NSTX

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Studies of Resonant and Non-Resonant 3-D Fields in NSTX

Stefan Gerhardt, PPPL

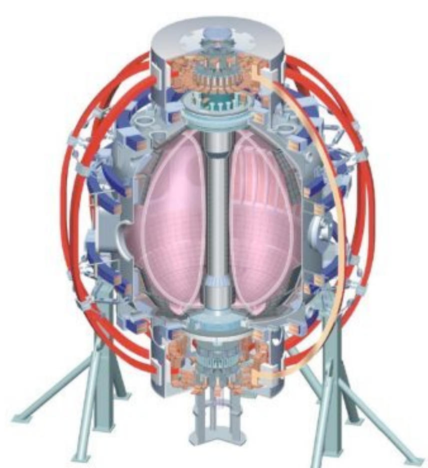
J-W. Ahn (ORNL), J.M. Canik (ORNL),
J. Menard (PPPL), J-K. Park (PPPL), S. Sabbagh (CU)

R. Bell (PPPL), B. LeBlanc (PPPL),
R. Maingi (ORNL), H. Yuh (Nova Photonics)

and the NSTX Research Team

14th Workshop on Active Control of MHD Stability
Nov. 11th, 2009

Work supported by US DOE contract no. DE-AC02-09CH11466



College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

What are 3-D Fields?
Aren't Tokamaks Axisymmetric Enough?

- 3-D fields come from static coil shifts, tilts, non-circularities, coil motion, and current feeds…and can be deliberately applied.
  - "Error Fields" are subset…use this term when the 3-D field is not deliberate.
- 10^{-3} level n=1 error fields can cause disruptive performance degradation.
  - Can cause stationary islands in low-density discharges (Error Field Penetration).
  - Can be amplified by marginally stable kink-modes, leading to rotation damping.
- n>1 3-D fields can degrade performance, or be used for control.
  - Neoclassical Toroidal Viscosity (NTV) can brake (or accelerate) the plasma.
  - Edge localized instabilities can be controlled (RMP).
  - Transient and steady state divertor heat loading patterns can be modified.

Purpose of this talk:

Explain how NSTX mitigates the deleterious 3-D field effects, utilizes positive effects.

Primarily use data from the 2009 campaign, but reach back farther where it is helpful.

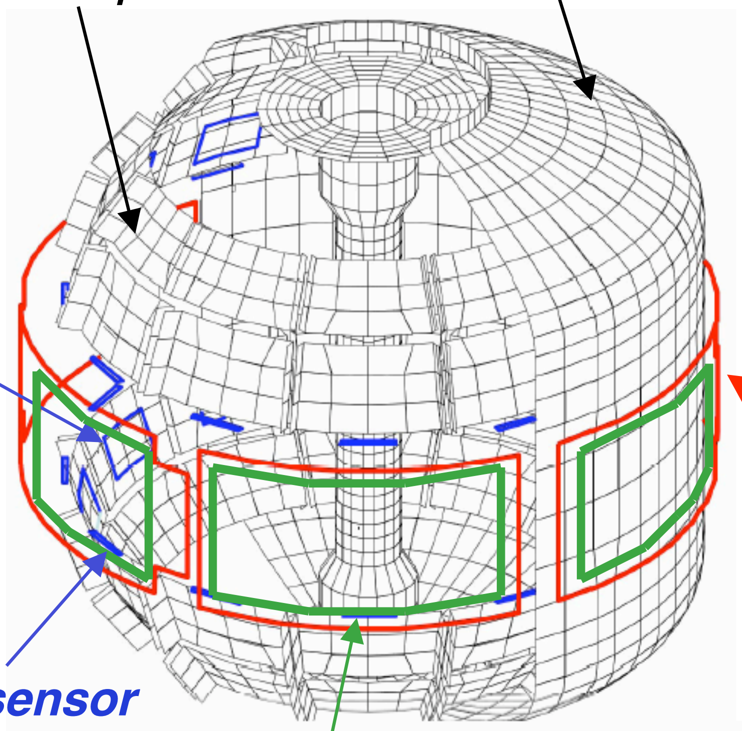
Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

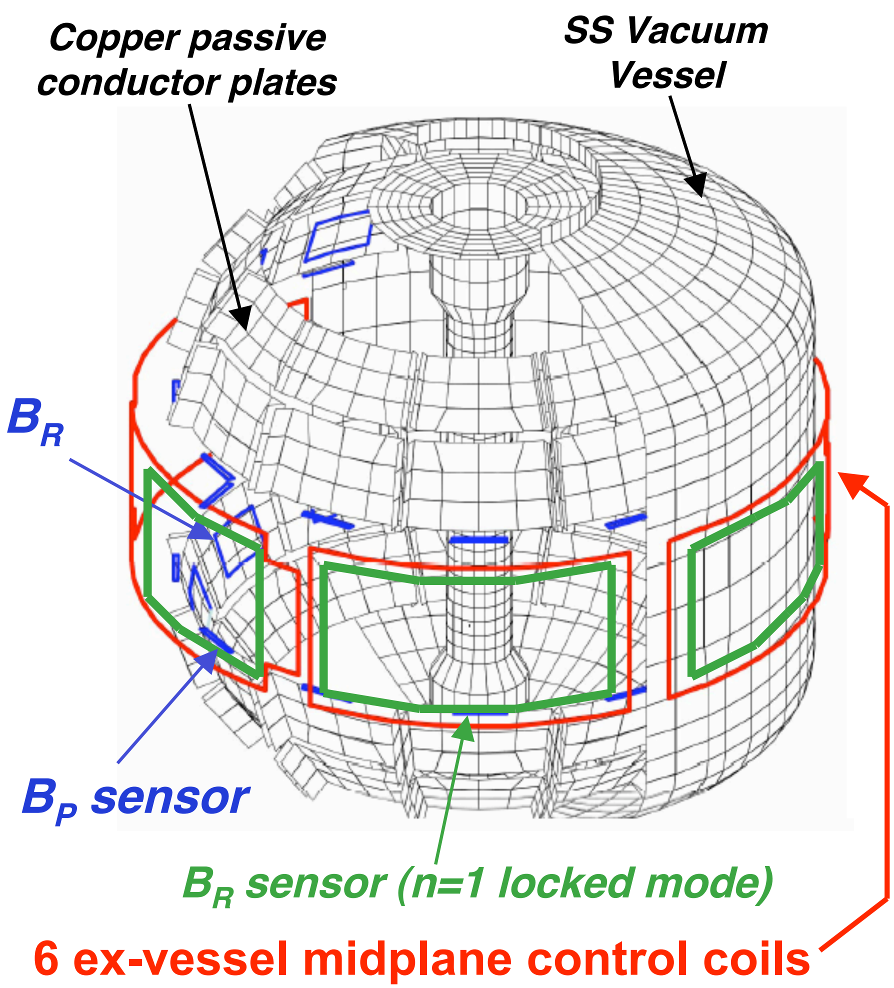
High-β Plasmas, Non-Axisymmetric Field Detection, and Midplane Radial Field Coils Facilitate 3-D Field Studies



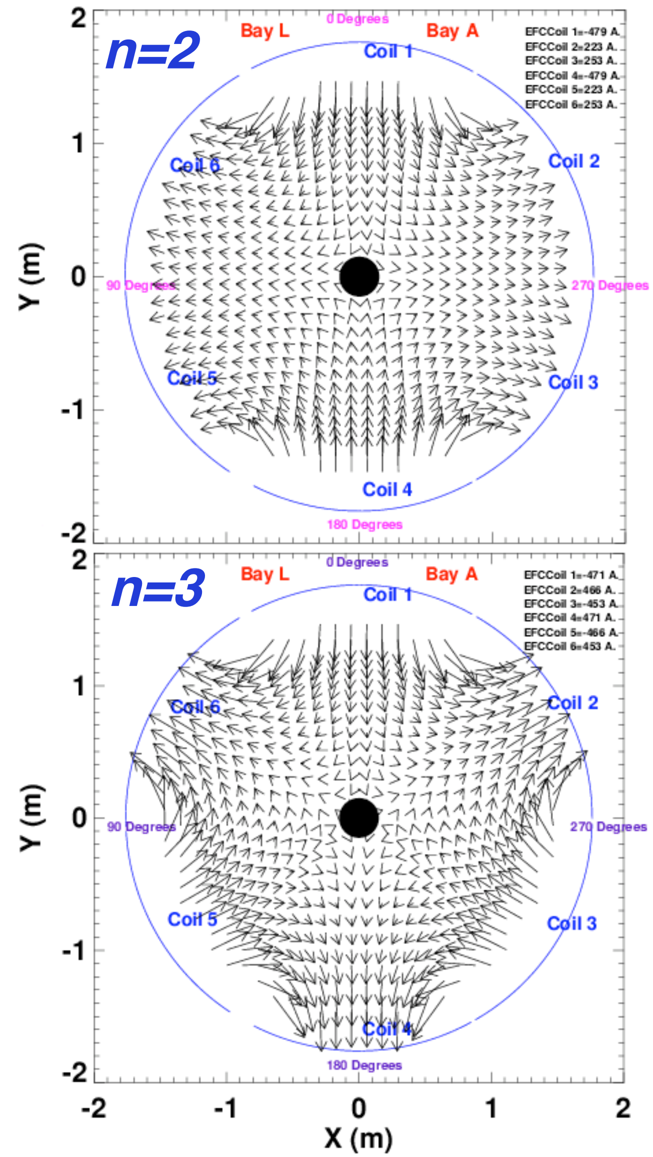
VALEN Model of NSTX (Columbia Univ.)

- Routine operation above the no-wall β-limit.
  - ~6 MW of 90kV NB injection.
  - Nearby copper stabilizing plates.
- Extensive non-axisymmetric field detection.
  - 24 off-midplane internal B_P sensors
  - 24 off-midplane internal B_R sensors
- Excellent profile diagnostics.
  - 30-point MPTS
  - 51-point toroidal CHERS
- 6 midplane radial field coils for 3-D field application.
  - Simultaneous n=1 & 3
  - Simultaneous n=0 & 2
  - Custom configurations
- Fast and slow non-axisymmetric feedback facilitated by the General Atomics Plasma Control System.

High-β Plasmas, Non-Axisymmetric Field Detection, and Midplane Radial Field Coils Facilitate 3-D Field Studies



VALEN Model of NSTX (Columbia Univ.)



The Ideal Perturbed Equilibrium Code (IPEC) is Used to Understand 3-D Field Effects

- IPEC[1] gives ideal 3-D free-boundary tokamak equilibria.
- Solves the perturbed force balance equation

$$\vec{F}\left(\vec{\xi}\right) = \vec{\nabla}\delta p - \delta\vec{j} \times \vec{B}_0 - \vec{j}_0 \times \delta\vec{B} = 0$$

$$\delta\vec{B} = \vec{\nabla} \times \left(\vec{\xi} \times \vec{B}_0\right)$$

$$\delta\vec{j} = \left(\vec{\nabla} \times \delta\vec{B}\right)/\mu_0$$

$$\delta p = -\vec{\xi} \cdot \vec{\nabla} p_0 - \gamma p_0 \left(\vec{\nabla} \cdot \vec{\xi}\right)$$

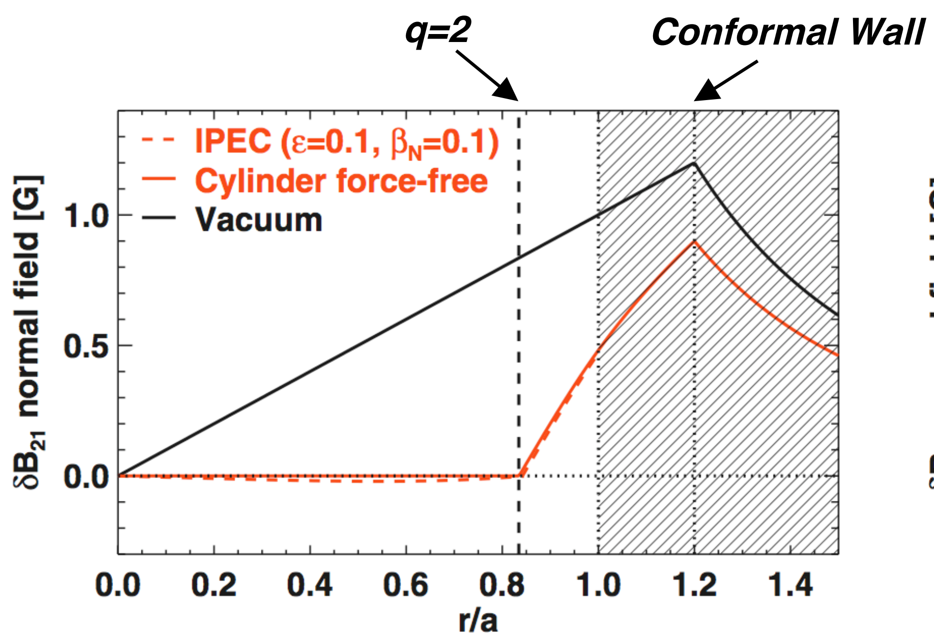
- Impose constraint that resonant magnetic perturbation vanishes at each surface.
  - Shielding currents are calculated to eliminate islands.
  - Relevant description of perturbed plasmas before the onset of error field penetration.
- Externally imposed non-axisymmetric fields represented by equivalent surface currents at the boundary.
- Shielding current determines ***locking*** properties.
- Lagrangian variation of the field strength determines ***NTV transport***

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

Example: Force-Free Cylinder

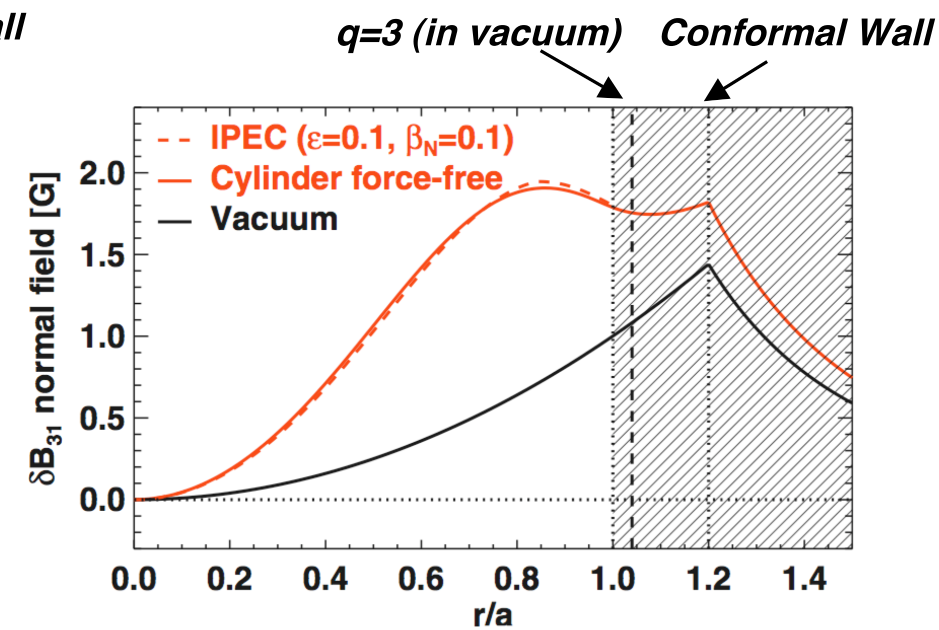
- Compare low-β, high-A IPEC solution to force-free cylindrical solution.
- Non-axisymmetric fields applied by currents in the conformal wall.

m=2, n=1 perturbation in a cylinder



Shielding currents at q=2 drive the resonant perturbation to zero.

m=3, n=1 perturbation in a cylinder



Easy to perturb the plasma.

