Fast Beta Collapses in NSTX

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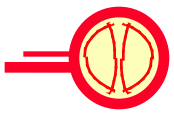

Abstract

Improvement of plasma stored energy in NSTX is presently limited by instabilities that cause fast collapses in plasma beta. Generally, operation with central safety factor, $q(0)$, greater than unity is required to prevent large major radius sawteeth, as determined by soft X-ray emissions. While these modes often do not cause a current quench, plasma beta is significantly reduced and does not recover. The deleterious effects of these modes have been reduced or eliminated by either creating plasmas with small inversion radii, leading to steady sawtooth oscillations, or by operating at higher toroidal field or modifying the current profile to maintain $q(0) > 1$. Tearing modes, high frequency Alfven eigenmodes, and kink instabilities can also limit plasma stored energy, the later resulting in fast beta collapses. Mode locking is observed on an array of toroidal Mirnov coils during these events. Toroidal mode number $n = 1$ is typically found. The mode amplitude increases, and rotation slows as the plasma approaches the collapse. Further improvement in beta by wall stabilization and active feedback of pressure-driven kinks will be discussed in the context of these results.

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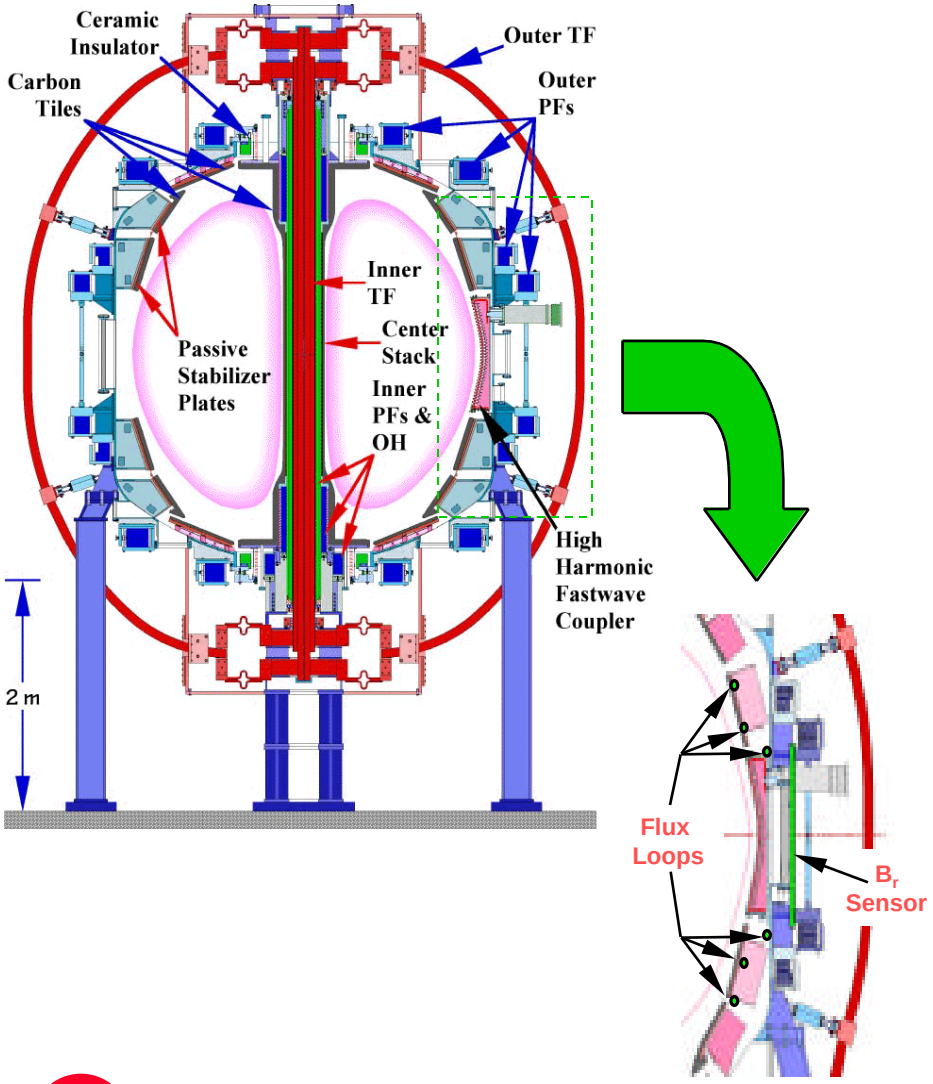
Several Instabilities Can Be Associated with Fast Beta Collapse

- n = 1 Modes and Sawteeth
  - n = 1 modes with large q =1 radius may cause fast collapse
  - Small sawteeth benign at low β_p
- External Kinks
  - Fast collapse occur from external kinks at lower q_a
- Pressure Driven Kinks
  - Low-n pressure driven kink can cause fast collapses
  - Pressure driven kink may develop to resistive wall mode
- RWM
  - Growth time slowed to τ_{wall}

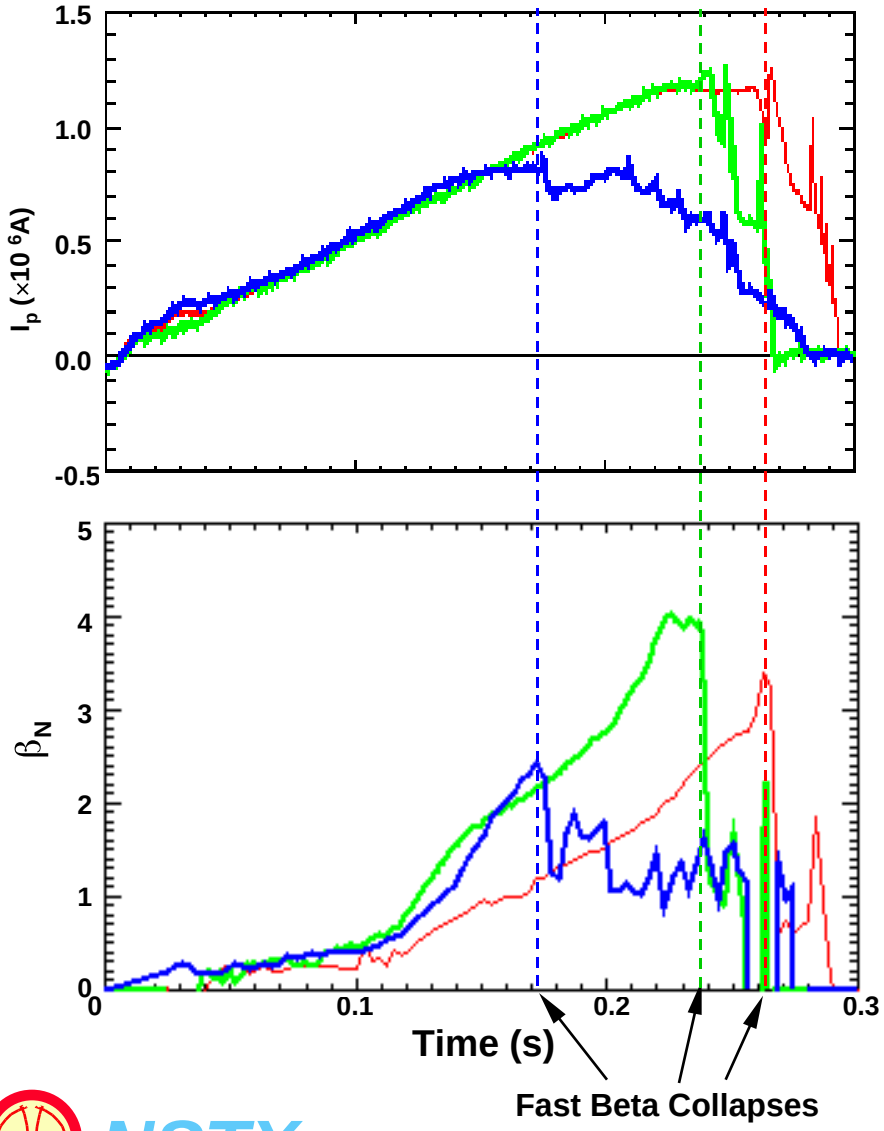
National Spherical Torus Experiment



NSTX Parameters
(Achieved)

- Major Radius 0.85 m
- Minor Radius 0.68 m
- Elongation 2.2 (2.5)
- Triangularity 0.6 (0.7)
- Plasma Current 1 MA (1.4 MA)
- Toroidal Field 0.3~0.6 T (0.45 T)
- Pulse Length < 0.5 s
- $0.4 < l_i < 1.6$
- $\beta_N < 4.3$, $\beta_T < 27\%$

Plasma Beta Significantly and Rapidly Reduced in Fast Beta Collapses



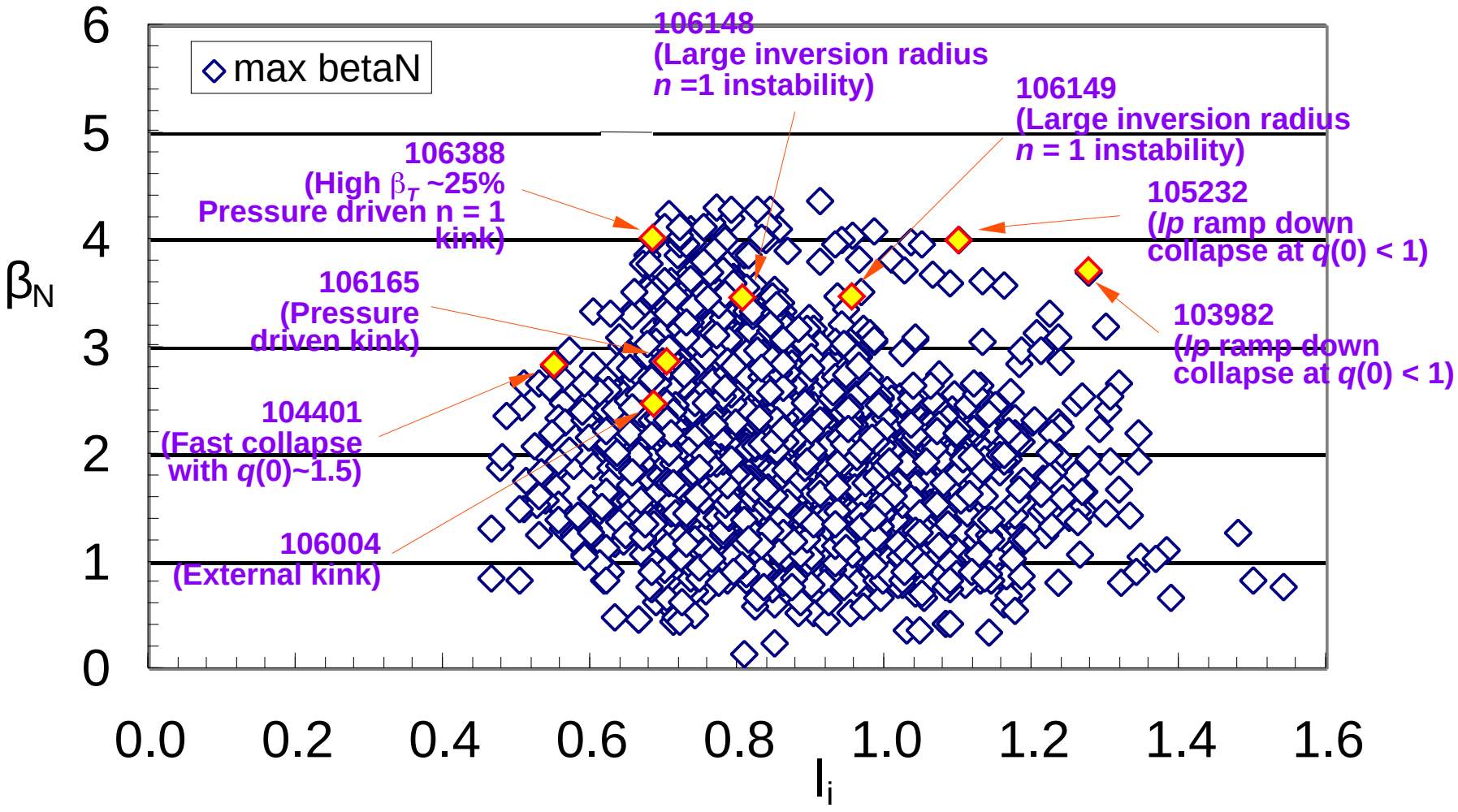
- May not cause a full current quench
- Generally, β does not recover
- $\tau_{collapse}$ ~ 0.3 – 3 ms
- τ_{alfven} ~ 5 μs; τ_{wall} ~ 5 ms

