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Internal kink mode dynamics in high-β NSTX plasmas

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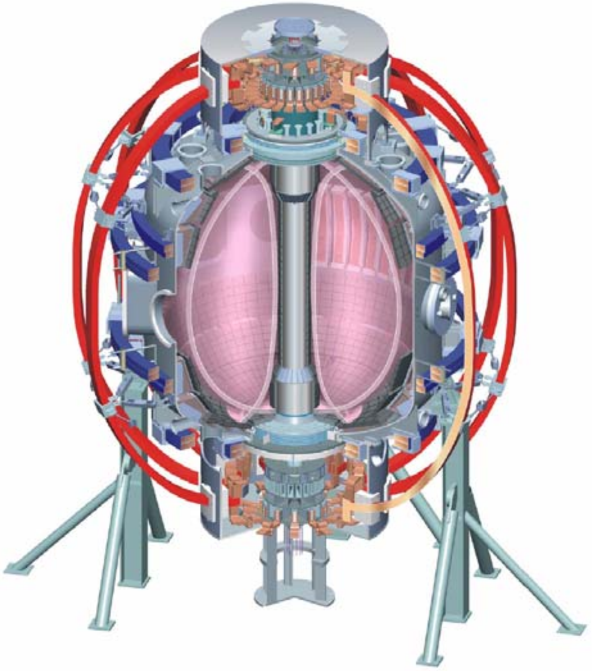

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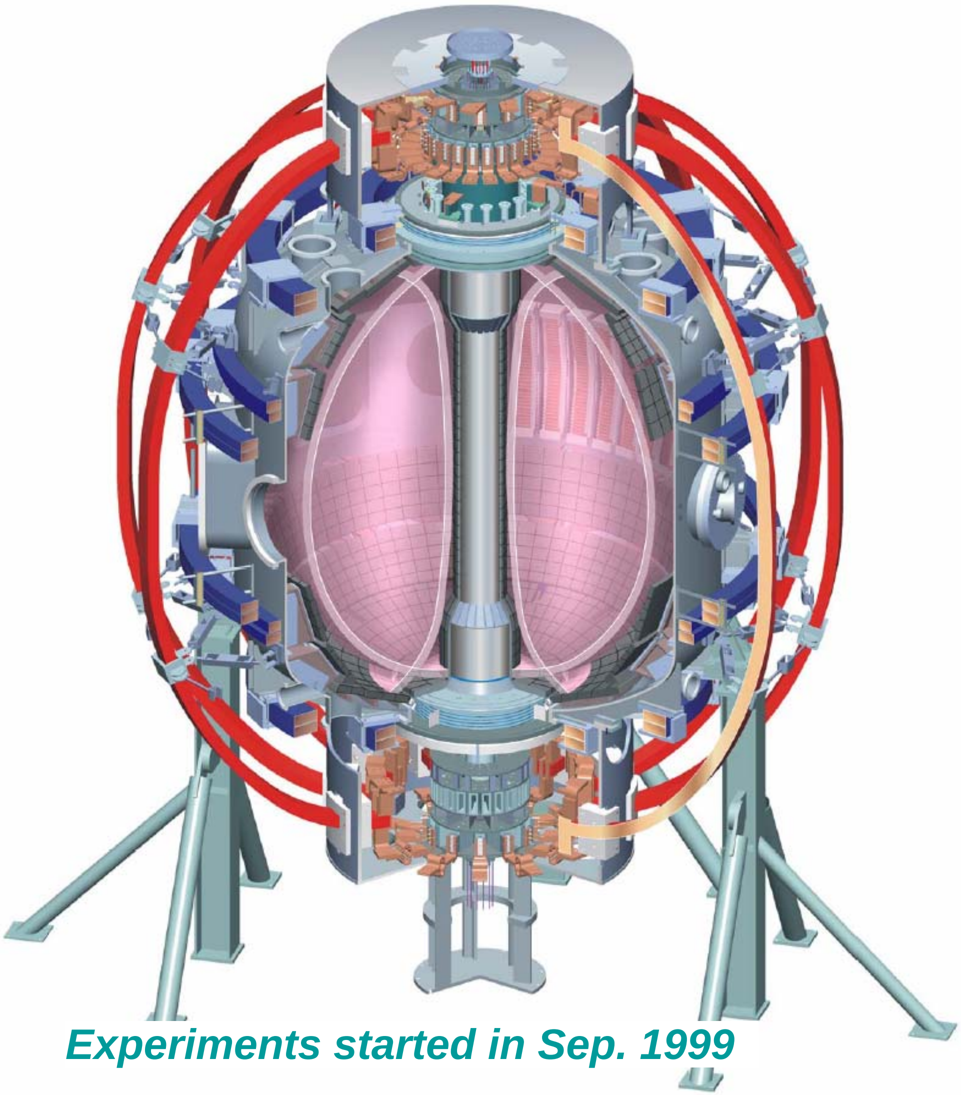
NSTX investigates low collisionality toroidal plasmas at low aspect ratio



Experiments started in Sep. 1999

Achieved Parameters

Aspect ratio A	**1.27**
Elongation κ	2.6
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Solenoid flux	0.7Vs
Pulse Length	1.1s
Te, Ti	**1-4keV**

Auxiliary heating & current drive:

RF (30MHz)	6 MW
CHI	0.4MA
NBI (100kV)	**7 MW**

Motivation

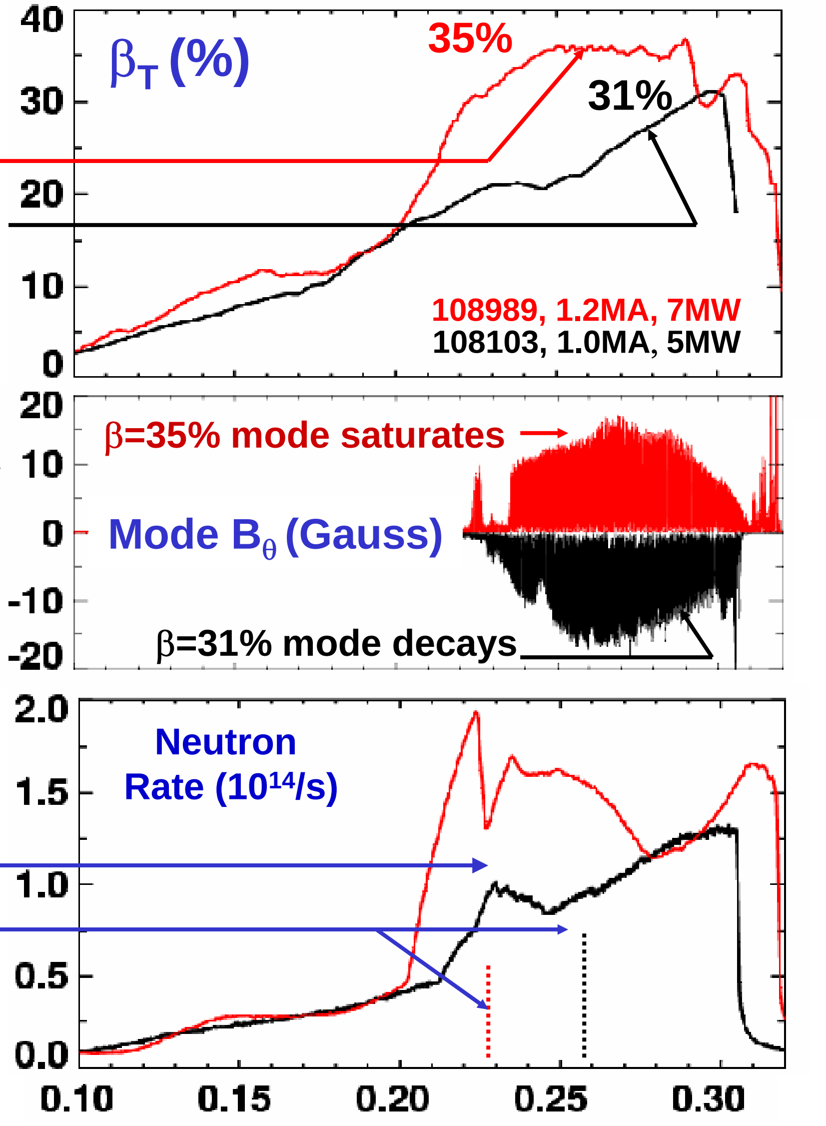
- Internal kink can limit β in highest-β_T shots of NSTX
  - Highest β_T shots typically have high I_P/aB_T and low q_0
  - 1/1 modes often saturate in amplitude
    - Cyclic sawtooth oscillations are rare at high-β
  - Modes degrade fast-ion & thermal confinement + rotation
  - Effect of mode ranges from benign to disruptive

- Want to improve understanding of:
  - Possible saturation mechanisms for 1/1 mode
    - Mechanism must be strong during non-linear phase of evolution
    - Fast ion, sheared flow, island pressure, and diamagnetic effects
  - Plasma rotation flattening and damping caused by mode
    - Important for shots that disrupt due to presence of 1/1 mode

