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Observation of MHD-induced current redistribution in NSTX

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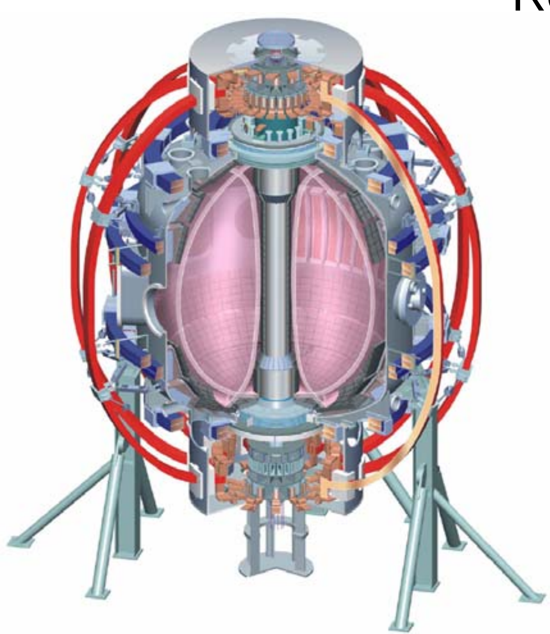

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Outline

- **Research discussed in this presentation is enabled by several improved diagnostic and control tools:**
  - **MSE diagnostic capability**
  - **Enhanced plasma shaping and control**
  - **Active error field and RWM control**

- **Progress in combining high β, good confinement, and high non-inductive current fraction**

- **Phenomenology of NSTX long-pulse discharges**

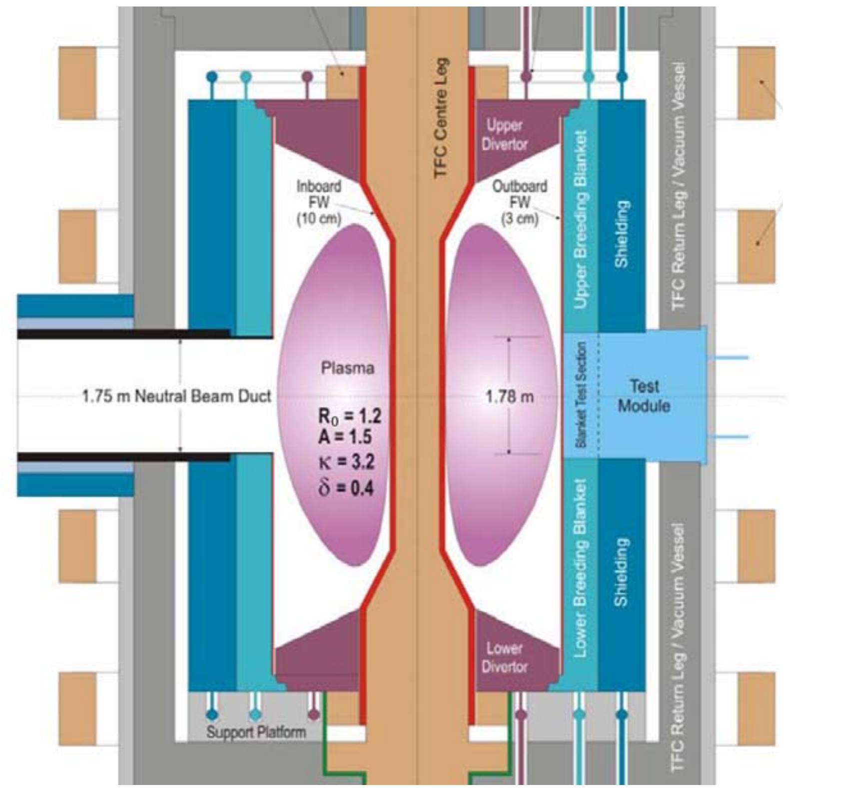
- **Measurements and modeling of current profile evolution**
  - **Observation of anomalous current diffusion**

NSTX plasmas approach the normalized performance levels needed for a Spherical Torus Component Test Facility (ST-CTF)