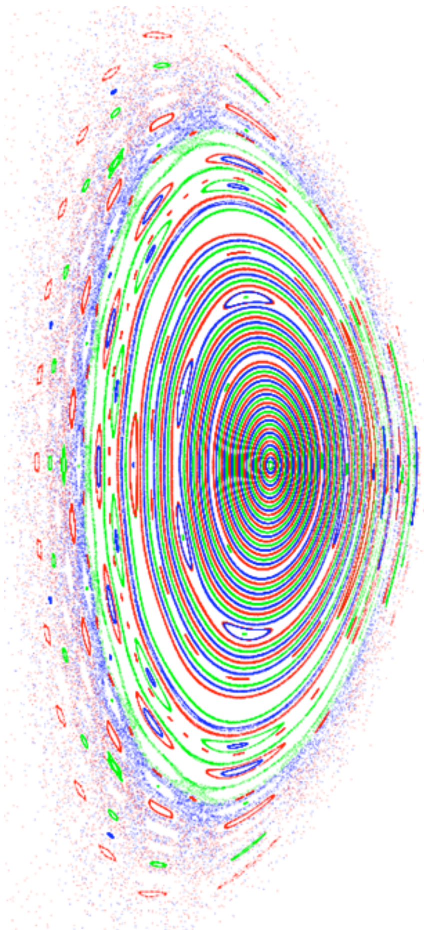
Large amplification of the applied fields

Example: High-β NSTX Plasma
(Finite Beta, Toroidicity)

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

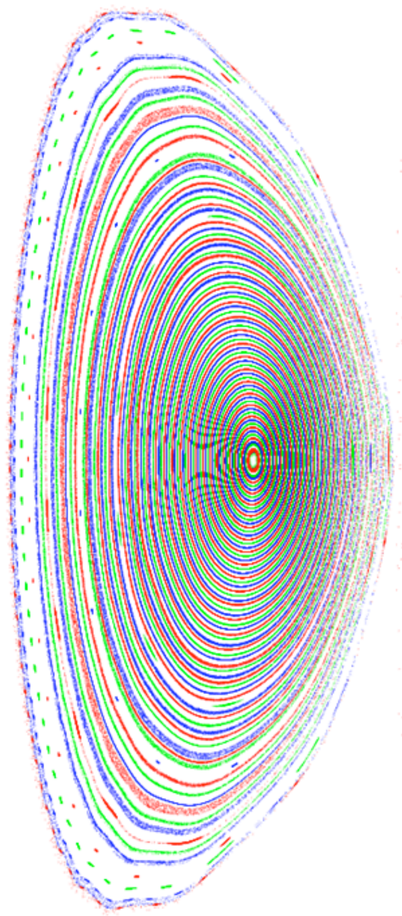
Vacuum Superposition

Islands and Stochastic Regions



IPEC

Surface Deformation



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

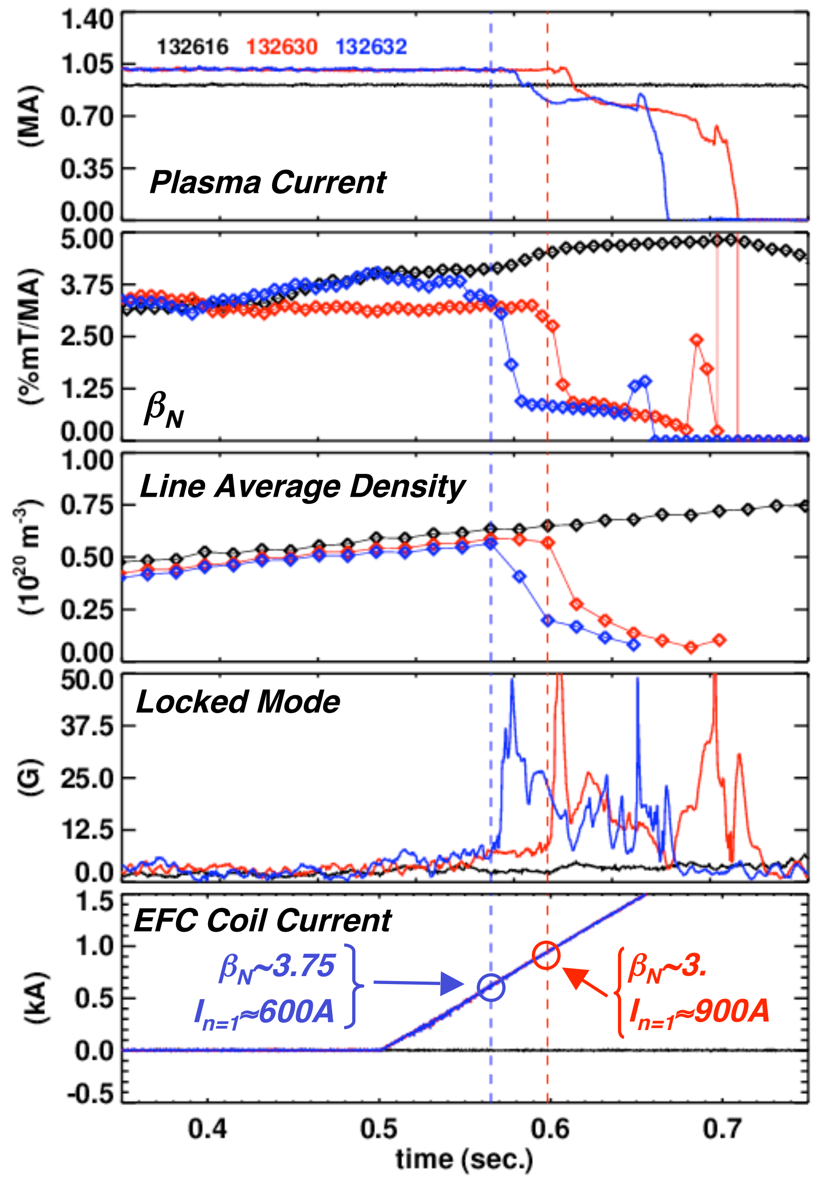
Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

Increased n=1 Error-Field Sensitivity Observed at Higher-β_N

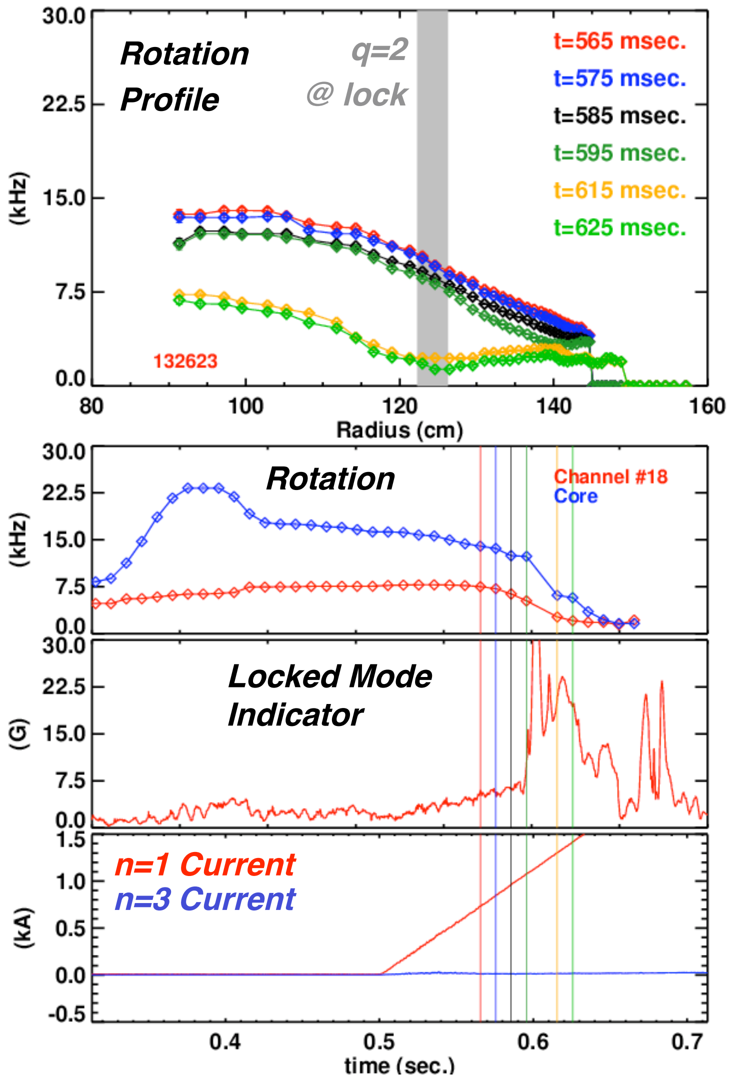
- Varied P_{inj}, I_P, and B_T to achieve different β_N at fixed q_{95}.
- Apply ramping n=1 field using the EFC coils.
- Measure the time of mode penetration using the internal resistive wall mode sensors.
- β-dependence of locking at near identical density.
  - Higher-β_N locks with ~600 Amps of n=1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

Increased error-field sensitivity at higher-β_N!

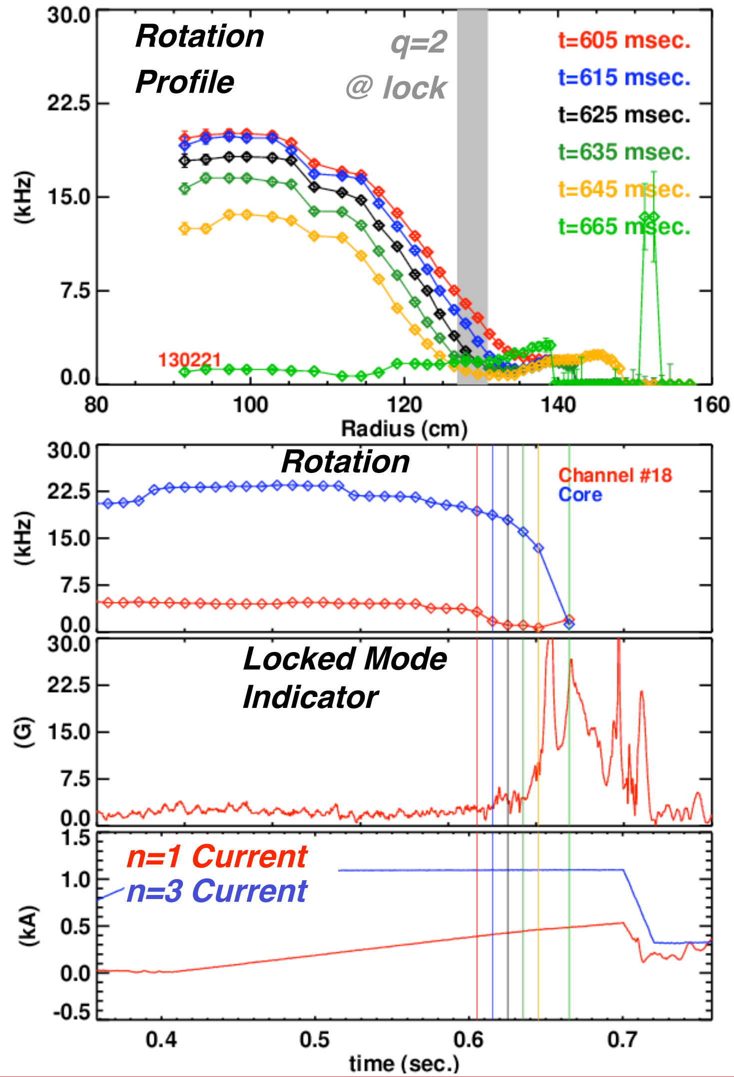


Different Magnetic Braking Profiles Observed Before EF Penetration

Large n=1, Small n=3
Broad Braking Profile

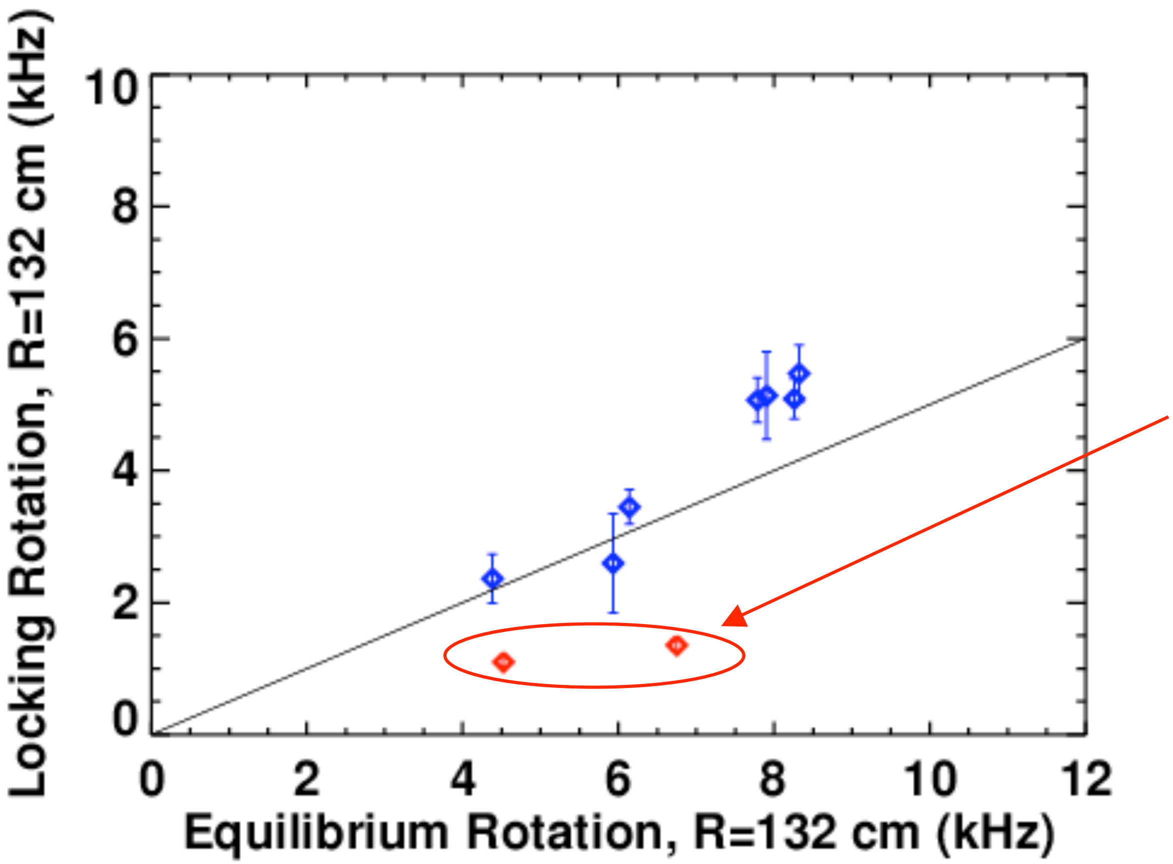


Large n=3, Small n=1
Strong Edge Braking



EF Penetration Generally Occurs When Rotation is Reduced by Half

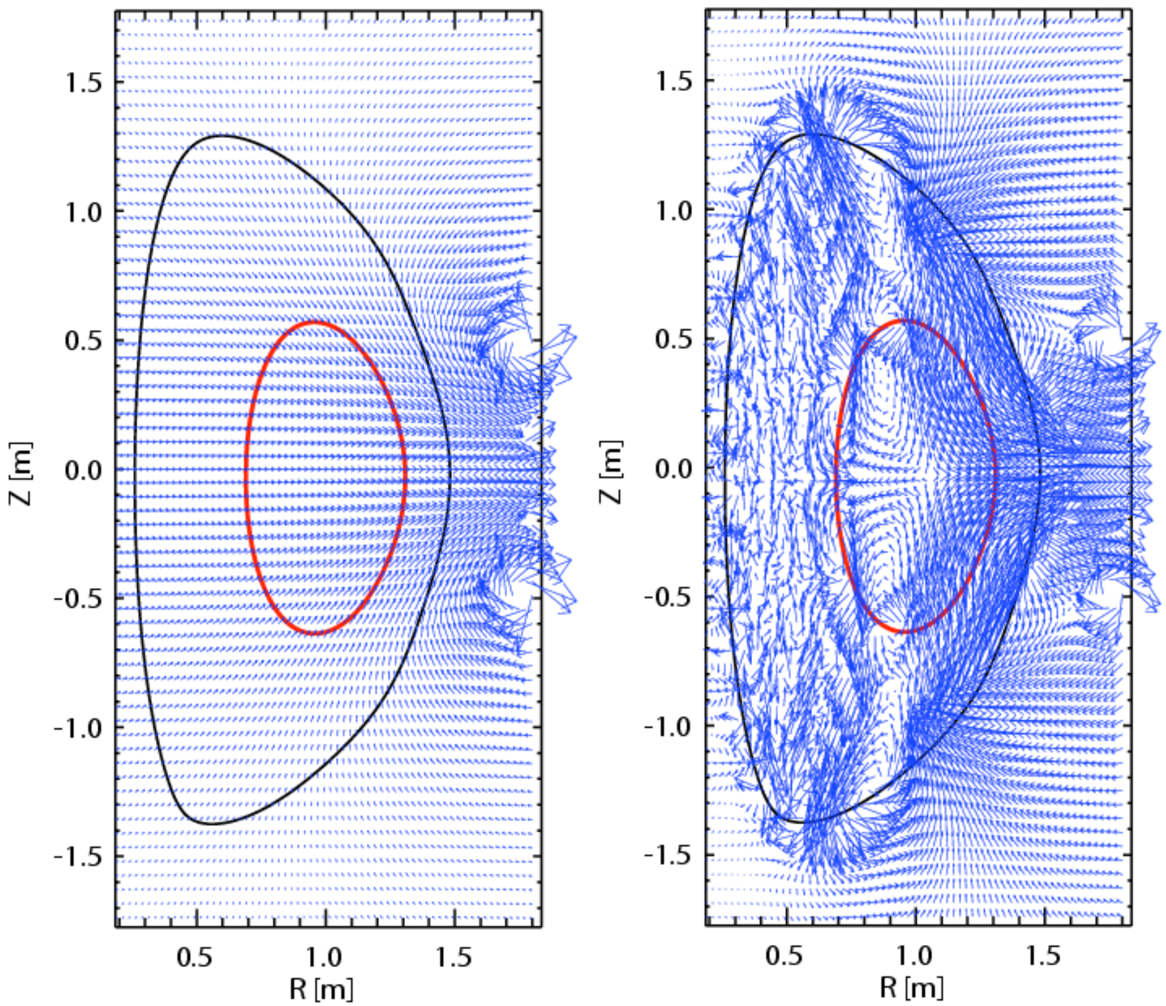
- Use CHERS rotation at R=132 cm, at the typical q=2 radius
- Data only available for a limited # of discharges.
  - Most discharges have no CHERS data after EF penetration.



