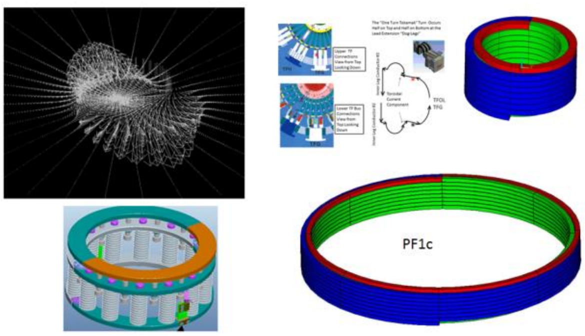
NSTX-U

Loads and Error Fields Due to Coil Winding Patterns and Alignment Tolerances

NSTXU-CALC-131-08-00

March 18 2018



Prepared By:

Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.03.29 08:39:55 -04'00'

Peter Titus, Engineering Analyst

	Reviewed By:
Content in Table 4.0-3 and 4.0-4	
	Arthur Brooks Engineering Analysis Division
Content in Table 4.0-3 and 4.0-4	Art Brooks Digitally signed by Art Brooks Date: 2018.03.29 09:39:57 -04'00'
	Stefan Gerhardt, Integration RE

PPPL Calculation Form

Calculation # **NSTXU-CALC-12-01-01** Revision # **00** ____ WP #, **1672**
(ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

The purpose of this calculation is to evaluate loads on the PF and other coils due to winding patterns and position errors. These loads are summarized in the Inner PF Requirements Document [2] , and the purpose of this report is to document the calculations that support the tabulated values in Ref [2]. Secondarily, error fields are calculated for a selected number of coils and errors to compare with a more exhaustive assessment in CALC NSTXU 11-09-00 prepared by Art Brooks

References

These are included in the body of the calculation, in section 6.3

Assumptions (Identify all assumptions made as part of this calculation.)
At this writing, the PF position errors are assumed to be 5mm lateral position error and .57 degrees rotation of the coil with respect to the toroidal field. The actual position errors and resulting loads will be a function of the tile heat flux "enhancement" accommodated in the tile design and what the coil and coil support designers can achieve. Forces and moments computed in this calculation can be assumed to be linearly varying with respect to position errors

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

Cognizant Engineer's printed name, signature, and date

____

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

____

2.0 Table of Contents

Part 1 Loads on Coils Due to Position Errors

Part 2 Field Errors Due to Coil Position Errors

3.0 Revision Status Table

Rev 0	Initial Issue

4.0 Executive Summary

NSTX Upgrade is a large spherical tokamak being built, and operated at Princeton Plasma Physics Laboratory. In this calculation a number of load interactions with the toroidal fields and misaligned poloidal fields are investigated. The purpose of this calculation is to evaluate loads on the PF and other coils due to winding patterns and position errors. These loads are summarized in the Inner PF Requirements Document [2] , and the purpose of this report is to document the calculations that support the values in table 2.2.-1in the requirements document in Ref [2]. Secondarily, error fields are calculated for a selected number of coils and errors to compare with a more exhaustive assessment in CALC NSTXU 11-09-00 prepared by Art Brooks

There are many physics issues and issues with respect to plasma facing components that are effected by coil position errors. These are addressed elsewhere. Coil and coil support designs are effected by the coil position error loads. In this report, loads are calculated for arbitrarily selected shifts and rotations. The project has an extensive metrology program and assessments of manufacturing tolerances that ultimately

Engineering Motivations:

Net Loads on coils
Magnetic-Structural Stability, Strength , stiffness and accuracy of slings
PF4/5 ovality – Accept n=1, Assess effects of stuck slides? Vertical Motion/Bending?
PF2,3 Position errors if slides stick
TF One Turn – Where is it and what effect does it have? This is not included in the currents in the 96 equilibria. It occurs in the lead extension area. Locally, an additional PF coil-like current may affect coil loading. The TF toroidal current is one turn at 130ka vs 400 ka in pf1b

Table 4.0-1 Coil Data

Coil	nr	nz	r	z	dr	dz
OH	4	222	.2421	0	.0694	4.2605
PF1a	4	15.25	.32334	1.5906	.06985	.4634
PF1b	2	10	.39217	1.8042	.039624	.1814
PF1c	2	8	.555	1.8136	.051816	.1664

Part 1 Loads on Coils Due to Position Errors

Lateral shifts of coils with respect to the toroidal field produce a moment about an axis parallel to the shift vector.
At this writing, the PF position errors are assumed to be 5mm lateral position error and .57 degrees rotation of the coil with respect to the toroidal field. The actual position errors and resulting loads will be a function of the tile heat flux “enhancement” accommodated in the tile design and what the coil and coil support designers can achieve. Forces and moments computed in this calculation can be assumed to be linearly varying with respect to position errors

Table 4.0-2 Moments for a net lateral translation of 5mm (x direction) with respect to the TF centerline, Perfect Axisymmetric Winding, Newton Meter (Input to [2] Table 2.2.1)

Coil	file	Mx (N-m)	Calculation Section
OH	ocoi	235422.9	8.0
PF1a	atra	20037	9.0
PF1b	btra	6290.14	10.5
PF1c	ctra	5030.7	11.0

Table 4.0-3 .57deg Rotation about x, Perfect Circular Winding in a TF Field , Newton, Newton Meter (Input to [2] Table 2.2.2)

