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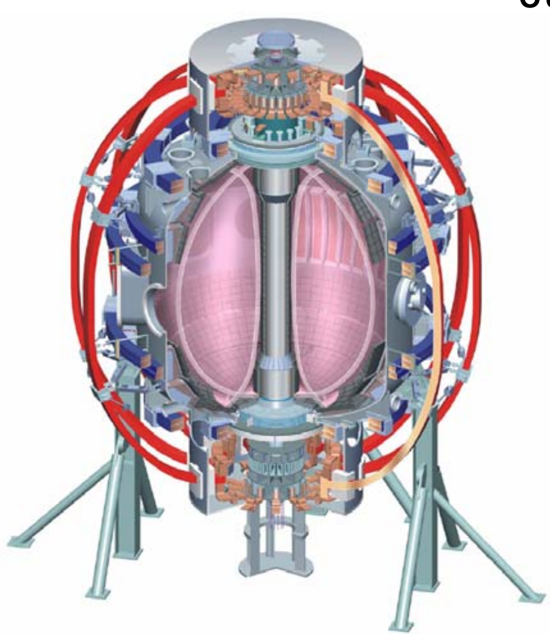
Physics of integrated high-performance NSTX plasmas

(derived from EPS-2005 talk)

Jonathan Menard
For the NSTX Team

NSTX Physics Meeting
July 25, 2005



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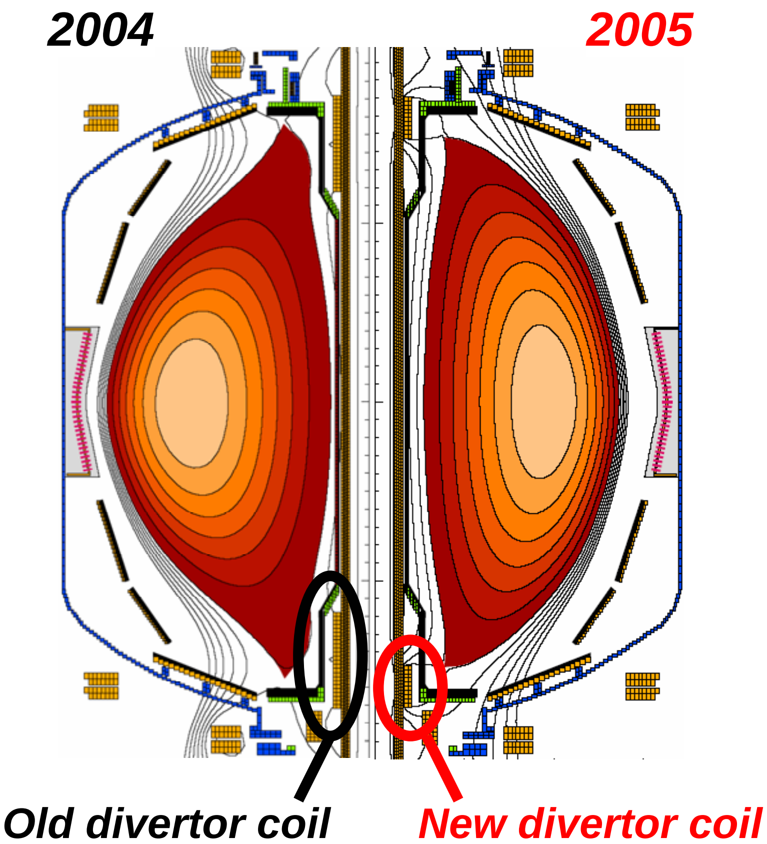
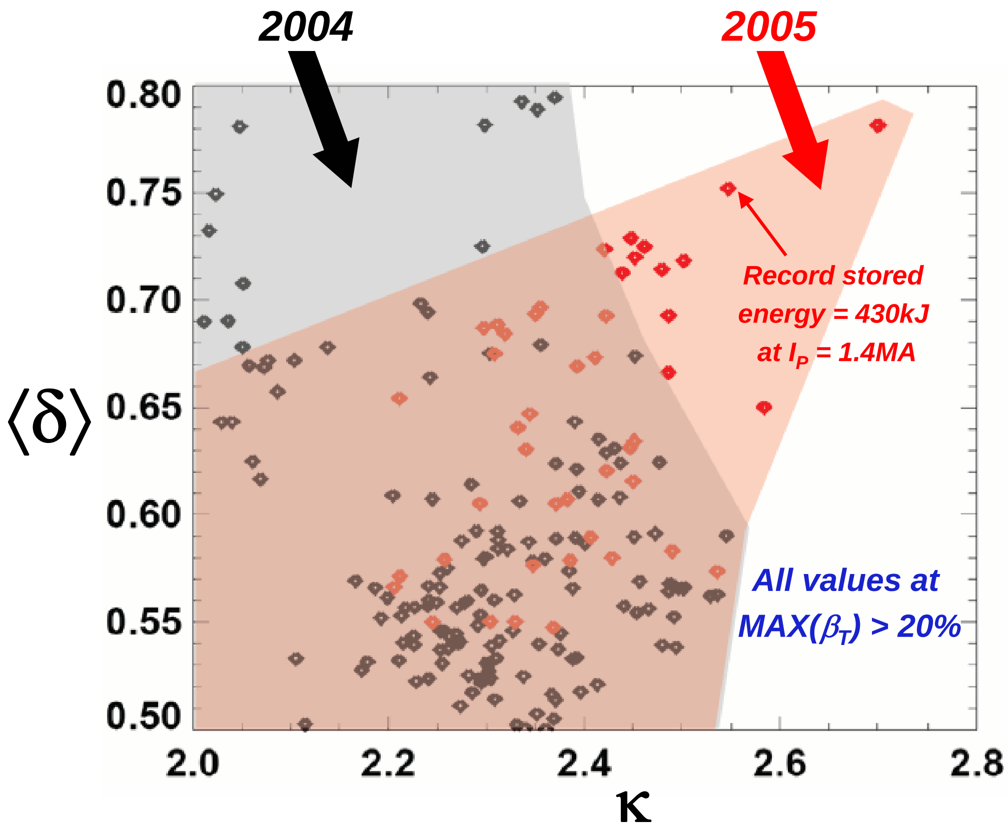
NSTX is pursuing the integration of high β and high confinement with fully non-inductive operation

- **High beta**
  - **Increased plasma shaping factor**
  - **Rotational stabilization of the resistive wall mode (RWM)**
- **High confinement**
  - **Developing small ELM regimes at high shaping factor**
  - **New MSE data elucidating role of q profile in electron transport**
- **High non-inductive current fraction**
  - **Using NBI + BS to achieve high f_{NI}**
  - **Determining requirements for $f_{NI} \rightarrow$ 100%, stationary J profile**
- **Plasma startup without solenoid**
  - **Coaxial Helicity Injection**

New divertor poloidal field coils have significantly enhanced the plasma shaping capabilities of NSTX

- **Highest $\kappa \rightarrow 2.7$ now obtained at highest $\delta \rightarrow 0.8$, $S \equiv q_{95}\, I_P/aB_T \rightarrow 35$**
  - **Record stored energy = 430kJ at I_P=1.4MA, β_N=5.3, β_T = 29%, q*=2.3**