Cases where $I_{n=3}$>>$I_{n=1}$
Very strong edge braking proceeds EF penetration.
Proper calculation of ω_0?

β-Dependence: The Resonant Field that Drives Islands can be Amplified by the Plasma at Higher β_N

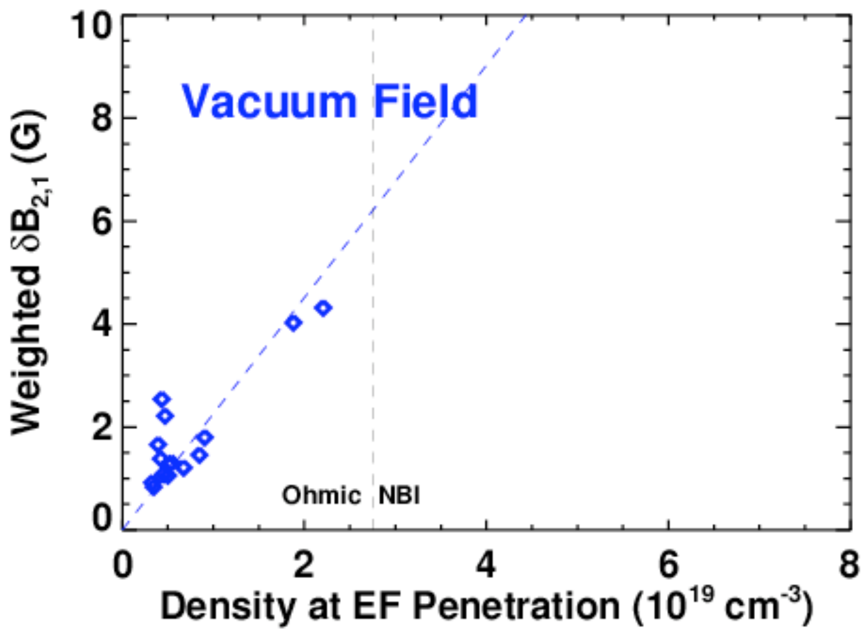
Vacuum Field | *Vacuum + Plasma Response (IPEC)*



- 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.

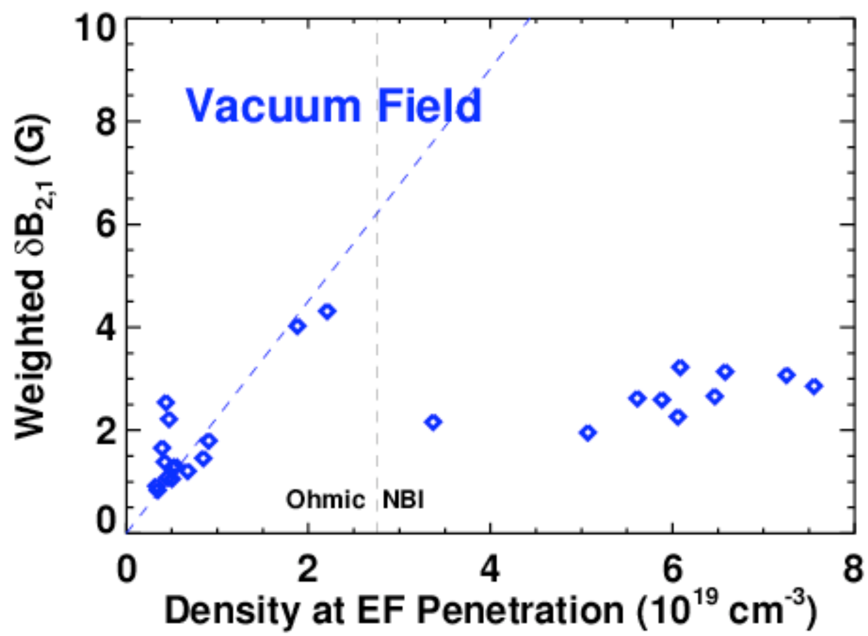
Linear Correlation Between Resonant Field for Penetration and Density Can be Restored Using IPEC

- Wide variety of data in the scan:
  - Ohmic L-mode plasma at low density



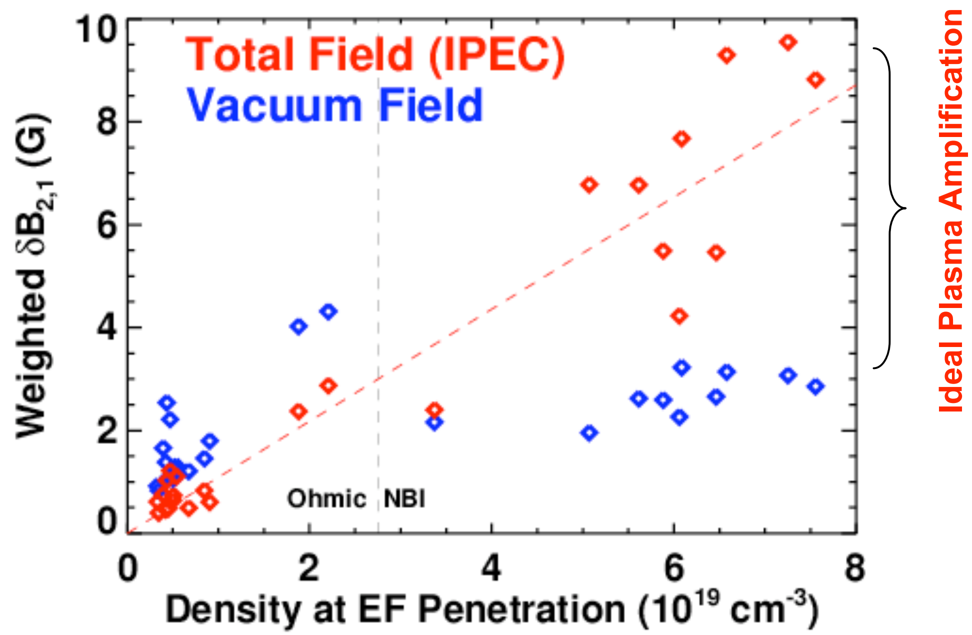
Linear Correlation Between Resonant Field for Penetration and Density Can be Restored Using IPEC

- 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.



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

- 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.



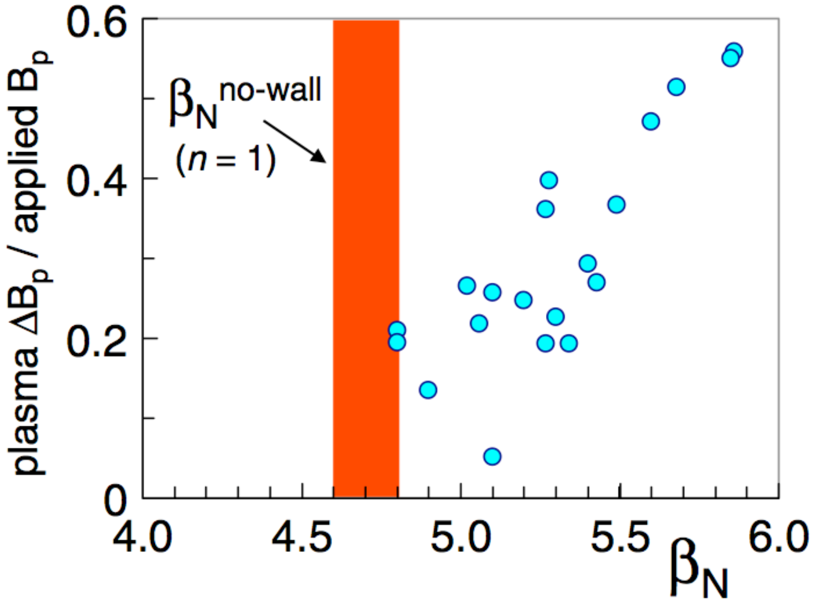
Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

Reminder: Plasma Amplification of Applied n=1 Fields is Well Documented in NSTX

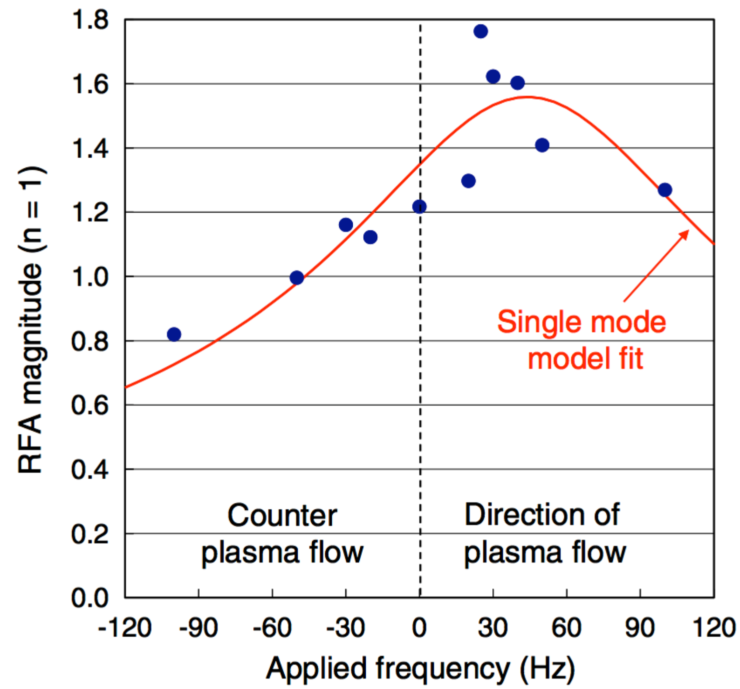
Columbia University

β-Dependent RFA Response to a Standing Wave n=1 Field



S. A. Sabbagh, et al., Nuclear Fusion 46, 635 (2006)

Frequency Dependent Response to a Traveling Wave n=1 Field



A. C. Sontag, et al., Nuclear Fusion 47, 1005 (2007)
Supportive of single-mode RFA model.

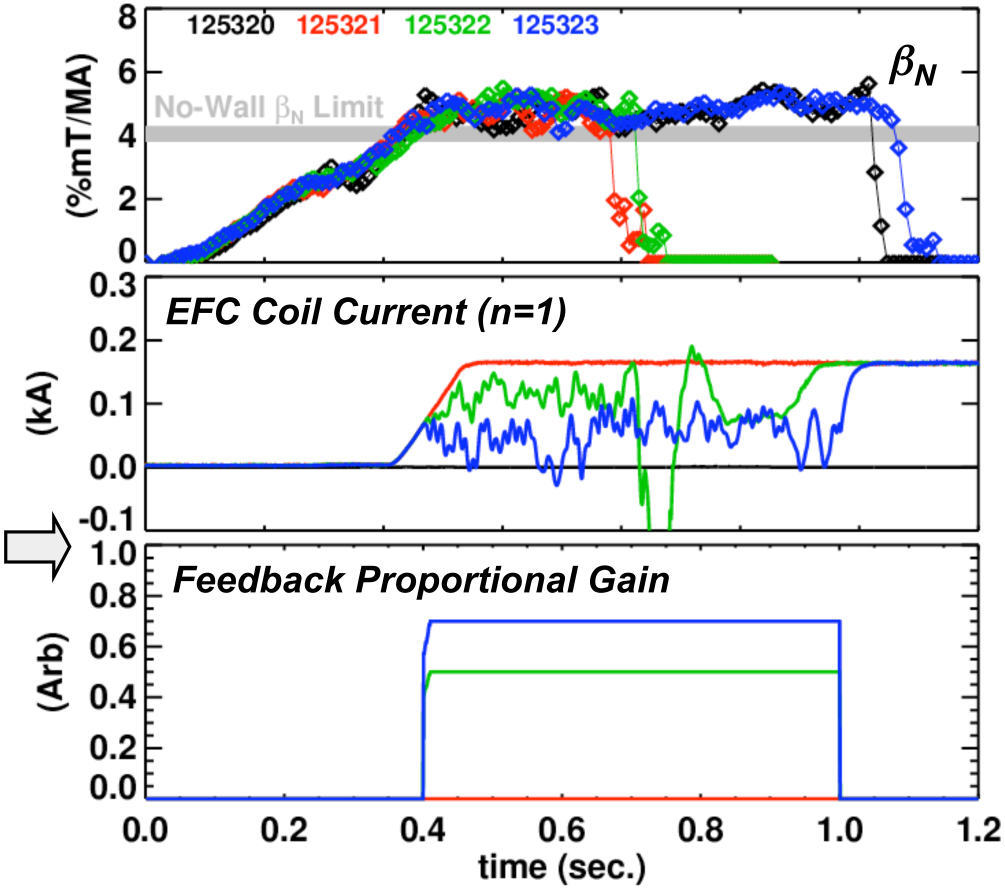
We can use this physics for n=1 EF correction.

Use Plasma Amplification of Error Fields as a Control Tool

- **Pre-programmed n=1 EF correction requires a priori estimate of intrinsic EF**
- Detect plasma response → **EF correction using *only feedback on RFA***

RFA Suppression Algorithm

- **Use discharge with rotationally stabilized RWM.**
- **Deliberately apply n=1 EF in order to reduce rotation, destabilize an RWM.**
- **Find feedback phase that reduces the applied n=1 currents (B_P sensors).**
  - **Direct coil-sensor pickup is removed.**
- **Increase the gain until currents are nearly nulled and plasma stability is restored.**



→ *Use same gain/phase settings to suppress RFA from intrinsic EF **and** any unstable RWMs*

J.E. Menard et al., to be published in Phys. Plasmas

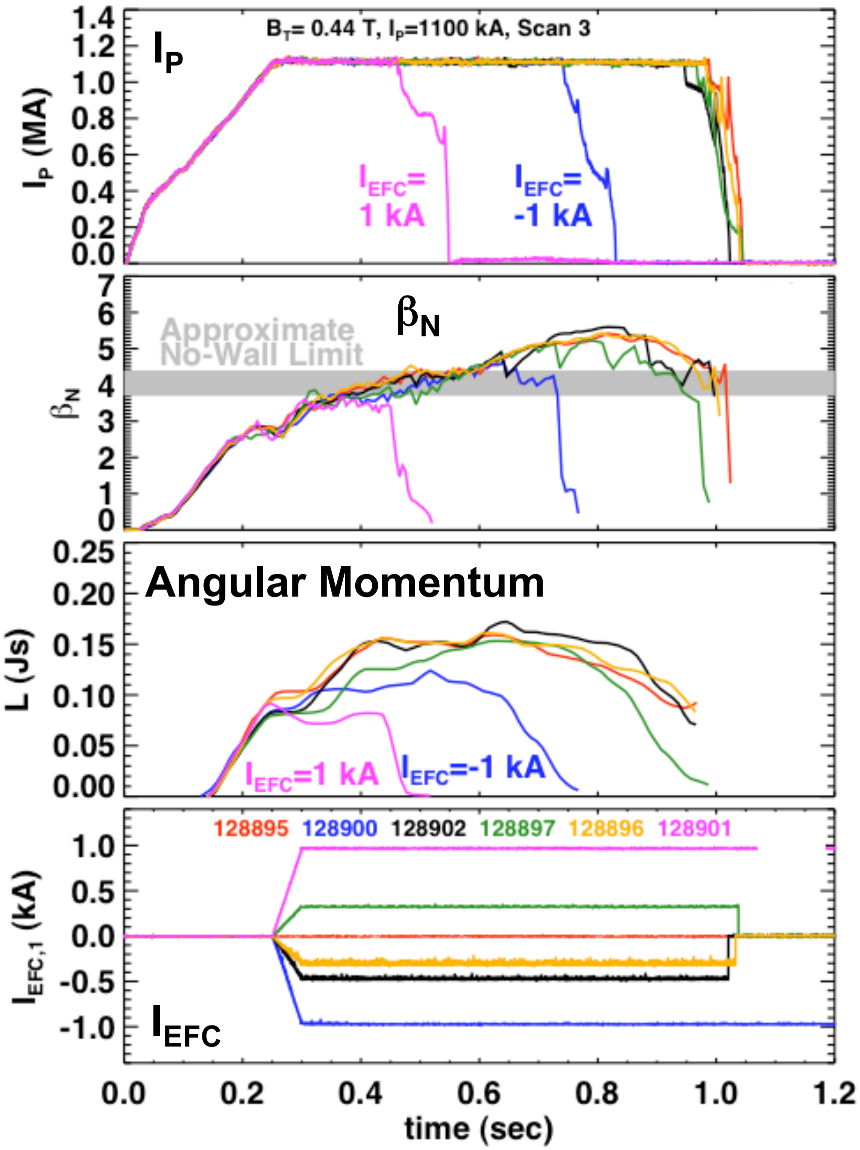
Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

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

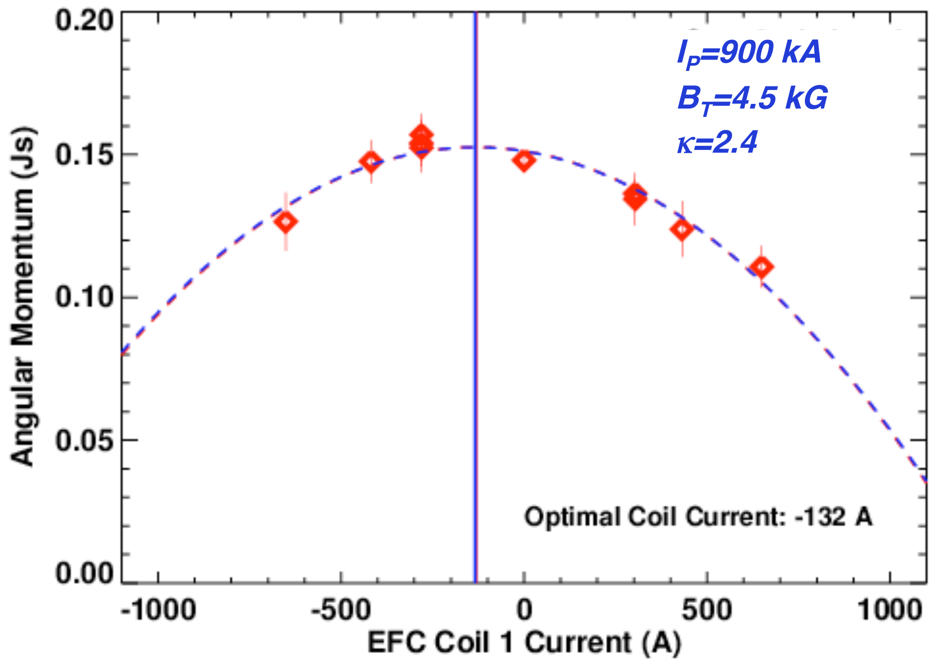
- Use a long-pulse high-β_N discharge.
- Apply n=3 fields of two different polarities, many amplitudes.
- Asymmetric response in the pulse length:
  - Discharge with 1000 A applied n=3 field disrupts before that with -1000 A.
- Asymmetric response in the angular momentum:
  - Discharge with $I_{n=3}$=+1000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

There is an intrinsic n=3 error field.



