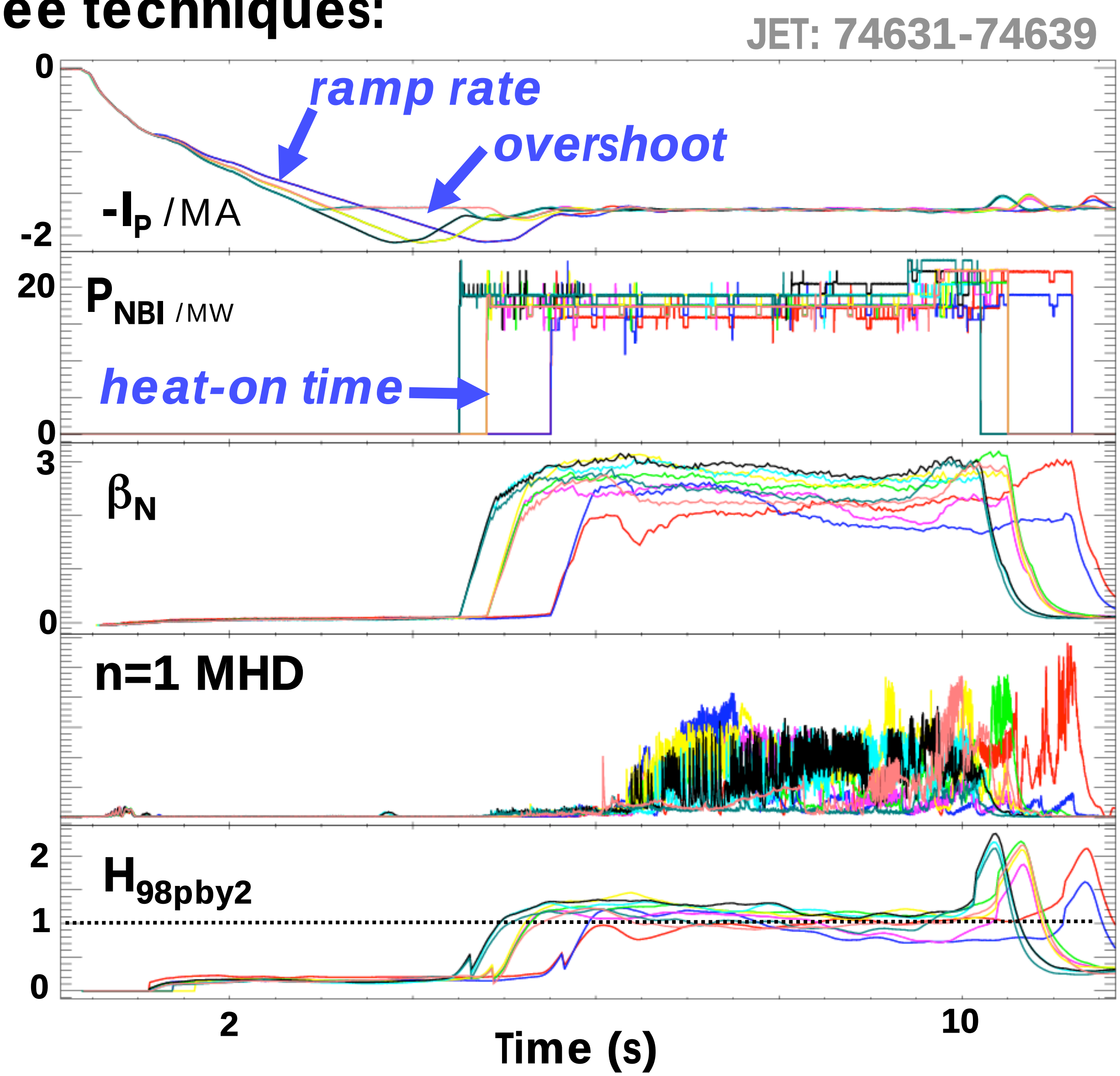
q profile varied with three techniques:

- current overshoot
  - J in 'outer third'
- I_P ramp up rate & beam-on time
  - q_{min} value