Coil	file	fx	Calculation Section
OH	ocoi	468345	8.0
PF1a	arot	39893	9.0
PF1b	brot	12507	10.6
PF1c	crot	10012.9	11.0

Table 4.0-4 No Translation, No Rotation, Helical Winding in TF Field , Newton, Newton Meter (Excluding the Leads)

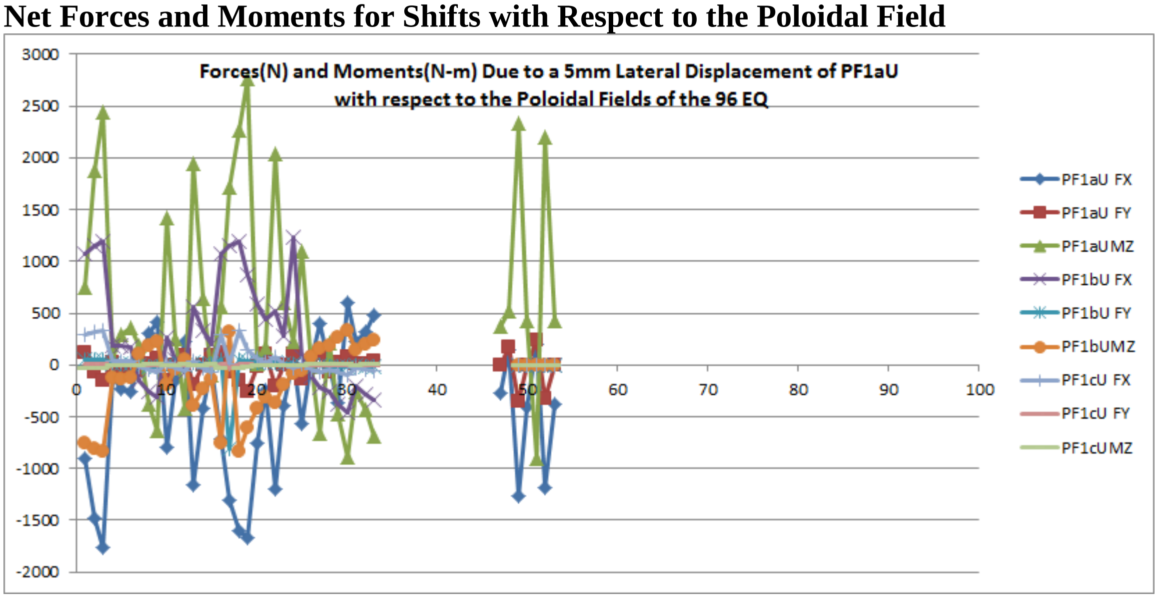
Coil	file	fx	fy	fz	Mx	My	Mz	Sect
PF1a	acoi	880	-2849.9	144.66	-606	0	-991	9.4
		1107	3039	-245				9.4
PF1b	bcoi	-29.9	-995.64	3.71	-37.83	0	-342.1	10.3
PF1c	ccoi	-7.7	798	-31	42	.172	450	11.4

Table 4.0-5 5mm Translation, No Rotation, Helical Winding in TF Field , Newton, Newton Meter

Coil	file	fx	fy	fz	Mx	My	Mz	Sect
PF1a	acoi							
PF1b	bcoi	-29.604	-987.3	3.63	4962.7	0	-344.26	10.4
PF1c	ccoi							

Comparing magnitudes of forces resulting from just the helical winding geometry to those from shifts and tilts, the helical winding effect is at least an order of magnitude lower. This is the rational for using circularly swept conductors in the load assessments for the coil and sling support

Net Forces and Moments for Shifts with Respect to the Poloidal Field



In the figure above the blue line with a diamond labeled PF1aU FX ranges from -1750 to 500 N compared with 39893N in table 4.0-3 for a 5.9 degree rotation. The interaction with the PF field is significant, but doesn't have the same potential for loads as interactions with the TF field.

Part 2 Field Errors Due to Coil Position Errors

There are a few sources of field errors from position errors .and other geometric effects they impact the plasma performance and a significantly the incident angle variation on tile heat loads –Use of helical windings significantly improves the errors. The coil lead separation. For the inner PF coils have been quanitifed

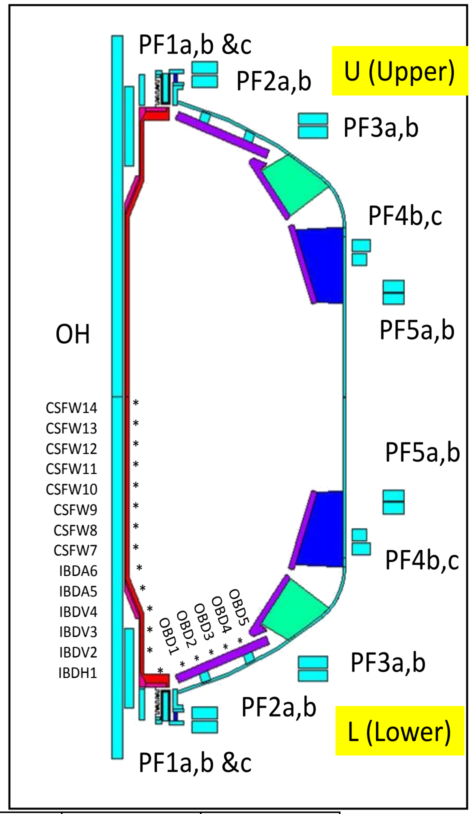
Approx 5 mm height change due to casing heat up

Top of oh moves down .120 as it is energized

Startup eddy currents in new tile support structures. Is 90 degree segmentation too coarse 180 degree segments in Danny's heater?

