NSTX

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Error Field Physics and Correction at High Beta in NSTX

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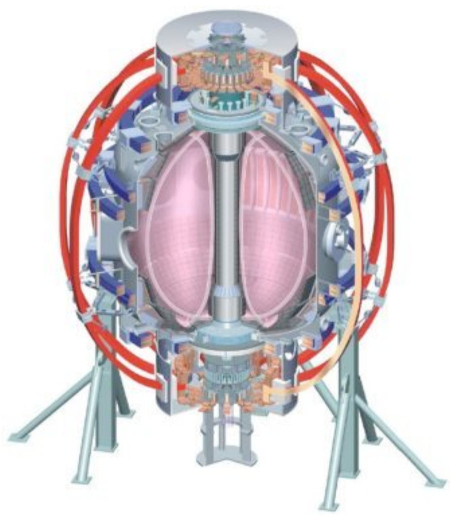

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Introduction and Preview

- NSTX research utilizes powerful tools for error field (EF) research.
  - Set of 6 midplane radial field coils permits application of n=1, 2, & 3 fields to high-β plasmas.
  - IPEC code is a powerful tool for EF studies.

- Studies of n=1 error field penetration in high-β plasmas.
  - Plasma response physics amplifies the externally applied fields, increasing the sensitivity to error-field penetration and disruption.

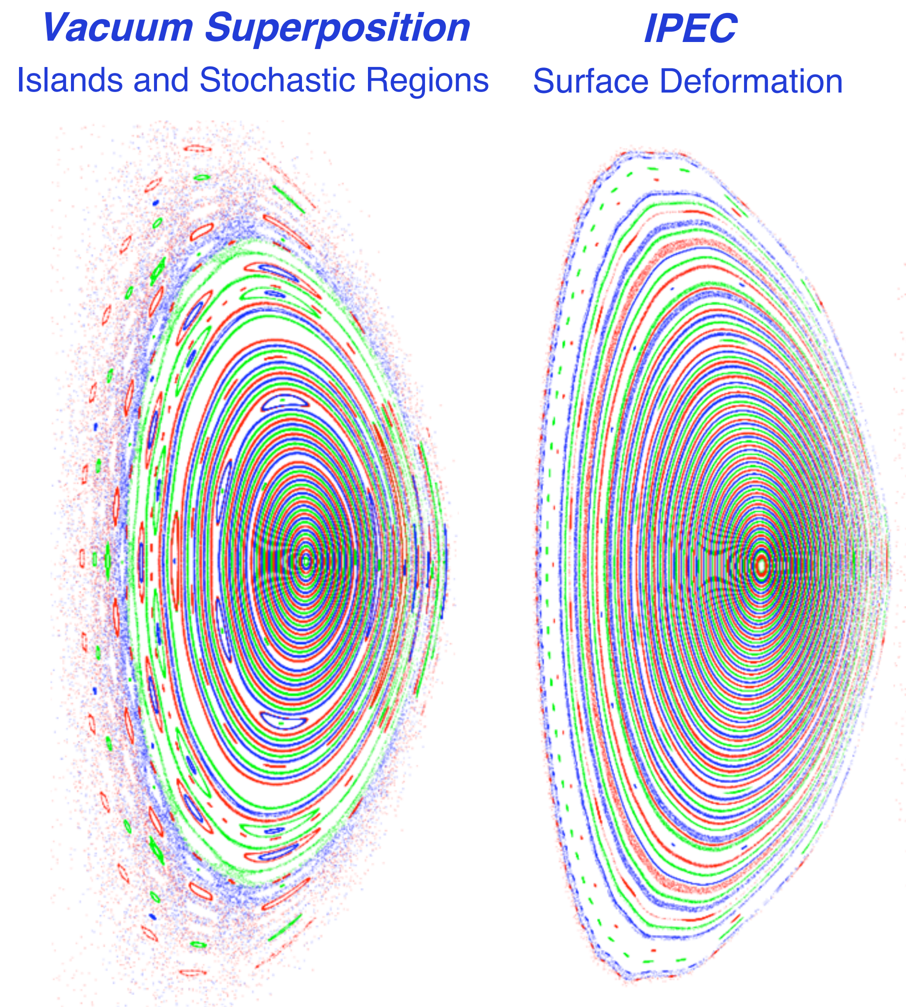
- Studies of non-resonant error field detection and correction.
  - Determined that there is an n=3 EF in NSTX, due to the out-of round vertical field coil.

