National Spherical Torus eXperiment - Upgrade

# NSTX-U

## Field Errors and Heat Flux Enhancement

### NSTXU-CALC-11-09-00

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# NSTX-U CALCULATION

## Record of Changes

| Rev. | Date | Description of Changes | Revised by |
|---|---|---|---|
| 0 | 01/12/18 | Initial Release | |
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**NSTX-U Calculation Form**

Purpose of Calculation: Evaluate Field Errors and Heat Flux Enhancement at PFCs from fabrication and assembly tolerances of Coils and PFC Tiles.

References: See References section in body of report

Assumptions: See Assumptions section in body of report

Calculation: See body of report

Conclusion: See body of report

**Executive Summary**

This report presents the impact of coils and tile tolerances on heat fluxes to the PFCs. A product of this work is a spreadsheet calculator that allows a user to study the relative importance of displacements and distortion of coils and tiles.

**Introduction**

The PFC heat fluxes could be significantly enhanced by changes to the field line impingement angles and alignment of the PFC tiles.

The heat flux parallel to a field line is much higher than the heat flux normal to an axisymmetric surface ($Q_{para}$=$Q_{norm}$/sin(alp)). At small angles (1deg for the high heat flux tiles) the $Q_{para}$ is 57 times greater than $Q_{norm}$ ($Q_{para}$ is 400 MW/m2 for a $Q_{norm}$ of 7 MW/m2). Small changes to either the tile surface normal or the flux angle or both can have a significant impact on heating (at 1deg a .5 deg change increases surface normal heat fluxes by 50%).

Changes to field lines will be introduced by non-axisymmetric misalignment of coils and adversely impact heat flux impingement angles. Tile misalignment will also impact impingement angle changes. These effects will be added to the fishscaling of the tile surfaces designed to mitigate edge heating.

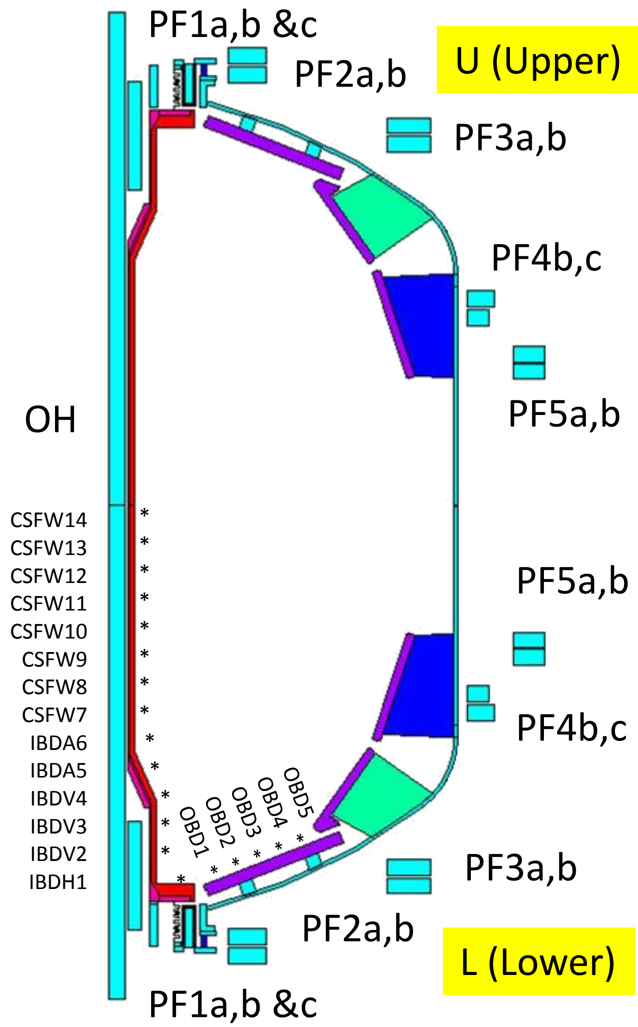
To assist in the evaluation of tolerance demands (what's important, what's not for minimizing the impact on heat flux) the influence of unit displacements and distortion – for unit coil currents – is calculated for each coil at each of the PFC tile locations. Given this matrix of coefficients [A] and any user chosen vector of displacements and distortions {x} the vector of field error at each of the PFCs {b}could be calculated by a simple matrix multiplication (ie within a spreadsheet). This approach however assumes the peak field errors occur at the same toroidal location which is not necessarily true resulting in an overestimate of the total field error. It also ignores the effect of the direction of displacement, rotation and distortion.