TF Ripple – With Position tolerances

Any Instrumentation needed to track



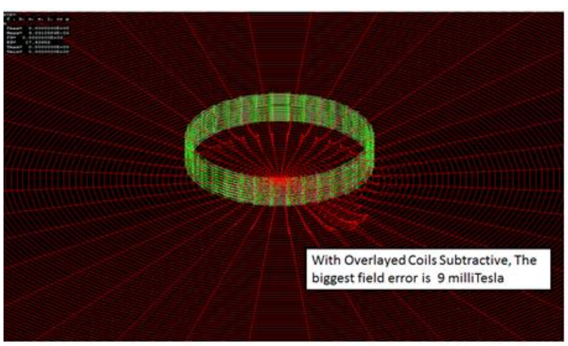
Review of Art Brooks Tile Field Errors - Translations

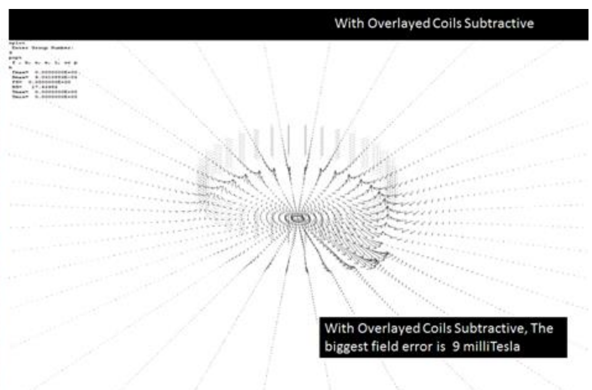
	file	Translation (.001m)	Titus	Brooks		
PF1au	aerr					
IBDH1	aerr	Peak	-1.7366e-3 T -17.366 Gauss (-13.8Gauss)			
IBDH1		Middle	9.88 Gauss	8.18 Gauss		
IBDV2				29.39Gauss		
PF1b	berr	Middle				
IBDH1	berr	Middle	3.066 Gauss	3.65 Gauss		
IBDH1		Peak (Inner Rad)	22.37Gauss			
PF1c	cerr					
IBDH1		Middle	9.4e-4 9.4 gauss	8.58gauss		
		Outer Edge	1.7e-3 17 gauss			
OH		.007 Vertical	.9906e-3 9.9 Gauss			

Review of Art Brooks Tile Field Errors - Rotations

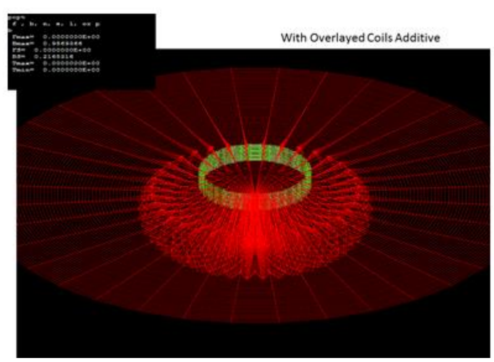
	File	Rotation (Rad)	Titus (Gauss)	Brooks Gauss)		Section
TF IBDH	Ter2	.001 Peak	22.91	22		18.0
TF IBDH	Ter2	.001 Mid	19.55	18.5		18.0
TFIBDV	Ter2.txt	.001 OD	16.86	17		18.0
PF1au		.001				
IBDH1		Peak	.9 Gauss			
IBDH1		Middle	.09 Gauss	.05		
IBDV2				29.39Gauss		
OH		.007vert	.9906e-3			
PF1b		Middle	3.9			
PF1b		Peak (Inner Rad)	5.32			
PF1c Lead			1.37 MilliT 13.7 Gauss			
IBDH1		Middle	6.684Gauss	4.06		
IBDH1		Outer Edge	5.14			
PF1a Lead			2.1milli T 21 Gauss			

Two PF1b coils are overlayed – One with stacked 180 degree transitions, and the other an "ideal" coil with only circular current vectors





Because of the net loads developed in PF1a due to the TF field, Mike Kalish is investigating the use of a spiral wound layout to minimize lateral loading. PF1b has lower loads because it is shorter and a bit further away from the TF. Mike wants some freedom to keep the most efficient winding pattern he can. The only concern I had was that the transitions might produce a field error close to the X point. I overlayed an "ideal" conductor layout and a coil with stacked 180 degree transitions and differenced the field they produce. The biggest variation I got was 9 milli-Tesla on a surface .2m below the coil centerline. Do you think this will be OK? -Peter



We have stick models of PF1aL and PF1cU courtesy of Wenping and Jiarong estimates of the fields due to these were run and the field errors obtained are t 1.3 for the PF1c and 2.1 milliTesla from PF1bl

5.0 Digital Coil Protection System.

There is no input to the DCPS planned

6.0 Design Input

6.1 Criteria

Loads will be provided to the design and analysis engineers for evaluation as to the acceptability with respect to criteria for the supports and coils.

