National Spherical Torus eXperiment Upgrade

Magnet and PFC Alignment Requirements Basis

NSTX-U-DOC-101-00

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Critical contributions from M. Reinke, N. Ferraro, J.-K. Park, C. Myers, W. Guttenfelder, M. Mardenfeld, and A. Brooks are acknowledged.

Executive Summary

This memo addresses the physics considerations that drive the PFC and coil alignment tolerances, and makes recommendations for the tolerances based on those considerations.

PFC heat flux asymmetries are driven by small field perturbations, due to tilts, shifts, and elliptical distortions of the coils. An excel-based tool has been developed to understand these effects. The coil perturbations that drive these heat flux enhancements are assessed on a per-region basis, to determine the coil perturbations that are most impactful for each region. This information is used in Monte-Carlo analysis to determine the recommended envelope of coil perturbations, relative to the divertor target surface. These are provided in Section 2.3.

Global disruptive behavior is mostly closely tied to the alignments of the outer PF coils relative to each other, and those coils relative to the TF inner bundle. The effect of misalignments is studied with the codes M3D-C1 and IPEC. L-mode scenarios, and H-mode equilibria with β_N values up to 5.5, are considered. The effects of tilts and shifts is studied, from the view of both the resonant error field and the non-resonant breaking torque. Four physics criteria for determining the allowed level of error field effects, based on limiting error fields, limiting NTV torques, and limiting the required error correction current. These criteria & code data are used in the context of physics and operational goals to determine requirements for the global alignments. These are provided in Section 3.3.6.

References

[1] NSTX-U-RQMT-GRD-001, NSTX-U General Requirements Document
[2] NSTX-U-RQMT-SRD-002, System Requirements Document - Magnets
[3] NSTX-U-RQMT-SRD-003, System Requirements Document - Plasma Facing Components
[4] NSTX-U-RQMT-SRD-004, System Requirements Document - Vacuum Vessel and Internal Hardware
[5] NSTX-U Design Point Spreadsheet, available at this link.
[6] *PFC Engineering Loads and BC*, talk by Art Brooks at High Heat Flux Tile PDR.
[7] NSTXU-CALC-11-09-00, *Field Errors and Heat Flux Enhancements*
[8] PFCR-MEMO-006, "Impact of Non-Axisymmetric Fields on PFC Heat Flux in NSTX-U, PART 1: Toroidal Field Rod Misalignment", available at this link
[9] Milestone R17-3 Report, within NSTX-U FY-17 annual report.
[10] *Summary of Coil and Vessel Metrology in Support of Error Field Correction*, Clayton Myers, presented at the September 20, 2017 Dimensional Control Meeting.
[11] INT-180117-JKP-01, Response to additional questions on coil alignment and error field correction plans, by Jong-Kyu Park

1: Overview

There are two primary physics consequences of system misalignments in NSTX-U, as indicated in table 1-1:

Table 1-1*: Consequences of Error Fields on NSTX-U physics and operations*

Consequence	Explanation	Key drivers	Mitigating Capabilities During Operations
Enhanced PFC heat fluxes	Small field perturbations lead to changes in the incident field line angle. This creates toroidal variation in the peak heat flux (i.e. locally changing $\widehat{B} \cdot \widehat{n}$) as manifest by the enhancement factors	Alignment of TF inner legs, divertor coils with the surfaces of the divertor tiles	strike point sweeping, enhanced radiation
Global MHD Effects	Field inhomogeneity in the toroidal direction results in strong damping of the plasma flow. This can be due to both non-resonant effects (NTV) and resonant effects (torque due to shielding currents at resonant surfaces). In either case, the reduced plasma flow velocity has negative consequences for stability and confinement, reduces operational space, and increases the likelihood of disruption	Alignment of TF inner legs with the outer-PF coils Alignment between the upper and lower outer PF coils.	Error field correction via RWM coils

This memo will contain some recommendations on tolerances, based on trade-off as seen by the author. Rationale will be spelled out as best possible. This document recommends specific tolerances that augment the requirements to be found in Refs. [1-4].

Additional considerations involve pure mechanical fit-up and coil EM loads due to deviations from axisymmetry. These are not addressed in the present study.

Summary information is provided in Sections 2.3 and 3.3.6.

2: Positional Alignment between PFCs and the Coils

2.0 Assumptions

Full PF current capabilities are provided in the Design Point Spreadsheet [5]. The currents that can run in the coils for the full 5 second shot are:

PF-1a : 11.5 kA[1]
PF-1b : 8.2 kA
PF-1c : 10.0 kA
PF-2: 16 kA
TF : 130 kA

These currents are used in all calculations presented below for the calculation of perturbed fields. For the OH, a current of 10 kA is assumed. Note that these choices of PF coils are conservative, in the sense that no actual equilibrium scenario uses all these coils at full current simultaneously, especially for the full five second duration. Note also that the background equilibrium poloidal field is set by the incident field line angle input within the calculation method, and is not consistent with the currents noted above.

The target goal is to keep heat fluxes, with all geometric enhancements, beneath 8 MW/m^2. As shown in Fig. 2.0-1, this heat flux, when applied uniformly over the surface, results in nominally reaching the 1600 degC [6]. This value (1600 degC) is the defined temperature limit for the wetted surface area of the graphite tiles [3]. Note that this is conservative, in that heat diffusion into unwetted areas of the tile, which will arise from 'fish-scaling' at small angles of incidence, are not considered in this simple analysis.

All heat flux calculations are based on the file "Field Error Calc r3.xlsx", by Art Brooks, provided in email to the memo author on December 13th, 2017. This calculation is documented in Ref. [7].

For all calculations included here, the maximum field line angles and tile tolerances are as per Table 2.0-1, where Figure 2.0-2 provides a graphical explanation of some table entries. These tolerances dictate the fish-scale angle which is partially responsible for lowering the effective axisymmetric heat flux such that the peak remains below the 8 MW/m^2 limit. Note that changes in either the tile tolerances or maximum field line angles may result in changes to the sensitivity of the heat loads to coil displacements.

[1] This number is based on a 2.1 s ESW duration.

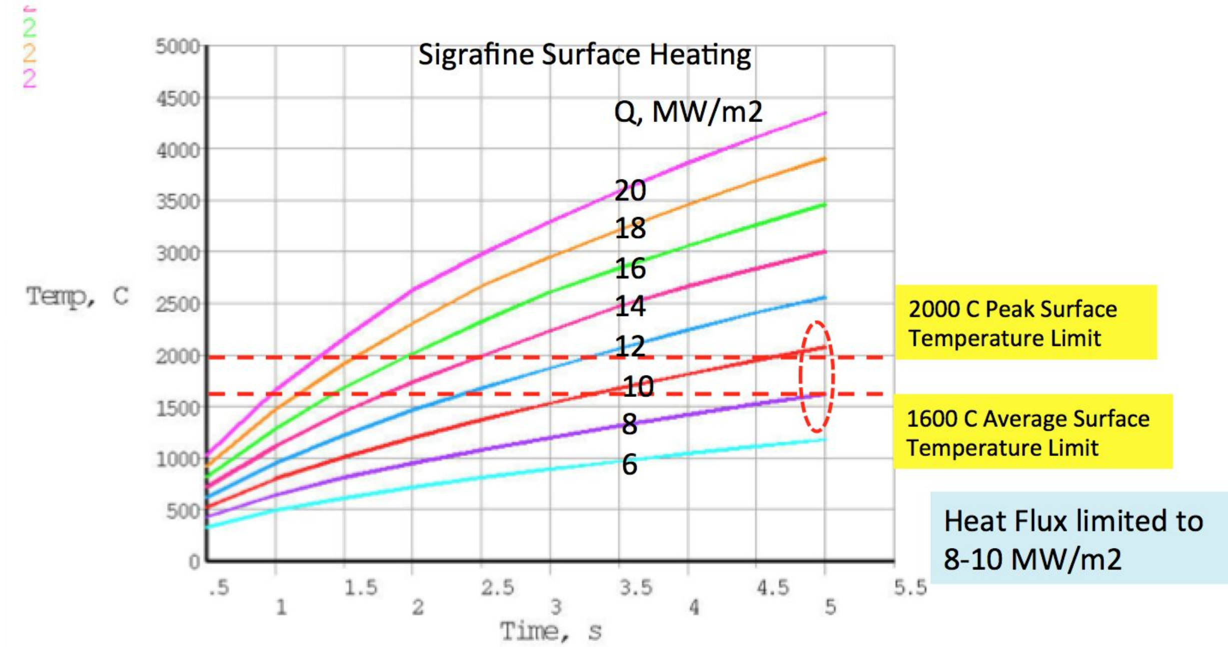


Figure 2.0-1*: Surface temperature as a function of time, for various heat flux values, under a 1D assumption. This figure is from Ref. 6, and uses the thermal conductivity of a specific material.*

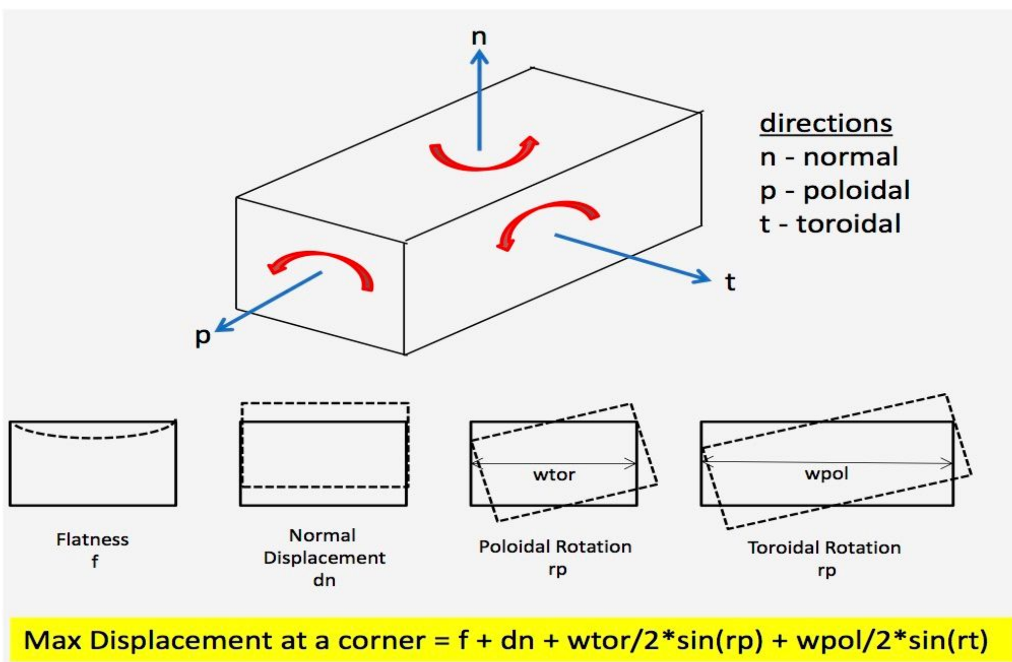


Figure 2.0-2*: Definitions of geometric quantities in Table 2.0-1.*

Horizontal Target	**Normal Displacement Tol**	**in**	**0.005**	**mm**	**0.1**

	assumed toroidal width	in	5.000	mm	127.0
	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.007	mm	0.2
	Maximum Field Line Angle	deg	5.000	mrad	87.3
	Poloidal Rotation Tol.	**deg**	**0.011**	**mrad**	**0.2**
	Toroidal Rotation Tol.	**deg**	**0.009**	**mrad**	**0.2**
	Fishscale Angle	deg	0.223	mrad	3.9
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**
Vertical Target	**Normal Displacement Tol**	**in**	**0.010**	**mm**	**0.3**
	assumed toroidal width	in	4.123	mm	104.7
	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.012	mm	0.3
	Maximum Field Line Angle	deg	5.500	mm	139.7
	Poloidal Rotation Tol.	**deg**	**0.014**	**mrad**	**0.2**
	Toroidal Rotation Tol.	**deg**	**0.014**	**mrad**	**0.2**
	Fishscale Angle	deg	0.416	mrad	7.3
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**
OBDR1	**Normal Displacement Tol**	**in**	**0.010**	**mm**	**0.3**
	assumed toroidal width	in	3.453	mm	87.7
	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.012	mm	0.3
	Maximum Field Line Angle	deg	5.000	mrad	87.3
	Poloidal Rotation Tol.	**deg**	**0.017**	**mrad**	**0.3**
	Toroidal Rotation Tol.	**deg**	**0.010**	**mrad**	**0.2**
	Fishscale Angle	deg	0.488	mrad	8.5
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**

Table 2.0-1*: Assumptions on tolerances and maximum field line angles used in Sections 2.1 and 2.2, resulting in design fish-scale angles. This will be referred to as Tile Tolerance Set #1. See Ref. 7 for an explanation of these parameters.*

Calculations done here assume vacuum field variation. Studies with M3D-C1 [8] have demonstrated that the plasma response can amplify the impact angle perturbation, up to a factor of three in the case of high poloidal flux expansion, and result in strike point splitting. A more accurate calculation should be considered if TF tilts of > 1 mrad are considered. Note that this is the TF relative to the PFCs, while the effect on the core plasma MHD is connected to the alignment of the TF relative to the outer PF coils.

2.1: Single Coil Positional Sensitivities

This section describes sensitivity of the heat loading to specific coil perturbations.

In the tables below in this section, there are a series of heat fluxes noted, as specified in Table 2.1-1. In this table, “Coil Perturbation” can refer to either shifts or tilts of coils.