To overcome this, the field error toroidal distribution is calculated as well. For small perturbations the error fields are sinusoidal varying in magnitude, phase and mode number. For each coil unit perturbation (displacement, rotation or distortion) the distribution of field errors normal to tile surfaces are calculated then fourier decomposed to determine the magnitude, phase and mode number.  Given a vector of displacements and direction (ie toroidal angle) as well as current scaling, the toroidal distribution of field errors from each coil is evaluated and summed. The maximum normal field error of this distribution and the local TF field determine the maximum change in field angle. Adding to that the tolerance in surface normal and/or fishscale angle leads to the heat flux enhancement actor.

**Assumptions**

Small perturbations are assumed which allows the superposition of field errors from each source.

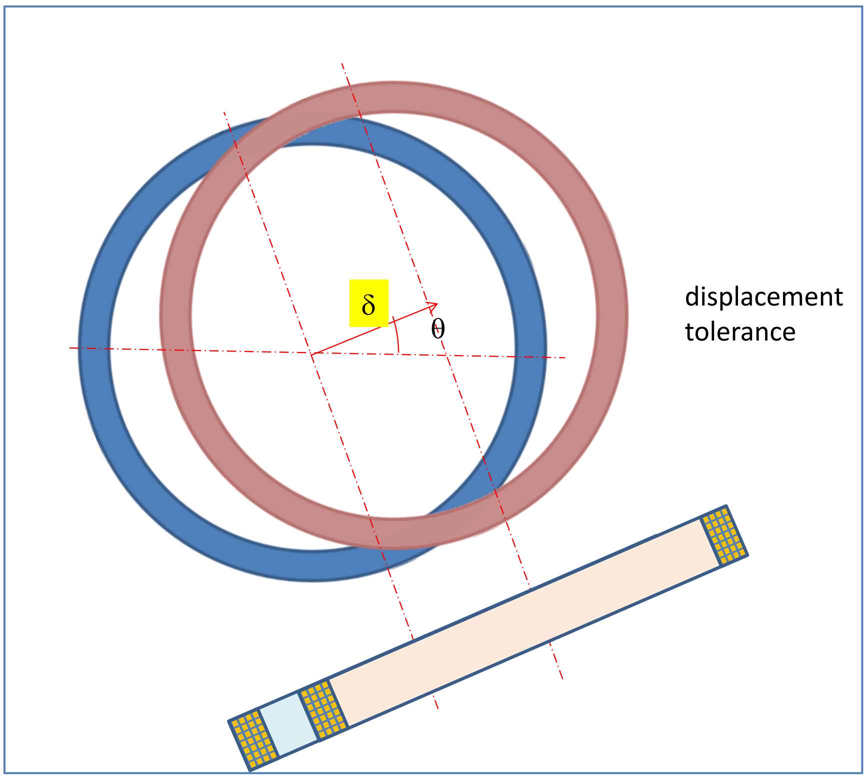
The PF coil Geometry and location of PFCs is given below:



Field Errors and Heat Flux Enhancement

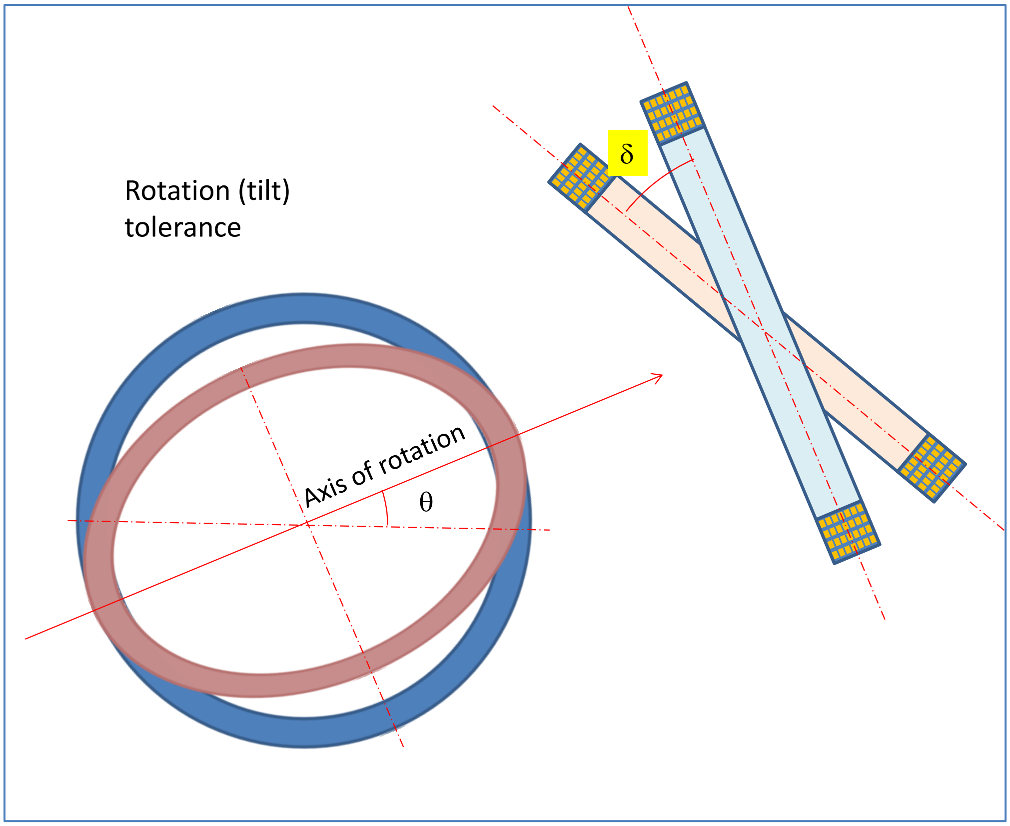
| Coil | rc, m | zc, m | dR, m | dZ, m | Turns | Cur, kA |
|---|---|---|---|---|---|---|
| OHU | 0.2421 | 1.0604 | 0.0693 | 2.1208 | 884 | 24 |
| PF1a | 0.3244 | 1.5906 | 0.0625 | 0.4633 | 64 | 19 |
| PF1b | 0.4004 | 1.8042 | 0.0336 | 0.1812 | 32 | 13 |
| PF1c | 0.5505 | 1.8136 | 0.0373 | 0.1664 | 20 | 16 |
| PF2a | 0.8000 | 1.9335 | 0.1627 | 0.0680 | 14 | 15 |
| PF2b | 0.8000 | 1.8526 | 0.1627 | 0.0680 | 14 | 15 |
| PF3a | 1.4945 | 1.6335 | 0.1864 | 0.0680 | 15 | 16 |
| PF3b | 1.4945 | 1.5526 | 0.1864 | 0.0680 | 15 | 16 |
| PF4b | 1.7946 | 0.8072 | 0.0915 | 0.0680 | 8 | 16 |
| PF4c | 1.8065 | 0.8881 | 0.1153 | 0.0680 | 9 | 16 |
| PF5a | 2.0128 | 0.6521 | 0.1353 | 0.0686 | 12 | 34 |
| PF5b | 2.0128 | 0.5780 | 0.1353 | 0.0686 | 12 | 34 |

The coil perturbations considered are displacements $\delta x$, rotations/tilt $\delta\gamma$ and elliptical (n=2) distortions $\delta r$:

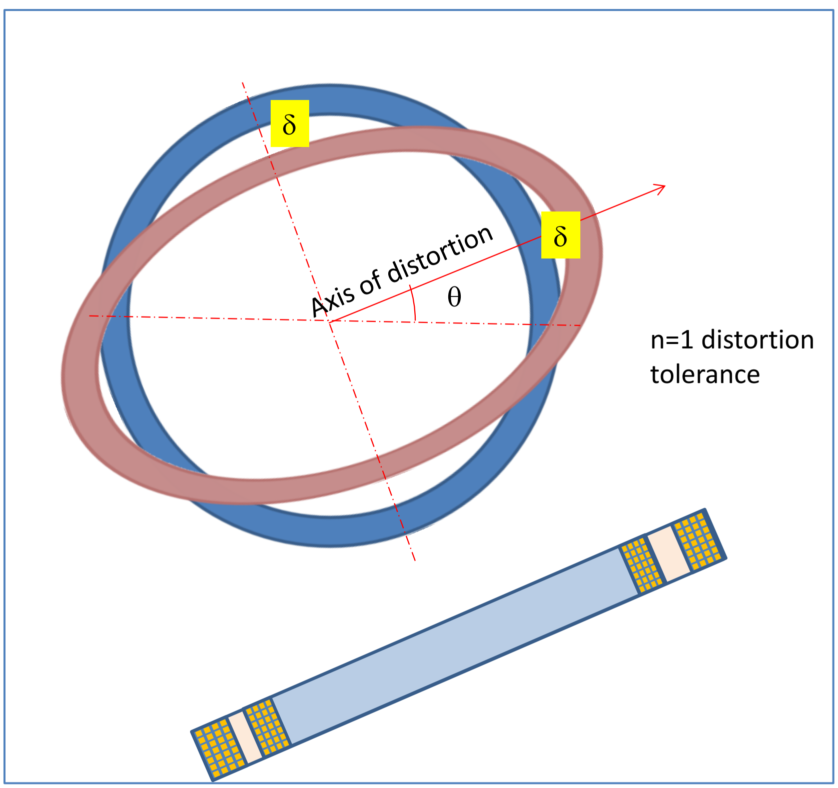



displacements $\delta x$

Field Errors and Heat Flux Enhancement




rotations/tilt δγ




elliptical (n=2) distortions δr

Field Errors and Heat Flux Enhancement

## Method of Analysis

Field Errors

The field errors for a given coil with a unit current (10 kA) and unit perturbation (1 mm or 1 mrad) are calculated by subtracting the fields from an unperturbed coil from a perturbed coil. Only the field normal to a tile is of interest. Calculations are done along a number of toroidal locations then Fourier decomposed to get the magnitude $B_{mag}$, phase angle $\phi$ and dominate mode number m. For free body displacements or rotations/tilts along a radial vector a mode number of 1 is found as expected. Elliptical distortions have a mode number of 2 which is the highest mode number considered.

Calculations are done for displacements, rotation and distortions in the radial direction at a zero degree toroidal angle. Perturbations at other toroidal angles are just phase shifted and are handled as such. The field error variation from a given source perturbation is then

$$B_{coil}(\theta) = B_{mag}*\sin(m*(\theta-\theta_0+\phi))*I_{coil}*\delta$$

where

$B_{mag}$ is the magnitude of the field error from a unit perturbation
m is the mode number
$\phi$ is the phase angle

and

$\theta_0$ is the toroidal direction of the perturbation
$I_{coil}$ is the actual coil current in 10 kA
$\delta$ is the actual perturbation magnetude (in mm for displacements $\delta x$ and distortion $\delta r$ or mrad for rotations $\delta r$)

The total normal field error is the sum of each distribution. The change in field angle, $\delta\alpha$, is calculated using the max of the total normal field distribution and the local TF field. Given the nominal field angle $\alpha$, and the design fishscale angle $\beta$ and its tolerance $\delta\beta$, the heat flux enhancement is

$$EF = \sin(\alpha_+\delta\alpha+\beta+\delta\beta)/\sin(\alpha)$$

And the enhanced heat flux is just

$$Q_{ef} = Q_{nom}*EF$$

The field calculations were done using FORTRAN routines (ie coilfld.f) developed and benchmarked for the NCSX program. While some of the perturbations could be analyzed with axisymmetric codes by simply perturbing the target points in the opposite direction, other perturbations such as distortion are intrinsically non axisymmetric. To handle this 3D multifilament coil models were created and perturbed. PF, OH and TF coils were modeled in similar ways. The TF was represented as a very long filament along the machine axis providing a 1/R field normal to the axis. The filament was displaced or tilted to produce the error field when the unperturbed 1/R field was subtracted out.

