National Spherical Torus eXperiment Upgrade

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SUBJECT: Impact of Non-Axisymmetric Fields on PFC Heat Flux in NSTX-U
PART 1: Toroidal Field Rod Misalignment

1.1 Summary

The impact of non-axisymmetric fields on the heat flux to the plasma facing components is important to consider for the integrated design of the NSTX-U Recovery Project. This document examines the impact of misalignments of the NSTX-U TF bundle that was measured during the FY16 operations. Impacts on PFCs were computed by looking at M3D-C[1] predicted changes in the field line impact angle at the horizontal (IBDH) and vertical (IBDV) divertor surfaces. Vacuum field calculations showed an n=1 perturbation to the IBDV impact angle of ~ 0.43^{o} which were not significantly impacted when examining resistive MHD solutions. Vacuum field calculations showed an n=1 perturbation on the IBDH of < 0.10^{o} but showed up to a factor of three enhancement from the plasma response using M3D-C[1], but were sensitive to the details of the simulation.

Changes in the TF alignment motivated by reducing the impact on locked modes [REF] are expected to reduce this error field source by approximately a factor of three. This should make the impact on the IBDV and IBDH heat flux manageable, although perhaps not ignorable and thus important to confirm during commissioning. The total impact of error fields should be examined within context of other poloidal field coil misalignments which will be the focus of future MEMOs.

1.2 Equilibrium

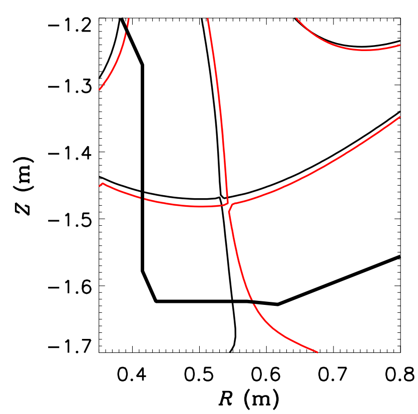

*Figure 1—The magnetic geometry in the lower divertor region in the original LRDFIT g-file (**black line**) and for the recalculated M3D-C1 equilibrium (**red line**).*

For this study, we have used the model equilibrium NSTX-U 115313.00851_NfHz0+_0. This is an H-mode equilibrium with IP=2 MA and BT=1 T. In order to get an accurate response calculation, M3D-C1 re-solves the Grad-Shafranov equation on its own computational meh using the coil currents, pressure, and toroidal field profiles specified in the g-file produced by LRDFIT. Because details of this calculation differ from the original LRDFIT calculation, including different methods for keeping the plasma correctly positioned and symmetry assumptions (M3D-C1 does not enforce up-down symmetry), the shape final M3D-C1 equilibrium can differ from the original LRDFIT equilibrium. This case, which features a significant flux expansion near the horizontal divertor target, is especially susceptible to shape differences. The shape of the M3D-C1 equilibrium and the original LRDFIT equilibrium near the lower divertor in this case is shown in Figure 1.

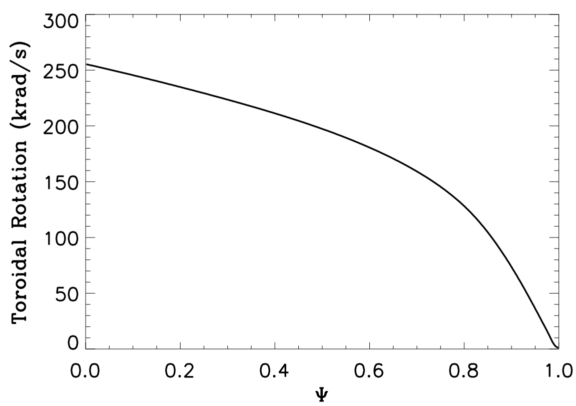

Figure 2—The equilibrium toroidal rotation profile assumed here.

Rotation plays a significant role in the plasma response calculated by the resistive MHD model. Therefore, an equilibrium rotation profile is included in this equilibrium. We assumed the toroidal ion rotation is proportional to the square-root of the pressure, with a central angular rotation frequency of approximately 250 krad/s (*c.f.* Figure 2). In the single-fluid model considered here, the ion, electron, and E×B rotation profiles are equivalent. Equilibrium poloidal rotation is not considered.