More detailed discussion of all these points in Poster PP8.00051, J-K. Park, Wed. afternoon

The Ideal Perturbed Equilibrium Code (IPEC) is a Powerful Tool for Understanding Error Field Effects

- IPEC[1] gives ideal 3-D free-boundary tokamak equilibria
  - Solved the perturbed force balance equation subject to constraint that resonant magnetic perturbation vanishes at each surface.
  - Relevant description of perturbed plasmas before the onset of error field penetration
- IPEC calculates surface deformation including ideal plasma response effects such as shielding currents, field amplification, and poloidal coupling.
  - Shielding current determines ***locking*** properties.
  - Lagrangian variation of the field strength determines ***NTV transport***

Application of n=3 Fields to a High-β_N Equilibrium

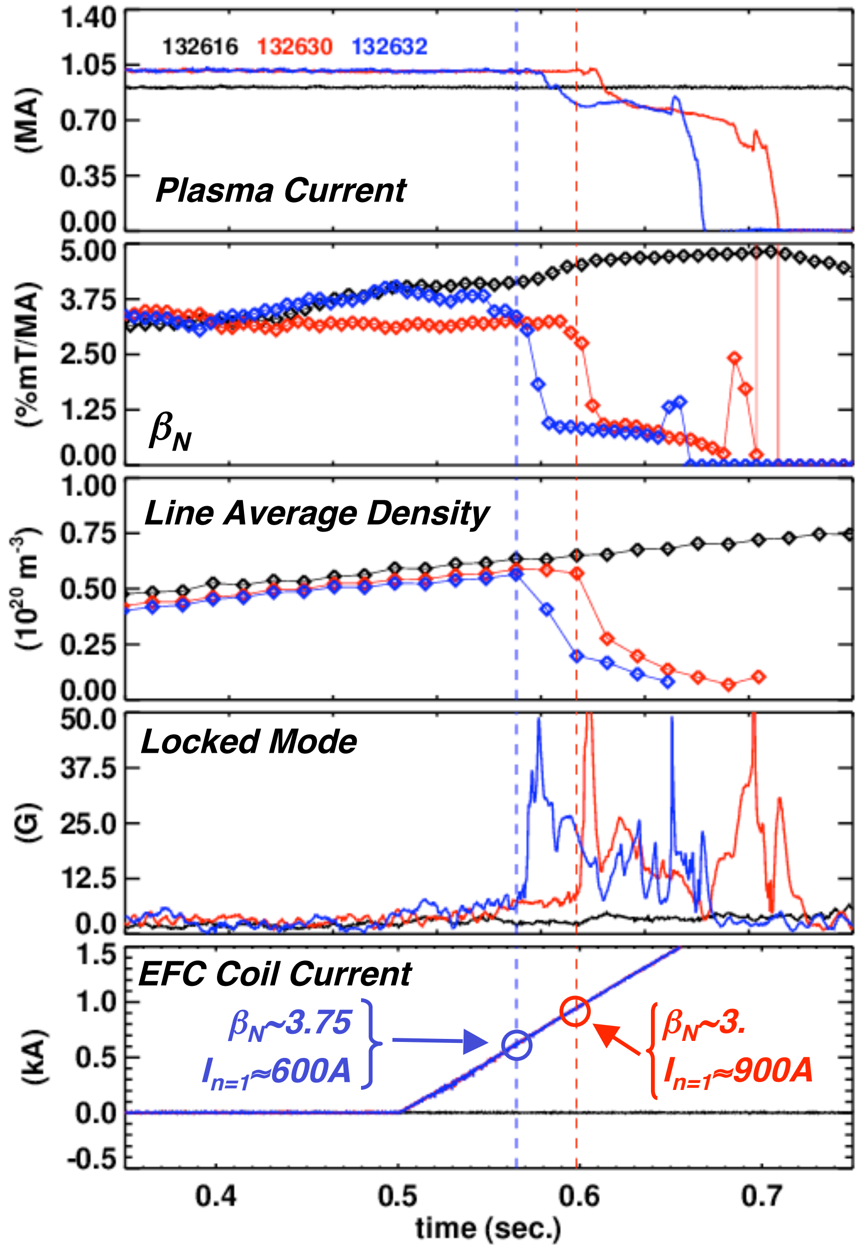


*[1] J. Park et al, Phys. Plasmas **14**, 052110 (2007)*

Increased Error-Field Sensitivity Observed at Higher-β_N

- Varied P_{inj}, I_P, and B_T to achieve different β_N at fixed q_{95}.
  - Beneath the no-wall limit in both cases (no RWM!)
- Apply ramping n=1 field using the EFC coils.
- Measure the time of mode penetration using the internal resistive wall mode sensors.
- β-dependence of locking at near identical density.
  - Higher-β_N locks with ~600 Amps of n=1 current
  - Low-β_N locks with ~900 Amps of n=1 current