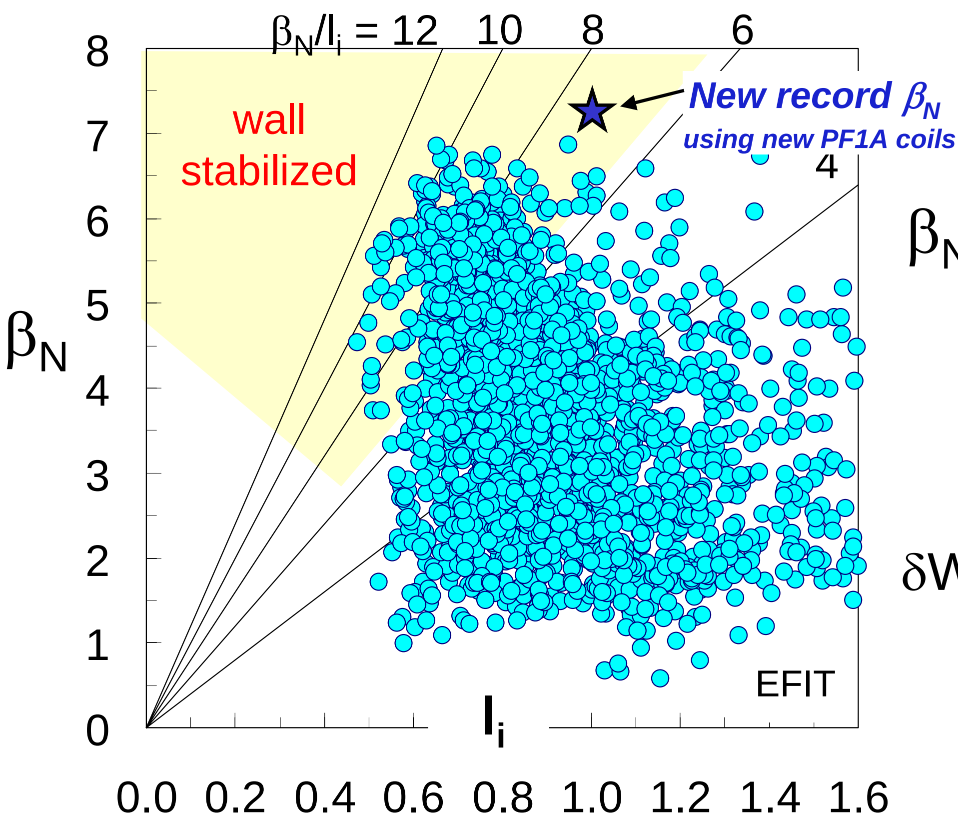




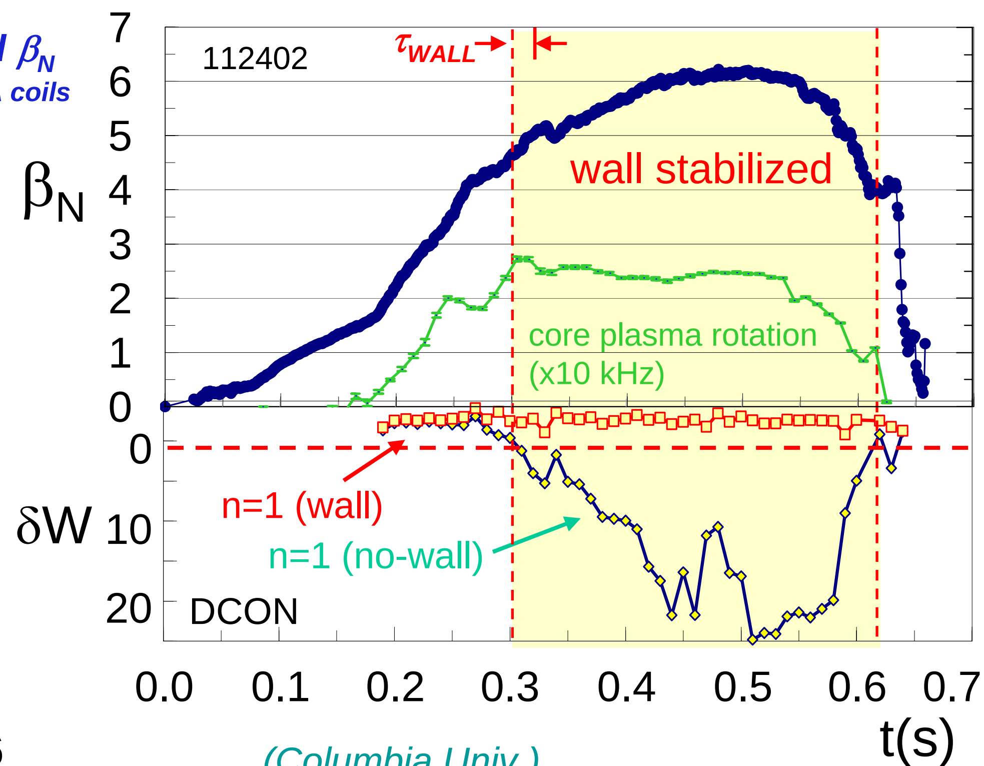
- Small ELM regime recovered at high $\kappa > 2.5$ with new divertor coils
  - Previously observed onset of large ELM-like events when $\kappa > 2.2$

Rotational stabilization of the RWM is key to *sustained* plasma operation at maximum β in NSTX

- High β_t < 40%, β_N = 7.2 reached



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



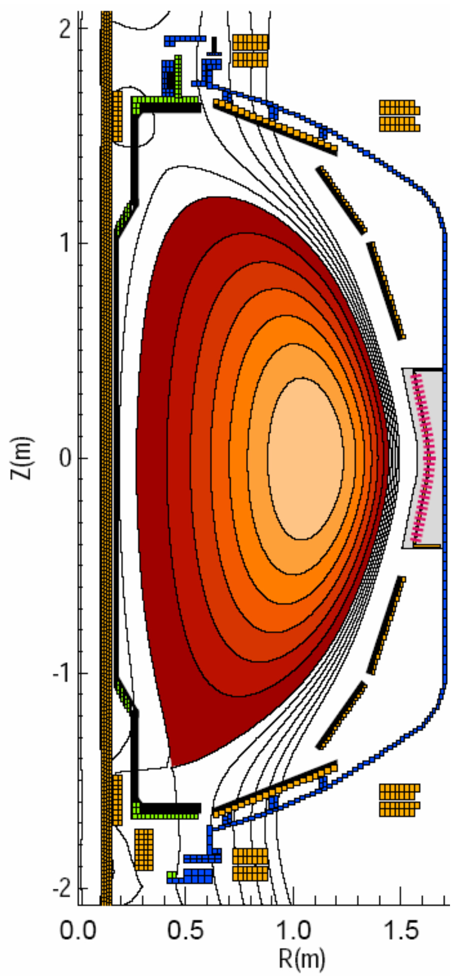
(Columbia Univ.)