→ ***Impacts H factor***

These 'performance' shots skirted stability limit

→ ***Raise power to access 2/1 NTM…***

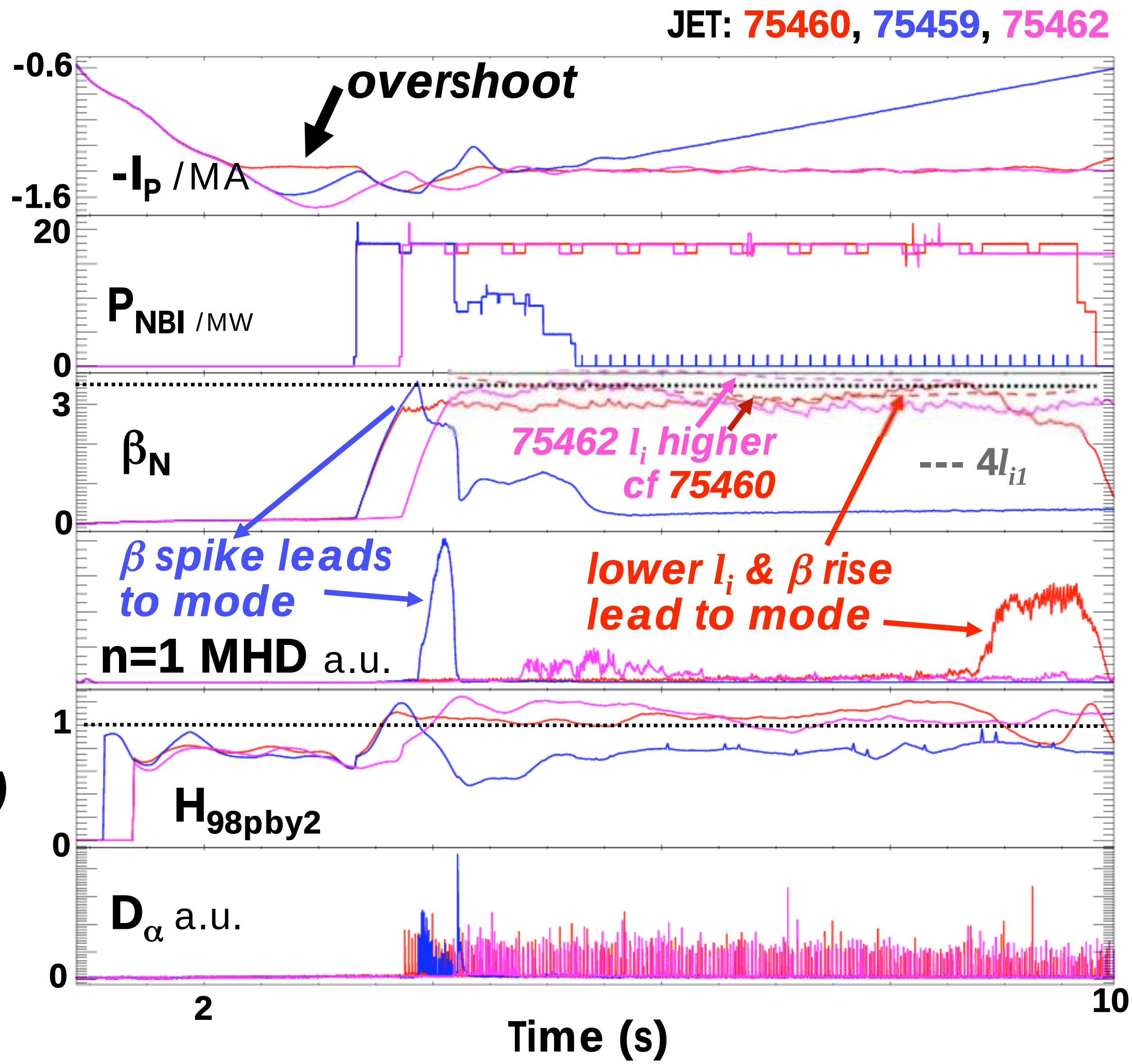


Discharges show a β_N threshold for the mode & q profile dependence (1: I_P overshoot scan)

Vary I_P overshoot

- *No overshoot:*
  - → *late mode as beta rises?*
- *Modest overshoot:*
  - → *prompt mode with ELM free high β_N spike*
- *Strong overshoot:*
  - → *No 2/1 mode despite early high β_N*