Highest β shots obtained despite large 1/1 modes

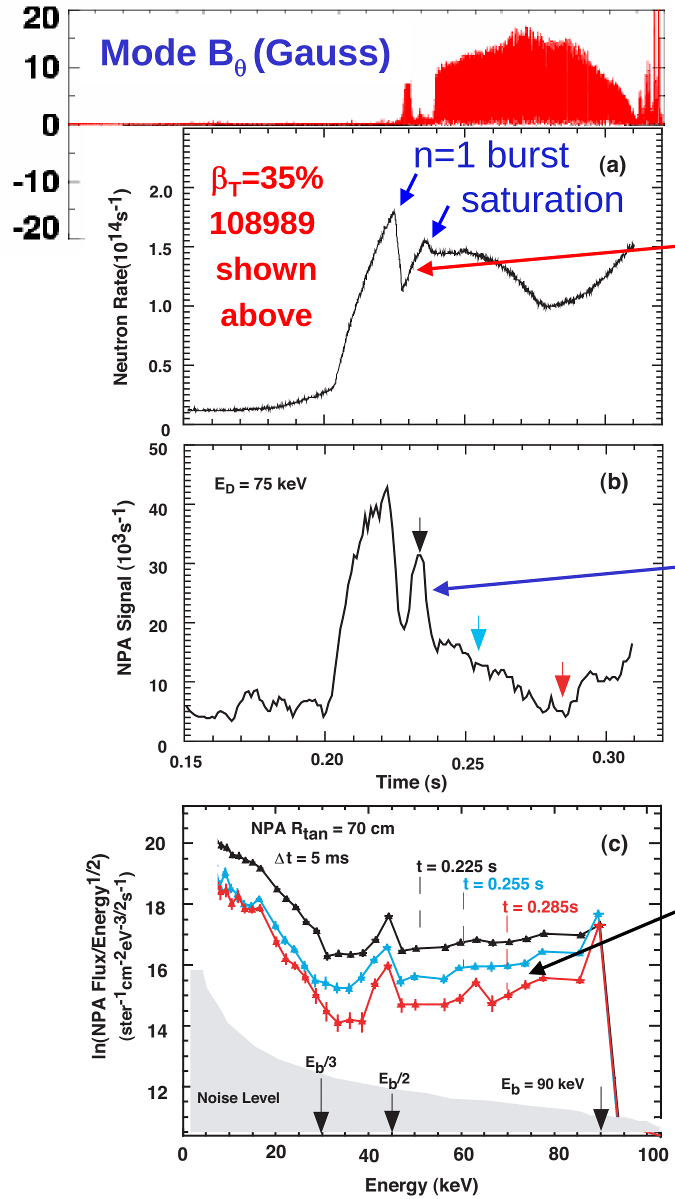
- Sawtooth activity rare at high β
  - Rotating 1/1, usually $\Rightarrow$ β roll-over
- In highest β shots, β saturates or actually rises during 1/1 activity
- 1/1 saturates or decays at high β
- $\beta \rightarrow$ 1.2-1.4 × onset β
  - Onset β_N = 4.2 - 4.5 ≈ n=1 ideal limit
  - These shots reach β_N = 5.5 – 6
- Synergistic effects may aid high β
  - 1/1 mode flattens core *p* and *J*
    - Large fast ion diffusion or loss
  - **H-mode** onset broadens *p* and *J*
  - **Broad *p, J* + rotation stabilizing**

How do the modes saturate?



Saturation physics

Fast ion stabilization likely ***not*** aiding saturation



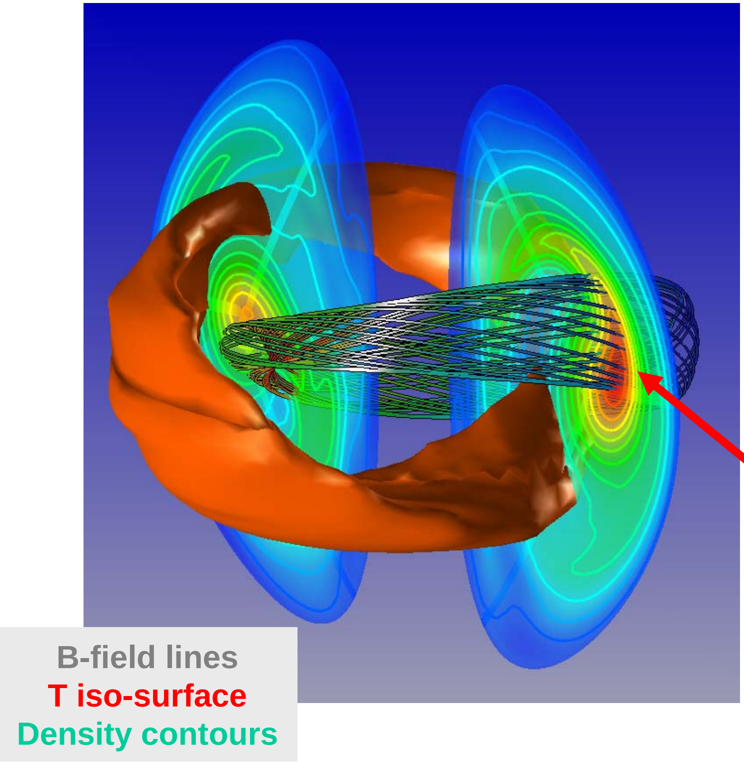
- **Neutron rate drops significantly at mode onset and during saturation**
- NPA shows most energetic ions are rapidly depleted during mode growth
- Fast ion population from 20-80keV reduced by factor of 3-5 during saturation phase ⇒ **likely reduction in possible stabilizing effect of trapped fast ions**
- Could reduced core β_P keep plasma near marginal stability ⇒ saturation?

Saturation mechanisms studied with **M3D** code

(W. Park, et al., Nucl. Fus. **43** (2003) 483.)

- Simulations ⇒ at least partial reconnection should occur
  - ⇒ saturation process will be acting on subsequent non-linear state

Saturated state with higher p in island



Possible mechanisms:

(1) Sufficient source rate and viscosity to ***maintain sheared flow with island***
  - Requires slow reconnection rate
  - Robust, experimentally possible

(2) Following reconnection, island develops with ***p* highest inside island**
  - Mechanism is robust, not easily obtained

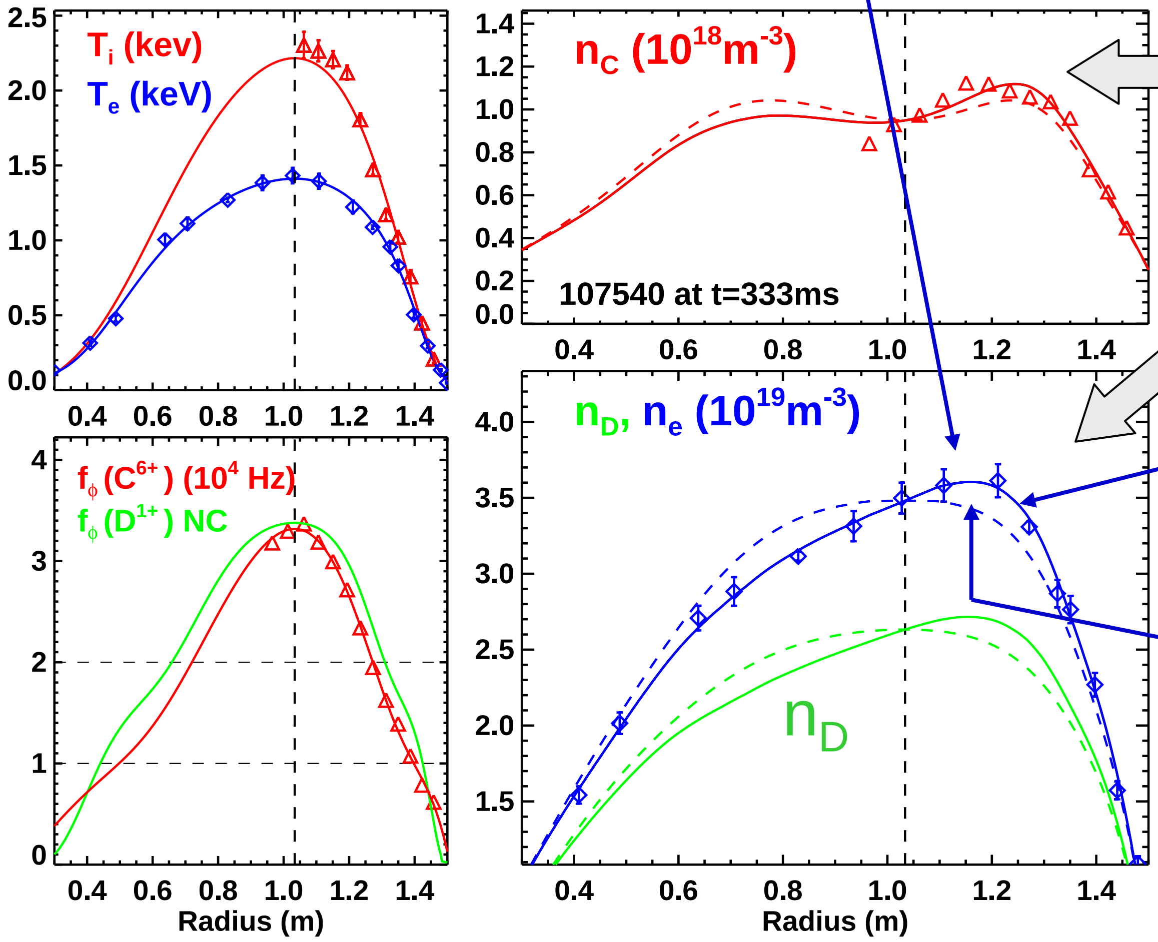
(3) Fast particles, 2-fluid - being studied now
  - Fast particles initially lost/diffused at onset
  - **Diamagnetic flow potentially important**