— ***n*** = 1 mode with large ***r***(***q*** = 1) (106148)

— low-***n*** external kink (106004)

— low-***n*** pressure driven kink (106388)

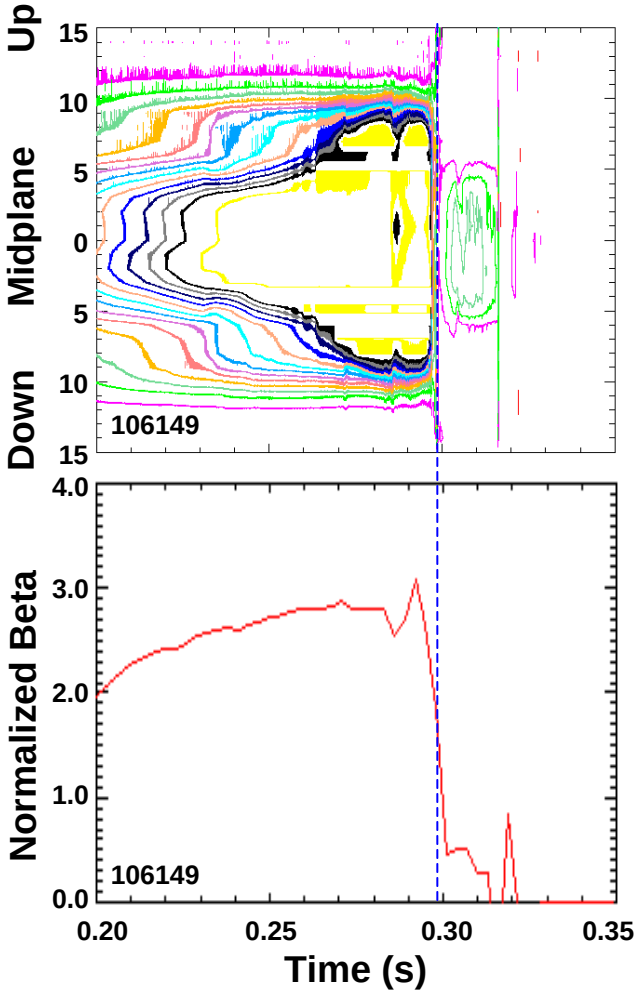
Fast Beta Collapse Occurs at All Values of l_i



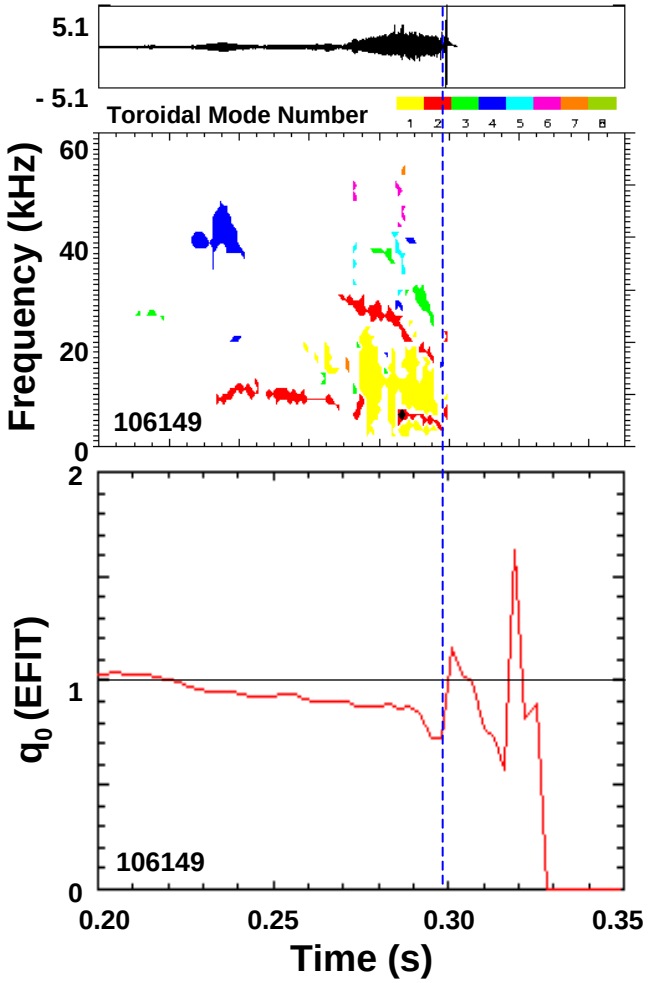
n = 1 Mode and Sawteeth

n = 1 Mode Activity Is Typically a Precursor to Fast Beta Collapse in Longer Discharges

USXR Emission Contour



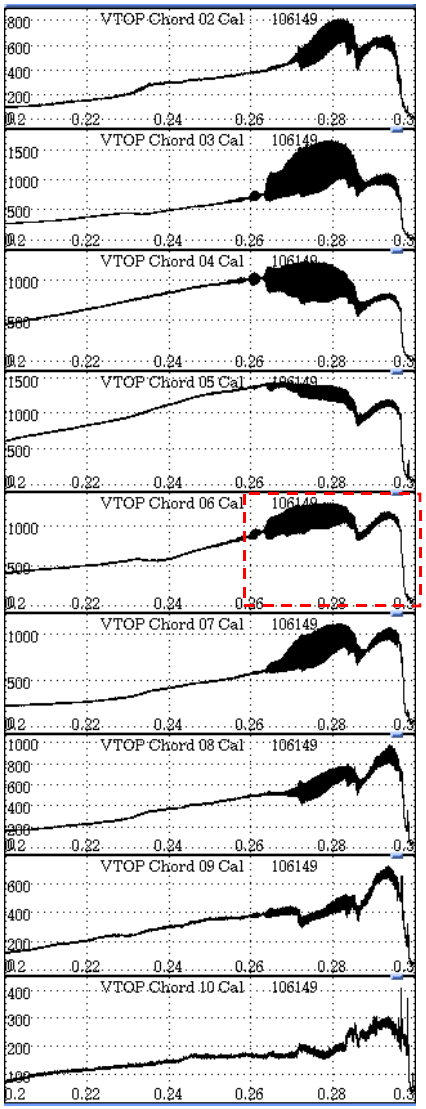
Mirnov Spectrum



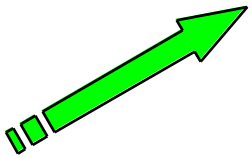
- Mode onsets when $q_0 < 1$
- Strong *n* = 1 mode activity precedes fast beta collapse
- *n* = 2 mode activity also present