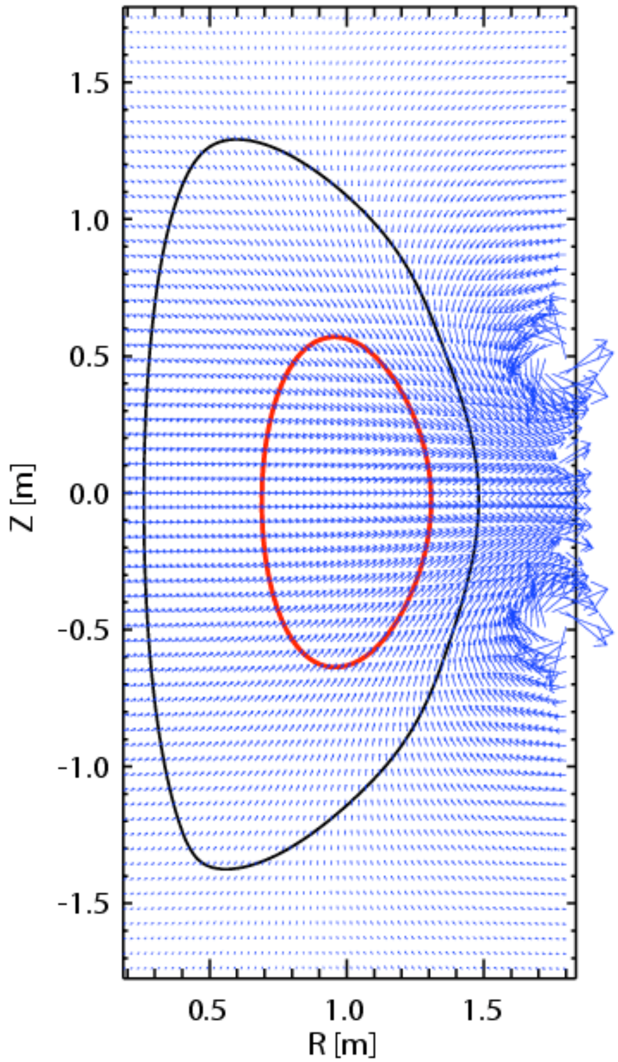
Increased error-field sensitivity at higher-β_N![1,2]



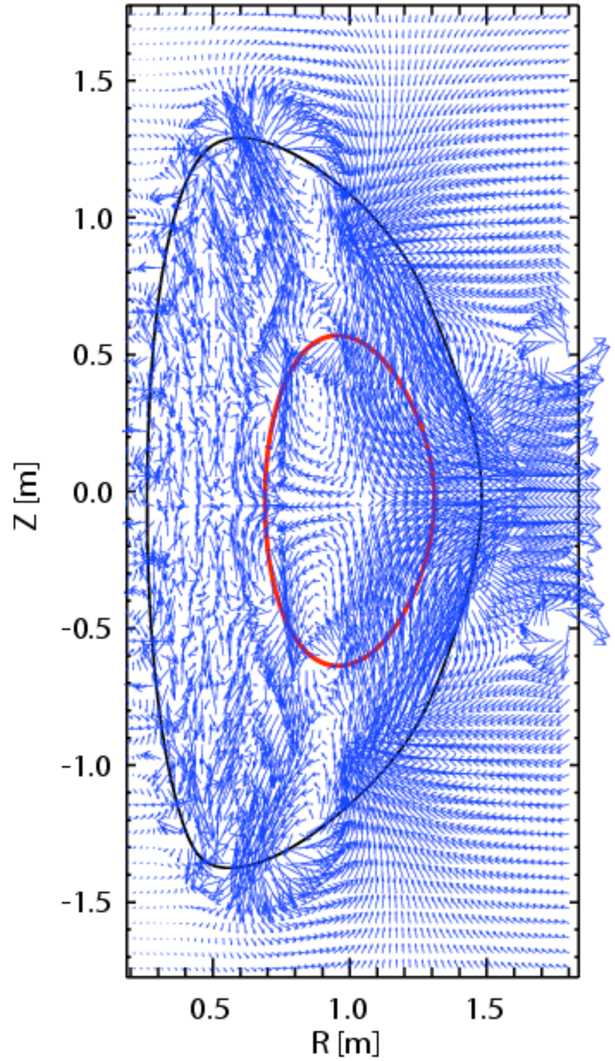
[1] R.J. La Haye et al., Nuclear Fusion **32**, 2119 (1992)
[2] H. Reimerdes et al., Nuclear Fusion **49**, 1, (2009)

The Resonant Field that Drives Islands can be Amplified by the Plasma at High-β_N