Effects of field errors will be incorporated into the tile assessments of resulting heat flux changes in accordance with calculation #

6.2 References

[1] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[2] "Inner-PF Coil Interfaces to Coil Support Designs and Cooling Systems" NSTX-U-RQMT-RD-012-00 S. Gerhardt March 2018
[5] "Stress Analysis of ATJ Center Stack Tiles and Fasteners" NSTXU-CALC-11-03-01 Revision 1 by Art Brooks
[6] Global Thermal Analysis of Center Stack Heat Balance,NSTXU-CALC-11-01-00 A. Brooks June 1, 2011
[7] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 6, P. Titus, August 3 2015, Original issue by C. Neumeyer, March 30, 2009
[8] Inductive and Resistive Halo Current s in the NSTX Centerstack, A.Brooks, Calc # NSTX-103-05-00
[9] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-01 March 30, 2012 Rev 0/1 by Len Myatt.
[10] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-02 May, 2014 Rev 2 by Len Myatt. Rev 2 by A Zolfaghari and A Brooks
[11] NSTX Integrated Machine Bakeout Operations, D-NSTX-OP-G-156, Rev 4 Mark Cropper
[12] Microtherm Thermal Insulation Solutions, Product Performance Data, www.microthermgroup.com Microtherm Inc. 3269 Regal Drive Alcoa, Tennessee 37701 T. (+1) (865) 681 0155 F. (+1) (865) 681 0016 E. sales@microtherm.us
[13] CHI Bus Bar Analysis NSTXU-CALC-54-0 P. Titus, November 21 2013
[14] On Wed, Oct 22, 2014 at 10:31 AM, William Blanchard <wblancha@pppl.gov> wrote: All,
The majority of leaks are on the inside of the can in the 10-7 t-l/sec range. We recommend these be sealed with leak sealer (good to 450 C). There appears to be one leak on the outside corner that will have line of sight to the plasma. S. Vinson is localizing and measuring the leak rate. If it is in the 10-7 range, we recommend using leak sealer for that leak also. Bill Blanchard Joseph Winston
[15] Viton Seal Properties http://www.row-inc.com/techspecs.html
[16] NSTX Integrated Machine Bakeout Operations, D-NSTX-OP-G-156. M. Cropper, Rev 4 August 28 2015
[17] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2

7.0 Models

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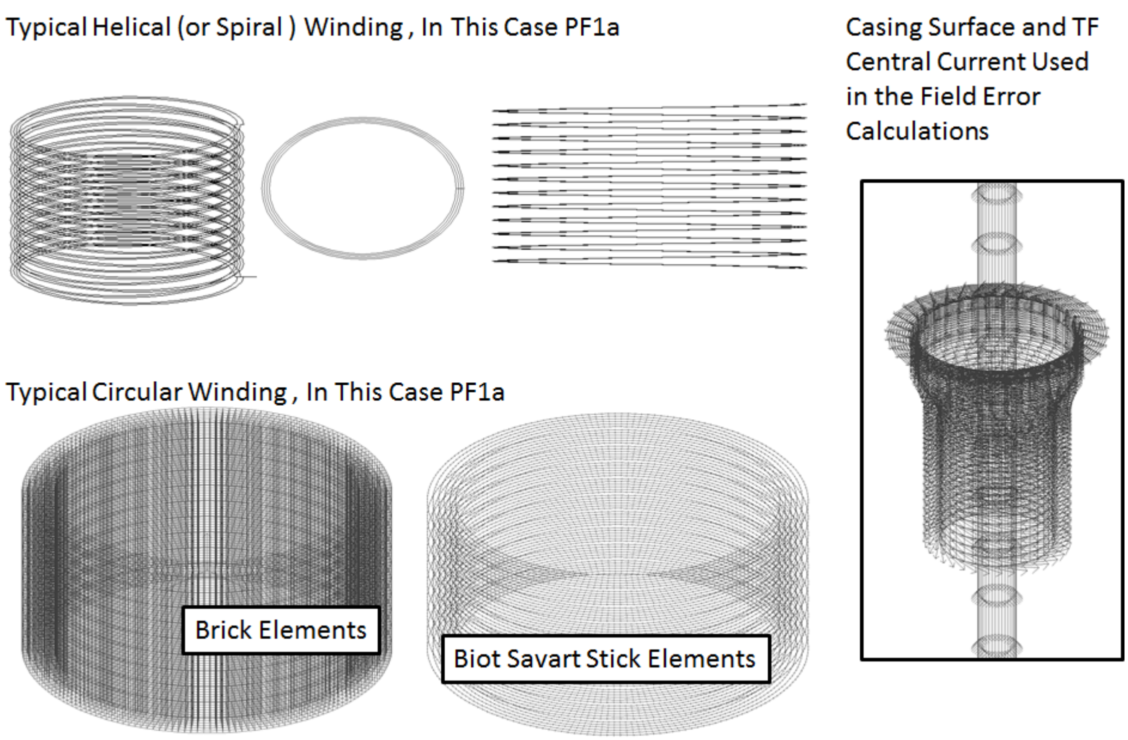

Figure 7.01 Biot Savart Stick Elements Used for PF1a Analyses
Helical or spiral winding patterns were first generated with a Treoie Basic Code (Appendix B)