Quantity	Definition	Dependences Relative to Nominal
Nominal	The nominal perpendicular heat flux	---
Fishscale Only	The enhancement on the perpendicular heat flux due to fish-scaling.	Fishscale Angle
Fishscale+Field Error	The enhancement on the perpendicular heat flux due to fish-scaling and field errors.	Fishscale Angle, Coil Perturbations
Fishscale + Surface Norm Deviation	The enhancement on the perpendicular heat flux due to fish-scaling and tile rotational variations	Fishscale Angle, Tile Perturbations
Fishscale+Field Error+ Surface Norm Deviation	The enhancement on the perpendicular heat flux due to fish-scaling, error fields, and tile rotational variations	Fishscale Angle, Coil Perturbations, Tile Perturbations

***Table 2.1-1**: Different definitions of heat flux used in this section*

The tables also use a “sensitivity”, as defined by the equation:

sensitivity=(“*Fish-scaling Only” - “Fish-scaling+Field Error”) / (shift or tilt magnitude)*

Hence, it attempts to measure the extent to which the error field increase the heat load compared to the baseline fish-scaled case.

2.1.1 TF Tilt and Shift Sensitivity

Here, study the effect of tilting and shifting of the TF bundle only. The nominal heat flux is selected in each case to give fully enhanced heat flux of 8 MW/m^2, i.e., the maximum value that can be sustained for 5 seconds before reaching 1600 C.

TF Coil Shift Sensitivity Study		
TF Current	kA	130
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	5.6
Fishscaling Only	MW/m^2	6.8
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	6.8
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.4
Impingement Angle	degrees	4
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	7.3
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.3
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.2
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.0
Fishscaling Only	MW/m^2	7.4
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.5
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	6.2
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1

TF Coil Tilt Sensitivity Study		
TF Current	kA	130
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.4
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.2
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.6
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.7
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.7
Impingement Angle	degrees	4
Nominal	MW/m^2	7.0
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.4
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0

***Table 2.1.1-1**: Tilt and shift sensitivity for the TF inner legs*

2.1.2: PF-1a Tilt and Shift Study

PF-1a tilt and shift sensitivities are provided in Table 2.1.2-1.

PF-1a Coil Shift Sensitivity Study		
PF-1a Current	kA	12
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.1
Fishscaling Only	MW/m^2	7.5
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.5
Fiscaling + Field Error + Surf Norm	MW/m^2	8.1
Field Error Sensitivity ->		0.2
Impingement Angle	degrees	2
Nominal	MW/m^2	6.9
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.7
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.6
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.7
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	4
Nominal	MW/m^2	7.0
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.1
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.2
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0

PF-1a Coil Tilt Sensitivity Study		
PF-1a Current	kA	12
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0

***Table 2.1.2-1**: Tilt and shift sensitivity for the PF-1a coil*

2.1.3: OH Coil Tilt and Shift Study

OH coil tilt and shift sensitivities are provided in Table 2.1.3-1.

OH Coil Shift Sensitivity Study		
OH Current	kA	12
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.2
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.8
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0

OH Coil Tilt Sensitivity Study		
OH Current	kA	12
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0

Table 2.1.3-1: *Tilt and shift sensitivity for the OH coil.*

2.1.4: PF-1b Coil Tilt and Shift Study

PF-1b tilt and shift sensitivities are provided in Table 2.1.4-1.

PF-1b Coil Shift Sensitivity Study		
PF-1b Current	kA	8.2
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0

PF-1b Coil Tilt Sensitivity Study		
PF-1b Current	kA	8.2
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.8
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0

Table 2.1.4-1: *Tilt and shift sensitivity for the PF-1b coil*

2.1.5: PF-1c Coil Tilt and Shift Study

PF-1c tilt and shift sensitivities are provided in Table 2.1.5-1.

PF-1c Coil Shift Sensitivity Study		
PF-1c Current	kA	10
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.1
Fishscaling Only	MW/m^2	7.5
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.5
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.2
Impingement Angle	degrees	2
Nominal	MW/m^2	6.9
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.7
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	6.3
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0

PF-1c Coil Tilt Sensitivity Study		
PF-1c Current	kA	10
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.2
Fishscaling Only	MW/m^2	7.7
Fishcaling + Field Error	MW/m^2	7.8
Fishcaling + Surf Norm Deviation	MW/m^2	7.8
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0

Table 2.1.5-1*: Tilt and shift sensitivity for the PF-1c coil.*

2.1.6: PF-2 Coil Tilt and Shift Study

PF-2 tilt and shift sensitivities are provided in Table 2.1.6-1.

PF-2 Coil Shift Sensitivity Study		
PF-2 Current	kA	16
shift	mm	3
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.0
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.5
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	4.9
Fishscaling Only	MW/m^2	7.3
Fishcaling + Field Error	MW/m^2	7.8
Fishcaling + Surf Norm Deviation	MW/m^2	7.4
Fiscaling + Field Error + Surf Norm	MW/m^2	7.9
Field Error Sensitivity ->		0.2
Impingement Angle	degrees	2
Nominal	MW/m^2	6.1
Fishscaling Only	MW/m^2	7.6
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.6
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1

PF-2 Coil Tilt Sensitivity Study		
PF-2 Current	kA	16
tilt	mrad	0.52
Horizontal Target, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	7.8
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	7.1
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	7.9
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Vertical Target, Central Row, Max Field Line Angle of 5.5 degrees		
Impingement Angle	degrees	2
Nominal	MW/m^2	6.6
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
Impingement Angle	degrees	4
Nominal	MW/m^2	7.2
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.0
OBDR1, Max Field Line Angle of 5 degrees		
Impingement Angle	degrees	1
Nominal	MW/m^2	5.3
Fishscaling Only	MW/m^2	7.9
Fishcaling + Field Error	MW/m^2	7.9
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1
Impingement Angle	degrees	2
Nominal	MW/m^2	6.4
Fishscaling Only	MW/m^2	8.0
Fishcaling + Field Error	MW/m^2	8.0
Fishcaling + Surf Norm Deviation	MW/m^2	8.0
Fiscaling + Field Error + Surf Norm	MW/m^2	8.0
Field Error Sensitivity ->		0.1

Table 2.1.6-1: *Tilt and shift sensitivity for the PF-1c coil.*

2.1.7: Summary of Sensitivities

These results are summarized in Table 2.1.7-1, where sensitivities are provided for all relevant coils, for both small shifts and tilts.

Table 2.1.7-1: *Sensitivities of various regions to shifts and tilts of coils*

Region	Impingement Angle degrees	Coil	Shift Sensitivity MW/m2 / mm	Tilt Sensitivity MW/m2 / mrad
IBDH	1	TF	0.00	0.36
		PF-1a	0.18	0.00
		PF-1b	0.06	0.04
		PF-1c	0.16	0.08
		PF-2	0.01	0.08
		OH	0.06	0.13
	2	TF	0.00	0.20
		PF-1a	0.10	0.00
		PF-1b	0.03	0.02
		PF-1c	0.09	0.04
		PF-2	0.01	0.06
		OH	0.03	0.07
IBDV	2	TF	0.41	0.66
		PF-1a	0.11	0.06
		PF-1b	0.00	0.00
		PF-1c	0.01	0.00
		PF-2	0.02	0.00
		OH	0.00	0.01
	4	TF	0.24	0.36
		PF-1a	0.06	0.03
		PF-1b	0.00	0.01
		PF-1c	0.01	0.00
		PF-2	0.01	0.00
		OH	0.00	0.00
OBDR1	1	TF	0.15	0.04
		PF-1a	0.07	0.01
		PF-1b	0.02	0.01
		PF-1c	0.02	0.05
		PF-2	0.17	0.10
		OH	0.03	0.07
	2	TF	0.09	0.03
		PF-1a	0.04	0.01
		PF-2b	0.01	0.01
		PF-1c	0.01	0.03
		PF-2	0.11	0.06
		OH	0.02	0.04

From this table, the relative sensitivities can be assessed. The greatest sensitivities are clearly with the TF inner legs. Beyond that, clear points of sensitivity include those in Table 2.1.7-2.

Table 2.1.7-2: Key coil displacement for each region of the machine

Tile Region	Displacement Type
IBDV	TF shift, TF tilt, PF-1a shift, PF-1a tilt
IBDH	TF tilt, PF-1a shift, PF-1c shift, PF-1c tilt, OH tilt
OBDR1	TF shift, PF-2 shift, PF-2 tilt, OH tilt, PF-1a tilt

Also note the significant reduction in sensitivity when the field line incident angle is doubled. In general, only the shallow field line conditions result in significant variations in heat flux with coil positional perturbations.

2.2 Monte Carlo Analysis

Monte-Carlo analysis was performed on the full set of coil perturbations. All PF coil radial shifts and tilts were given an upper bound, and for each iteration, individual coils were shifted randomly to one of 10 values between 0 and that bound.

In some cases, the TF tilt was fixed at 0.5 mrad; in others, the TF tilt was allowed to randomly vary. The OH tilt and shift was always fixed to the same value. The TF and OH coils were also given the same randomly chosen shift amplitudes and phases.

All phases were randomly chosen, and the TF and OH were given the same phase in all cases.

In each case, a nominal, axisymmetric heat flux was derived so that the mean + 1 standard deviation of the peak heat flux was equal to 8 MW/m^2. This implies that for a given set of tolerances, it is likely that maintaining this nominal heat flux would maintain all tiles below the temperature limit. However, it remains possible that the distribution of coil displacements could result in greater than an 8 MW/m^2 heat flux for the stated nominal heat flux.

These calculations were done using multiple calls to RANDBETWEEN() in Excel, and therefore no single result can be reproduced. Note that all cases here have incident field line angles of {1,2,1} degrees for the {IBDH, IBDV, OBDR1}, with maximum field line angles of {5,5.5,5} degrees. Cases with other incident field line angles are considered in the appendix.

2.2.1: Case 1 - Loose PF Tilt/Shift Tolerances & TF Shift Tolerance, TF Tilt Fixed

Numerous cases were assessed to bound the problem. The first case used rather loose tolerances on the PF tilt/shift and TF shift; see Table 2.2.1-1.

PF & TF Shift Tolerance	mm	4
PF Tilt Tolerance	mrad	3
PF Ellipse Tolerance	mm	2
TF Tilt (fixed)	mrad	0.5

Table 2.2.1-1*: Tolerance bounds for Case 1*

The histogram of fully enhanced heat fluxes so computed in this case appears in Fig. 2.2.1-1. Note that there are some cases beyond 8 MW/m^2 for the chosen nominal heat fluxes, but that most cases are beneath this level as per the one standard deviation rule described above.

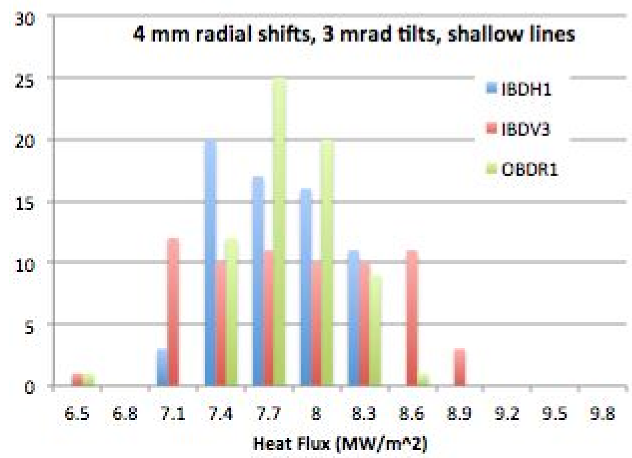


Fig. 2.2.1-1*: Histogram of Monte-Carlo results for the case in Table 2.2.1-1.*

The nominal heat fluxes themselves are indicated in Table 2.2.1-2. Compared to fishscale only heat fluxes of {6.5, 6.5, 5.4} MW/m^2 for the {IBDH, IBDV,OBDR1}, the nominal heat fluxes based on the Monte Carlo (MC) analysis are {5.6, 5.6, 4.7}. The sum of the distribution mean and standard deviation in the lower two rows is always approximately 8 MW/m^2.

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.6**	**5.6**	**4.7**
Mean of Distribution	MW/m^2	7.6	7.7	7.7
standard deviation	MW/m^2	0.3	0.5	0.3

Table 2.2.1-2: *Heat fluxes for Case 1*

2.2.2: Case 2 - Tight PF Tolerances, TF Tilt Fixed

In this case, the tolerances indicated in Table 2.2.2-1 are meaningfully tighter than the previous section. The resulting histogram is shown in Fig. 2.2.2-1, and is noticeably more peaked than in the previous section.

