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Error Field Impact on Mode Locking and Divertor Heat Flux in NSTX-U

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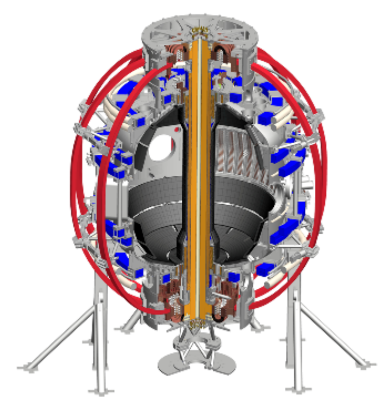

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Error Fields Impacted NSTX-U Performance in 2016

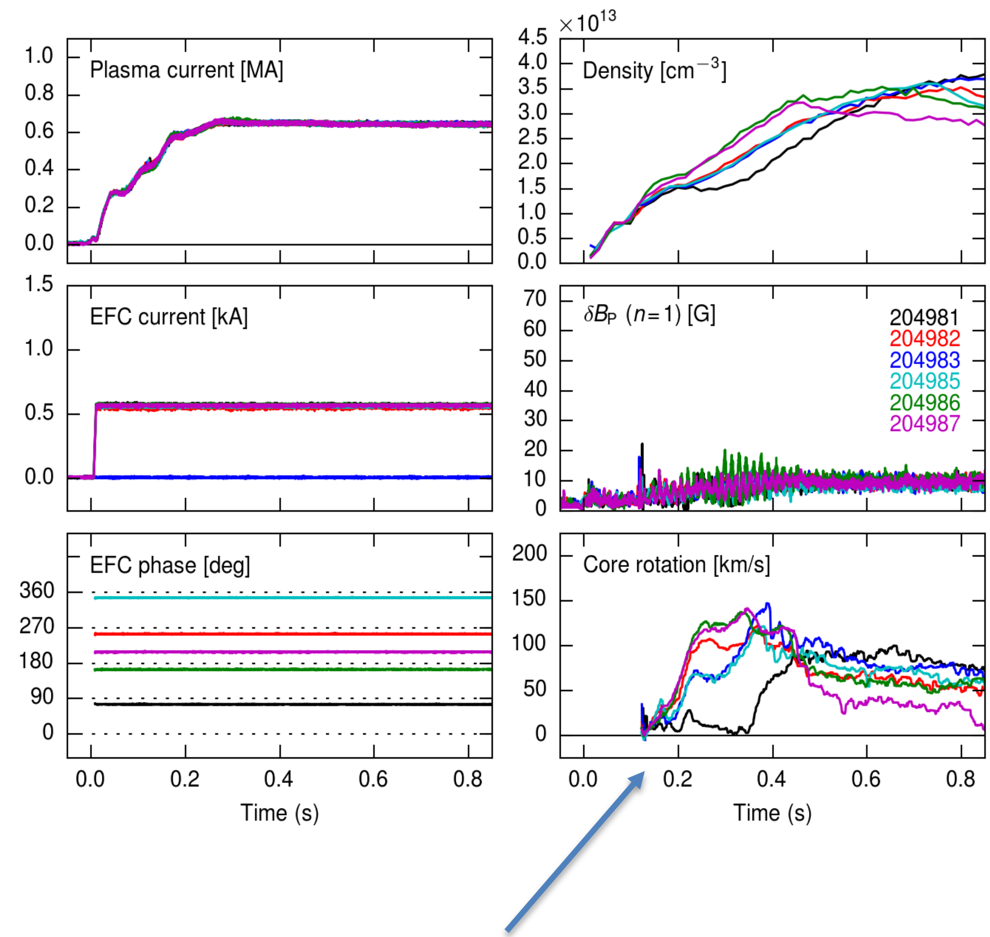
- Most NSTX-U L-modes were locked from q=2 outward
- Significant tearing mode activity could be a consequence of rotation braking from EFs
- Locked modes were not preventable or correctable with NSTX-U RMP coils
- Experiments reveal multi-mode, time-dependent sensitivity, making EFC very challenging
- Goal of this work is to identify sources of error fields and sensitivity of plasma, to help eliminate most deleterious error fields before NSTX-U resumes operation