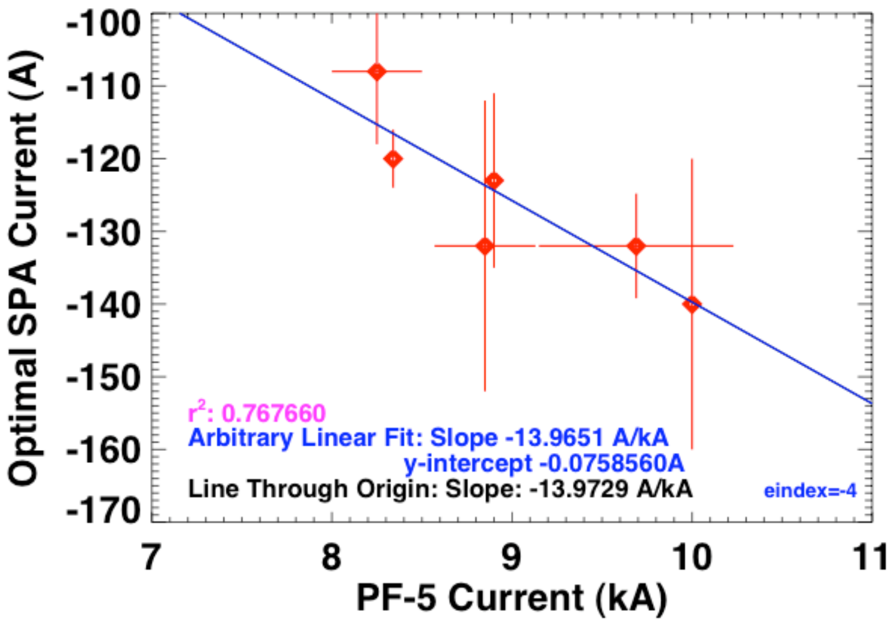
Determine Optimal Correction by Maximizing the Angular Momentum

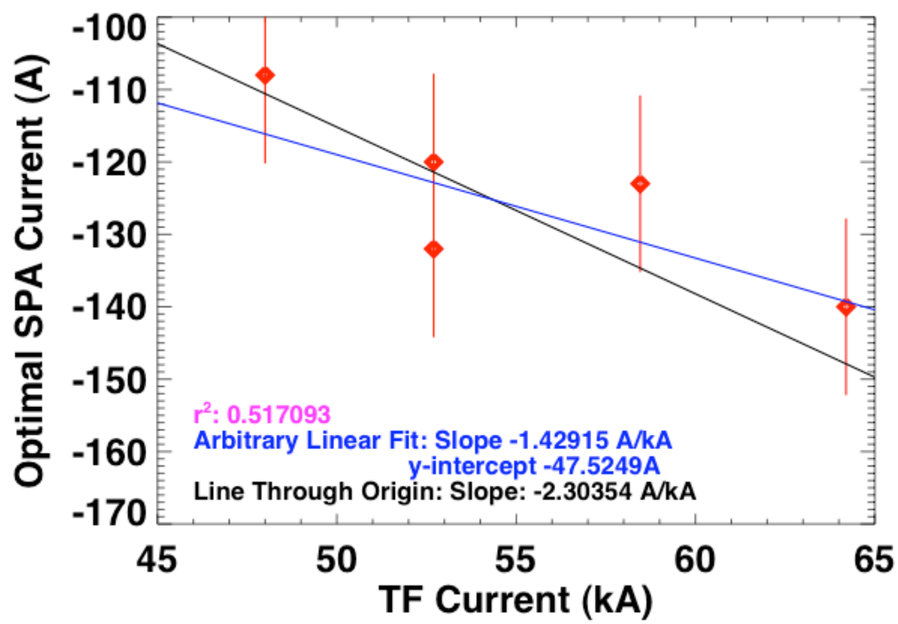
- Likely sources of the EF:
  - Vertical Field Coil → Function of I_P
  - Radial Field Coil → Function of I_P, κ
  - Toroidal Field Coil → Function of B_T
- Choose 6 configurations with different values of I_P, B_T, and κ.
- For each configuration, determine the optimal n=3 correction



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

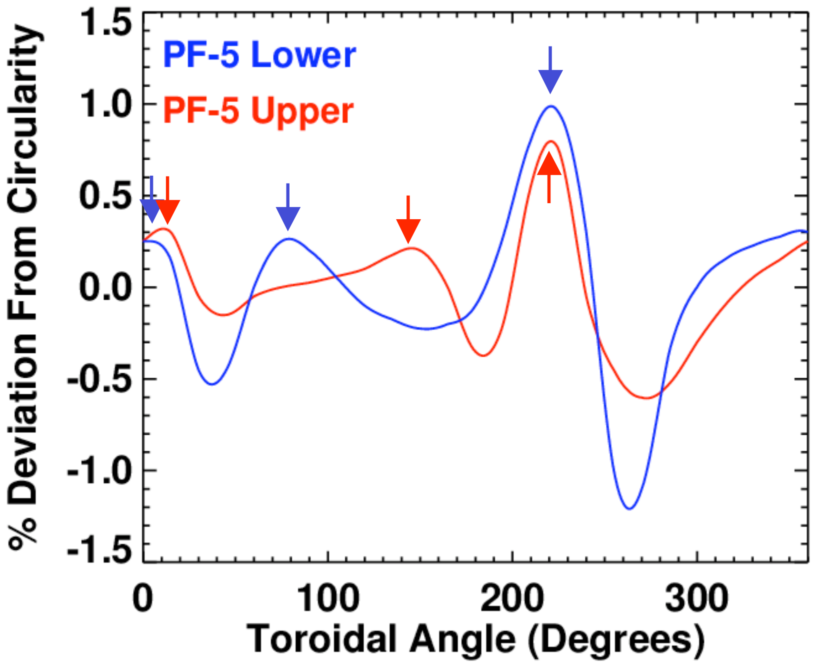
- Optimal correction correlates well with the current in the vertical field coil.
- Correlation not as strong with the other coils:
  - Correlation coefficients not as large.
  - Best fit lines do not extrapolate to zero correction at zero coil current.
  - Changing the TF direction did NOT change the sign of the correction.





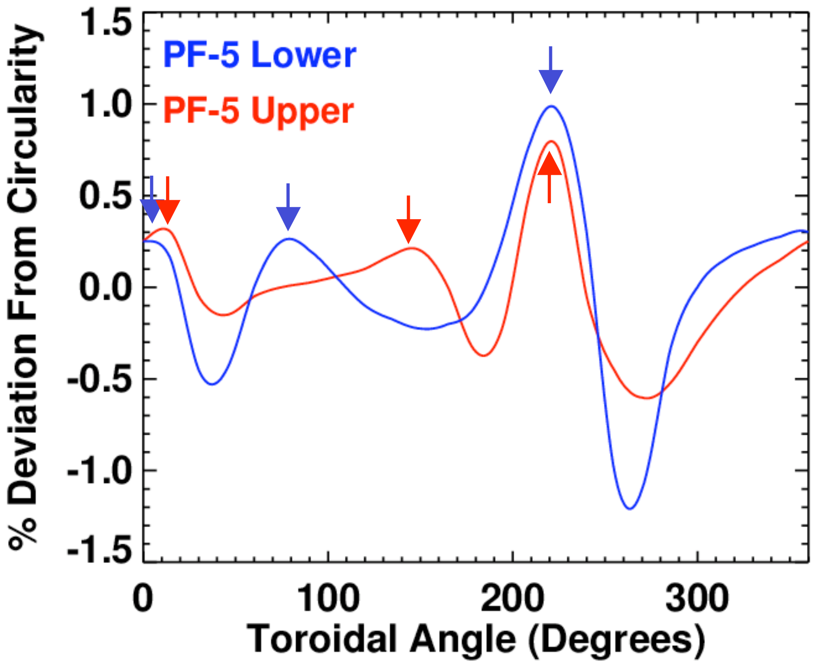
Correction is Consistent With Known Out-of-Round Vertical Field Coil

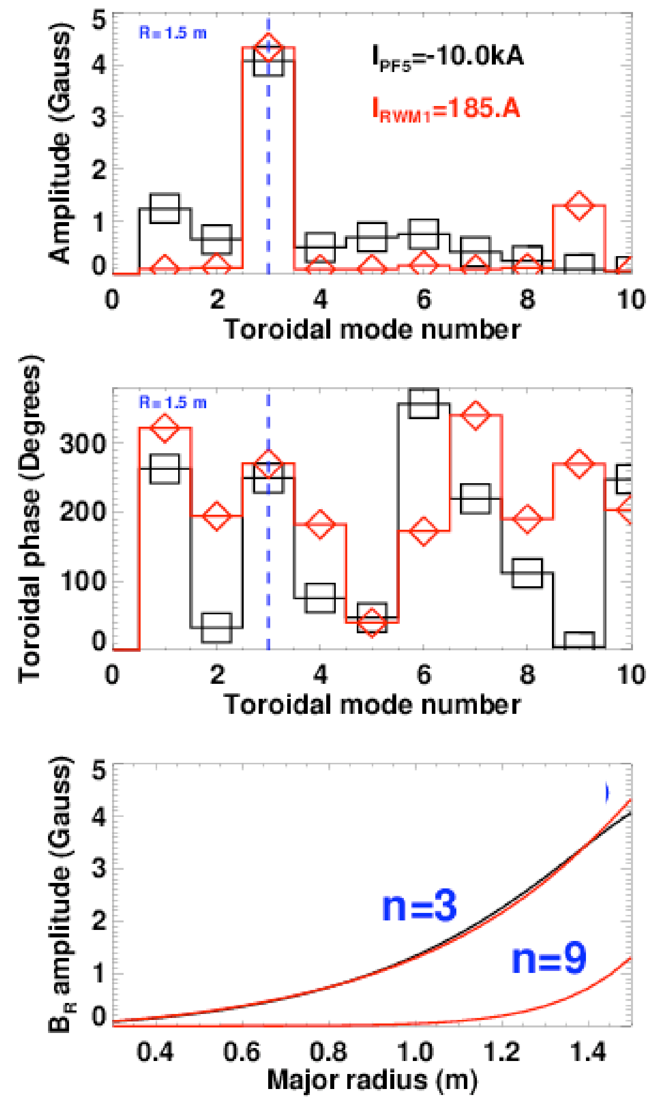
- Vertical field coils have a dominantly n=3 radial variation.
  - Makes an n=3 error field.
- Experimental correction $I_{EFC}/I_{PF-5} \approx 14\ A/kA$
- Optimal vacuum correction: $I_{EFC}/I_{PF-5} \approx 18.5\ A/kA$



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

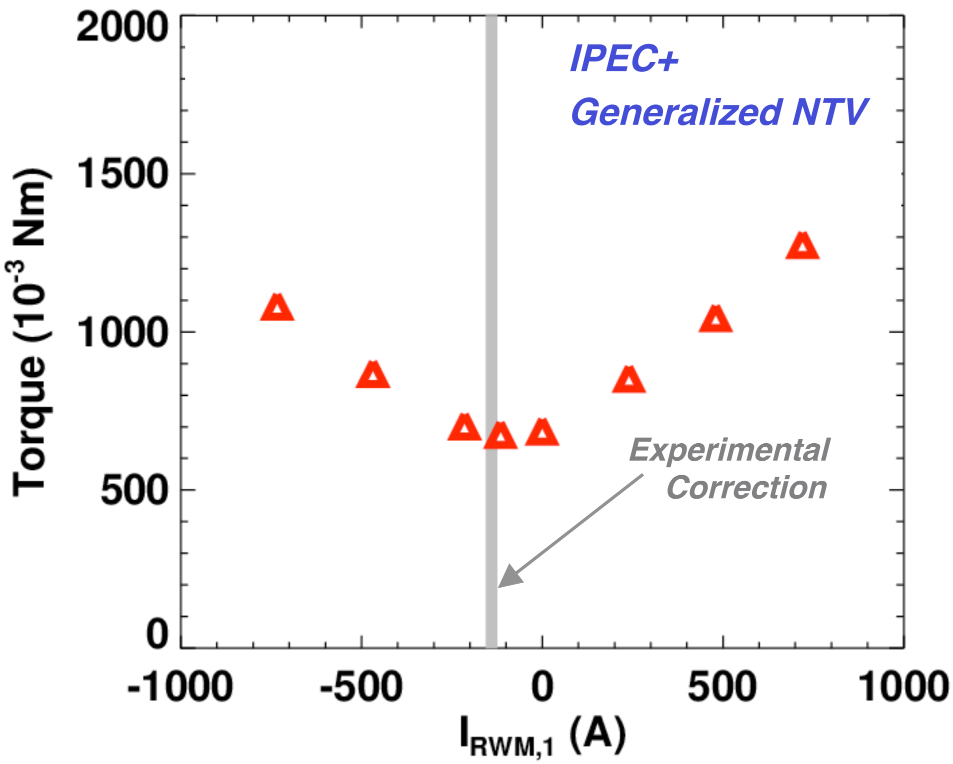
- Vertical field coils have a dominantly n=3 radial variation.
  - Makes an n=3 error field.
- Experimental correction $I_{EFC}/I_{PF-5} \approx 14\ A/kA$
- Optimal vacuum correction: $I_{EFC}/I_{PF-5} \approx 18.5\ A/kA$





Minimal NTV Torque at the Experimentally Determined Correction

- Computed the expected braking torque using the IPEC total field and generalized NTV theory.[1]
- Include the intrinsic EF, scan the EFC coil current.
- Predicts minimum total torque at $I_{EFC} / I_{PF-5} \approx 15\ A/kA$



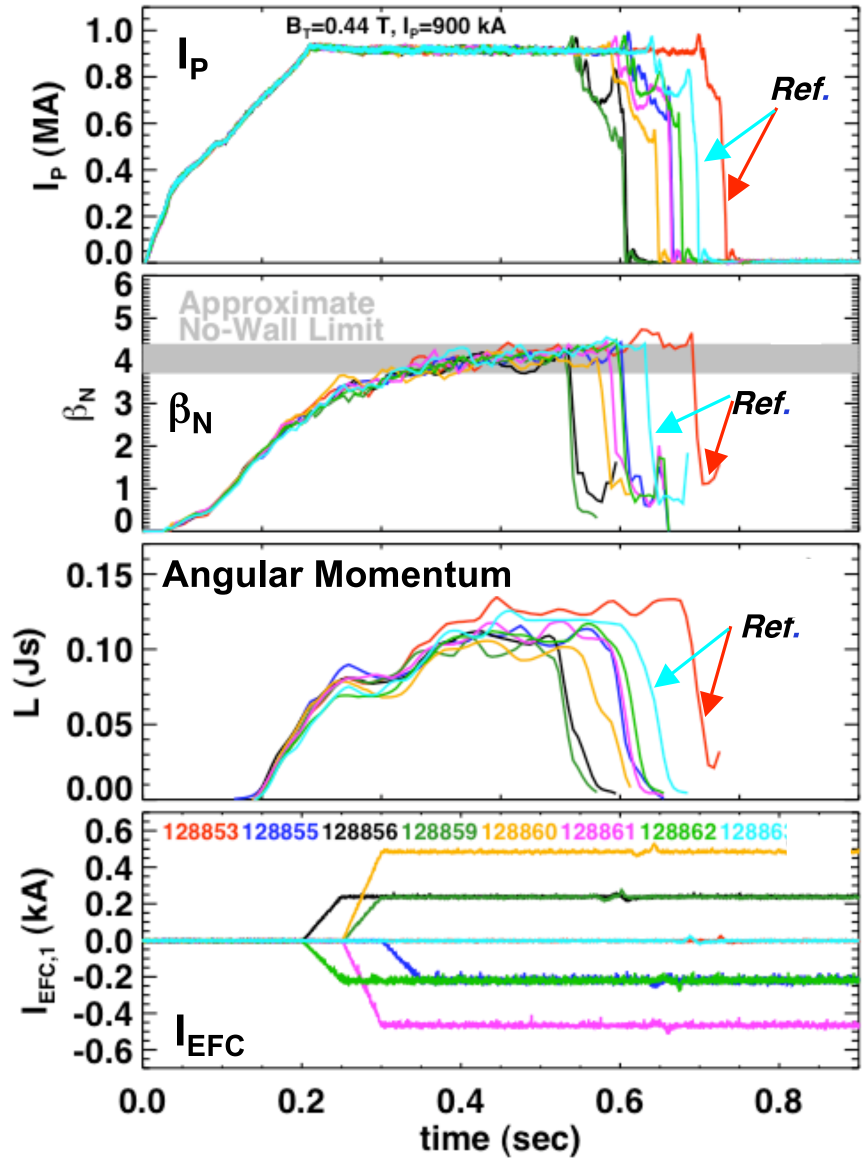
Torque magnitude is consistent with experiment

- ***Angular momentum changes by 0.05 J·s in ~100 msec***
- ***Implied toque of .05/0.1=0.5 N·m is consistent with the change in calculated torque.***

[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.