PF & TF Shift Tolerance	mm	3
PF Tilt Tolerance	mrad	2
PF Ellipse Tolerance	mm	2
TF Tilt (fixed)	mrad	0.5

Table 2.2.2-1: *Tolerance bounds for Case 2*

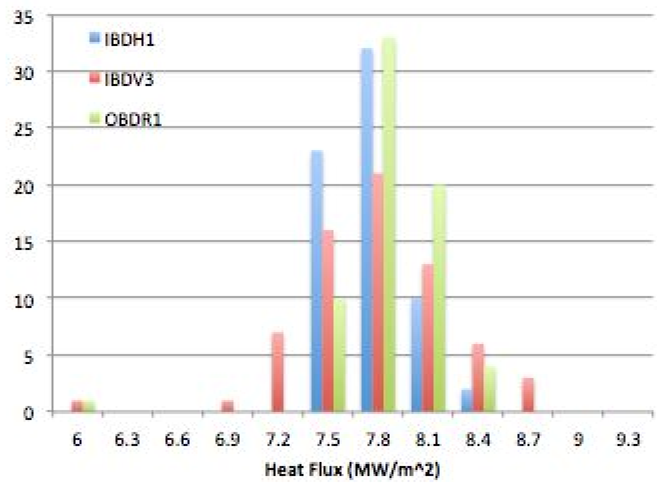


***Fig. 2.2.2-1**: Histogram of Monte-Carlo results for the case in Table 2.2.2-1.*

The resulting nominal heat fluxes of {5.7, 5.6, 4.8} MW/m^2 for the {IBDH, IBDV,OBDR1} in Table 2.2.2-1 are marginally higher than the previous section.

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.7**	**5.6**	**4.8**
Mean of Distribution	MW/m^2	7.6	7.6	7.7
standard deviation	MW/m^2	0.2	0.4	0.2

***Table 2.2.2-2**: Heat fluxes for Case 2*

2.2.3: Case 3 - Loose PF Tolerances, TF Shift MC Analysis

A case with more loose tolerances, and with the TF shift undergoing MC analysis, is shown in Table 2.2.3-1 and 2.2.3-2, and Fig. 2.2.3-1. This case shows nominal fluxes of {5.5, 5.3, 4.5} MW/m^2 for the {IBDH, IBDV,OBDR1}.

PF & TF Shift Tolerance	mm	5
PF Tilt Tolerance	mrad	3
PF Ellipse Tolerance	mm	2
TF Tilt Tolerance	mrad	1.3

***Table 2.2.3-1**: Tolerance bounds for Case 3*

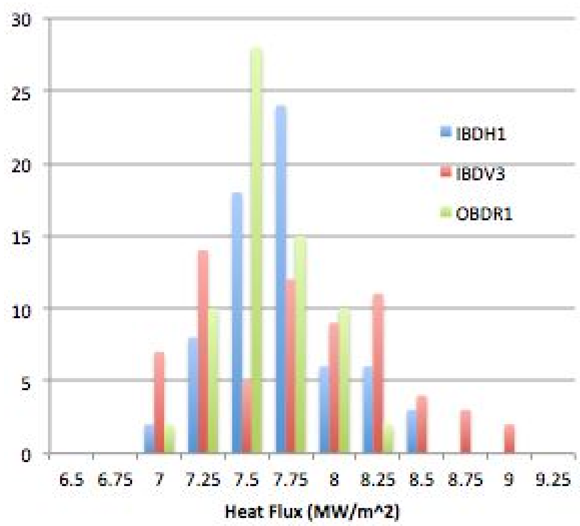


***Fig. 2.2.3-1**: Histogram of Monte-Carlo results for the case in Table 2.2.3-1.*

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.5**	**5.3**	**4.5**
Mean of Distribution	MW/m^2	7.6	7.7	7.5
standard deviation	MW/m^2	0.3	0.5	0.3

***Table 2.2.3-2**: Heat fluxes for Case 3*

2.2.4: Case 4 - Tight Tolerances, TF Tilt MC

A case with very tight tolerances, and with the TF shift undergoing MC analysis, is shown in Table 2.2.3-1 and 2.2.3-2, and Fig. 2.2.3-1. This case shows nominal fluxes of {6.1, 6.1, 5.0} MW/m^2 for the {IBDH, IBDV,OBDR1} are close to the fishscale values.

PF & TF Shift Tolerance	mm	1
PF Tilt Tolerance	mrad	1
PF Ellipse Tolerance	mm	1.5
TF Tilt Tolerance	mrad	0.4

***Table 2.2.4-1**: Tolerance bounds for Case 4*

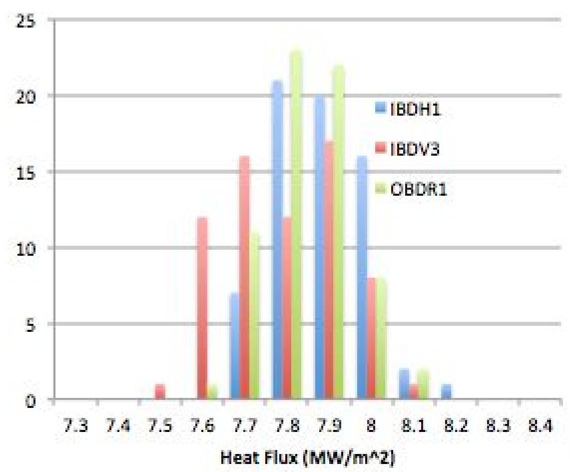


***Fig. 2.2.4-1**: Histogram of Monte-Carlo results for the case in Table 2.2.4-1.*

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**6.1**	**6.1**	**5**
Mean of Distribution	MW/m^2	7.8	7.7	7.8
standard deviation	MW/m^2	0.1	0.1	0.1

***Table 2.2.4-2**: Heat fluxes for Case 4*

2.2.5: Case 5 - Loose PF, Tight TF

A case with loose PF tolerances and tight TF tolerances, is shown in Table 2.2.5-1 and 2.2.5-2, and Fig. 2.2.5-1. This case shows nominal fluxes of {5.8, 6.0, 4.8} MW/m^2 for the {IBDH, IBDV,OBDR1}.

PF-1a shift tolerance	mm	3.5
PF-1a tilt tolerance	mrad	2.0
PF-1b shift tolerance	mm	3.5
PF-1b tilt tolerance	mrad	2.0
PF-1c shift tolerance	mm	3.5
PF-1c tilt tolerance	mrad	2.0
PF-2 shift tolerance	mm	3.5
PF-2 tilt tolerance	mrad	5.0
TF shift tolerance	mrad	2.0
TF tilt tolerance	mm	0.4
MC on TF tilt		yes
PF ellipticity tolerance	mm	2.0

***Table 2.2.5-1**: Tolerance bounds for Case 5*

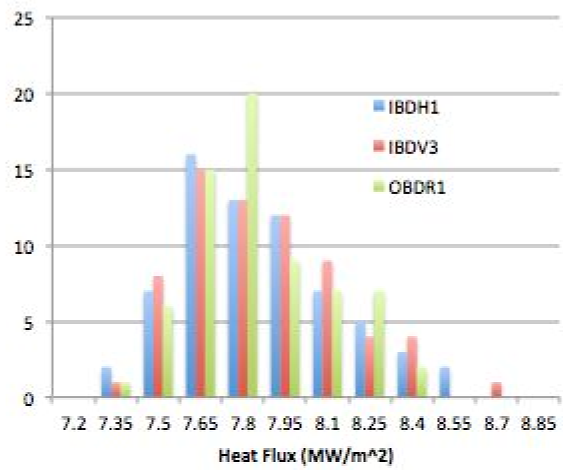


***Fig. 2.2.5-1**: Histogram of Monte-Carlo results for the case in Table 2.2.5-1.*

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.8**	**6**	**4.8**
Mean of Distribution	MW/m^2	7.8	7.8	7.8
standard deviation	MW/m^2	0.3	0.3	0.2

***Table 2.2.5-2**: Heat fluxes for Case 5*

2.2.6: Case 6 - Loose TF, Tight PF

A case with tight PF tolerances and loose TF tolerances, is shown in Table 2.2.6-1 and 2.2.6-2, and Fig. 2.2.6-1. This case shows nominal fluxes of {5.9, 5.6, 5.7} MW/m^2 for the {IBDH, IBDV,OBDR1}.

PF-1a shift tolerance	mm	2.00
PF-1a tilt tolerance	mrad	1.00
PF-1b shift tolerance	mm	2.00
PF-1b tilt tolerance	mrad	1.00
PF-1c shift tolerance	mm	2.00

PF-1c tilt tolerance	mrad	1.00
PF-2 shift tolerance	mm	5.00
PF-2 tilt tolerance	mrad	5.00
TF shift tolerance	mrad	3.00
TF tilt tolerance	mm	1.30
MC on TF tilt?		1.00
PF ellipticity tolerance	mm	2.00

Table 2.2.6-1: *Tolerance bounds for Case 6*

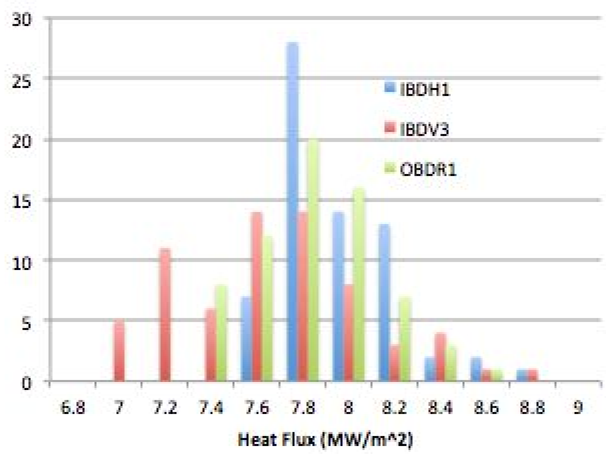


Fig. 2.2.6-1: *Histogram of Monte-Carlo results for the case in Table 2.2.6-1.*

		IBDH	**IBDV**	**OBDR1**
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.9**	**5.6**	**4.7**
Mean of Distribution	MW/m^2	7.9	7.6	7.8
standard deviation	MW/m^2	0.2	0.4	0.3

Table 2.2.6-2: *Heat fluxes for Case 6*

2.2.7: Case 7 - Tight TF, Tighter PF-1a & 1b, Loose PF-1c and 2

This case is based on the acknowledgement that a tight tolerance on the -1c and -2 are difficult to achieve, as these components are mounted to the outer vessel, not the casing. As a consequence, this case relaxes the -1c and -2 tolerances relative to the IBDV, but imposes more strict tolerances on the PF-1a and -1b to compensate.

PF-1a shift tolerance	mm	3.00
PF-1a tilt tolerance	mrad	2.00
PF-1b shift tolerance	mm	3.00
PF-1b tilt tolerance	mrad	2.00
PF-1c shift tolerance	mm	5.00
PF-1c tilt tolerance	mrad	4.00
PF-2 shift tolerance	mm	5.00
PF-2 tilt tolerance	mrad	5.00
TF shift tolerance	mrad	2.00
TF tilt tolerance	mm	0.40
MC on TF tilt?		1.00
PF ellipticity tolerance	mm	2.00

Table 2.2.7-1*: Tolerance bounds for Case 7*

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.7**	**5.9**	**4.7**
Mean of Distribution	MW/m^2	7.77	7.71	7.79
standard deviation	MW/m^2	0.31	0.25	0.29

***Table 2.2.7-2**: Heat fluxes for Case 7*

2.2.8: Case 8 - Tight TF, Tighter Yet PF-1a & 1b, Loose PF-1c and 2

This case is similar to Case 7, but with even more strict tolerance on PF-1a and -1b positions

PF-1a shift tolerance	mm	2.00
PF-1a tilt tolerance	mrad	1.50
PF-1b shift tolerance	mm	2.00
PF-1b tilt tolerance	mrad	1.50
PF-1c shift tolerance	mm	5.00
PF-1c tilt tolerance	mrad	4.00
PF-2 shift tolerance	mm	5.00
PF-2 tilt tolerance	mrad	5.00
TF shift tolerance	mrad	2.00
TF tilt tolerance	mm	0.40
MC on TF tilt?		1.00
PF ellipticity tolerance	mm	2.00

***Table 2.2.8-1**: Tolerance bounds for Case 8*

		IBDH	IBDV	OBDR1
Max Field Line Angle	deg	5	5.5	5
incident angle	deg	1	2	1
Fishscale only	MW/m^2	6.5	6.6	5.3
nominal heat flux	**MW/m^2**	**5.7**	**6.**	**4.7**
Mean of Distribution	MW/m^2	7.72	7.86	7.79
standard deviation	MW/m^2	0.24	0.23	0.23

Table 2.2.8-2*: Heat fluxes for Case 8*

2.2.9: Summary of Monte-Carlo Results

The summary table of MC studies are shown in Table 2.2.9-1.

Based on these results, the tolerances in **Case 5** are recommended, with **Case 7** as a fall-back position. This choice is made for the following reasons:

- The somewhat larger nominal fluxes on the IBDV are attractive in this tolerance scenario, relative to for instance Case 6. While either case satisfies the requirements on the IBDV in a strict sense, plasma control issues that result in deviations from double null can result in a significant increase in the IBDV heat flux. This tolerance set is more attractive from that regard.
- The tight tolerance on the TF alignment is consistent with the tight tolerances described in Section 3 of this report, with regard to alignments of the TF to the outer-PF coils.