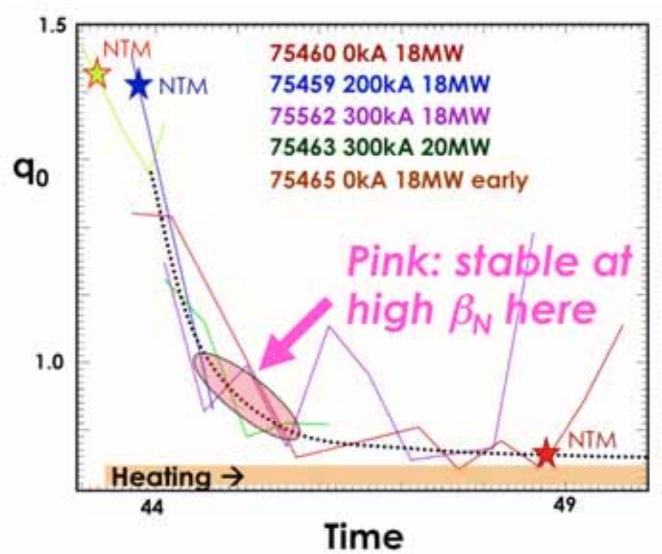
→ ***q profile effect on stability (red cf pink)***

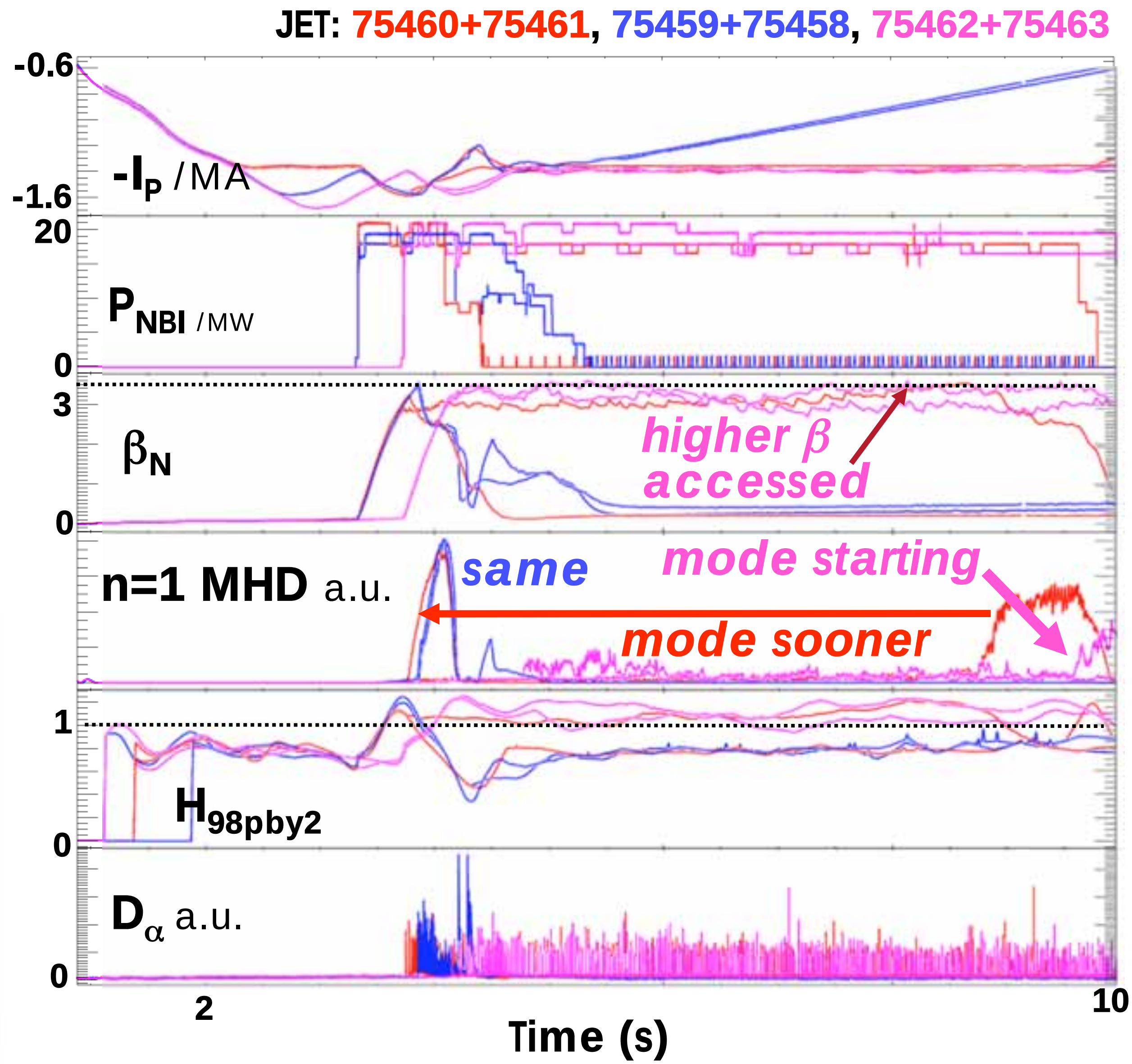


FYI: JET q profile evolves on timescale of seconds, once a strongly heated plasmas is established

Discharges show a β_N threshold for the mode & q profile dependence (2: with increased power)

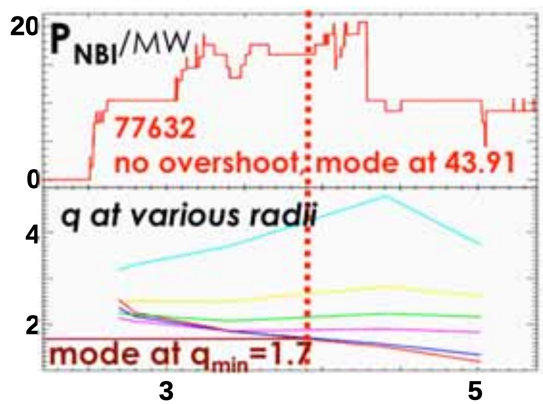
- ***No overshoot:***
  → ***mode sooner as β_N higher***
- ***Modest overshoot:***
  → ***no change same β_N trajectory***
- ***Strong overshoot:***
  → ***Mode at previously stable β_N, once q profile evolved:***