Introduction and Preview

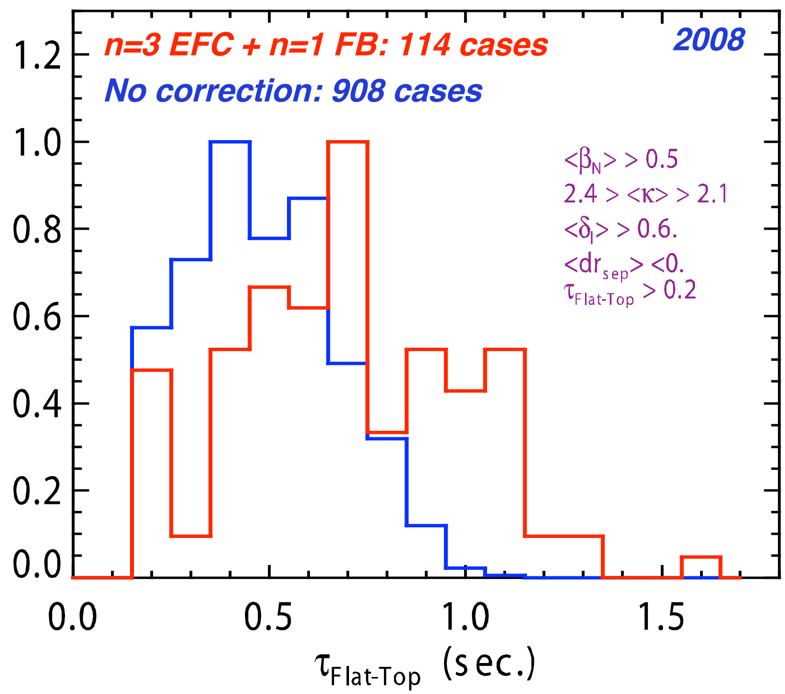
- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

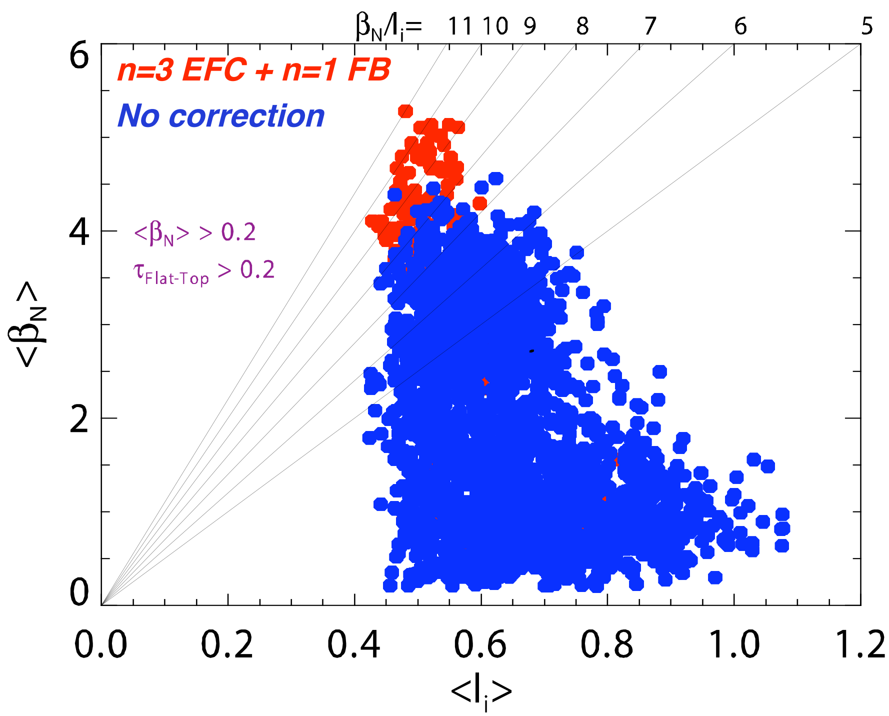
Combined n=1 Feedback and n=3 Correction Yield Improved Performance

n=1 DEFC (slow) and RWM (fast) feedback combined in these cases

Probability of a long-pulse shot increases with n=3 correction and n=1 feedback.

High average values of β_N/l_i achievable with n=3 correction and n=1 feedback.





No equivalent data for 2009 run…DEFC used on nearly every NB heated shot starting from the beginning of the run.

[1] S. Sabbagh et al., submitted to Nuclear Fusion.

Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

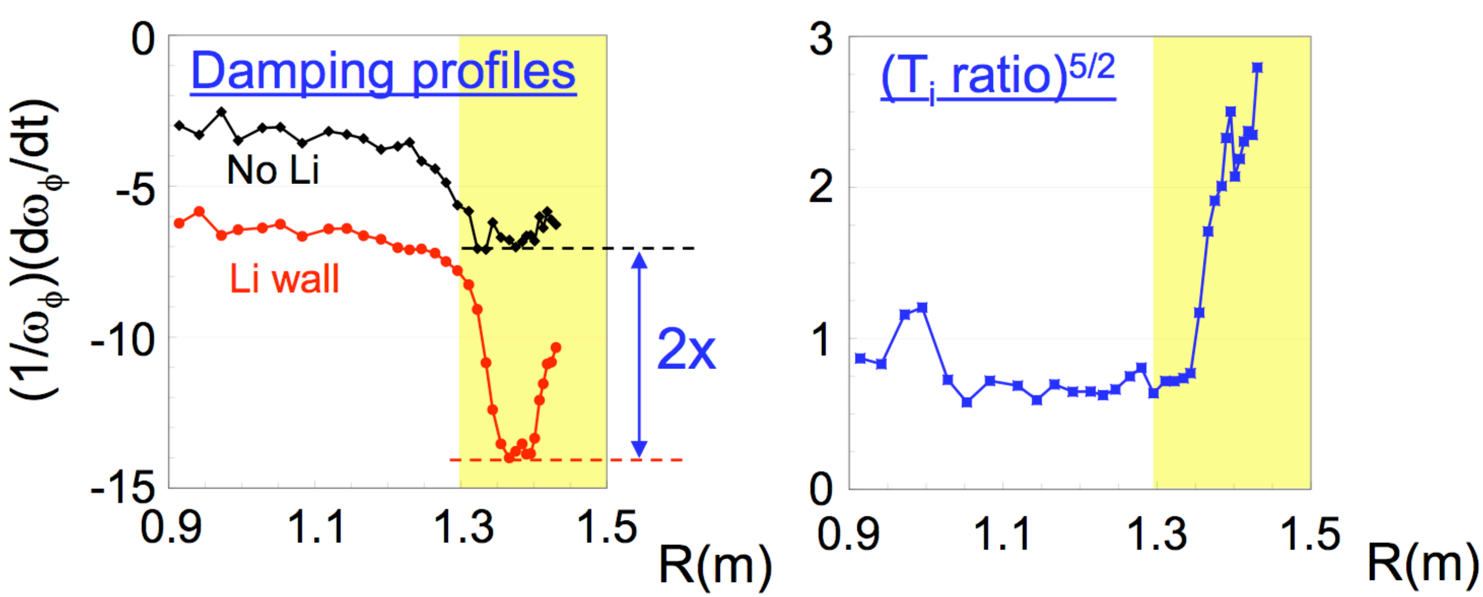
Stronger Non-Resonant Braking at Increased T_i

COLUMBIA UNIVERSITY

- Neoclassical toroidal viscosity (NTV) is the damping of toroidal flows due to the loss of toroidal symmetry.
  - Neoclassical fluxes loose their intrinsic ambipolarity.
  - Results in a braking torque.
- Expression in "1/ν" regime, $q\omega_E < \nu_i/\varepsilon < \sqrt{\varepsilon}\omega_{ti}$

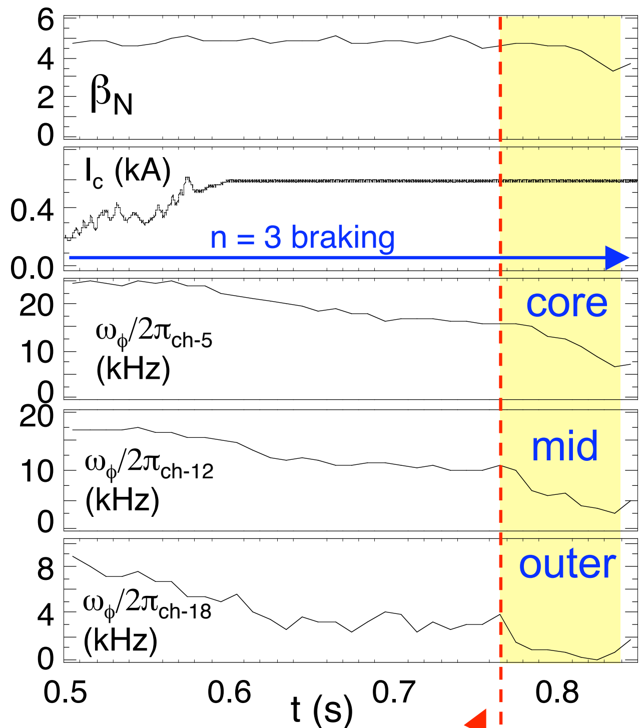
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\Omega_\phi - \Omega_{NC}) I_\lambda \quad \Rightarrow \quad \frac{d\Omega}{dt} \propto \frac{p_i}{\nu_i} \Omega \quad \Rightarrow \quad \frac{1}{\Omega}\frac{d\Omega}{dt} \propto T_i^{5/2}$$

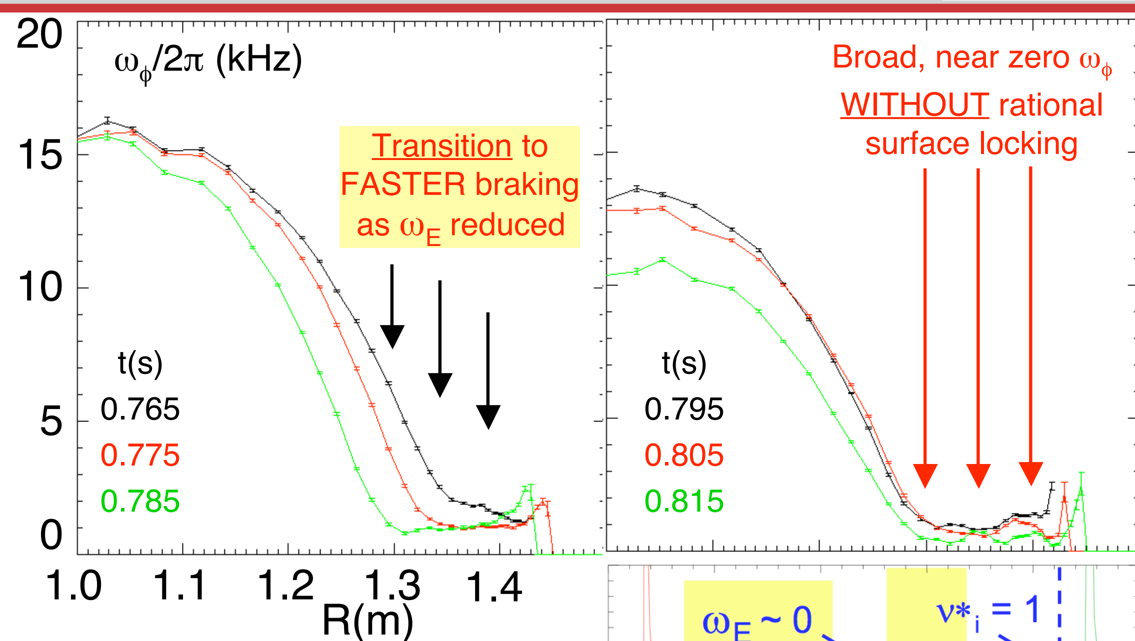
- Use Lithium evaporation to increase T_i, apply n=2 fields and measure rotation damping.
- Verified $T_i^{5/2}$ dependence of NTV torque in region of max braking.

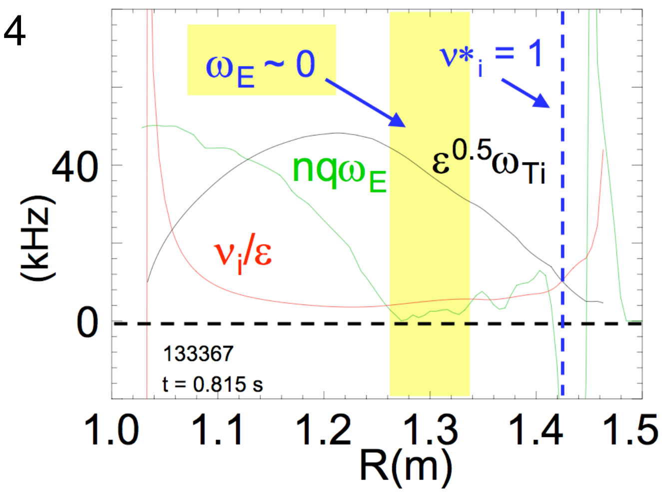


S. Sabbagh, et al, 2008 IAEA FEC & submitted to Nuclear Fusion

Stronger Braking With Constant n = 3 Applied Field as ω_E Reduced – Accessing Superbanana Plateau NTV Regime







- Faster braking with
  - Constant β_N, applied n = 3 field
  - No mode activity
- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV in "1/ν regime" ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$)
  - Stronger braking expected when $\omega_E \sim 0$ (superbanana plateau)
  - Important for predicting NTV effects in low-rotation plasmas -> RWMs, NTMs, rotation control, RMP effects

S.A. Sabbagh (CU)

