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MHD, disruptions, and control on NSTX - status and plans

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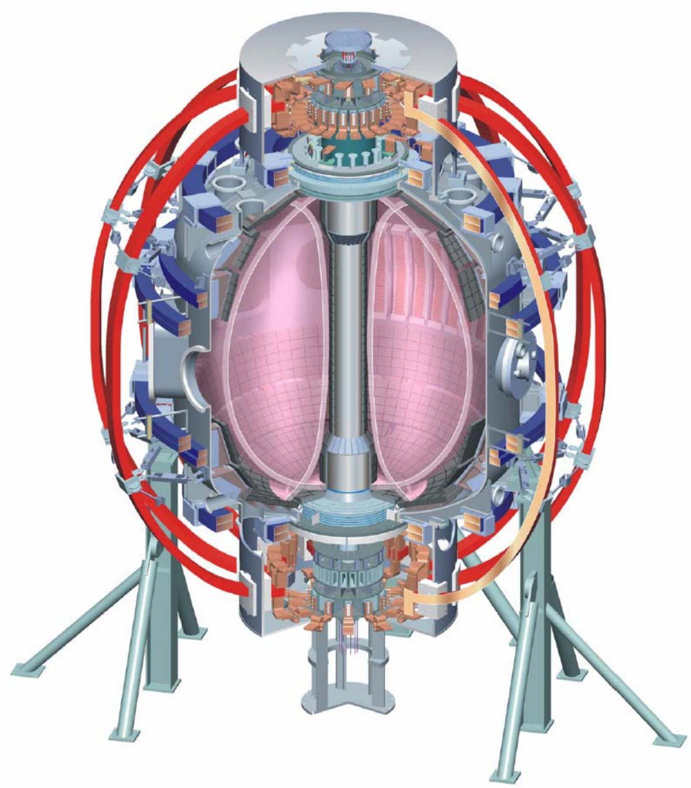

Task Group Meeting on MHD, Disruptions, and Control

November 8-10, 2004
Lisbon, Portugal

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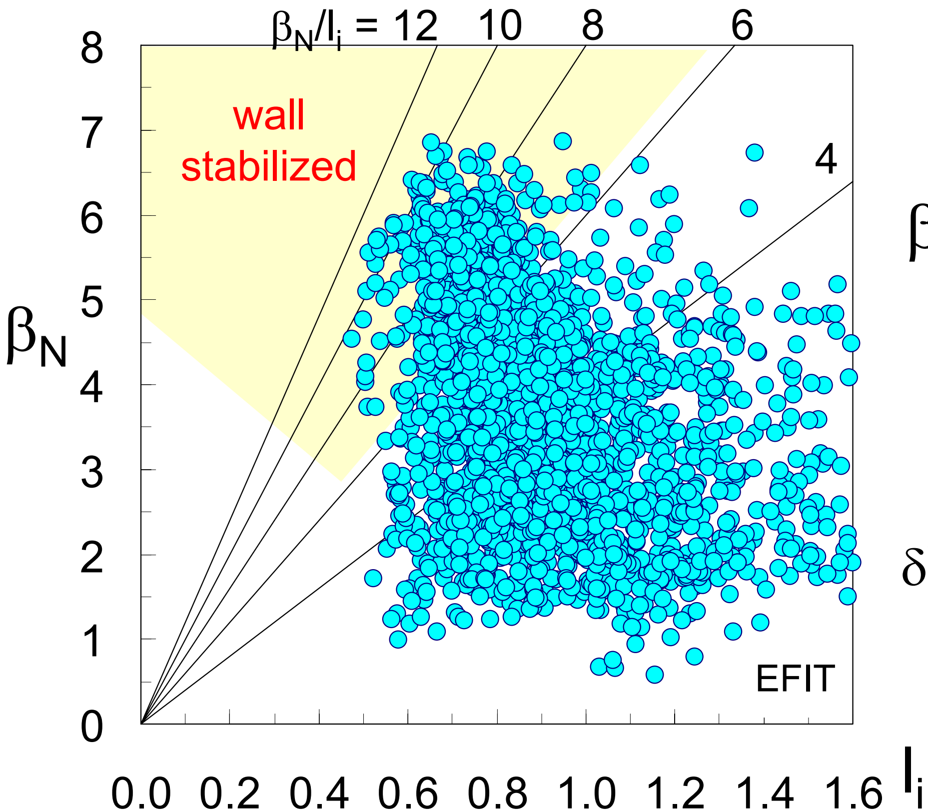
Overview

- NSTX research can contribute to many issues relevant to the M, D, & C task group
- This presentation contains content on:
  - Resistive wall mode physics
  - Internal disruptions and flow damping
  - Locked modes and error fields
  - Plasma control and modeling
- NSTX had MSE for first time during last run
  - 4 core channels, and only for last few weeks of run
    - Initial reconstructions of q_0, q_{min} consistent with MHD signatures
  - 14 channels next year → well constrained $q(\psi)$ profile
    - Very challenging measurement at B_T = 0.3T

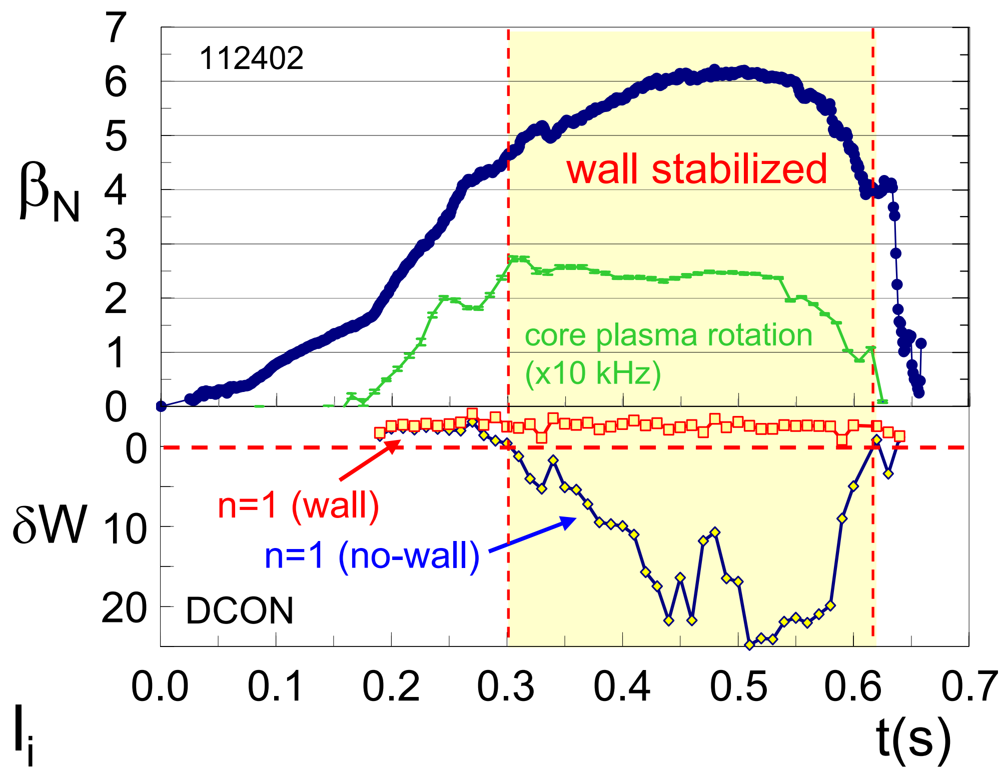
RWM physics

Wall stabilization physics understanding is key to sustained plasma operation at maximum β

- High β_t = 39%, β_N = 6.8 reached



- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ > 1.3 at highest β_N for pulse >> τ_{wall}



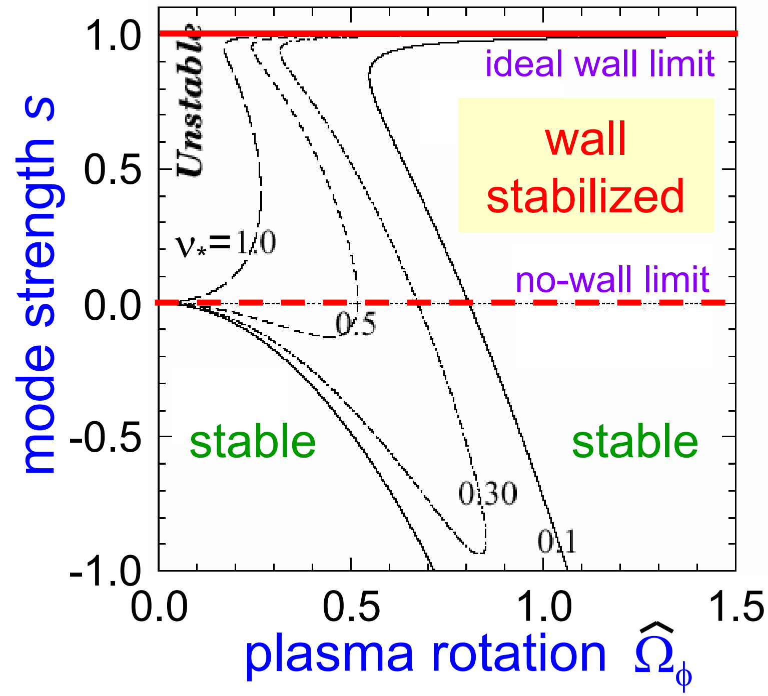
- Global MHD modes can lead to rotation damping, β collapse
- Physics of sustained stabilization is applicable to ITER

Theory provides framework for wall stabilization study

- This talk: Resistive Wall Mode physics
  - RWM toroidal mode spectrum
  - Critical rotation frequency, Ω_{crit}
  - Toroidal rotation damping
  - Resonant field amplification (RFA)
  - Active stabilization system design
- Theory
  - Ideal MHD stability – DCON (Glasser)
  - Drift kinetic theory (Bondeson – Chu)
  - RWM dynamics (Fitzpatrick – Aydemir)

Fitzpatrick-Aydemir (F-A) stability curves

Phys. Plasmas **9** (2002) 3459

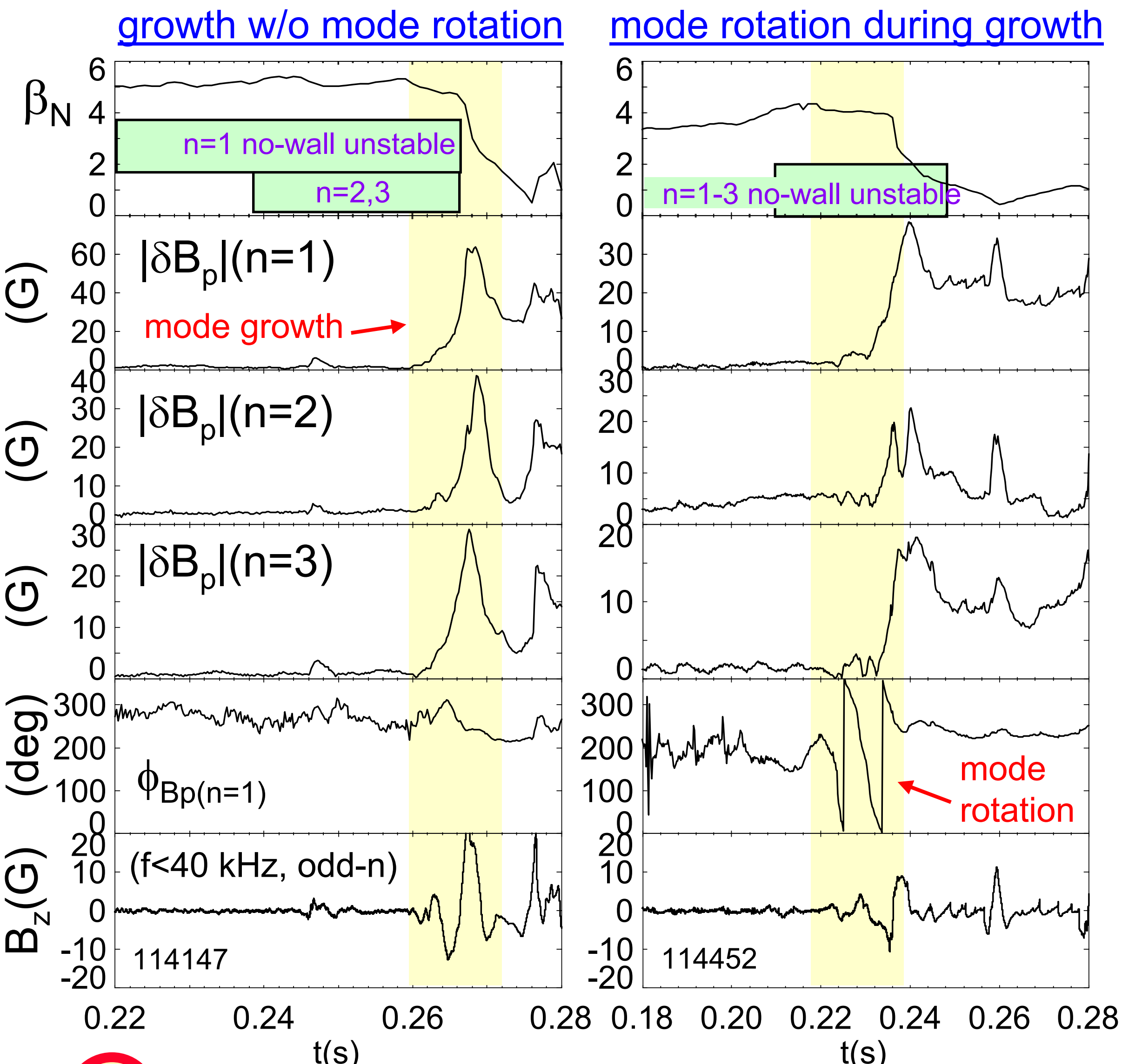


$$\left[\left(\hat{\gamma} - i\hat{\Omega}_\phi\right)^2 + \nu_*\left(\hat{\gamma} - i\hat{\Omega}_\phi\right) + (1-s)(1-md)\right]\left(S_*\hat{\gamma} + (1+md)\right) = \left(1-(md)^2\right)$$

plasma inertia — dissipation — mode strength — wall response — wall/edge coupling

$S_* \sim 1/\tau_{wall}$

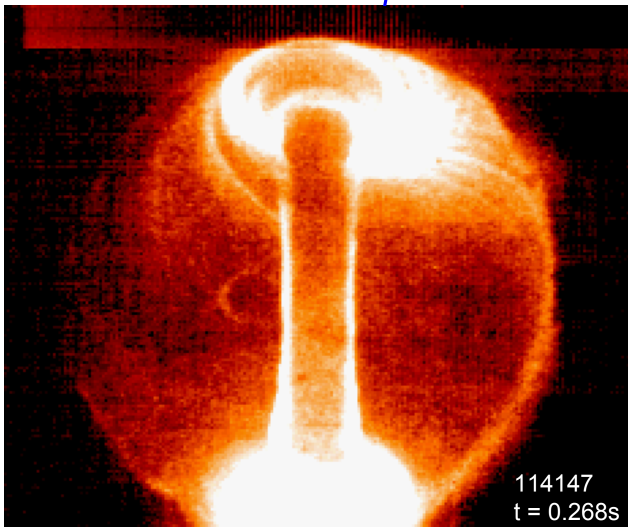
Unstable RWM dynamics follow theory



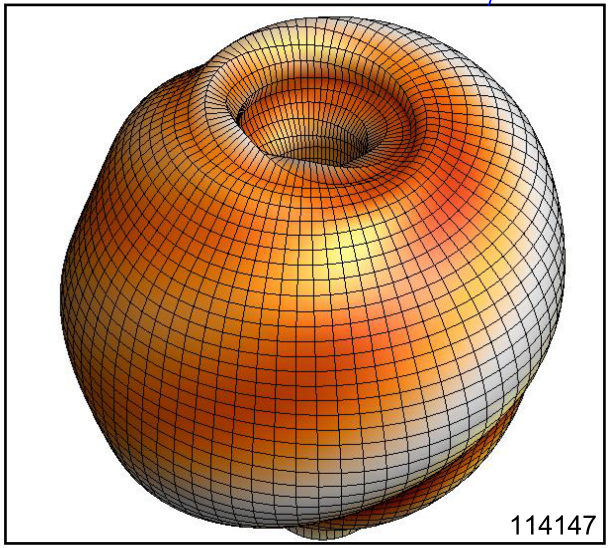
- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high β_N
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma flow
  - n=1 phase velocity not constant due to error field
- Low frequency tearing modes absent

Camera shows scale/asymmetry of theoretical RWM

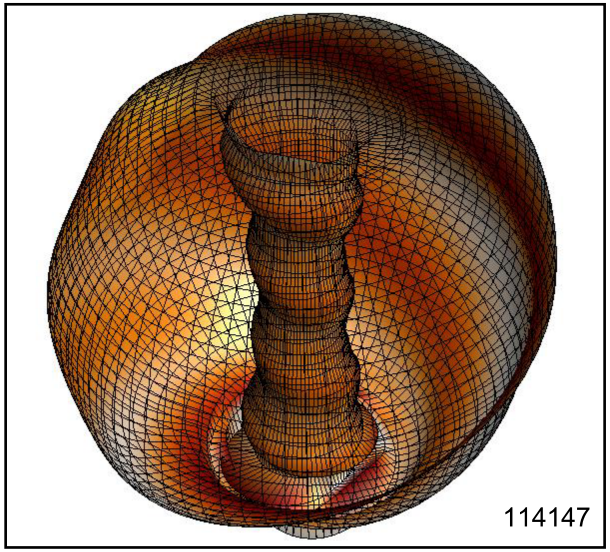
RWM with ΔB_p = 92 G



Theoretical ΔB_ψ (x10) with n=1-3 (DCON)

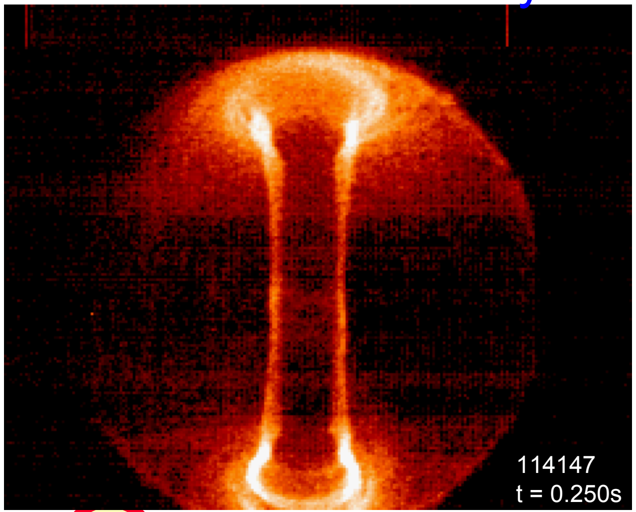


(exterior view)



(interior view)

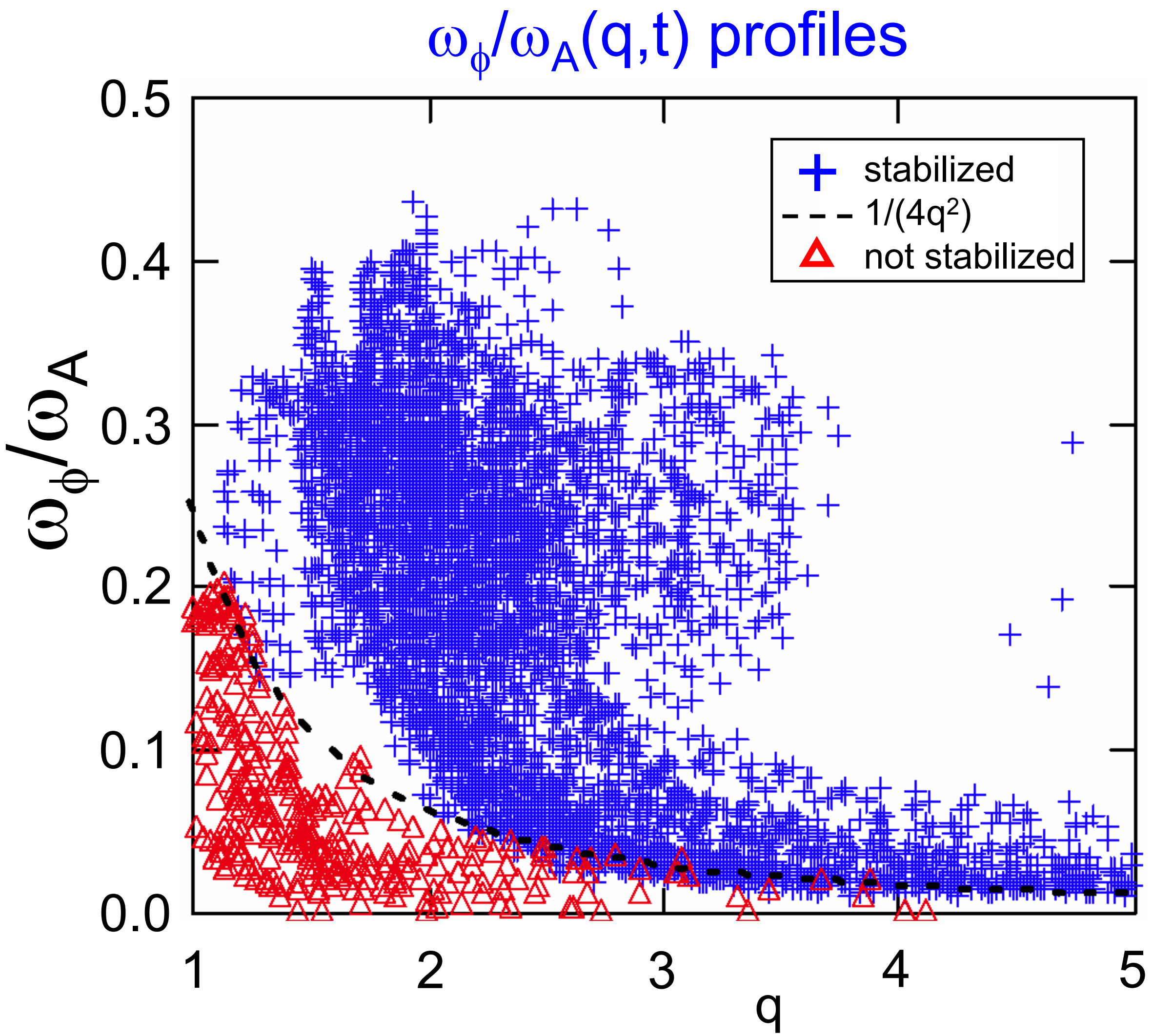
Before RWM activity



- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

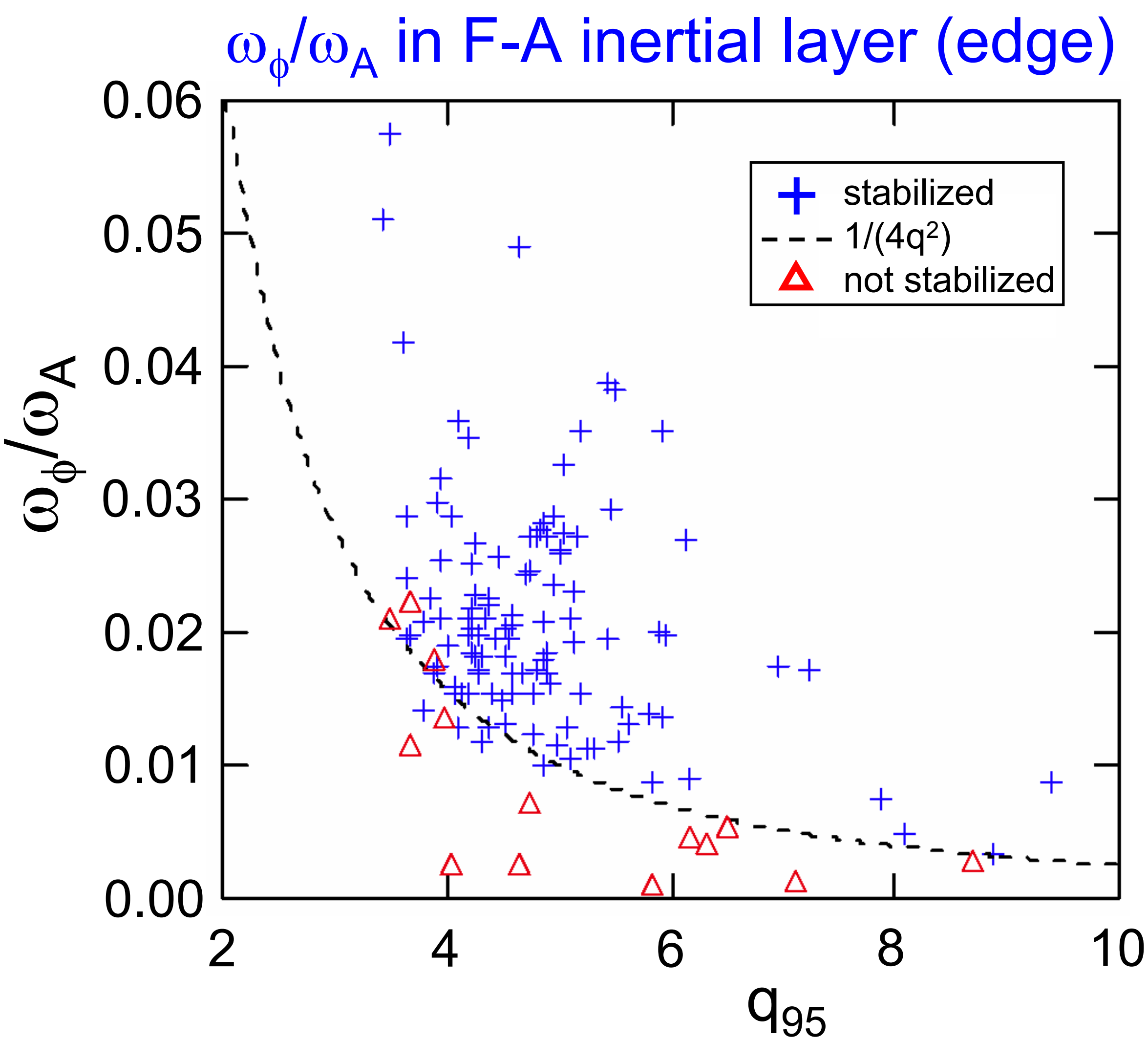
Experimental Ω_{crit} follows Bondeson-Chu theory