The output of the FORTRAN code is $B_{mag}$, m and $\phi$ for each coil (PF1a, PF1b, PF1c, PF2, PF3, PF4 & PF5 Upper and Lower plus OH and TF); each perturbation (displacement dx, rotation rx and n=2 radial distortion); at each PFC location (IBDH1, IBDV2-4, IBDA5-6 and OBD1-5). The data was imported into a spreadsheet organized with worksheets for each PFC location and an interface sheet for specifying user parameters (actual coil perturbation magnitudes, direction/phase and currents plus tile surface normal perturbations). Other parameters needed are tile design fishscale angles, design impingement angles and nominal heat fluxes.

PFC Tolerances

The design fishscale angle $\beta$ and its tolerance $\delta\beta$ used above to calculate the heat flux enhancement factor is a function of the PFC tolerances. Of the six degrees of freedom on the alignment of the tiles, only the out of plane components significantly impact the required fishscale angle: displacement normal to the surface (dn) and rotations about the poloidal (rp) and toroidal (rt) axes. All these can displace all or part of the tile toward the plasma. The inplane components – displacements in poloidal and toroidal directions and rotations about the normal axis – while they may slightly alter the gaps between tiles do not significantly impact the calculation of the fishscale angle. The tile fabrication tolerances are expected to be small relative to the alignment tolerances and again the inplane components – width and length – are not important. The tile thickness and the surface flatness are lumped into a single parameter (f). The fishscale angle chosen is calculated to shade the leading edge of a tile from the largest tile to tile offset that might occur if all the tolerances act unfavorably. The maximum incident field angle is used to assure there is not gap heating over the full range of incident field angles. The governing equation of fishscale angle is then

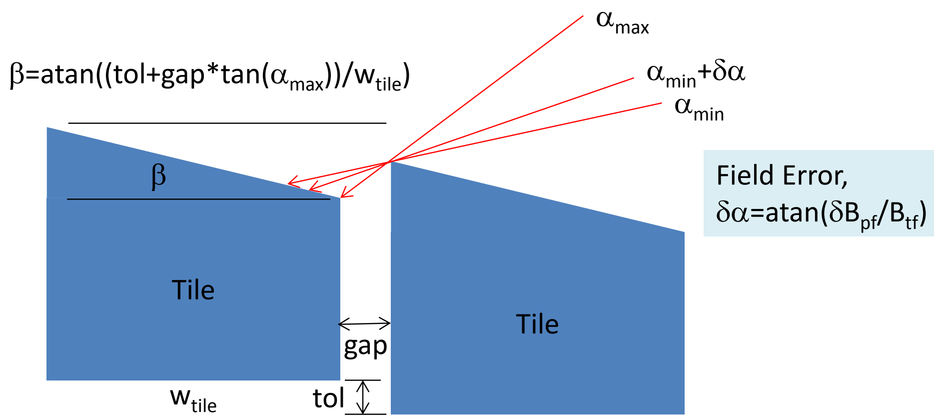
$$\beta=\mathrm{atan}((tol+gap*\tan(\alpha_{max}))/w_{tile})$$

Here tol is the summation of the contributions from all sources which assumes the heat tile is displaced toward the plasma and the shielding tile is displaced away from the plasma.

The figures bellow illustrate the calculation of the fishscale angle $\beta$ and the accumulation of tolerances tol.