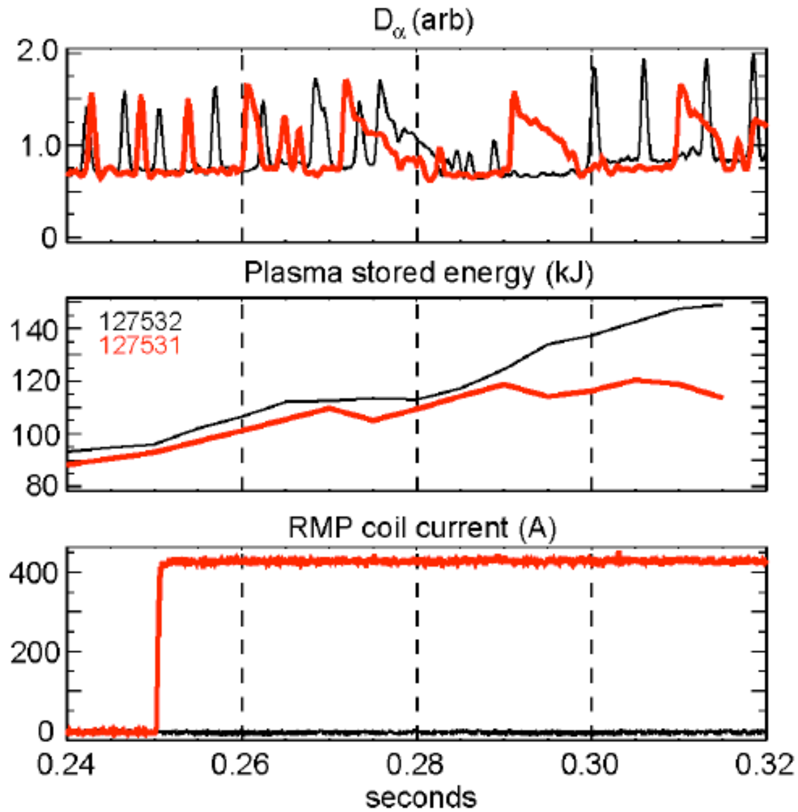
Introduction and Preview

- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

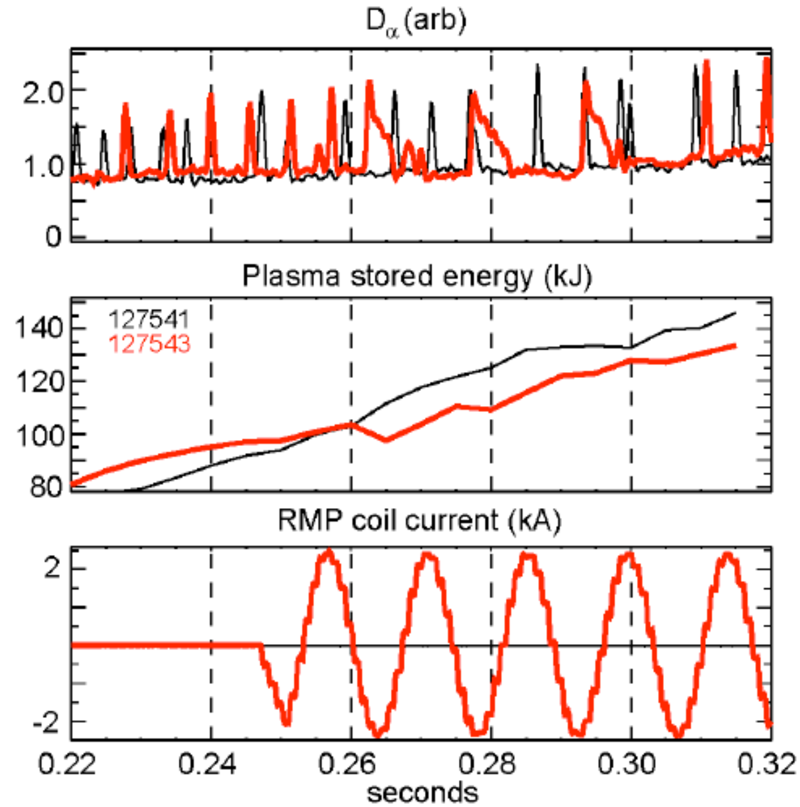
3-D Field Modified ELMs in NSTX, But Suppression Not Observed

- Satisfy the standard vacuum Chirikov > 1 outside of ψ_N>~0.85.
- Broadly similar results for n=3, n=2+3 fields.
- See S. Sabbagh's GA RMP workshop talk.

n = 2 DC field vs. no field



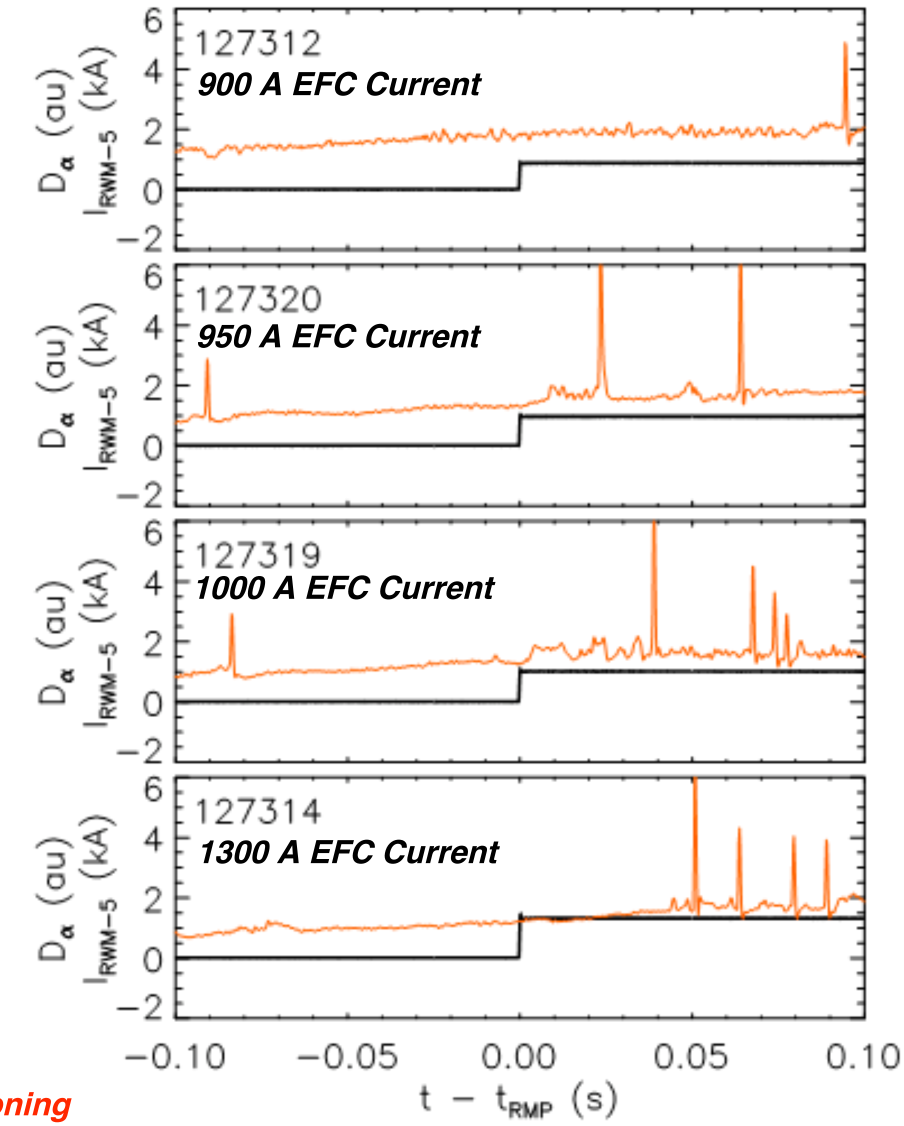
n = 2 AC field, 70 Hz vs. no field



If 3-D Fields Don't Suppress ELMs in NSTX, then use them for ELM triggering!

EFC Current Scan Shows Threshold for ELM Destabilization with 3-D Fields

- Threshold coil current for ELM-triggering is ~950 A ->$\Delta B/B = 6\times10^{-3}$
  - No triggering at 900 A (natural ELMs start at ~0.5s in control discharge)
  - Intermittent ELMs at 950 and 1000 A
- ELM frequency appears to increase with n=3 field magnitude
  - ELMs become more regular
  - Trend clouded by tendency of plasma to lock high currents-too much braking



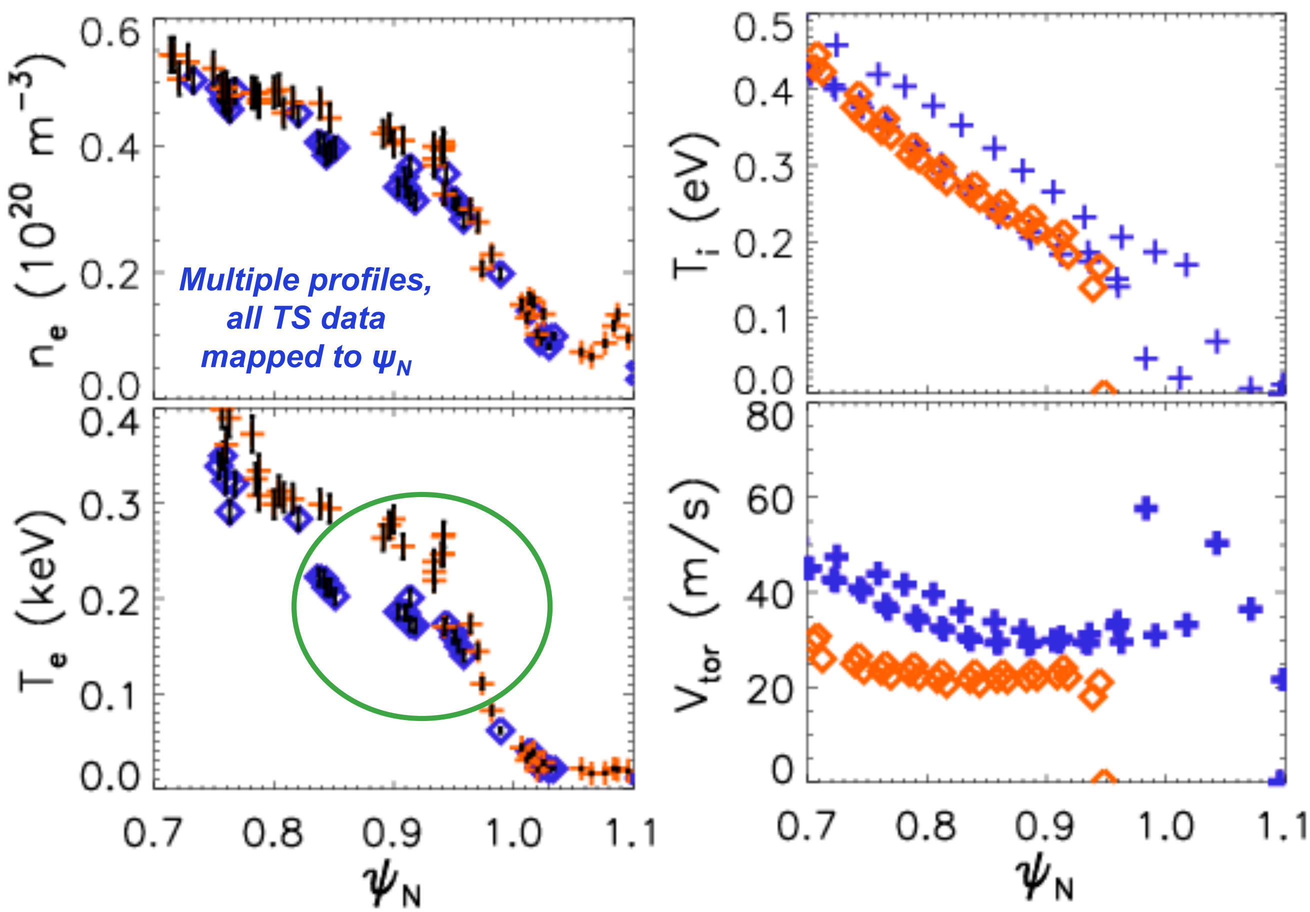
No Li Conditioning

J.M. Canik , A.C. Sontag, R. Maingi (ORNL)

T_e^{ped} Increases When n=3 Fields are Applied

- Blue profiles: no n=3 applied
- Red profiles: 20 ms after n=3 applied (before ELMs)

No lithium coatings in these shots

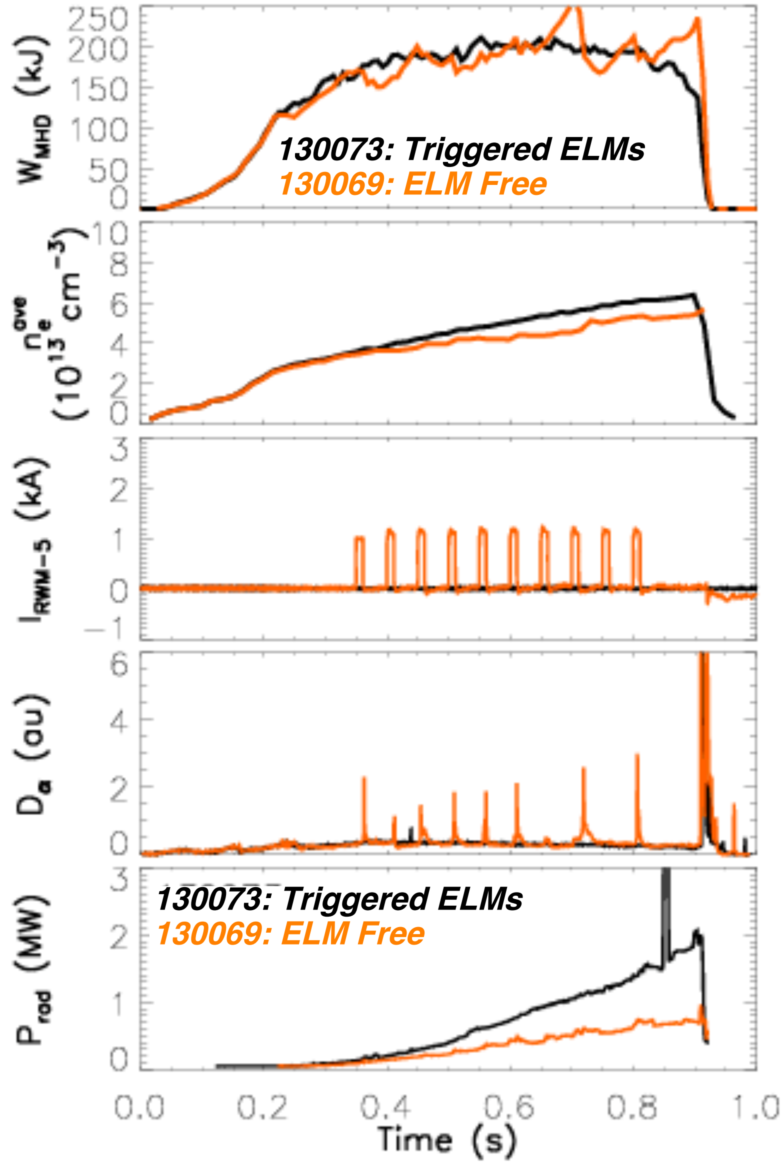


- No density pumpout is observed
- Te, pressure gradient increases after n=3 field is applied
  - Tanh fitting gives ~30% increase in peak pressure gradient
  - PEST shows edge unstable after n=3 application

J.M. Canik , A.C. Sontag, R. Maingi (ORNL)

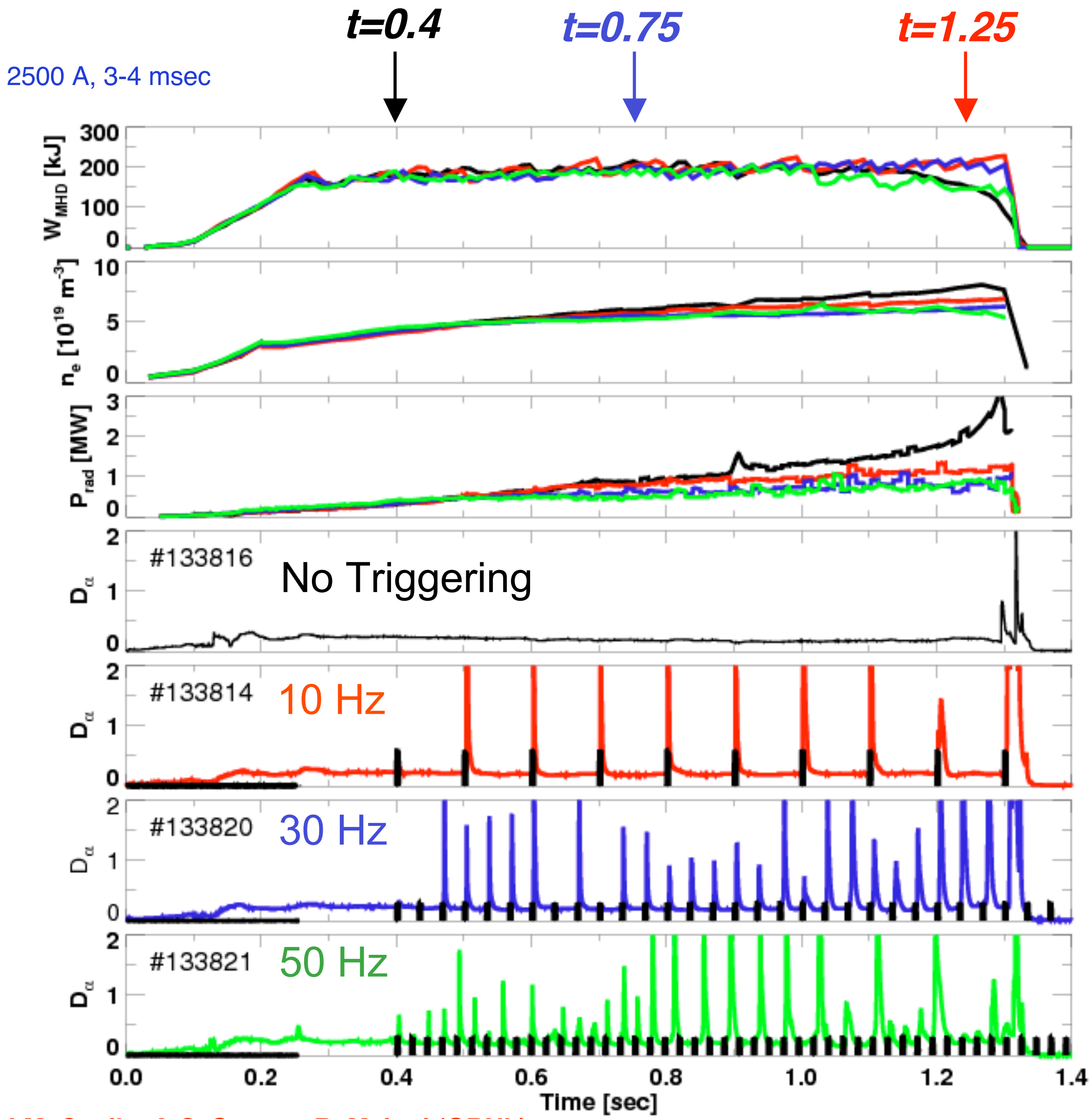
Magnetic ELM Triggering has been Applied to Lithium Enhanced ELM-free H-modes

- Typical behavior with Li wall conditioning:
  - ELMs suppressed
  - P_{rad} ramps to ~2 MW, for P_{NBI}=3 MW
- Steady n=3 fields not optimal for ELM triggering.
  - Too much rotation braking.
- Square-wave n=3 fields applied to trigger ELMs.
  - 10 ms pulses, f=20 Hz, 1.2 kA
  - ELMs triggered on 8 of 10 pulses
  - Radiated power reduced by a factor of 2.
  - Density ramp rate reduced
  - Stored energy relatively unaffected.