Phys. Plasmas **8** (1996) 3013



- **Experimental Ω_{crit}**
  - stabilized profiles: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - profiles not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- **Drift Kinetic Theory**
  - Trapped particle effects significantly weaken stabilizing ion Landau damping
  - Toroidal inertia enhancement more important
    - Alfven wave dissipation yields $\Omega_{crit} = \omega_A/(4q^2)$

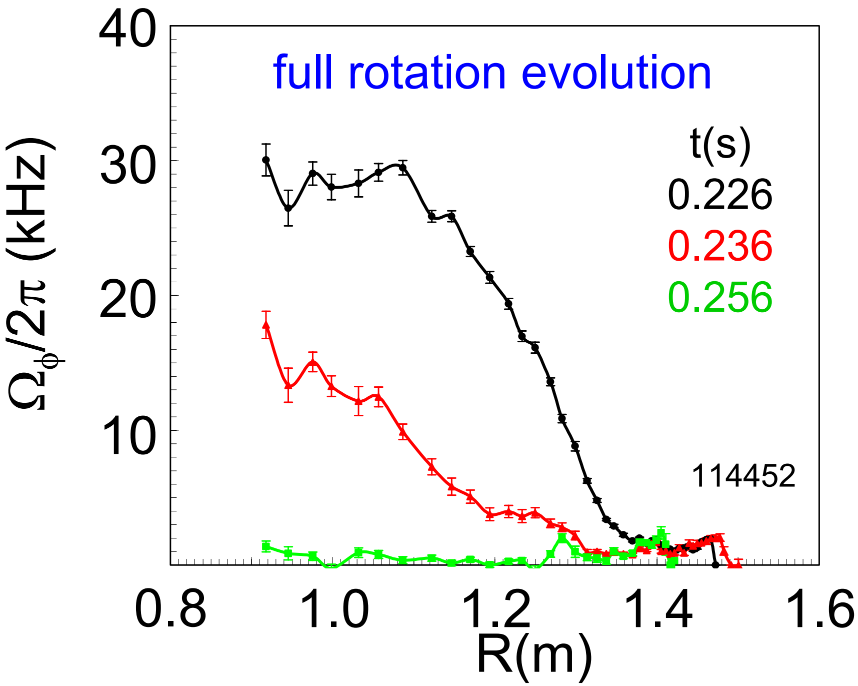
Ω_{crit} follows F-A theory with neoclassical viscosity

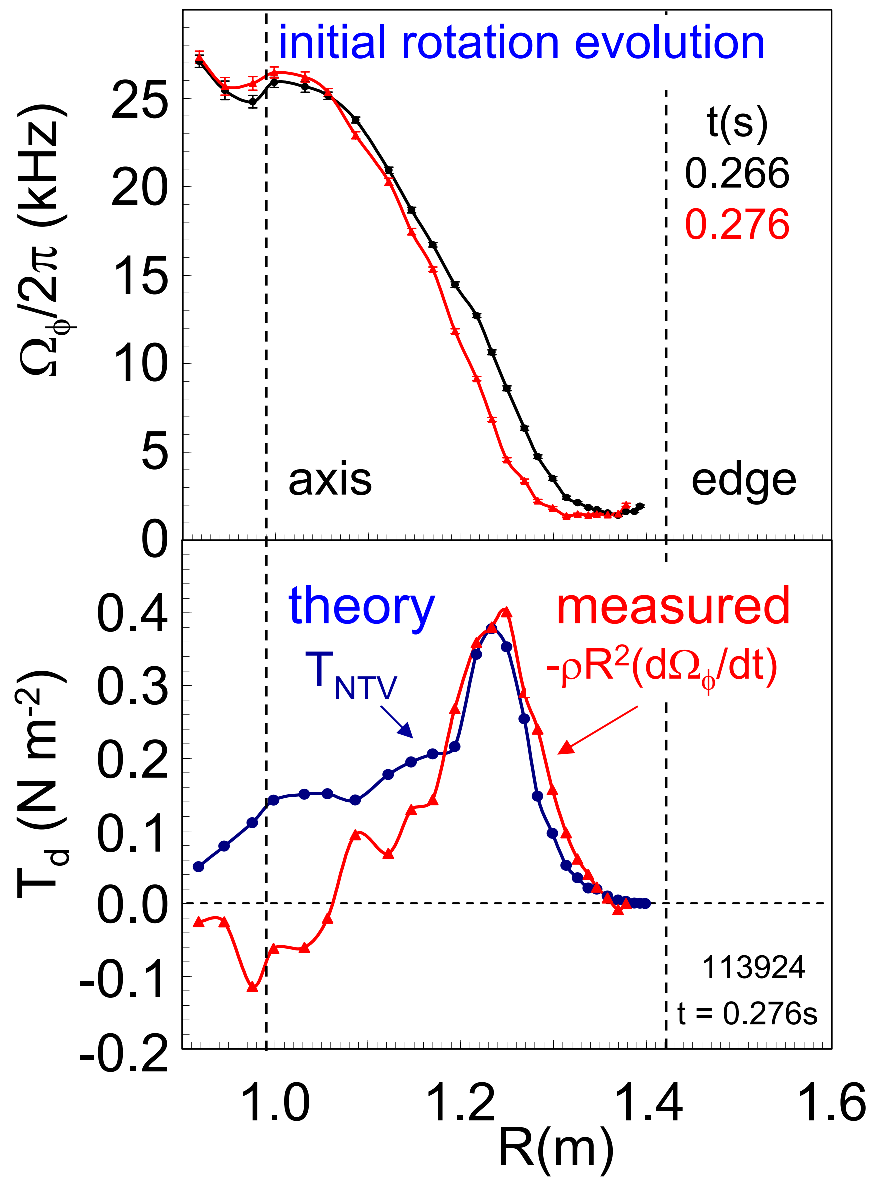


- **Experimental Ω_{crit}**
  - stabilized points: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - points not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- **F-A Theory**
  - Standard F-A theory has $\Omega_{crit} \sim 1/q$
  - neoclassical viscosity includes toroidal inertia enhancement (K. Shaing, PoP 2004)
    - yields $\Omega_{crit} \sim 1/q^2$

Plasma rotation damping described by NTV theory

- Neoclassical toroidal viscosity (NTV) ~ $\delta B^2 {*} T_i^{0.5}$
- Rapid, global damping observed during RWM
  - Edge rotation ~ 2kHz maintained
  - Low frequency tearing modes absent

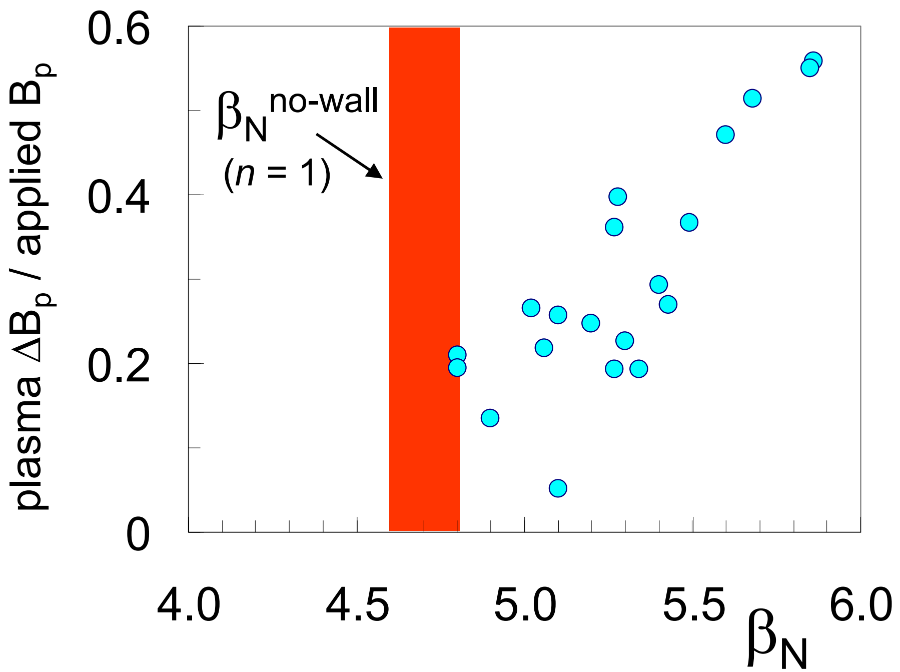


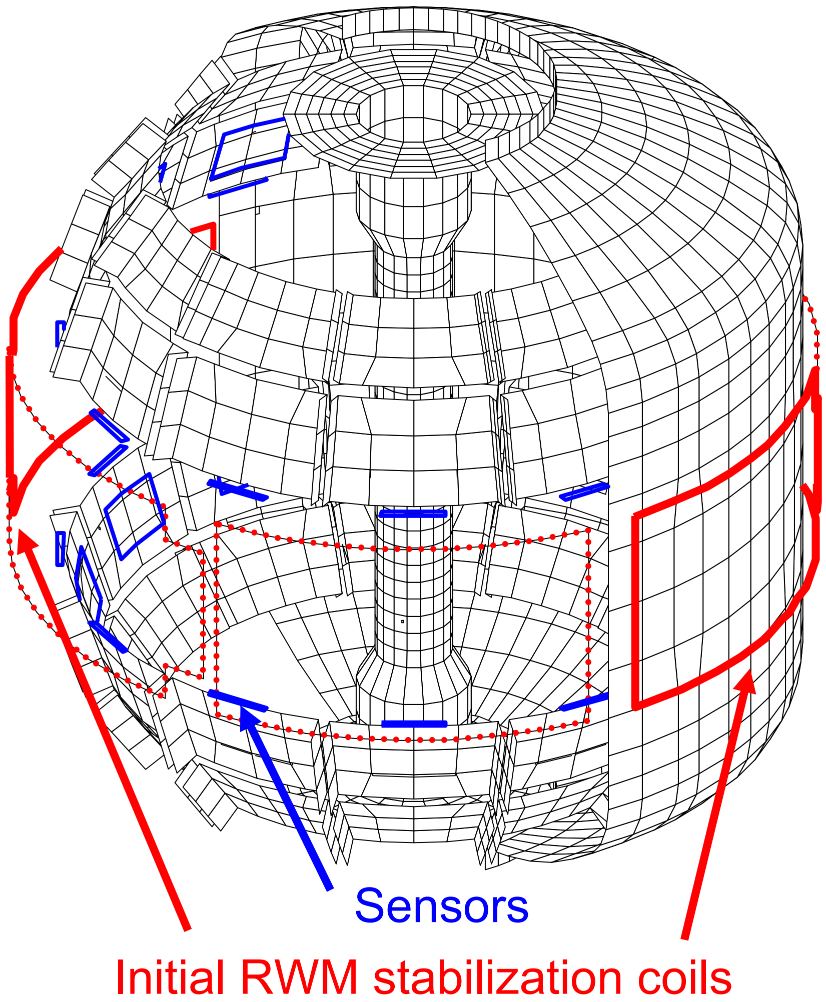


- Evolution detail differs for other modes
  - no momentum transfer across rational surfaces
  - no rigid rotor plasma core (internal 1/1 mode)

see EX/P2-26 Menard

Resonant Field Amplification increases at high β_N





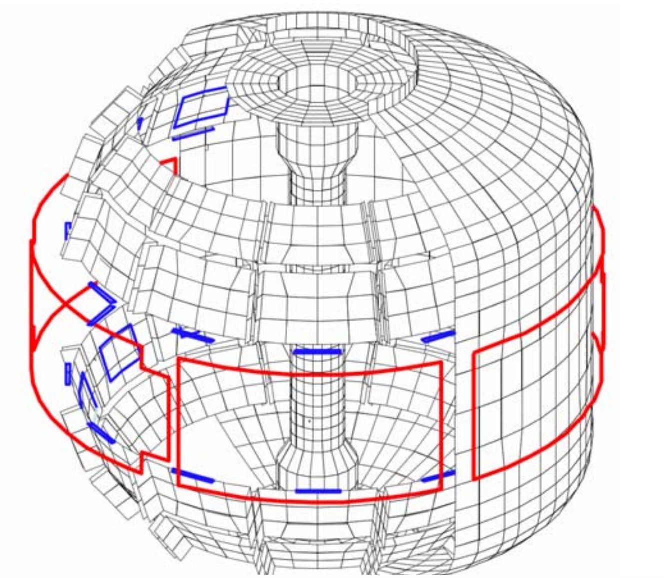
- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed n = 1 field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of $300 s^{-1}$ measured

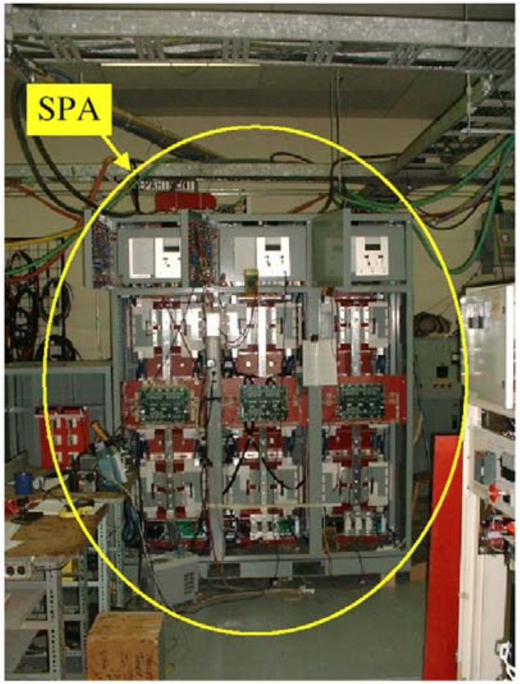
Completed coils will be used to suppress RFA, stabilize RWM, sustain high β

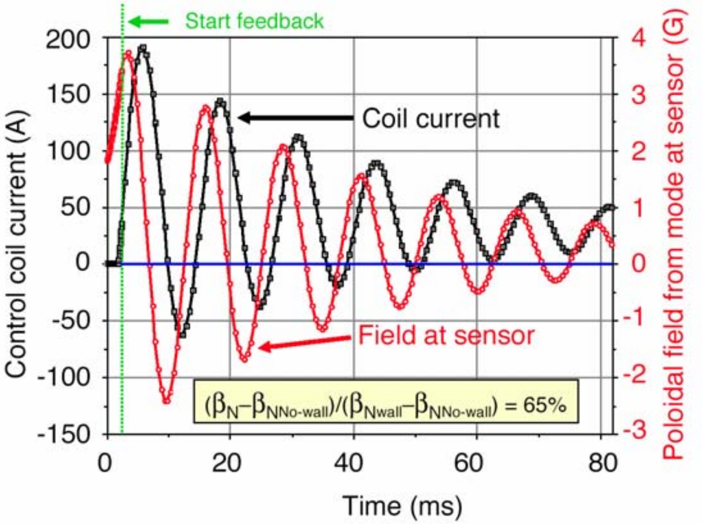
RWM stabilization system being installed for 2005 run

- RWM sensor array used in 2004 experiments
- 6 B_r coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback experiments

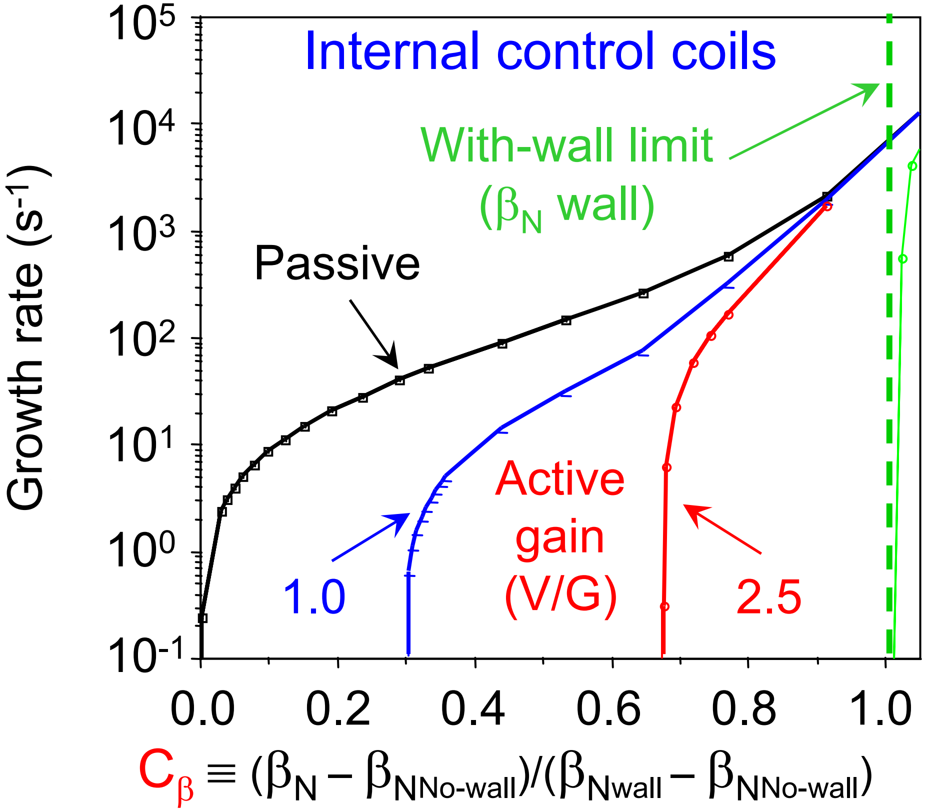
Physics design (VALEN code)

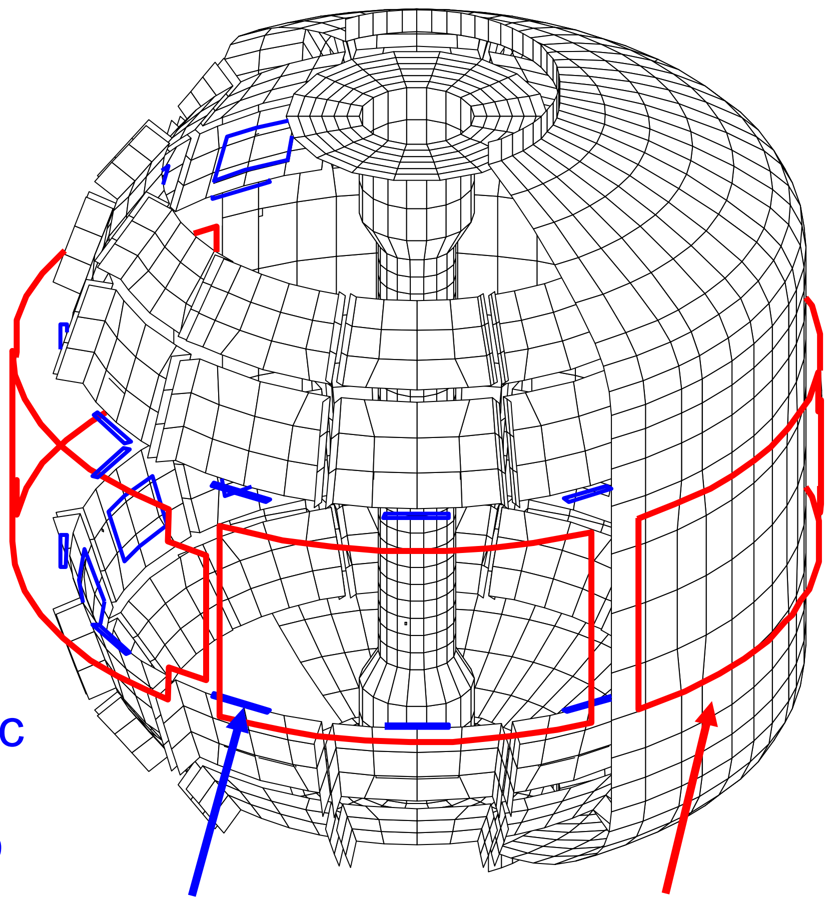






NSTX control modeling predicts 68% stable margin above $\beta_{Nno\text{-}wall}$ with initial external coil system