7.2 Model and Analysis Used for Net Forces and Moments for Shifts with Respect to the Poloidal Field

```
! NSTX coil 3D Coil Shift analysis
pfcb
33
 1 , .2344 , .0021 , .01 , 4.3419 ,2,20
 2 , .2461 , .0067 , .01 , 4.2803 ,2,20
 3 , .2577 , .0022 , .01 , 4.2538 ,2,20
 4 , .2693 ,-.0021 , .01 , 4.1745 ,2,20
 5 , .3184957 , 1.5906 , .069664565 , .50439 ,8,20
 6 , .3886730 , 1.8042 , .033800 , .1749101 ,8,8
 7 , .56 , 1.8252 , .042 , .1206 ,8,8
 8 , .7992 , 1.8526 , .1627 , .068 ,8,8
 9 , .7992 , 1.9335 , .1627 , .068 ,4,4
 10 , 1.4829 , 1.5696 , .1631 , .034 ,4,4
 11 , 1.4945 , 1.5356 , .1864 , .034 ,4,4
 12 , 1.4829 , 1.6505 , .1631 , .034 ,4,4
 13 , 1.4945 , 1.6165 , .1864 , .034 ,4,4
 14 , 1.795 , .8711 , .0922 , .034 ,4,4
 15 , 1.8065 , .9051 , .1153 , .034 ,4,4
 16 , 1.7946 , .8072 , .0915 , .068 ,4,4
 17 , 1.795 ,-.8711 , .0922 , .034 ,4,4
 18 , 1.8065 ,-.9051 , .1153 , .034 ,4,4
 19 , 1.7946 ,-.8072 , .0915 , .068 ,4,4
 20 , 2.0118 , .6489 , .1359 , .0685 ,4,4
 21 , 2.0118 , .5751 , .1359 , .0685 ,4,4
 22 , 2.0118 ,-.6489 , .1359 , .0685 ,4,4
 23 , 2.0118 ,-.5751 , .1359 , .0685 ,4,4
 24 , 1.4829 ,-1.5696 , .1631 , .034 ,4,4
 25 , 1.4945 ,-1.5356 , .1864 , .034 ,4,4
 26 , 1.4829 ,-1.6505 , .1631 , .034 ,4,4
 27 , 1.4945 ,-1.6165 , .1864 , .034 ,4,4
 28 , .7992 ,-1.8526 , .1627 , .068 ,8,8
 29 , .7992 ,-1.9335 , .1627 , .068 ,8,8
 30 , .56 ,-1.8252 , .042 , .1206 ,8,8
 31 , .3886730 , -1.8042 , .033800 , .1749101 ,8,8
 32 ,.3184957 , -1.5906 , .069664565 , .50439 ,8,20
 33 , .9344 , 0 , .5696 , 1 ,6,8
zero
egrp
0
ngrp
0
gpla
.1,.05,40,-2.5,.05,100
grpmat
0,10
repla
grid
Zero
seal
0
srel
1,1
srel
2,1
srel
3,1
srel
4,1
divi
1,1,4,1
snal
1
merge
1,.0001
redu

irdt
2
pfcu
33,4,4,1.1
      1 , 2.8782515 , -5.3039999 , 0.0000000 , 2.8782515 , -
      2 ,  2.878252   , -5.304000   , 0.0000000E+00 ,  2.878252
      3 ,  2.878252   , -5.304000   , 0.0000000E+00 ,  2.878252
      4 ,  2.878252   , -5.304000   , 0.0000000E+00 ,  2.878252
      5 , 0.4023682   , -0.4165696   , -0.3884800   , -0.3743345
      6 , -4.8787646E-02 , 0.2617024   , 0.3022432   , 0.3247257
      7 , 5.2048396E-02 , 0.2275660   , 0.2661020   , 0.2874393
      8 , 0.1581762   , -2.5680201E-02 , 4.0668599E-02 , 7.6548636E-02
      9 , 0.1581762   , -2.5680201E-02 , 4.0668599E-02 , 7.6548636E-02
     10 , -5.6940049E-02 , -7.3950097E-02 , -6.1753996E-02 , -5.5138741E-02
     11 , -6.5074340E-02 , -8.4514394E-02 , -7.0575997E-02 , -6.3015707E-02
     12 , -5.6940049E-02 , -7.3950097E-02 , -6.1753996E-02 , -5.5138741E-02
     13 , -6.5074340E-02 , -8.4514394E-02 , -7.0575997E-02 , -6.3015707E-02
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     19 , -1.8697971E-02 , 2.8452000E-02 , 2.7856002E-02 , 2.7553849E-02
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     21 , -0.2518167   , -0.3049860   , -0.2950068   , -0.2896084
     22 , -0.2518167   , -0.3049860   , -0.2950068   , -0.2896084
     23 , -0.2518167   , -0.3049860   , -0.2950068   , -0.2896084
     24 , -6.5074340E-02 , -8.4514394E-02 , -7.0575997E-02 , -6.3015707E-02
     25 , -5.6940049E-02 , -7.3950097E-02 , -6.1753996E-02 , -5.5138741E-02
     26 , -5.6940049E-02 , -7.3950097E-02 , -6.1753996E-02 , -5.5138741E-02
     27 , -6.5074340E-02 , -8.4514394E-02 , -7.0575997E-02 , -6.3015707E-02
     28 , 0.1581762   , -2.5680201E-02 , 4.0668599E-02 , 7.6548636E-02
     29 , 0.1581762   , -2.5680201E-02 , 4.0668599E-02 , 7.6548636E-02
     30 , 5.2048396E-02 , 0.2275660   , 0.2661020   , 0.2874393
     31 , -4.8787646E-02 , 0.2617024   , 0.3022432   , 0.3247257
     32 , 0.4023682   , -0.4165696   , -0.3884800   , -0.3743345
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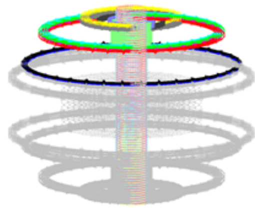