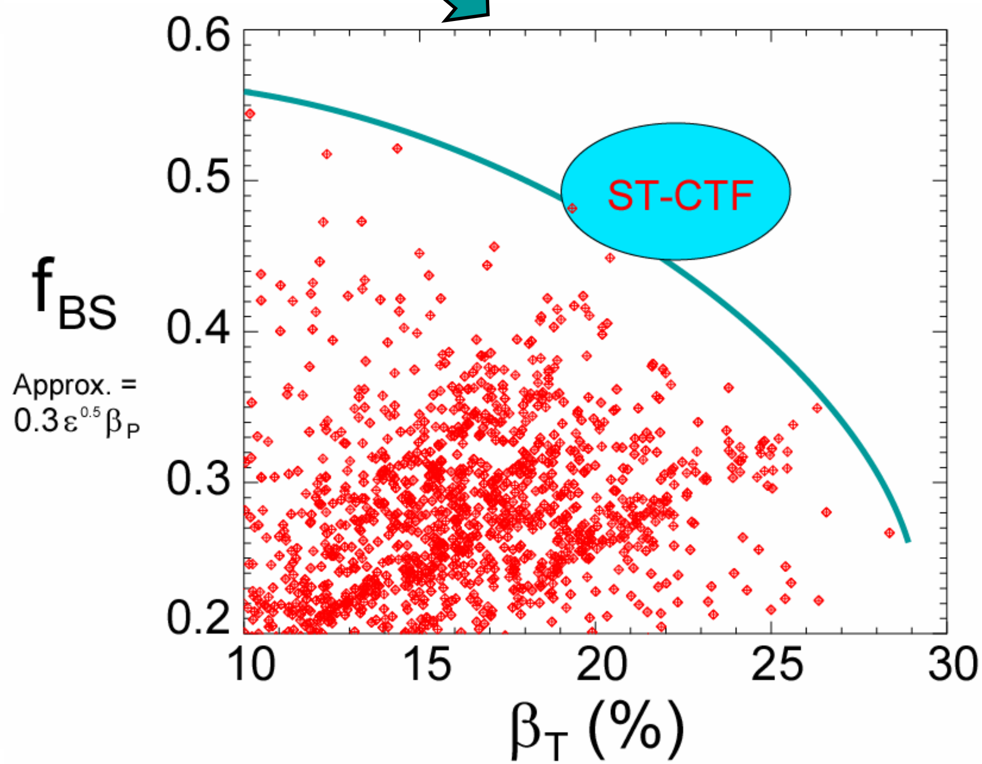
ST-CTF goal: neutron flux = 1-4MW/m²

A=1.5, κ = 3, R_0 = 1.2m, I_P= 8-12MA, β_N ~ 5, HH=1.3,

β_T = 20-25%, f_{BS}=50%



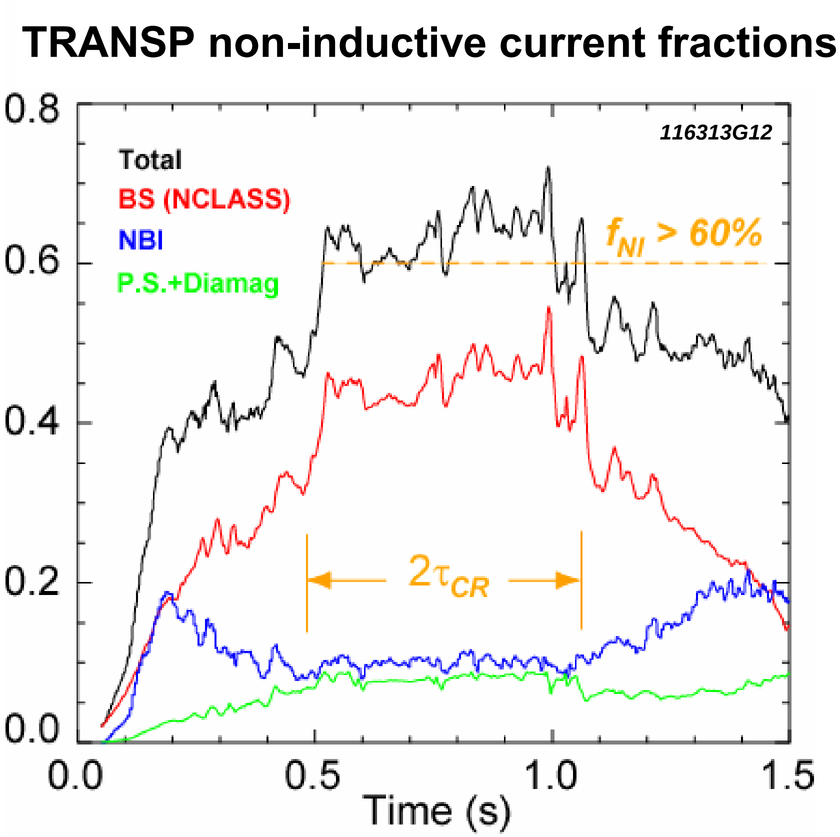
*Peng et al, PPCF, **47** (2005) B263.*

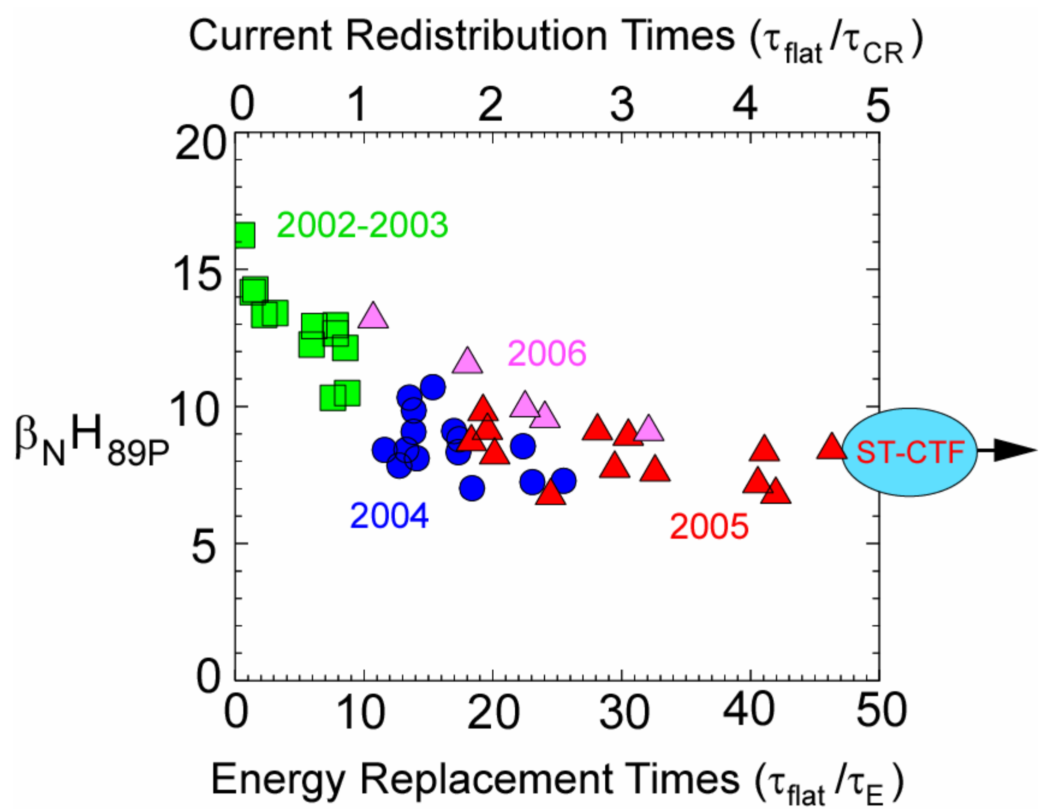


Lower ν_{*e} in CTF → higher f_{BS} for same β_P

High performance can be sustained for several current redistribution times at high non-inductive current fraction

• ∇p and NBI current drive provides up to 65% of the plasma current → High $\beta_N \times H_{89P}$ sustained for many τ_{CR} → record NSTX pulse-lengths (1.6s)