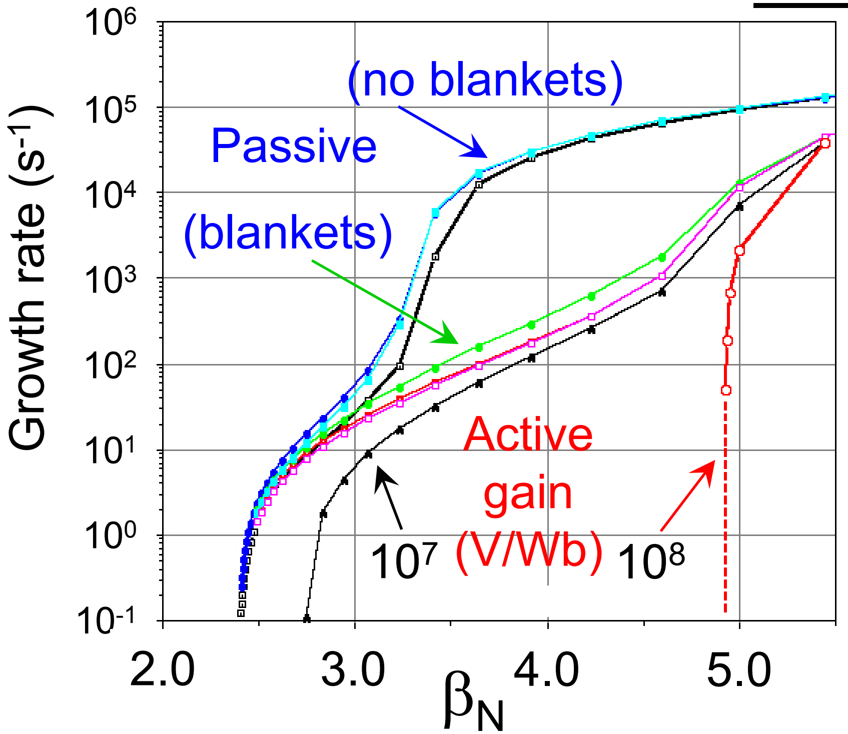


- Control coil / sensor design with realistic geometry
- Internal control coil design computed to reach C_β = 94%

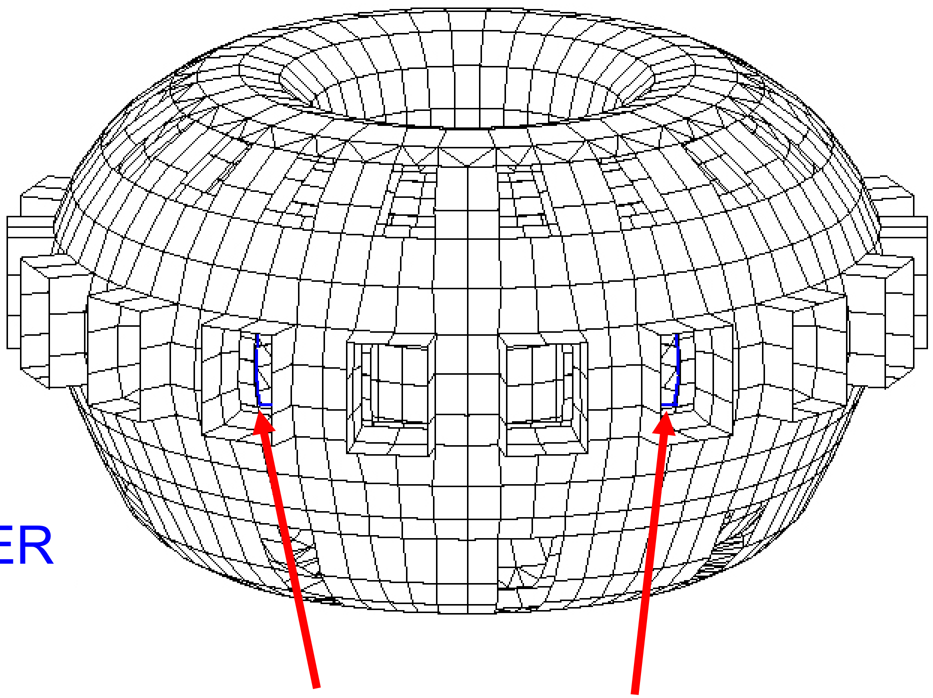
(Equilibria used have $\beta_{Nno\text{-}wall}$ = 5.1; β_{Nwall} = 6.9)

NSTX

ITER active coil modification can significantly raise stable β_N



VALEN dual-wall vessel / blanket model
(full view)



Active feedback coil modification
(coils in ports)

- Original external coil design for ITER stabilizes up to β_N = 2.7
- Proposed improvement raises maximum stable β_N to near 5
- Dual-wall vacuum vessel and blanket used in VALEN model

Wall stabilization research at low aspect ratio illuminates key physics for general high β operation

- Plasma β_t = 39%, β_N = 6.8, β_N/l_i = 11 reached; $\beta_N/\beta_N^{no\text{-}wall} > 1.3$
- Unstable n = 1-3 RWMs measured (n > 1 prominent at low A)
- Critical rotation frequency ~ ω_A/q^2 strongly influenced by toroidal inertia enhancement (prominent at low A)
- Rapid, global plasma rotation damping mechanism associated with neoclassical toroidal viscosity
- Resonant field amplification of stable RWM increases with increasing β_N (similar to higher A)
- An active RWM stabilization system is being implemented in 2005
- RWM active stabilization design studies show that significant increase to β_N ~ 5 might be achieved and sustained in ITER

Internal kink mode dynamics

Motivation

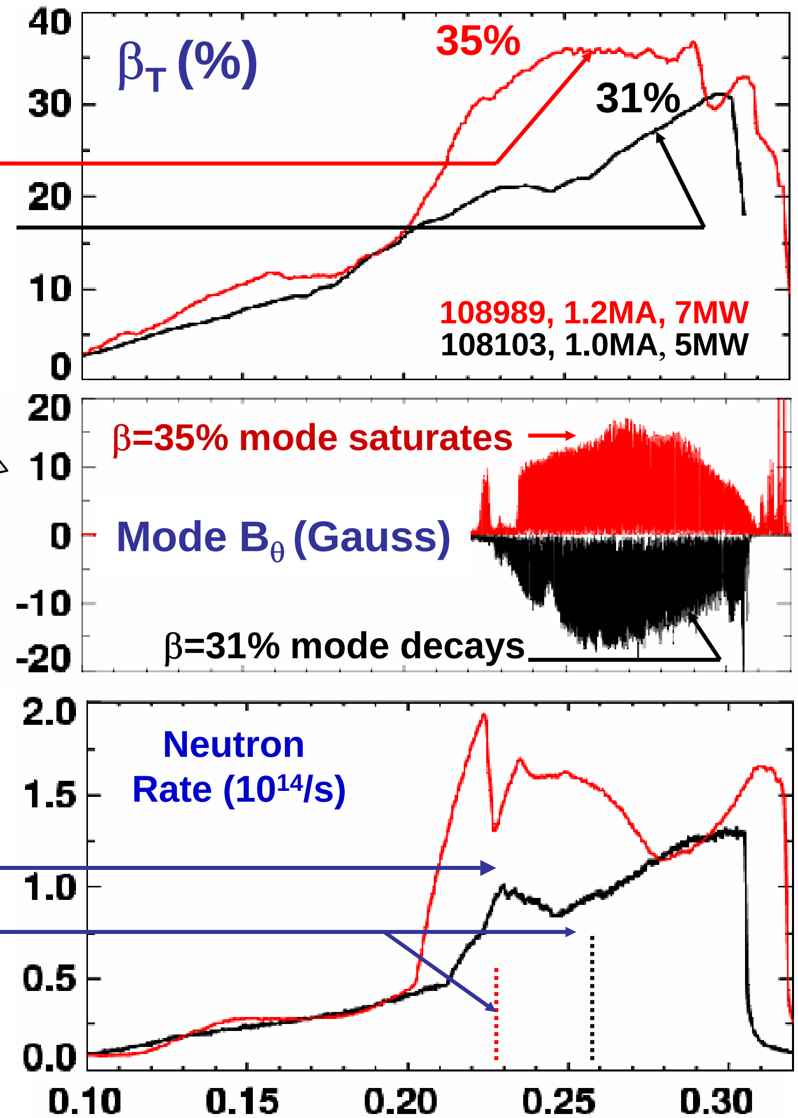
- Internal kink can limit β in highest-β_T shots of NSTX
  - Highest β_T shots typically have high I_P/aB_T and low q_0
  - 1/1 modes often saturate in amplitude
    - Cyclic sawtooth oscillations are rare at high-β
  - Modes degrade fast-ion & thermal confinement + rotation
  - Effect of mode ranges 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 ⇒ β roll-over
- In highest β shots, β saturates or actually rises during 1/1 activity
- 1/1 saturates or decays at high β
- β → 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?



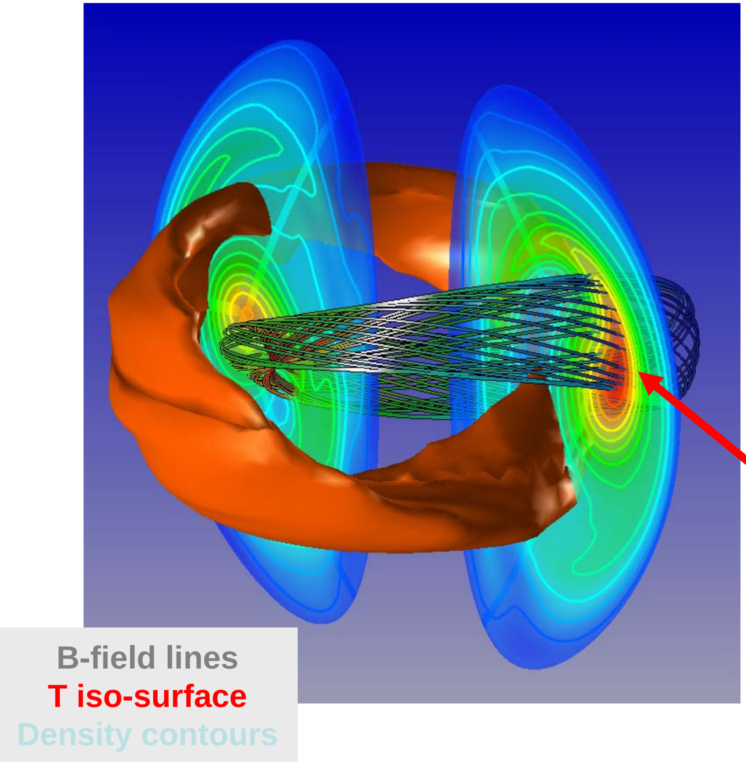
Saturation mechanisms studied with **M3D** code

(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

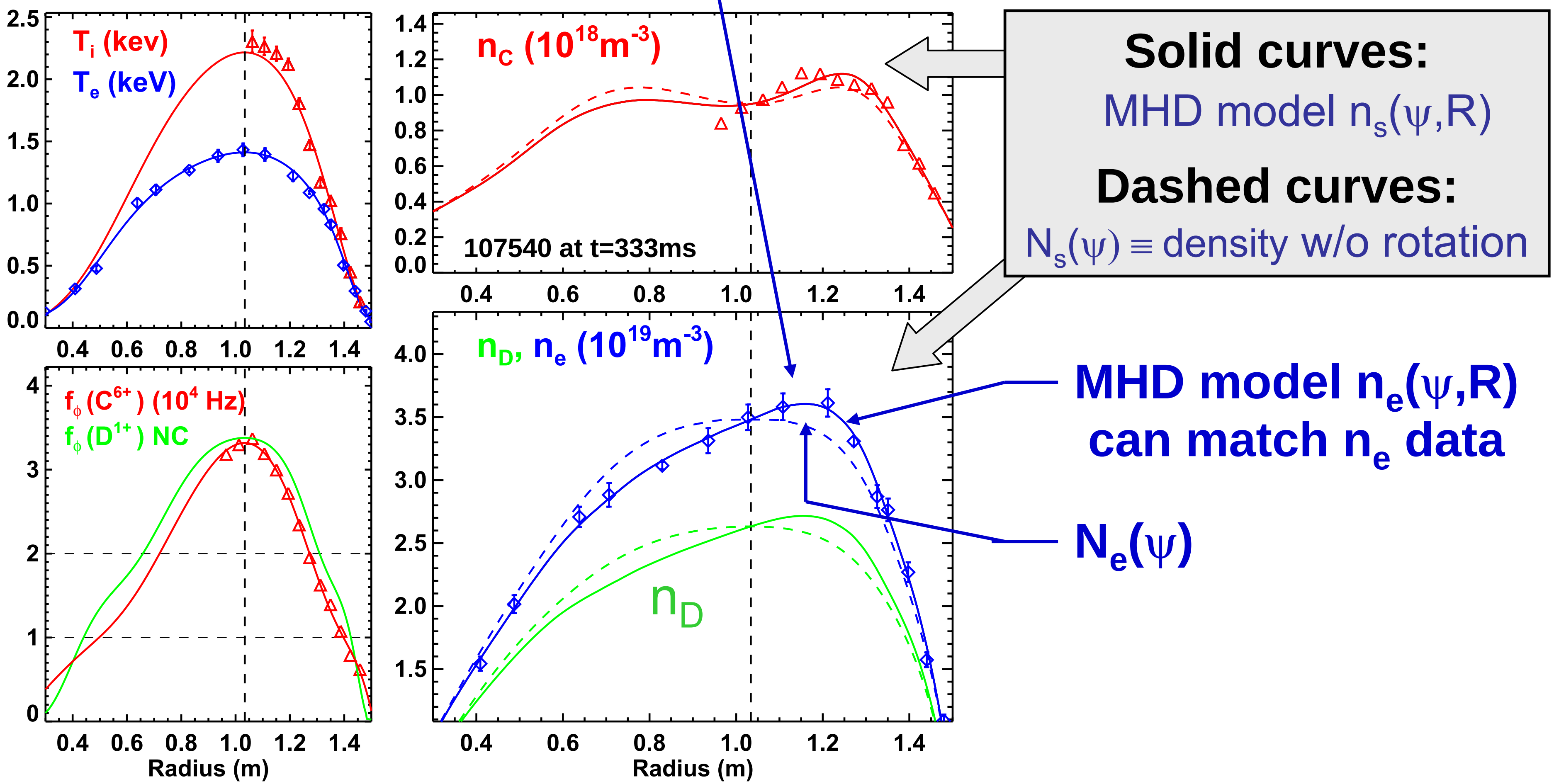
(3) Fast particles, 2-fluid - ***being studied now***
- Fast particles initially lost/diffused at onset
- **Diamagnetic flow potentially important**

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

Rotation effects are strong in NSTX plasmas

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

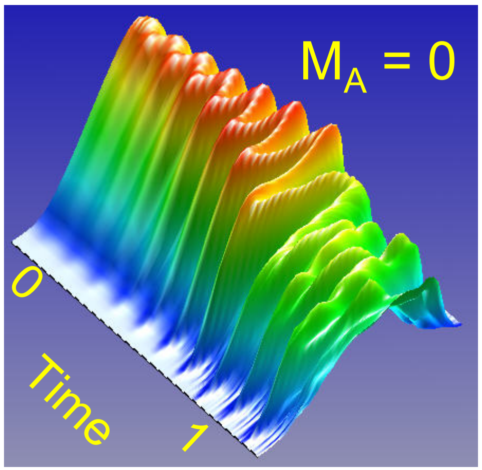
Centrifugal effects evident in $n_e(R)$ profiles:

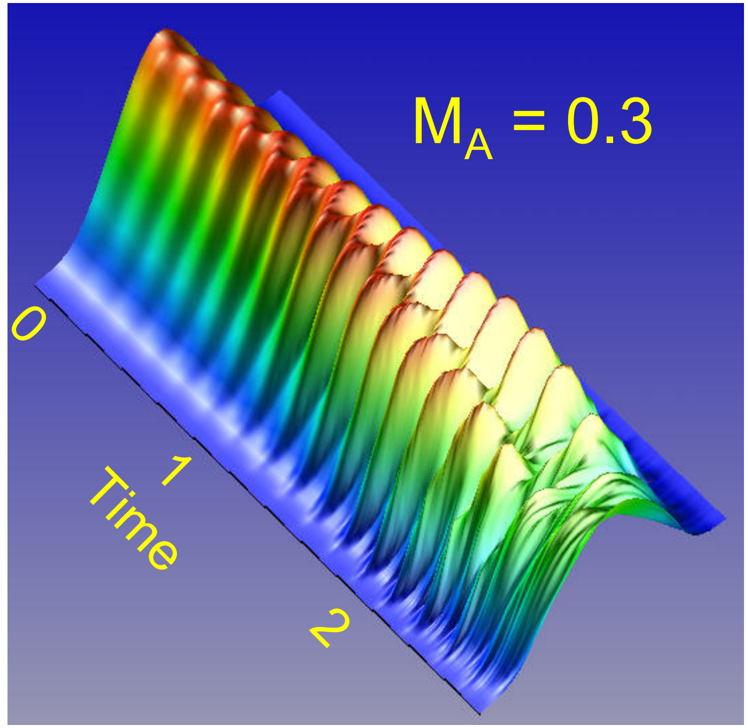


M3D: Sheared-flow reduces growth rate by factor of 2-3

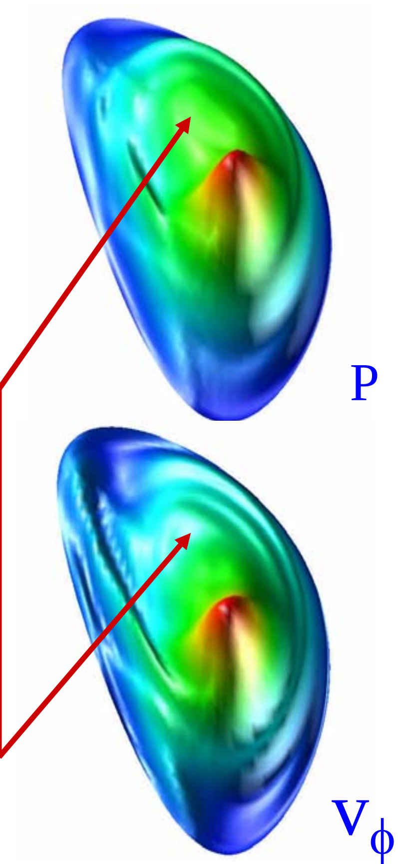
- **Possible because $\gamma_{shear} \sim \Omega_{rotation}$ can be of > γ_{linear}**

Simulated SXR signals





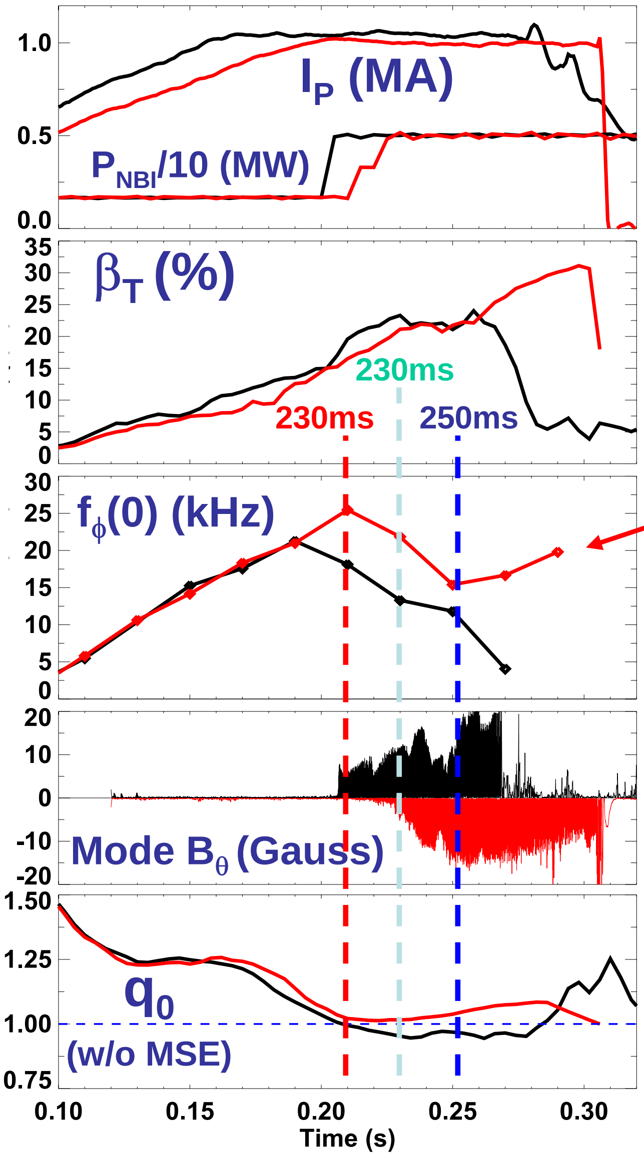
M3D simulations



- 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)**

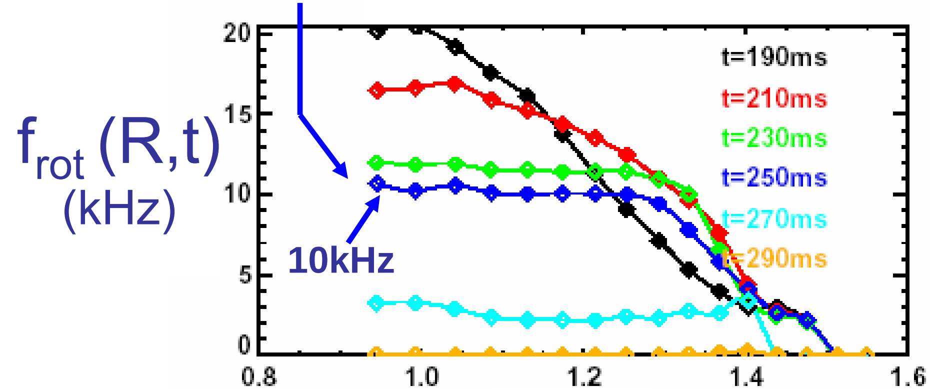
Rotation data ⇒ shear-flow correlates with saturation