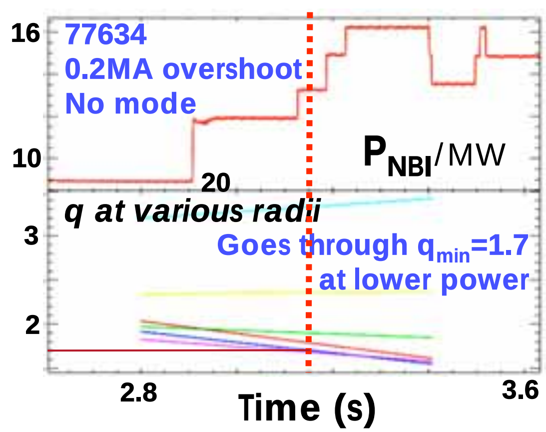


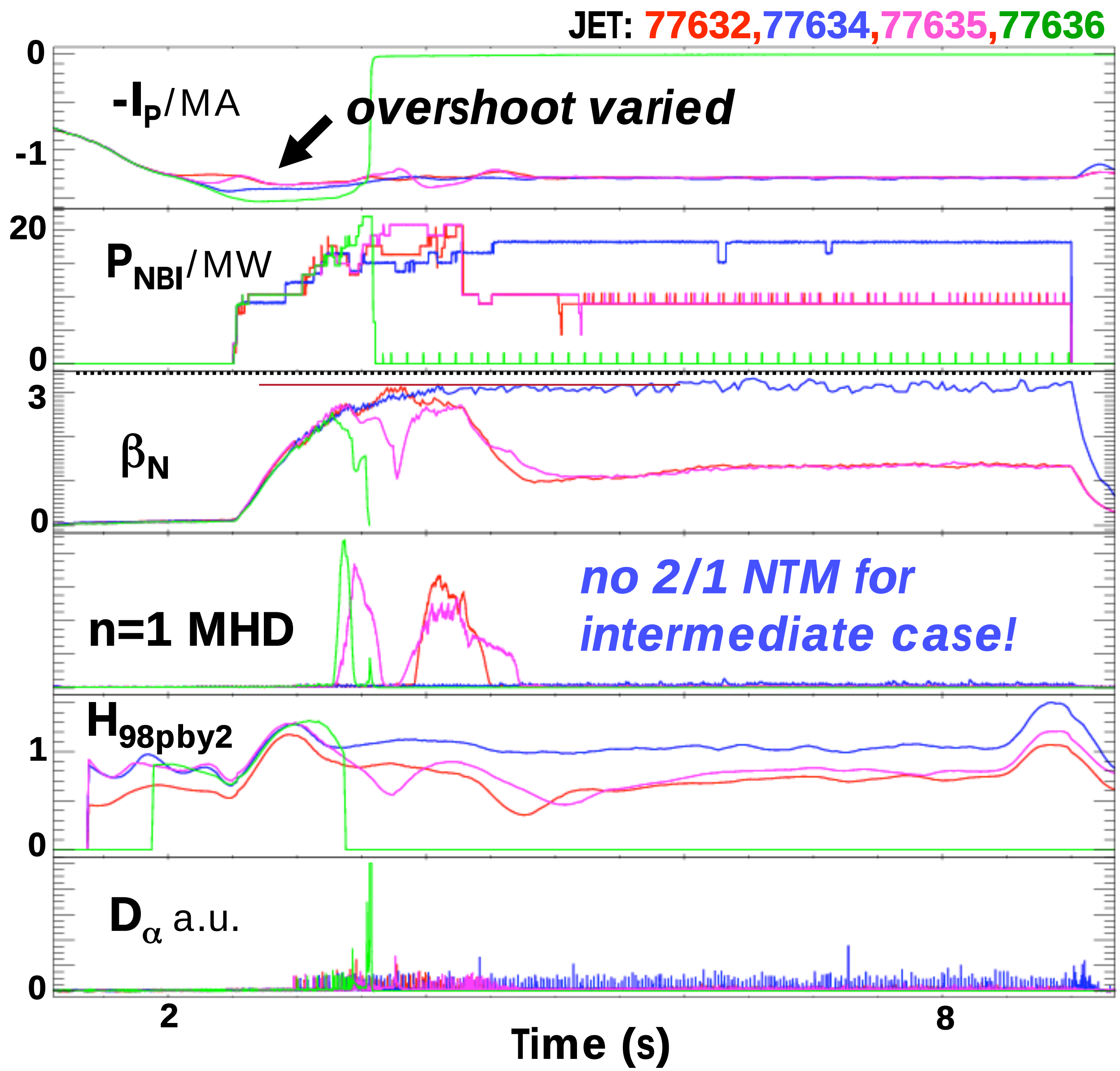


Possible Optimal Degree of Current Overshoot

- *Beta feedback to avoid peak in ELM free phase*
- **MSE data limited**
  - *q_{min} time history may play role:*