- **Rotational shear and 2-fluid effects appear most relevant**

Rotation effects are strong in NSTX plasmas

$M_S = v_\phi / v_{sound} = 0.4\text{-}0.8$, $M_A = v_\phi / v_A = 0.2\text{-}0.4$

Centrifugal effects evident in $n_e(R)$ profiles:



Solid curves:

MHD model $n_s(\psi,R)$

Dashed curves:

$N_s(\psi) \equiv$ density w/o rotation

MHD model $n_e(\psi,R)$ can match n_e data

$N_e(\psi)$

MHD force balance model of density asymmetry

- Total force balance in multi-species plasma ⇒

$$\mathbf{J} \times \mathbf{B} = \Sigma_s \nabla (n_s T_s(\psi)) - \Sigma_s m_s n_s \Omega_{\phi s}(\psi)^2 \nabla(R^2/2)$$

B • this equation = 0 has a solution:

$$n_s(\psi,R) = N_s(\psi) \underbrace{\exp(U(\psi) (R^2/R_0^2-1))}$$

$U(\psi) = P_\Omega(\psi) / P_T(\psi)$

$P_\Omega(\psi) = \Sigma_s m_s N_s(\psi) \Omega_{\phi s}(\psi)^2 R_0^2 / 2$ **Centrifugal pressure**

$P_T(\psi) = \Sigma_s N_s(\psi) T_s(\psi)$ **Thermal pressure**

$\Sigma_s N_s(\psi) Z_s = 0$ **Charge neutrality**

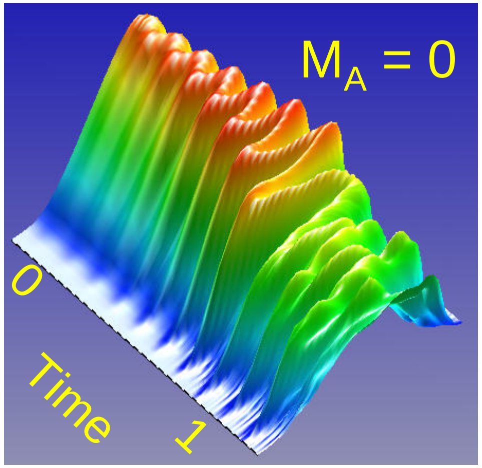
- Charge neutrality ⇒ all species have ***same*** exponential form
  - **Test consistency:** can this model fit measured n_{e}, T_e, T_C, $\Omega_{\phi C}$, n_C ?
    - Use neoclassical $\Omega_{\phi D}$ from TRANSP/NCLASS ($\approx \Omega_{\phi C}$)
    - Treat fast ions as having $P_{fast} = P_{fast}(\psi)$, $\Omega_{\phi fast} = \Omega_{\phi fast}(\psi)$

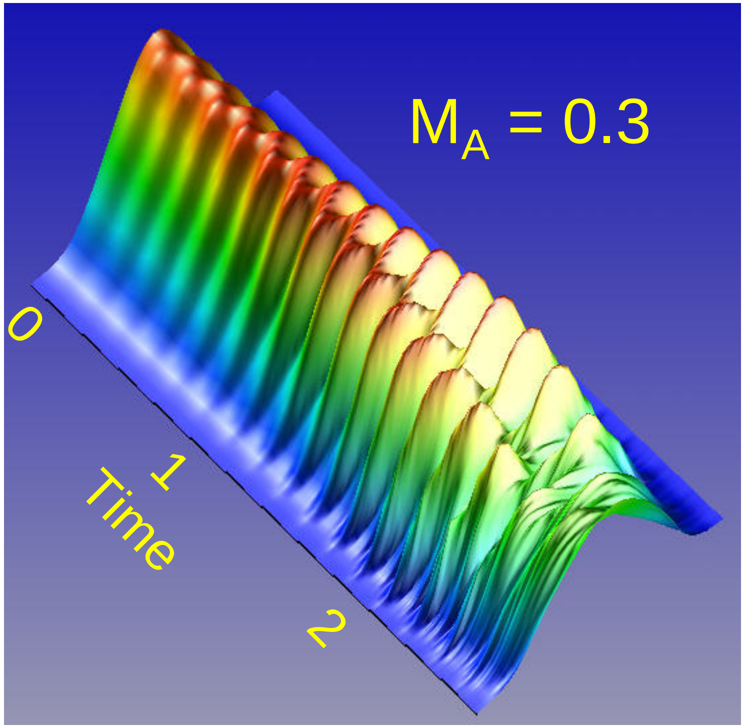
- Solutions in collisionless limit will have $\Phi=\Phi(\psi,\theta)$

M3D: Sheared-flow reduces growth rate by factor of 2-3

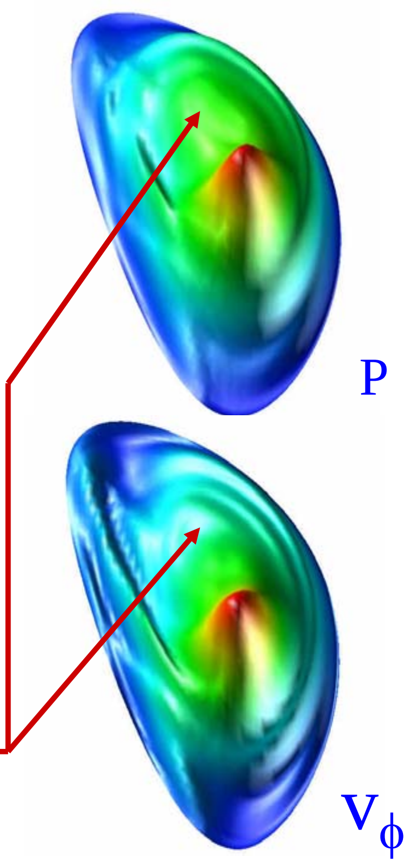
- **Possible because $\gamma_{shear} \sim \Omega_{rotation}$ can be of > γ_{linear}**