Experiments Show Clear Evidence of Multi-Mode Sensitivity

- In single-mode model, one RMP coil row should be able to prevent or correct locked mode without causing additional locking
- However, q=2 mode could not be unlocked using RMP coils due to q=1 locking at large RMP amplitude
  - Shows multi-mode sensitivity
- Also, q=2 mode could not be prevented by RMP coils
  - Shows that error field is large
- Mode was unlocked by tangential beams, and healed by H-mode transition

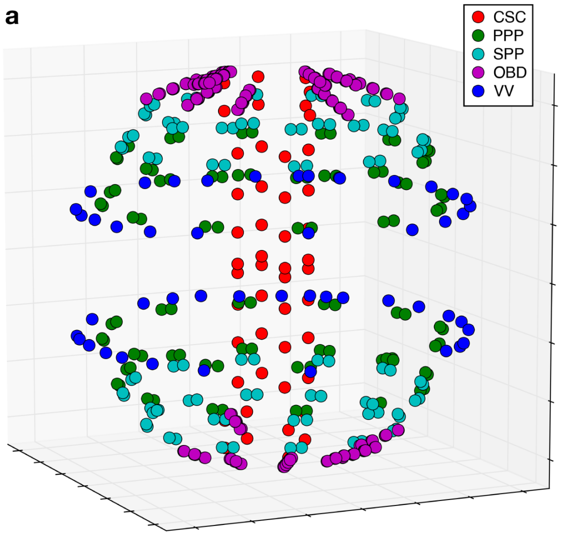
Optimal Error Field Correction Phase Found to Change in Time

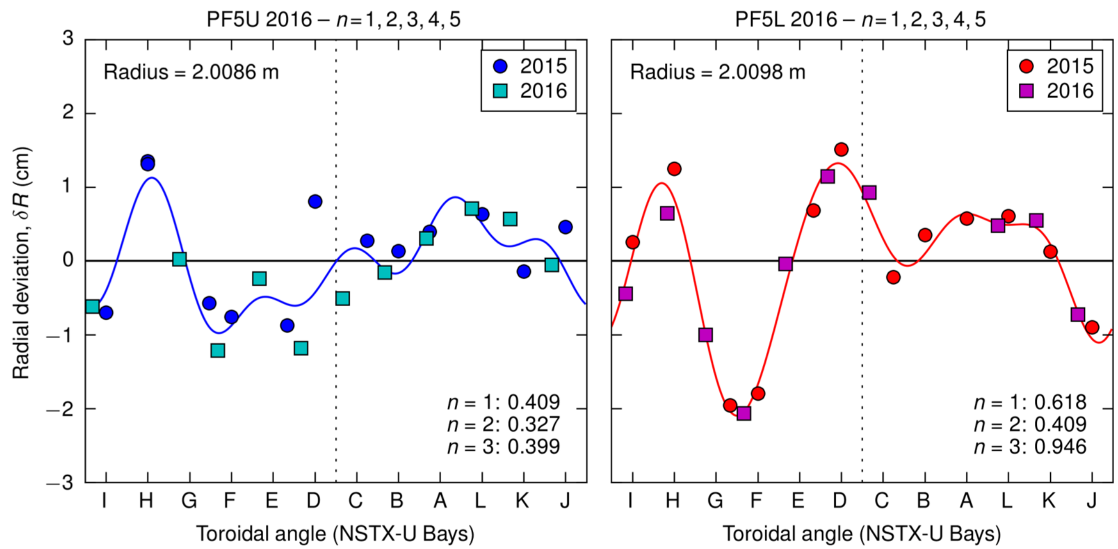
- The EFC phase that optimizes rotation and density early in shot does poorly later (and vice-versa)
- Change appears to occur after formation of q=1 surface (0.4 s)
- Experiments rule out change in OH current as source
- Would require time-dependent (or equilibrium-dependent) EFC algorithm