$\beta_T \leq 23\%$ $\beta_T \leq 31\%$

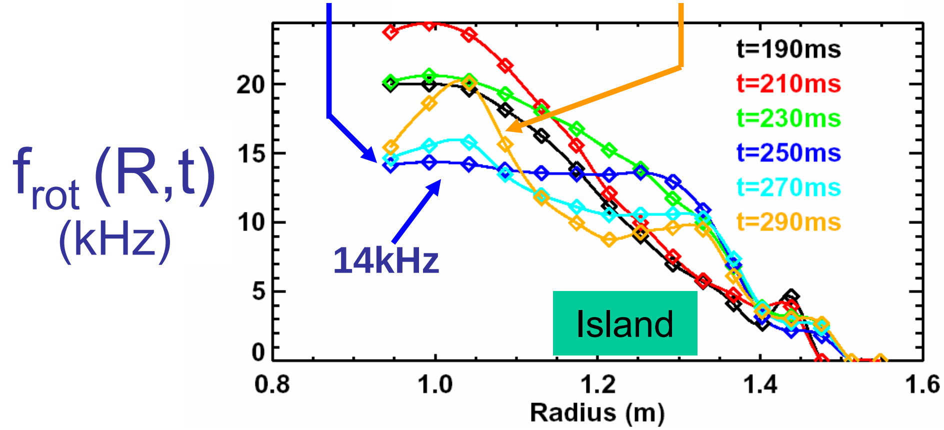


NOTE: Carbon f_ϕ data is 20ms average >> τ_{growth} , $1/f_\phi$

β_T=23% - Rotation flattens, broadens, collapses

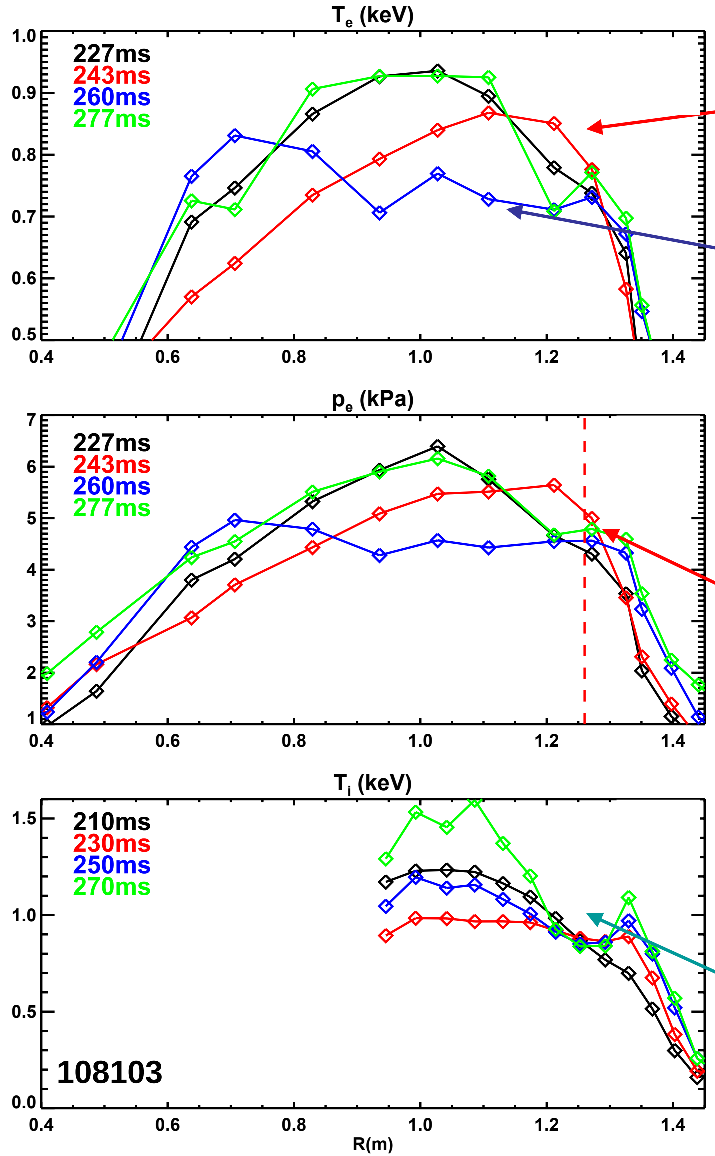


β_T = 31% - Rotation flattens, then core recovers



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

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

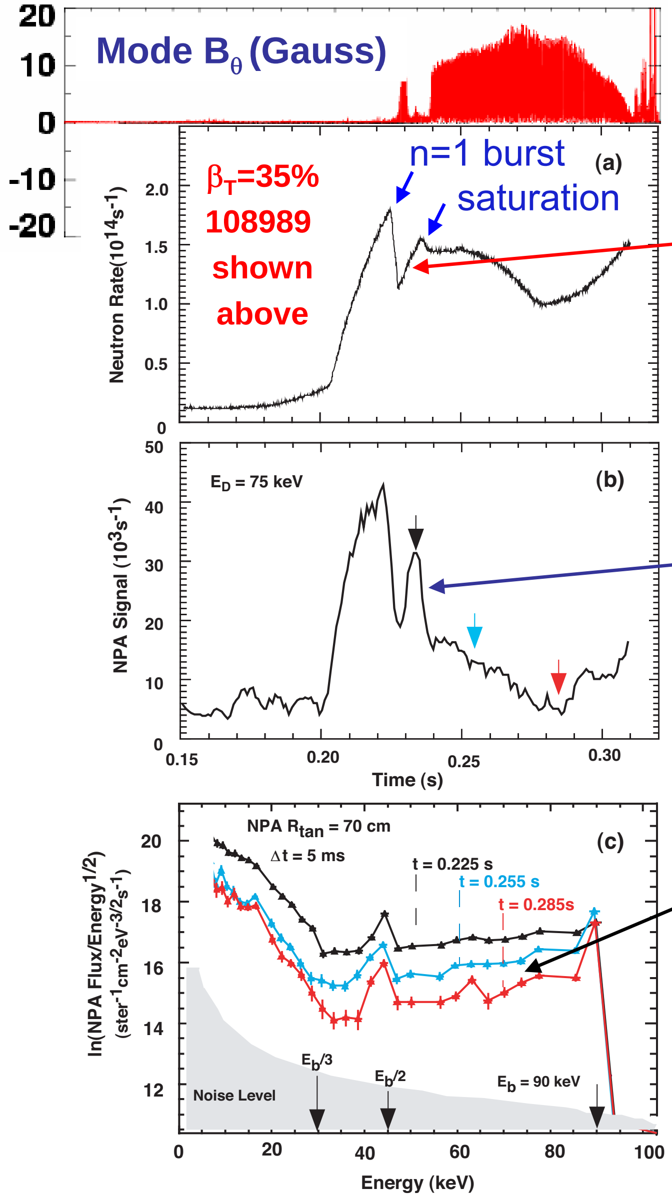
p_e <u>highest in displaced core</u>

∇p_e enhanced by mode near q=1

Time average T_i has local minimum in island region during saturation

<u>Max.</u> p_i <u>in island region unlikely</u>

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?

SXR inversion aids analysis of mode evolution

NSTX

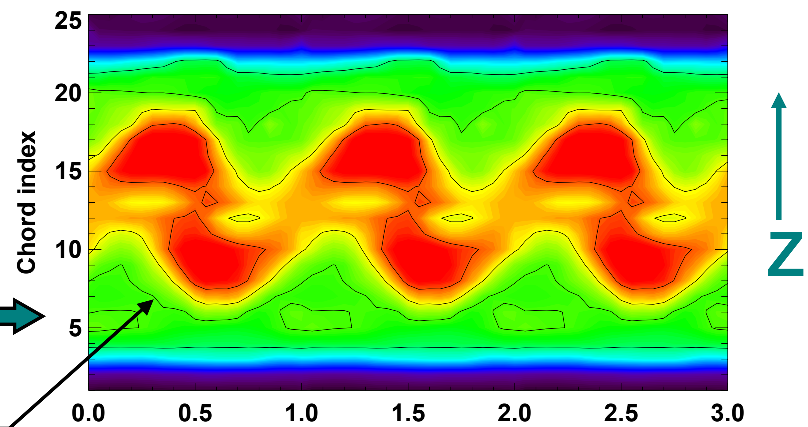
- Perturb EFIT equilibrium **helical flux** with *m/n* = **1/1** $\delta\psi_h$
  - Reconstruct total emission as function of total helical flux

Island model fits data well

SXR Data

Contours from *SXR data*

Line-integrated SXR data for NSTX shot 108103 at t=230ms

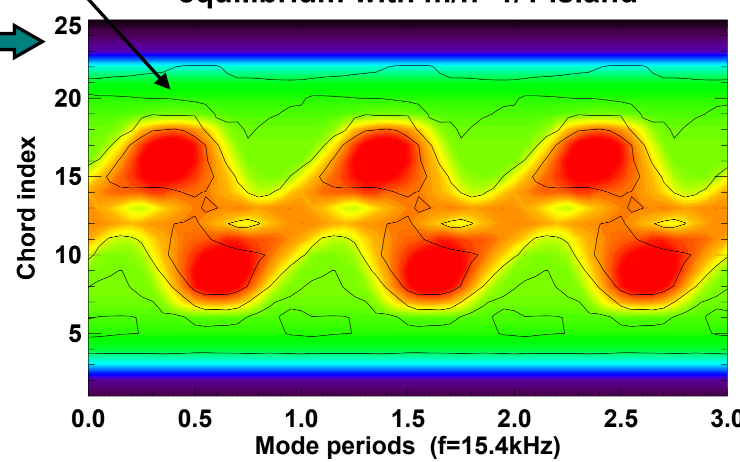


Island Model

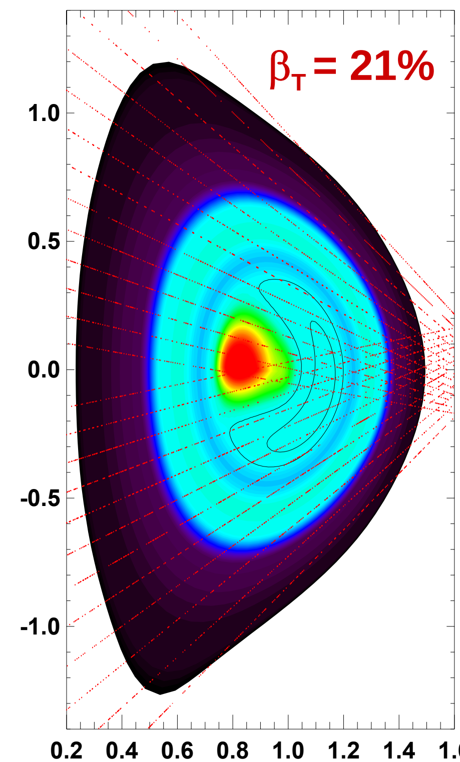
Fit error < 6%

r_s = 0.43
w = 0.3
f = 15.4 kHz

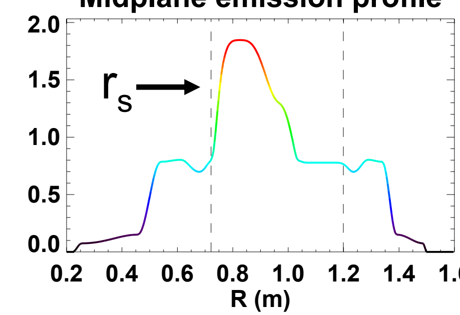
SIMULATED SXR data from equilibrium with m/n=1/1 island



Reconstructed SXR emission NSTX shot 108103 at t=230ms



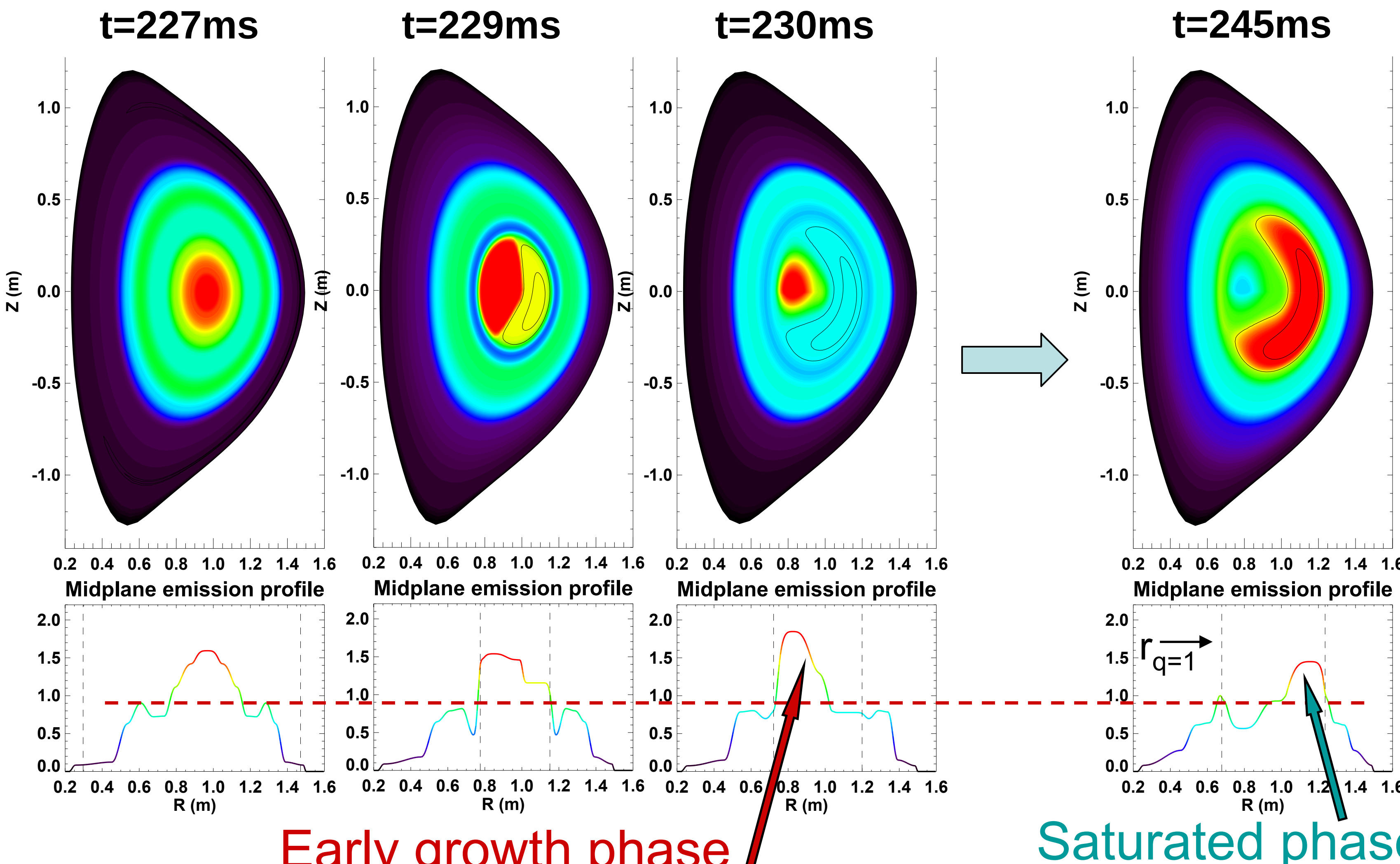
Midplane emission profile



SXR data consistent with incomplete reconnection

NSTX

$\beta_T \leq 31\%$ 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

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 ω_{*e} = 0:

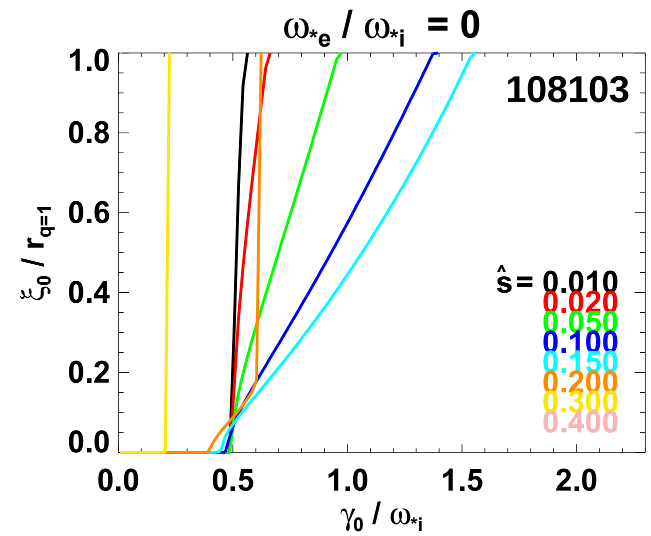
ROGERS, B. and ZAKHAROV, L., Phys. Plasmas 2 (1995) 3420.

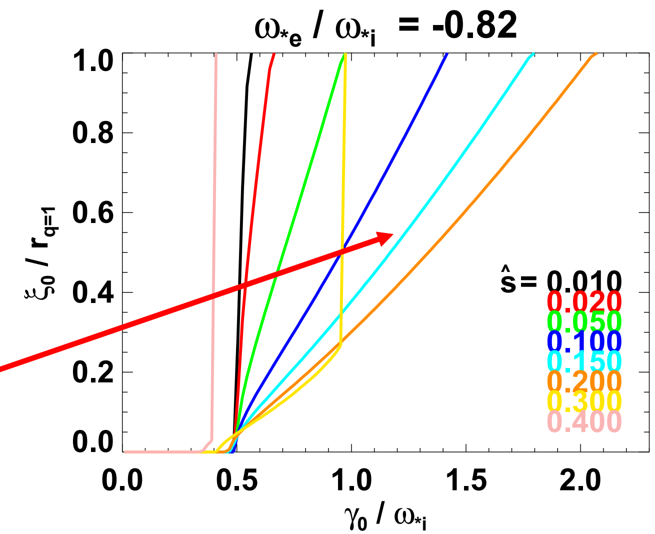
$$\alpha \omega_{*i} \tau_A > 2\sqrt{(\gamma_0 \tau_A / \bar{q}')^2 + (\bar{q}' q')^2 (\rho_s^2 + 5 d_e^2)/2}.$$

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

  - 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 $\xi_0 / r_{q=1} \approx 0.5$



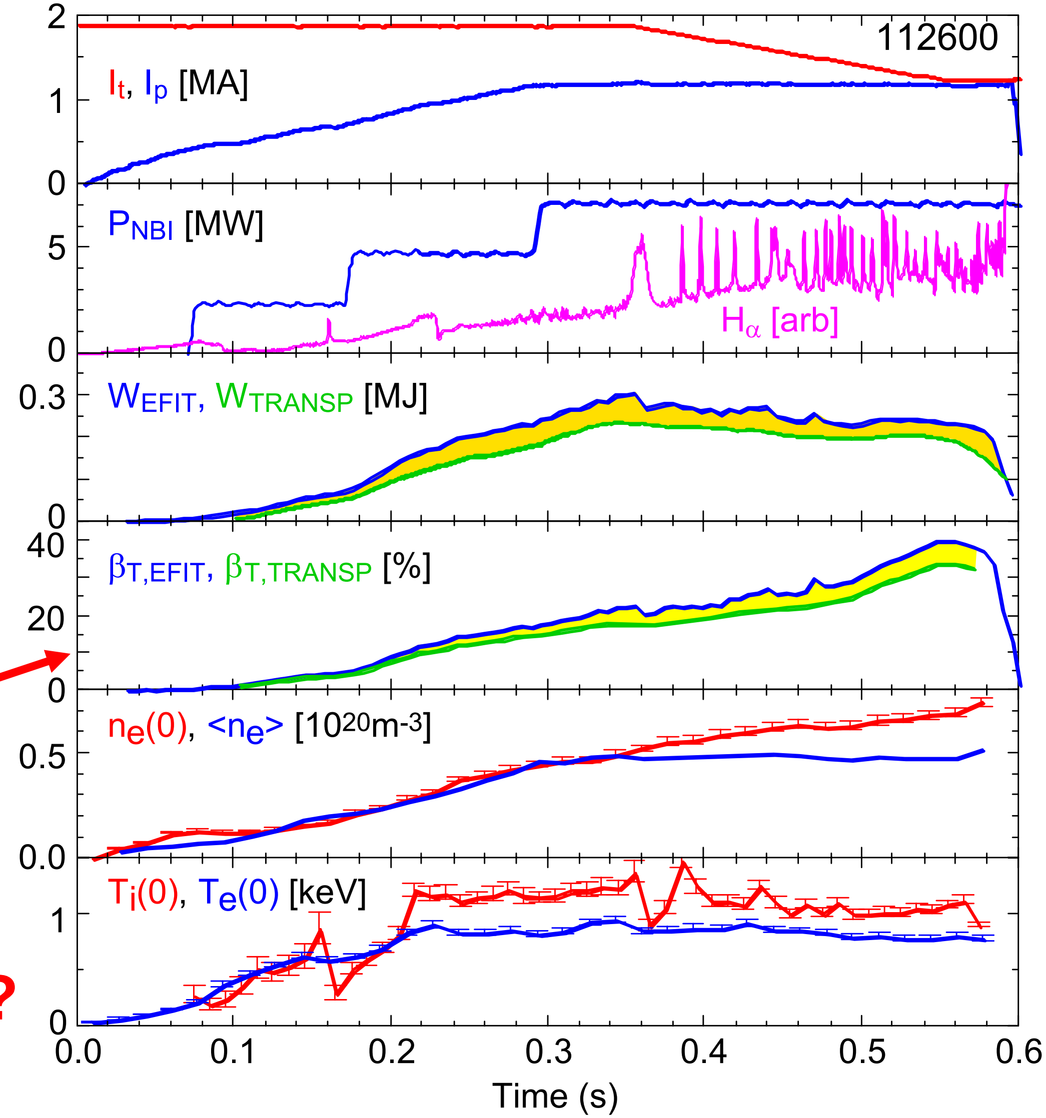


Operational and diagnostic upgrades have improved understanding of role of 1/1 mode in β and Ω_ϕ collapse

NSTX

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?**

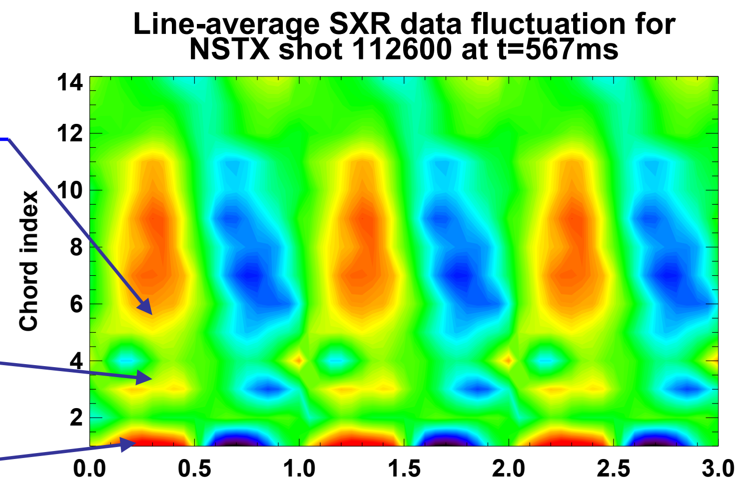


SXR indicates coupled 1/1 and 2/1 modes during disruption of this high-β discharge