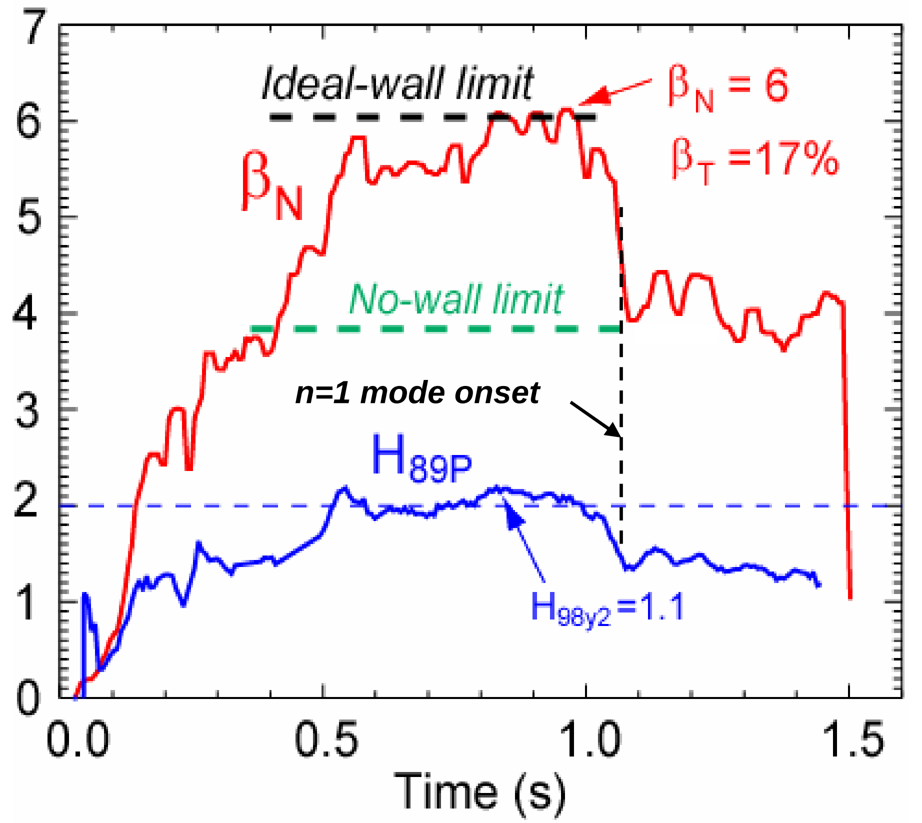


High beta phase of longest-pulse discharges is degraded by core MHD activity

- Strong shaping (κ=2.4, δ_L= 0.7, LSN) improves global and edge stability

- MSE diagnostic enables accurate stability limit calculations:
  - Plasma β_N above n=1 no-wall limit
    - Rotational stabilization of n=1 RWM
  - Repeated excursions above n=1 ideal-wall limit trigger core MHD

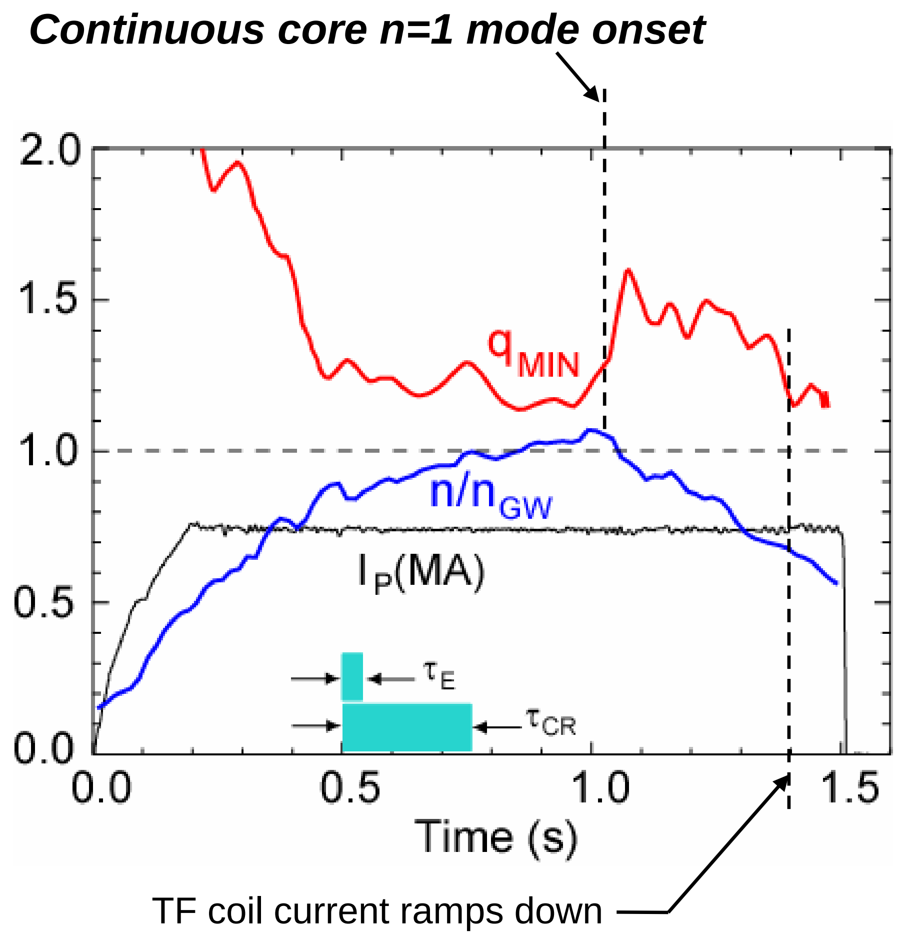
- Confinement reduced by core MHD
  - Core MHD is n=1 continuous mode
  - → β_N decreases 30% after mode onset



Current profile and density evolution of longest-pulse discharges are also modified by core MHD activity