"Black" phase does poorly early, but well in flattop
"Purple" phase does well early, but poorly in flatto

Extensive Metrology Conducted After 2016 Campaign to Identify EF Sources





- Vessel measured using ROMER Arm
  - Show no changes relative to 2004 measurements
- PF5 measured relative to vessel
  - Show significant changes relative to 2004 measurements, due to removal of mechanical constraints to allow thermal expansion of coils
- TF center rod / CS casing measured using FARO laser tracker

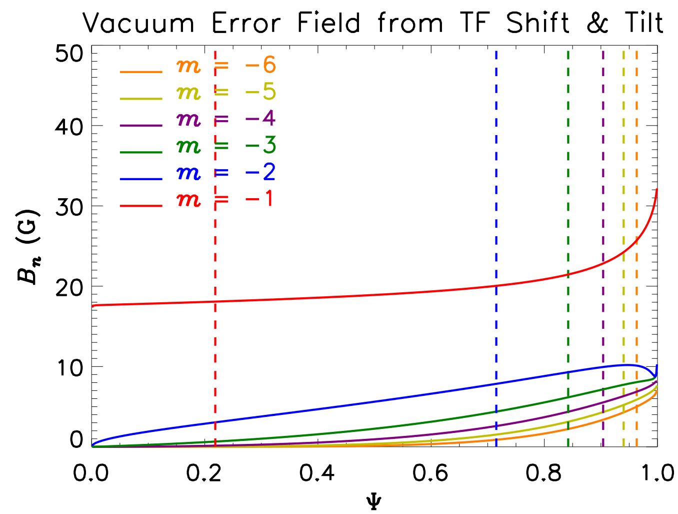
Error Field Models Constructed From Metrology Data

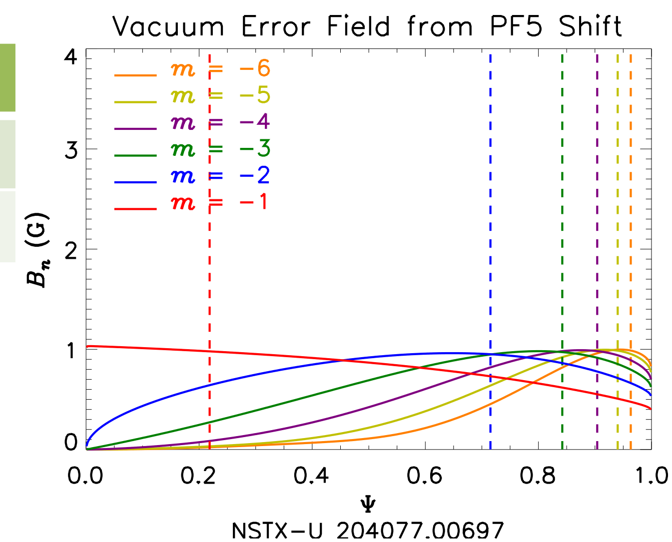
- n=1 error field calculated from measured shift / tilt of TF, PF5, and OH coils

- Several model scenarios and NSTX-U equilibrium reconstructions considered
  - Error fields proportional to coil currents, and therefore scenario-dependent.

Coil	$\delta R_{n=1}$	$\varphi_{n=1}$	$\delta R_{n=2}$	$\varphi_{n=2}$	$\delta R_{n=3}$	$\varphi_{n=3}$
PF5U	4.09 mm	121°	3.42 mm	113°	4.01 mm	323°
PF5L	6.19 mm	55°	4.09 mm	11°	9.45 mm	292°

	Shift	Shift Angle	Tilt	Tilt Angle
CS Casing	1.8 mm	242°	0.15 mrad	156°
TF Center Rod	4.9 mm	246°	1.15 mrad	206°





Effect of Error Fields on Plasma Calculated with M3D-C1 and IPEC/GPEC

- Given error field sources, perturbed equilibria calculated using M3D-C1 and IPEC/GPEC