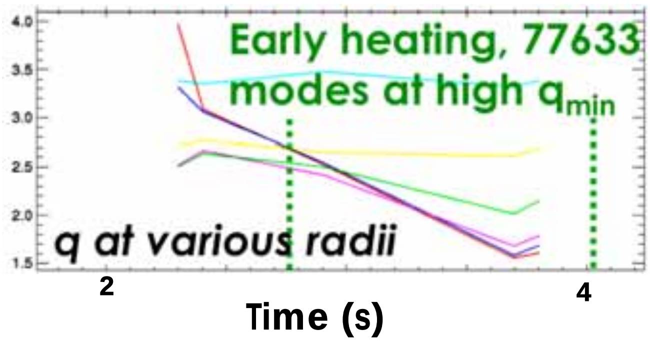




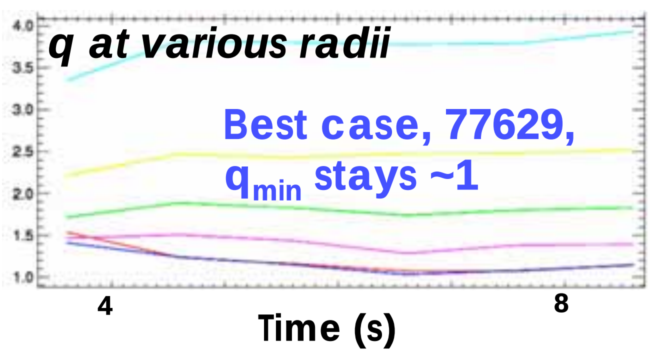


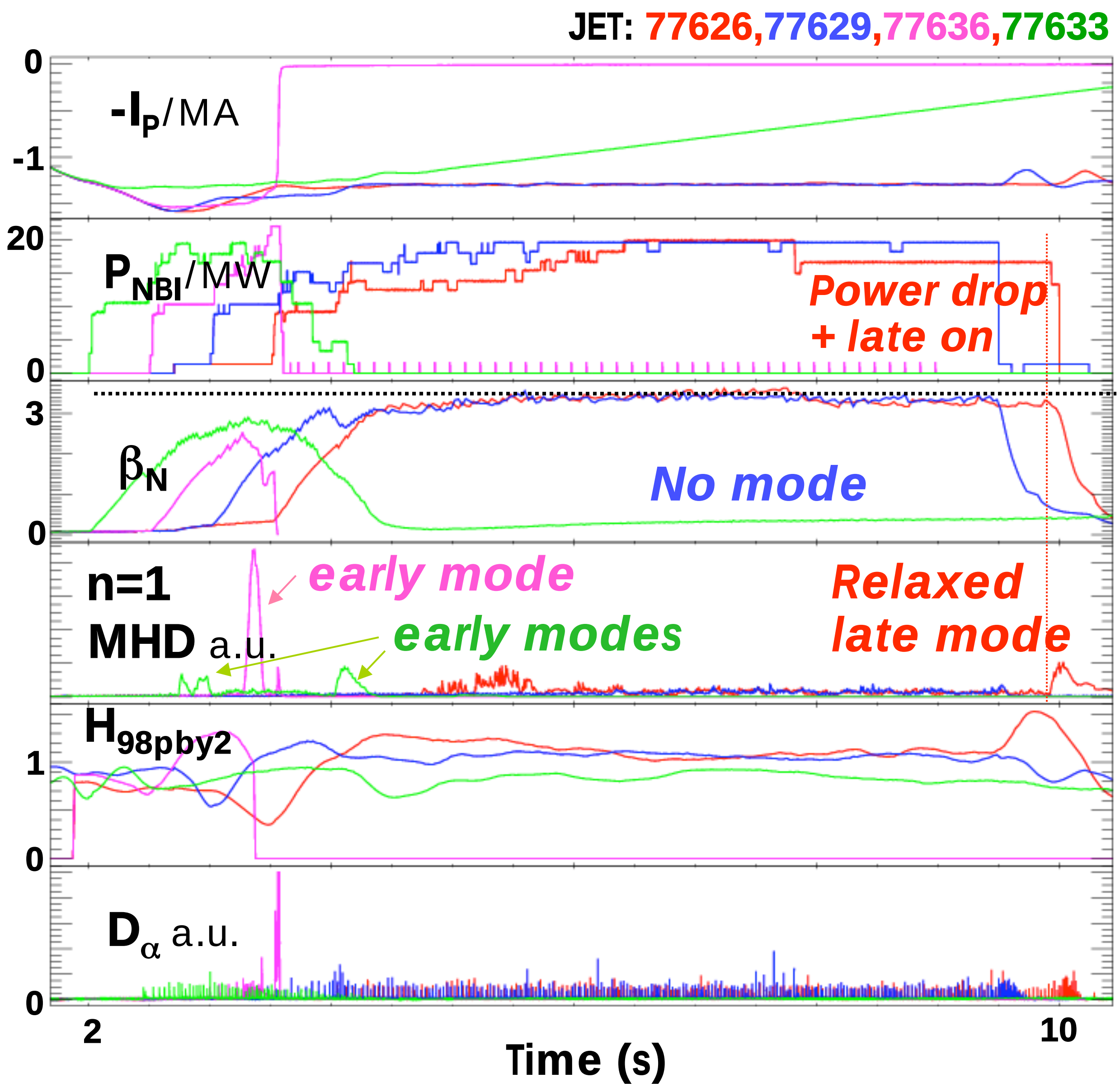
Heating timing scan shows 'just right' degree of relaxation needed

- **Mode if profiles too 'advanced':**



- **Fully relaxed plasma also less stable**
  - Mode at lower β_N or occurs later