```
rscale
1,1,1,.25
rscale
2,1,2,.25
rscale
3,1,3,.25
rscale
4,1,4,.25
snal
1
merge
1,.0001
redu
todr
36,0,10
seal
1
egrp
8
ngrp
8
rcur
1,1,2,3,4,5,6,7,8
redu
snal
1
merge
1,.00001
redu
repla
vect
!exit
!read
grid
srel
5,5
srel
6,5
srel
7,5
snel
5,5
field
5
mfor
5,1,1,1,1,2,2,2,2
repla
nomi
zero
read
vect
srel
5,5
snel
5,5
gtrans
5,.005,0,0,0
srel
6,5
srel
7,5
snel
5,5
field
5
mfor
5,1,1,1,1,2,2,2,2
repla
erro
supe
nomi,-1,-1
plce
fsum
5
repla
se18
srel
5,5
srel
6,6
srel
7,7
snel
5,5
snel
6,6
snel
7,7
fsum
5
fsum
6
fsum
7
exit
```

Figure 7.2-1 Input Listing and generated model for Computing Loads due to shifts with Respect to the Poloidal Field

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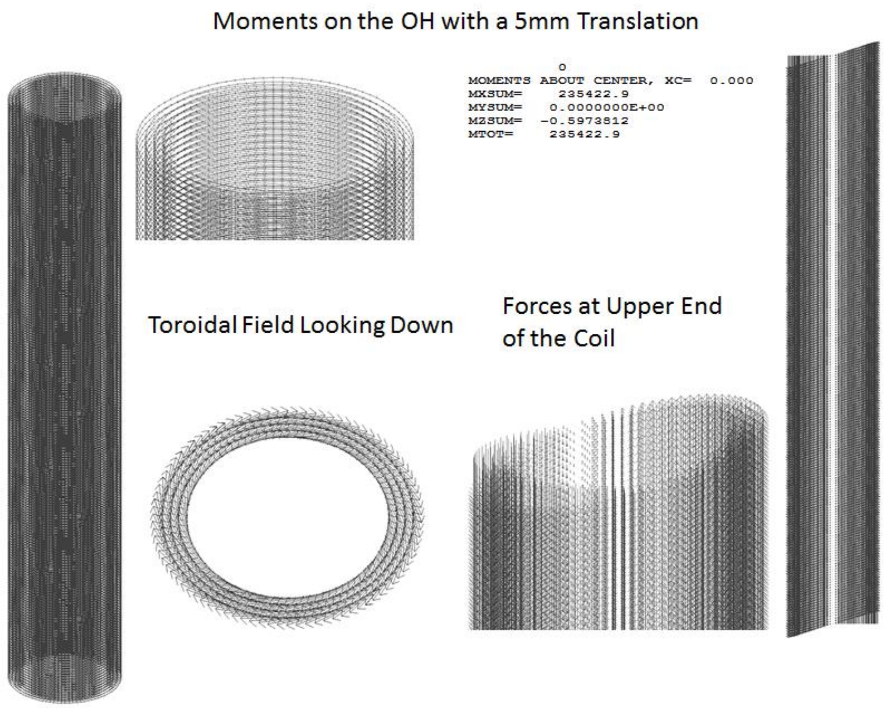
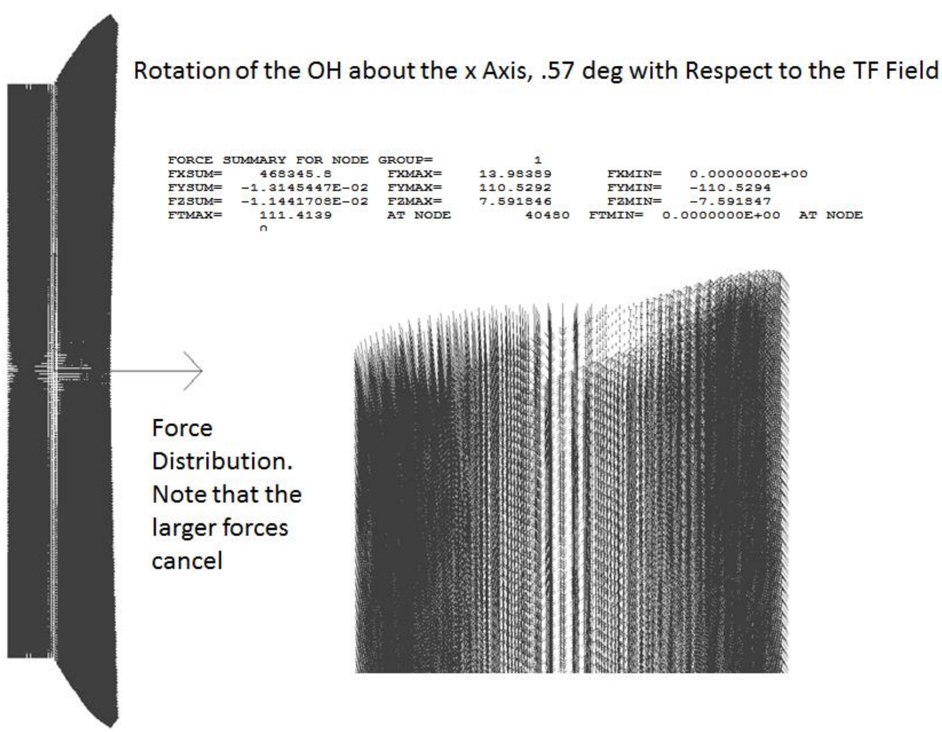
8.0 OH Loads due to Position Errors