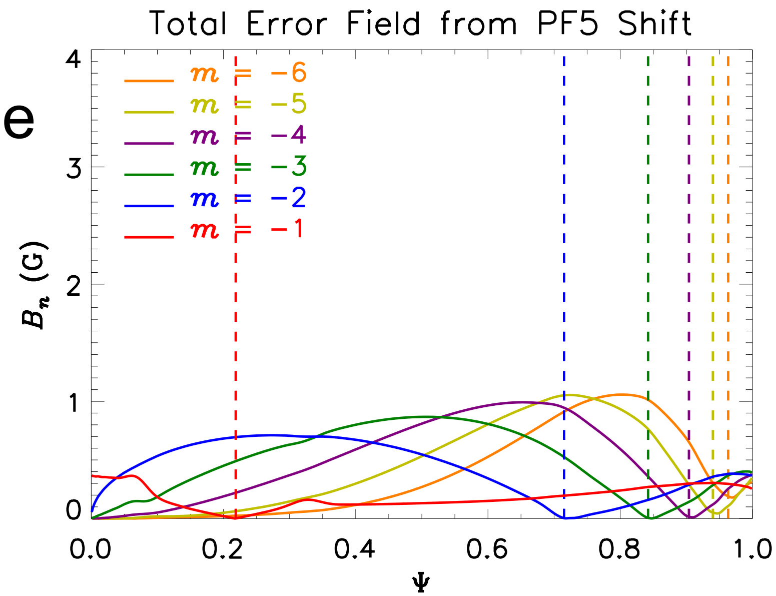
- M3D-C1 is an extended-MHD code that includes resistivity, viscosity, and anisotropic thermal conductivity

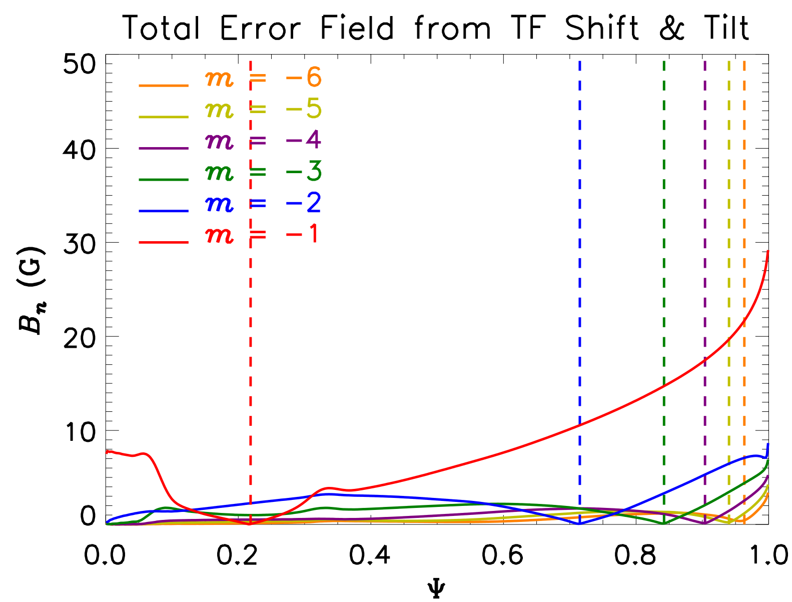
- IPEC / GPEC is an ideal-MHD code that optionally includes self-consistent kinetic effects (e.g. NTV)

- Linear, single-fluid models are used here for convenience

Total Resonant Fields

- Confinement and locking are strongly correlated with the total resonant field in the perturbed equilibrium
- TF misalignment is found to be dominant source of total resonant field, due to large current in TF
- TF error field is dominantly m/n = 1/1, consistent with finding of sensitivity to q=1 surface
- IPEC finds time-dependent plasma response and optimal EFC phase in agreement with experiment
  - Calculation fails when q=1 surface is present, complicating analysis