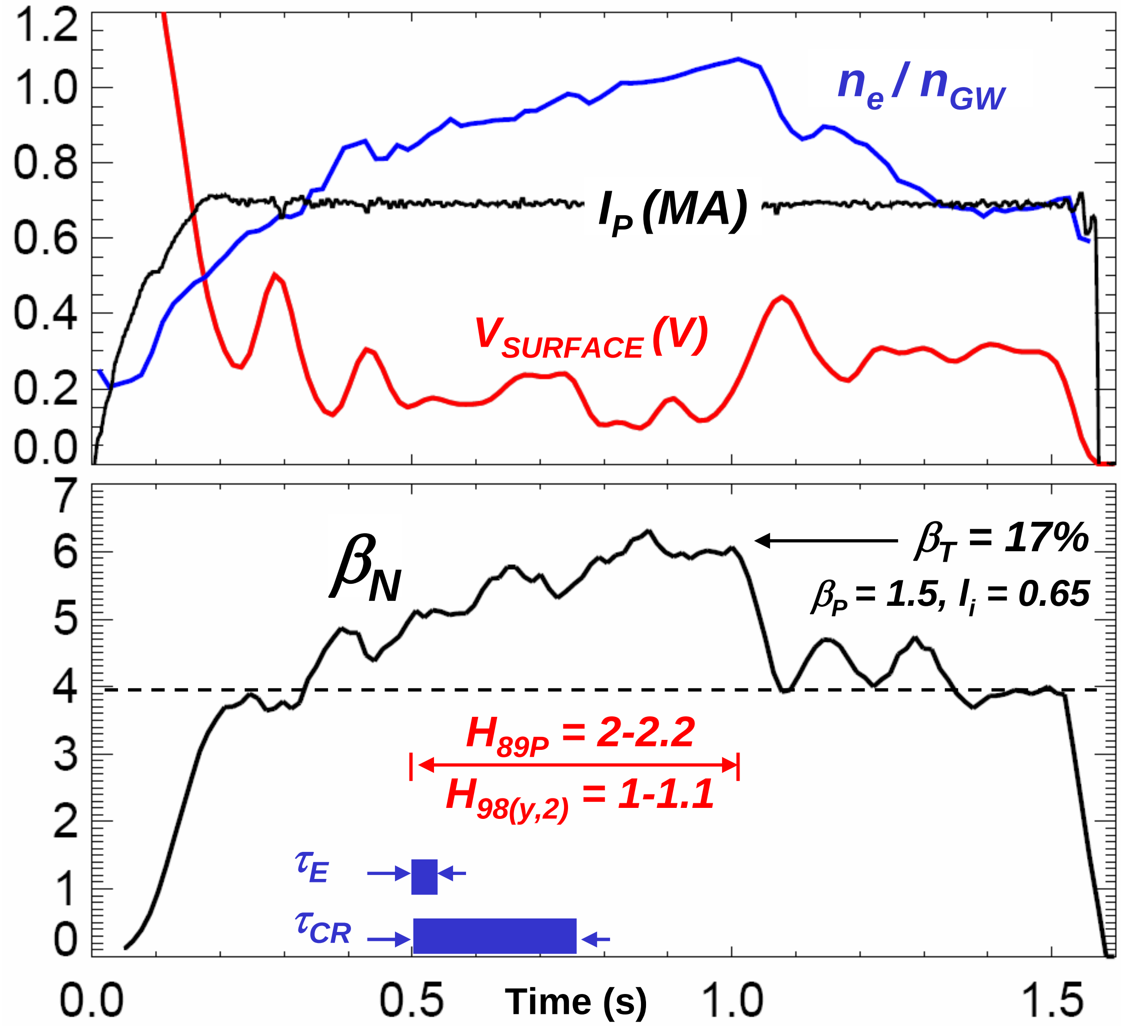
- Global MHD modes can lead to rotation damping, *β* collapse
- Understanding of sustained RWM stabilization needed for ITER-AT

Record discharge pulse-lengths have been achieved by operating with sustained H-mode and high β_N

- H-mode with small ELMS ⇒ reduced flux consumption, slow density rise
- $\beta_N > 4$ for $\Delta t > 1$s at high $\beta_P > 1$ increases bootstrap fraction, lowers V_{LOOP}

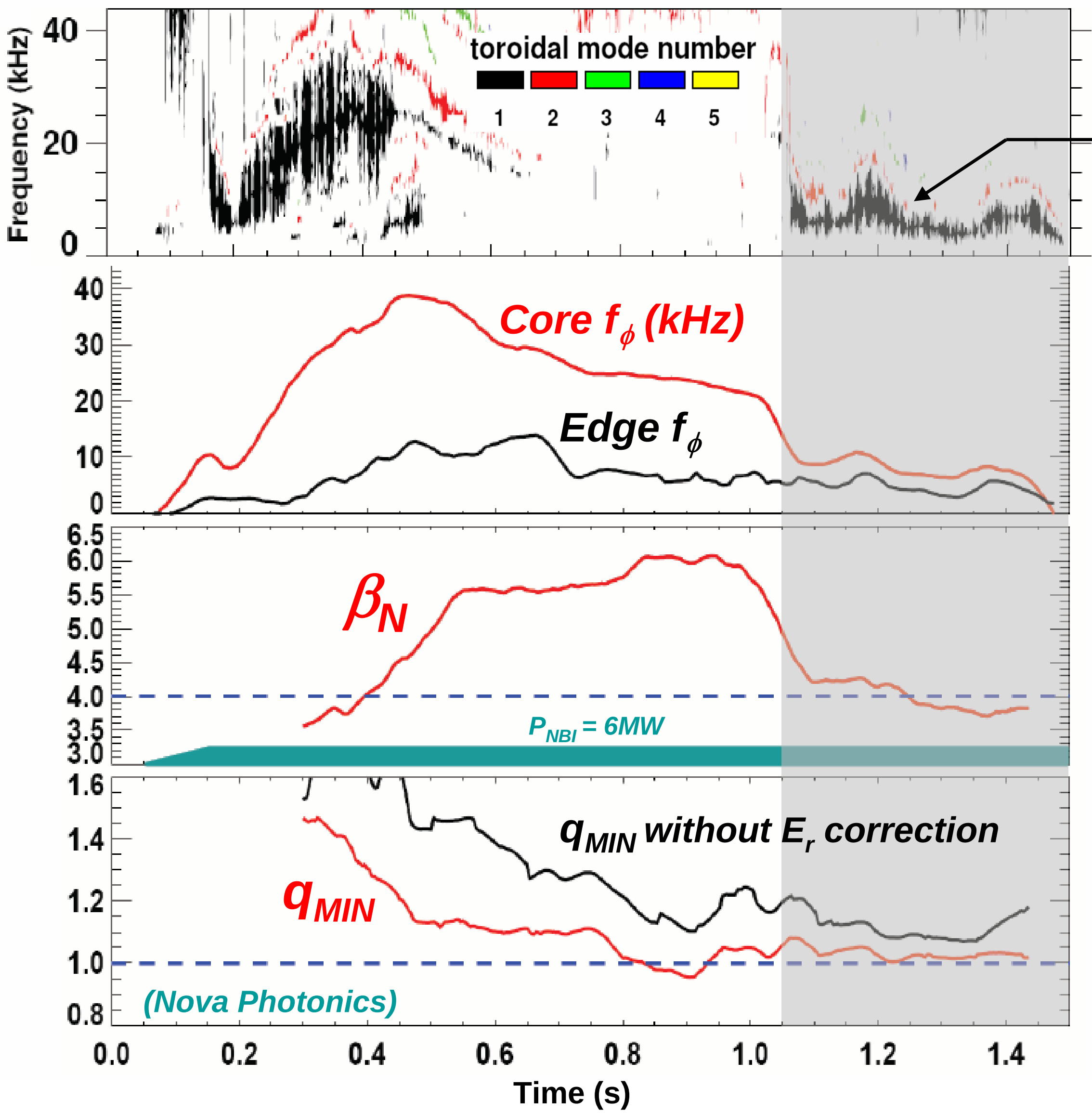
$\kappa = 2.3$, $\delta_L = 0.75$, $\delta R_{SEP} = -1$cm





MSE data indicates low loop-voltage phase ends at onset of saturated n=1 mode when $q_{MIN} \rightarrow 1$

NSTX



- Saturated n=1 mode persists for 0.5s late in discharge evolution
- Central rotation drops by factor of 3 at mode onset
  - Edge f_ϕ maintained
  - $T_i / T_e \rightarrow 1$ (not shown)
- β_N = 6 decreases to 4
  - β_N = 6 above no-wall limit
  - β_N = 4 below no-wall limit?
    - No RWM observed…
- q_{MIN} sustained near 1
  - No sawteeth observed
  - Discharge runs out of OH flux and TF flat-top
  - “Hybrid” mode?