Simulated SXR signals



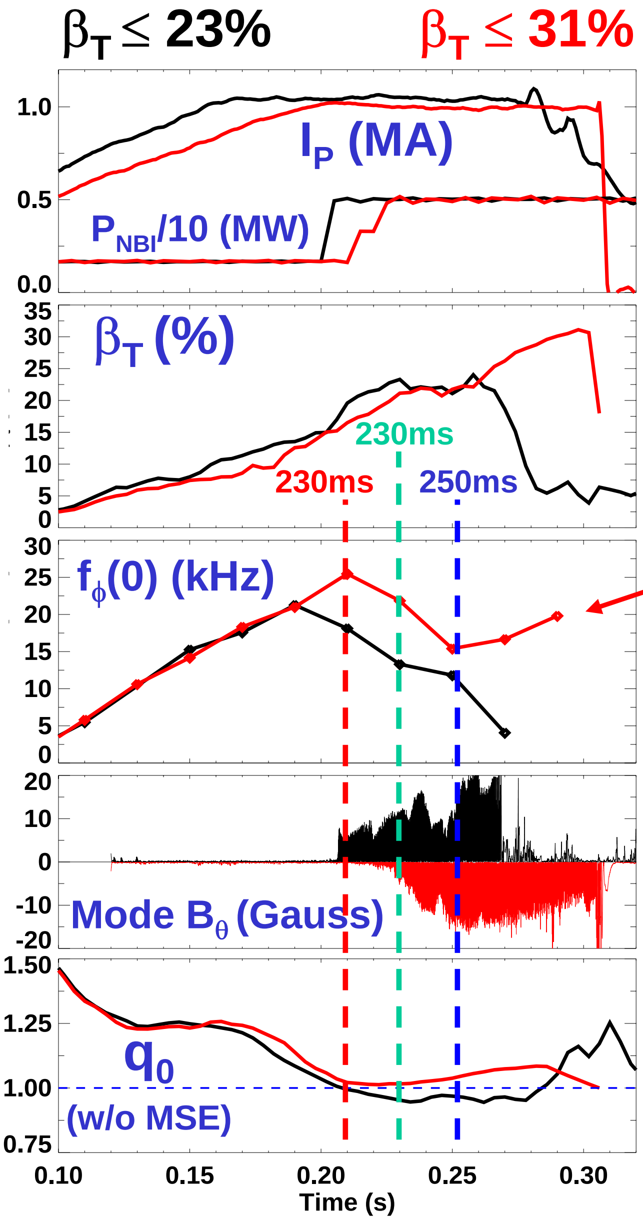


M3D simulations



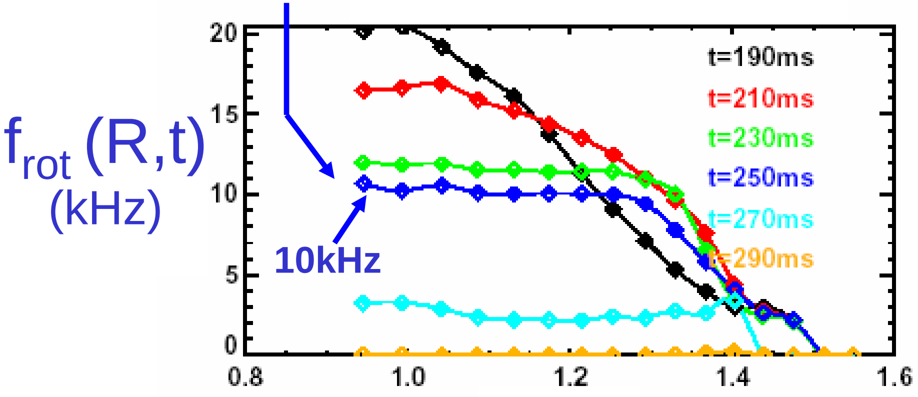
- In experiment, the NBI power is held roughly fixed
- In **M3D**, with a *fixed momentum source rate*, the v_ϕ and ***p*** profiles *flatten* inside the island, **reconnection *still* occurs (saturated state rare)**

Rotation data ⇒ shear-flow correlates with saturation

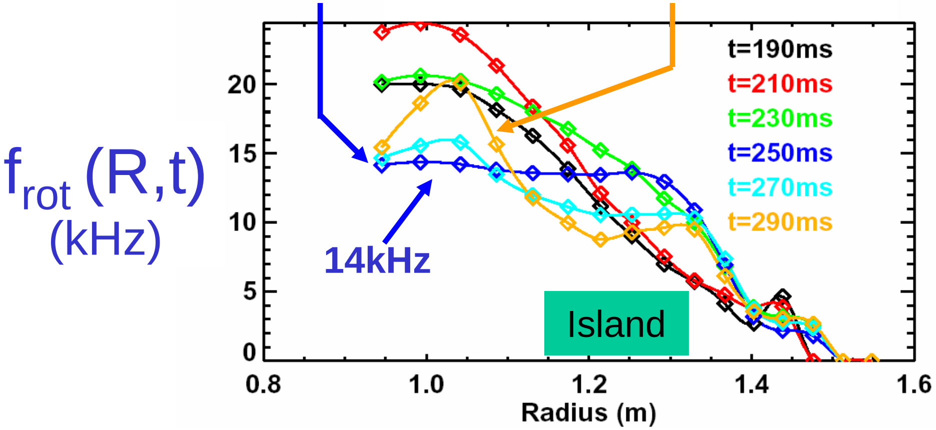


NOTE: Carbon f_ϕ data is 20ms average >> τ_{growth} , $1/f_\phi$

β_T=23% - Rotation flattens, broadens, collapses



β_T = 31% - Rotation flattens, then core recovers



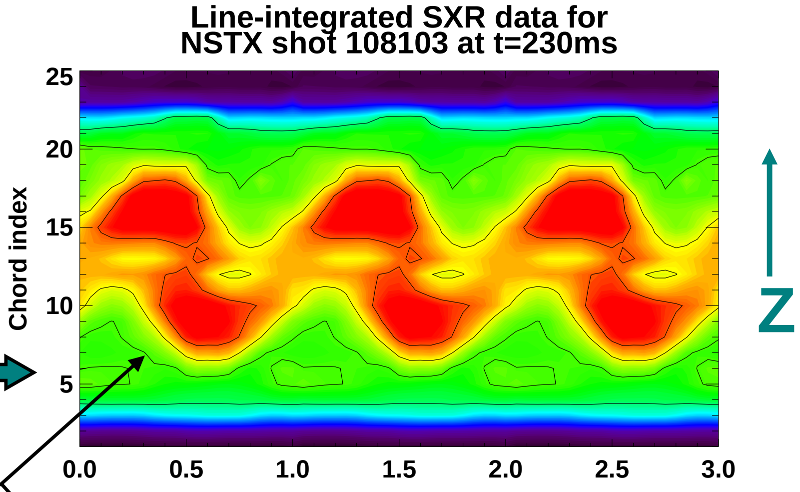
Favorable q or Ω_ϕ profile slows mode growth?
Enough rotation retained for later saturation?

SXR inversion aids analysis of mode evolution

- Perturb EFIT equilibrium **helical flux** with *m*/*n* = **1/1** $\delta\psi_h$
  - Reconstruct <u>total</u> emission as function of <u>total helical flux</u>