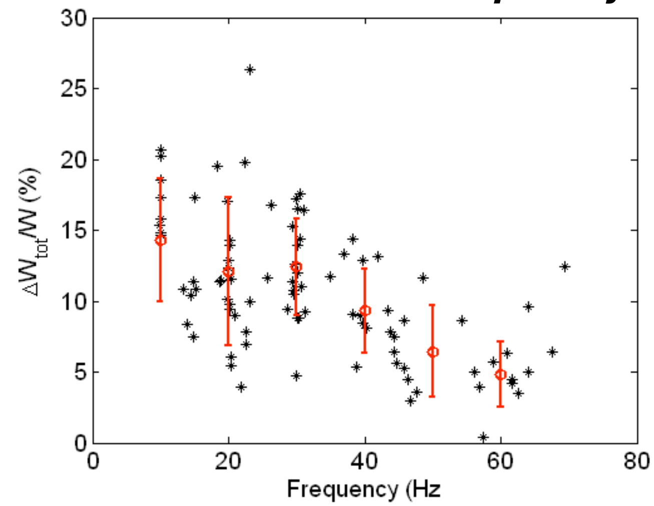


J.M. Canik , A.C. Sontag, R. Maingi (ORNL)

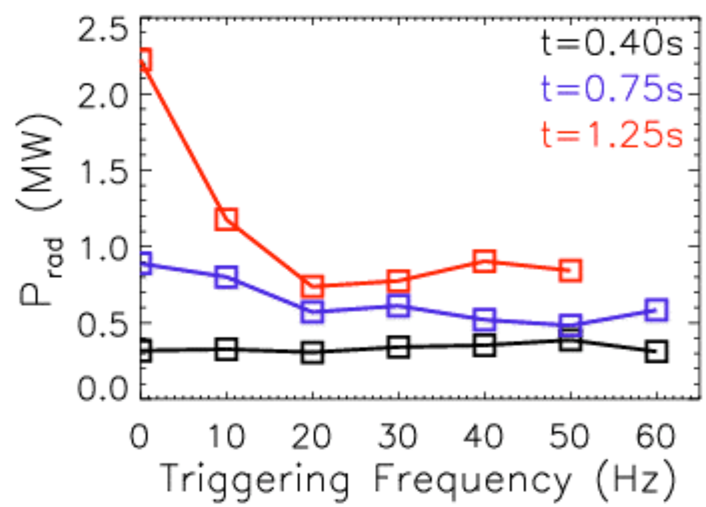
Maximizing the n=3 Pulse Amplitude Allows Rapid Frequency Triggering with Very High Reliability



ELM Size vs. Frequency



P_{Rad} vs. Triggering Frequency



J.M. Canik , A.C. Sontag, R. Maingi (ORNL)

Introduction and Preview

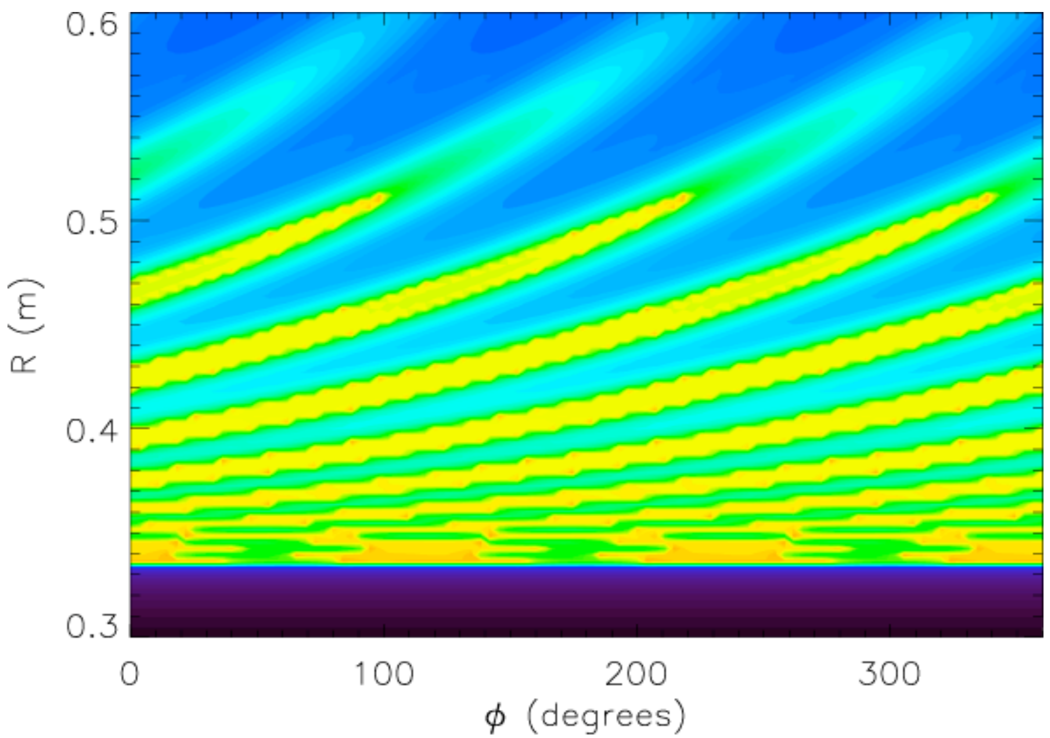
- Background:
  - The NSTX Device
  - The IPEC code
- Effects of 3-D fields on the core plasma
  - Studies of n=1 error field penetration in high-β plasmas.
  - Dynamic correction of n=1 error fields.
  - Non-resonant error field detection and correction.
  - Improved NSTX performance with resonant and non-resonant EF correction.
  - Neoclassical toroidal viscosity (NTV).
- Effects of 3-D fields on the edge plasmas
  - Magnetic ELM pacing
  - 3-D effects on the divertor footprint.
- Summary

Strike-Point Splitting Predicted…

- Effects of axisymmetric fields (flux expansion) on divertor heat loading has been characterized in NSTX.[1,2]
- What happens when 3-D fields are applied?

[1] D. Gates et al, Phys. Plasmas **13**, 056112 (2006)
[2] V. Soukhanovskii, et al., "High flux expansion divertor studies in NSTX", 36th EPS Conference on Plasma Physics

Connection Length for Field Lines Launched From Divertor Floor (n=3)



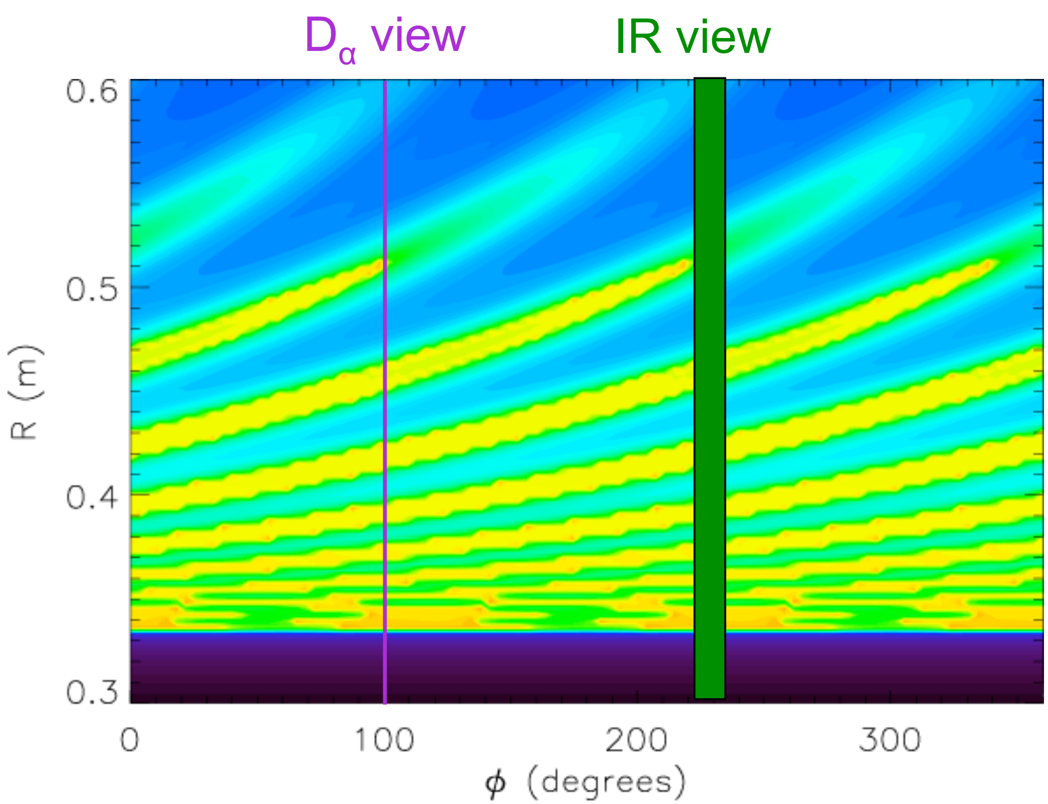
J-W. Ahn, J.M. Canik (ORNL)

Strike-Point Splitting Predicted…

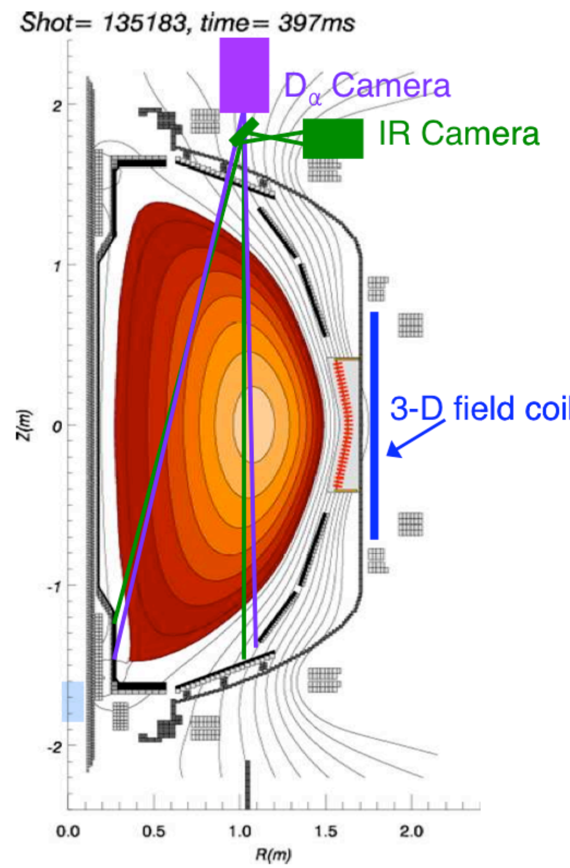
- Effects of axisymmetric fields (flux expansion) on divertor heat loading has been characterized in NSTX.[1,2]
- What happens when 3-D fields are applied?

[1] D. Gates et al, Phys. Plasmas **13**, 056112 (2006)
[2] V. Soukhanovskii, et al., "High flux expansion divertor studies in NSTX", 36th EPS Conference on Plasma Physics

Connection Length for Field Lines Launched From Divertor Floor



NSTX Diagnostics For Viewing This Splitting

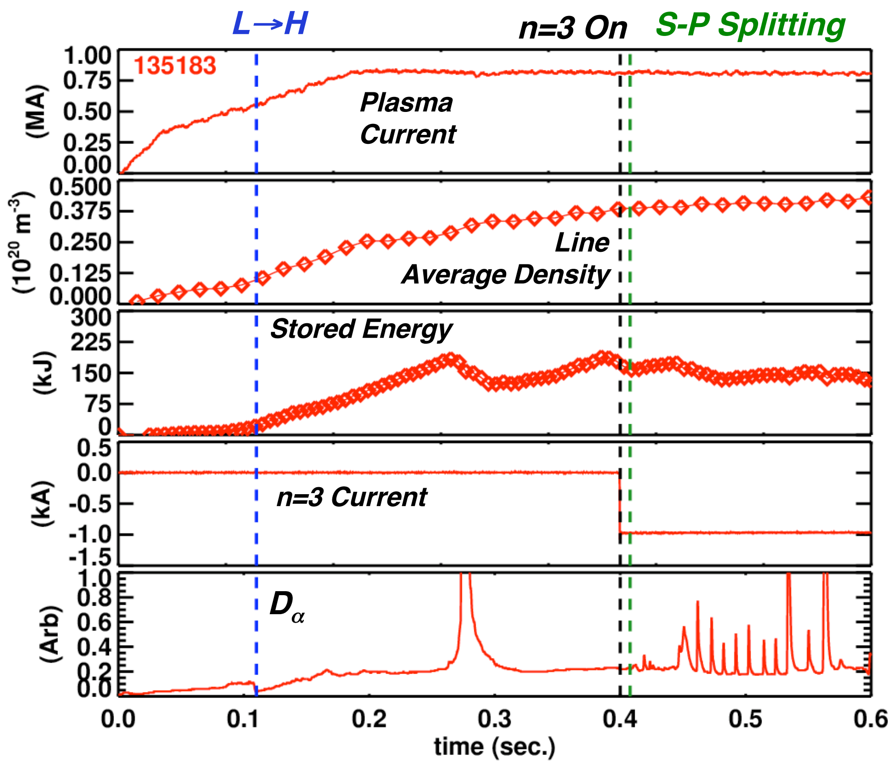


J-W. Ahn, J.M. Canik (ORNL)

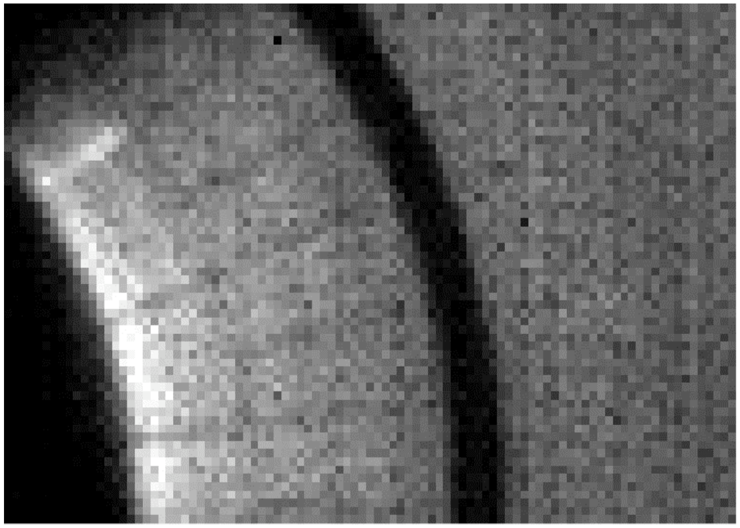
Strike-Point Splitting Predicted… …And Observed

- H-mode discharge with 4 MW NBI.
- Steady n=3 fields used to trigger ELMs.
- S-P. splitting clearly observed in period before ELMs.[1]

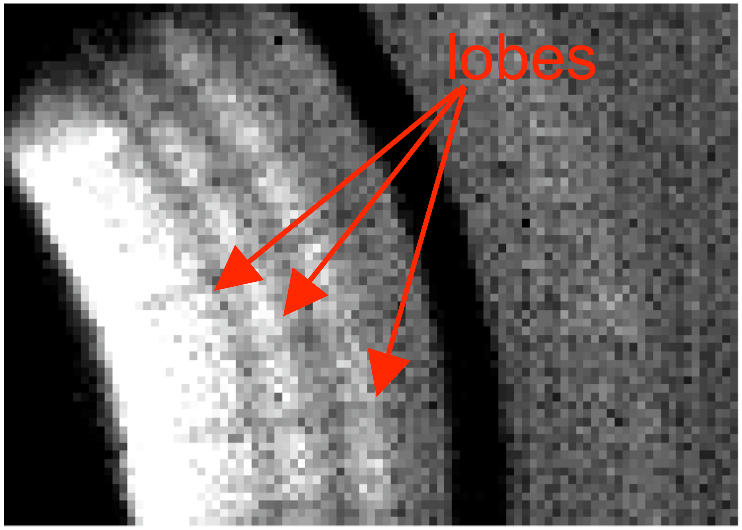
[1] J-W. Ahn et al, submitted to Nuclear Fusion (2009)