Synergistic coupling between rotation and diamagnetic stabilization may explain saturation of 1/1 mode in NSTX

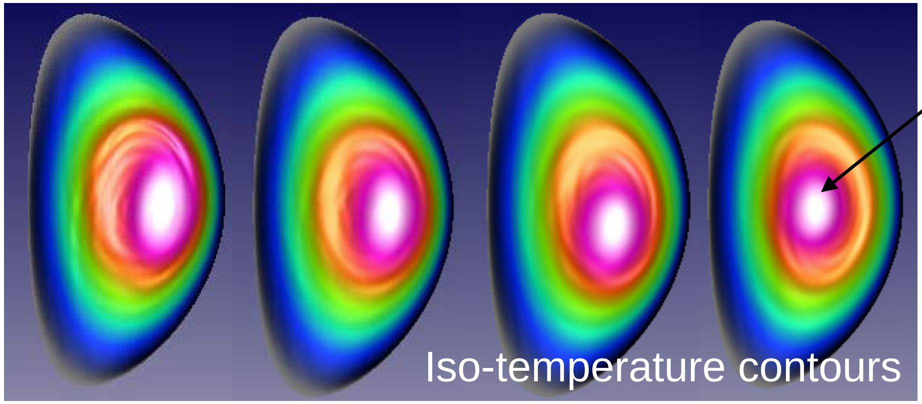
NSTX

- Rotational and kinetic stabilization effects are amplified at high β and M_A
  - Non-linear 2-fluid **M3D** simulations predict transformation from sawtooth to saturated 1/1

Saturation with hot spot pulled away from x-point

Co-injection w/ 2-fluid

M_A=+0.3



Displaced core "hot-spot"

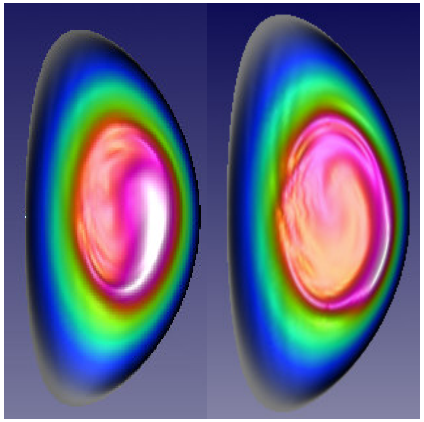
Nonlinear 2-fluid MHD simulations

(M3D – PPPL, NYU, MIT)

Mode crashes faster than single-fluid MHD

Counter injection w/ 2-fluid

M_A=-0.3

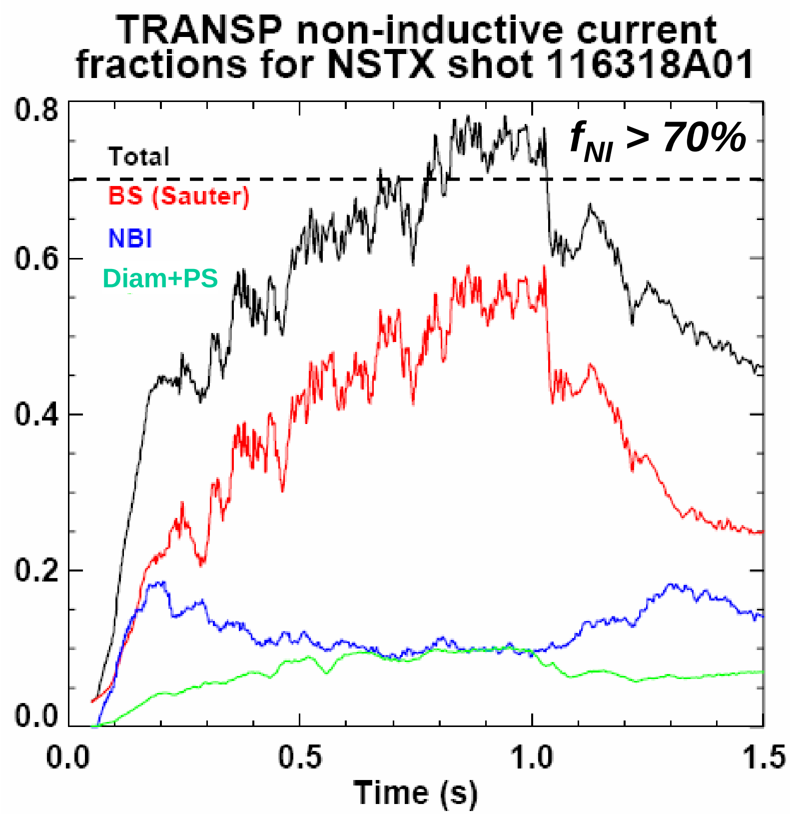


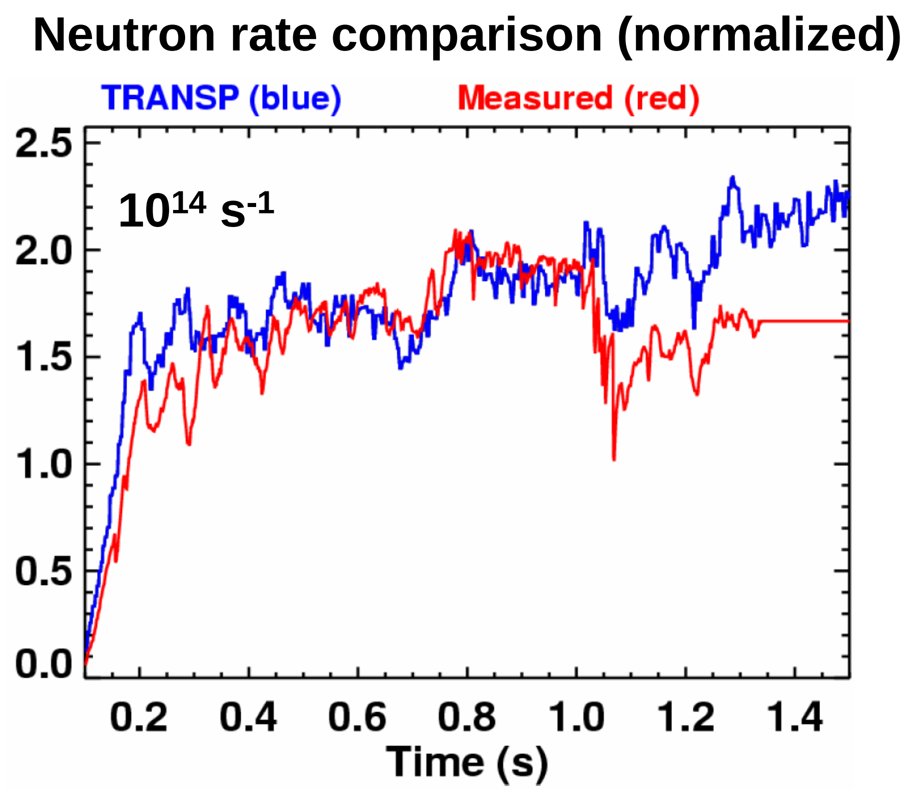
Rotation damping physics:

- **Neoclassical Toroidal Viscosity (NTV) from mode δB good candidate to explain rotation flattening**
- **Observe that coupled islands can lead to complete rotation collapse and disruption**
- **Core mode alone apparently only flattens profile**

Longest duration discharges exceed 70% non-inductive current fraction during high-β phase

- **85% of non-inductive current is ∇p-driven = BS + Diamagnetic + PS**





- TRANSP agrees with measured neutron rate to within ± 15% during high-β phase
- Normalize at high β ⇒ TRANSP over-predicts neutron rate early and late in shot
  - Low-f MHD is present at these times ⇒ fast-ion diffusion and/or loss likely
  - Assessing impact of MHD on J_{NBI} profile and q-profile evolution

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NSTX Error Fields & Locked Modes

Plans and initial results from the 2005 campaign

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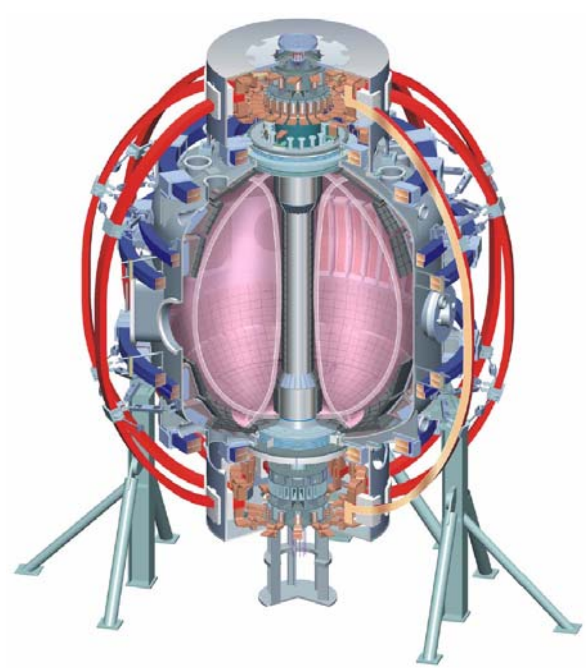

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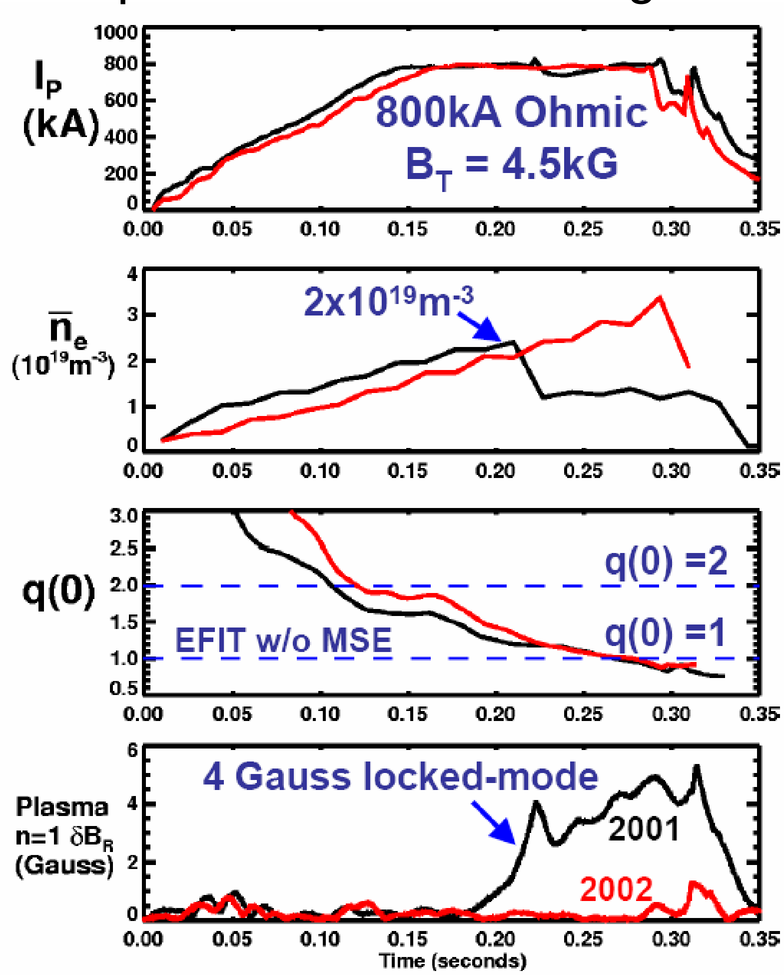
Goals of experiment

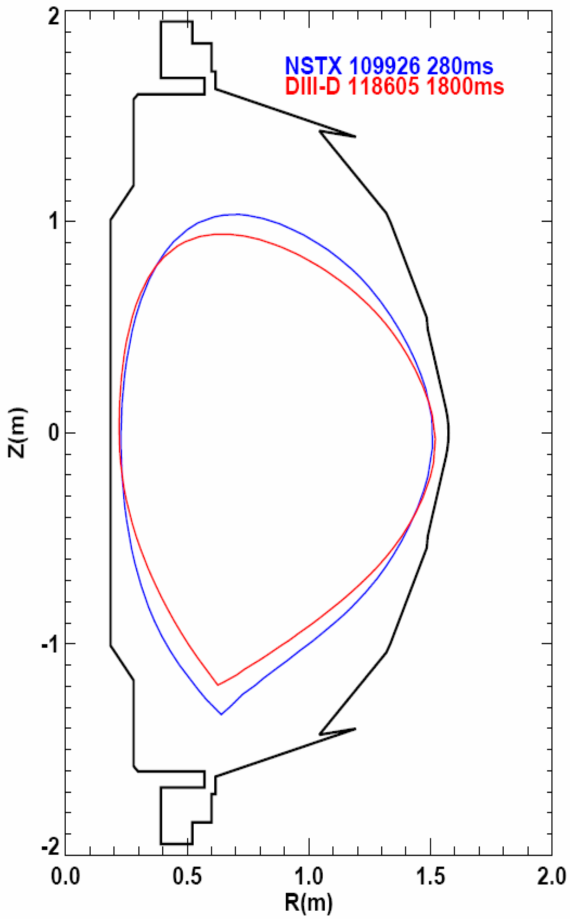
- Study low-β locked-mode threshold during I_P flat-top
  - Contribute low-A data to scaling studies: $\frac{b_{pen}}{B_t} \propto n^{\alpha_n} B^{\alpha_B} q^{\alpha_q} (R/a)^{\alpha_A}$
    - $\alpha_n \approx 1$, $\alpha_B \approx -1$, **$\alpha_q \approx$ 0.8 – 1.6, $\alpha_A \approx$ 0.4-0.8 (MAST)**
  - Measure threshold for locking vs. phase at fixed *n, B,* shape
    - **"Measure" any static intrinsic error field, and correct for it**
  - Determine density scaling of threshold
  - Determine B scaling of penetration threshold
  - Determine elongation scaling of threshold
    - Scan range of κ from 1.6 for MDC-6 LSN to typical NSTX κ=2
  - Determine q* and q_{95} (triangularity) scaling of threshold