# Field Errors and Heat Flux Enhancement

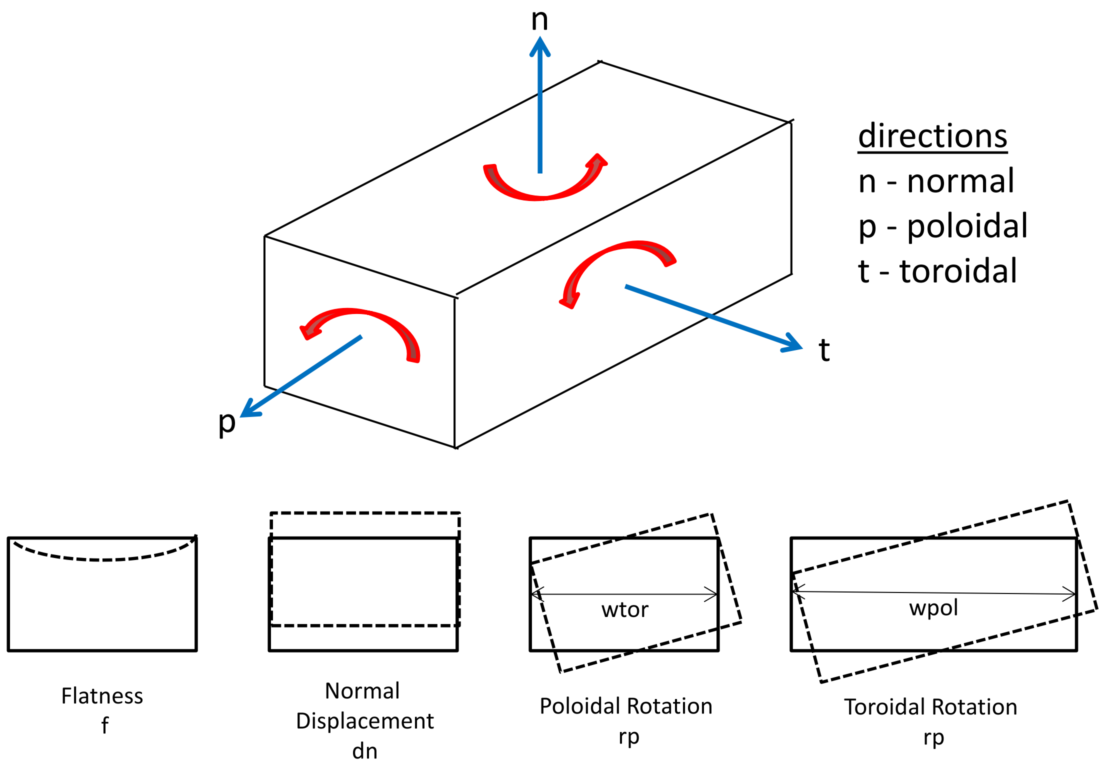
$Q_{||}=Q_{nom}/\sin(\alpha)$
$Q_{\perp}=Q_{||}*\sin(\alpha+\beta)$
$EF= Q_{\perp}/Q_{nom}=\sin(\alpha+\beta)/\sin(\alpha)$




Basic Fishscaling Heat Flux Enhancement given by $EF_{fs}=\sin(\alpha_{min}+\beta)/\sin(\alpha_{min})$

Addition Enhancement from Field Errors given by $EF_{tot}=\sin(\alpha_{min}+\beta+\delta\alpha)/\sin(\alpha_{min})$
(assumes $Q_{||}$ unchanged by field errors)