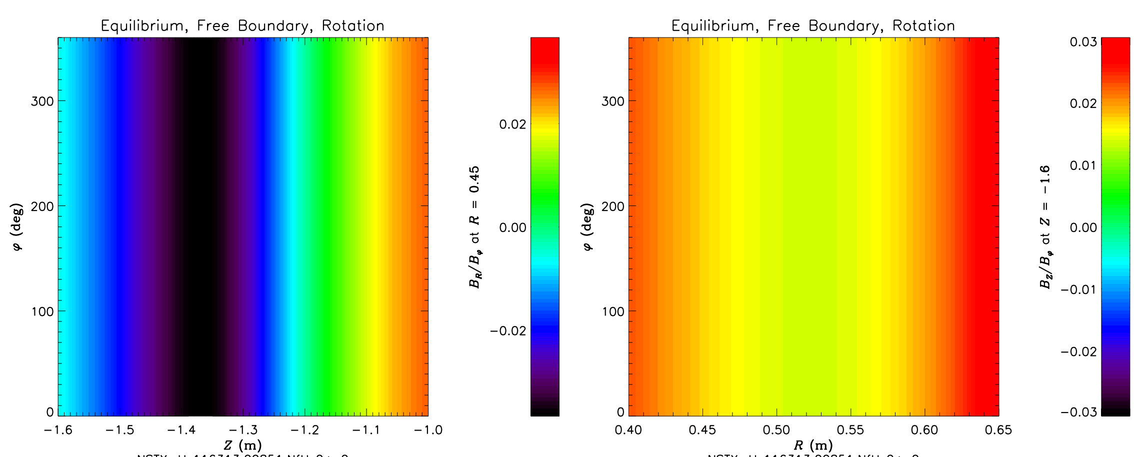

*Figure 3—**Equilibrium Field.** The equilibrium values of B_R/B_φ at $R = 0.45$ m (left) and B_Z/B_φ at $Z = -1.6$ m (right) for the model equilibrium NSTX-U 11613.00851_NfHz0+_0. The inner divertor leg*

passes through $R = 0.45$ at $Z = -1.477$ m, and the outer divertor leg passes through $Z = -1.6$ m at $R = 0.569$ m.

Heat flux to PFC surfaces, q_{SURF}, can be computed (see PFCR-MEMO-004) via $q_{SURF} = q_{\parallel}\,(\hat{B}\cdot\hat{n})$, where $\hat{n}$, is the surface normal. The impact of non-axisymmetric fields is assumed to not change the parallel heat flux but to change the local $(\hat{B}\cdot\hat{n})$. The values of B_R/B_φ at $R = 0.45$ m (left) and B_Z/B_φ at $Z = -1.6$ m for the (axisymmetric) equilibrium are plotted in Figure 3. Given that $B_\varphi \gg B_R, B_Z$, these values are approximately the pitch angle (in radians) at which the magnetic field strikes the inner vertical target and lower horizontal target, respectively.

1.3 Error Field from TF Rod Misalignment

The dominant source of error fields in NSTX-U during the FY16 campaign is believed to be due to misalignment of the TF coil [FMP 2017]. This assessment was based on metrology of the center stack and PF5 coils, as well as modeling using IPEC and M3D-C1. From the metrology data, it was inferred that the TF rod was tilted 1.15 mrad towards 206°, where 0° points East (between the C and D ports), and shifted horizontally 4.9 mm towards 246°.

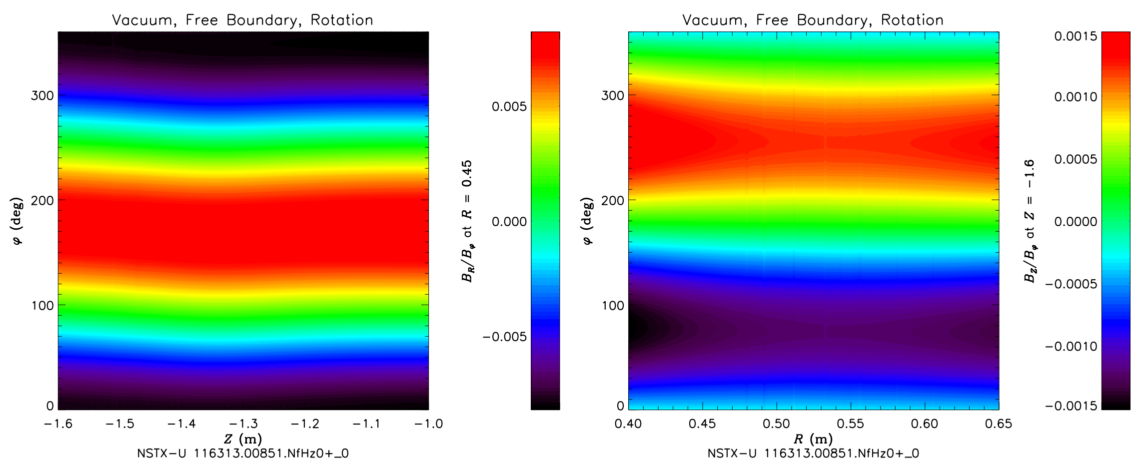

*Figure 4—**Vacuum Field.** The values of $\delta B_R/B_\varphi$ at $R = 0.45$ m (left) and $\delta B_Z/B_\varphi$ at $Z = -1.6$ m (right) for the model equilibrium NSTX-U 11613.00851_NfHz0+_0, from the TF error field model in the absence of plasma response (i.e. the vacuum field). The inner divertor leg passes through $R = 0.45$ at $Z = -1.477$ m, and the outer divertor leg passes through $Z = -1.6$ m at $R = 0.569$ m.*