8.1 Moment due to 5mm shift

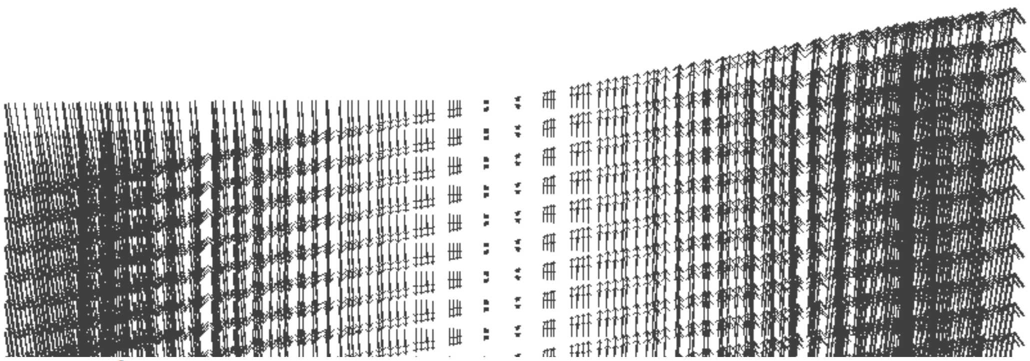


8.2 Forces on the OH Due to Rotation



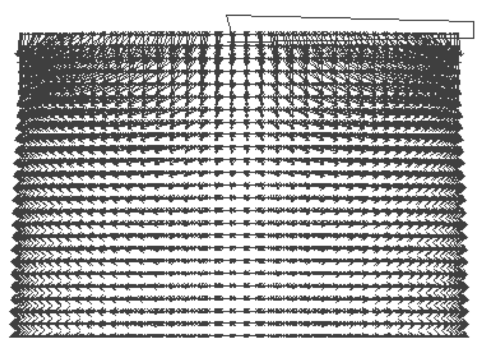
```
Enter Group Number:
9
snal
 ENTER ngrp number
1
gsel
fsum
 ENTER node group for Force Summation
0
 FORCE SUMMARY FOR NODE GROUP=           0
 FXSUM=    1063.269      FXMAX=    13.96737      FXMIN=   0.0000000E+00
 FYSUM=    11798.84      FYMAX=    110.5290      FYMIN=   0.0000000E+00
 FZSUM=    106.2983      FZMAX=    7.591846      FZMIN=   -6.343747
 FTMAX=    111.4135      AT NODE          1759  FTMIN=  0.0000000E+00  AT NODE
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=  0.0000000E+00
 MXSUM=   0.1178056
 MYSUM=   7.9703042E-03
 MZSUM=  -0.8134722
 MTOT=   0.8219968
```

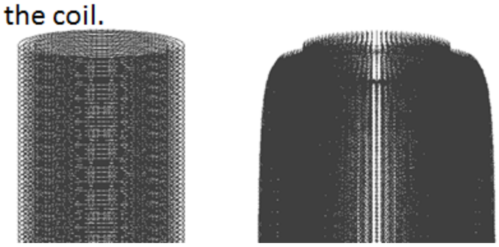
11798 N = 2652.2 Lbs