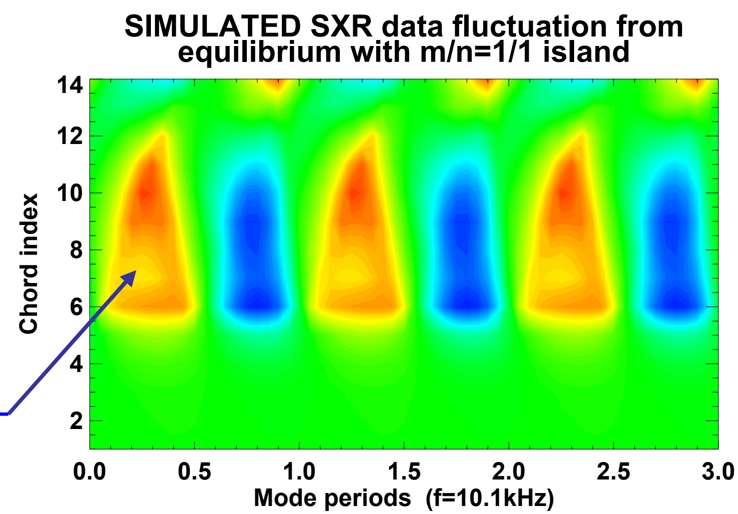
1/1 mode + SXR locate q=1 position

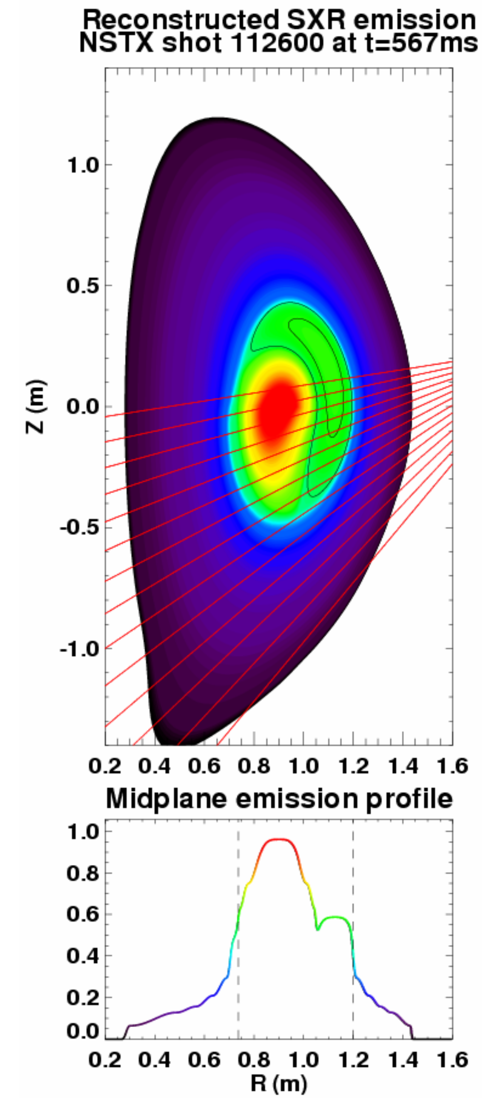
2/1 mode

Edge mode

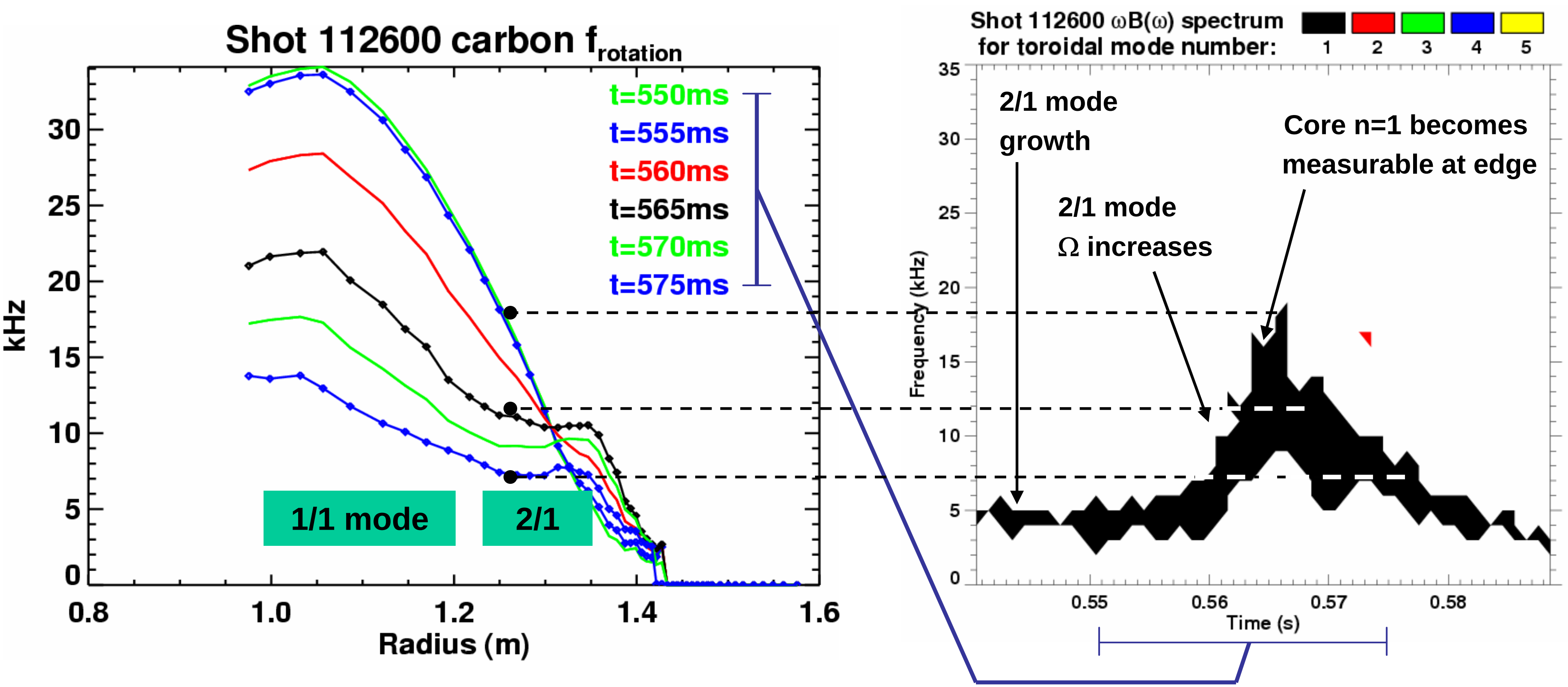


Simulated line-average emission fluctuation from model 1/1 mode





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…

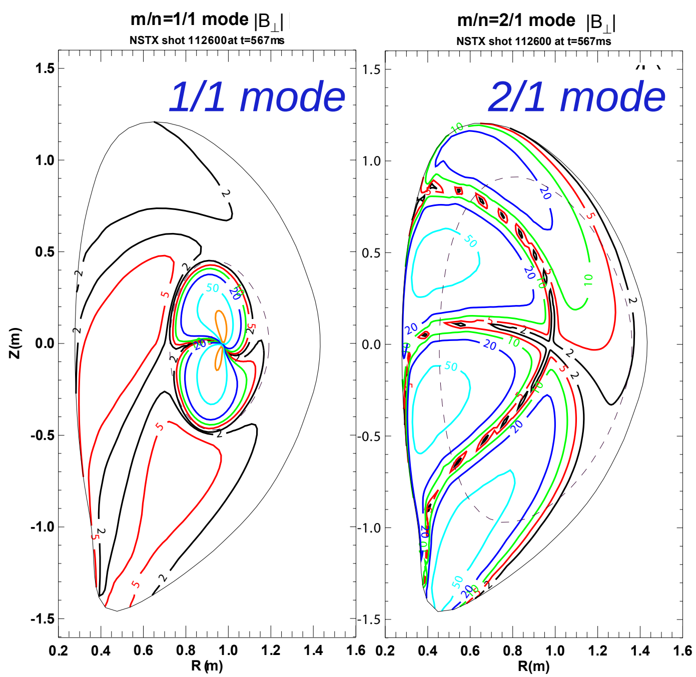
Core plasma rotation flattening consistent with combined torques of 1/1 and 2/1 modes

NSTX

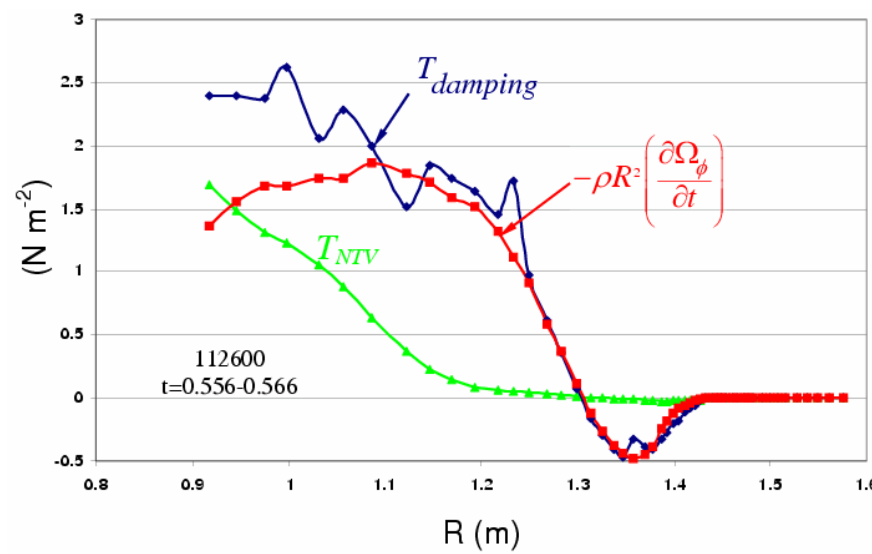
Torque balance ⇒ $\rho R^2 \frac{\partial \Omega_\phi}{\partial t} - R^2 \frac{1}{r}\frac{\partial}{\partial r}\left[\rho \mu_\perp r \frac{\partial \Omega_\phi}{\partial r}\right] + T_{NTV} + T_{EM}\,(\text{on island only}) = S_\phi$

→ $\boldsymbol{T_{damping}}$

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

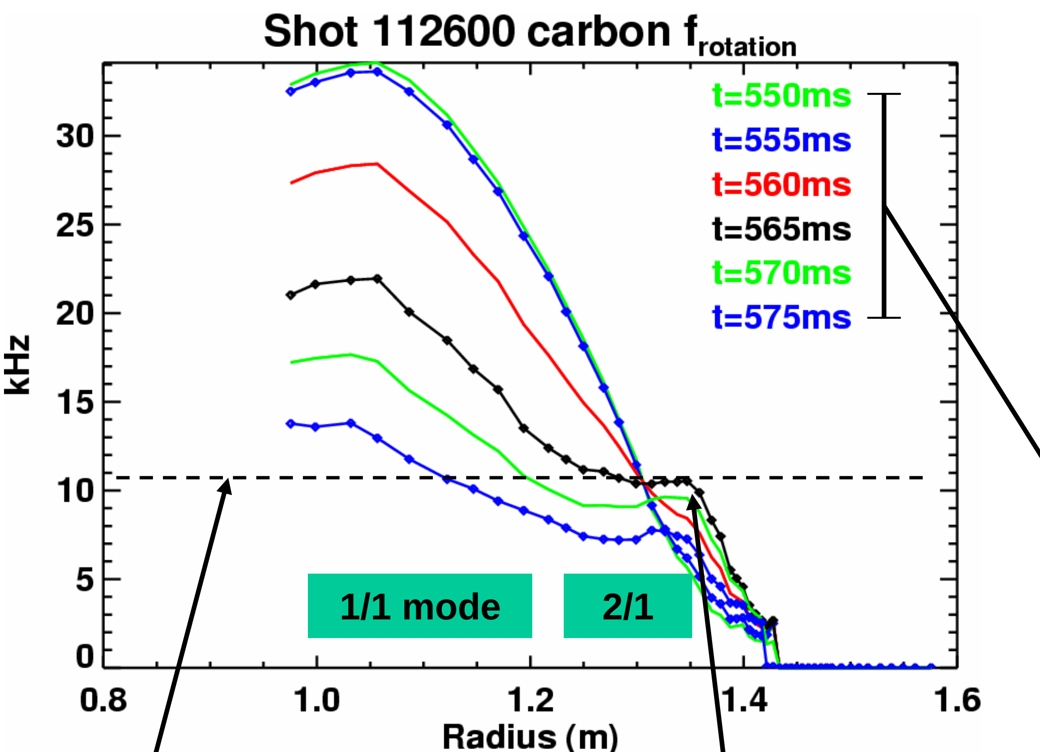


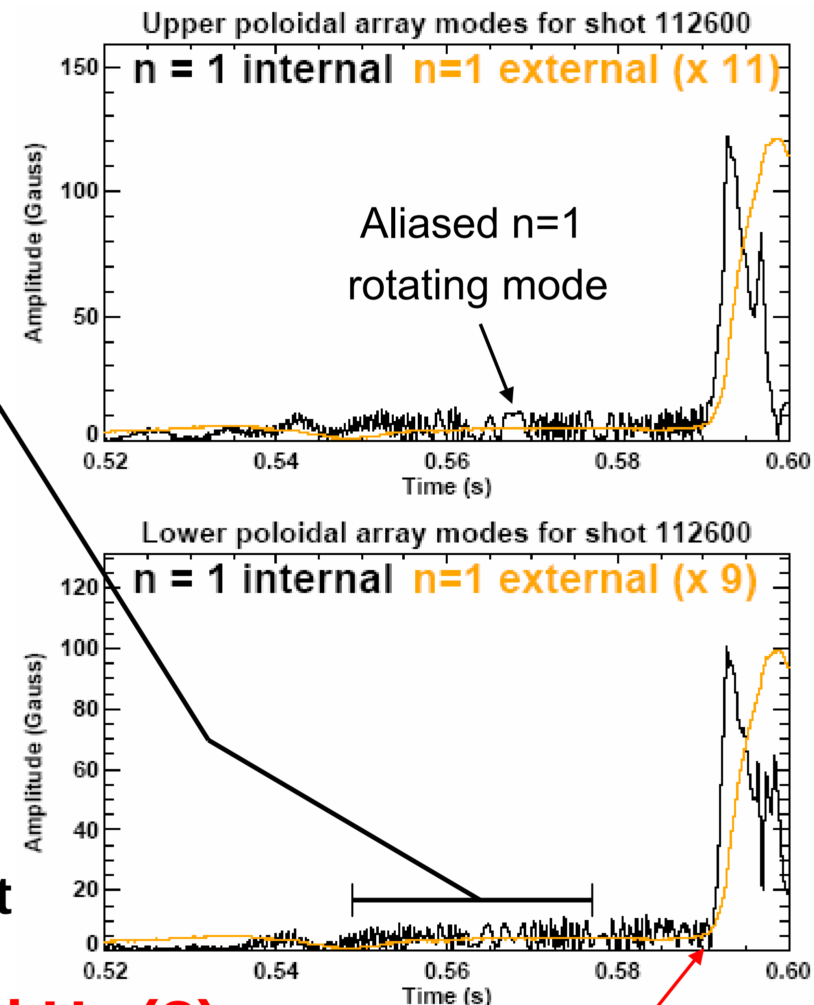
$$T_{\mathrm{NTV}} \sim \left(T_{\mathrm{i}}\right)^{\frac{1}{2}} \sum_{m,n} \left(\Omega_\phi - \Omega_{\mathrm{mode}}^{m,n}\right) \left(\frac{b_r^{m,n}}{B}\right)^2$$



- **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**

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 of internal kink dynamics

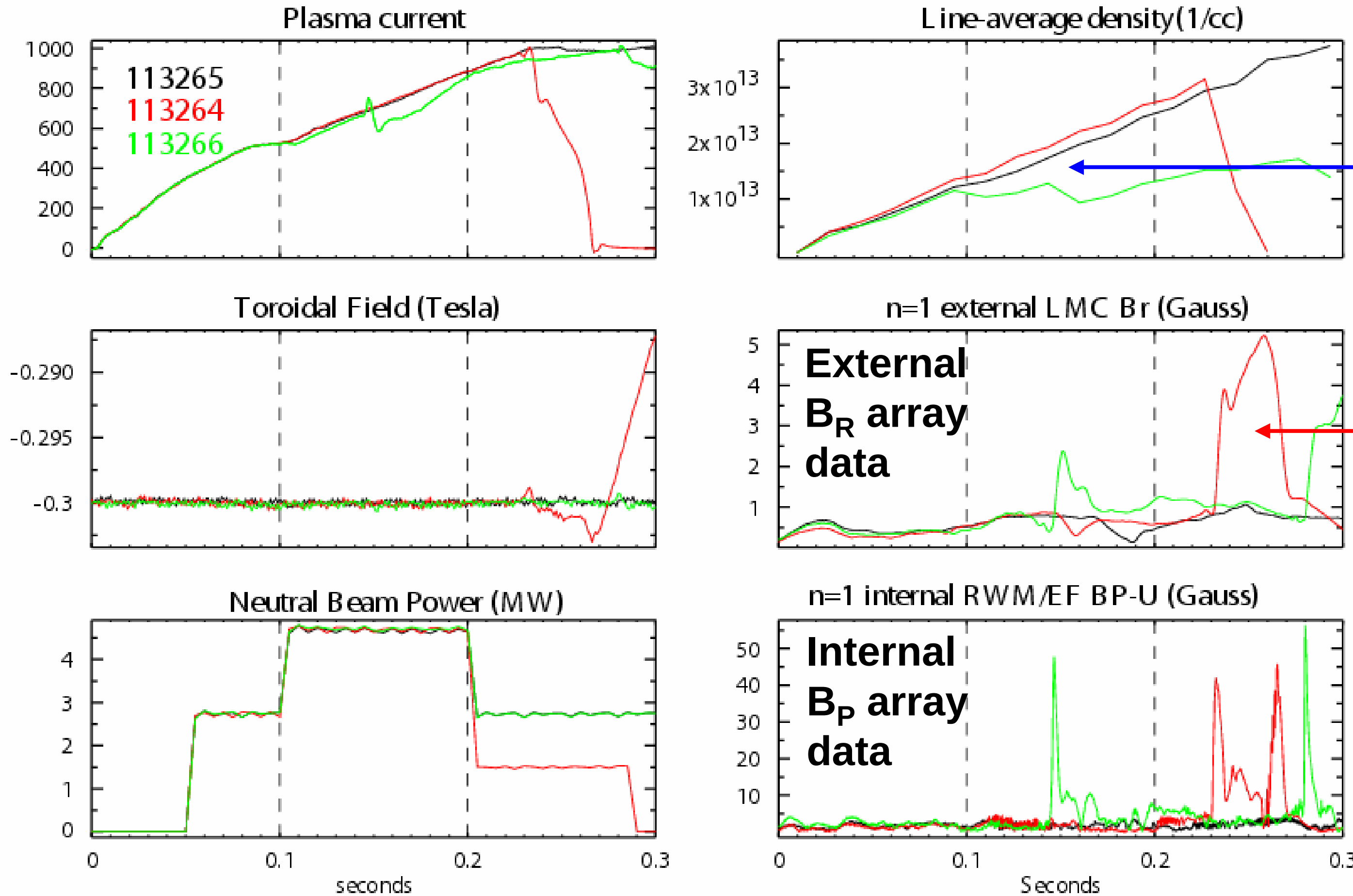
- **Highest β_T shots in NSTX can be limited by 1/1 modes**
- **Modes often saturated for $\tau \gg \tau_{growth}$, high-β sawteeth rare**
- **Modes degrade fast-ion & thermal confinement + rotation**
- **Sheared flow and diamagnetic effects most likely suspects in explaining non-linear mode saturation**
- **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**

Locked modes and error fields

Locked-mode control studies during I_P ramp-up

NSTX

- **Mode locking most problematic during I_P ramp-up at low TF = 3kG**
  - **Large structural currents during ramp $\approx$ 0.1-0.5 $\times$ I_P $\Rightarrow$ transient error-field?**
  - **Know passive plates and vacuum vessel not perfectly aligned w.r.t. coils**

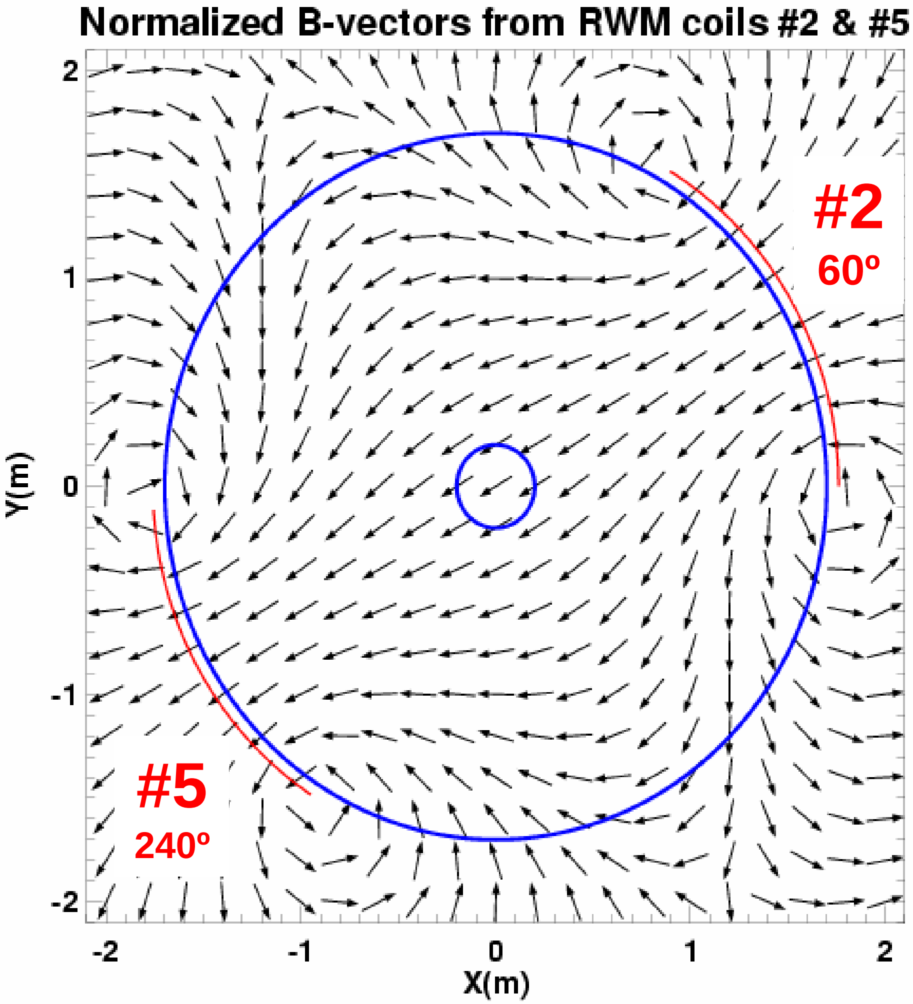


Threshold @ 3kG
n_e-bar = 1.2$\times$10^{19} m^{-3}

Rotating 2/1 can lock later w/o sufficient plasma rotation

- **In-vessel conductor asymmetries likely important for next-step devices…**

Two external mode control coils used for n=1 mode locking & error field studies



1kA per turn × 2 turns / coil ⇒

1-5 G resonant 2/1 $B_\perp$

There is uncertainty in ρ(q=2) surface w/o MSE for this data

ρ(q=2) is also expected to change rapidly during ramp

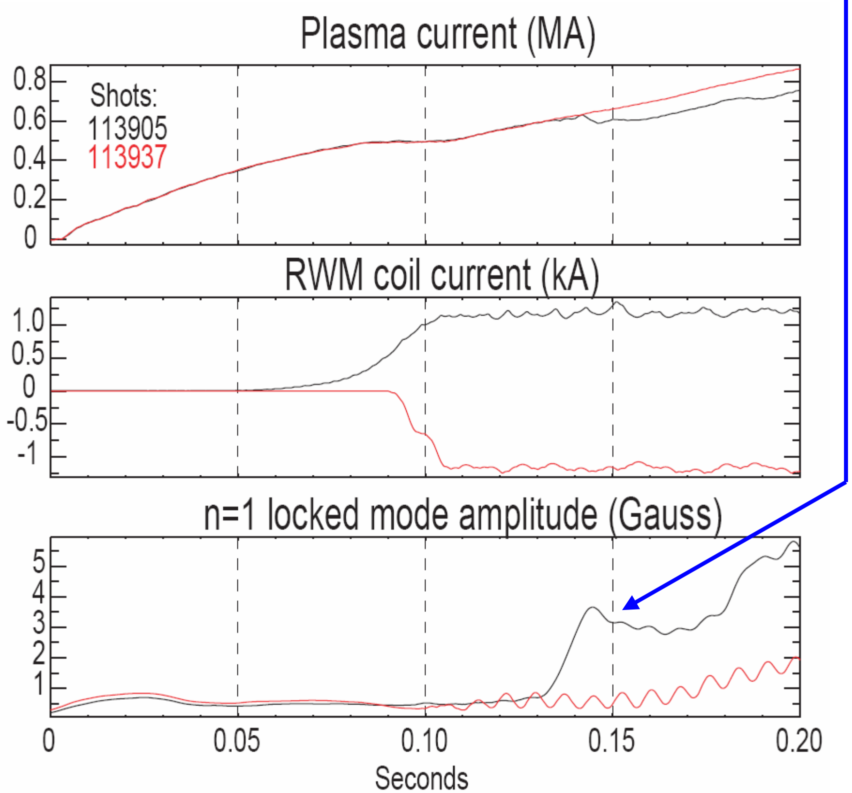
- **1kA I_{RWM} ⇒ 10G of n=1 radial field @ external B_R sensors**
- **n=3 amplitude similar @ ext. sensors, but w/ much faster radial fall-off into plasma**