The perturbation to the pitch angle at $R = 0.45$ m (left) and $\delta B_Z/B_\varphi$ at $Z = -1.6$ m due to the TF error field in the absence of the plasma response (*i.e.* the vacuum field) is shown in Figure 4. At $R = 0.45$ and $Z = -1.6$, the maximum perturbed pitch angle is roughly 7.5 mrad (0.43°) and 1.5 mrad (.09°), respectively.

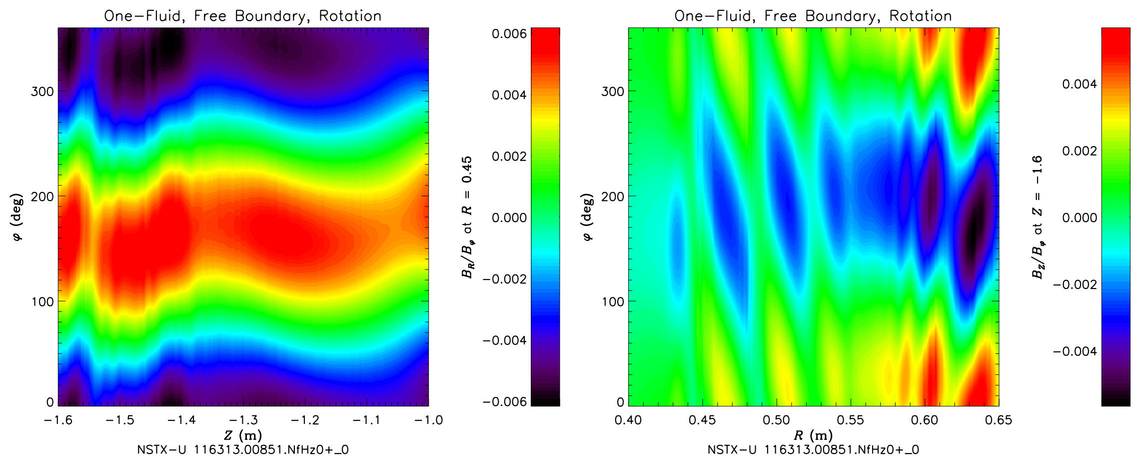

*Figure 5—**Total Field, Free-Boundary**. The values of $\delta B_R/B_\varphi$ at $R = 0.45$ m (left) and $\delta B_Z/B_\varphi$ at $Z = -1.6$ m (right) for the model equilibrium NSTX-U 11613.00851_NfHz0+_0, from the TF error field, including the plasma response. The inner divertor leg passes through $R = 0.45$ at $Z = -1.477$ m, and the outer divertor leg passes through $Z = -1.6$ m at $R = 0.569$ m.*

The plasma response currents alter the perturbed field. The total perturbed field (vacuum plus plasma response) calculated using the linear, one-fluid model in M3D-C1 [Ferraro 2012] with a "free" boundary is shown in Figure 5. By "free" boundary it is meant that the computational domain boundary, at which superconducting boundary conditions are applied ($\mathbf{B} \cdot \hat{\mathbf{n}} = \text{const.}$), is outside the poloidal field coils; this gives a good approximation to the true free-boundary solution. Here, the pitch angle at $\mathrm{R} = 0.45$ m is not significantly different from the vacuum case. However, the pitch angle at $\mathrm{Z} = -1.6$ m is seen to develop striations, with the maximum perturbation to the pitch angle increasing to roughly 5 mrad (0.29°). The toroidal phase of the pitch angle perturbation also shifts relative to the vacuum field by roughly 90°.