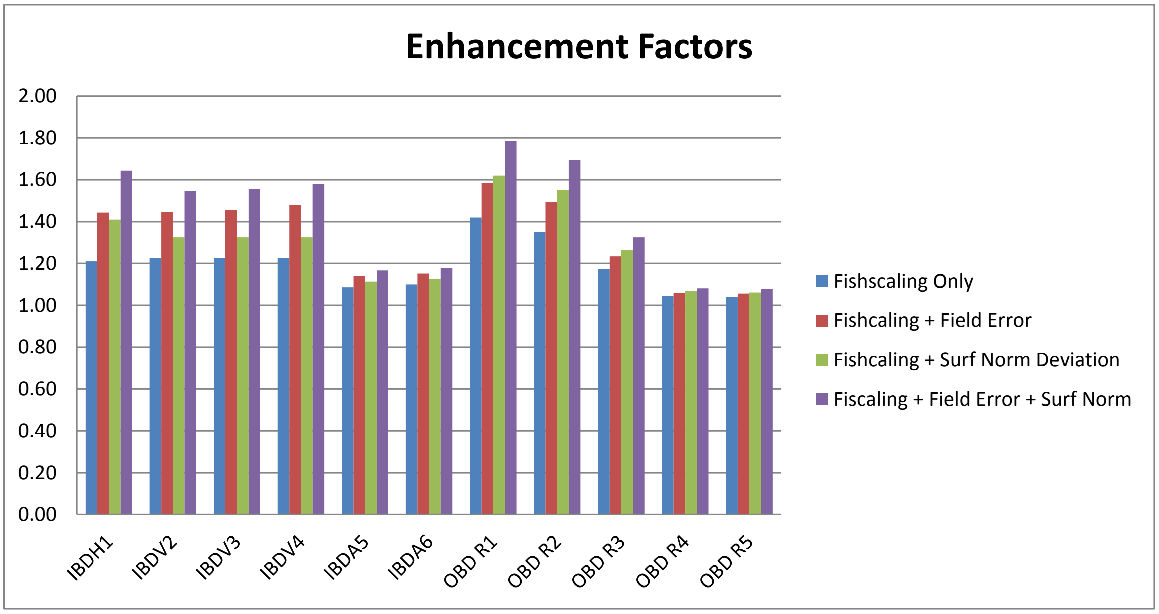
# Field Errors and Heat Flux Enhancement

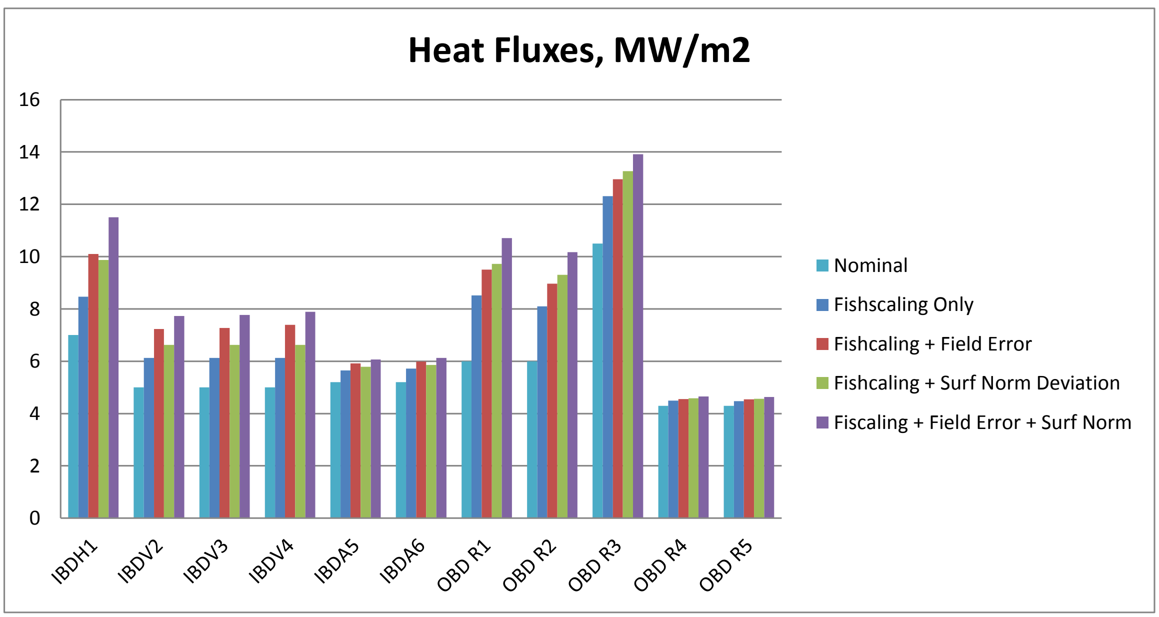



Max Displacement at a corner = f + dn + wtor/2*sin(rp) + wpol/2*sin(rt)