Mode locking threshold during I_P ramp depends on sign of applied external field

NSTX

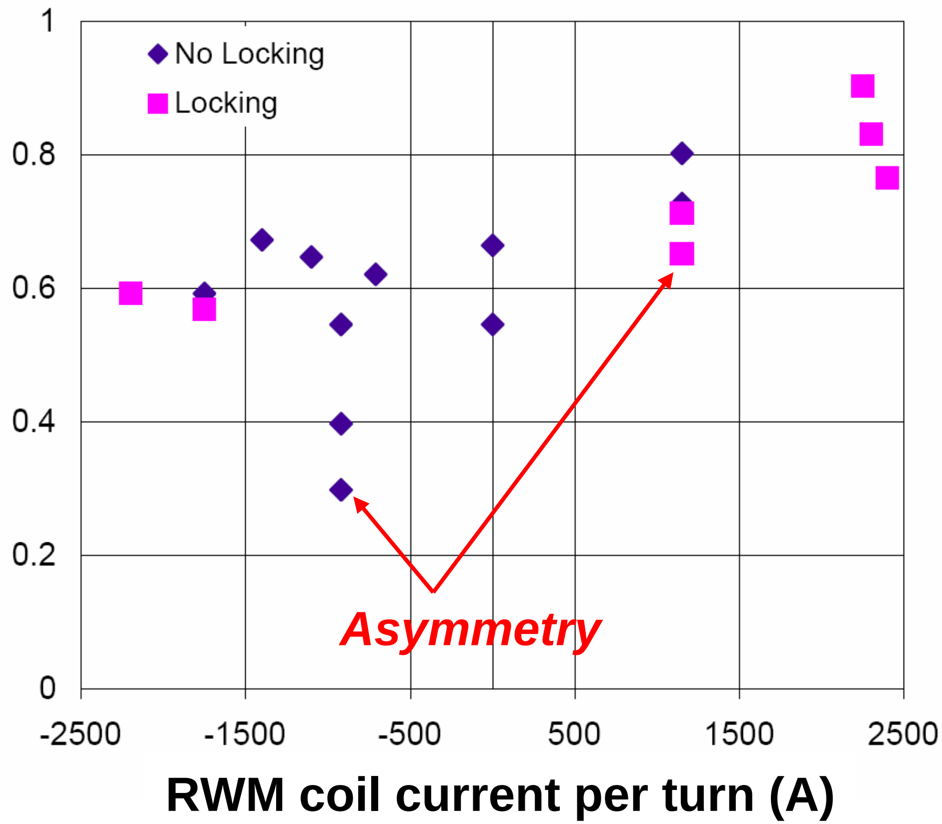
➔ *residual error field during I_P ramp*

Typical 2/1 locked mode signatures during I_P ramp w/ RWM coil current on

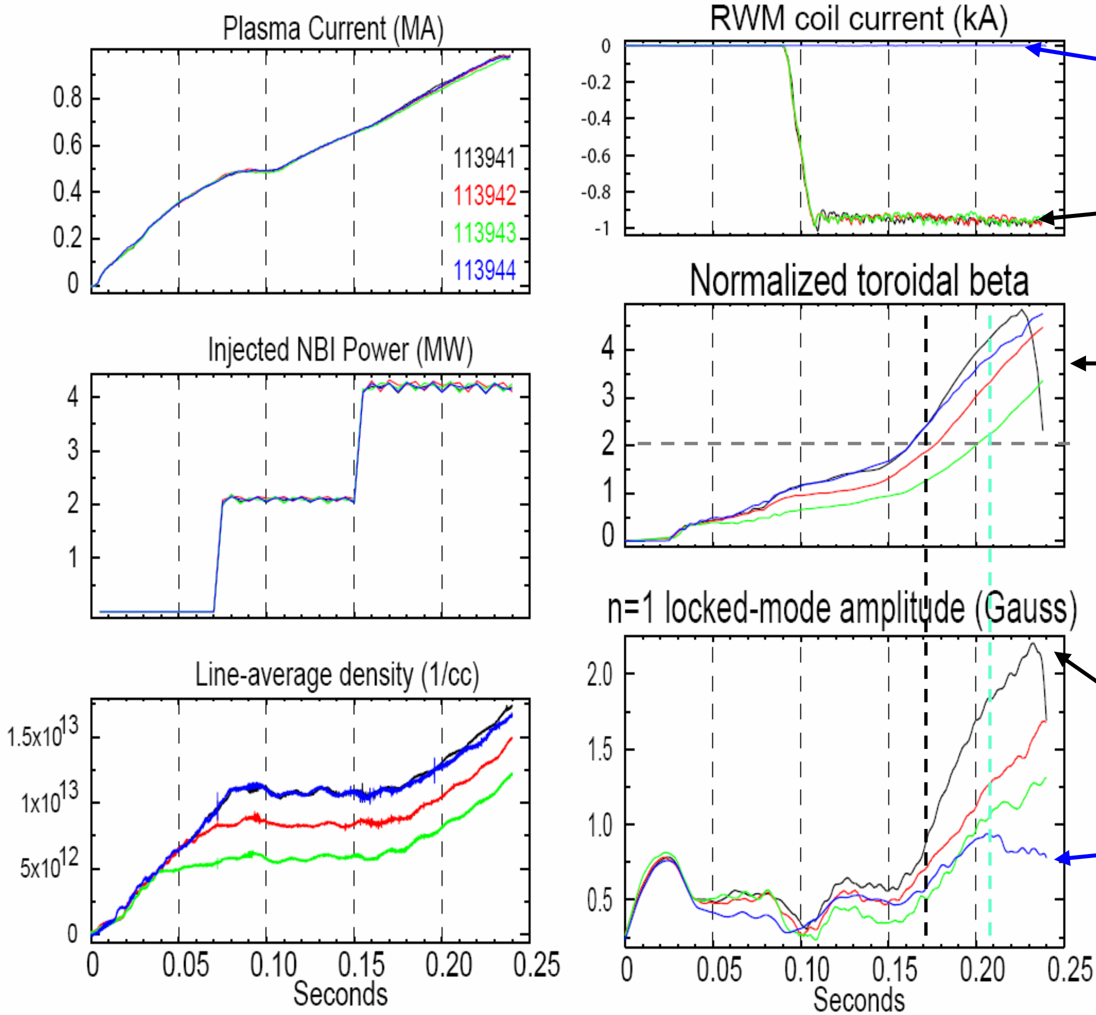


Density threshold vs. RWM coil current:

$\overline{n}_e(20) \times q_{95}^{0.8}$ (DIII-D scaling)



Locked-mode shots also demonstrate error field amplification (EFA) dependence on β_N at low-n_e

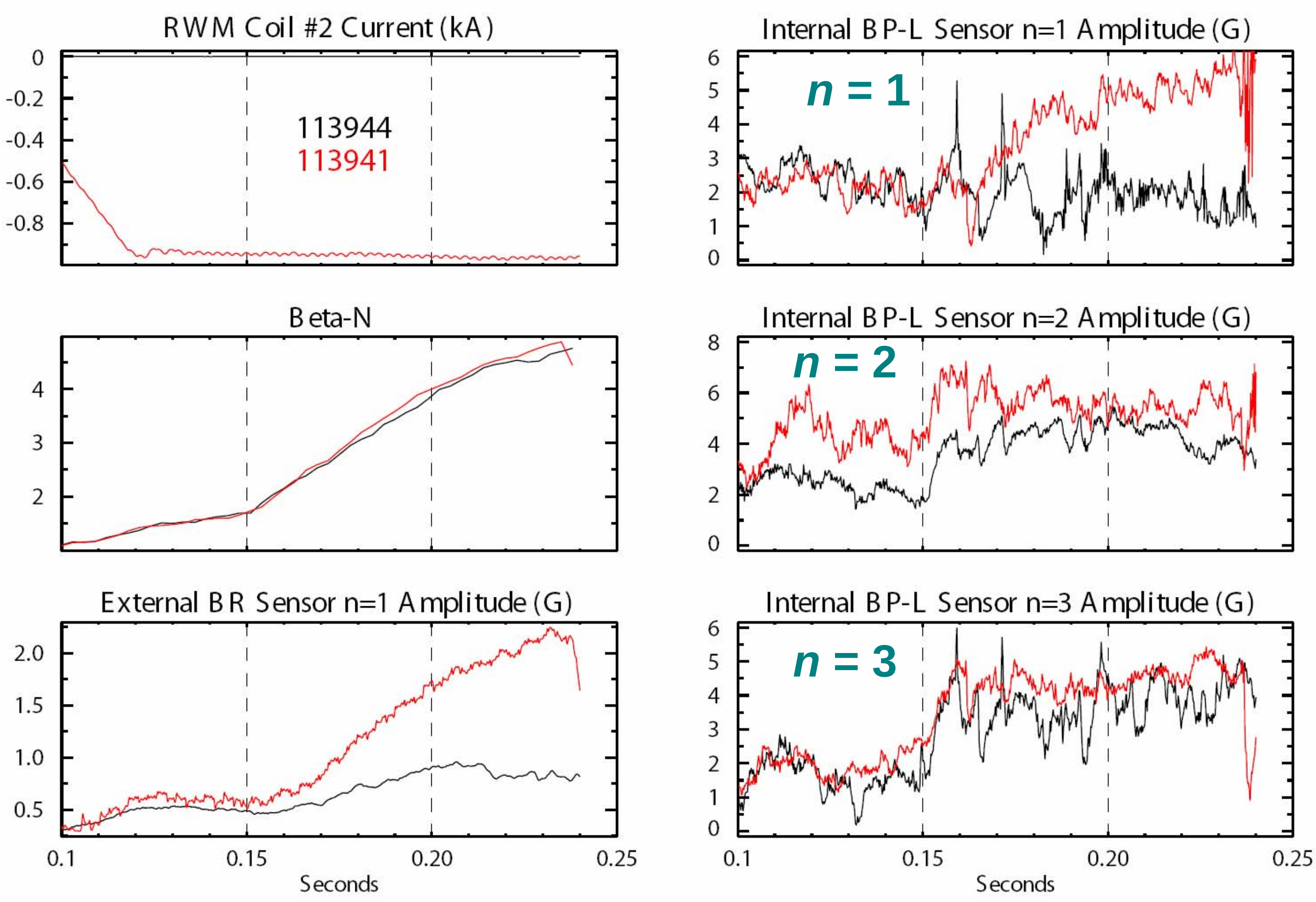


- Blue shot has $I_{RWM} = 0$
- Others use I_{RWM} that doesn't cause locking at t=140ms
- n_e scan yields β scan after 2nd source fires
  - NBI waveforms fixed
- Plasma amplifies field when β_N > approx. 2

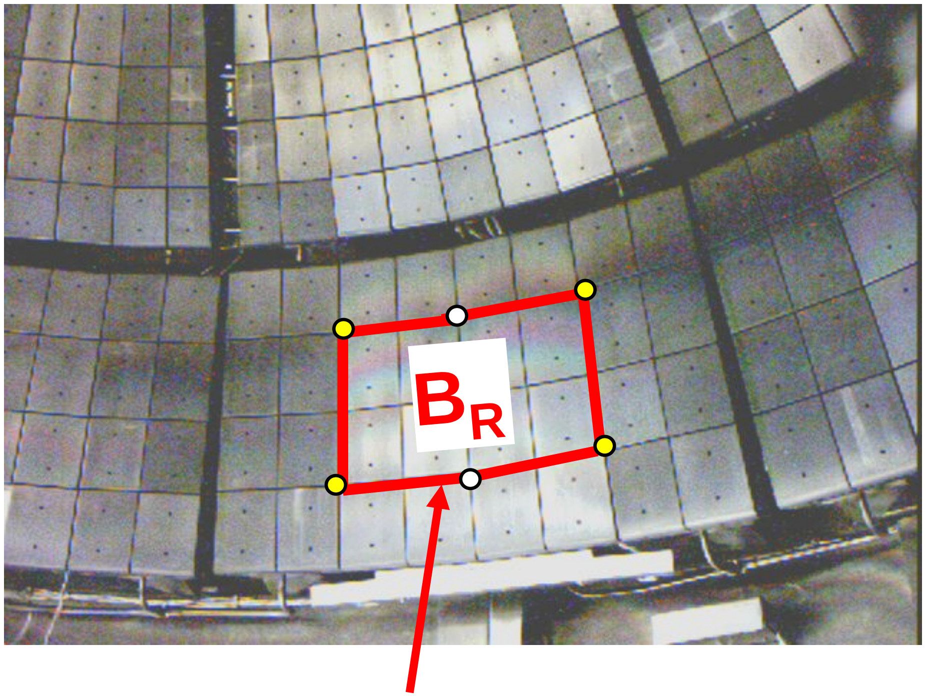
$I_{RWM} = 0$ shot has smallest LM signal ➔ smaller residual error field later in shot?

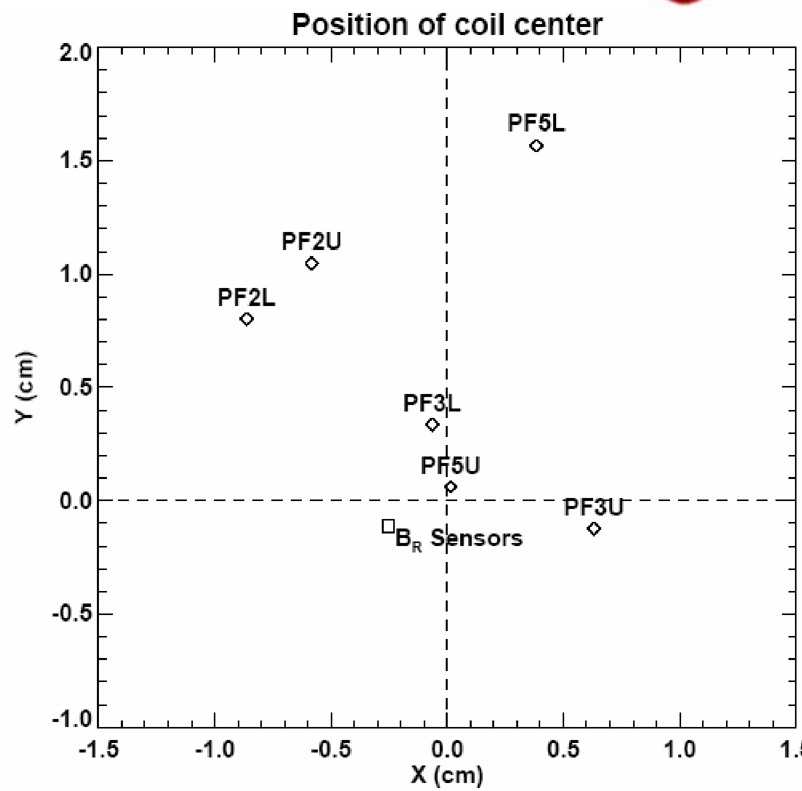
Internal sensors find only n=1 EFA

- n=1 EFA factor ≈ 2-3 at maximum β_N
- n=2 and n=3 EFA weak or absent



NSTX static error-field measurements & modeling



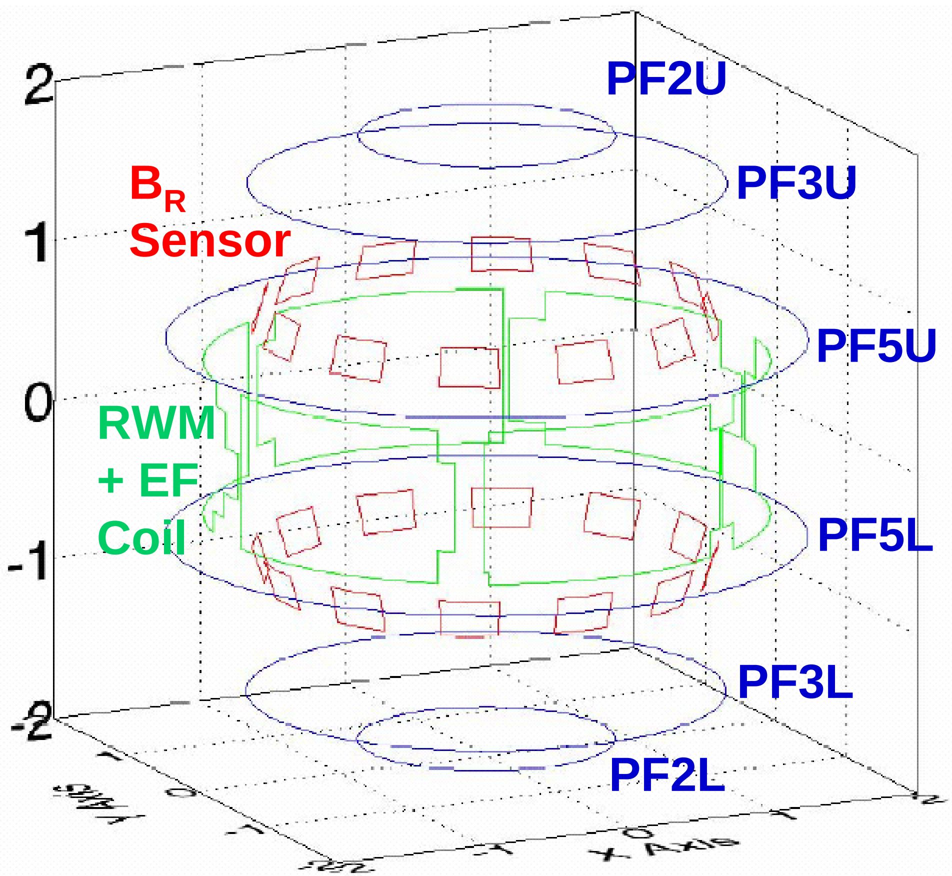


- Measure vacuum fields from PF coils with B_R sensors
  - 12 above, 12 below midplane
- Relative position of sensors measured to mm precision

- PF coil shape and position estimated from sensor data
- Comparing to physical measurements of shape now

Filament model of sensors and PF coils

(RWM coils not used yet in this analysis)



- Allow X,Y shift of coil center + *n*=2-3 elliptical deformation
  - *n* > 3 also tried - only PF5 is close enough to B_R sensors to possibly trust the results.
  - Only shift allowed for PF2
- Mean R of coils constrained to match measured values
- No Z-variation of coils allowed
  - Coils assumed to all be co-planar based on how supports on vessel were originally machined

Locked-mode and EF plans

- Use all 6 RWM coils in threshold scans
  - Scan n=1 amplitude and toroidal phase
  - Find optimal n=1 **B** for minimizing locking
    - Compare I_P ramp and flat-top corrective fields
    - Compare threshold scaling to existing high-A data
- Compute error fields from coil shifts
  - Compute corrective fields from RWM coils
- Compare error fields inferred from coil shifts to corrective fields that minimize locking
- Implementation of dynamic EF correction

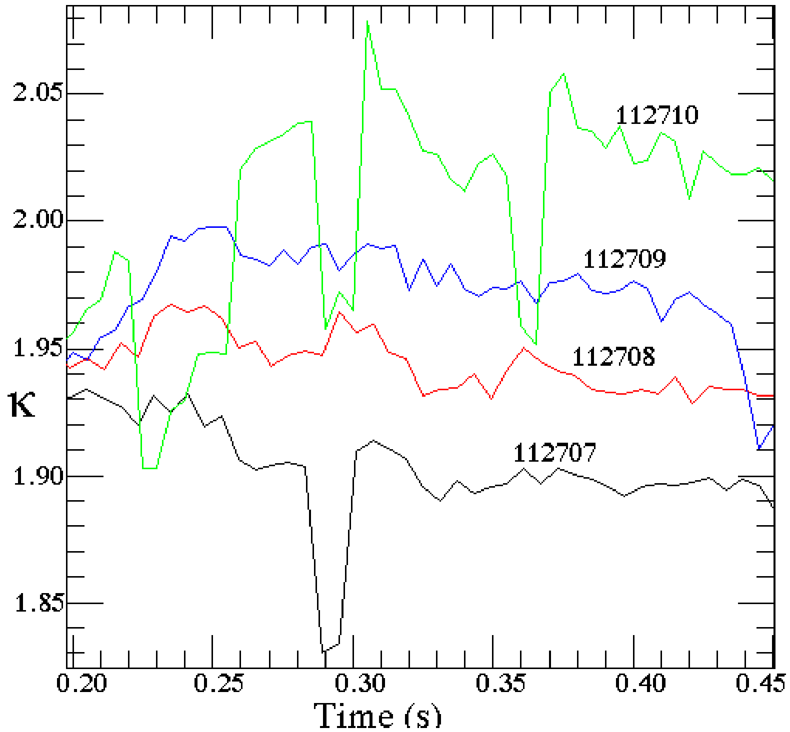
Plasma control and modeling

rtEFIT IMPLEMENTATON

- NEW ALGORITHM FOR REAL TIME SHAPE CONTROL COMMISSIONED IN 2002
- 62 MAGNETIC FIELD AND FLUX MEASUREMENTS, 11 POLOIDAL FIELD COIL CURRENT MEASURMENTS, AND 9 LOOP VOLTAGE MEASUREMENTS
- FACTOR OF 4 REDUCTION IN CONTROL SYSTEM LATENCY ACHIEVED IMPROVED VERTICAL POSITION CONTROL