NSTX

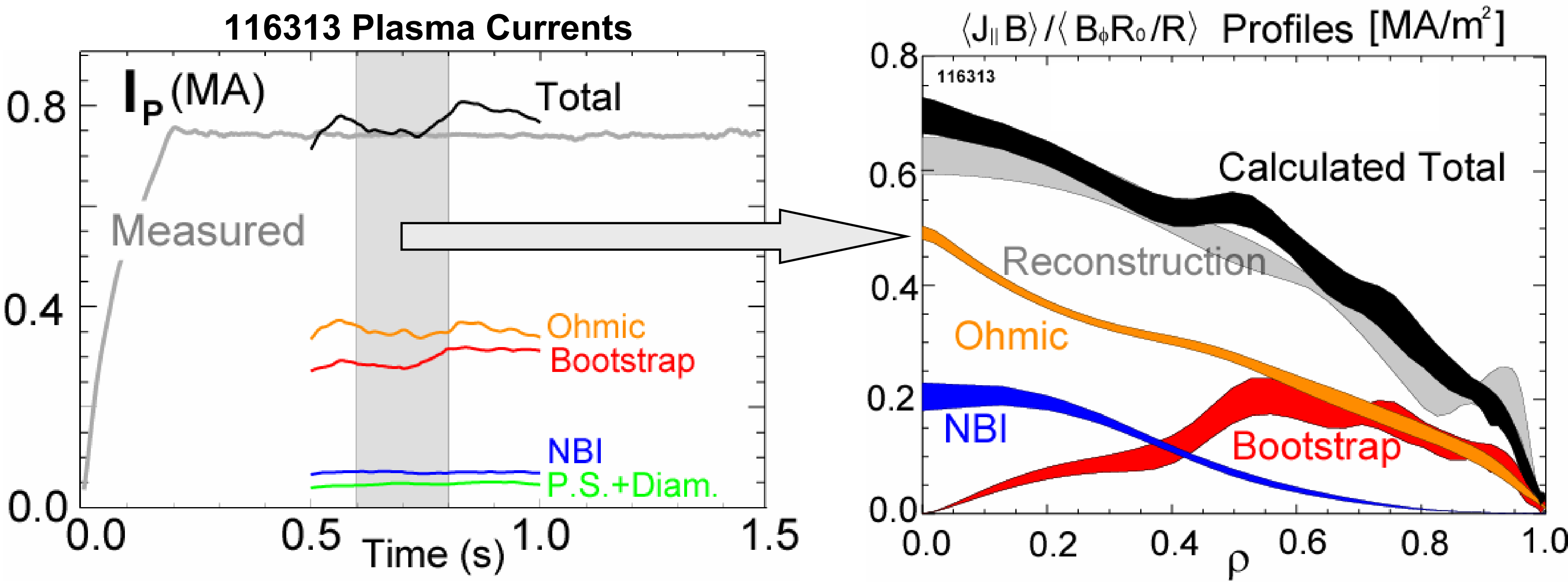
- MSE fits show q_{MIN} → 1.15
  - q_{MIN} increases at mode onset
  - remains elevated ≥ 1.25 until TF ramp-down at t=1.4s
- Electron density reaches Greenwald value at mode onset (coincidental?)
  - Density *decreases* during core MHD
- Discharge only ends because TF and OH current/heating limits are reached



MSE diagnostic enables testing of models of inductive and non-inductive current drive sources

- **Compute V_{LOOP} distribution/evolution directly from MSE-constrained fits**
  - **Long pulse-length and quiescent discharges needed for analysis**
- **Fit *T, p, Z_{eff}* to ψ, compute σ_{NC}, J_{OH} & J_{BS} (Sauter model), add TRANSP J_{NBI}**

Sauter collisional NC model consistent with experimental I_P and $J_{||}$

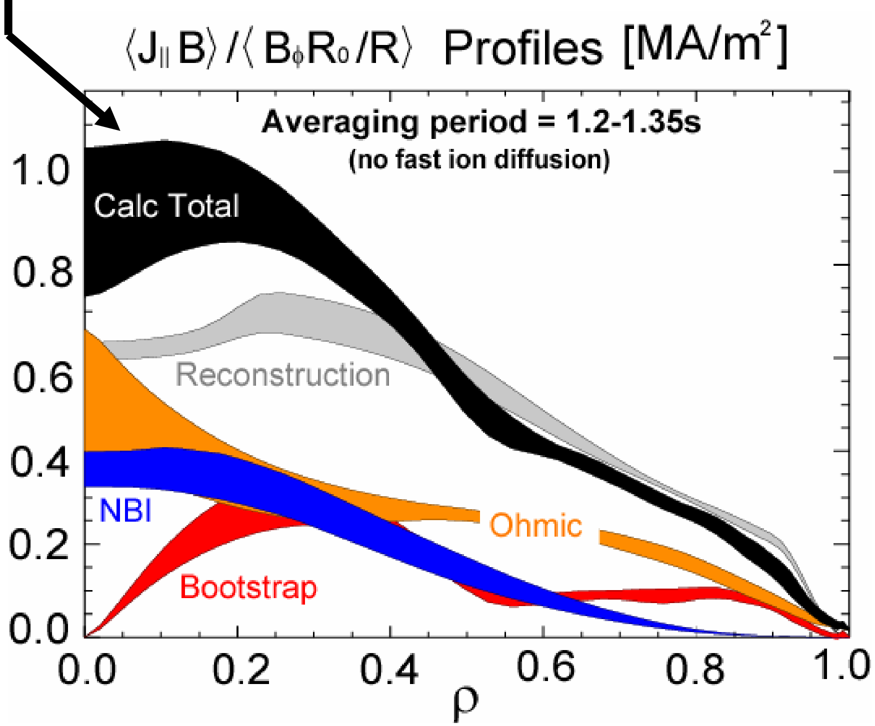


I_P=750kA, f_{NI} = 55-60%

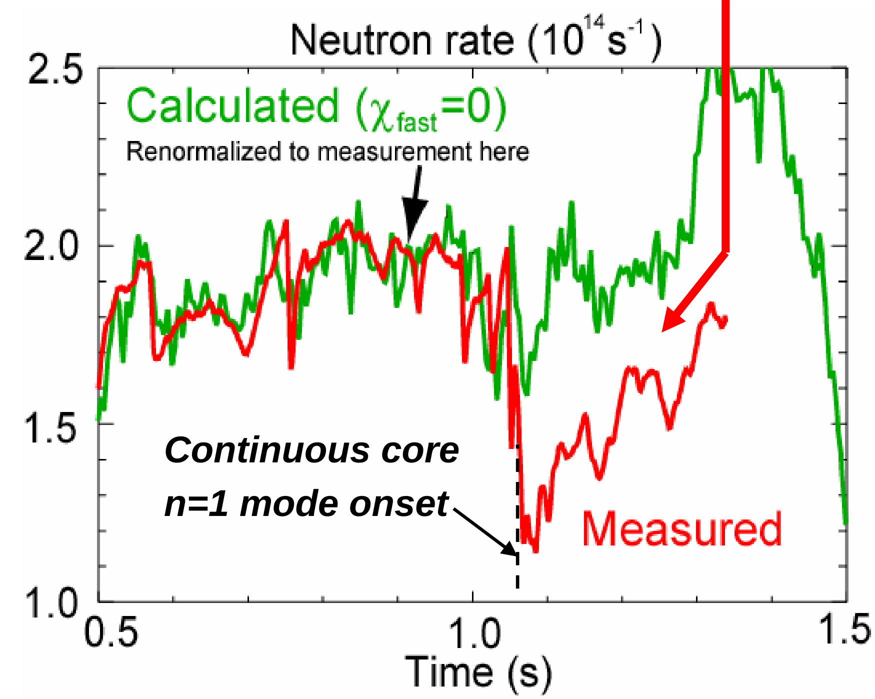
Stand-alone $f_{BS} \approx$ 10% higher than TRANSP – exploring NC models and mapping issues