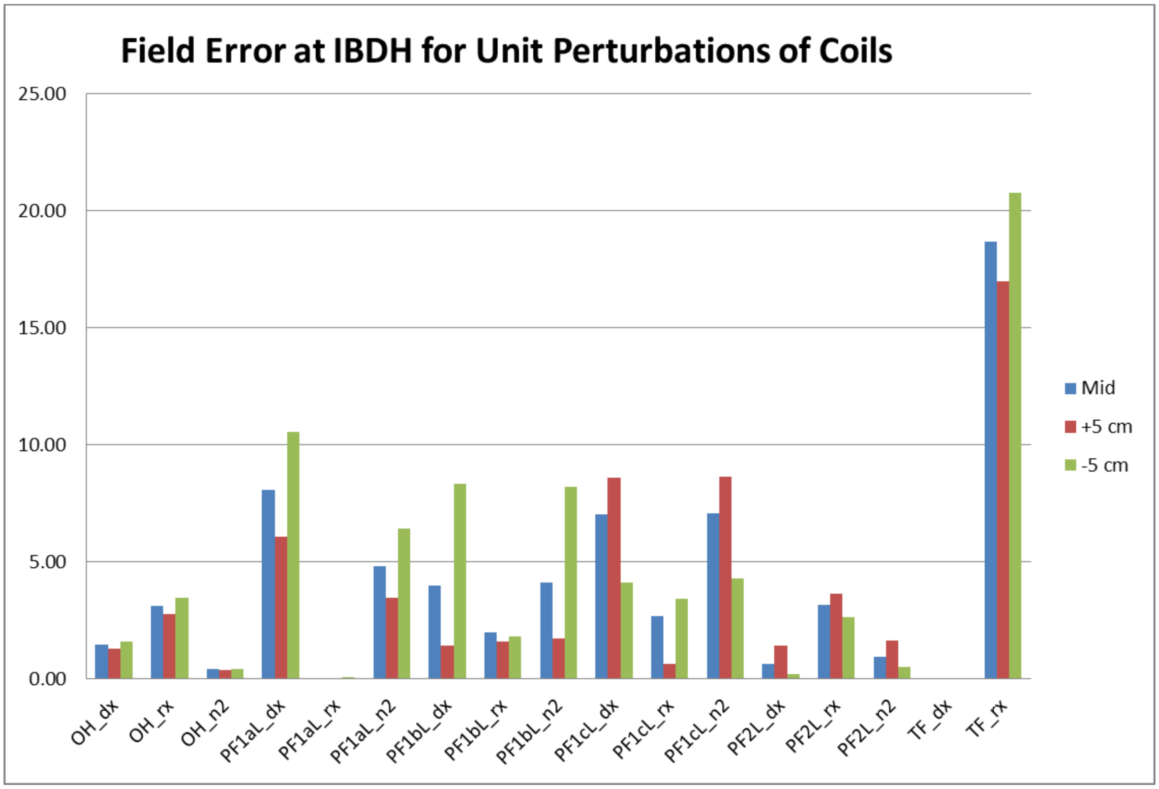
**Results**

The results of this analysis are contained in the accompanying spreadsheet "Field Error Calc.xlsx". Below is a sample of some of the results obtained. Note this is a tool designed to be changed so the results below represent only one snapshot based on 10 kA in each PF coil with nominally 1 mm or 1 mrad perturbations in displacement, rotation and distortion using the existing design parameters for fishscale angles, design impingement angles and nominal heat fluxes.




The above results were based on using a single point at the center of each PFC tile to evaluate field errors. Further examination showed a significant gradient can exist within a tile so the spreadsheet was expanded to include 3 points per tile: the middle, +5cm poloidally and –5 cm poloidally (ie near the edges). The distribution of field errors at the IBDH from each coil perturbation is shown below. Others can be obtained from the spreadsheet.




**Summary**

This analysis results in a analytic tool to be used by others to study the effect of tolerances on PFC heat fluxes.