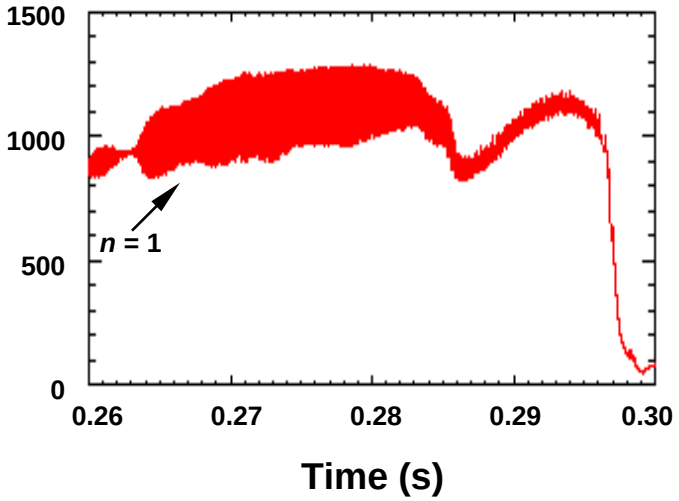
USXR Emission

Outer bound



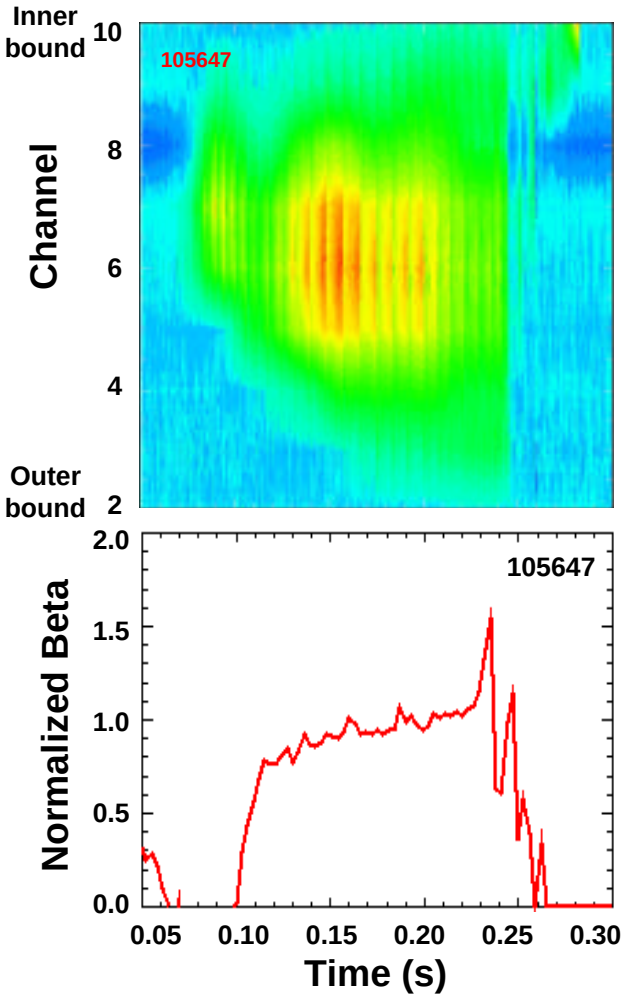
Inner bound



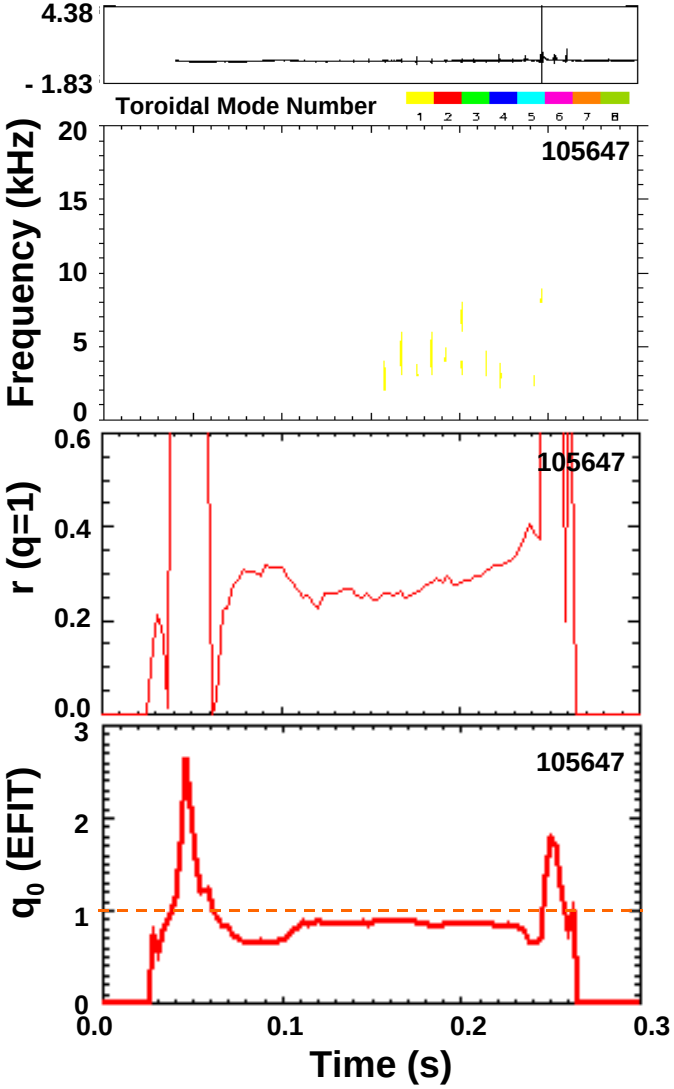


Small Inversion Radii Sawteeth Are Generally Benign

USXR Emission Contour



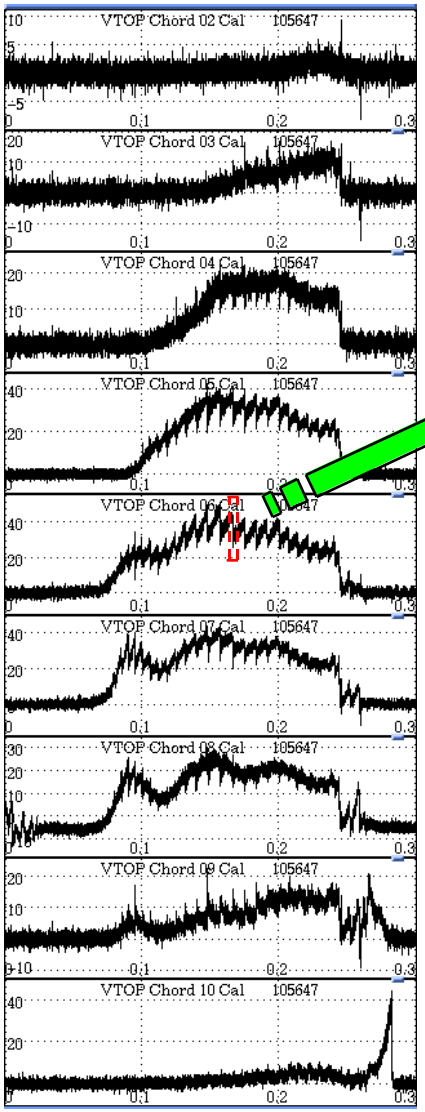
Mirnov Spectrum



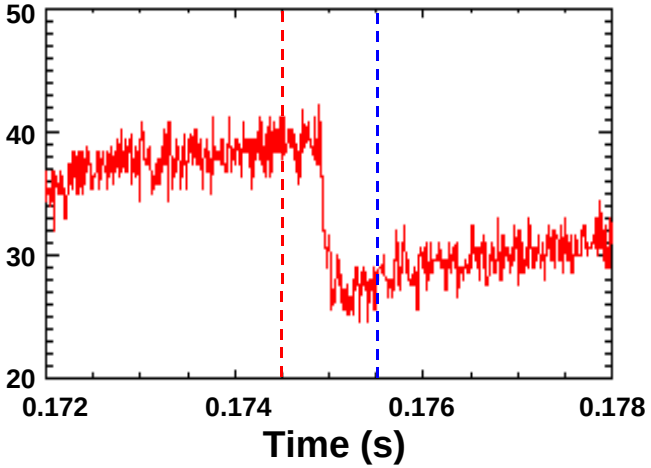
- Sawtooth onsets after $q_0 < 1$
- $r(q=1)$ reaches $0.4a$
- Mode activity observed weakly in Mirnov signal