Table 2.2.9-1*: Summary of Monte-Carlo results. All cases here have incident field line angles of {1,1.5,1} degrees for the {IBDH, IBDV, OBDR1}, with designed maximum angles of {5,5.5,5}.*

		1	2	3	4	5	6	7	8	9	Fishscale Only
PF-1a shift tolerance	mm	4.0	3.0	5.0	1.0	3.5	2.0	3.0	2.0	3.0	0
PF-1a tilt tolerance	mrad	3.0	2.0	3.0	1.0	2.0	1.0	2.0	1.5	2.0	0
PF-1b shift tolerance	mm	4.0	3.0	5.0	1.0	3.5	2.0	3.0	2.0	3.0	0
PF-1b tilt tolerance	mrad	3.0	2.0	3.0	1.0	2.0	1.0	2.0	1.5	2.0	0
PF-1c shift tolerance	mm	4.0	3.0	5.0	1.0	3.5	2.0	5.0	5.0	5.0	0
PF-1c tilt tolerance	mrad	3.0	2.0	3.0	1.0	2.0	1.0	4.0	4.0	4.0	0
PF-2 shift tolerance	mm	4.0	3.0	5.0	1.0	3.5	5.0	5.0	5.0	5.0	0
PF-2 tilt tolerance	mrad	3.0	2.0	3.0	1.0	5.0	5.0	5.0	5.0	5.0	0
TF shift tolerance	mm	4.0	3.0	5.0	1.0	2.0	3.0	2.0	2.0	4.0	0
TF tilt tolerance	mrad	0.5	0.5	1.3	0.4	0.4	1.3	0.4	0.4	1.4	0
MC on TF tilt?	0 or 1	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0
PF ellipticity tolerance	mm	2.0	2.0	2.0	1.5	2.0	2.0	2.0	2.0	2.0	0
IBDH	MW/m^2	5.6	5.7	5.5	6.1	5.8	5.9	5.7	5.7	5.7	6.5
IBDV	MW/m^2	5.6	5.6	5.3	6.1	6.0	5.6	5.9	6.0	5.5	6.6
OBDR1	MW/m^2	4.7	4.7	4.5	5.0	4.8	4.7	4.7	4.7	4.6	5.3

If the tolerance scenario in Case 5 proves problematic from the perspective of the PF-1c and PF-2 alignments[2], then the tolerance scenario in **Case 7** may be adopted. This case has the same TF tolerances as Case 5, but relaxes the PF-1c and PF-2 alignment, with somewhat stricter PF-1a and PF-1b tolerances.

2.3: Studies with Tilt Tolerances Increased a Factor of 2

Selected magnet tolerances were studied with revised PFC tolerances. These new tolerances are indicated in Table 2.3-1

Horizontal Target	**Normal Displacement Tol**	**in**	**0.005**	**mm**	**0.1**
	assumed toroidal width	in	5.000	mm	127.0

[2] The PF-1c and PF-2 coils are mechanically connected to the outer vessel, and so not easily aligned to CS tiles.

	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.013	mm	0.3
	Maximum Field Line Angle	deg	5.000	mrad	87.3
	Poloidal Rotation Tol.	**deg**	**0.023**	**mrad**	**0.4**
	Toroidal Rotation Tol.	**deg**	**0.018**	**mrad**	**0.3**
	Fishscale Angle	deg	0.360	mrad	6.3
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**
Vertical Target	**Normal Displacement Tol**	**in**	**0.010**	**mm**	**0.3**
	assumed toroidal width	in	4.123	mm	104.7
	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.013	mm	0.3
	Maximum Field Line Angle	deg	5.500	mm	139.7
	Poloidal Rotation Tol.	**deg**	**0.028**	**mrad**	**0.5**
	Toroidal Rotation Tol.	**deg**	**0.029**	**mrad**	**0.5**
	Fishscale Angle	deg	0.444	mrad	7.8
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**
OBDR1	**Normal Displacement Tol**	**in**	**0.010**	**mm**	**0.3**
	assumed toroidal width	in	3.453	mm	87.7
	assumed tile gap	in	0.062	mm	1.6
	assumed tile offset	in	0.013	mm	0.3
	Maximum Field Line Angle	deg	5.000	mrad	87.3
	Poloidal Rotation Tol.	**deg**	**0.033**	**mrad**	**0.6**
	Toroidal Rotation Tol.	**deg**	**0.019**	**mrad**	**0.3**
	Fishscale Angle	deg	0.521	mrad	9.1
	Surface Flatness Tol	**in**	**0.001**	**mm**	**0.03**

Table 2.3-1*: Assumptions on the PFC tolerance used in Section 2.3. This will be referred to as Tile Tolerance Set #2.*

The result of this study is shown in Table 2.3-2. It can be seen that relaxing these PFC tolerances results in typically 0.1-0.2 MW/m^2 reduction in the allowed nominal heat flux.

Tile Tolerance	Tile Tolerance Set	T1-T2

		Set #1	#2	
		Nominal Heat Flux (MW/m^2)	Nominal Heat Flux (MW/m^2)	MW/m^2
IBDH1	**Case 5**	5.8	5.7	0.10
	Case 7	5.7	5.5	0.20
INDV3	**Case 5**	6	5.8	0.20
	Case 7	5.9	5.8	0.10
OBDR1	**Case 5**	4.8	4.7	0.10
	Case 7	4.7	4.6	0.10
			mean (MW/m^2) ->	0.13

***Table 2.3-2**: Nominal heat fluxes for two tile tolerances, and two sets of coil position tolerances.*

2.4: Heat Flux and Component Position Requirements

2.4.1 IBDH Heat Fluxes

The PDR 5 second requirements for the inner horizontal target are provided in Table 2.4.1-1. These were presented at the PDR.

IBDH	**Case # ->**	**1**	**2**
Range of Application	m	0.47 < R < 0.6	
Extent	cm	15	full
Max Angle	degrees	1.0	5.0
Min Angle	degrees	1.0	1.5
Heat Flux	MW/m^2	7.0	5.5
Duration	sec	5	5
Reference Scenario	---	Stationary High Ip/Bt w/ large poloidal flux expansion	High Ip/Bt Long Pulse Swept Case

***Table 2.4.1-1**: PDR required heat flux parameters for the IBDH.*

Based on the studies presented in Section 2.2 and summarized in Section 2.2.7, the recommended heat flux requirements *based on an axisymmetric heat loading assumption*, and associated coil position tolerances are given in Table 2.4.1-2 and Table 2.4.1-3. Tile designs should accommodate this level of axisymmetric nominal heat flux, with the understanding that the positional tolerances of tiles and coils may result in some regions reaching the surface temperature limit after 5 seconds at nominal powers less than this.

IBDH	Case # ->	1	2
Range of Application	m	0.47 < R < 0.6	
Extent	cm	15	full
Max Angle	degrees	1.0	5.0
Min Angle	degrees	1.0	1.5
Heat Flux	MW/m^2	6.5	5.5
Duration	sec	5	5
Reference Scenario	---	Stationary High Ip/Bt w/ large poloidal flux expansion	High Ip/Bt Long Pulse Swept Case

***Table 2.4.1-2**: Revised heat flux parameters for the 5 second case for the IBDH.*

2.4.2 OBDR1 Heat Fluxes

Near OBD (aka R1,R2)	Case # ->	1	2	3
Range of Application	m	R < 0.7	R < 0.7	0.70 < R < 0.81
Extent	cm	13	10	full
Max Angle	degrees	1.0	5.0	4.4
Min Angle	degrees	1.0	1.5	2.6
Heat Flux	MW/m^2	6.0	5.5	3.0
Duration	sec	5	5	5
Reference Scenario	---	‘Spillover’ for stationary large poloidal flux expansion	‘Spillover’ for High Ip/Bt Long Pulse Swept Case	Swept Case on OBD

***Table 2.4.2-1**: PDR required heat flux parameters for the OBDR1-R2.*

The PDR OBDR1-R2 requirements are presented in Table 2.4.2-1. Based on the results of

Section 2.2, the recommended new tolerances are provided in Table 2.4.2-2. Again, this is based on an axisymmetric analysis assumption.

Near OBD (aka R1,R2)	Case # ->	1	2	3
Range of Application	m	R < 0.7	R < 0.7	0.70 < R < 0.81
Extent	cm	13	10	full
Max Angle	degrees	1.0	5.0	4.4
Min Angle	degrees	1.0	1.5	2.6
Heat Flux	MW/m^2	**5.4**	5.5	3.0
Duration	sec	5	5	5
Reference Scenario	---	'Spillover' for stationary large poloidal flux expansion	'Spillover' for High Ip/Bt Long Pulse Swept Case	Swept Case on OBD

***Table 2.4.2-2**: Revised heat flux parameters for the 5 second case for the OBDR1-R2.*

2.4.3 IBDV Heat Fluxes

While the coil misalignments increase heat flux on the IBDV, the PDR requirement of 5.0 MW/m^2 at 2.0 angle of incidence are low enough such that after fish-scaling and applying coil tolerances given in Table 2.4.1-3, the heat flux remains below the 8.0 MW/m^2 limit introduced above.

3: Positional alignment between the TF and the Outer-PF coils

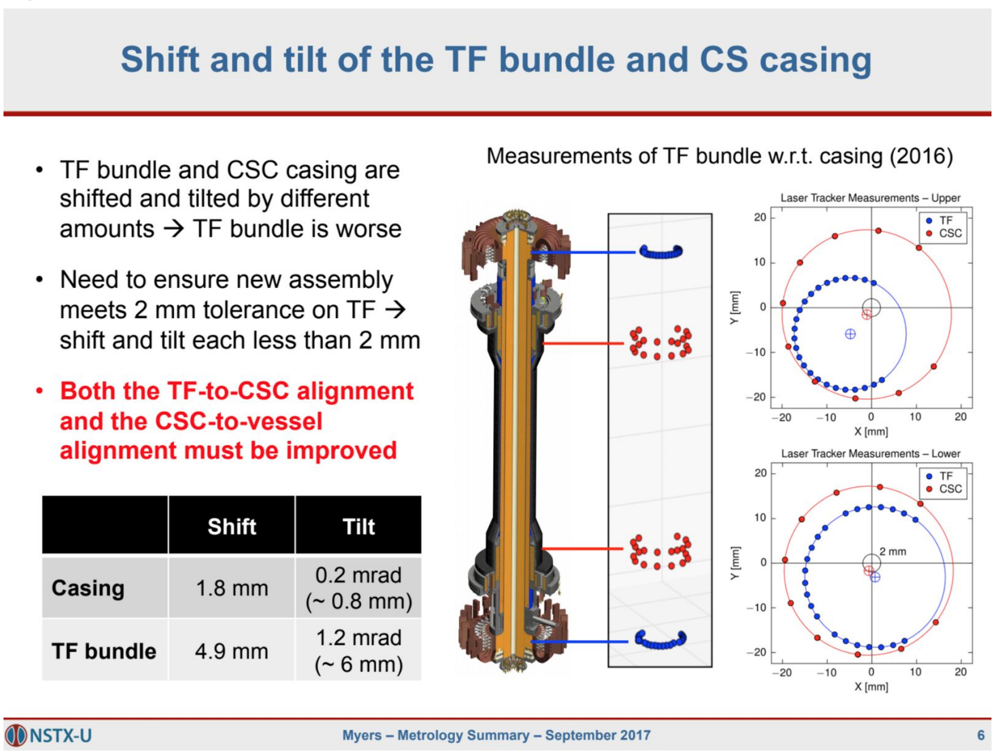
3.1: Input Data - Measurements

Profound error field issues were encountered during the 2016 run, with many days dedicated to error field identification and correction experiments [9]. This section describes measurements that were made following the run, in response to these issues. The measurements can be found in Refs [9,10].

3.1.1: TF Tilt Measurements

Metrology by C. Myers and machine techs assessed the relationship between the TF bundle and the casing, and between the casing and the vessel.

Figure 3.1.1-1*: Measured shift and tilt of the OH bundle, from Ref. [10]*

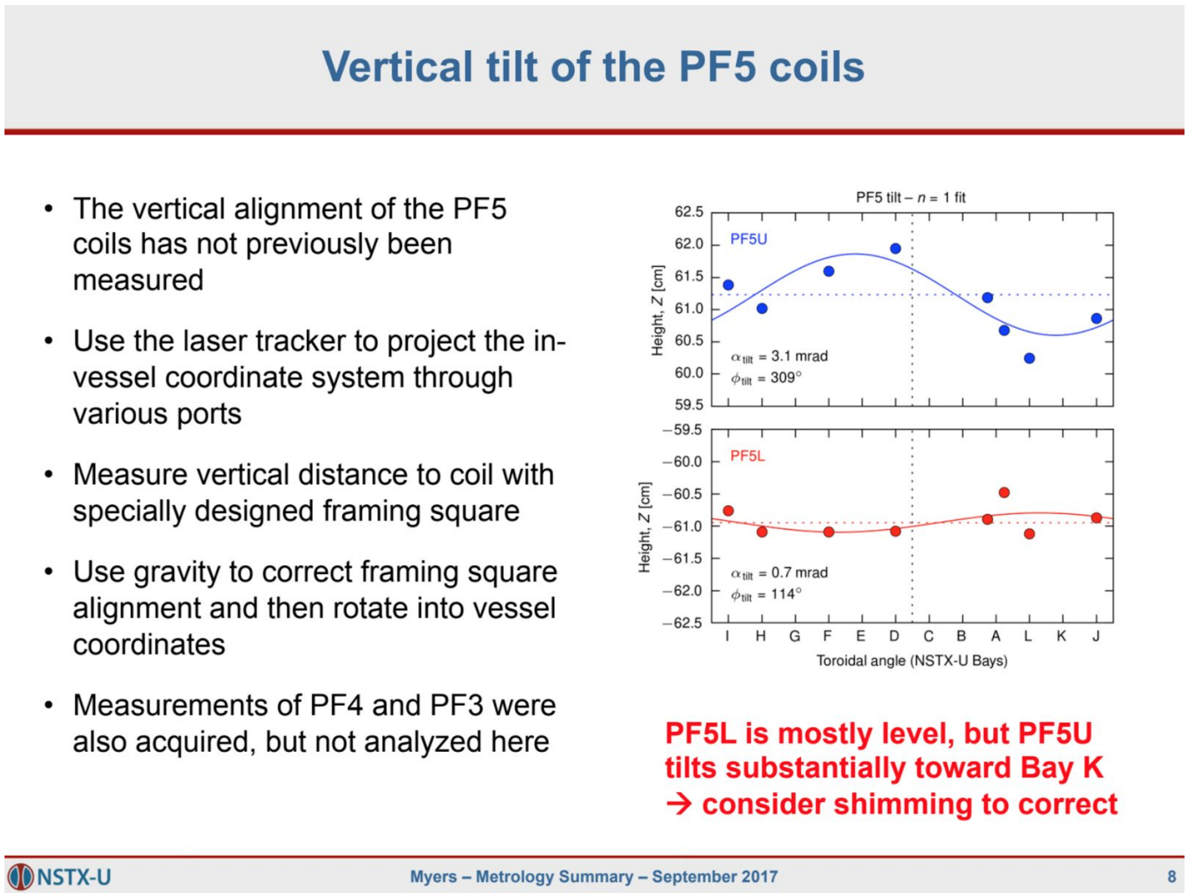


It was found that the bundle had a significant (1.2 mrad) tilt within the casing. It should be noted that no effort was made during installation to fix this tilt, and the presence of the tilt in that assembly does not imply that it could not have been corrected.