Experiment focuses on moderate δ LSN shape

Can compare results to previous NSTX locking data

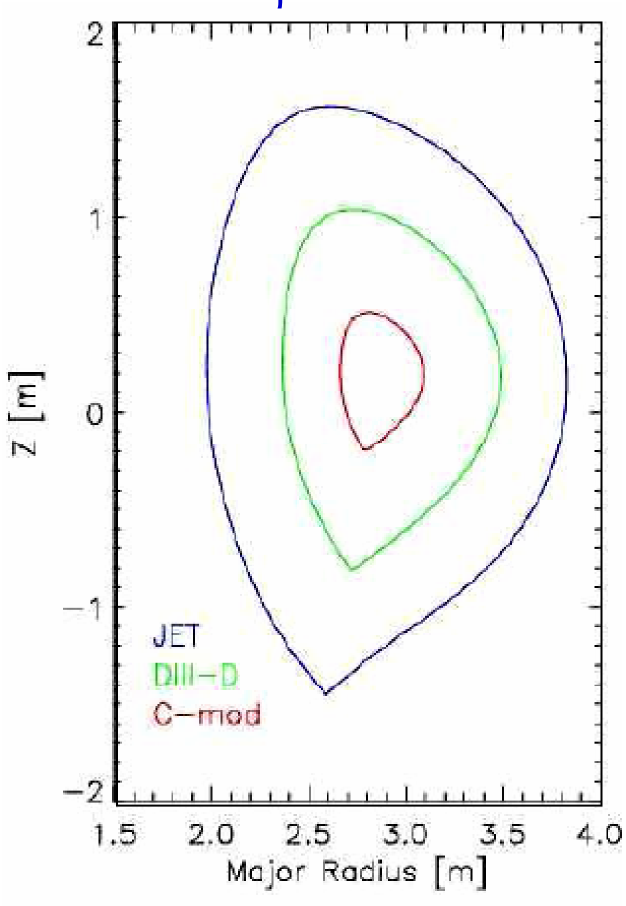


Can compare directly to ITPA Joint-Expt locked-mode results



Relationship to other experiments and results

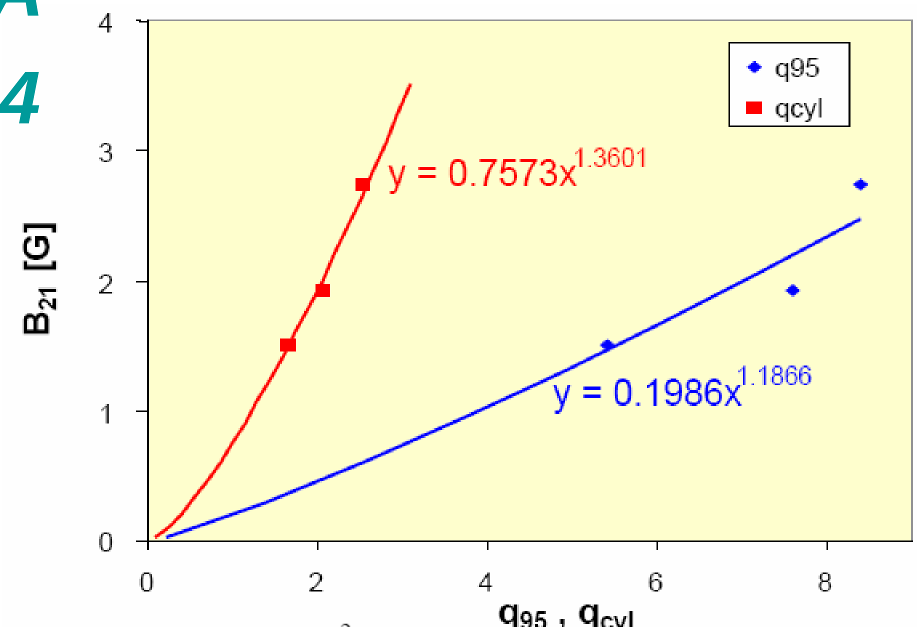
- LSN shape used in high-A identity experiments which matched ρ^* and ν^*



From ITPA 2004

- Shaping dependence and separation of q_{95}, q^*, q_{cyl} at low-A not considered yet in high-A scaling studies…

MAST Data:



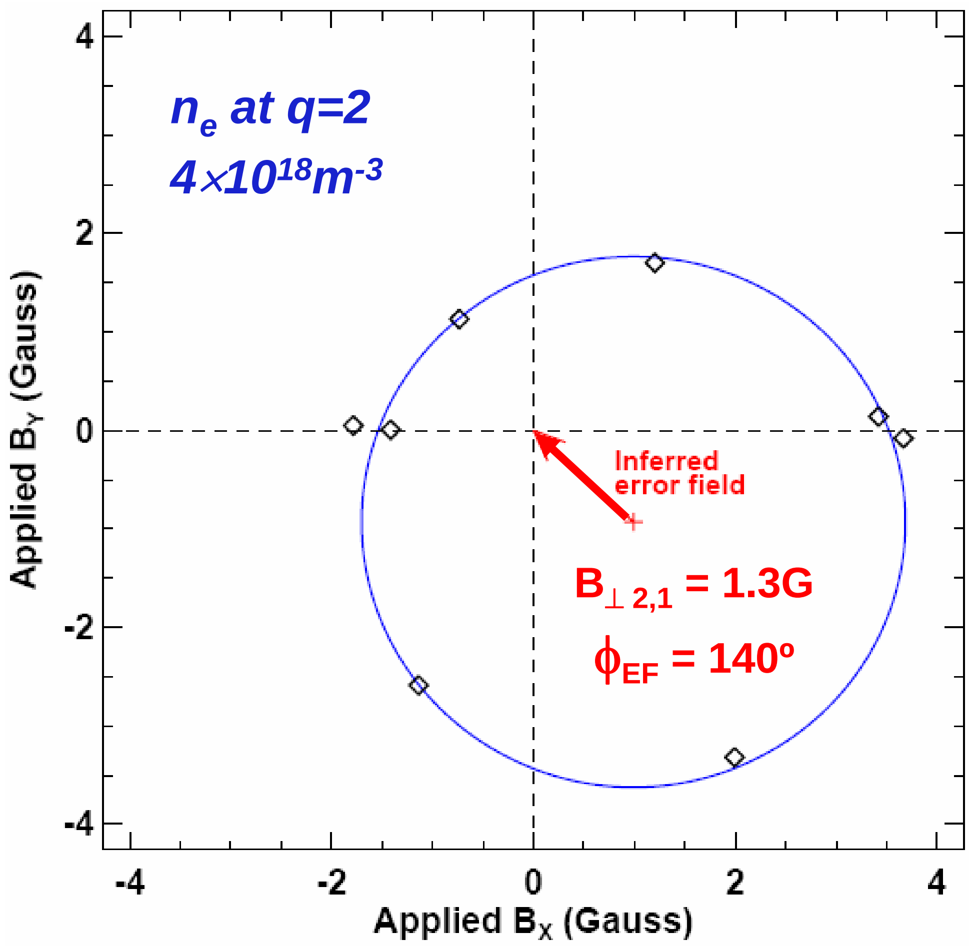
$$q_{cyl} = \frac{aB_t}{RB_\theta} = \frac{2\pi a^2 B_t}{R\mu_0 I_p}$$

Locking threshold experiments indicate clear asymmetry in response to varied EF direction