Vacuum Field



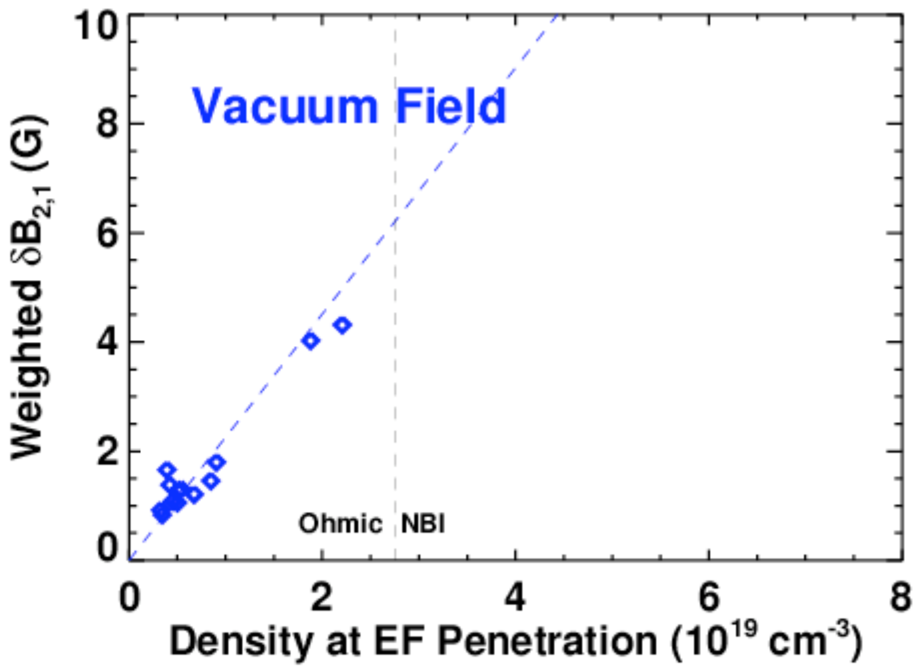
Vacuum + Plasma Response (IPEC)



- EFC coil currents and vacuum resonant fields are not the correct quantities when considering locking.
- The resonant field driving islands can amplified at high-β_N.

Linear Correlation Between Resonant Field for Penetration and Density Can be Restored Using IPEC

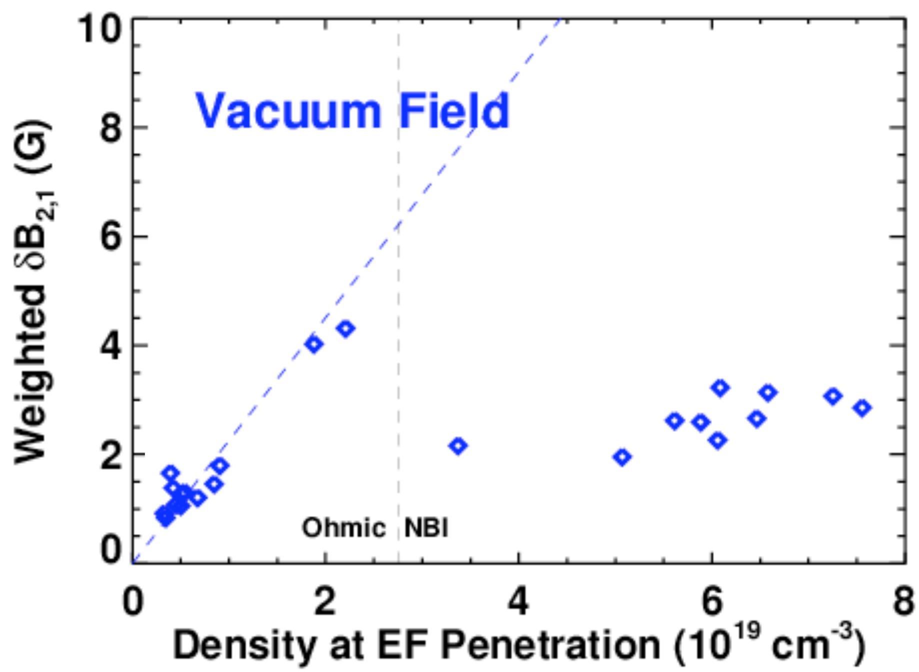
- Compare the resonant 2/1 amplitude to the line average density, at the time of mode penetration.
- Wide variety of data in the scan:
  - Ohmic L-mode plasma at low density



Linear Correlation Between Resonant Field for Penetration and Density Can be Restored Using IPEC