Predicted $J_{||}(\rho)$ and neutron rate inconsistent with measurement when continuous n=1 mode is present

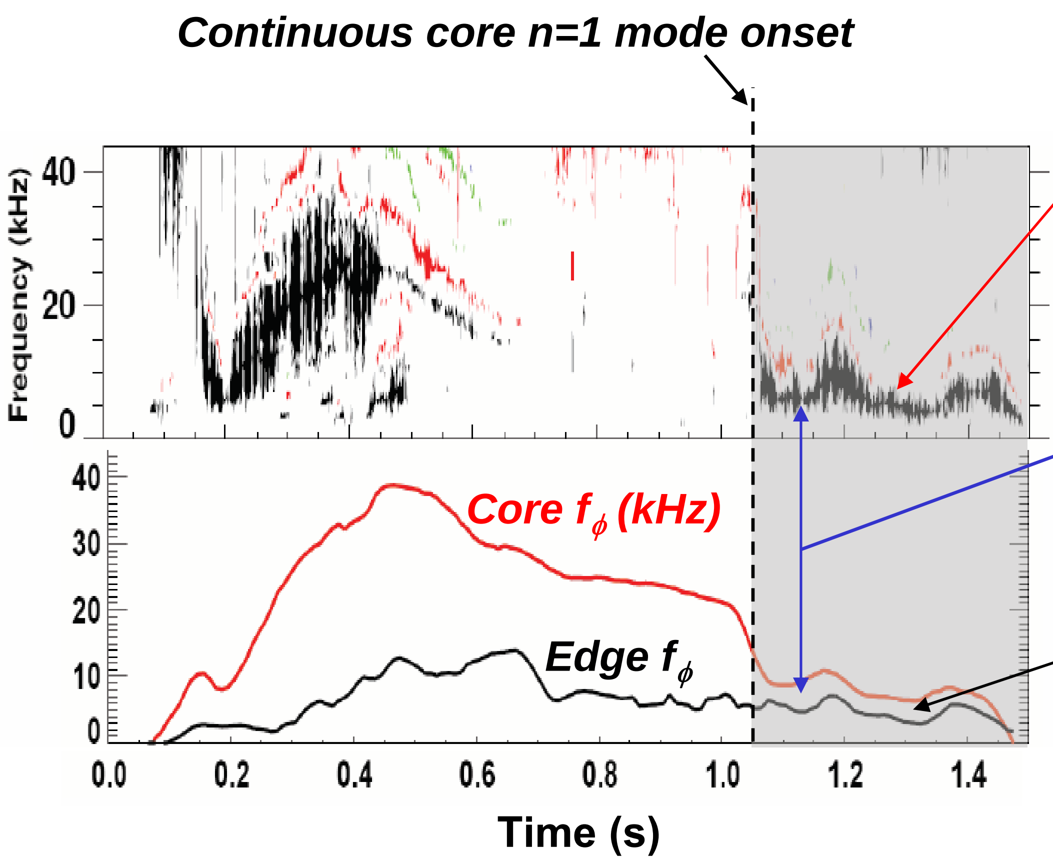
- Predicted $J_{||}$ in plasma core is 40% higher than reconstruction
- Assumes ***NO*** anomalous fast-ion redistribution or loss



- Calculated neutron rate (TRANSP) agrees with measured value to within ± 10% before late MHD mode onset
  - → **Normalize to this value to isolate effect of late MHD mode**
  - → **20% neutron rate deficit observed during late mode activity**



Mode perturbed B-field sufficiently large to flatten rotation profile



- Core mode propagates at f = 5-8kHz without locking for remainder of shot
  - Some shots lock and disrupt
- Mode $\omega \approx$ plasma Ω_ϕ
  → Tearing mode?
  → Saturated kink?
- Mode flattens core Ω_ϕ profile
  - Neoclassical Toroidal Viscosity (NTV) between mode & plasma

*Shaing - PF 1986, Menard - NF 2005, **Zhu - PRL 2006***

- ***Mode clearly impacts angular momentum diffusion (NTV)***
- ***Loss of sheared flow may degrade thermal confinement***
- ***Large δB of mode likely impacts fast-ion confinement***

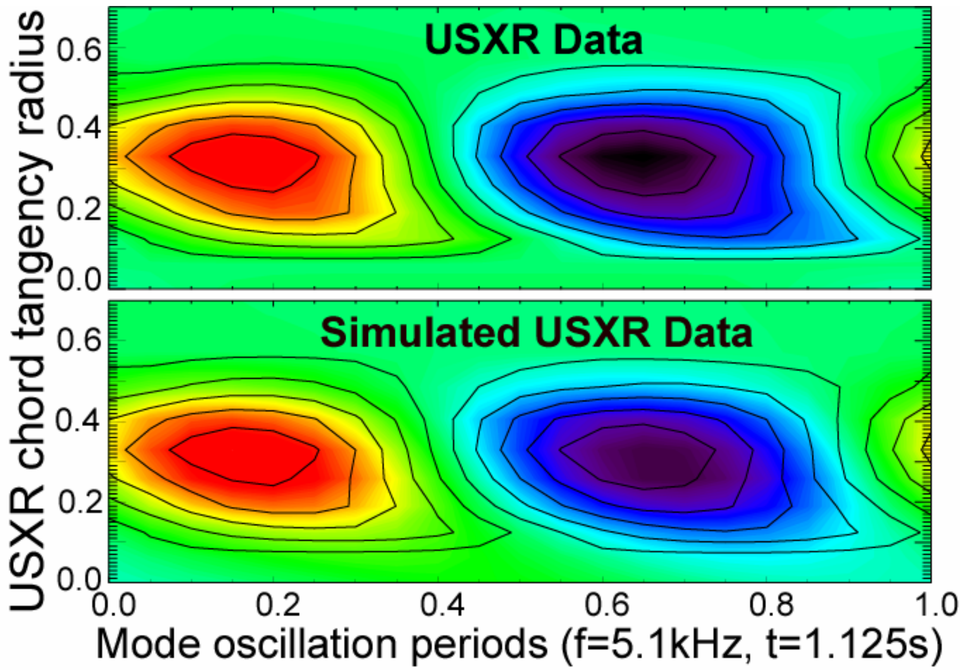
Continuous n=1 mode identified as saturated infernal or quasi-interchange mode