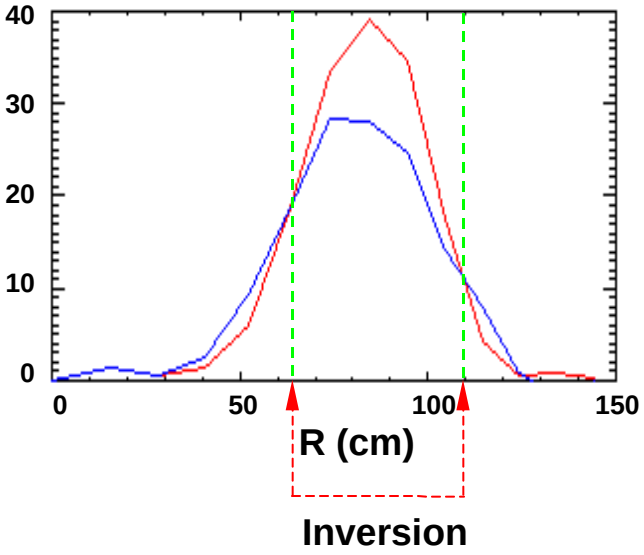
USXR Emission

Outer bound



Inner bound



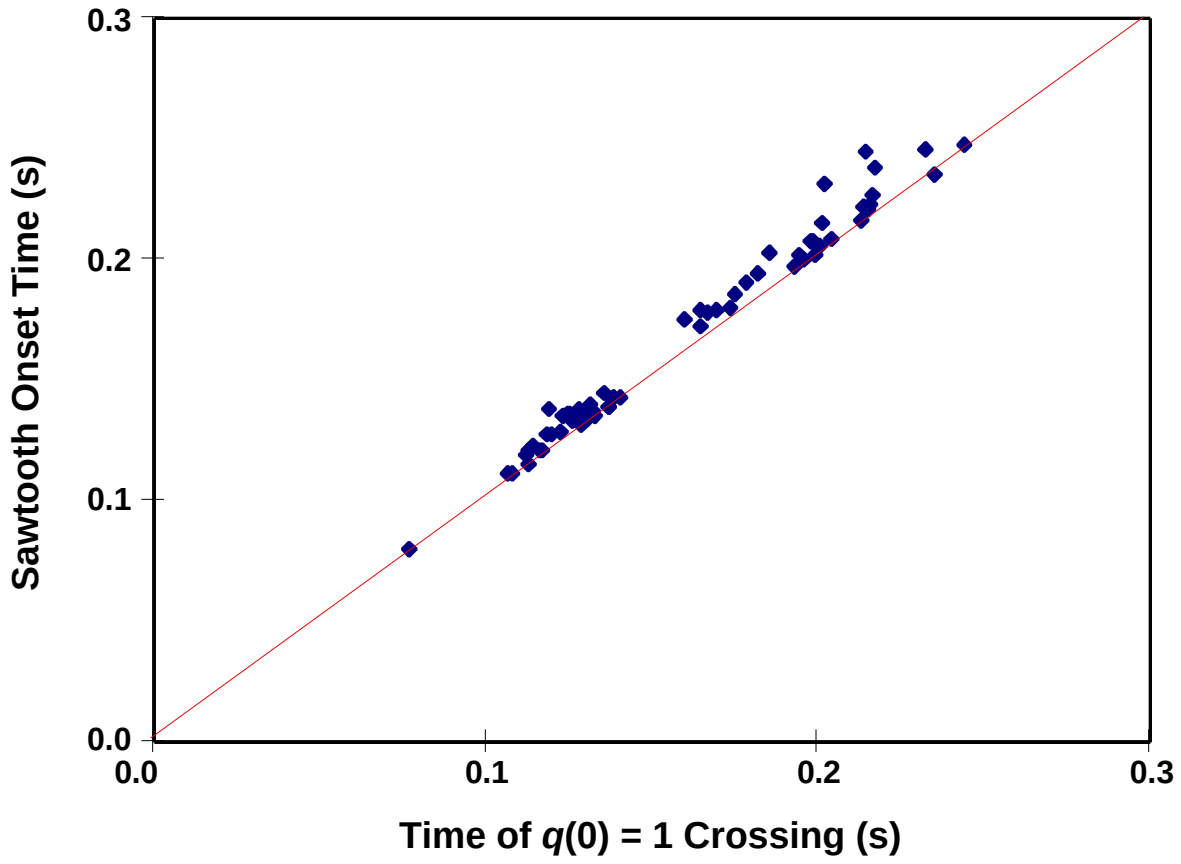


Before crash

After crash

NSTX

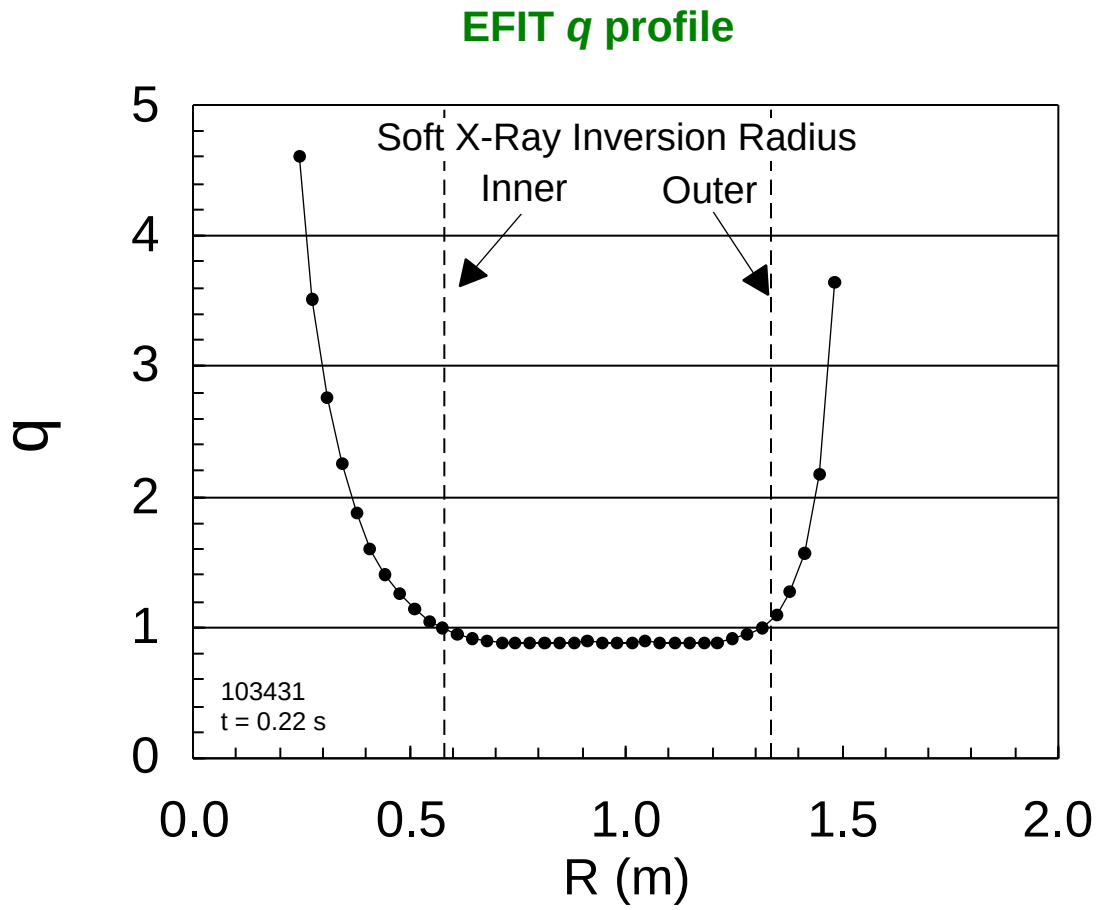
Sawteeth Onset after q_0 Drops below Unity



- q_0 reconstructed with EFIT
- 80 Ohmic only heated plasma checked
- Sawteeth onset at $q_0 = 0.96 \pm 0.05$
- Can be avoided by either creating plasmas with small inversion radii, steady sawtooth oscillations, or maintaining $q_0 >= 1$

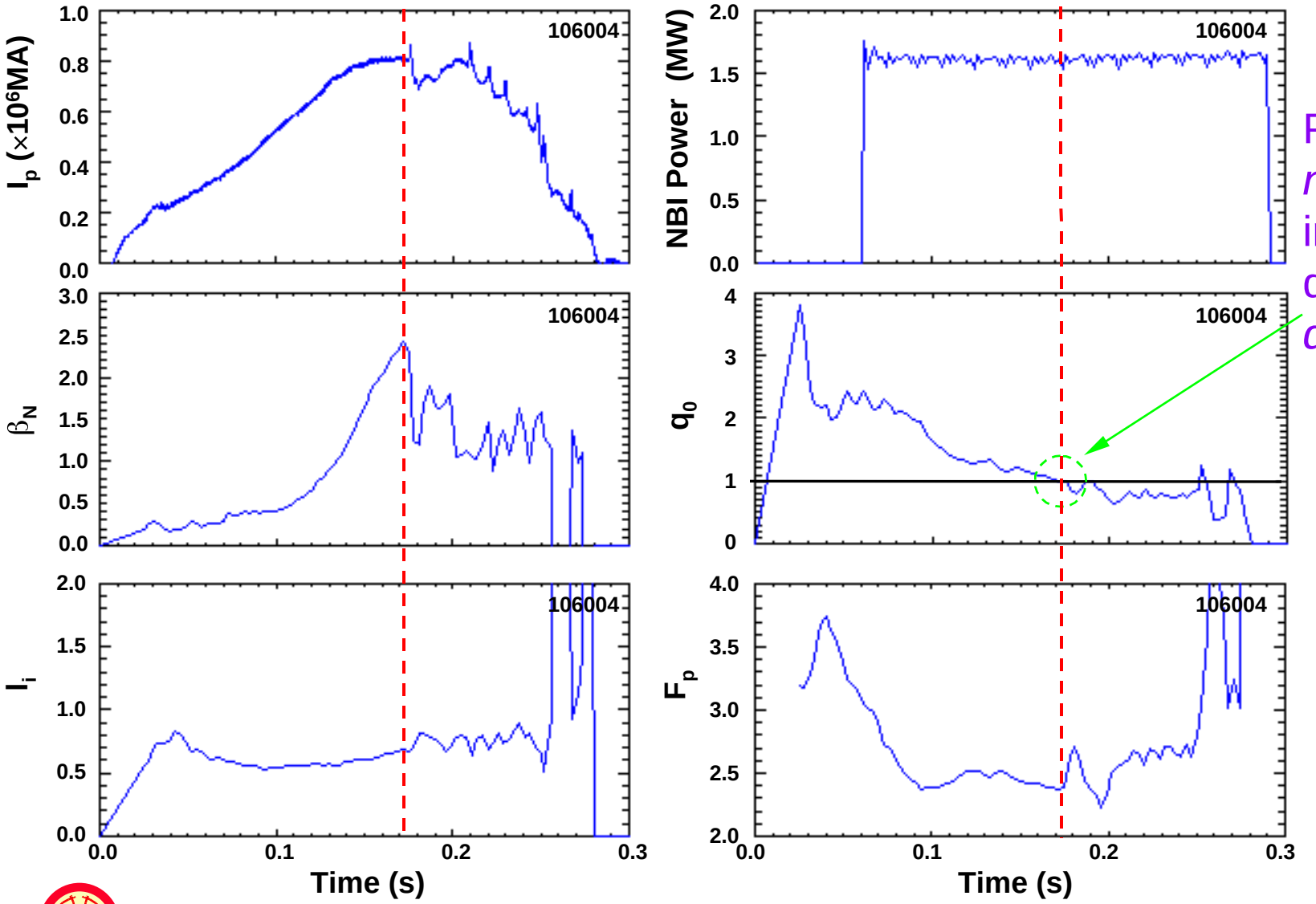
* S. A. Sabbagh, et. al, IAEA 2000, to appear in Nuclear Fusion 11/01 issue

Reconstructed q = 1 Surface Agree with SXR Inversion Radius



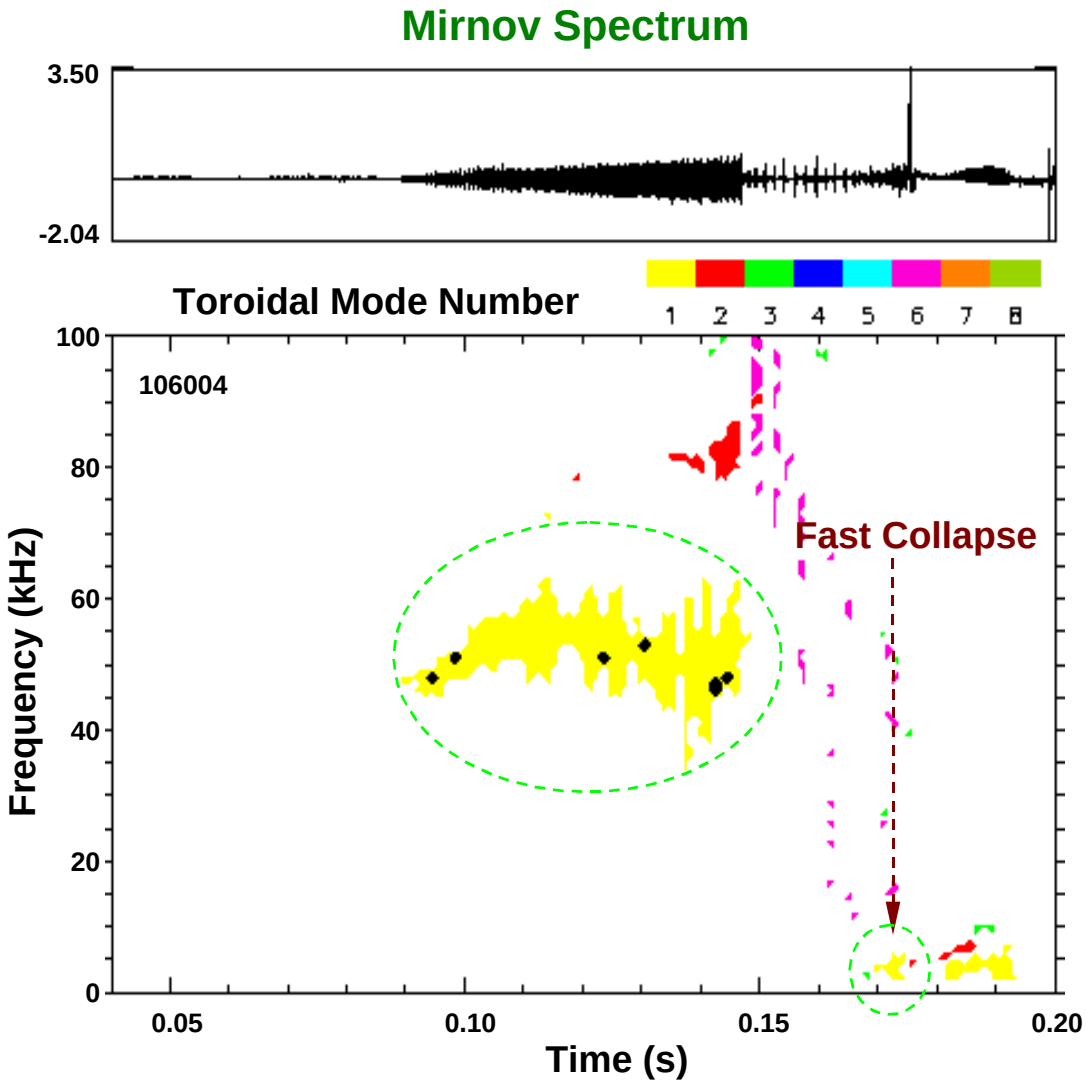
Low-*n* External Kinks

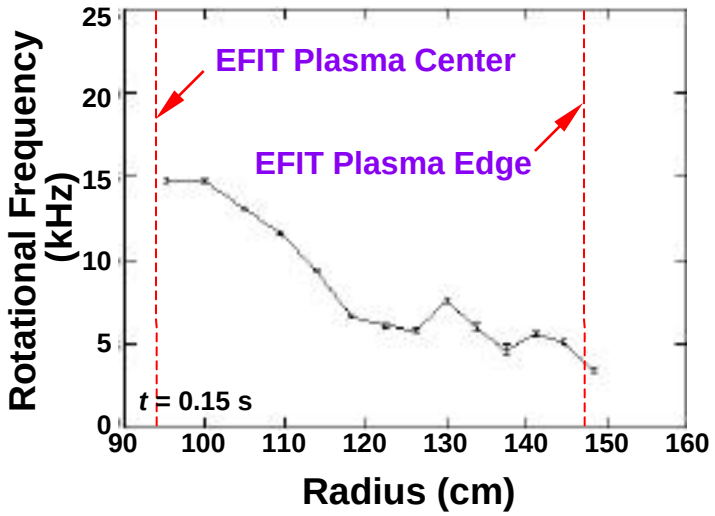
Low-*n* External Kink May Be Related to Fast Collapse