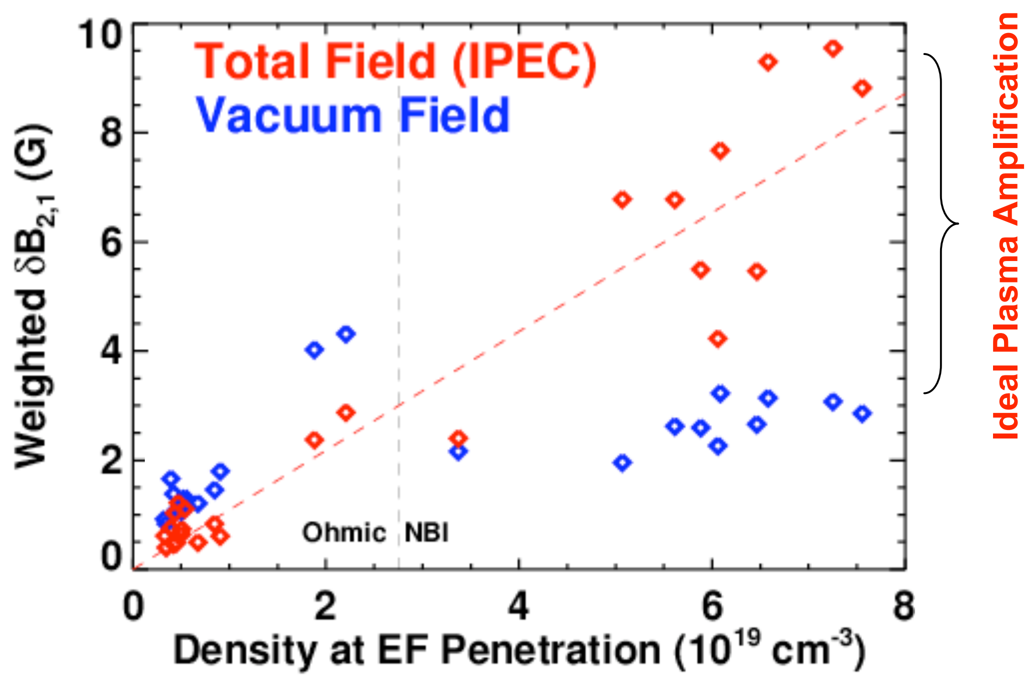
- Compare the resonant 2/1 amplitude to the line average density, at the time of mode penetration.
- Wide variety of data in the scan:
  - Ohmic L-mode plasma at low density
  - NBI-heated H-mode at high density.

  - Vacuum: Linear scaling with density fails; error field penetration at high-β seems anomalously easy.



Linear Correlation Between Resonant Field for Penetration and Density Can be Restored Using IPEC

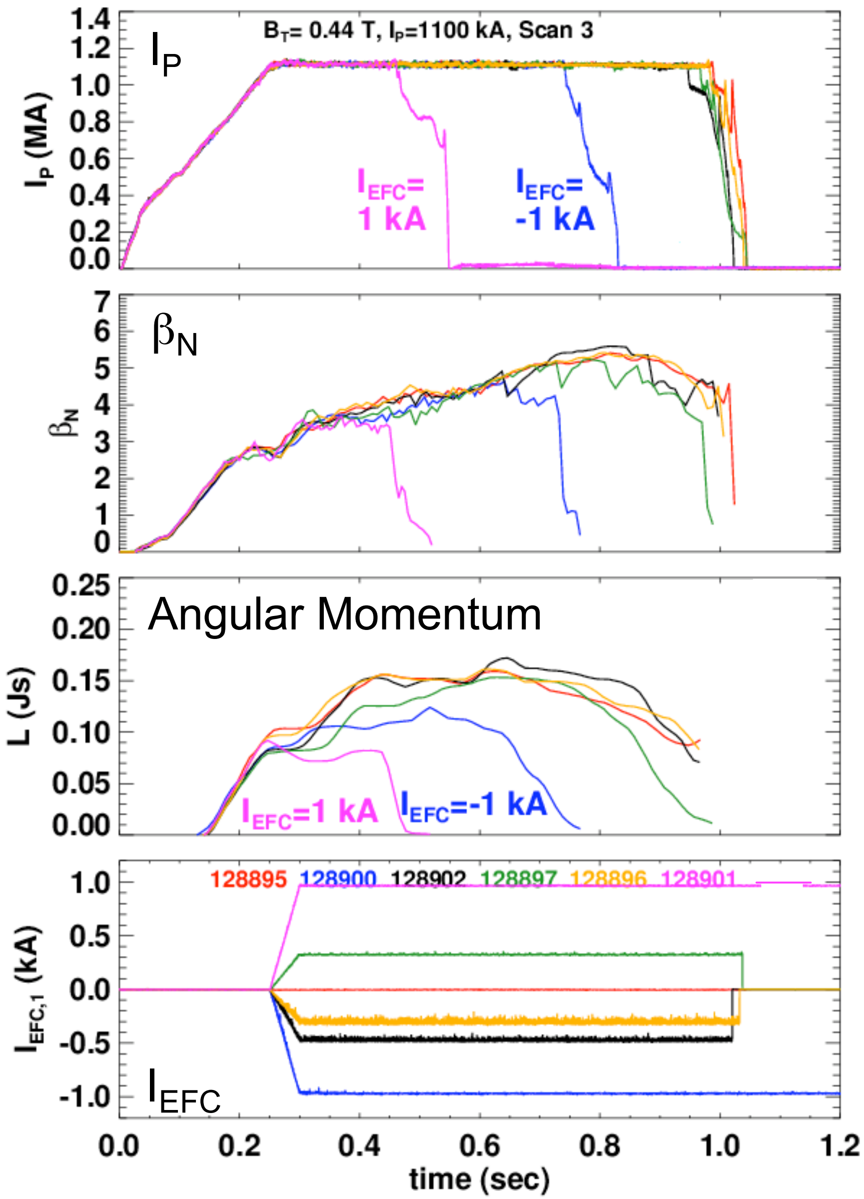
- Compare the resonant 2/1 amplitude to the line average density, at the time of mode penetration.
- Wide variety of data in the scan:
  - Ohmic L-mode plasma at low density
  - NBI-heated H-mode at high density.
- IPEC results demonstrate importance of plasma response:
  - Vacuum: Linear scaling with density fails; error field penetration at high-β seems anomalously easy.
  - IPEC: Error field penetration threshold scales with density.