- I_P=0.7MA
- B_T = 4.5kG
- q(0) =1.1-1.5

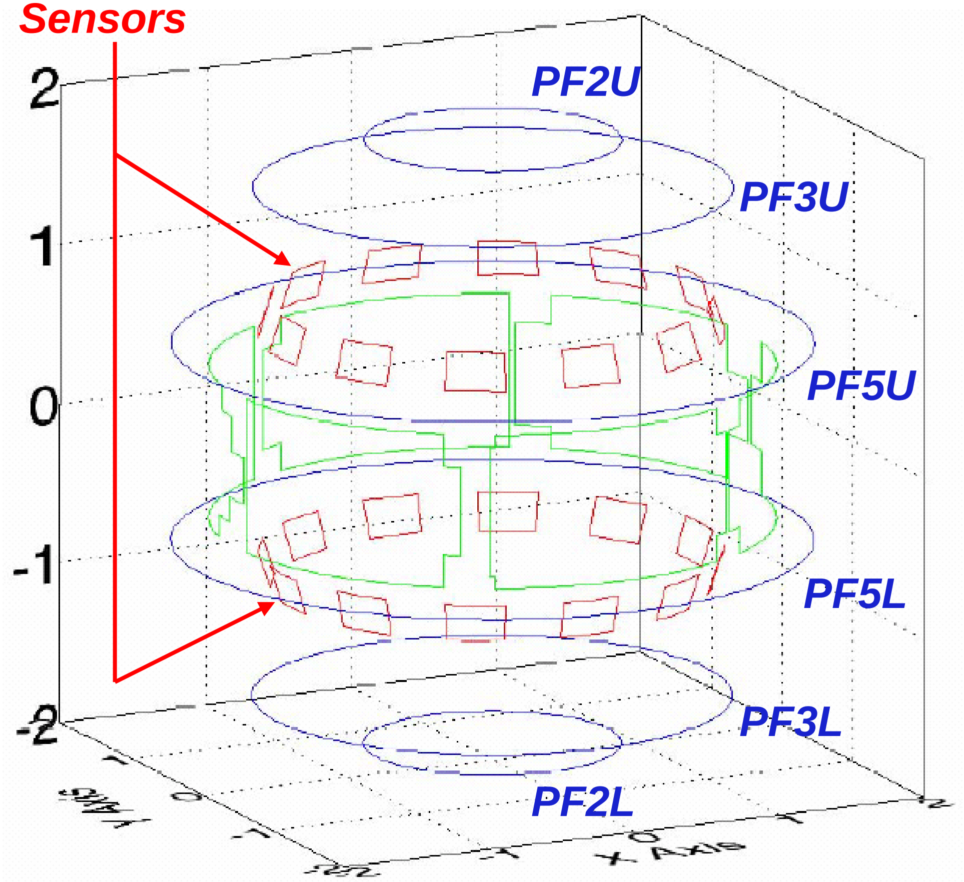
  (no sawteeth)

Inferred amplitude and direction of EF can change 30% and 15º if line-average density is used in place of local n_e

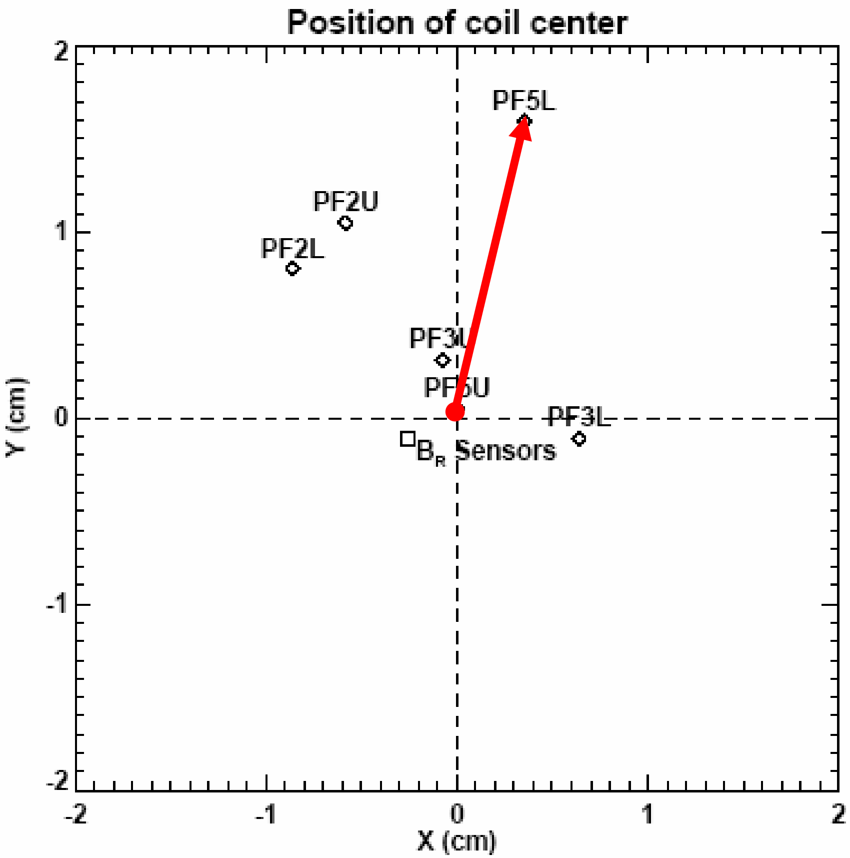


Internal B_R sensors measure up/down asymmetries in PF coil systems → error fields

Filament model of coil/sensor system

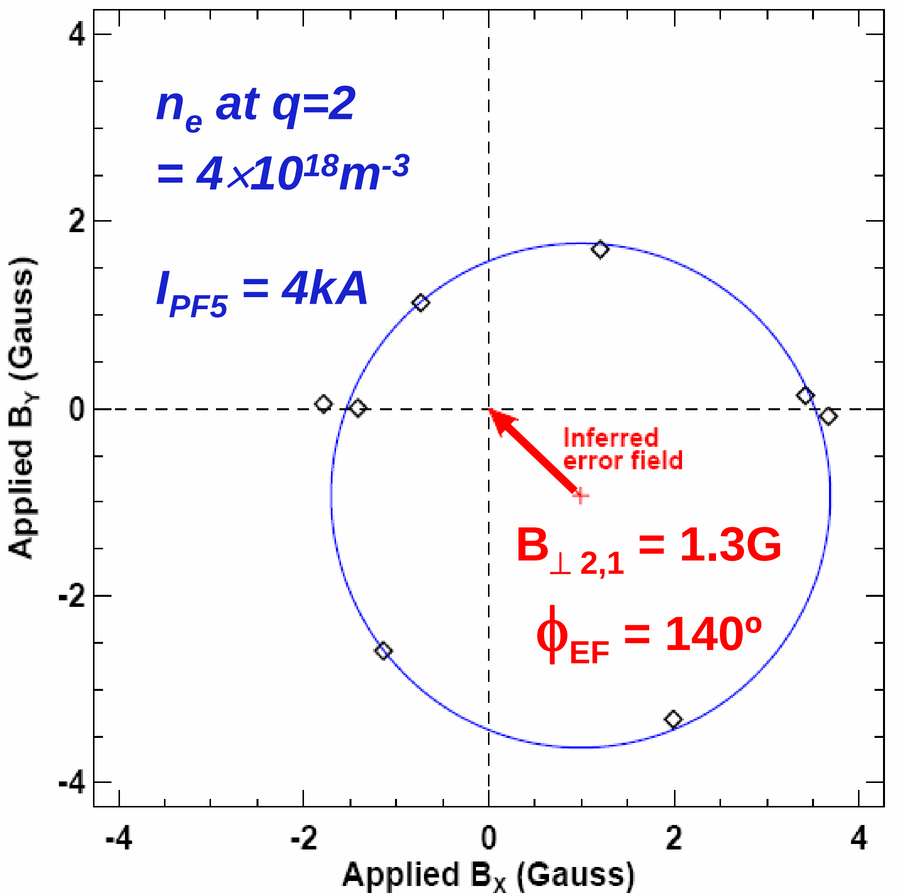


Largest apparent shift occurs in primary vertical field coils (PF5)