Possible *n* = 1 instability due to *q*(0) < 1

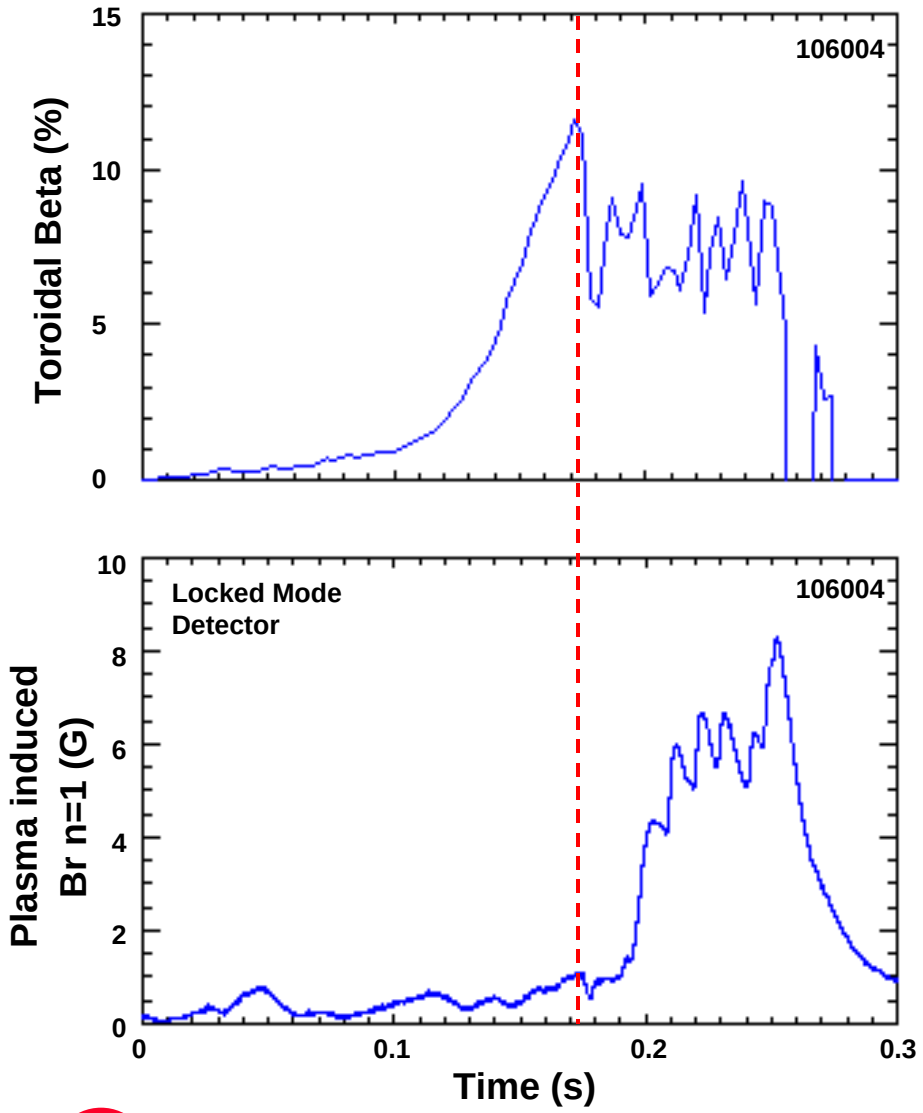
n = 1 Mode Observed on Mirnov Coils





- Early higher frequency *n* = 1 mode observed on Mirnov coils
- Lower frequency *n* = 1 mode appears as plasma approaches fast collapse

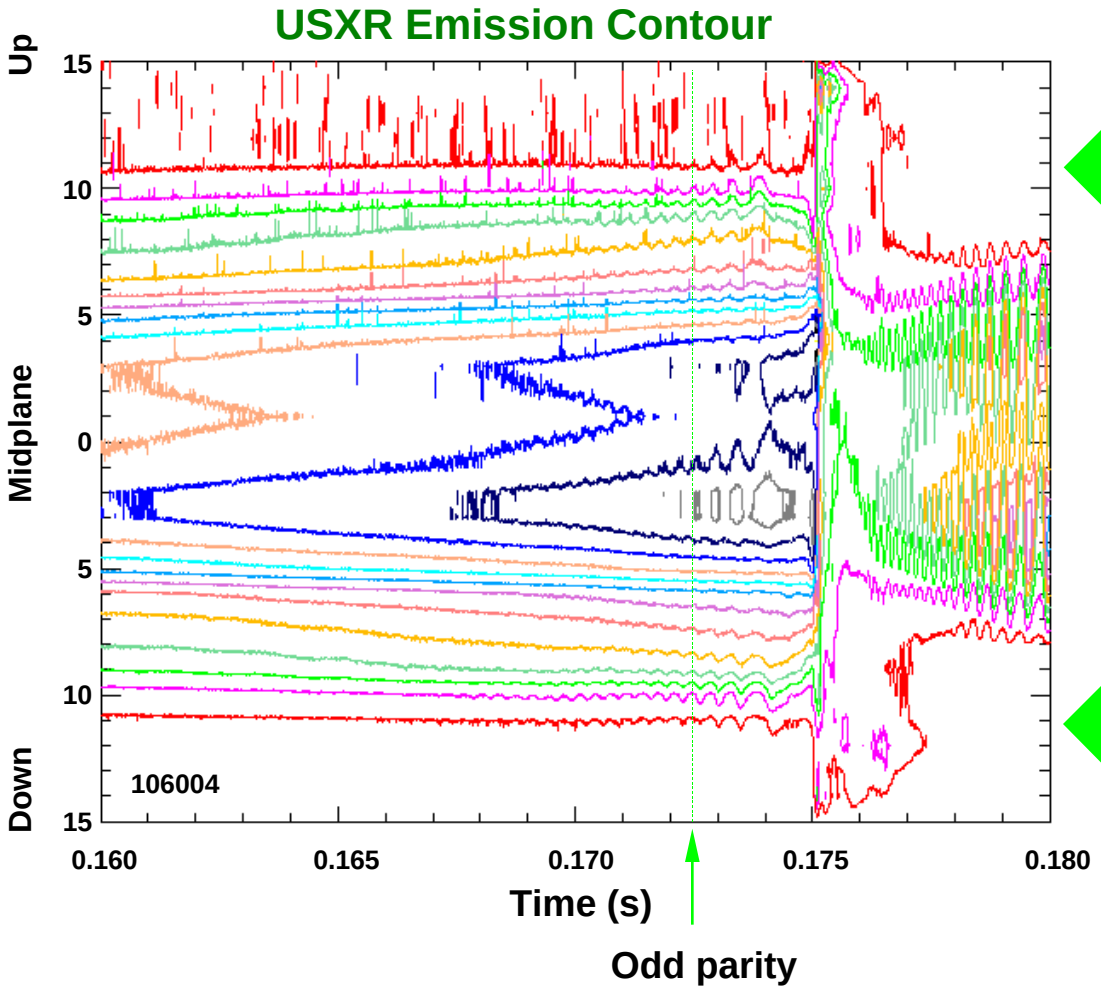
No *n* = 1 Locked Mode Precursor to Kink



- No locked mode observed
- τ_{wall} ~ 5 ms for *n* = 1 mode

*Locked mode data: J. Menard

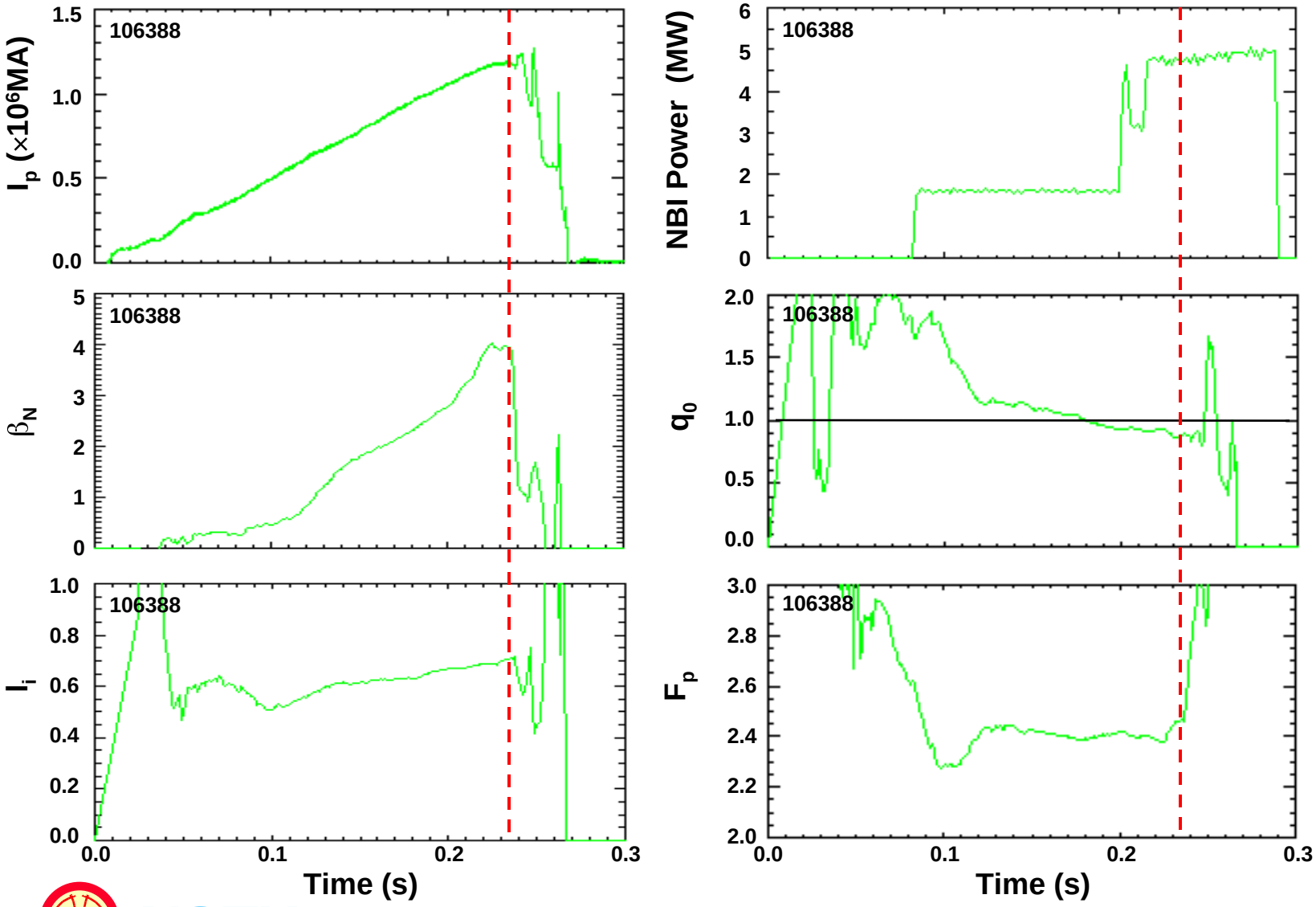
USXR Shows the External Kink



- External kink observed on USXR signals when plasma approaches fast collapse
- $n = 1$ mode