Non-Resonant (n>1) Error Fields Observed in NSTX

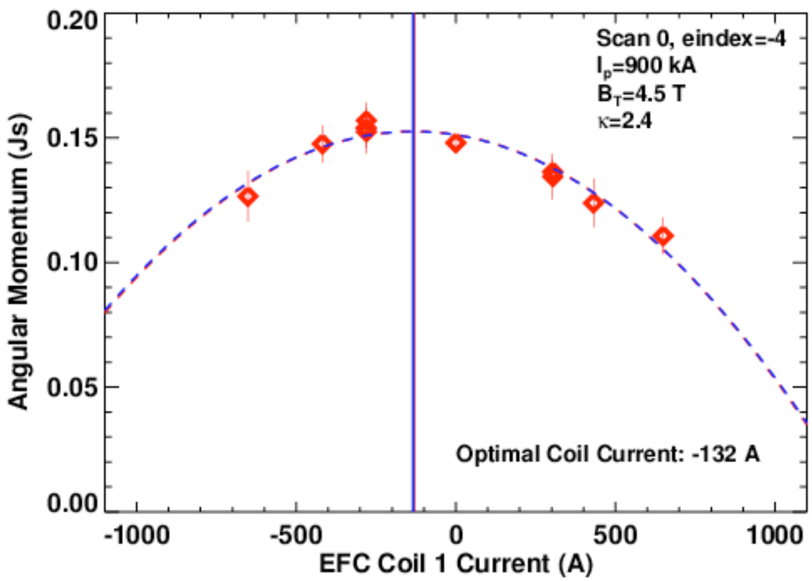
- Use a long-pulse high-β_N discharge.
- Apply n=3 fields of two different polarities, many amplitudes.
- Asymmetric response in the pulse length:
  - Discharge with 1000 A applied n=3 field disrupts before that with -1000 A.
- Asymmetric response in the angular momentum:
  - Discharge with $I_{n=3}$=+1000 A has less angular momentum before the disruption than that with $I_{n=3}$= -1000 A

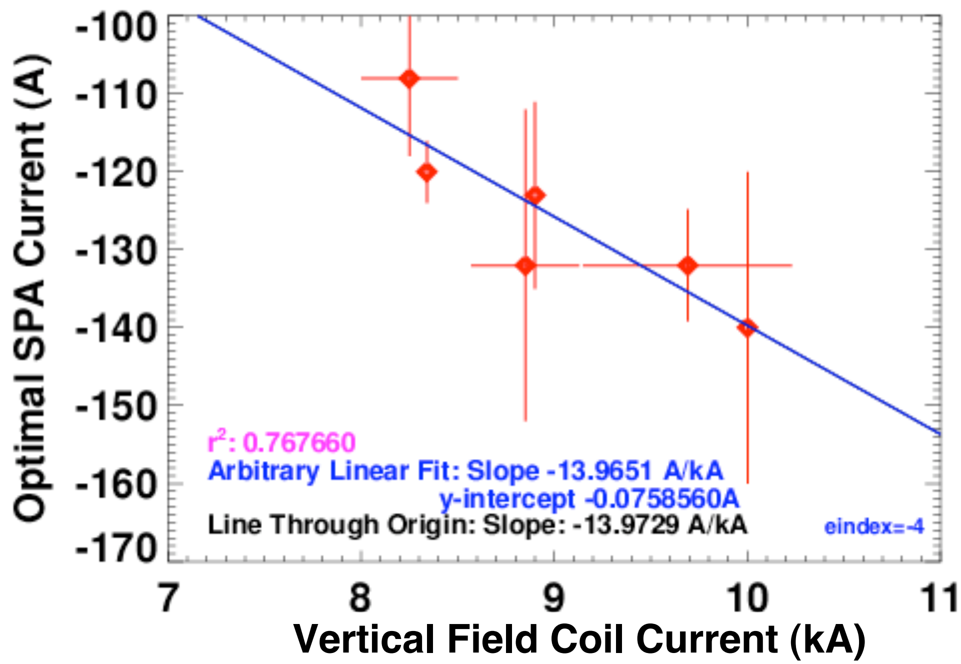
There is an intrinsic n=3 error field.