3.1.2: Assessments of the PF-5 tilt and shift

Measurements were made by C. Myers and the machine techs, using a combination of standard metrology devices and custom tooling. The results are shown in Fig. 3.1.2-1. The conclusion of this study is that the lower PF-5 coil is largely flat (<1 mrad) in the reference coordinate system, but the upper PF-5 coil has a tilt of order ~3 mrad.

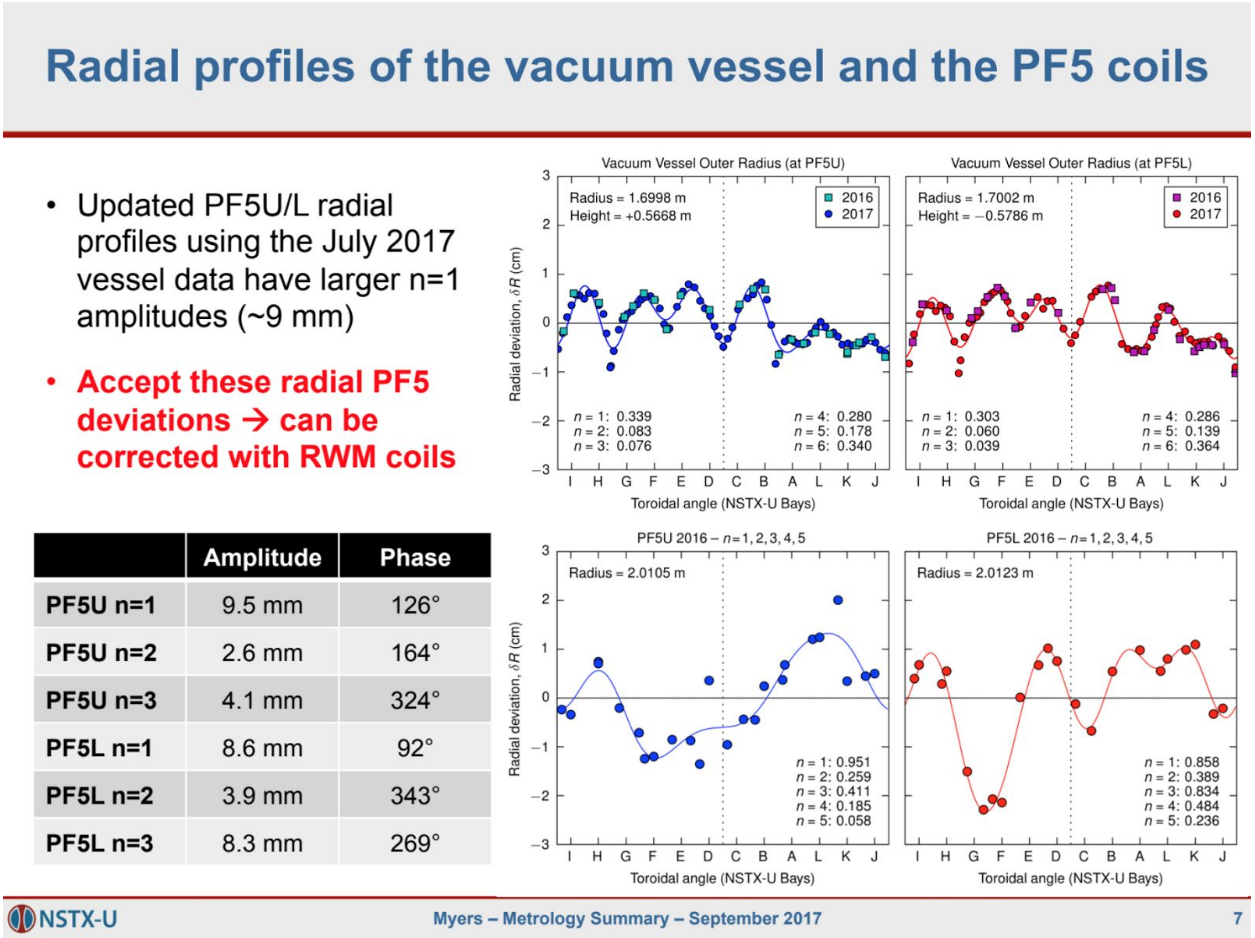
Fig. 3.1.2-1*: Measured tilt of the PF-5 coil, from Ref. [10]*



Equivalent tilt measurements were made of the PF-4, but they have not been processed.

The PF-5 coils radial variation was also studied, and is shown in Fig. 3.1.2-1. The coil radial variation has all harmonics through at least n=3. Note that the n=1 harmonic (average radial shift) is large, but also shows nearly matched phases.

Fig. 3.1.2-1*: Measured radial variations of the PF-5 coil, from Ref. [10]*



3.2: Input Data - Numerical Simulations

3.2.1: IPEC Analysis

Jong-Kyu Park did a study of the sensitivity to plasma shifts and tilts, based on both three time slices from a 0.65 T, 650 kA L-mode discharge, and an H-mode case. The parameters of these equilibria are indicated in Table 3.2.1-1, as are the parameters of other cases to be considered in other sections of this report. These simulations use IPEC to compute the 2/1 resonant field[3]. Values of 0.5-1 G for the 2/1 resonant field are a rule-of-thumb thresholds for mode locking

[3] 2/1 Resonant Field: This is the component of the error field with toroidal decomposition m=2, n=1, where n is the toroidal mode number and m is the poloidal mode number. These perturbations are strongly resonant with the plasma at locations where the field line helicity matches the perturbation (at the location where the safety q is equal to 2. m/n=2/1 resonant fields drive currents on the q=2 surface), resulting in electromagnetic torques that reduce rotation. This effect can cause the plasma rotation to halt, resulting in severe confinement degradation and typically disruption.

($1x10^{-4}$ of the toroidal field). Note that the IPEC calculations are only valid below the no-wall limit, and therefore there is no IPEC calculation for the β_N=5.5 case.

In these simulations, the full set of TF outer legs were shifted, or tilted, with respect to the vertical axis. Displacements of individual PF coils are of a single coil, i.e "PF-5" represents the tilt or shift of an upper or lower PF-5 coil. Shifts and tilts of the TF inner legs are can be considered as being with respect to the full set of PF coils.

Table 3.2.1-1: Equilibria used in IPEC and M3D-C1 simulations

Case	shot	time	I_P	B_T	q_0	β_N	Regime
		s	MA	T	---	%mT/A	L or H
1	204077	0.307	0.7	0.63	1.3	0.7	L
2	204077	0.349	0.7	0.63	1.02	1.02	L
3	204077	0.697	0.7	0.63	0.89	1.3	L
4	142301O84	11.875	0.7	1	1.3	3.8	H
5	142301C94	8.75	2	1	1.366	2.98	H
6	142301C94	8.75	2	1	1.4	5.5	H

Table 3.2.1-1: Calculations done based on the equilibria in Table 3.2.1-1.

Case	IPEC $B_{2,1}$ Calculation	M3D-C1 $B_{2,1}$ Calculation	IPEC NTV Calculation
1	Yes	Yes	No
2	Yes	No	No
3	Yes	Yes	No
4	Yes	No	Yes
5	Yes	No	Yes
6	No	Yes	No

3.2.1.1: IPEC Resonant Field Analysis

Fig. 3.2.1-1 illustrates the dependence of the resonant field component $B_{2,1}$, normalized to the kA-turns in each coil, for shifts and tilts of all major coil systems. Here, the RWM coils are omitted, as their value of (2.4 G/kA-turn) would be fully off scale. On this basis, the coils with the largest tilt/shift impact per kA-turn are the PF-4 and PF-5 coils, with the PF-3 coils as the third most significant contributor.

However, there can be large variations in the kA-turns between coils systems. Therefor, Fig. 3.2.1-2 illustrates the total resonant field component $B_{2,1}$, with the coil kA-turns selected as in Table 3.2.1-2.

Figure 3.2.1-1*: Dependence of B_{21}, normalized by the coil kA-turns, on individual coil tilts and shifts using IPEC.*

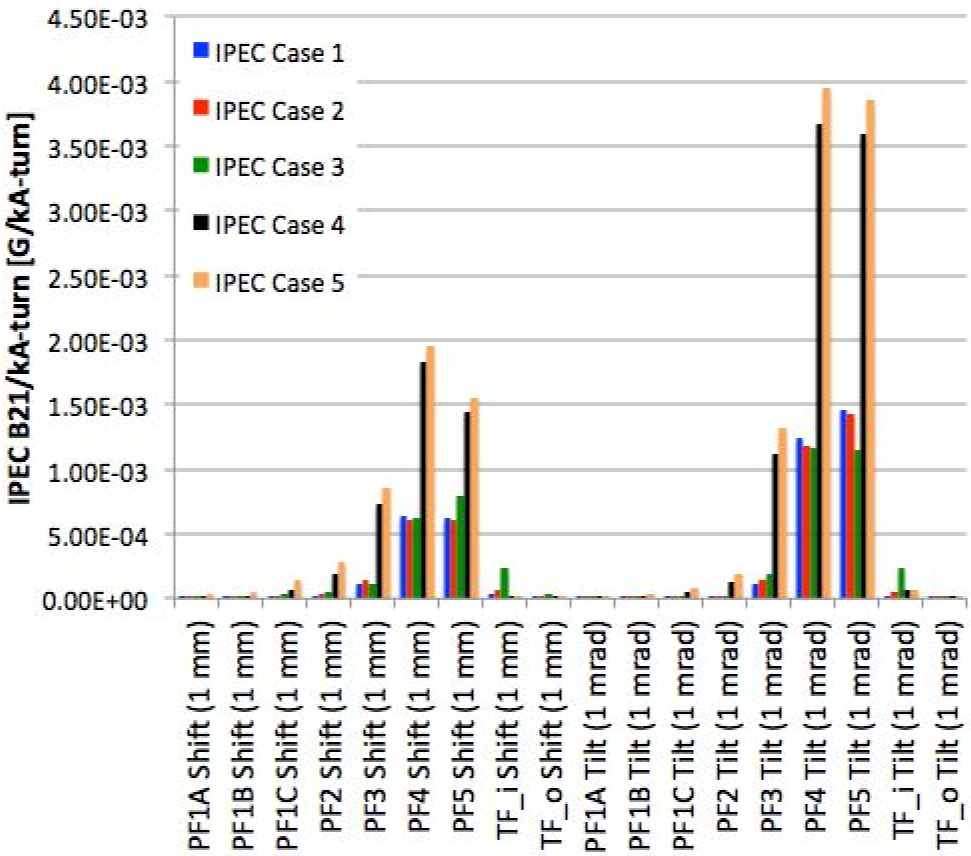
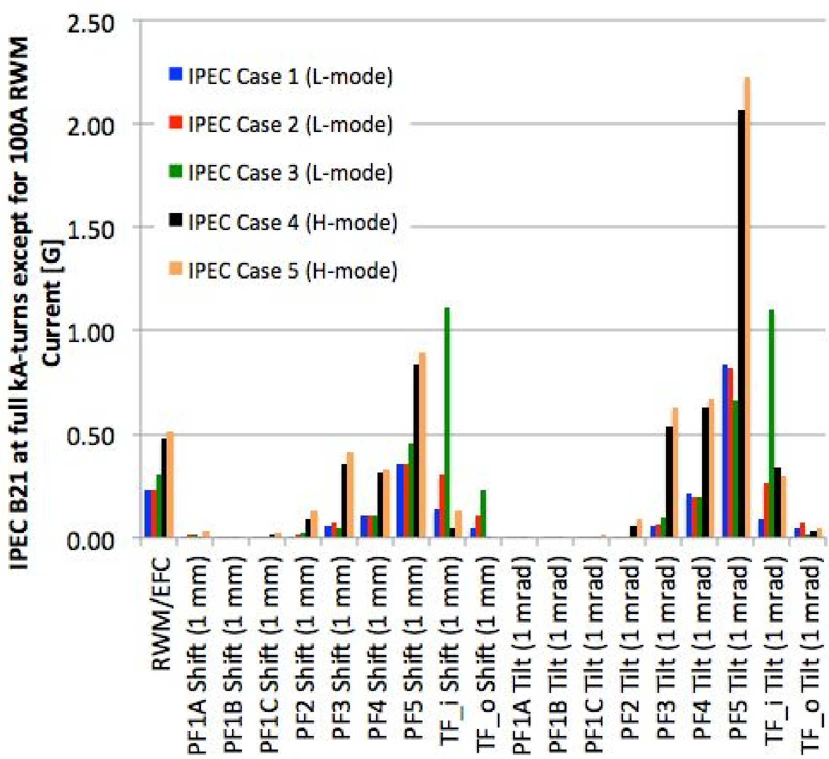


***Table 3.2.1-2**: Currents and turns used in estimating worst case fields*

Coil	# turns (Recovery)	Typical Current [kA]
RMP	2	0.1
PF-1a	60	12
PF-1b	20	8.2
PF-1c	16	10
PF2	28	16
PF-3	30	16
PF-4	17	10
PF-5	24	24
TF	36	130

***Figure 3.2.1-2**: Dependence of B_{21}, for full coil kA-turns on the TF and PF coils and 100 A on the RWM coils, on individual coil tilts and shifts using IPEC.*



In inspecting the data in Figs. 3.2.1-1 and 3.2.1-2, a few conclusions can be quickly drawn:

- Shifts and tilts of the TF inner legs relative to the PF coils are problematic, especially in L-mode plasmas (cases 1-3).