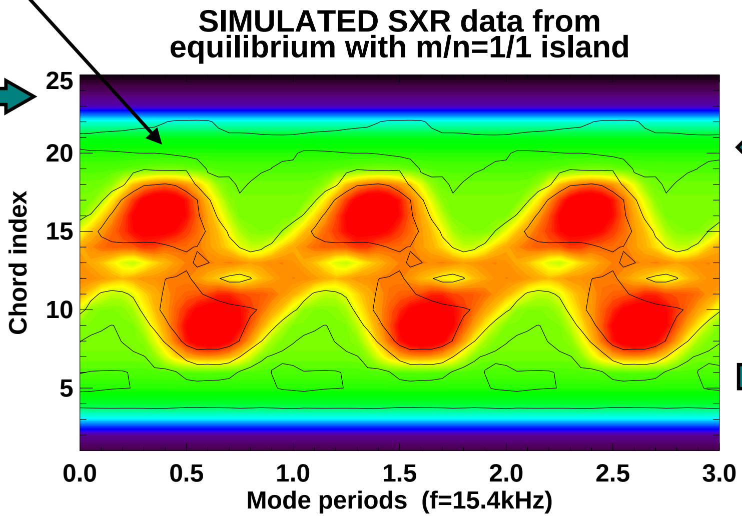
Island model fits data well

SXR Data



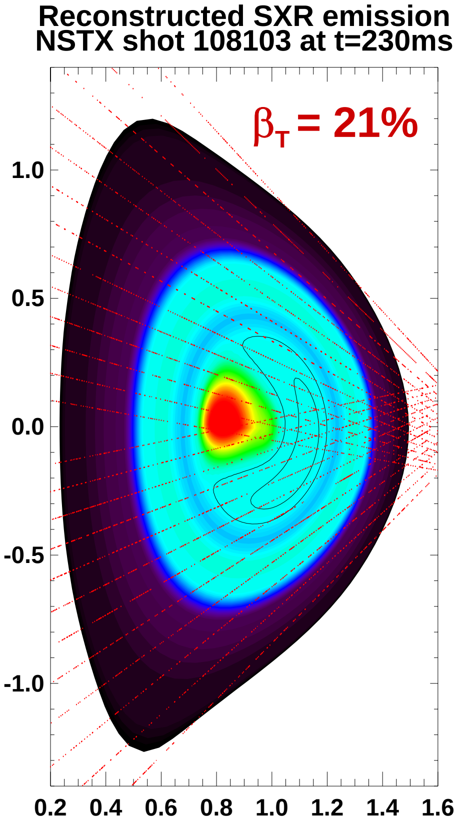
Contours from *SXR data*

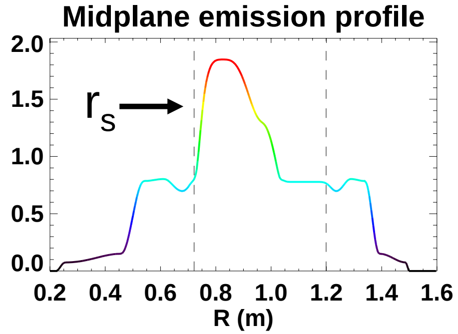
Island Model



<u>Fit error < 6%</u>

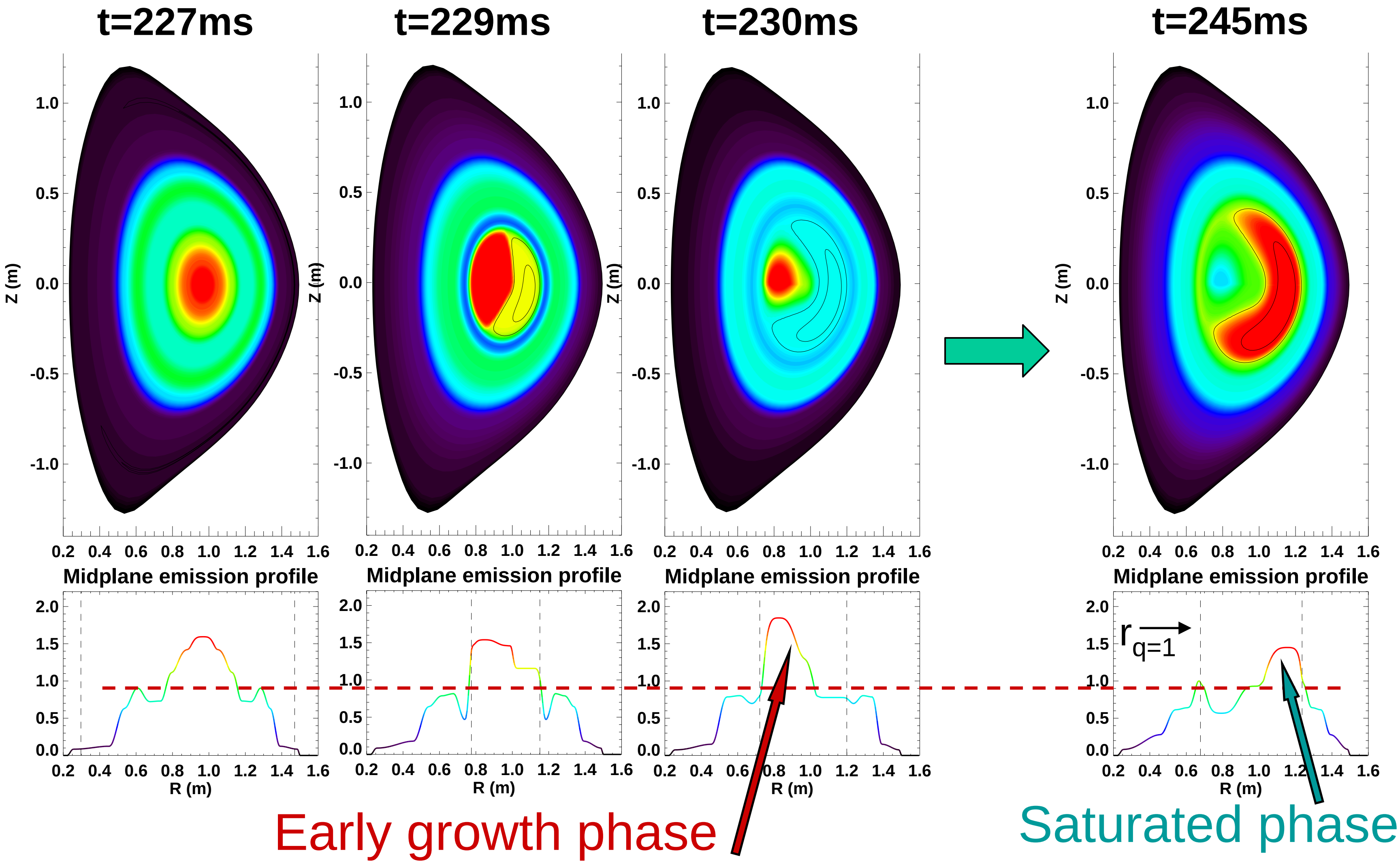
r_s = 0.43
w = 0.3
f = 15.4 kHz





SXR data consistent with incomplete reconnection

$\beta_T \leq 31\%$ island grows slowly ($\tau \approx 1$ms), saturates with $r_{q=1} \approx 0.5$



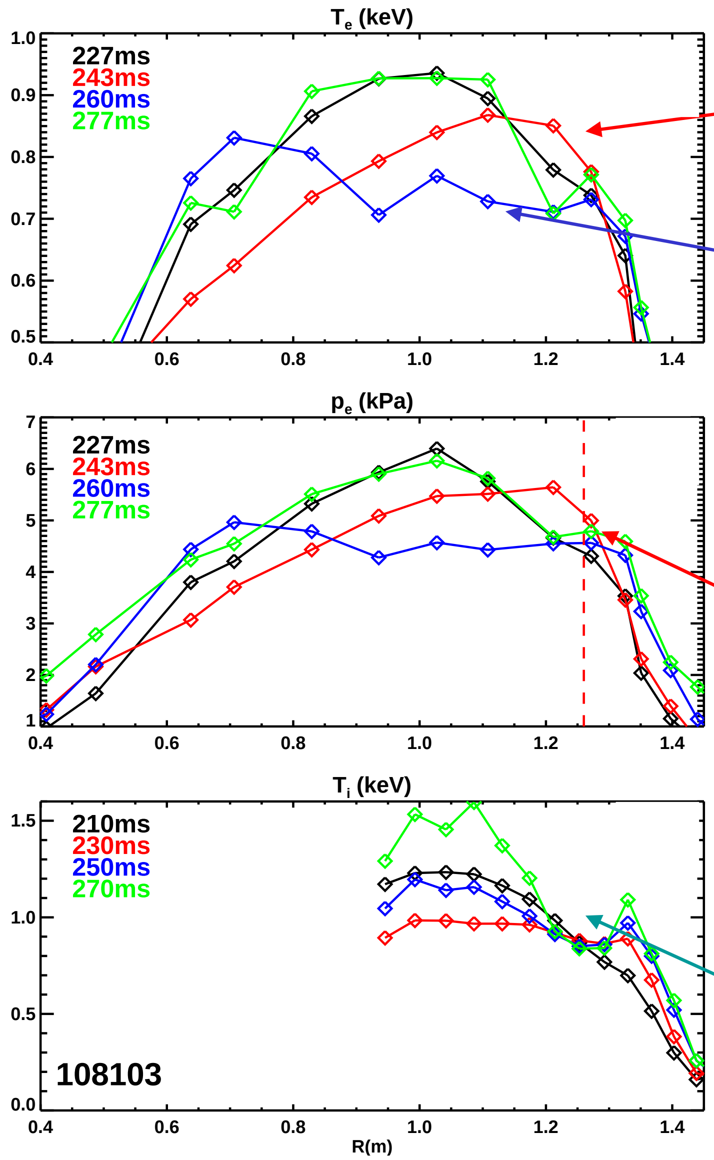
Early growth phase

emission highest in displaced core

Saturated phase

emission highest in island

Kinetic profiles ***inconsistent*** with *p* peaking inside island



Core clearly displaced by island

Flat-spot in T_e observed

Interpreted as island O-point

Electron pressure evolution similar

Density profile is nearly flat

p_e highest in displaced core

∇p_e enhanced by mode near q=1

Time average T_i has local minimum in island region during saturation

Max. p_i in island region unlikely

Non-linear diamagnetic effects may aid 1/1 saturation

- **High $\beta \Rightarrow$ increased $\omega_{*i} / \omega_A \propto \beta_i A \delta_i /a$** ⟵ **A = R_0/a = plasma aspect ratio**
  δ_i = ion skin depth, a = minor radius
- **Displacement of plasma core by island can enhance local pressure gradient and magnetic shear in reconnection region:**
  - Quasilinear stability criterion with $\omega_{*e} = 0$: ⟶

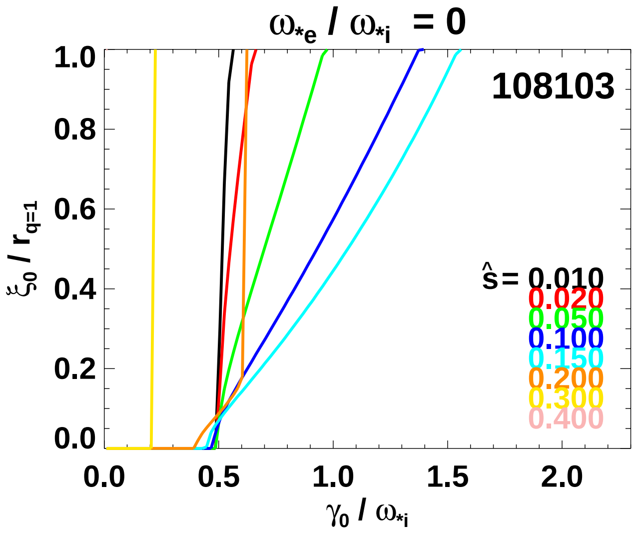
ROGERS, B. and ZAKHAROV, L., Phys. Plasmas 2 (1995) 3420.