Experiments Indicate that the Vertical Field Coils are the Source of the Error Field

- Likely sources of the EF:
  - Vertical Field Coil → Function of I_P
  - Radial Field Coil → Function of I_P, κ
  - Toroidal Field Coil → Function of B_T
- Choose 6 configurations with different values of I_P, B_T, and κ.
- For each configuration, determine the optimal n=3 correction



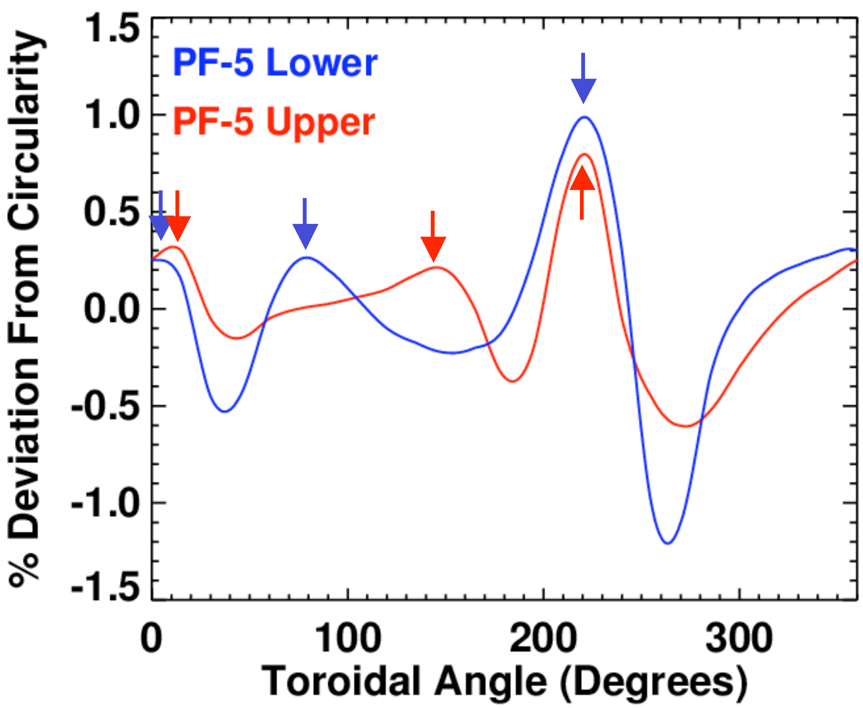


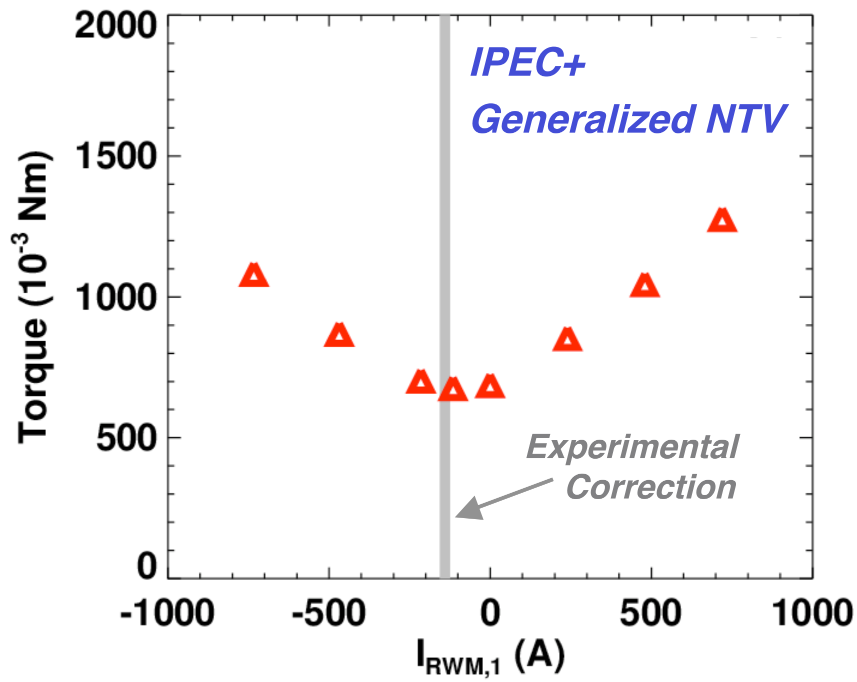
- Optimal correction correlates well with the current in the vertical field coil.
- Correlation not as strong with the other coils:
  - Correlation coefficients not as large.
  - Best fit lines do not extrapolate to zero correction at zero coil current.

Correction is Consistent With Known Out-of-Round Vertical Field Coil

- Vertical field coils have a dominantly n=3 radial variation.
  - Makes an n=3 error field.
- Optimal vacuum correction: $I_{EFC}/I_{PF-5} \approx 18\ A/kA$
- Experimental correction: $I_{EFC}/I_{PF-5} \approx 14\ A/kA$

- Computed the expected braking torque using the IPEC total field and generalized NTV theory.[1]
- Predicts minimum total torque at $I_{EFC}/I_{PF-5} \approx 15\ A/kA$
- Magnitude of the torque is consistent with the observed magnetic braking.