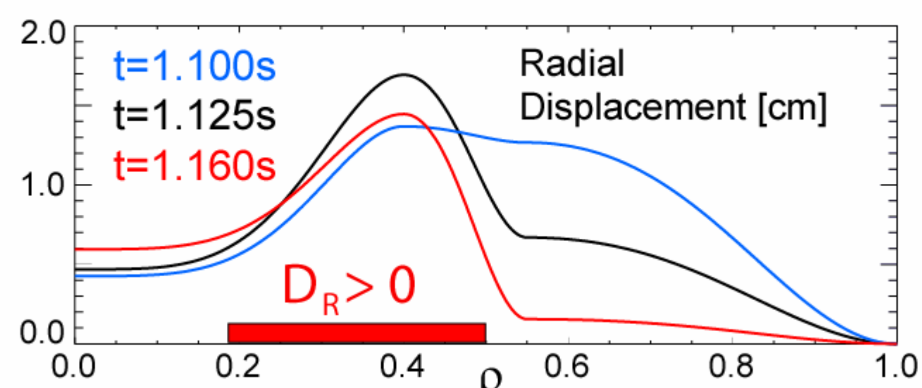
- Soft X-ray + q(ρ) → ***not*** an island
- 1-2cm displacement peaks at ρ = 0.4
- q(ρ) weakly reversed
  - $\Delta q = q(0) - q_{MIN} = 0.1\text{-}0.2$
  - $\rho(q_{MIN}) \approx 0.4$
- $D_R > 0$ for $q_{MIN} < 1.4$ →
  - Interchange drive

→ Saturated infernal or quasi-interchange mode

- More unstable at higher β
- More unstable as $q_{MIN} \to 1$
- More unstable with deeper reversal

Both sets of black contours below are from data



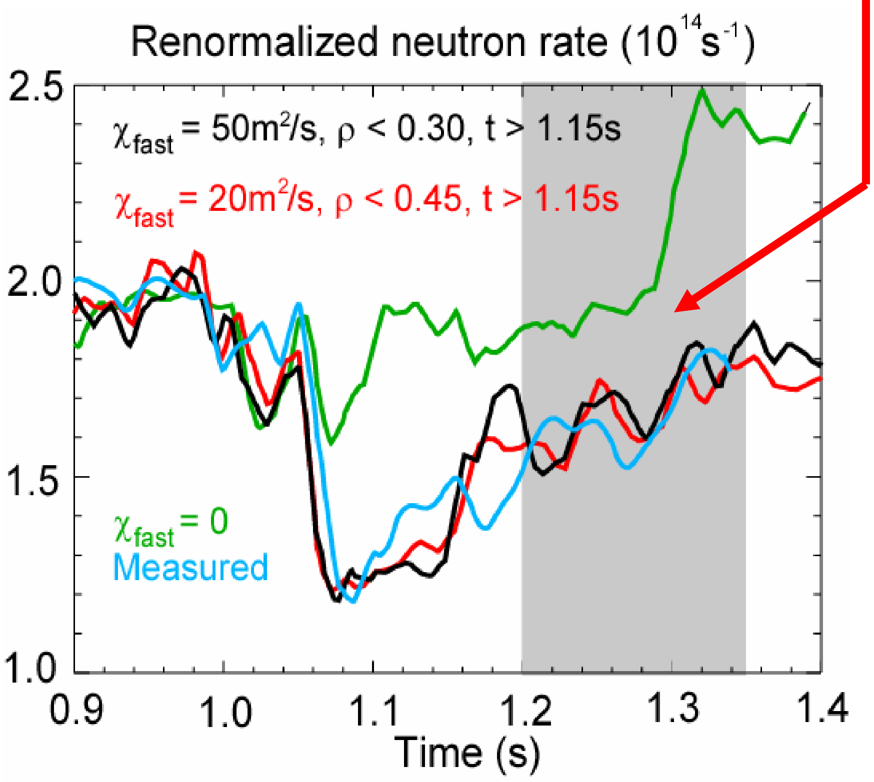


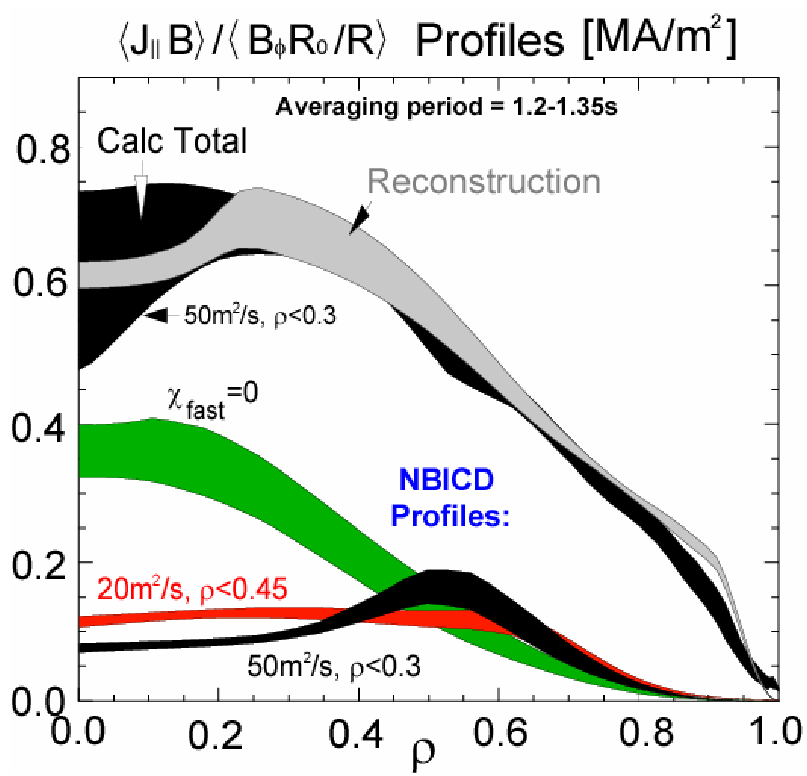
Mode-induced diffusion of fast ions can explain neutron rate and $J_{||}(\rho)$ evolution in high-performance shots

NSTX

- High core-localized anomalous fast ion diffusion can account for neutron rate deficit
- Core δB from mode estimated to be 100's of Gauss → large χ_{fast}