Neoclassical Toroidal Viscosity

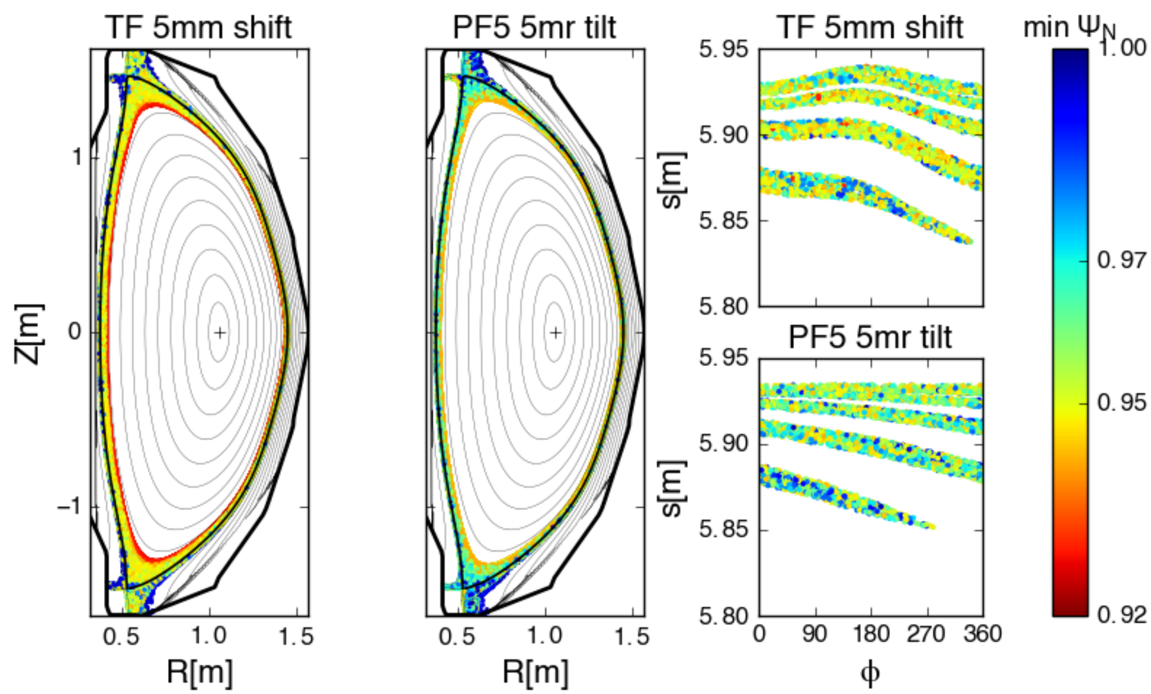
- Non-axisymmetric perturbations lead to braking of toroidal rotation
  - Can destabilize tearing modes & resistive wall modes
- Even when single-mode model applies, NTV cannot be fully corrected with single RMP coil
  - NTV is quadratic in δB and radially nonlocal
- GPEC calculations find NTV torques greater than 1 Nm in some cases
  - Each neutral beam source injects 1—2 Nm of torque
- NTV is very scenario-dependent and nonlinear (NTV torque depends on rotation profile); therefore we do not use NTV calculations to set tolerances

Field Line Pitch at Divertor Plates

- For high-power discharges, pitch angle must be shallow to handle heat flux
- Perturbations to pitch angle at strike points could cause localized hot spots
- Perturbations to pitch angle (including plasma response) calculated by M3D-C1
- The biggest perturbation to pitch angle are caused by misalignment of coils near the divertor (i.e. PF1, PF2) cause
- Plasma response does not strongly affect pitch angle
  - ”Vacuum” field analysis is usually good enough