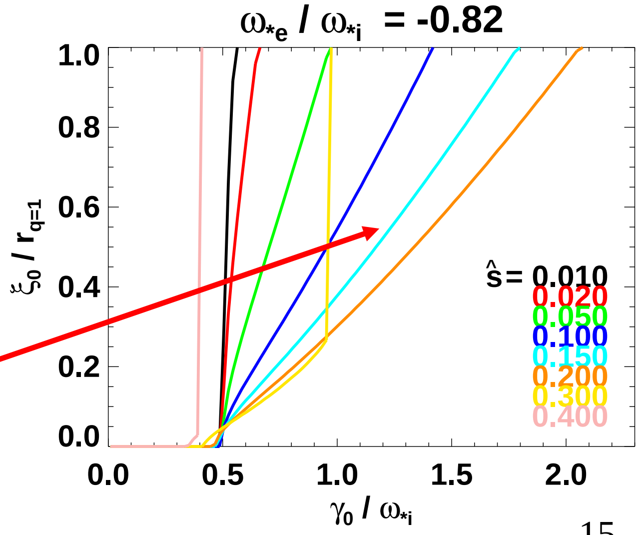
$$\alpha\omega_{*i}\tau_A > 2\sqrt{(\gamma_0\tau_A/\bar{q}')^2 + (\bar{q}'q')^2(\rho_s^2 + 5d_e^2)/2}.$$

$$\alpha = 1 + 2\chi^2 \qquad \bar{q}' = 1 + 6\chi^2 \qquad \chi = \xi_0/2\pi\lambda_h$$

  - γ_0 = ideal MHD linear growth rate
  - ω_{*i} = ion diamagnetic frequency
  - **ξ_0 = radial displacement of magnetic axis**
  - λ_h = ideal mode layer width
  - ρ_s = ion-sound Larmor radius
  - d_e = collisionless electron skin depth
  - $\hat{s}$ = normalized shear = r dq/dr

- **Significant non-linear stabilization possible**
  - Inclusion of electron diamagnetism important
  - Shear parameter $\hat{s} \approx 0.15$ allows $\xi_0 / r_{q=1} \approx 0.5$



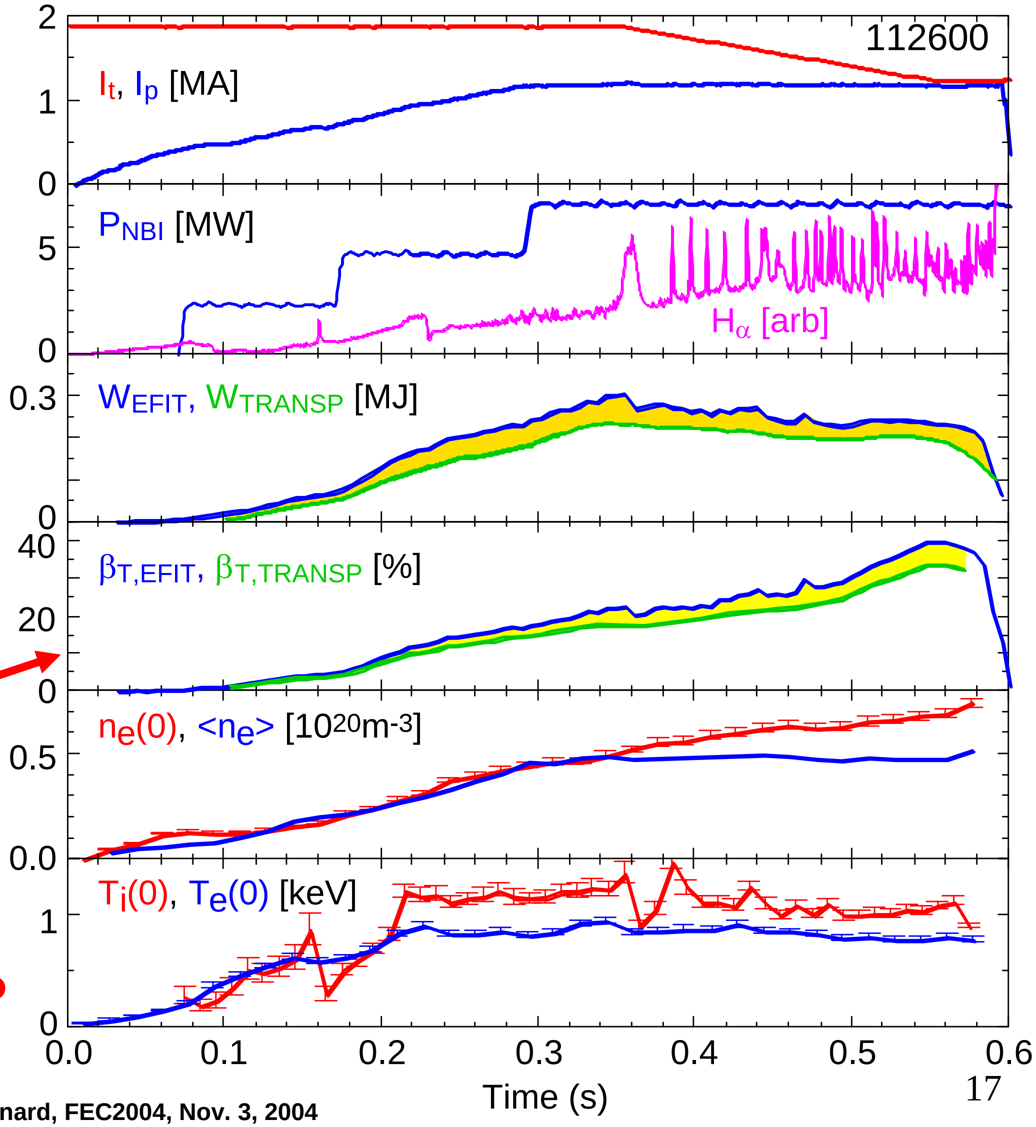


Flow damping physics

Operational and diagnostic upgrades have improved understanding of role of 1/1 mode in β and Ω_ϕ collapse

This run year:

- Early H-mode + high $\kappa \leq 2.6$ to raise q and lengthen pulse
- Achieved long 1.2MA pulses with **peak $\beta_T \leq$ 40%** in recent experiments (34% TRANSP)
  - Highest β "confirmed" by kinetics thus far (112600)
  - Improved resolution (in R, t) charge exchange diagnostic
  - Internal RWM sensors
- **Why does collapse occur?**



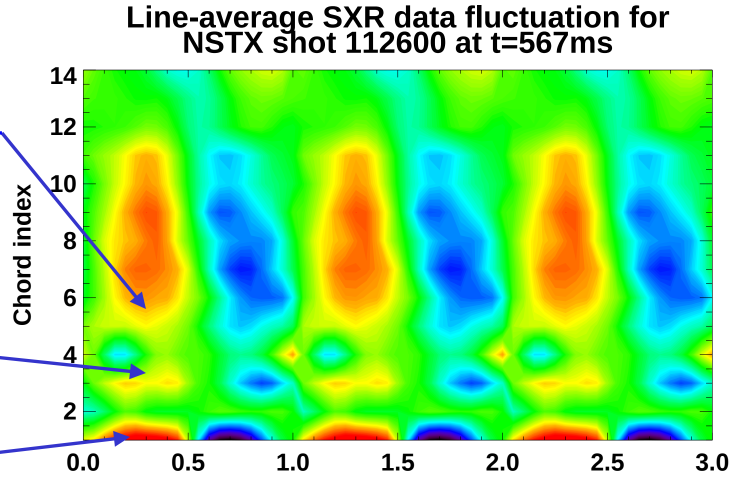
J.E. Menard, FEC2004, Nov. 3, 2004

SXR indicates coupled 1/1 and 2/1 modes during disruption of this high-β discharge