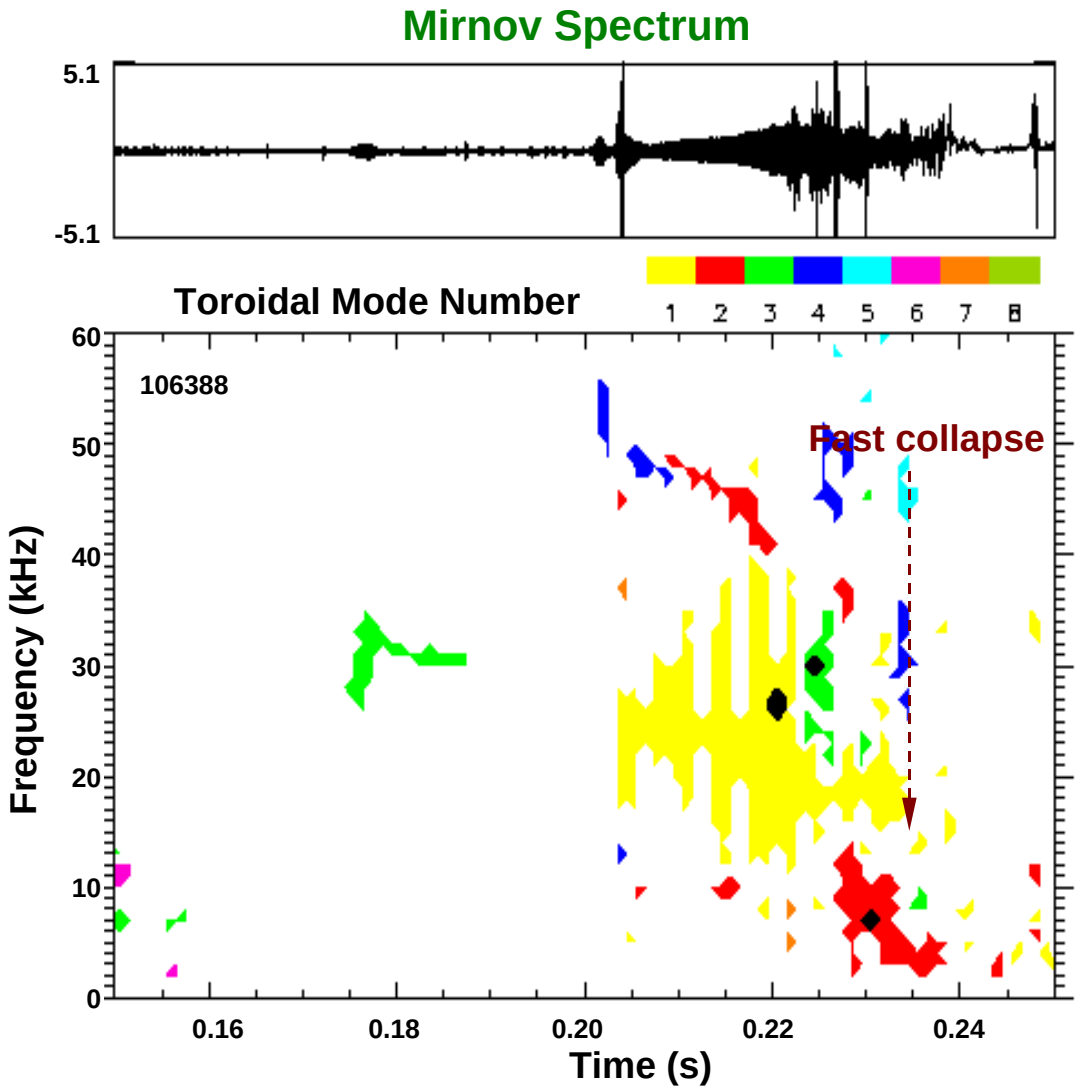
Low-*n* Pressure-driven Kinks

Low-*n* Pressure Driven Kink is Another Mode That May Cause Fast Collapses



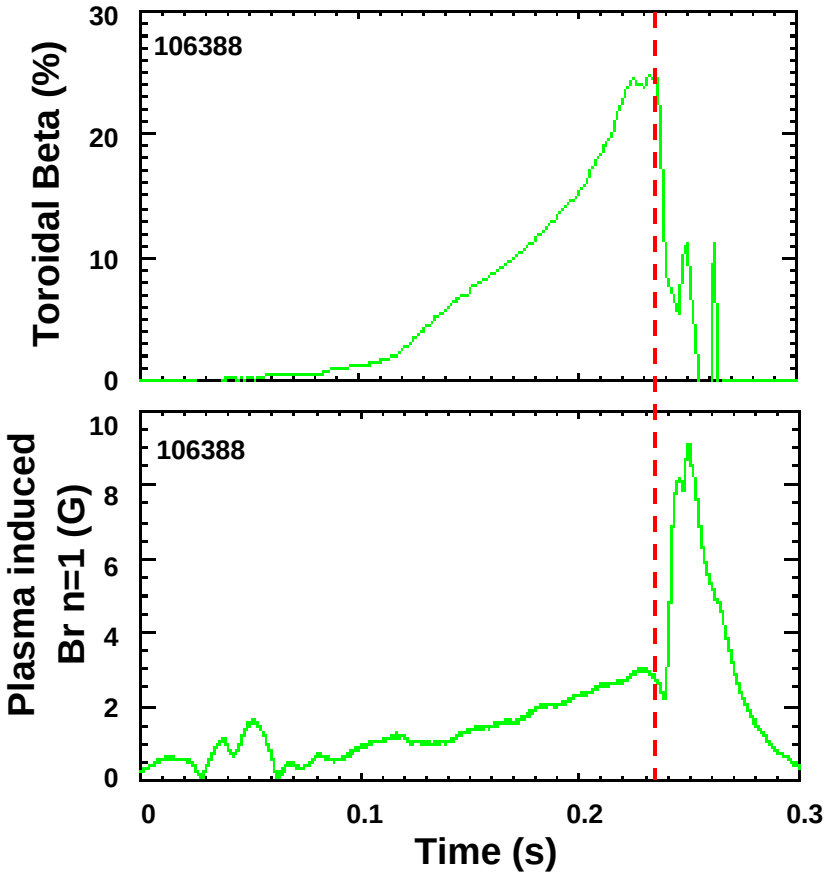
NSTX

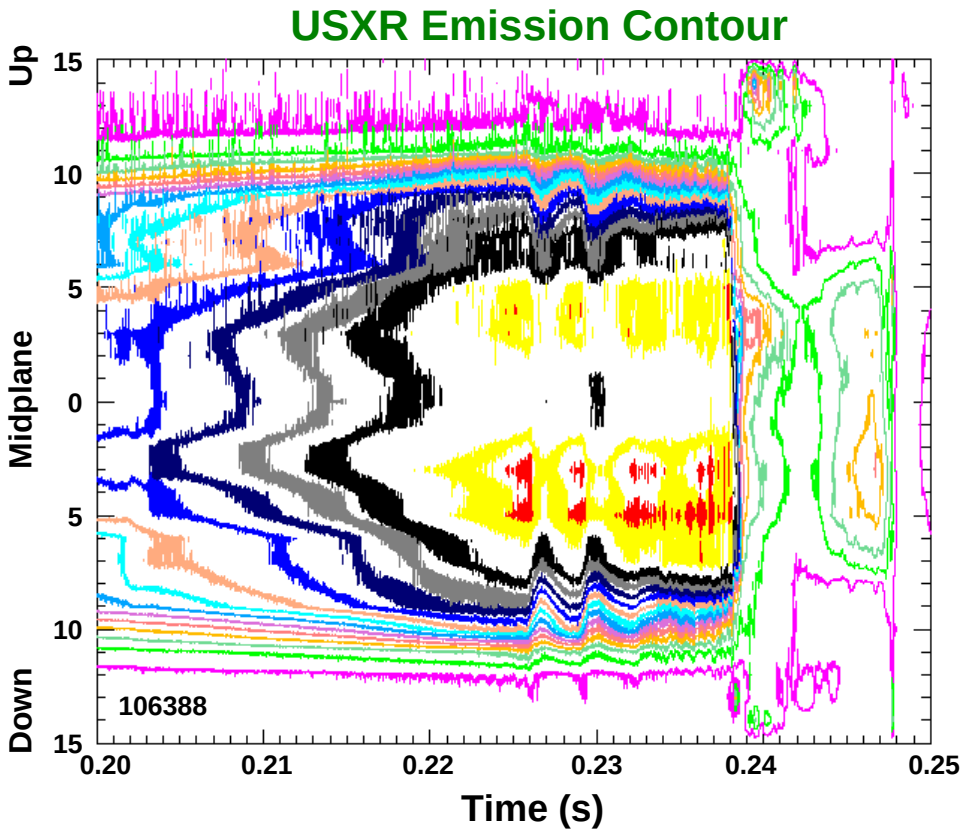
n = 1, 2 Modes Preceding Beta Collapse



- *n* = 1, 2 modes observed on Mirnov coils when plasma approaches collapse
- Ideal MHD stability calculation shows plasma unstable to pressure driven *n* = 1 mode at $\beta_N = 4.1$