Divertor Footprints

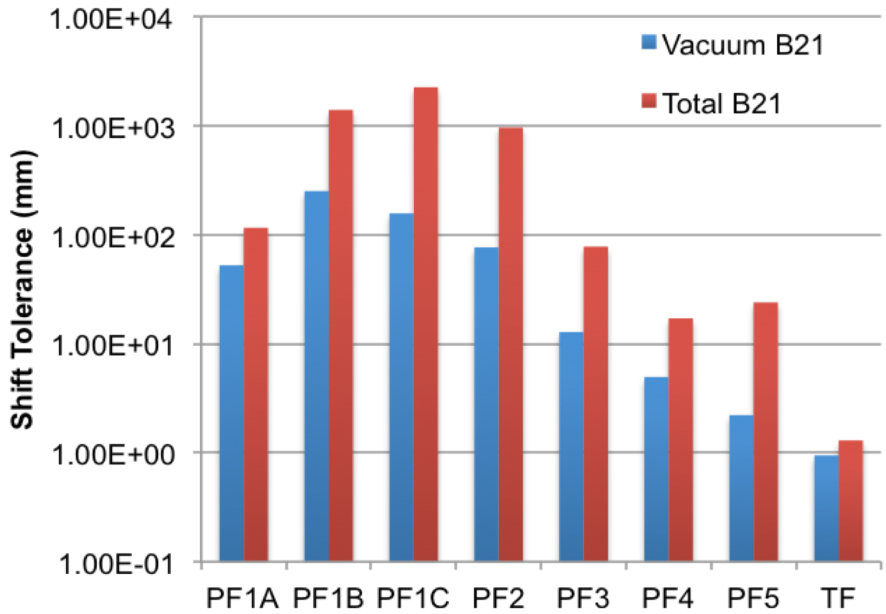
- TRIP3D calculates divertor footprint using perturbed equilibrium from M3D-C1

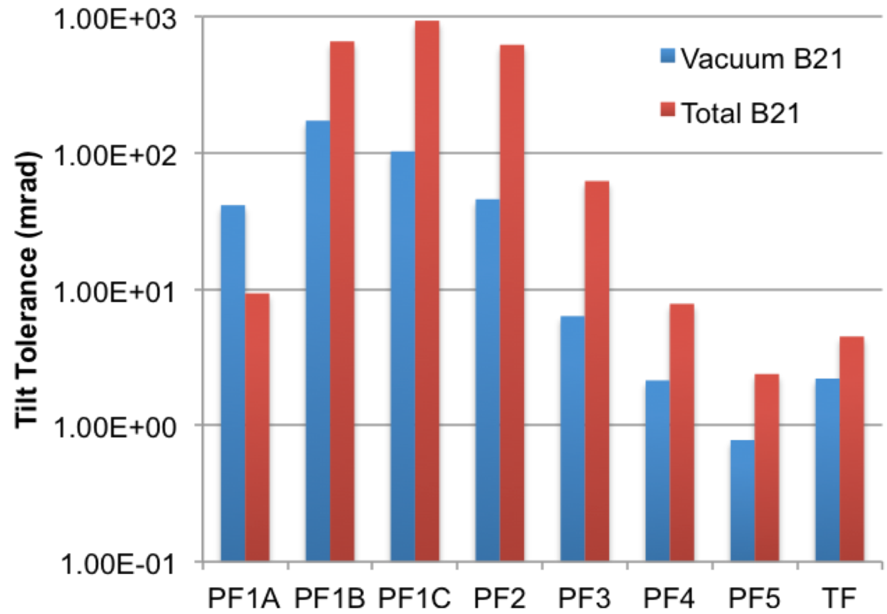


- Footprint area scales roughly linearly with error field

- Error fields that elicit strong plasma response (i.e. PF4, PF5 & TF) cause the biggest perturbation to the footprints