1/1 mode + SXR locate q=1 position

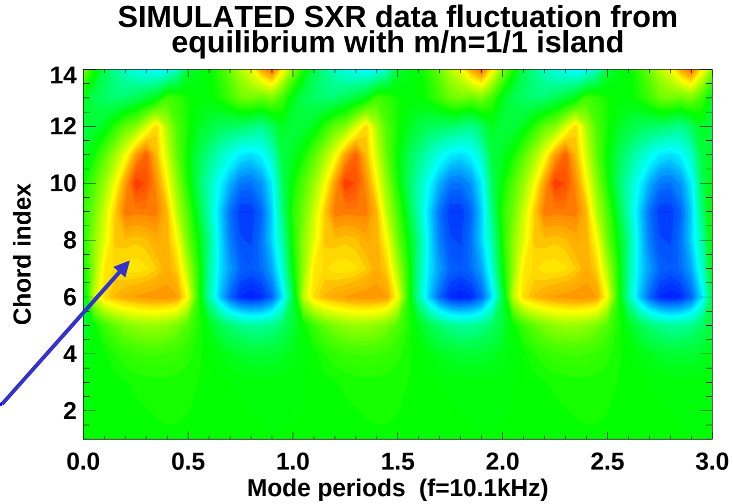
2/1 mode

Edge mode

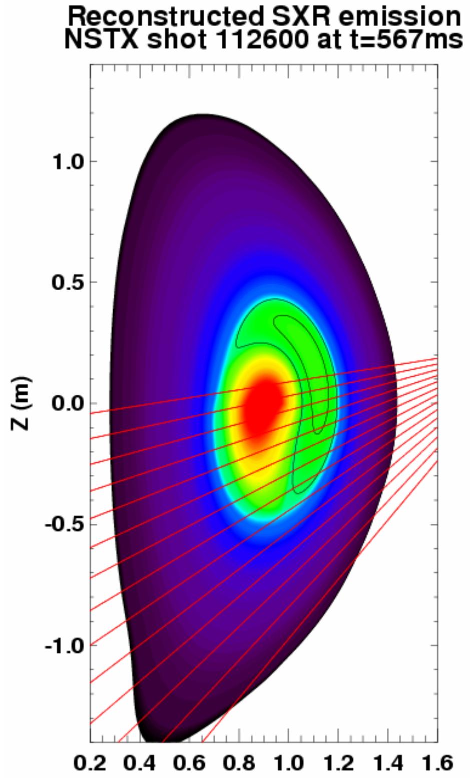


Line-average SXR data fluctuation for NSTX shot 112600 at t=567ms

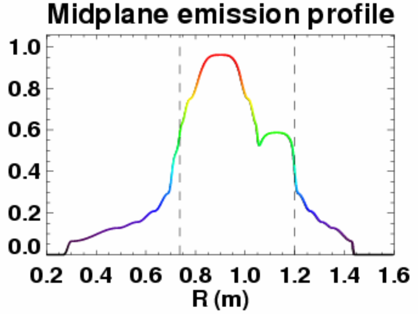
Simulated line-average emission fluctuation from model 1/1 mode



SIMULATED SXR data fluctuation from equilibrium with m/n=1/1 island

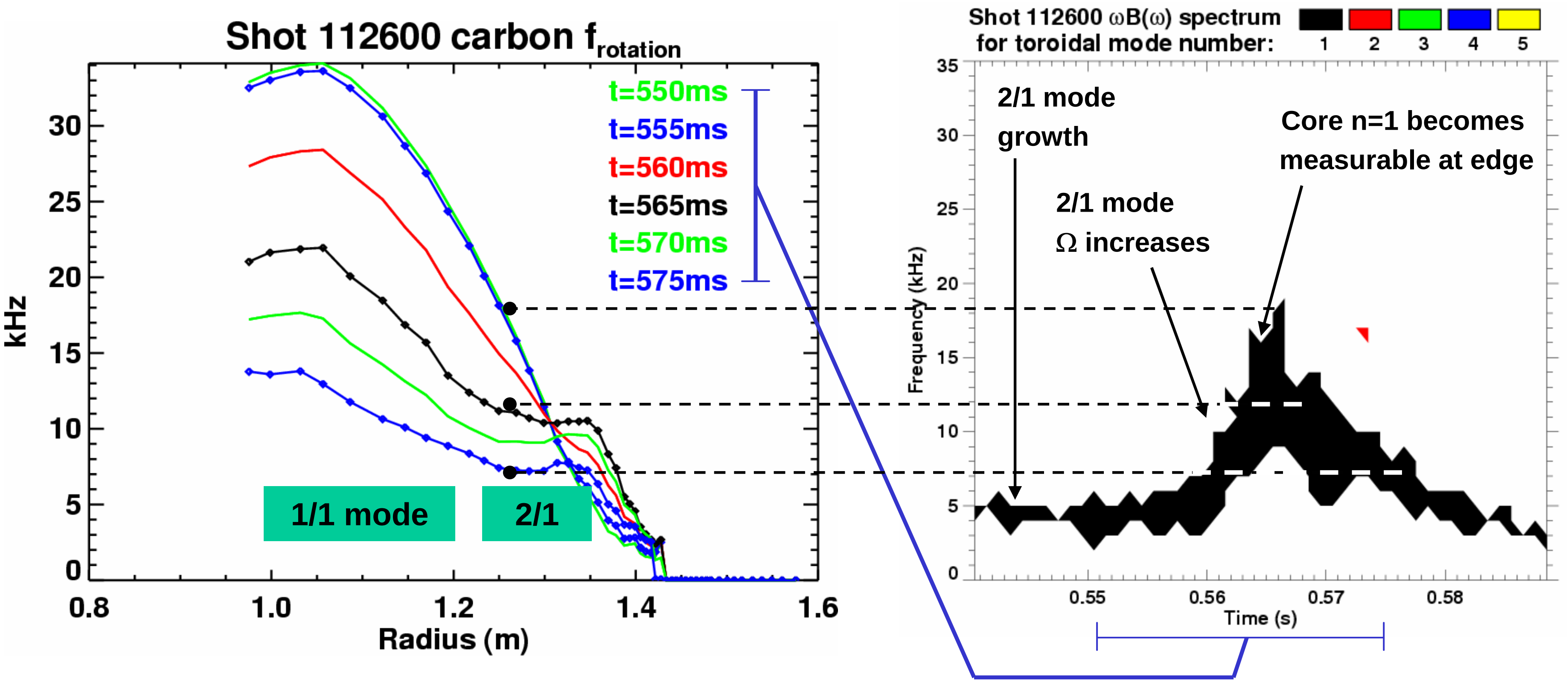


Reconstructed SXR emission NSTX shot 112600 at t=567ms



Midplane emission profile

Rotation profile decays with 2/1 island locked to local fluid Ω_ϕ



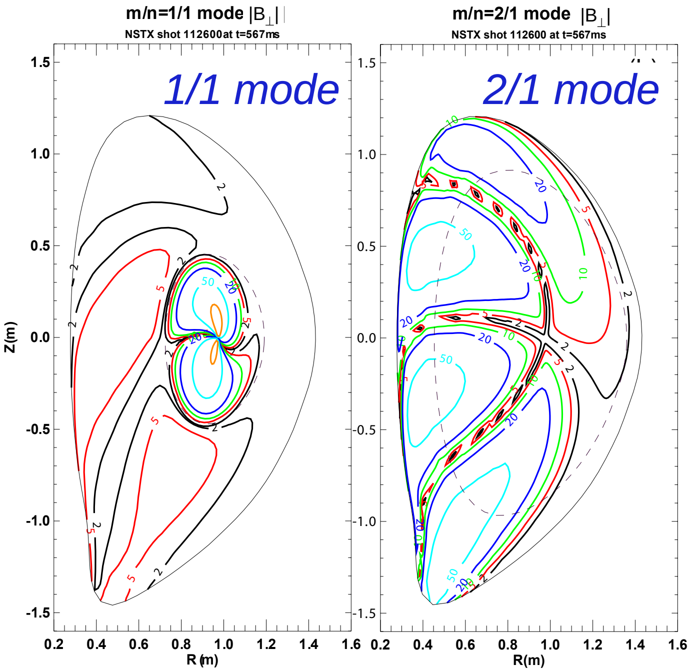
2/1 mode phase-locks with core 1/1 mode, and core mode apparently flattens rotation profile…

Core plasma rotation flattening consistent with combined torques of 1/1 and 2/1 modes

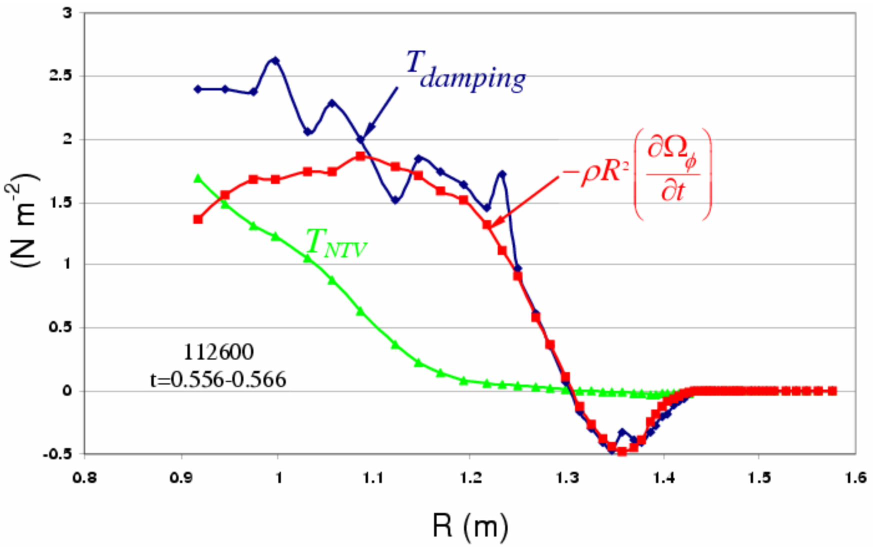
Torque balance $\Rightarrow$

$$\rho R^2 \frac{\partial \Omega_\phi}{\partial t} - \underbrace{R^2 \frac{1}{r}\frac{\partial}{\partial r}\left[\rho \mu_\perp r \frac{\partial \Omega_\phi}{\partial r}\right] + T_{NTV} + T_{EM}}_{\longrightarrow \boldsymbol{T_{damping}}} \text{(on island only)} = S_\phi$$