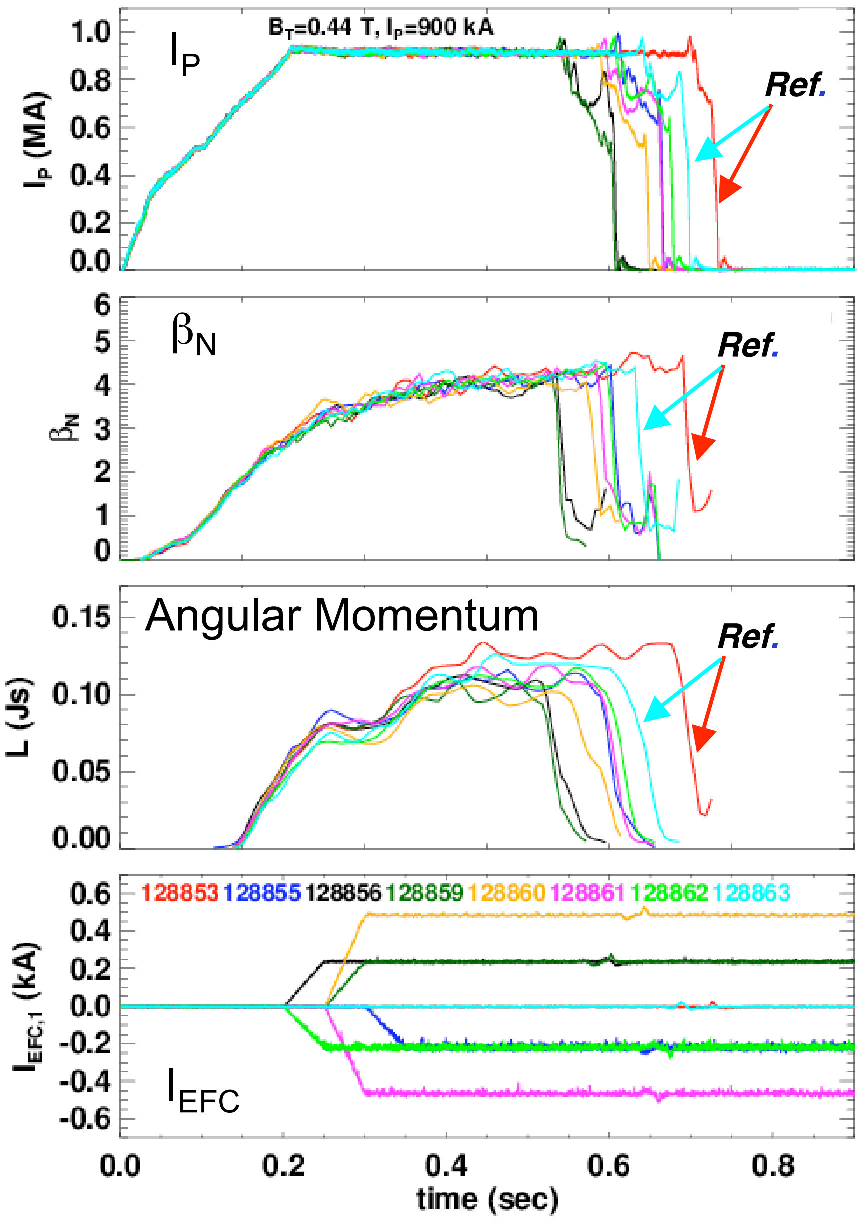




[1] J. Park et al, Phys. Rev. Lett. **102**, 065002 (2009)

Error Fields with n=2 Appear to be Beneath the Detection Threshold

- Utilize a long-pulse, high-β discharge.
  - Reference shots suffer an RWM followed by disruption at t=~0.7 sec.
- Apply n=2 fields of various phases.
- n=2 fields always cause the disruption to occur earlier.
- Momentum damping occurs in all cases with applied fields.
- Infer that n=2 error fields, if present, are small.
  - Consistent with modeled shape of the VF coil producing a dominantly n=3 EF.



NSTX device and IPEC code provide a powerful combination for understanding high-β error-field physics

- Error fields can penetrate and disrupt a high-β plasma more easily than might be expected from the low-β density scaling.
  - The plasma can amplify the error field.
  - Linear dependence of the threshold on density can be recovered when the total resonant field (vacuum + plasma response) is considered.
- Non-resonant error fields are present in NSTX, and can be corrected.
  - The observed n=3 error fields is experimentally found to scale with the vertical field coil current.
  - The correction magnitude and phase is consistent with the known out-of-round shape of the coil, when plasma response effects included.
  - Error fields with n=2, however, appear to be negligibly small.

More detailed discussion of all these points in Poster PP8.00051, J-K. Park, Wed. afternoon