Conclusions on q Profile Role & Generally

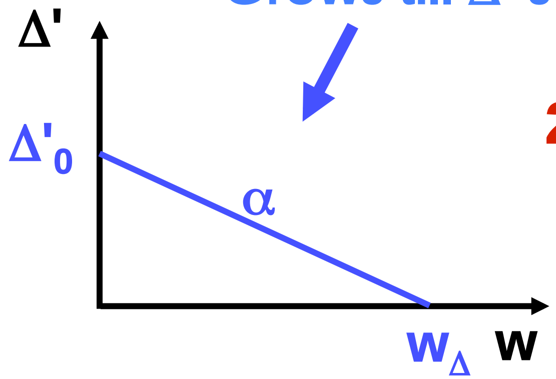
- **JET shows increased stability to 2/1 NTM cf other devices**
  - **Possible origin in q profile dependence**
- **q profile is observed to play a major role in 2/1 NTM threshold**
  - **Varying heating timing or Ip overshoot impacts mode onset**
  - **Allowing plasma to relax (by waiting or lowering power) can lead to mode at lower β_N**
  - **More 'advanced' q profiles (q_{min}<~2) are more unstable**
- **It seems that a 'just right' degree of relaxation is needed to maintain stability**

A common picture is emerging whereby 2/1 NTM thresholds are predominantly governed by changes in underlying tearing stability of the plasma, and that this can be influenced by manipulating **current profile** or **flow shear**, leading to ***risks from error fields and low torque*** and ***opportunities through q and flow profile tuning***.

‘Minimal’ Δ' seeding model to explain observations

1. Positive Δ' excites a small island

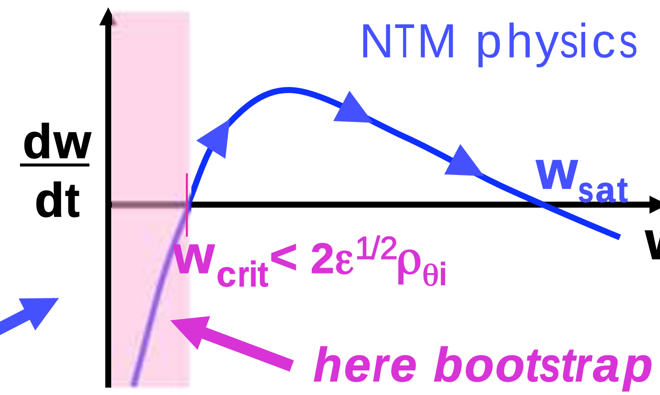
– Grows till Δ' saturation, $w_\Delta = \Delta'_0 / \alpha$



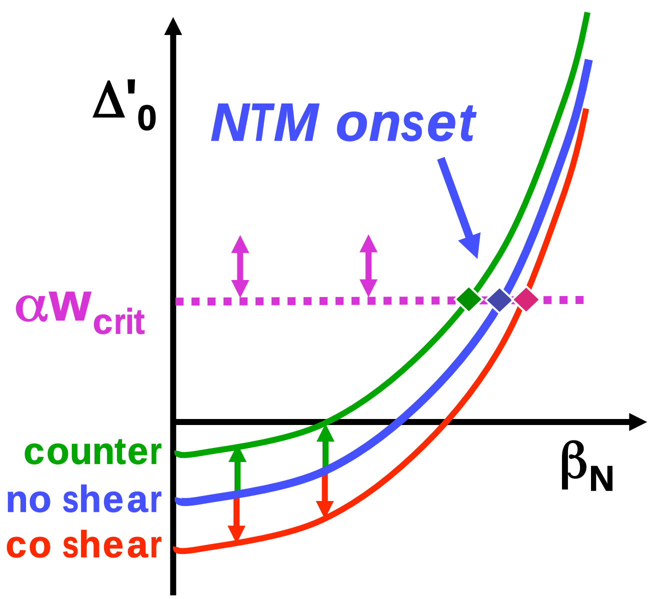
2. Growth becomes “neoclassical” if island big enough:

$w_\Delta > w_{crit}$

$\Rightarrow \Delta'_0 > \alpha\, w_{crit}$



here bootstrap hole suppressed by finite island transport



3. Δ'_0 is function of rotation shear and β_N

– **Increases/decreases** in **rotation shear** will change tearing mode onset β_N

– Similarly, **q profile** changes base Δ'

– ρ^* variation introduced through w_{crit}

– ***but note much harder to excite mode at low β_N away from Δ' pole***

Affiliations

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