SXR $\Rightarrow \delta\Psi_h \Rightarrow b_r^{m,n}$



$$T_{\text{NTV}} \sim \left(T_{\text{i}}\right)^{\frac{1}{2}} \sum_{m,n} \left(\Omega_\phi - \Omega^{m,n}_{\text{mode}}\right)\left(\frac{b_r^{m,n}}{B}\right)^2$$

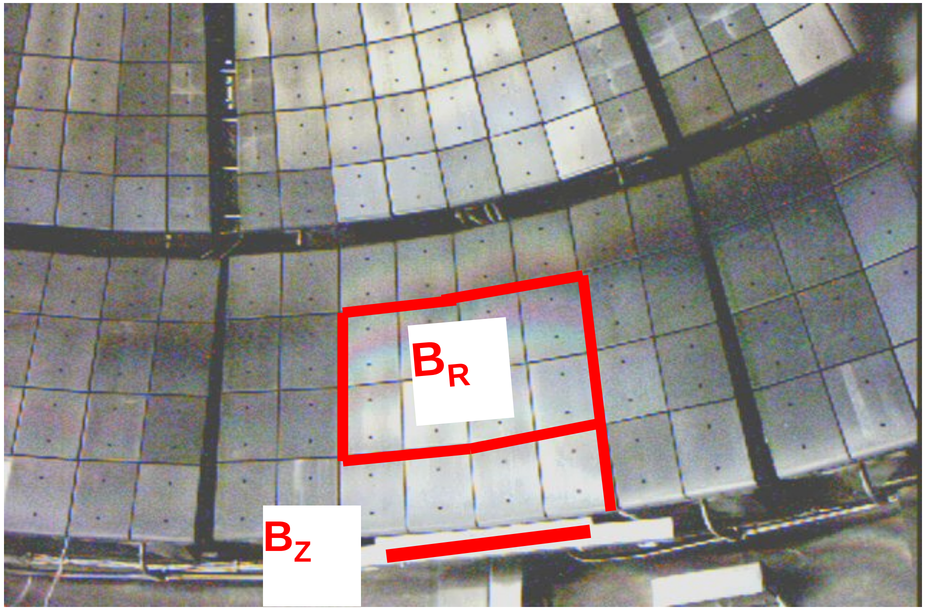


- **Total rotation damping rate $T_{damping}$ is sum of multiple effects:**
  - **Neoclassical Toroidal Viscous (NTV) differential torque from 1/1 mode**
  - **Entrainment of plasma mass inside 2/1 island (T_{EM} small)**
  - **Fluid viscosity outside islands**

New in-vessel magnetic sensor arrays are used to detect low-f modes during rotation decay of high-β discharges

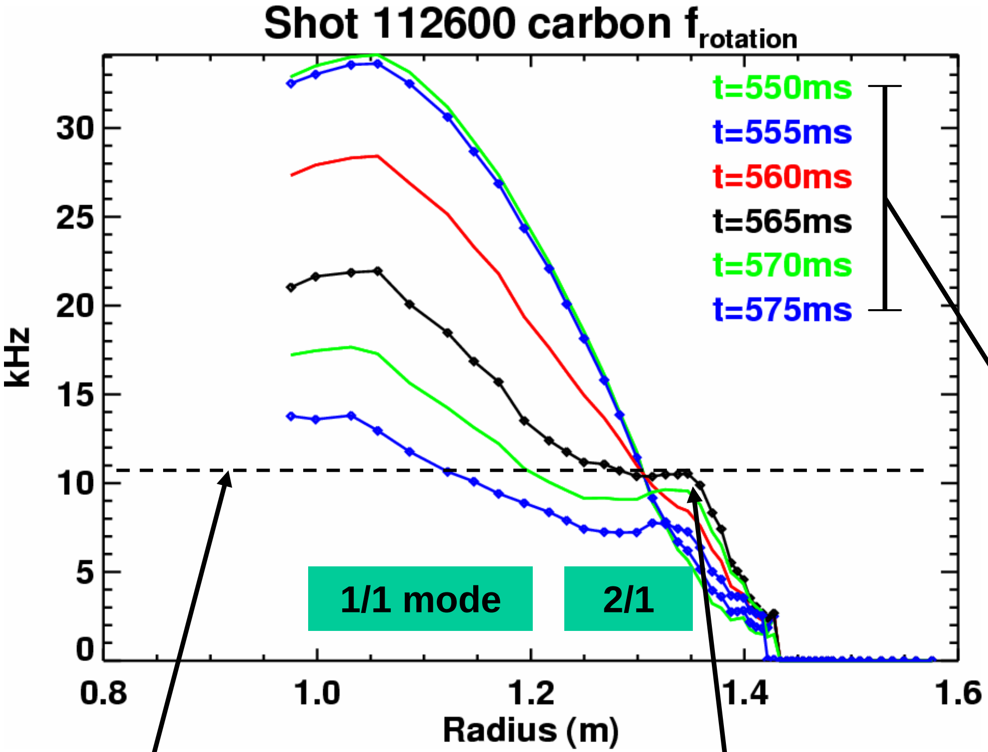
- **Greatly improved detection of f < 2kHz modes with n ≤ 3**

- 24 each large-area internal B_R, B_Z coils commissioned this run
  - Mounted on passive stabilizers
  - Symmetric about midplane



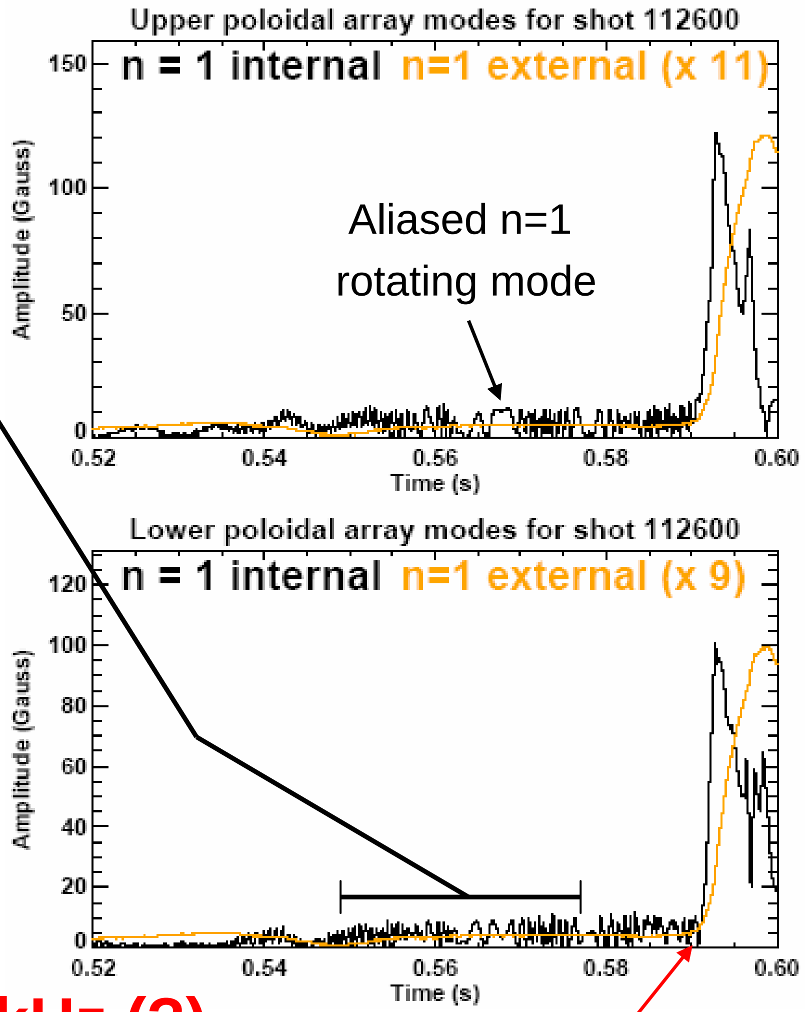
- **Internal sensor signal greater than external by factor of 5**
- **Internal sensors reveal clear up/down mode asymmetry**

Internal sensors indicate unstable RWM not present in early phase of rotation collapse



Mode f_ϕ at 565ms

Edge rotation increases after mode onset



RWM unstable once $f_{rotation}$ < 2-3kHz (?)

Summary

- **Highest β_T shots in NSTX can be limited by 1/1 modes**

- **Modes often saturated for $\tau \gg \tau_{growth}$, high-β sawteeth rare**

- **Modes degrade fast-ion & thermal confinement + rotation**

- **Sheared flow and diamagnetic effects most likely suspects in explaining non-linear mode saturation**

- **Core Ω_ϕ flattening consistent with 1/1 mode NTV damping**

- **Coupling to other modes at high β can cause global rotation collapse and lead to plasma disruption**