- Shifts and tilts of individual PF-4 and PF-5 coils are highly problematic. This is especially so in H-mode, where plasma response effects enhance the perturbation.
- Shifts and tilts of the TF outer legs are not significant.
- Shifts and tilts of the divertor coils (PF-1a/1b/1c and PF-2) are not significant for global MHD studies (they are quite significant for PFC heat loading, however, as described in Section 2 of this report).

3.2.1.2: IPEC NTV Analysis

An IPEC analysis of NTV has also been completed, for the H-mode Cases #4 and #5 (L-mode NTV is negligibly small). Note that the NTV torque will scale as $T_{NTV}=\alpha_{NTV}N^2I^2\delta^2$, where N is the number of coi turns, I is the coil current, δ is the perturbation in mm or mrad, and α_{NTV} is a coefficient.

The normalized NTV torque (T/N^2I^2 for δ=1mm or 1 mrad) is given in Fig. 3.2.1-3, while the total torque for full coil currents is given in Fig. 3.2.1-4. The NTV is clearly dominated by tilts and shifts of the outer PF coils, with tilts and shifts of the inner-TF the second strongest effect. Displacements of the outer-TF coils are less significant. *Note that NTV cannot be simply added, due to the quadratic dependence on field components.*

Figure 3.2.1-3*: Dependence of T_{NTV}, normalized by the squared coil kA-turns, on individual coil tilts and shifts using IPEC.*

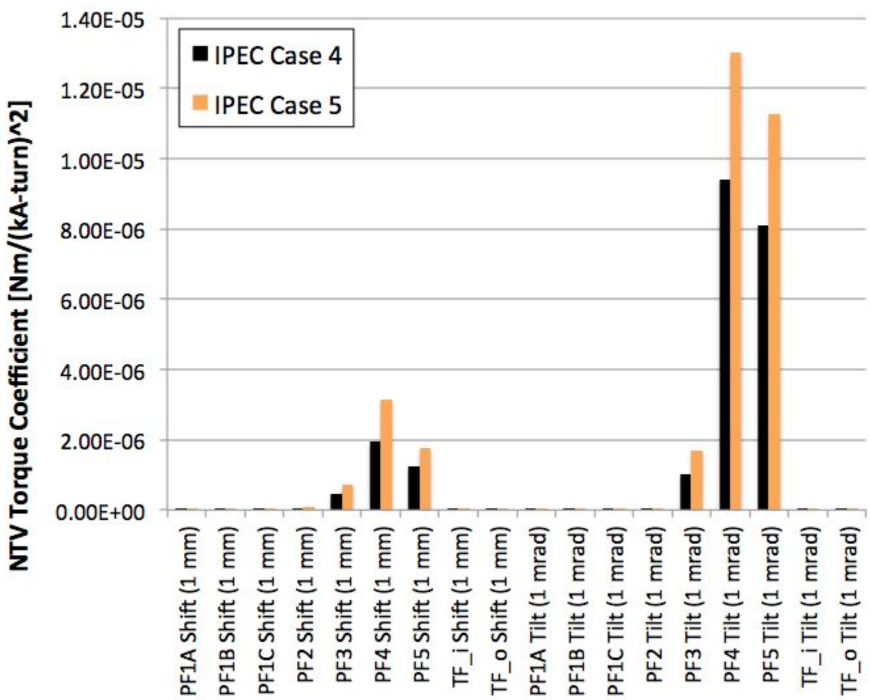


***Figure 3.2.1-2**: Dependence of T_{NTV}, for full coil kA-turns on the TF and PF coils and 100 A on the RWM coils, on individual coil tilts and shifts using IPEC. The equilibrium is the Case 4 H-mode case.*

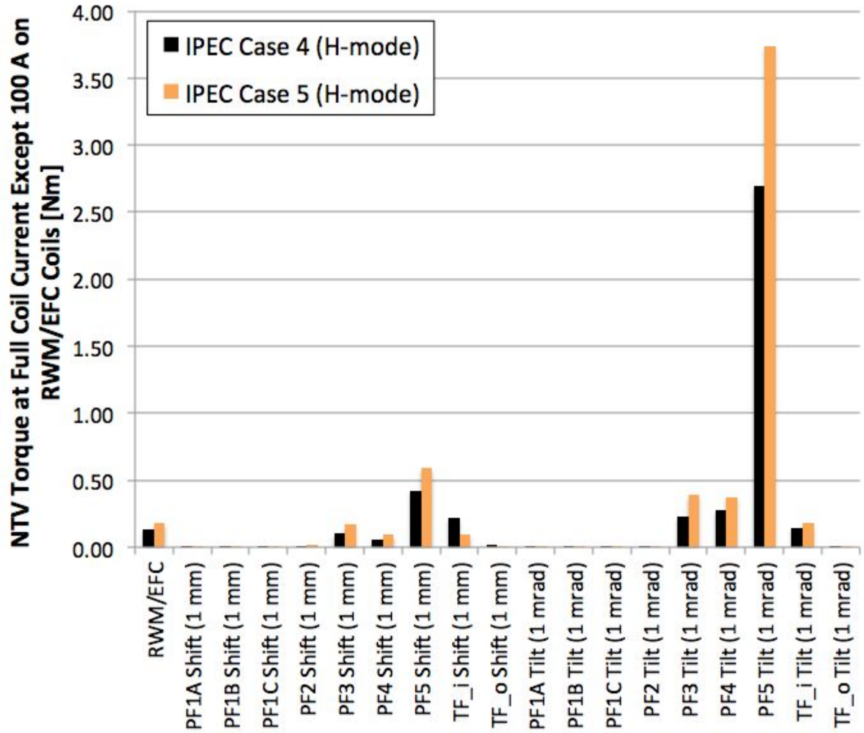
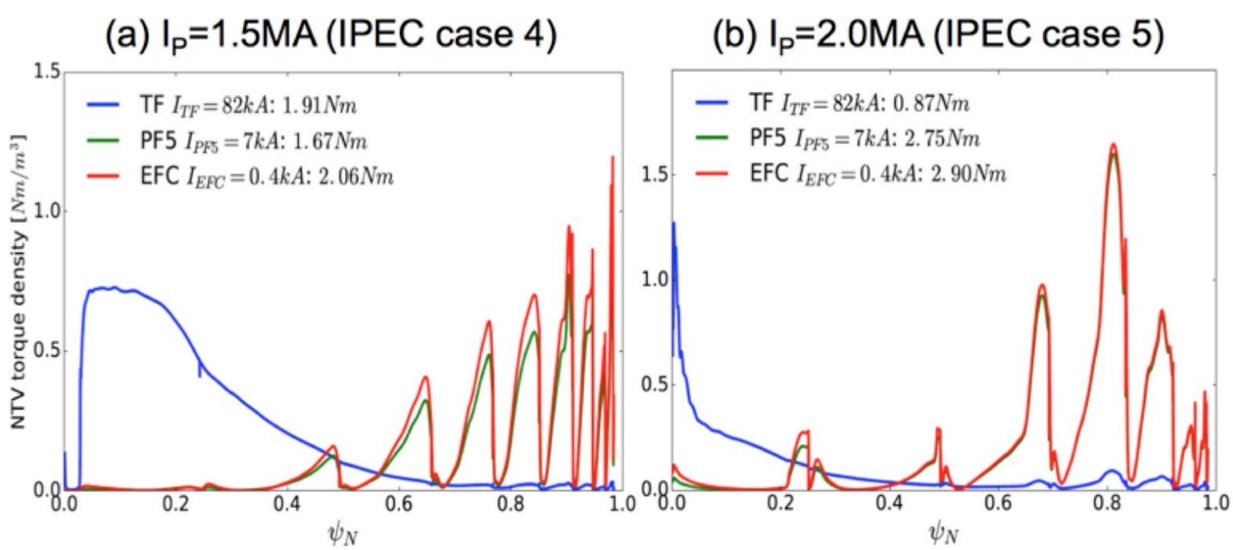


***Fig. 3.2.1-3**: Profiles of the NTC for the two cases under consideration*

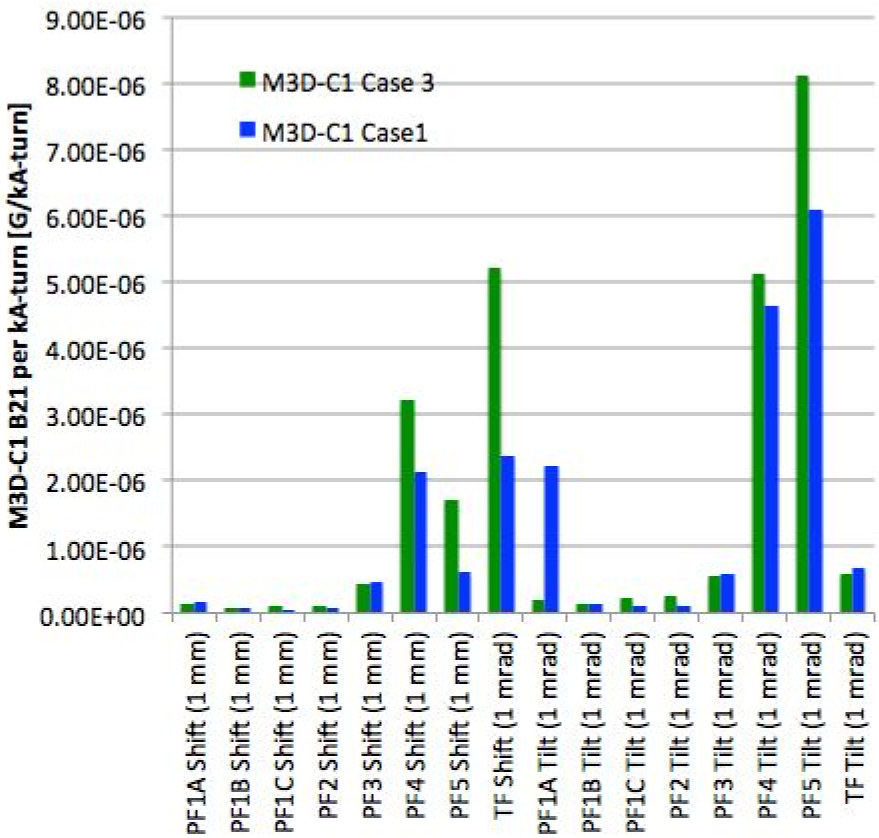


It should be noted, however, that NTV is a profile effect, with the values in Fig. 3.2.1-1 and 3.2.1-2 being integrated over the plasma volume to provide the total torque. Examples profiles are shown in Fig. 3.2.1-3, for the TF displacements and PF-5 radial variations observed during the FY-16 run (the measured PF-5U tilt is not included in this calculation). The NTV the RWM coils is also shown, with a magnitude selected to match that from the PF-5 perturbation. It is clear that the NTV can be from the outer-PF perturbation can be matched, and therefore cancelled by the RWM coils. However, the NTV from the TF perturbations has a completely different profile, and is not well matched by the EFC coils. Therefor, it will be difficult or impossible to eliminate the NTV effects of a large TF perturbation with the EFC coils.

3.2.2: M3D-C1 m/n=2/1 Analysis for Coil Shifts & Tilts in L-mode

A similar analysis was done with the M3D-C1 by Nate Ferraro, for the equilibria in L-mode equilibria in Case 1 and Case 3 of Table 3.2.1-1, as well as the H-mode equilibria in Case 6.