Before 3-D Field Application

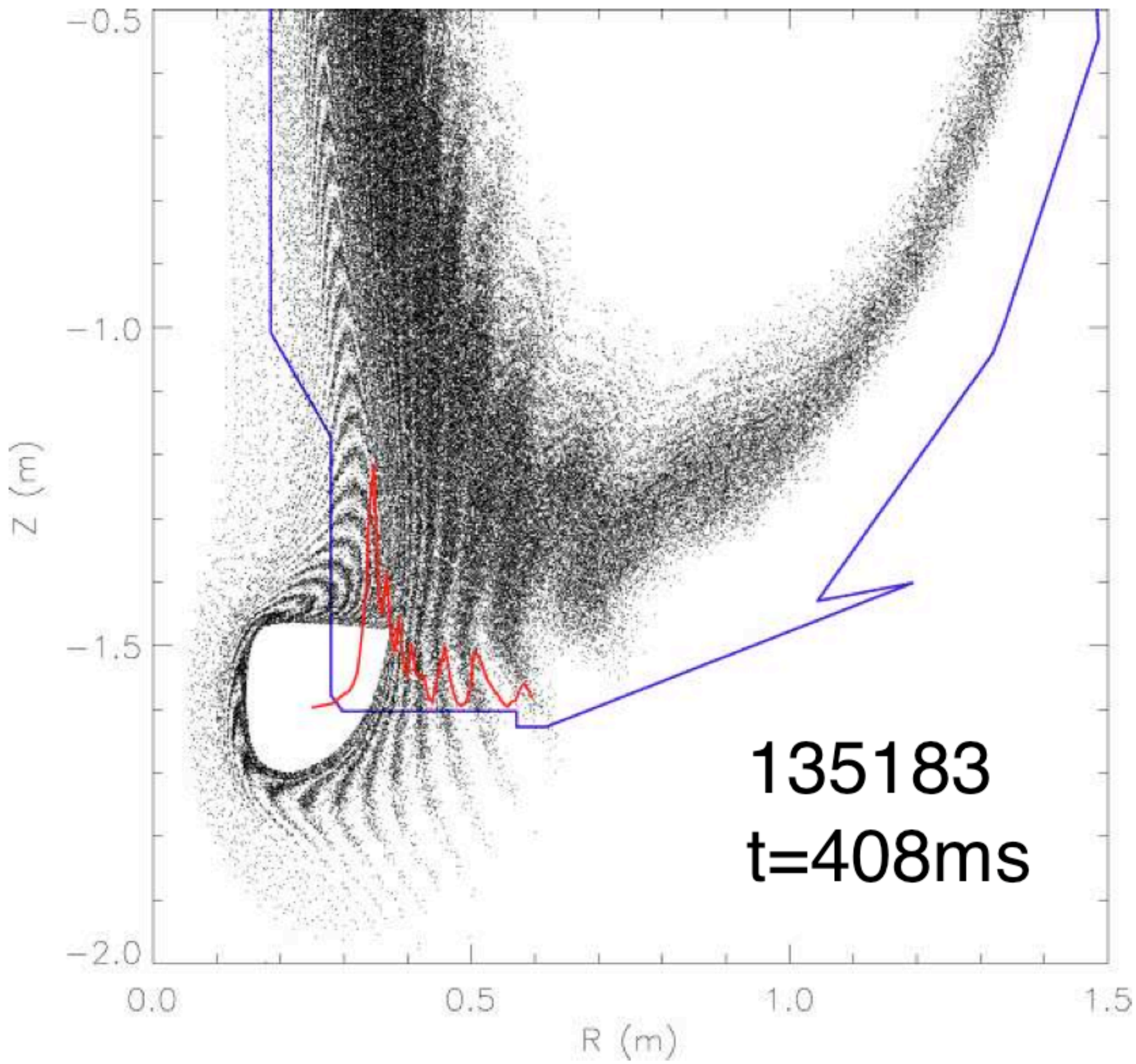


After 3-D Field Application



J-W. Ahn, J.M. Canik (ORNL)

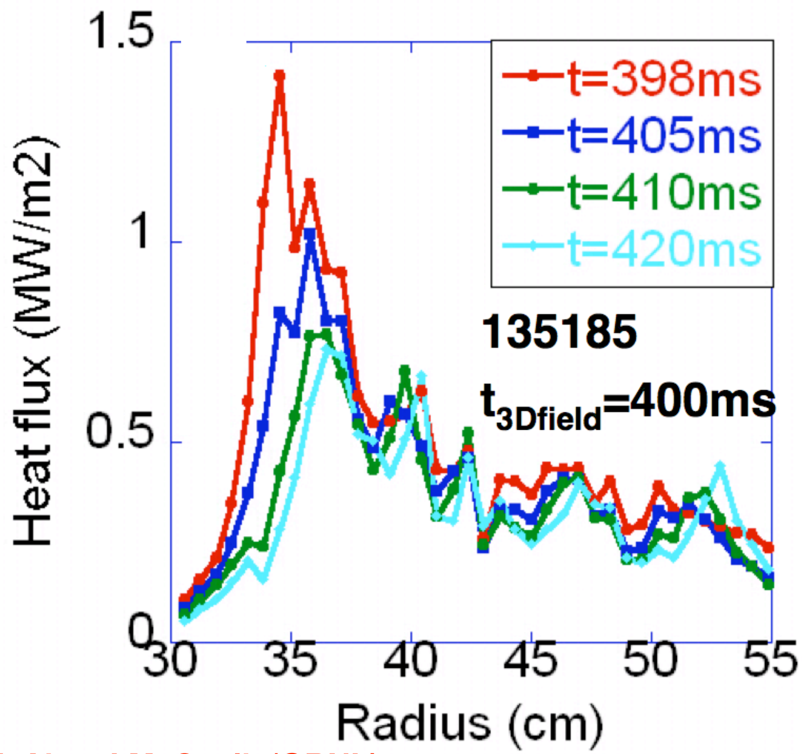
Heat Flux Profile Has Spatial Structure Similar to that From Vacuum Field Line Following



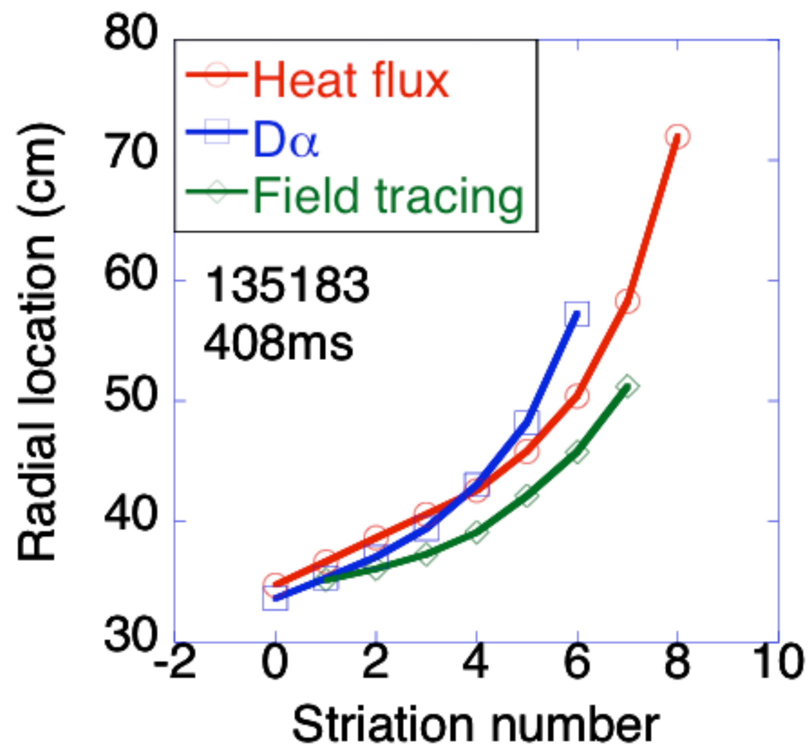
J-W. Ahn, J.M. Canik (ORNL)

Prompt Development of Lobes With 3-D Fields; Lobe Locations Consistent With Vacuum Modeling

- Development of lobe-structure.
- Rapid response after application of 3-D fields.
  - Time scale appears to be set by 3-D field penetration through vessel.
- Reduction of peak heat flux?



- Radial locations of D_α and heat flux lobes qualitatively consistent with vacuum modeling.
- Working on additional effects.
  - IPEC w/ various boundary truncations.
  - Intrinsic EFs



J-W. Ahn, J.M. Canik (ORNL)

Summary: 3-D Fields Can be Both Dangerous and Advantageous

- Error fields, coupled to the plasma response, can degrade performance.
  - Damp beneficial rotation.
  - Make plasma more susceptible to RWMs and NTMs.
  - Drive static islands.
  - All this makes the plasma more disruptive.
- 3-D fields can be useful tools for tokamak control needs.
  - Plasma response can be used to detect and correct slowly varying error fields.
  - NTV+non-resonant fields can drive rotation, or possibly tailor the rotation profile.
    - See papers by A. Garofalo, W. Solomon.
  - Beneficial modifications to the ELM characteristics.
    - Either suppression or triggering.
  - Modify divertor heat loading.
  - Deconfine disruption runaways.
    - See talk by Lehnen on Monday.

NSTX Research Forum is December 1st-3rd

Proposals for error field physics and control studies (and other MHD) are welcome.

See: http://nstx.pppl.gov/index.html

Backup

Summary

- Error fields can penetrate and disrupt a high-β plasma more easily than might be expected from the low-β density scaling.
- Plasma response can be used as a powerful tool for controlling error fields.
- Non-resonant error fields are present in NSTX, and can be corrected.
- Combined n=1 control and n=3 correction have dramatically improved NSTX long-pulse high-β reliability.
- Regime of enhanced NTV torque at low rotation, and $1/\upsilon$-like T_i dependence, have been observed.
- Applied 3-D fields can be used to trigger/pace ELMs.
- Modifications of divertor heat loading with 3-D fields has been observed.

NSTX Research Forum is December 1st-3rd

Proposals for error field physics and control studies are welcome.

See: http://nstx.pppl.gov/index.html

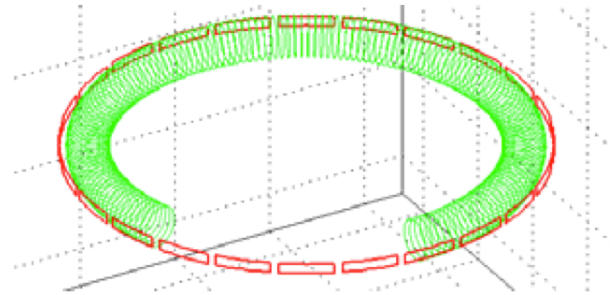
Example: Force Free Cylinder

$$\delta B = \delta B^X + \delta B^P$$

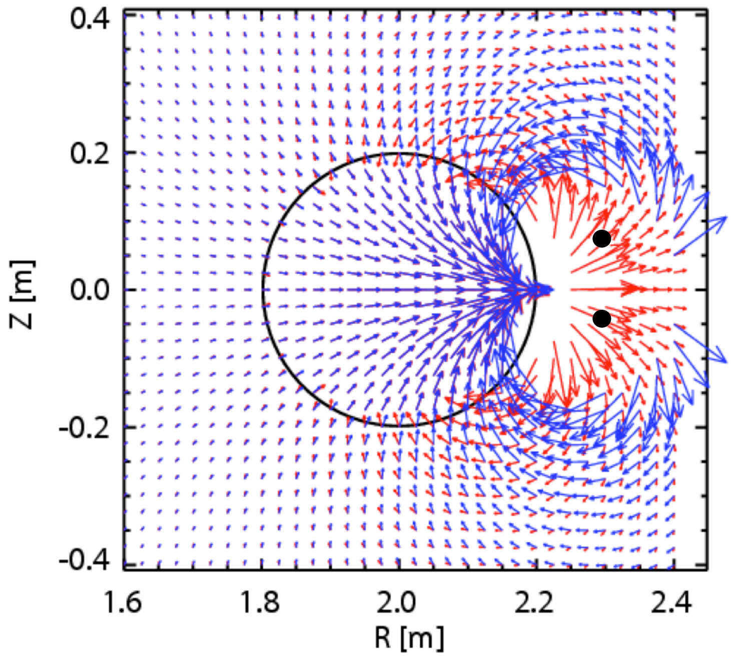
Total Perturbed Field

External Field

Plasma Response



Vacuum Fields

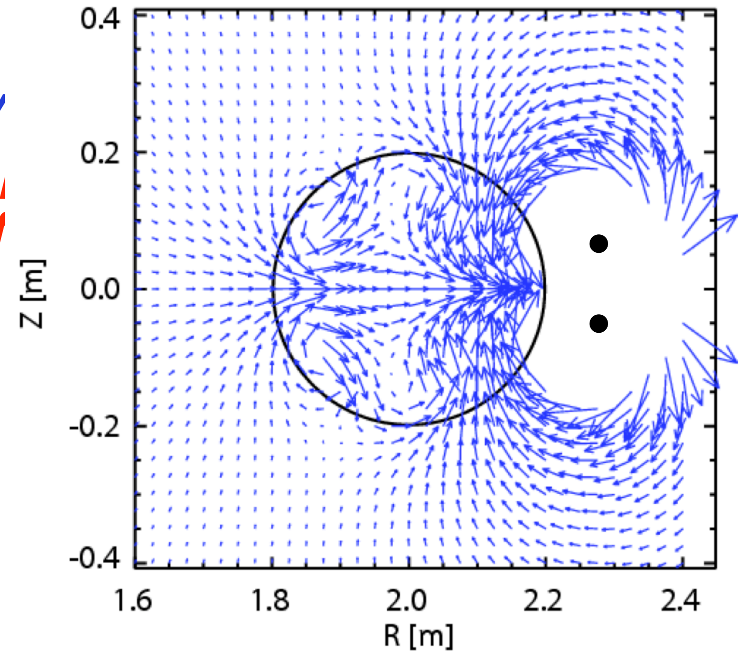


Actual v

Field in

to surf

Plasma + Vacuum



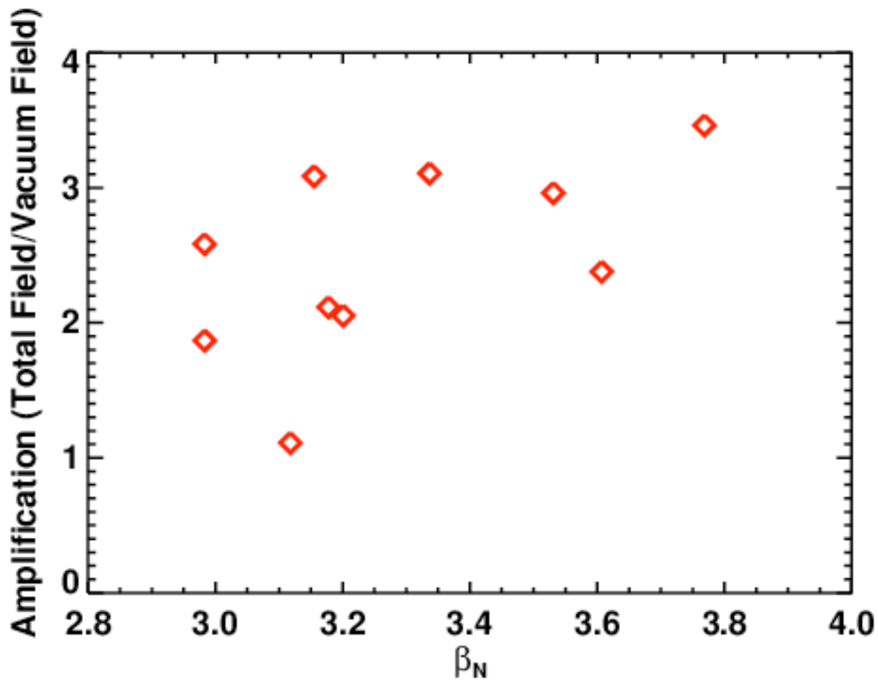
Continued Active Program in Error Field Physics

- RFA Suppression: Comparison of different sensor types for utility.
- Strike-Point splitting:
  - Role of q_{95}, toroidal mode number
  - Test of rotating perturbation for further heat flux mitigation.

NSTX Research Forum is December 1st-3rd

Proposals for error field physics and control studies are welcome

See: http://nstx.pppl.gov/index.html


Amplification (Total Field/Vacuum Field)
0
1
2
3
4
2.8
3.0
3.2
3.4
3.6
3.8
4.0
βN