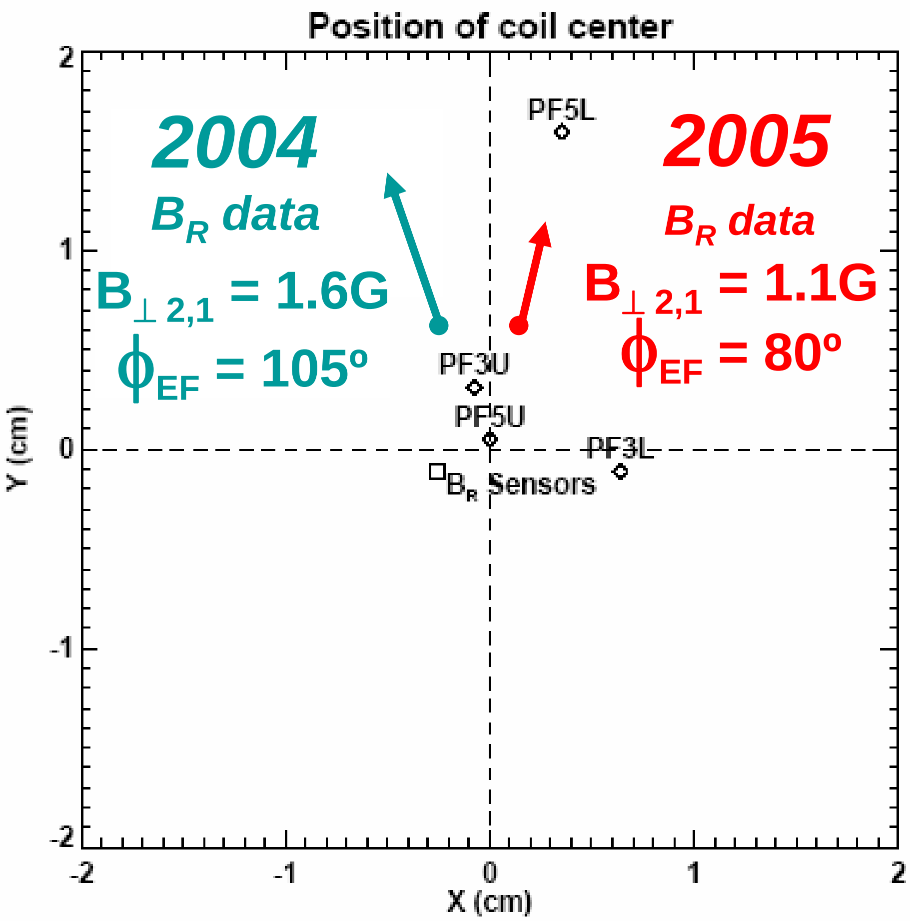


Measured EF amplitude is consistent with PF5 shift model, but EF directions disagree by 35-60º

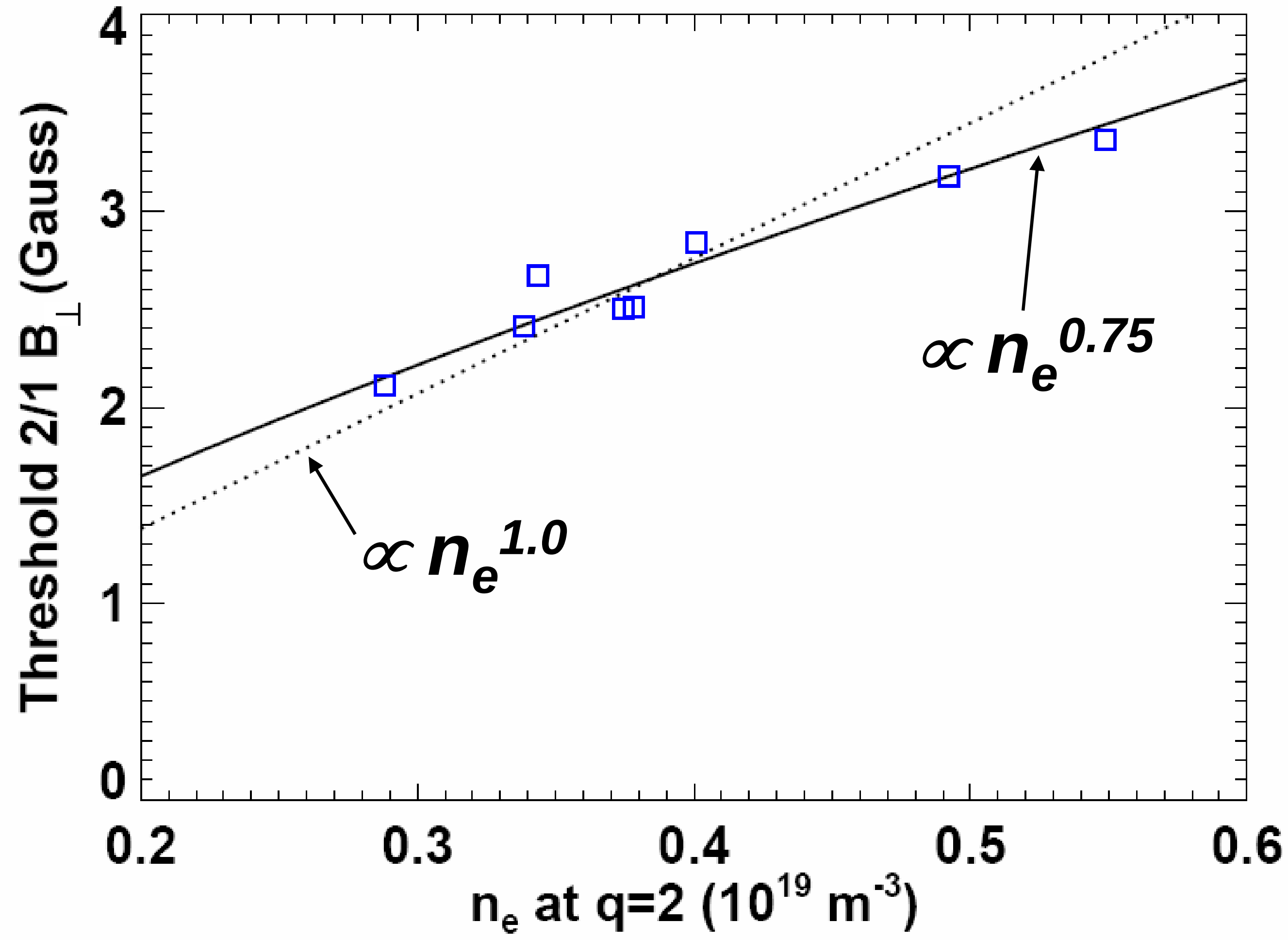
Error field inferred from 1st locked-mode experiments



Error field predictions from shifted PF5L model



Preliminary density threshold scaling results



Need to widen density scan, and test at other *B* and *q*

Near-term EF/locked-mode plans

- ***Expand density scan range → density scaling***

- ***Determine EF from locking at higher β in L-mode***
  - ***Higher β increases PF5 vertical field at fixed I_P and B_T***
  - ***Further test of PF5 as source of error field***

- ***Implement & test pre-programmed EF correction***
  - ***Then complete q, B, shape scans***

- ***Dynamic EF correction when feedback is ready***