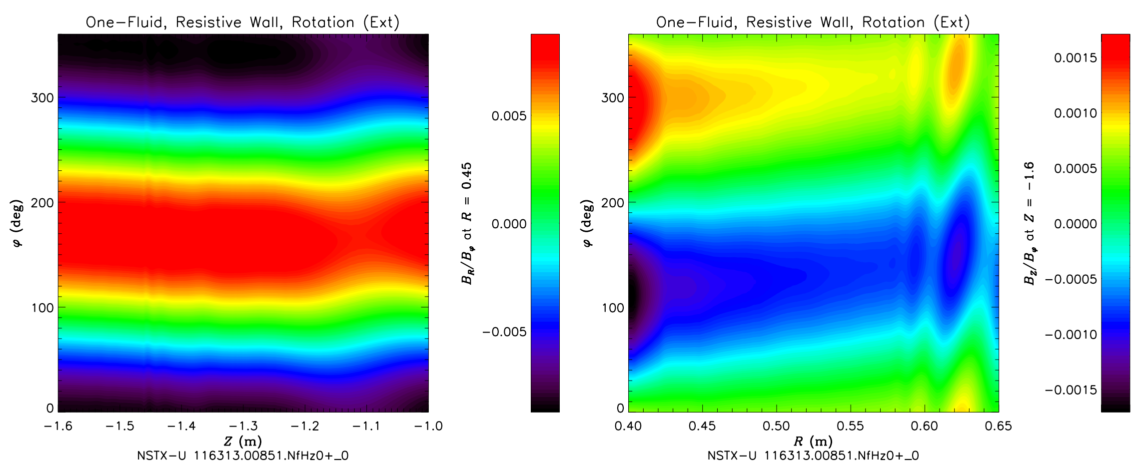

*Figure 6—**Total Field, Resistive Wall.** The values of $\delta B_R/B_\varphi$ at $R = 0.45$ m (left) and $\delta B_Z/B_\varphi$ at $Z = -1.6$ m (right) for the model equilibrium NSTX-U 11613.00851_NfHz0+_0, from the TF error field model, including the plasma response and the effect of a resistive wall. The inner divertor leg passes through $R = 0.45$ at $Z = -1.477$ m, and the outer divertor leg passes through $Z = -1.6$ m at $R = 0.569$ m.*

The free-boundary calculation may overestimate the plasma response by neglecting the fields due to eddy currents induced in surrounding conducting structures by the rotating plasma. Here we consider the effect of those currents by modeling the first wall as having resistivity $\eta_W = 1.9 \times 10^{-5}$ Ωm and thickness $d = 2$ cm. This implies a wall time of $\tau_W = \mu_0 da/2\eta_W = 0.6$ ms, choosing $a = 1$ m. As in the free-boundary case, the perturbed pitch angle at $\mathrm{R} = 0.45$ m is essentially unchanged from the vacuum field. However, the inclusion of the resistive wall causes the perturbed pitch angle at $\mathrm{Z} = -1.6$ to resemble the vacuum field more closely than the free-boundary calculation. With the resistive wall, the maximum perturbation to the pitch angle at $\mathrm{Z} = -1.6$ is roughly 1.5 mrad (the same as for the vacuum field), and the toroidal phase of the perturbation is smaller than in the free-boundary calculation.

1.4 Conclusions

We have analyzed the perturbation to the field line pitch angle due to a model of the NSTX-U TF rod misalignment in a high-beta model NSTX-U discharge. The perturbed pitch angle was calculated near the vertical ($\mathrm{R} = 0.45$ m) and horizontal ($\mathrm{Z} = -1.6$ m) divertor targets using a linear, single-fluid plasma response model with the M3D-C1 code.

It is found that the maximum perturbation to the pitch angle due to the error field alone (in the absence of plasma response) at $\mathrm{R} = 0.45$ and $\mathrm{Z} = -1.6$ is roughly 7.5 mrad (0.43°) and 1.5 mrad (.09°), respectively. The plasma response is generally found to increase the maximum perturbation to the pitch angle, especially at the horizontal target. However, when the effect of the resistive wall is included, the primary effect of the plasma response appears to be a toroidal phase shift of the perturbed field, with the maximum perturbed pitch angle remaining comparable to the vacuum field.

The TF error, while believed to be the largest error field in NSTX-U, is dominantly $m = 1$ and $n = 1$, and not strongly resonant with the plasma. This fact may contribute to the relative weakness of the plasma response in these calculations. We note, however, that in response calculations that did not include plasma rotation (not shown here), the perturbed fields due to the plasma response was found to exceed the vacuum field significantly. This is likely because the high-beta model equilibrium considered here is unstable in the absence of rotation, and therefore the large calculated response reflects the instability of the plasma [Lanctot 2010]. This does raise the concern that the plasma response may become quite large as the plasma approaches marginal stability.

1.5 References

[Ferraro 2012] Ferraro NM. *Phys. Plasmas* **19**, 056105 (2012)

[FMP 2017] Ferraro NM, Myers CE, Park J-K. "Assessment of error fields from TF Rod and PF5 in NSTX-U." PPPL Memo, (April 30, 2017)

[Lanctot 2010] Lanctot MJ, *et al.* *Phys. Plasmas* **17**, 030701 (2010)

Record of Changes

Rev.	Date	Description of Changes
0	10/20/2017	initial draft release to PFCR-WG
1	1/5/2018	added Record of Changes table