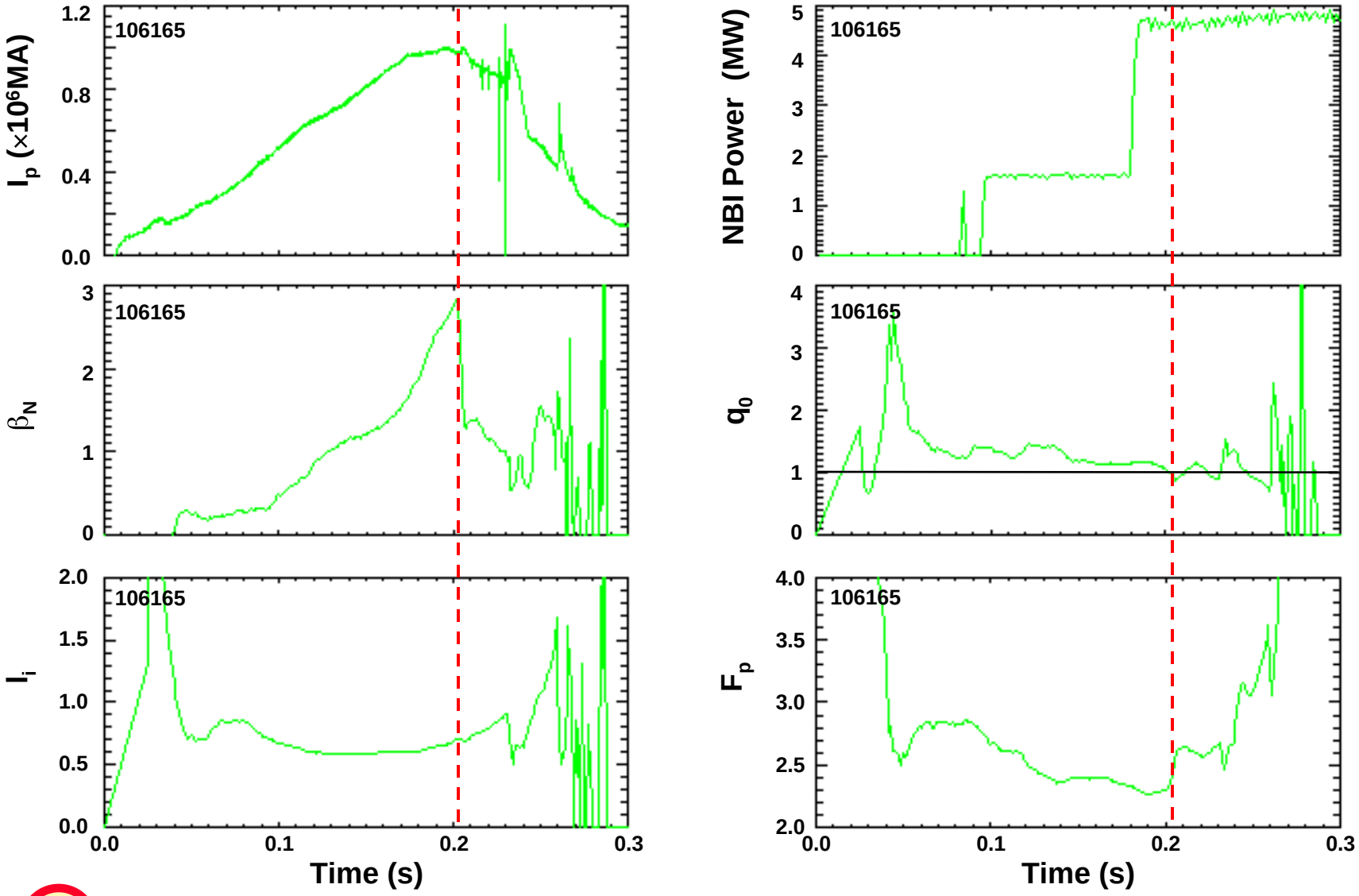
Pressure Driven Kink Does Not Lock to the Wall





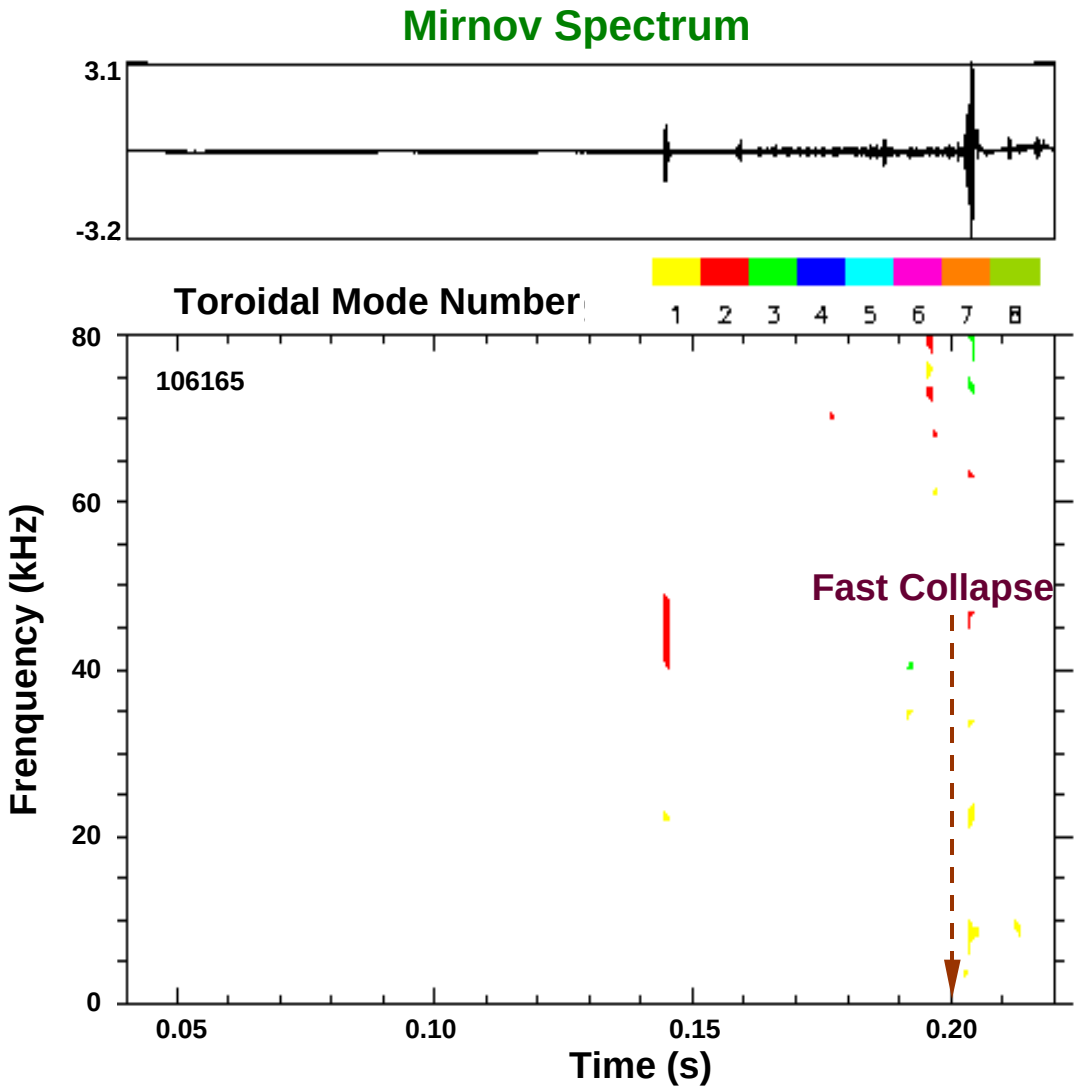
- No fast growing $n = 1$ locked mode preceding collapse

Some Pressure Driven Kinks Show RMW Characteristics



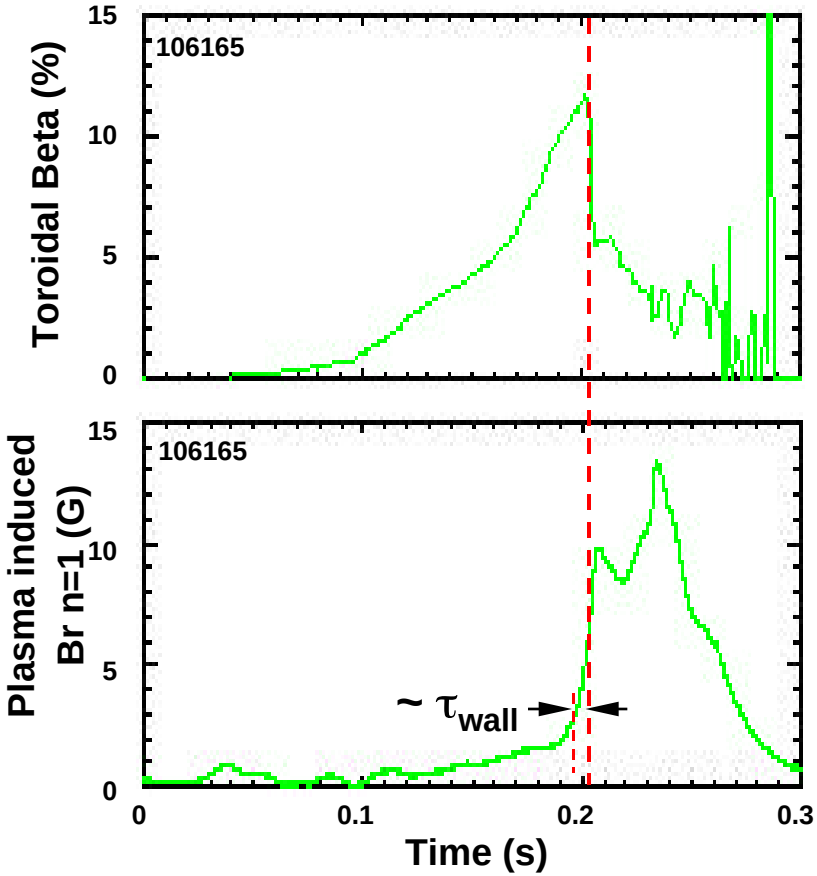
NSTX

No Mirnov Precursors to Beta Collapse

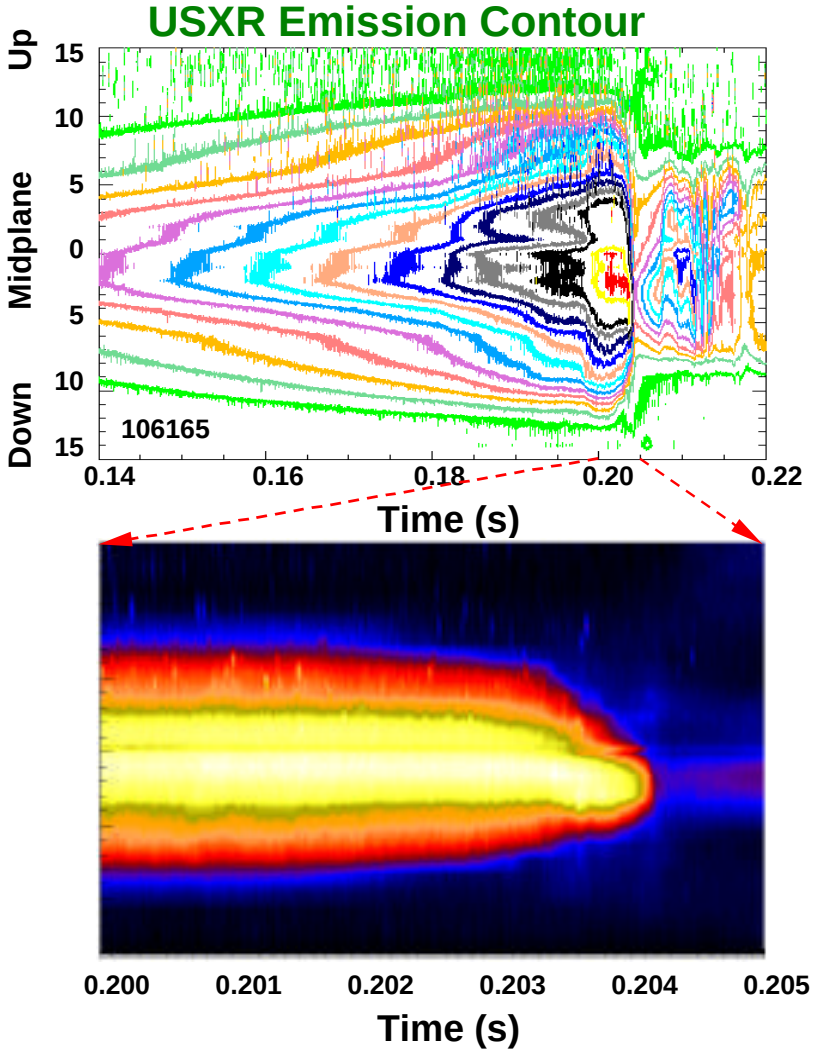


- No clear island-like precursor in Mirnov signal
- Ideal MHD stability calculation shows ***n*** = 1 pressure driven mode at $\beta_N = 2.7$
  - Computed mode couples to conducing wall