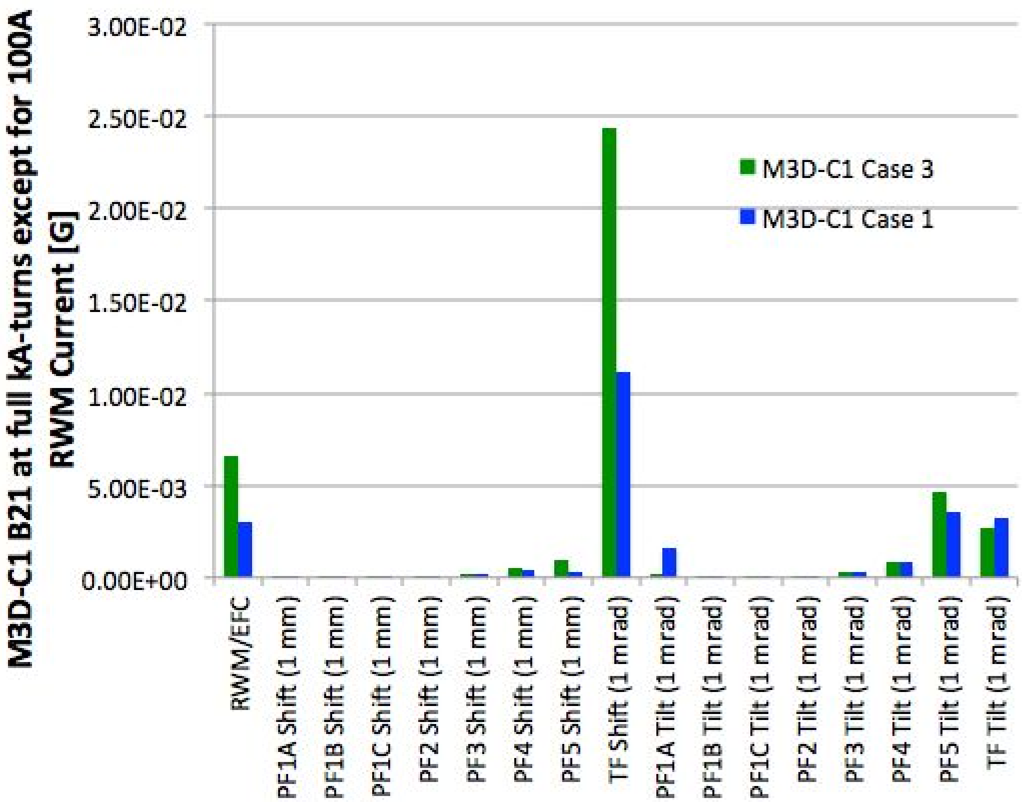
Figure 3.2.2-1*: Dependence of B_{21}, normalized by the coil kA-turns, on individual coil tilts and shifts in two L-mode cases using M3D-C1*



Results for the L-mode case are shown in Fig. 3.2.2-1 and 3.2.2-2, where the currents in the second case come from Table 3.2.1-2. These results are similar to the IPEC results, in the following ways:

- The dominant error fields are caused by tilts and shifts of the TF, PF-4, and PF-5 coils.
- Tilts and shifts of the inner-PF coils are largely irrelevant w/ regard to the global stability.

***Figure 3.2.2-2**: Dependence of B_{21}, for full coil kA-turns on the TF and PF coils and 100 A on the RWM coils, on individual coil tilts and shifts in two L-mode cases using M3D-C1.*



These calculations have also been done for an H-mode case, as shown in Figs. 3.2.2-3 and 3.2.2-4. The magnitudes of the plasma response are much larger than the L-mode cases, and therefore the results for the two regimes are not shown on the same graph. However, it is clear that the TF and outer-PF coils remain the dominant sources of error fields. Also note that, as with the IPEC calculations, the relative importance of TF perturbations relative to outer PF perturbations decreases when moving to H-mode.

***Figure 3.2.2-3**: Dependence of B_{21}, normalized by the coil kA-turns, on individual coil tilts and shifts in H-mode using M3D-C1*

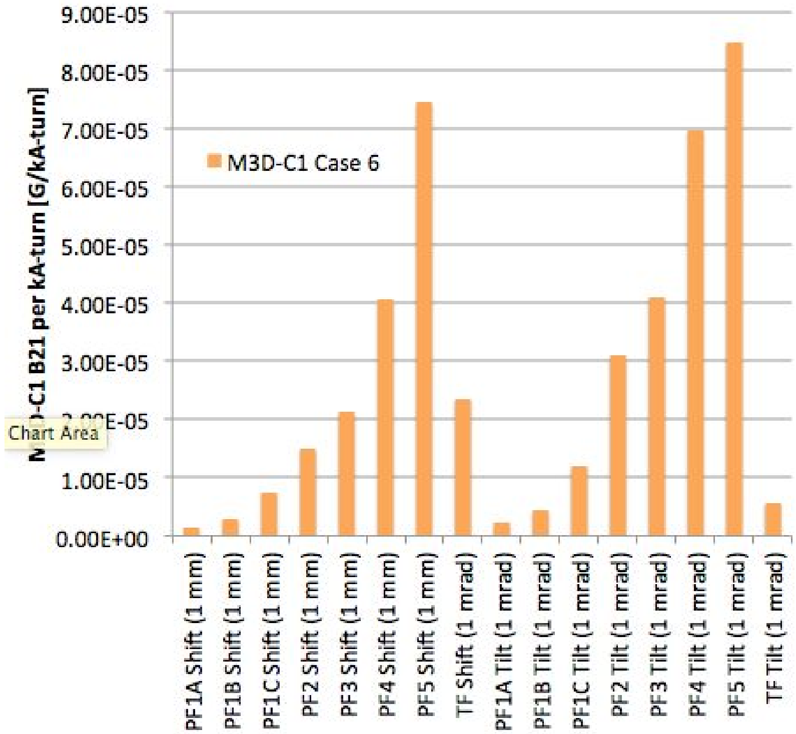
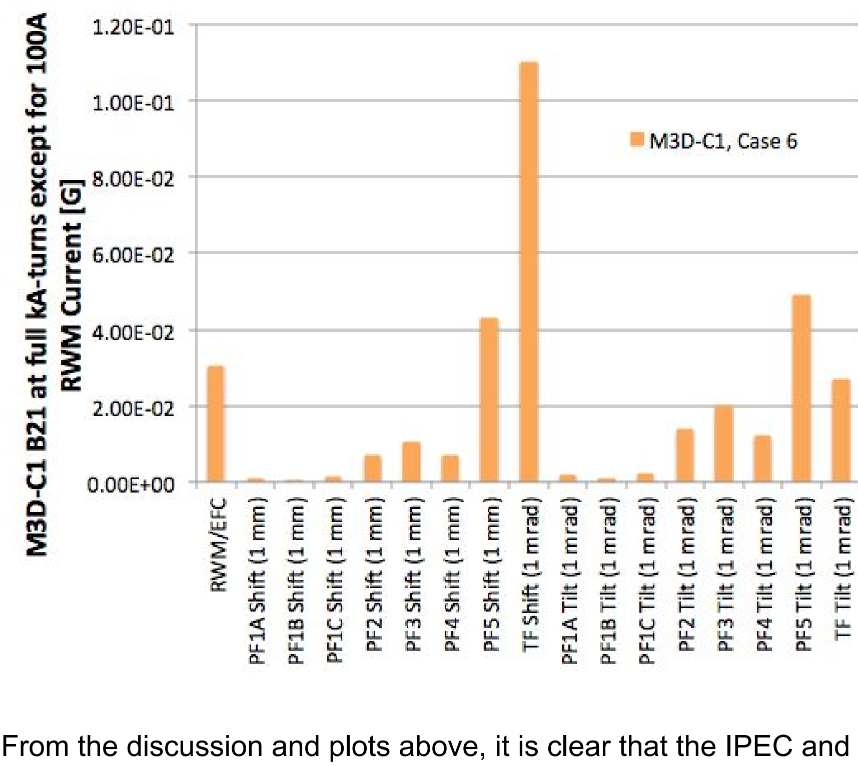


Figure 3.2.2-4*: Dependence of B_{21}, for full coil kA-turns on the TF and PF coils and 100 A on the RWM coils, on individual coil tilts and shifts in two L-mode cases using M3D-C1.*



From the discussion and plots above, it is clear that the IPEC and M3D-C1 models disagree in the relative sensitivity of TF to outer-PF perturbations. Part of this difference is due to the fact that the M3D-C1 B21 and IPEC B21 are not directly comparable quantities -- the IPEC B21 is an inferred value based on what would be present if the ideal resonant currents dissipated, and is therefore essentially a measure of the magnitude of the resonant currents; whereas the M3D-C1 B21 is the total resonant field in a resistive-MHD response model, and is therefore a measure of the tearing response of the plasma. Other numerical differences between the codes might also influence these results. In particular, neither code can properly handle a pure shift or tilt of the plasma, since this violates the boundary conditions at the magnetic axis in IPEC, and the outer conducting wall in M3D-C1. This is expected to be important in calculating the response to the TF error field, which is dominantly 1/1 in nature.

3.2.3: Additional Analysis of PF-5 shifts and TF

Additional key commentary can be found in available reports and memos.

According to the discussion of Fig. R17-3-14 of Ref. [9], the required correction phase of for the TF tilt is highly scenario dependent. This may explain some time-dependent EFC effects observed during the 2016 run. As per page 19, this phase sensitivity and time dependence is not typical of other error field sources.

According to the discussion near Fig. R17-3-9 and R17-3-10 of Ref. [9], the effect of OH coil shifts and tilts is dramatically smaller than inner-TF tilts and shifts. Therefor, it is possible to consider only the TF inner legs, and not additionally the OH coil, when defining alignment requirements relative to the outboard coils. This is reinforced in Ref. [11].

3.3: Alignment requirements

3.3.1: Development of Physics Requirements

In order to translate this data into conclusions, three ***Physics Requirements*** (PRs) are defined. These are given in Table 3.3-1.

Table 3.3.1-1: *List of Physics Requirements (PRs) that drive alignment needs*

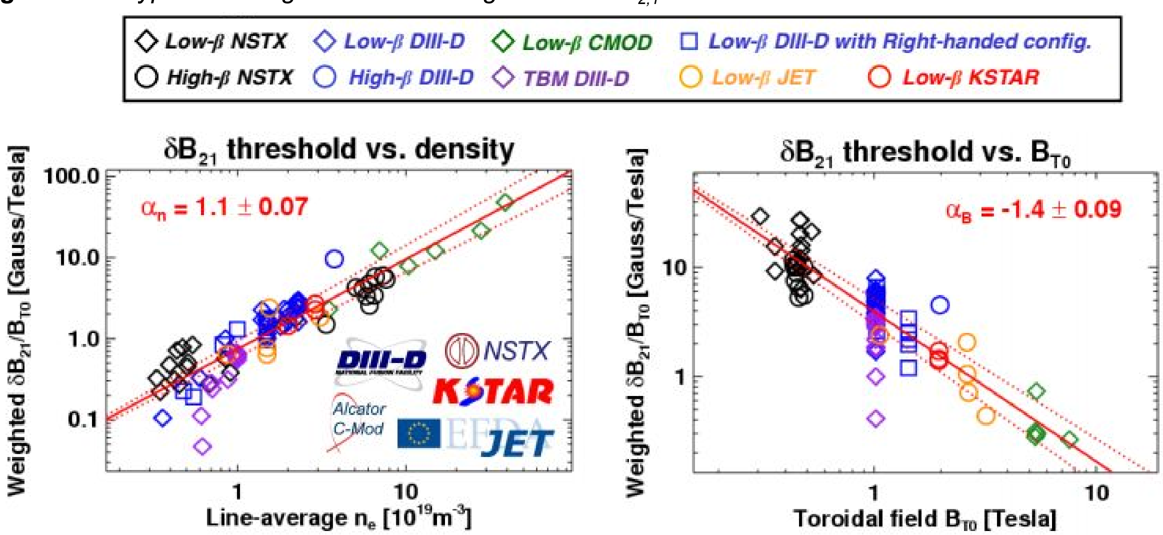
Physics Requirement Number	Physics Requirement
1	Full IPEC 2/1 EF from TF tilt/shift should be reduced to <0.5 G in L-mode
2	Full IPEC 2/1 EF from PF-5 tilt/shift should be <1.5 G in L-mode
3	TF EF NTV should be reduced to <0.9 Nm.
4	Any low-frequency EFC/DEFC coil current associated with residual error fields should be reduced to <1000 A supply current at full NSTX-U Performance (2MA, 1T).

The justifications for these PRs is as follows:

PR1: Reduced 2/1 TF EF

The limit on the $B_{2,1}$ in PR1 comes from data as in Fig. 3.3.1-1. It can be seen that the IPEC $B_{2,1}$ definition orders the data well, and that typical locking thresholds are 0.5-1 G for low-density L-mode cases. Because the TF EF phase has a strong equilibrium dependence and is therefore difficult to correct, it is deemed necessary to reduce this EF below the locking threshold level

Fig 3.3.1-1*: Typical locking thresholds using the IPEC $B_{2,1}$ definition.*



Note that the M3D-C1 resonant field calculations have not been benchmarked against experimental data in the same way, and so cannot be used against a simple threshold.

PR2: Reduced 2/1 PF-5 EF

A threshold of field of 1.5 G in L-mode from the PF-5 tilts/shifts is selected. This level of perturbation will still require substantial error field correction for some cases (low-density L-modes), but may be acceptable for some higher-density H-mode scenarios. Again, this analysis can only be done with IPEC calculations.

PR3: Reduced TF NTV

The NTV from the TF error fields is core-localized, and therefore cannot be corrected by the RWM coils. A study of TRANSP runs was done by S. Gerhardt and W. Guttenfelder, where the density was varied, while also varying which beam was on. Both new and old beamline sources were considered. The results are shown in Table 3.3.1-2.