Elongation (κ) control

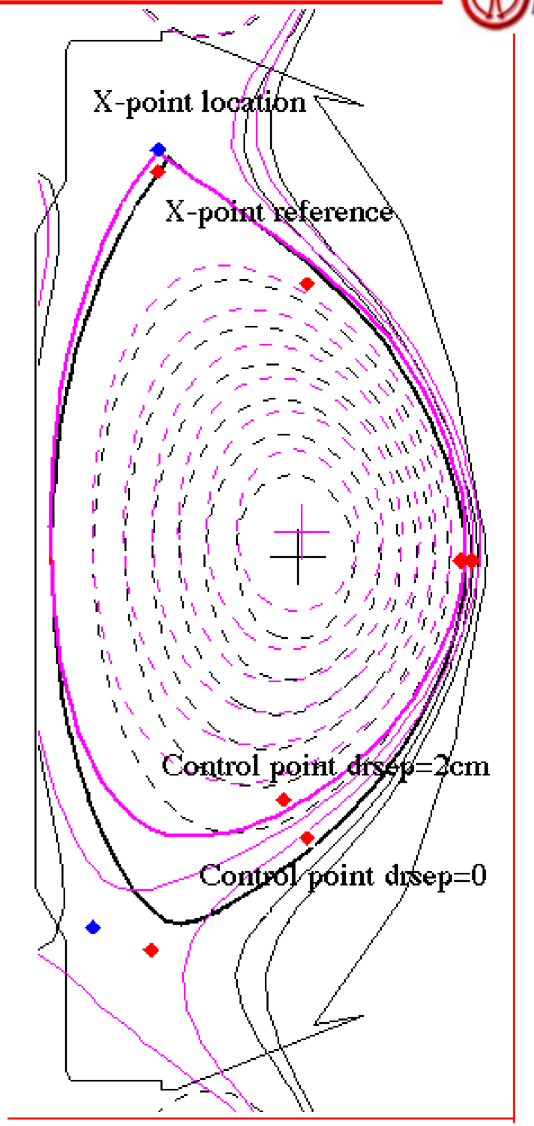
- High l_i (~1.5)double-null RF heated plasma
- κ was increased by increasing the requested height of the X-points after 0.2 s from shot-to-shot
- The sudden drops in kappa do not represent a large shape change, but rather are due to algorithm in EFIT used to get kappa



Control of drsep

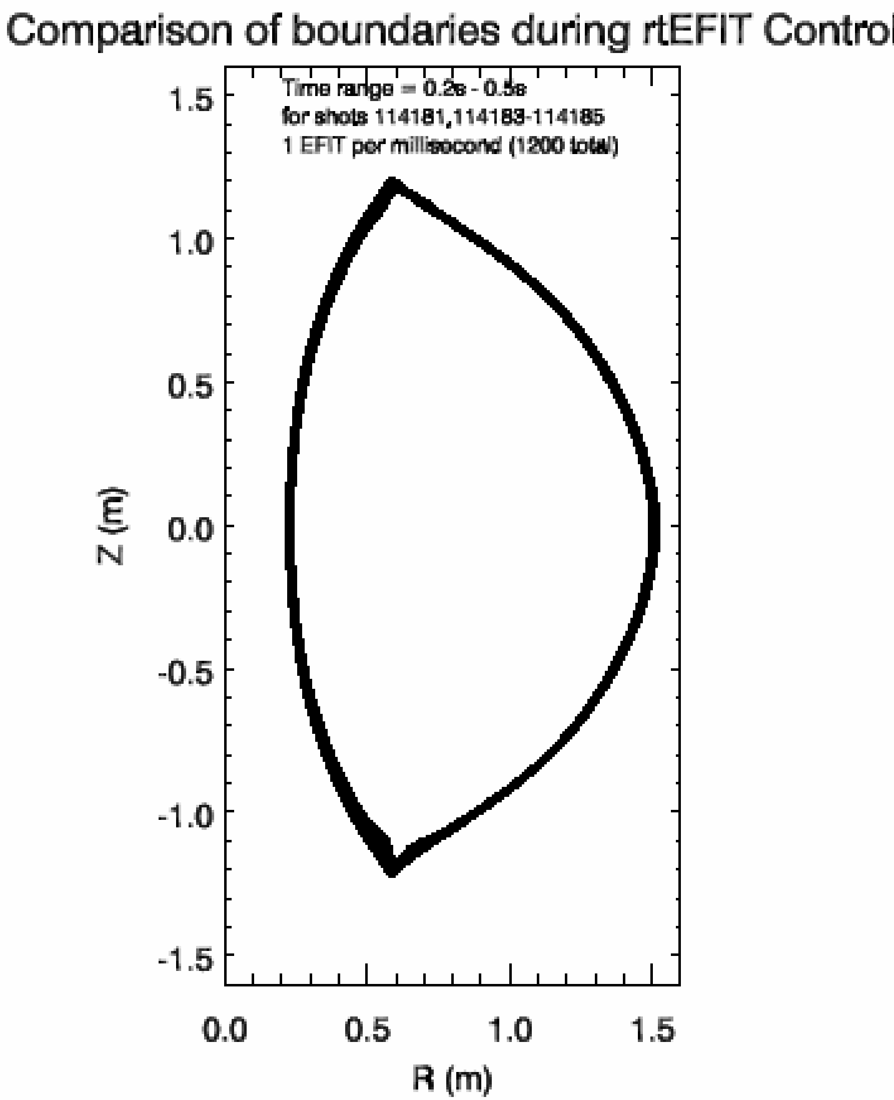
(the separation at the outboard midplane between the flux surfaces on which the X-points lie)

- Control of drsep is achieved by adjusting the control point for PF3L (for positive drsep) to be further inside the plasma than for drsep = 0 and by using a symmetry term to control the fluxes at the two control locations at the outer midplane
- The X-point references are unchanged, but the actual location of the lower X-point moves.



Boundary Control Results

- Reproducible boundary control demonstrated over a sequence of shots
- Reproducible boundary to ~ 1 cm
- Control maintained for ~ 0.3 sec plasma flattop



NSTX rtEFIT RESULTS SUMMARY

- rtEFIT successfully employed on XPs:
  - MAST similarity XP
  - Edge rotation during H-modes
  - EBW emission XP
  - HHFW + NBI XPs
  - HHFW heating and CD XPs
- rtEFIT used approximately 40% of XP shots this run period
- Significant experience gained in using rtEFIT features
- Improved kappa vs. li stability regime
- Improved boundary and outer gap control

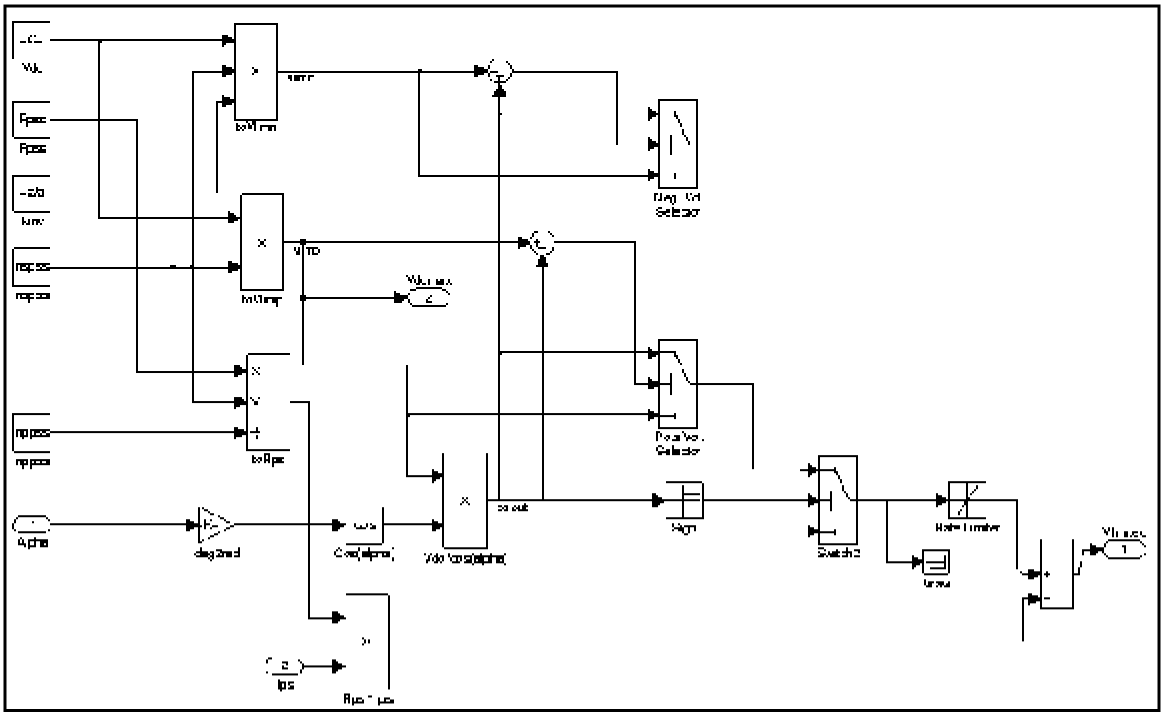
NOTE: *Development of single null shot scenarios planned for future XPs*

Summary of Recent Results

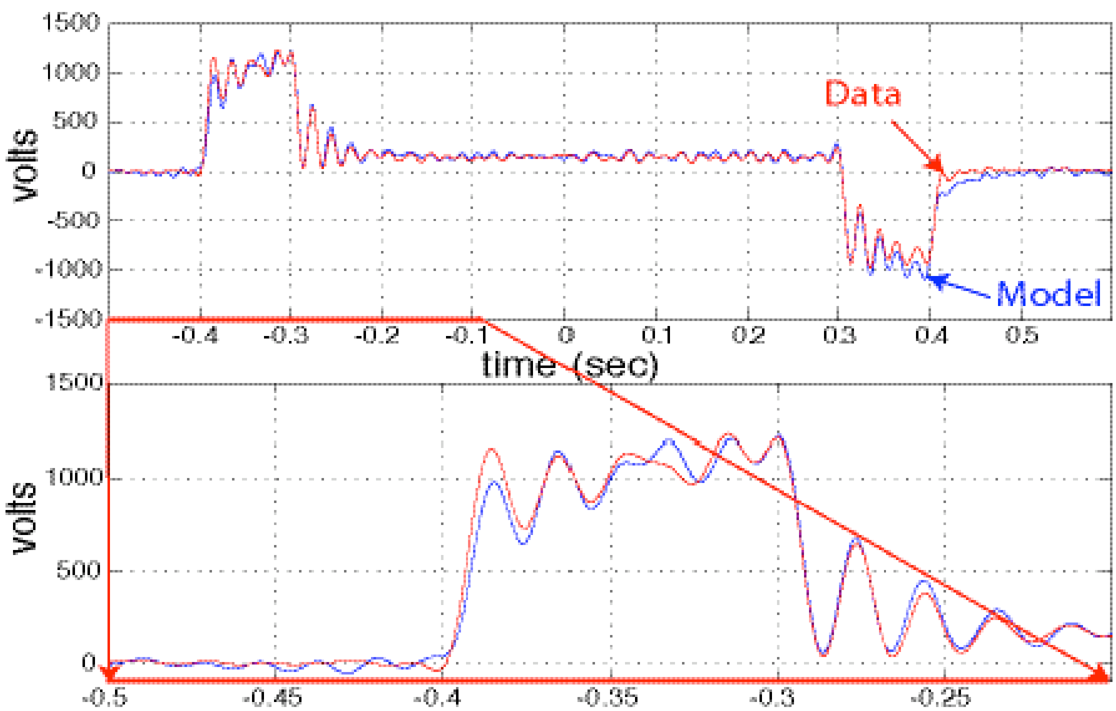
- PCS development and support
- Modeling, simulation, and validation:
  - tools, experimental analysis
  - power supplies
  - diagnostic Green functions
  - vacuum (coils/vessel) circuit response
  - plasma VDE
- OH-less startup scenario support
  - data to Khayrutdinov/Choi
  - DINA development
  - scenario design

EXAMPLE POWER SUPPLY MODEL VALIDATION

- **NSTX 12 pulse power supply model (R.Hatcher):**

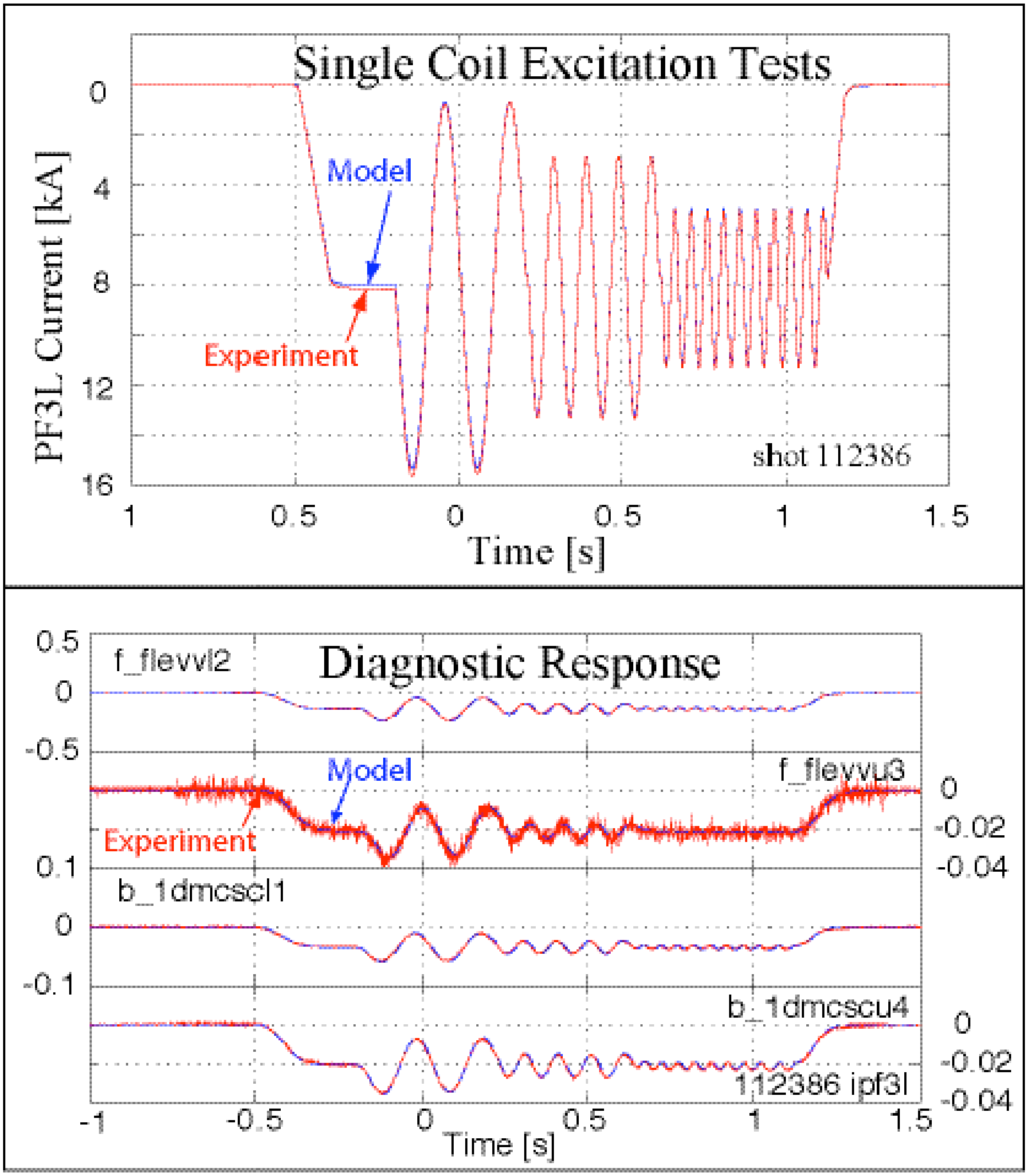


- **Typical validation results (OH, PF2u,l, PF3u,l, PF5u,l):**



SINGLE COIL EXCITATION TESTS VALIDATE MODEL

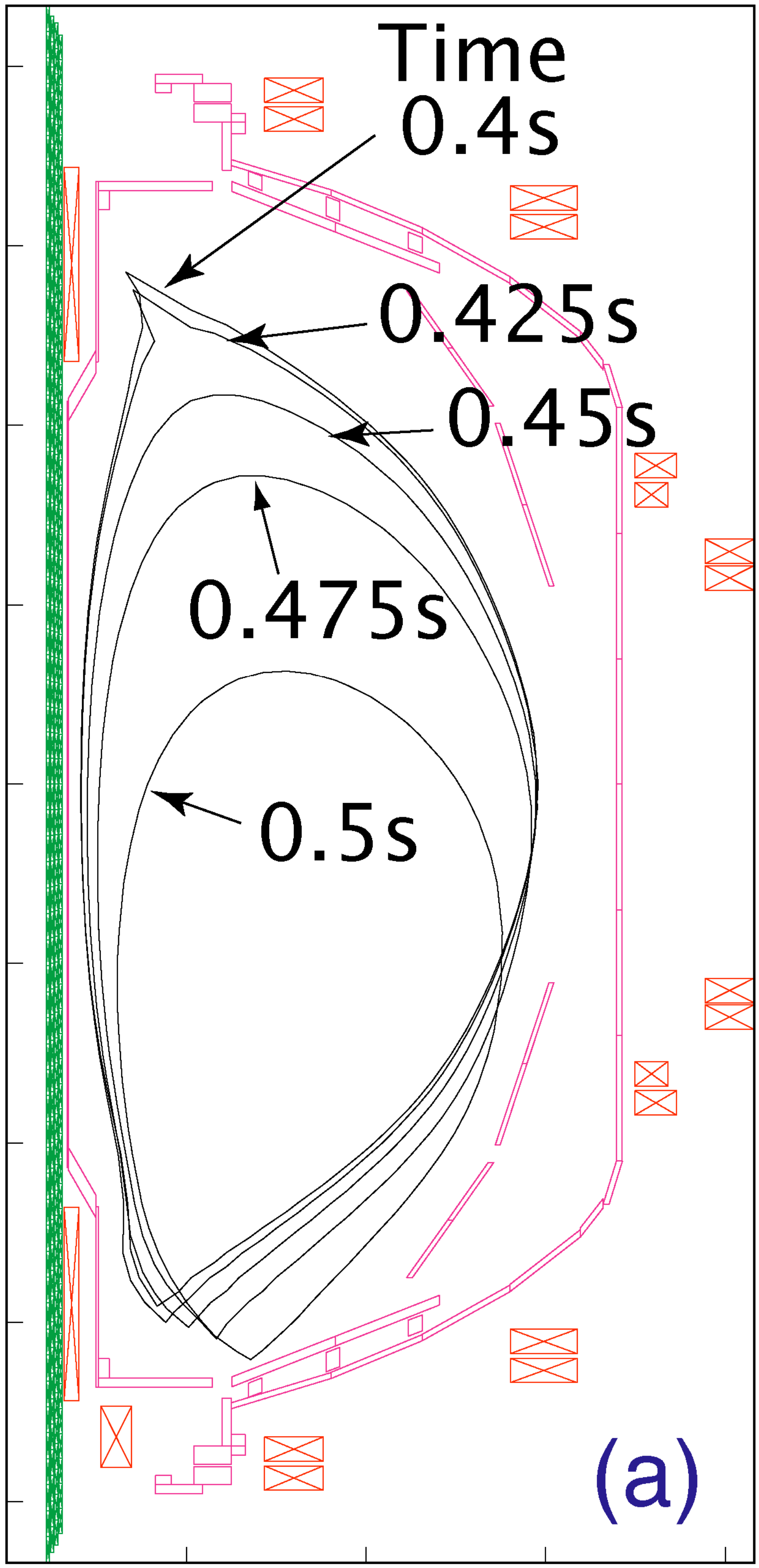
- **Single coil voltage waveforms from experiment excite model and results are compared with experiment.**



PCS Development and Support

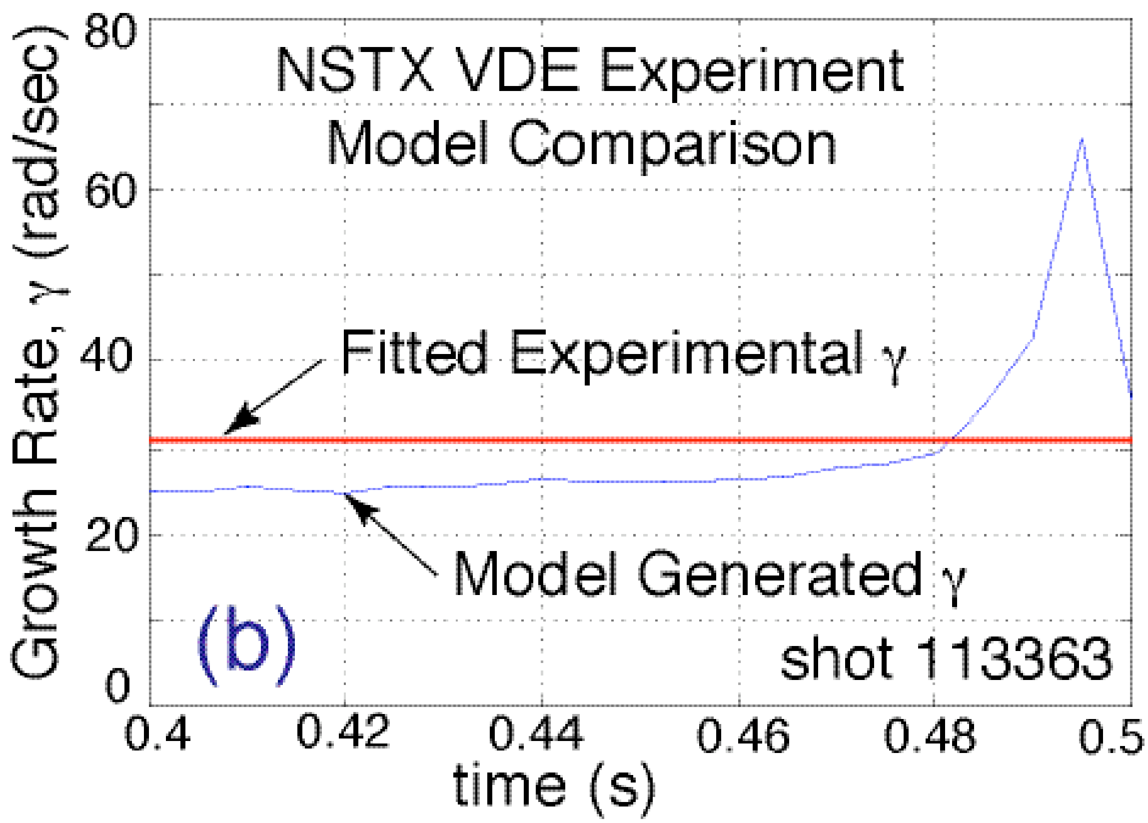
- Upgraded software versions to most recent PCS and rtefit/isoflux algorithm
- Supported rtefit/isoflux use in experiment during initial learning curve
- rtefit/isoflux use became more routine
- Enabled scans of double null shape up/down symmetry
- Enabled exploration of more strongly shaped single and double null plasmas