Low-n Pressure Driven Mode May Lock to the Wall

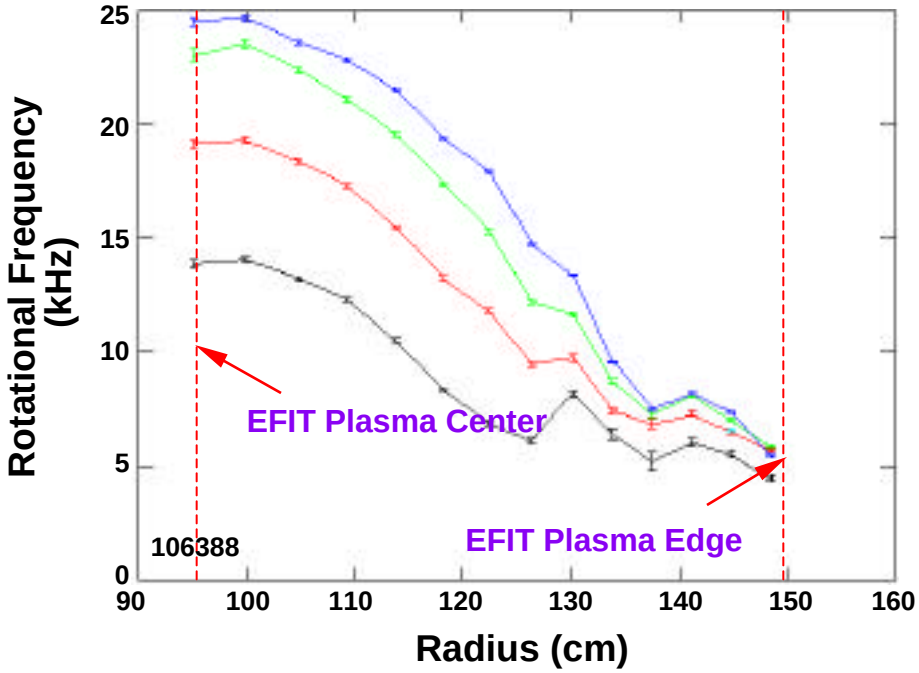


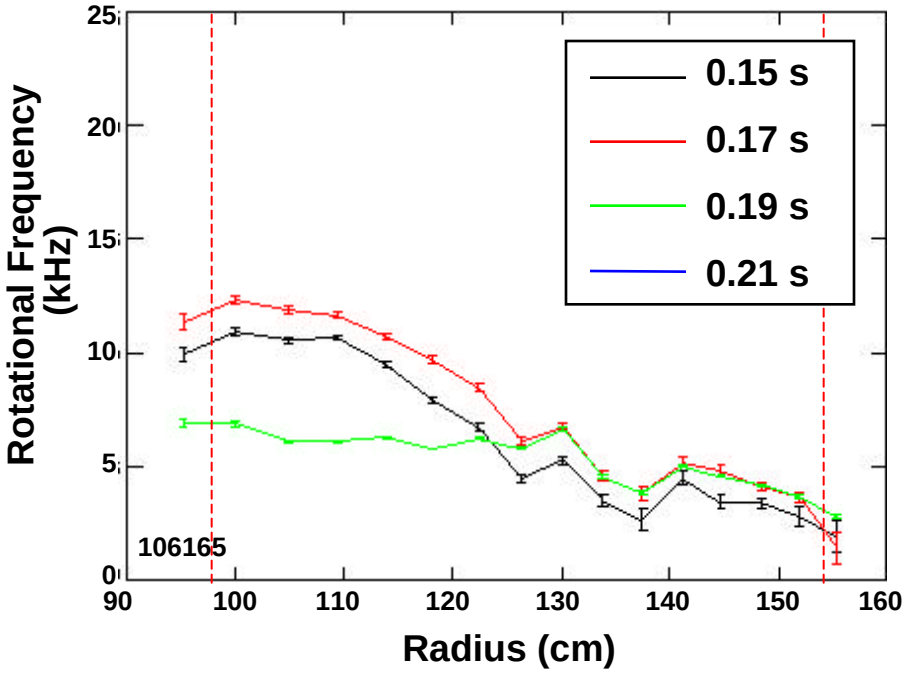
- Fast growing *n* = 1 locked mode precedes collapse
- Mode grows in τ_{wall} (~ 5 ms) timescale



- Kink-like perturbation observed in USXR signals

Two Types of Pressure Driven Kink Have Different Rotation Profile Evolution





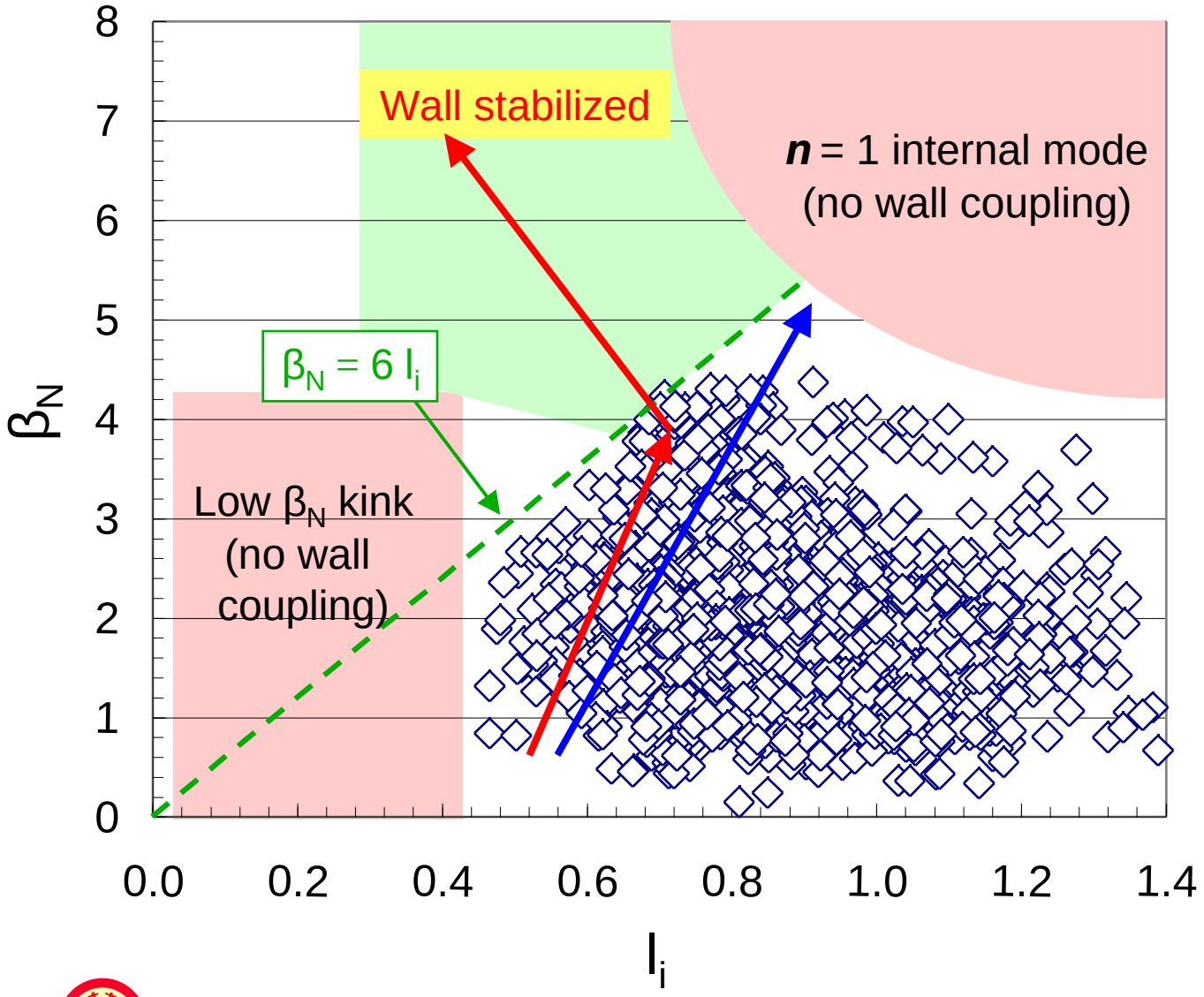
- Plasma rotational frequency grows with time

- Center plasma rotational frequency grows then slows down
- Edge plasma rotational frequency grows then keeps almost constant

Pressure Driven Kink May Develop to RWM

Resistive Wall Mode Characteristic	Observed in XP
Mode observed in locked mode signal	Yes
Mode growth rate ~ 1 / τ_{wall}	Yes
Slowed rotation leading to fast beta collapse	Yes
Mode growth during plasma rotation	Yes
No clear island-like precursor in Mirnov signal	Yes
USXR shows kink-like perturbation	Yes

Analysis Suggests Specific Route to High β_N



Low l_i

- Operate at low $F_p < 3$
- Increase l_i as β_N increases until pressure drive couples plasma to plates
- Bootstrap current will reduce l_i with mode stabilized by wall

High l_i

- Operate at high l_i and reduced F_p without wall stabilization (lower β_N)

Summary and Conclusion

- *n* = 1 Modes and Sawteeth
  - Significant β collapse by *n* = 1 mode when *r*(*q* = 1) is large
  - Small inversion radius sawteeth benign
- External Kinks
  - Fast collapse observed after external kink
- Pressure Drive Kinks
  - Low-*n* pressure driven kink may cause fast collapses
  - Some pressure driven kinks show RMW characteristics
- RWM
  - Locked mode detector shows growth rate ~ $1/\tau_{wall}$

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