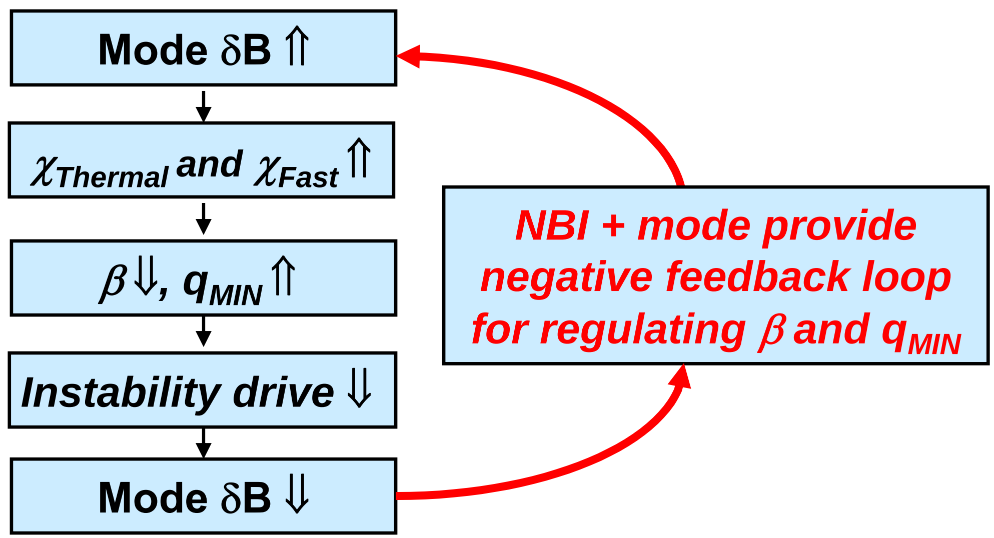
- Diffusion of fast ions can convert centrally peaked J_{NBI} to flat or hollow profile
- Redistribution of NBICD makes predictions consistent with MSE





Hypothesis for β and q_{MIN} regulation and mode persistence:

- **Mode Triggering:**
  - Rapidly growing n=1 instabilities encountered near ideal-wall limit redistribute current and/or fast ions → set up <u>weak reversed shear</u>
  - At low q_{MIN} and high β_N, interchange-type modes are destabilized
- **Mode Saturation:**

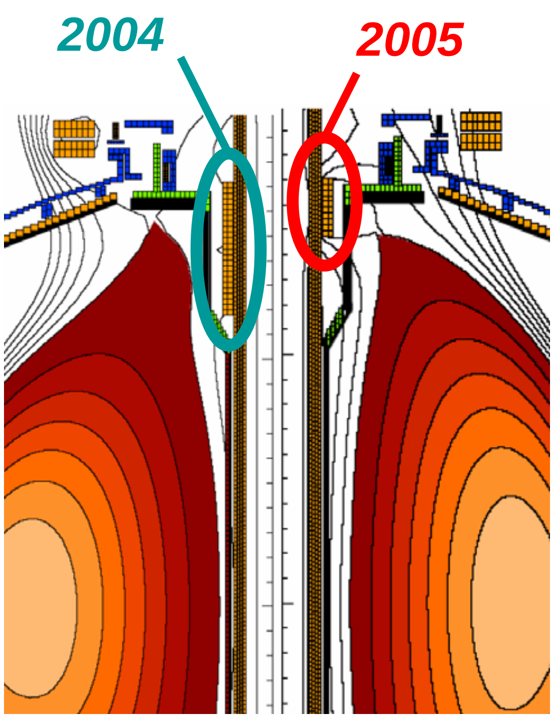


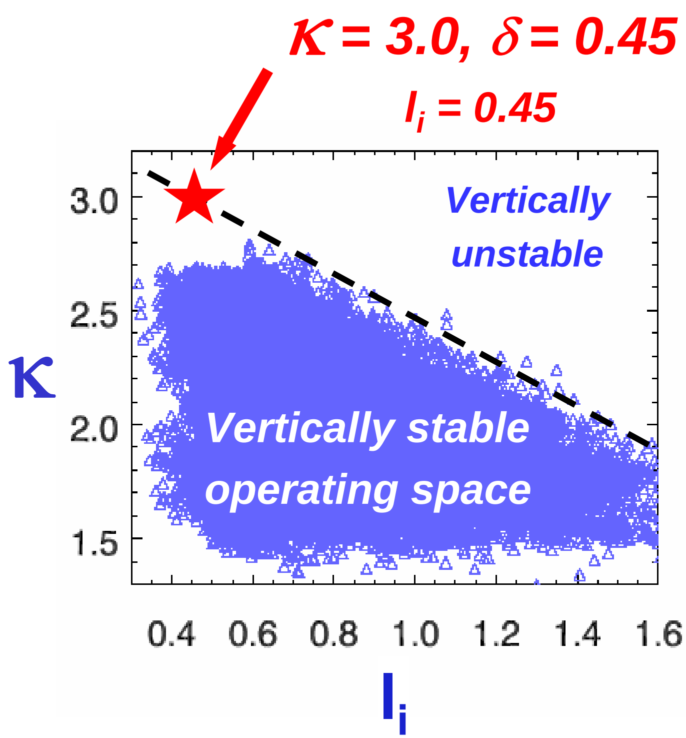
  - Potentially important for CTF which has up to 50% NBICD fraction
  - Similar processes may be active in the "hybrid" scenarios proposed for ITER and observed on ASDEX-U (fishbones) and DIII-D (NTMs)

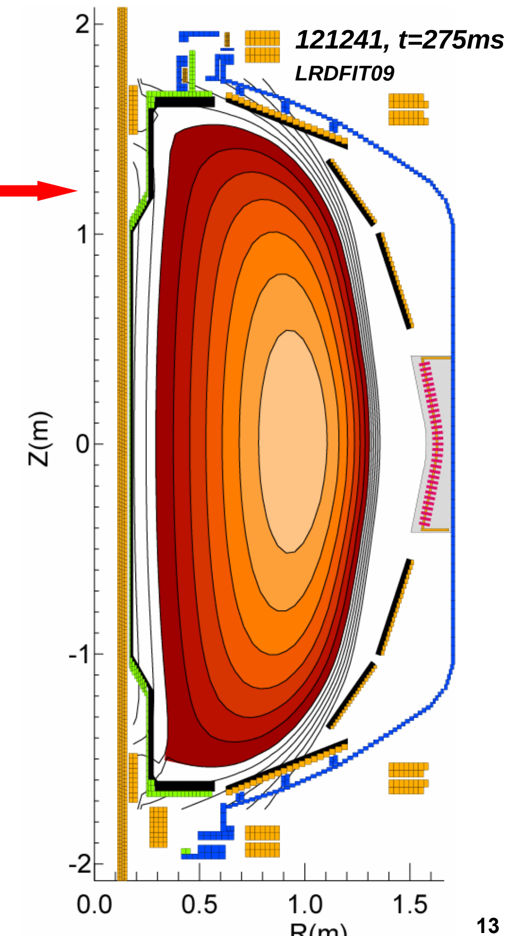
Recently achieved elongation κ up to 3 at low $l_i = 0.45$ → opens possibility of higher β_P, f_{BS} operation at high β_T