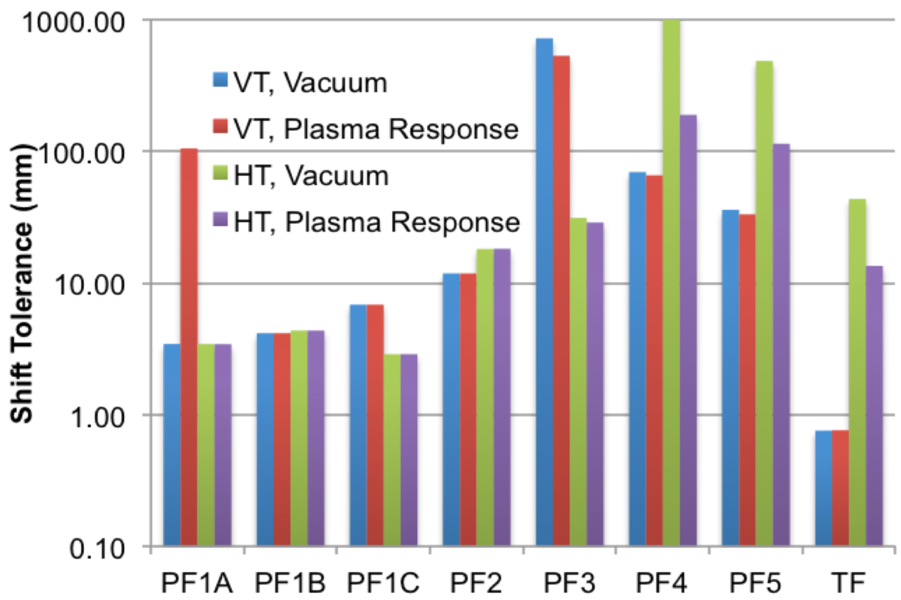
Alignment Tolerances Based on Total Resonant Field Criterion

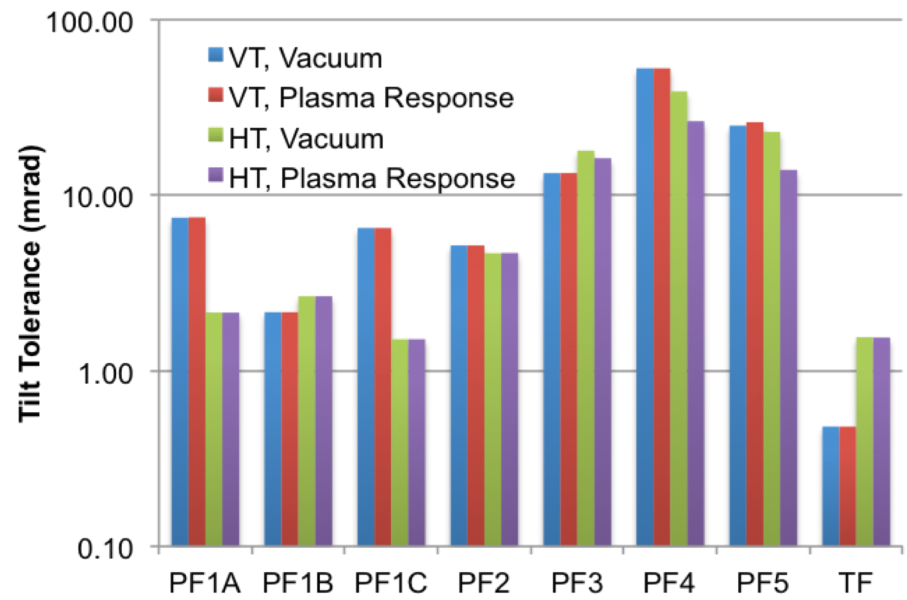




- Maximum shift or tilt of individual coil before total resonant field exceeds that produced by 1 kA-turn in RMP coil

Alignment Tolerances Based on Magnetic Pitch Angle Perturbation Criterion





- Maximum shift or tilt of individual coil before perturbation to magnetic pitch exceeds 10% of axisymmetric value

Summary

- Error fields (EFs) were found to affect performance of NSTX-U in 2016
- EF correction was challenging due to multi-mode, time-dependent plasma response
- Extensive metrology carried out to determine EF sources
- IPEC/GPEC and M3D-C1 modeling used to evaluate impact of Efs
- TF, PF5, and PF4 alignments found to have largest impact on resonant fields (braking / locking) and divertor footprints
- TF, PF1, and PF2 alignment found to have largest impact on magnetic pitch angle at divertors
- Modeling used to set engineering tolerances for magnets and PFCs