Table 3.3.1-2: *NB torques as a function of tangency radius and density (based on TRANSP run 142301B20)*

	Torque [Nm]					
N_e [10^{14} cm^{-3}]	**R_{tan}=50**	**R_{tan}=60**	**R_{tan}=70**	**R_{tan}=110**	**R_{tan}=120**	**R_{tan}=130**
1.75	0.7201	0.9129	1.1058	1.8166	1.988	2.0709
1.5	0.7153	0.912	1.103	1.8166	1.9873	2.0592
1.25	0.7039	0.9045	1.1	1.82	1.9876	2.0493
1	0.6844	0.8971	1.098	1.8169	1.9823	2.0185

The total torque values are on order 3 Nm for NB#1, and 6 Nm for NB#2. It is necessary that the NTV not dominate the neutral beam torque. Therefor a value of (3+6)/10 = 0.9 Nm is used as the target.

PR4: EFC current <1000 A

The RWM/EFC coils are used for many applications: error field correction, dynamic error field correction, magnetic braking, fast RWM control. The total current capability is ~3 kA. This requirement reserves ⅔ of the system capability for applications beyond error field correction.

Also note that the historical level of n=1 correction was 200-400 A; this level of required correction represents already a substantial increase in correction requirement.
The implications of each physics requirement for machine alignment is discussed in the following sections.

Note also that since the resonant field components from all coils have been computed with both IPEC and M3D-C1, it is possible to do this evaluation for the outputs from each codes. This includes the β_N=5.5 case.

3.3.2: PR #1 - IPEC 2/1 Field from TF EF

This PR is based on limiting the IPEC B_{21} due to TF tilts and shifts to <0.5 G in L-mode. Limiting the IPEC m/n=2/1 field due to TF misalignments can be accomplished in multiple ways. Two examples are shown in Tables 3.3.2-1 and 3.3.2-2.

These tables have as input a postulated EF from each of the TF shift and tilt; these are indicated in the green cells on the upper left, and sum to 0.5 G. The assumption is therefore that the fields from the tilt and shift have the worst case phase. The tables then use the numerical data presented in Figure 3.2.1-1 to infer allowed shift and tilt to achieve those EFs, based on the different equilibria; these are shown in the blue cells. On the lower right in pink, the allows shifts and tilts for the L-mode cases and H-mode cases are averaged, producing the final recommendation.

***Table 3.3.2-1**: Possible inner-TF shift and tilts to achieve a 0.5 G m/n=2/1 error field.*

Total EF [G] ->	0.5						
inner-TF Shift EF [G] ->	0.25						
Inner-TF Tilt EF [G] ->	0.25						
Case ->	**1**	**2**	**3**	**4**	**5**	L-Mode Average Allowed Tilt or Shift	H-Mode Average Allowed Tilt of Shift
betaN [%mT/MA] ->	0.7	1.02	1.3	3.8	2.984		
q_0 ->	1.3	1.02	0.89	1.3	1.366		
Regime ->	L	L	L	H	H		
allowed TF shift [mm] ->	1.76	0.83	0.23	5.26	1.97	0.94	3.61
allowed TF tilt [mrad] ->	2.76	0.94	0.23	0.74	0.84	1.31	0.79

***Table 3.3.2-2**: Possible inner-TF shift and tilts to achieve a 0.5 G m/n=2/1 error field.*

Total EF [G] ->	0.5	

inner-TF Shift EF [G] ->	0.4						
Inner-TF Tilt EF [G] ->	0.1						
Case ->	**1**	**2**	**3**	**4**	**5**	L-Mode Average Allowed Tilt or Shift	H-Mode Average Allowed Tilt of Shift
betaN [%mT/MA] ->	0.7	1.02	1.3	3.8	2.984		
q_0 ->	1.3	1.02	0.89	1.3	1.366		
Regime ->	L	L	L	H	H		
allowed TF shift [mm] ->	2.82	1.33	0.36	8.41	3.16	1.50	5.78
allowed TF tilt [mrad] ->	1.10	0.37	0.09	0.30	0.33	0.52	0.31

The net result of these calculations is to show that there are different ways to achieve the stated PR1 goal. For instance, an inner-TF {shift,tilt} envelope of {1.5 mm, 0.5 mrad} as in Table 3.3.2-2 would achieve the target by this metric, as would an envelope of {0.9 mm, 1.3 mrad} as in Table 3.3.2-1. For various practical reasons, it appears that the former case is the more likely candidate for implementation.

3.3.3: PR #2 - IPEC 2/1 Field from PF-5 EF

The displacements that result in 1.5 G of 2/1 EF from the PF-5 coils are provided in Table 3.3.3-1. In particular, displacements of one PF-5 relative to the other of {2.5 mm, 0.8 mrad} are allowed.

Table 3.3.3-1*: Tilts and shifts of the PF-5 that result in 4 G $B_{2,1}$ error fields for the full PF-5 amp-turns*

Total EF [G] ->	1.5						
PF-5 Shift EF [G] ->	0.9						
PF-5 Tilt EF [G] ->	0.6						
Case ->	**1**	**2**	**3**	**4**	**5**	L-Mode Average Allowed Tilt or Shift	H-Mode Average Allowed Tilt of Shift
betaN [%mT/MA] ->	0.7	1.02	1.3	3.8	2.984		
q_0 ->	1.3	1.02	0.89	1.3	1.366		
Regime ->	L	L	L	H	H		
allowed PF-5 shift [mm] ->	2.53	2.56	1.99	1.08	1.01	2.36	1.04
allowed PF-5 tilt [mrad] ->	0.72	0.73	0.90	0.29	0.27	0.78	0.28

3.3.4: PR #3 - TF EF NTV

The total NTV torque from a sum of N NTV torques $T = \alpha_{NTV} N^2 I^2 \delta^2$ is given by $(T_1^{1/2}+...+T_N^{1/2})^2$. Based on the data in Section 3.2.1, the types of displacements to give to give 0.9 Nm are given in Table 3.3.4-1. In this case, the {shift,tilt} tolerance is {2.0 mm, 0.4 mrad}.

Shift NTV	Nm	0.63		
Tilt NTV	Nm	0.025		
Total NTV	Nm	0.91		
Case	-	4	5	
betaN	%mT/MA	3.8	2.984	
q0	-	1.3	1.366	
Regime	H or L	H	H	Average
TF Shift	mm	1.70	2.56	2.13
TF Tilt	mrad	0.41	0.38	0.40

Table 3.3.4-1*: Calculation of TF displacements to achieve 0.9 Nm of NTV torque*

3.3.5: PR #4 - Residual EFC Requirement

The established requirement is for PR3 is to have the full residual error field correction current <1000 A in all configurations. Based on numerical coefficients presented in Sections 3.2.1 and 3.2.2, the EFC correction current associated with individual coil displacements can be computed. These EFC currents are summed to assess their level relative to the 1000 A goal, as a worst case assumption.

These results are shown in Table 3.3.5-1. Different equilibria and codes are used, producing different values of the total current; the displacements selected on the right of Table 3.3.5-1 tend to average approximately 1 kA of correction current.

Table 3.3.5-1: *Error correction currents for different equilibria, for the stated displacements*

	M3D-C1, Case 3	M3D-C1, Case 1	M3D-C1, Case 6	IPEC, Case 1	IPEC, Case 2	IPEC, Case 3	IPEC, Case 4	IPEC, Case 5	PF-5 shift [mm] ->	2
sum [A] ->	679	737	1047	828	932	1257	912	933	PF-5 tilt [mrad] ->	0.7
sum [A] (PF-5) ->	80	104	395	563	545	451	648	652	TF shift [mm] ->	1.5
sum [A] (TF) ->	573	591	580	108	239	692	43	60	TF tilt [mrad] ->	0.4
sum [A] (PF-4) ->	26	42	73	158	148	115	221	221	PF-4 shift [mm] ->	2
	RWM Coil Currents [A]								PF-4 tilt [mrad] ->	0.7

The suggested displacements are as in Table 3.3.5-2.

Table 3.3.5-2: *Suggested displacements based on PR4.*

Quantity	units	Upper Bound
TF tilt relative to ideal PF-5 pair	mrad	0.4
Tilt of PF-4/5 upper relative to the lower	mrad	0.7
Shift of PF-4/5 upper relative to the lower	mm	2
Relative TF centering accuracy of relative to the ideal PF-5	mm	1.5

3.3.6: Global Alignment Tolerance Summary

The recommendations provided above result in the following constraints provided in Table 3.3.6-1.

Table 3.3.6-1*: Magnet tolerances derived from global MHD.*

<table>
<tr><th>Quantity</th><th>units</th><th>PR1</th><th>PR2</th><th>PR3</th><th>PR4</th><th>Recommendation</th></tr>
<tr><td>TF Shift Relative to Outer PFs</td><td>mm</td><td>1.5</td><td>--</td><td>2</td><td>1.5</td><td>1.5</td></tr>
<tr><td>TF Tilt Relative to Outer PFs</td><td>mrad</td><td>0.5</td><td>--</td><td>0.4</td><td>0.4</td><td>0.5</td></tr>
<tr><td>PF-5 U/L Relative Shift</td><td>mm</td><td>--</td><td>2.5</td><td>--</td><td>2</td><td>2</td></tr>
<tr><td>PF-5 U/L Relative Tilt</td><td>mrad</td><td>--</td><td>0.8</td><td>--</td><td>0.7</td><td>0.7</td></tr>
<tr><td>PF-4 U/L Relative Shift</td><td>mm</td><td>--</td><td rowspan="2">Similar to PF-5</td><td>--</td><td>2</td><td>2</td></tr>
<tr><td>PF-4 U/L Relative Tilt</td><td>mrad</td><td>--</td><td>--</td><td>0.7</td><td>0.7</td></tr>
</table>

5: Implications of Tolerances for PFC Diagnostics and NSTX-U Operations

The suggested reduction in requirements for the IBDH (2.3.1-2) and OBD (2.3.2-2) reflect the axisymmetric heat flux that the PFCs should be designed to accommodate while also having sufficient margin for enhancement due to shaping and potential coil misalignments. This should not be interpreted as an upper limit on the heat flux that can be applied to these regions during actual NSTX-U operations which will depend on the actual misalignment that is present during a given campaign. This could evolve inter-campaign due to reassembly of the centerstack and may evolve intra-campaign due to creep, etc. The upper limit also depends on the operational philosophy for the PFCs that has yet to be determined. For example, if all tiles need to maintained below the 1600 degC limit, the heat flux will be lower than if the requirement is for net carbon influx from sublimation to be below some critical threshold. The later would allow higher heat flux since the coil misalignments create low-n variation in the heat flux and thus surface temperature, creating low-n variations in carbon sources. Additionally, a change in materials to one with higher thermal conductivity (e.g. CFC's or different grades of graphite) would reduce the surface temperature for a given heat flux sustained for 5 seconds. This would increase the 'starting point' of 8 MW/m^2 and thus increase the resulting 'nominal' heat fluxes.

The implication of potential coil misalignments needs to be carried through to the PFC diagnostics to ensure any low-n variation in the energy flux to the IBDH, IBDV and OBD-R1/R2 can be resolved. This is reflected in the present version of NSTX-U-RQMT-RD-004, but should also be considered for future enhancements or extensions to other diagnostic systems not covered in present diagnostic SRD/RDs

The existence of unknown, but diagnosable coil tilt and alignment implies a range commissioning or XMP procedures may need to be created and executed. Much like the standard ‘compass-scans’ that are done to determine dominant core error fields, each of the inner PF coils misalignment may need to be characterized. As noted above, the present understanding is that these alignments create vacuum field perturbations that strongly manifest as heat flux variations during high poloidal flux expansion scenarios. The effective plasma response which could enhance or reduce this effect may also need to be examined during plasma operations.

Appendix

A1: MC analysis for field line angles other than {1,2,1} degrees.

Monte-Carlo analysis has been done for cases with different incident field line angles, but for the tolerances cases described in Section 2.2. These are shown in tables as follows:

Angles of {1,2,1} on {IBDH, IBDV,OBDR1} -> Table A1-1.
Angles of {1.5,2,1.5} on {IBDH, IBDV,OBDR1} -> Table A1-2.
Angles of {5,5.5,5} on {IBDH, IBDV,OBDR1} -> Table A1-3.

Table A1-1: Nominal heat fluxes to achieve 8 MW/m^2, for field line angles of {1,2,1} degrees.

Case	IBDH	IBDV	OBDR1
	MW/m^2	MW/m^2	MW/m^2
Fishscale Only	6.5	6.6	5.3
1	5.6	5.6	4.7
2	5.7	5.6	4.8
3	5.5	5.3	4.5
4	6.1	6.1	5
5	5.8	6	4.8
6	5.9	5.6	4.7
7	5.7	5.9	4.7
8	5.7	6	4.7

Table A1-2: Nominal heat fluxes to achieve 8 MW/m^2, for field line angles of {1.5,2,1.5} degrees.

Case	IBDH	IBDV	OBDR1
	MW/m^2	MW/m^2	MW/m^2
Fishscale Only	6.9	6.6	6
1	--	--	--
2	--	--	--
3	--	--	--
4	--	--	--
5	6.4	6	5.5
6	6.4	5.6	5.5
7	6.3	5.9	5.5
8	--	--	--

Table A1-3: Nominal heat fluxes to achieve 8 MW/m^2, for field line angles of {5,5.5,5} degrees.

Case	IBDH	IBDV	OBDR1
	MW/m^2	MW/m^2	MW/m^2
Fishscale Only	7.6	7.4	7.3
1	--	--	--
2	--	--	--
3	--	--	--
4	--	--	--
5	7.4	7	7
6	7.4	7	7
7	7.4	7.1	7
8	--	--	--