- High κ beneficial in CTF scoping studies
- Can sustain $\kappa \geq 2.8$ for many τ_{WALL} using rtEFIT isoflux control
  - NO in-vessel vertical position control coils
- Reduced outboard coupling to plates & vessel may lower β_N limit

Divertor coil upgrade allows simultaneous high κ and δ



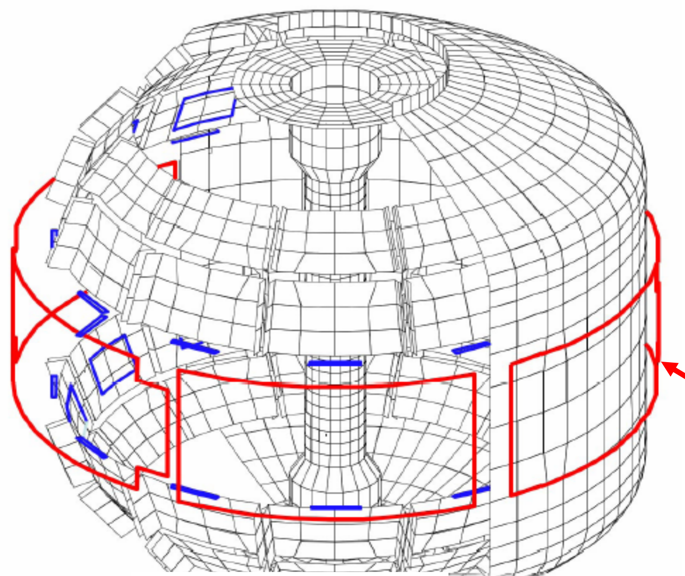




Error field correction can sustain plasma rotation and increase pulse-length of high-β_N NSTX discharges

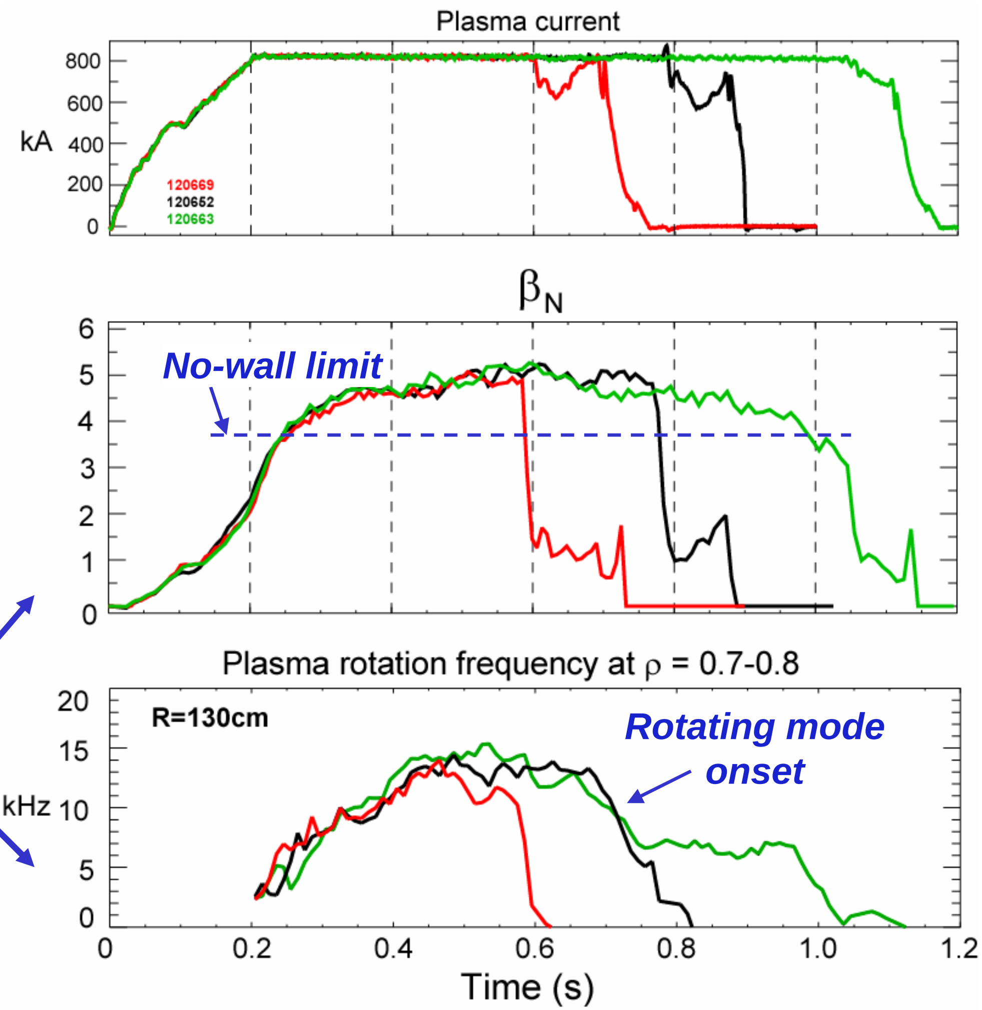
NSTX

- No error field control during high β_N phase
- Predictive correction of known error fields
- Predictive correction + active feedback



VALEN (Columbia Univ.)

6 ex-vessel mode control coils
+ 48 in-vessel sensors



Can sustain high β_N during rotation drop from saturated n=1 core mode

Can also stabilize RWM for over 90 RWM growth times when $\Omega_\phi << \Omega_{crit}$
(See E. Doyle paper I1.003, M. Bell poster P5.117)

Summary

- **Integrated high β, confinement enhancement, and non-inductive current fraction approaching CTF levels**

- **Operation near ideal-wall limit can trigger core MHD**

- **Persistent core mode identified as saturated "interchange"**

- **Core mode apparently induces anomalous NBICD diffusion**
  - **Mode regulates β and q_{MIN} – keeps q(0) > 1**
  - **Presently investigating possible J_{NBI} diffusion from *AE's**

- **New diagnostics and control tools are expanding NSTX operating space and physics understanding**
  - **Essential for projecting to CTF and ITER**

⇒ Please visit NSTX poster session Friday morning