NSTX GEOMETRY AND VERTICAL DISPLACEMENT EVENT (VDE)



EXPERIMENT/MODEL COMPARISON OF CONTROL-DISABLED VDE PROVIDES VALIDATION OF PLASMA/PASSIVE STRUCTURE MODEL

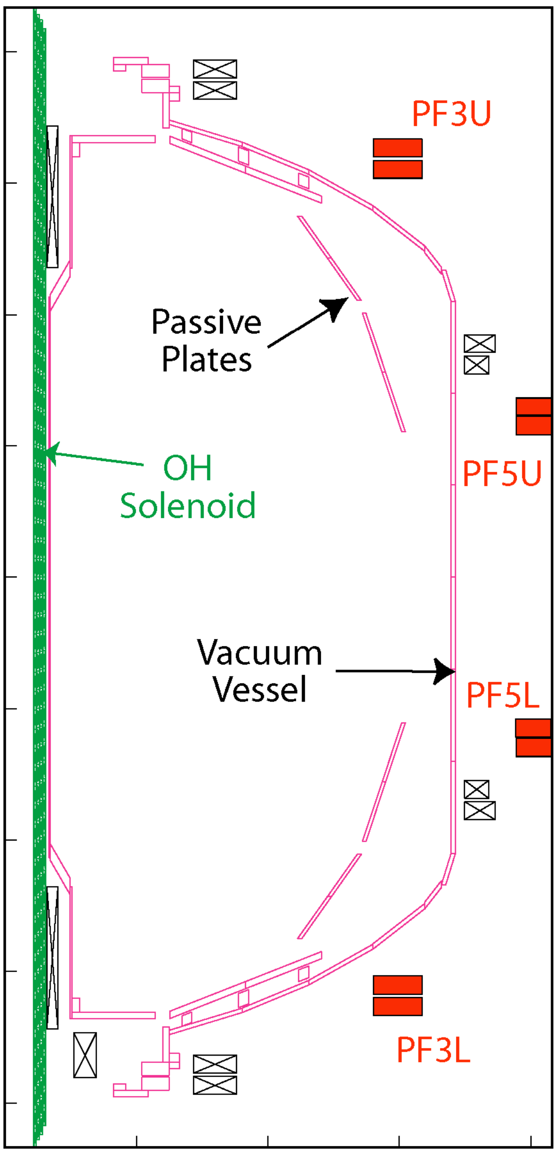
- **Vertical control is disabled at t= 0.4 s and unstable plasma evolves through a Vertical Displacement Event (VDE).**
- **Sequence of EFIT resonstructions (previous slide) provide time history of vertical position and allow fitting of overall growth rate, γ.**
- **Model calculations of γ, based on a linearized model calculated from each EFIT, compare favorably with growth rate fitted to experiment.**



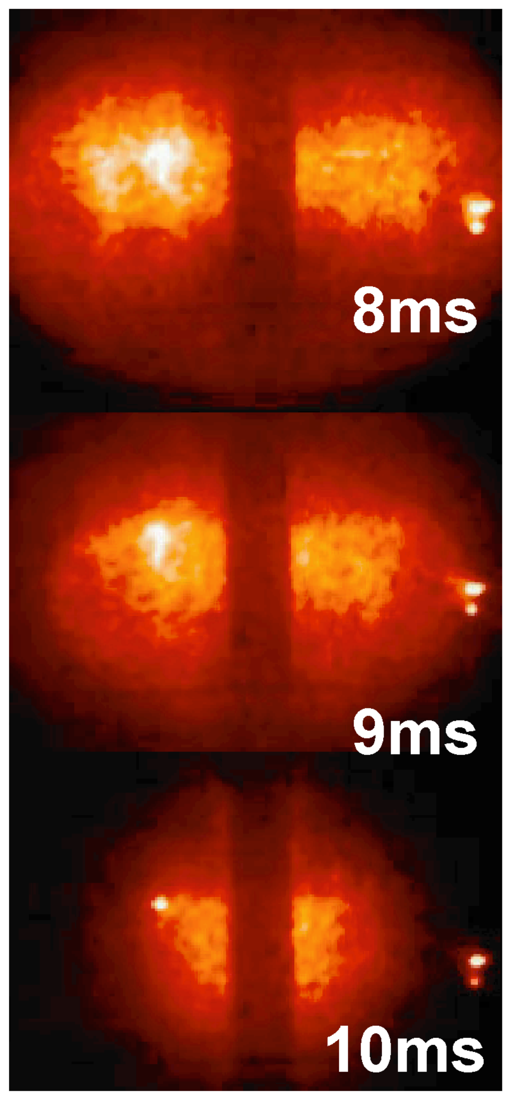
OH-less Startup Scenario Support

Initial Successful Solenoid-Less Operation in NSTX Used Outside Coil Pairs

- Analysis provides guidance for NSTX expermemt
- Allows validation of models under very severe accuracy requirements.



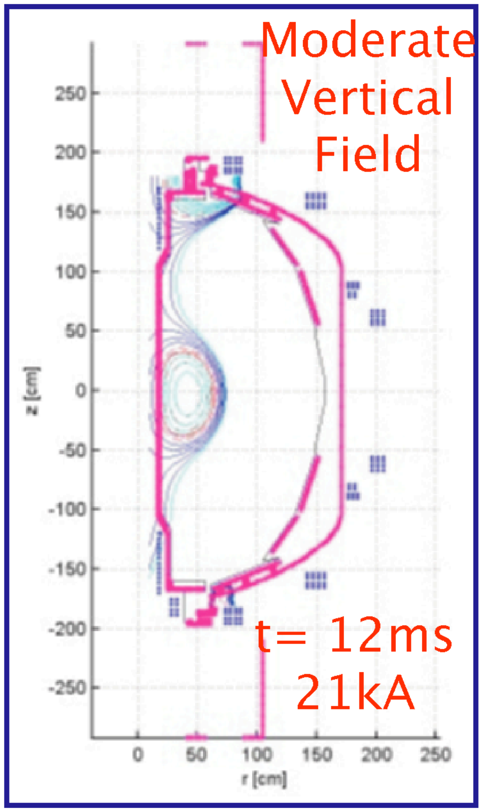
RF pre-ionization provides initial breakdown near outer extremes of chamber. At ~8ms vertical field switches sign and plasma is formed over a major part of the chamber. Vertical field continues to rise above that required for full bore plasma and compresses the plasma onto the centerpost.

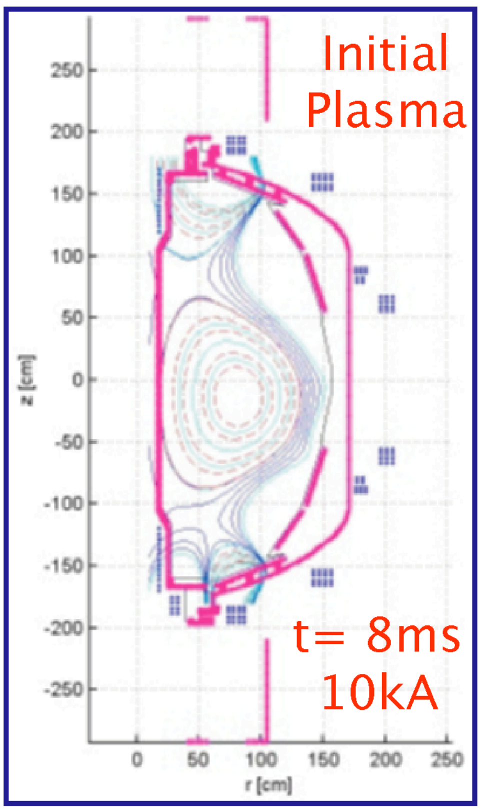


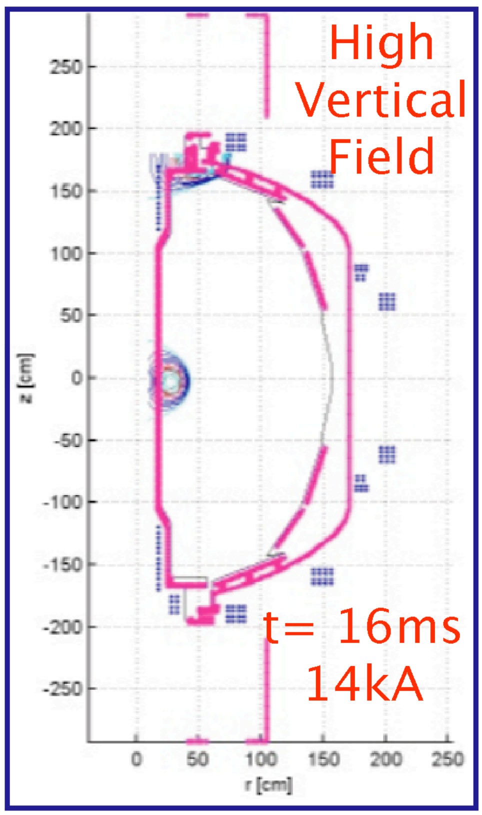
NSTX

DINA Simulation is Consistent With the Plasma Initiation Sequence

No plasma possible prior to ~8ms because of positive vertical field







Future plans - Present Collaboration

- Support engineering analyses
  - experimental needs
  - ongoing modifications
- Complete detailed system validation (all coils, vacuum vessel, VDEs)
- Simulink NSTX plant model
- Design vertical controllers
- Get ready for advanced shape control design
- Continued support OH-less startup
  - DINA development/simulations
  - scenario calculations

First MSE on NSTX

MSE-CIF at Low Magnetic Field

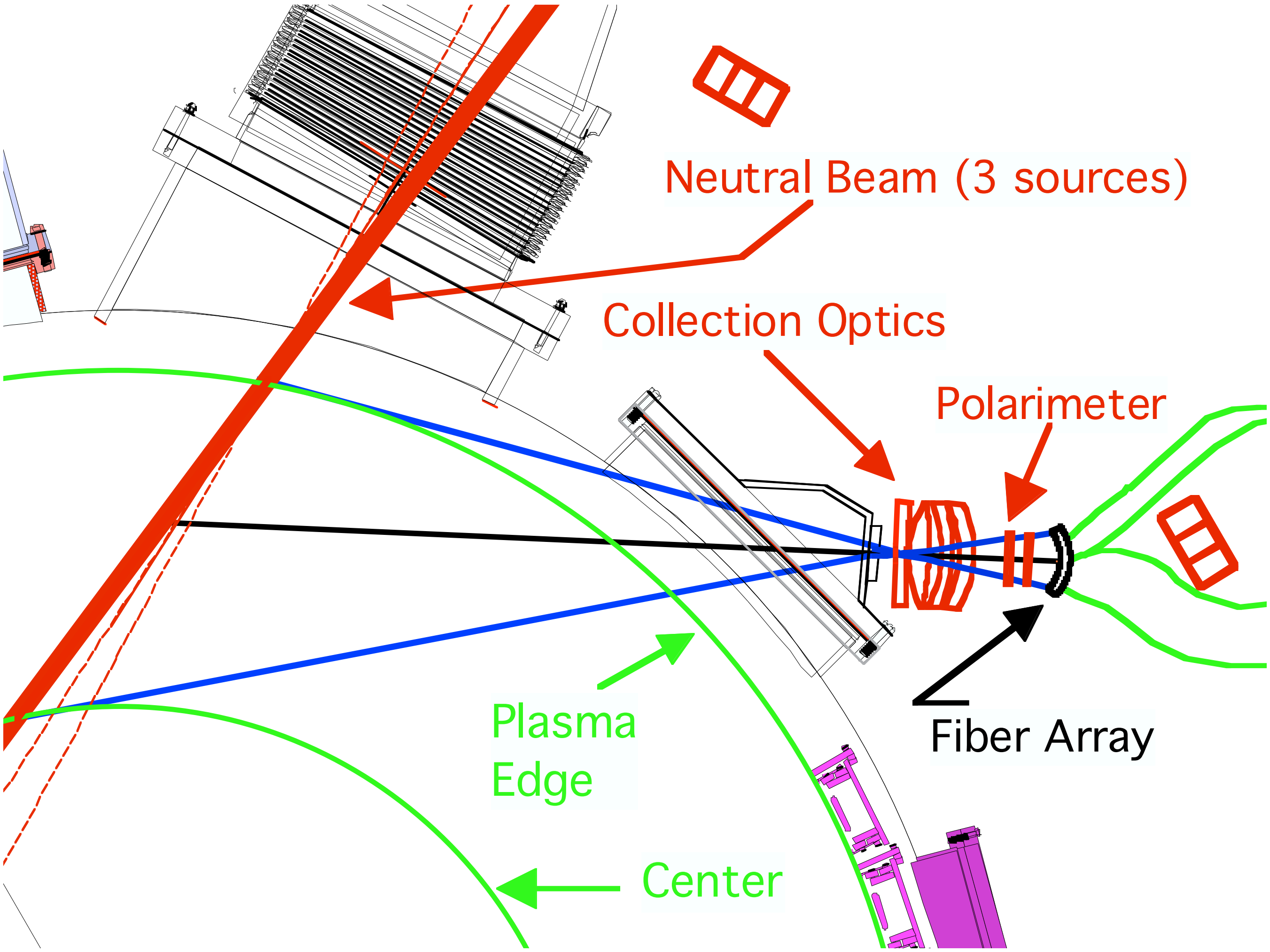
Nova Photonics, Inc.

- **Innovations improve the polarization fraction.**

  1. **Optimize optics to reduce geometric spectral broadening.**
     - **Spectral broadening is from the finite optics and image size. Optimization of the optics can reduce the spectral width.**
  2. **Development of high resolution, high throughput filter to extend measurements to $\sim$0.3 T.**
     - **Wide field Lyot type birefringent filter meets requirements.**

MSE-CIF Layout on NSTX

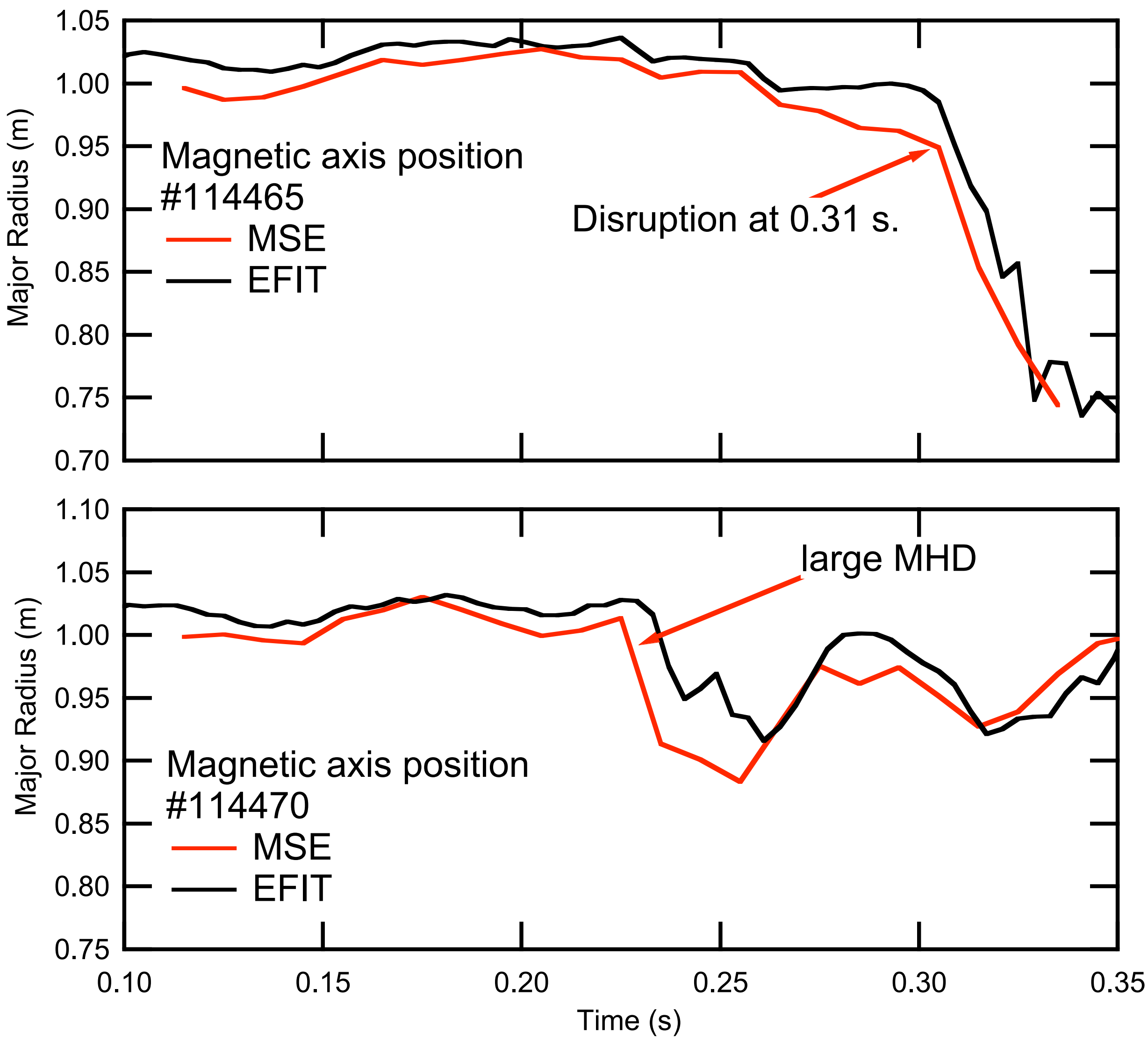
Nova Photonics, Inc.



- Tangential sight-lines at edge and center provide optimal spatial resolution over a wide field of view. [*Goldston & Goldston*, Rev. Sci. Instrum. 66, 5638(1995)].
- MSE and CHERS share collection optics, but have separate fiber arrays.

MSE Consistency: Magnetic Axis

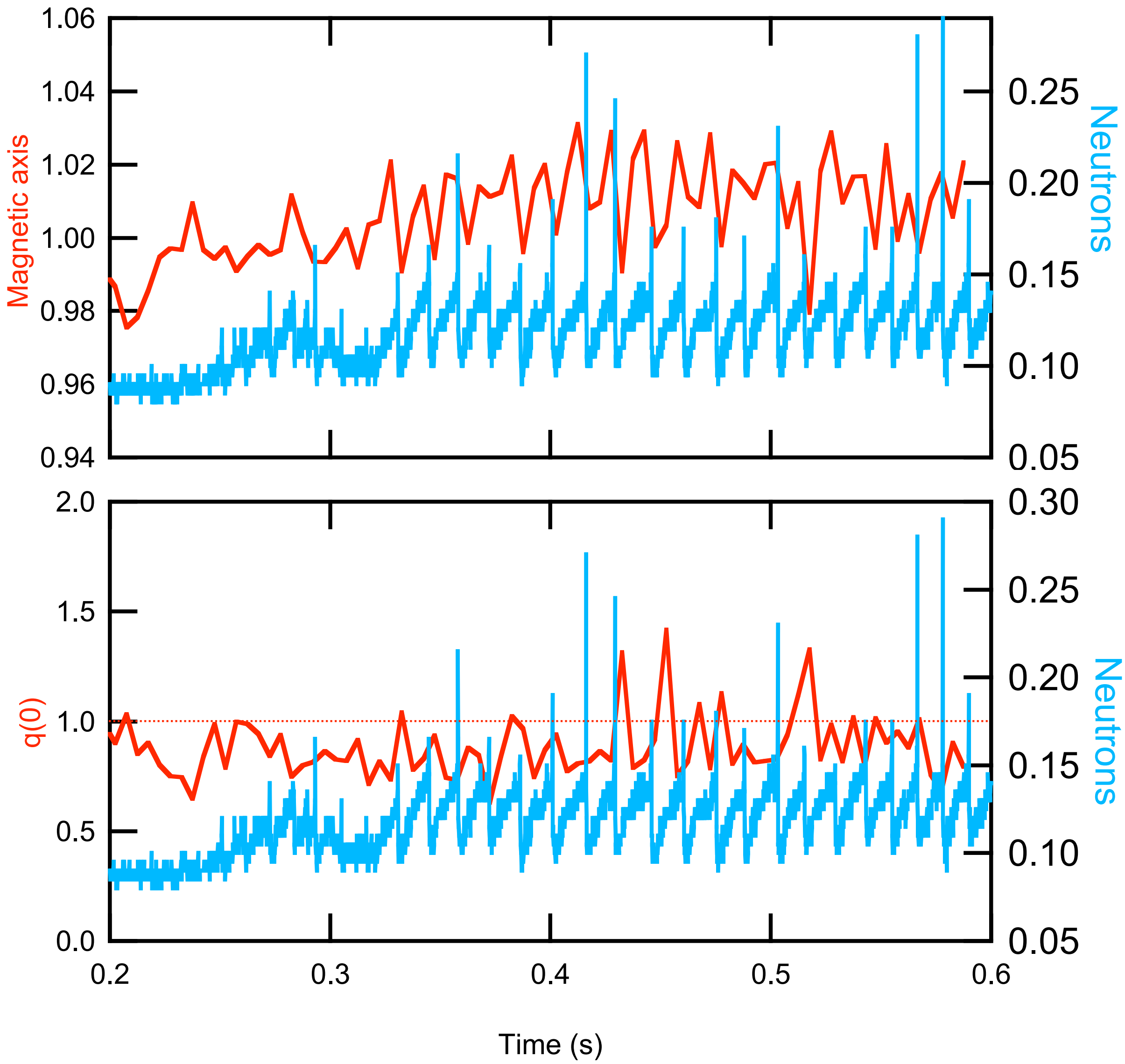
Nova Photonics, Inc.



- **MSE magnetic axis from zero crossing of pitch angle.**
- **Magnetic axis evolution is consistent with EFIT and magnetics.**

MSE Consistency: Sawteeth

Nova Photonics, Inc.



- $q(0) \sim 0.8$ **before sawtooth crash and rises to** $q(0) \sim 1$ **after crash. The magnetic axis shifts inboard ∼2 cm after sawtooth.**
- **MSE integration time is 5 ms. Sawtooth period is 15 ms.**