```
snal
 ENTER ngrp number
1
gsel
fsum
 ENTER node group for Force Summation
0
 FORCE SUMMARY FOR NODE GROUP=           0
 FXSUM=    71596.12      FXMAX=    1106.026      FXMIN=    -38.60081
 FYSUM=   -186885.1      FYMAX=   0.0000000E+00  FYMIN=    -1072.944
 FZSUM=   -1.439872      FZMAX=    1105.339      FZMIN=    -1105.394
 FTMAX=    1403.676      AT NODE         14366  FTMIN=  0.0000000E+00  AT NODE
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=  0.0000000E+00
 MXSUM=   -3.072931
 MYSUM=   2.0895374E-04
 MZSUM=   -179476.0
 MTOT=    179476.0
```

Self field and force analysis with 24 kA to check that the top layer of conductor will be held down if there is a rotation of the coil. -186885N Offsets 11798 N due to a rotation of the coil.





9.0 PF1a

9.1 Moment Due to 5mm Translation in X

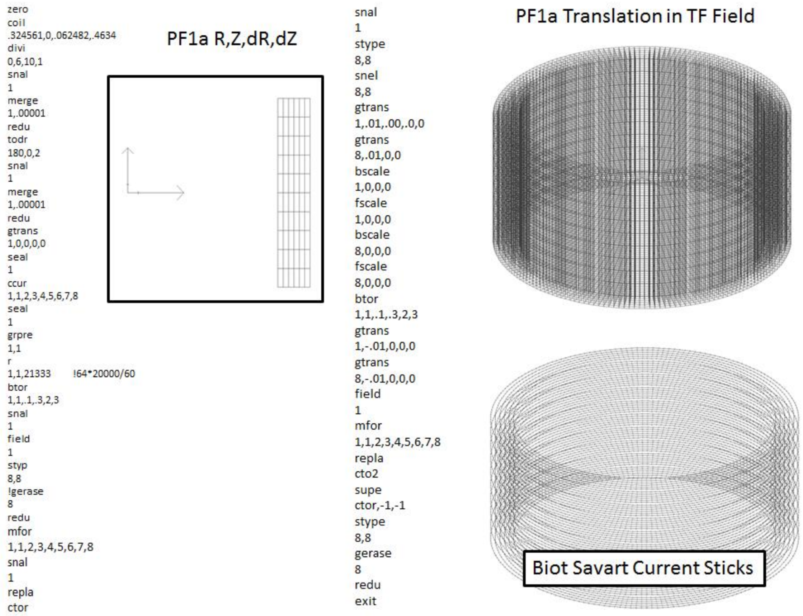
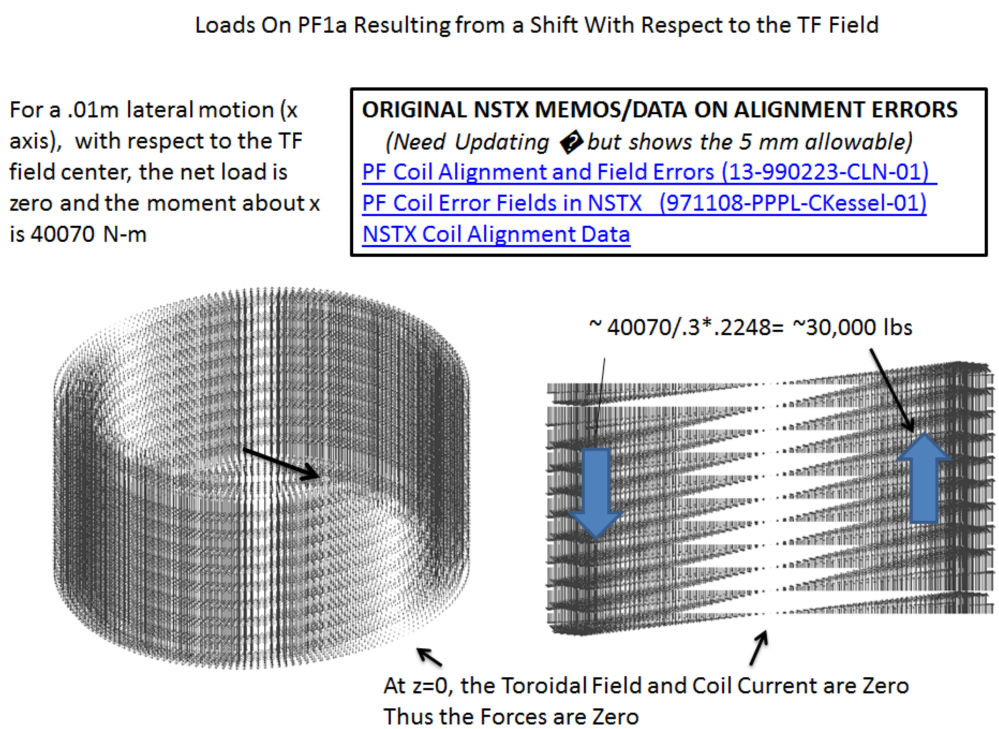
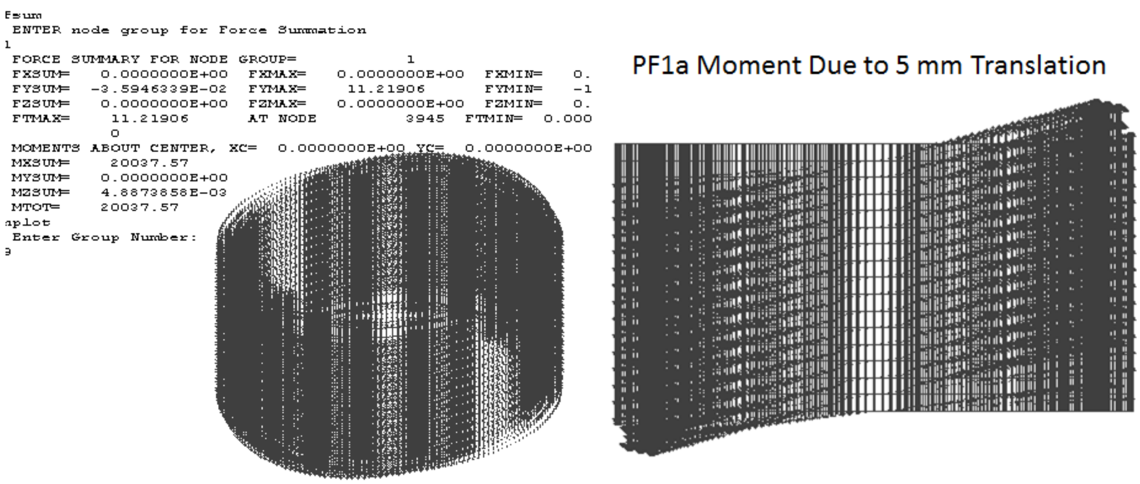


Figure 9.1-1 PF1a Shift With Respect to the TF Field, NTFTM Input Listing





9.2 PF1a Axisymmetric Winding, Force due .57deg Rotation About x in the NSTX 1/r TF Field

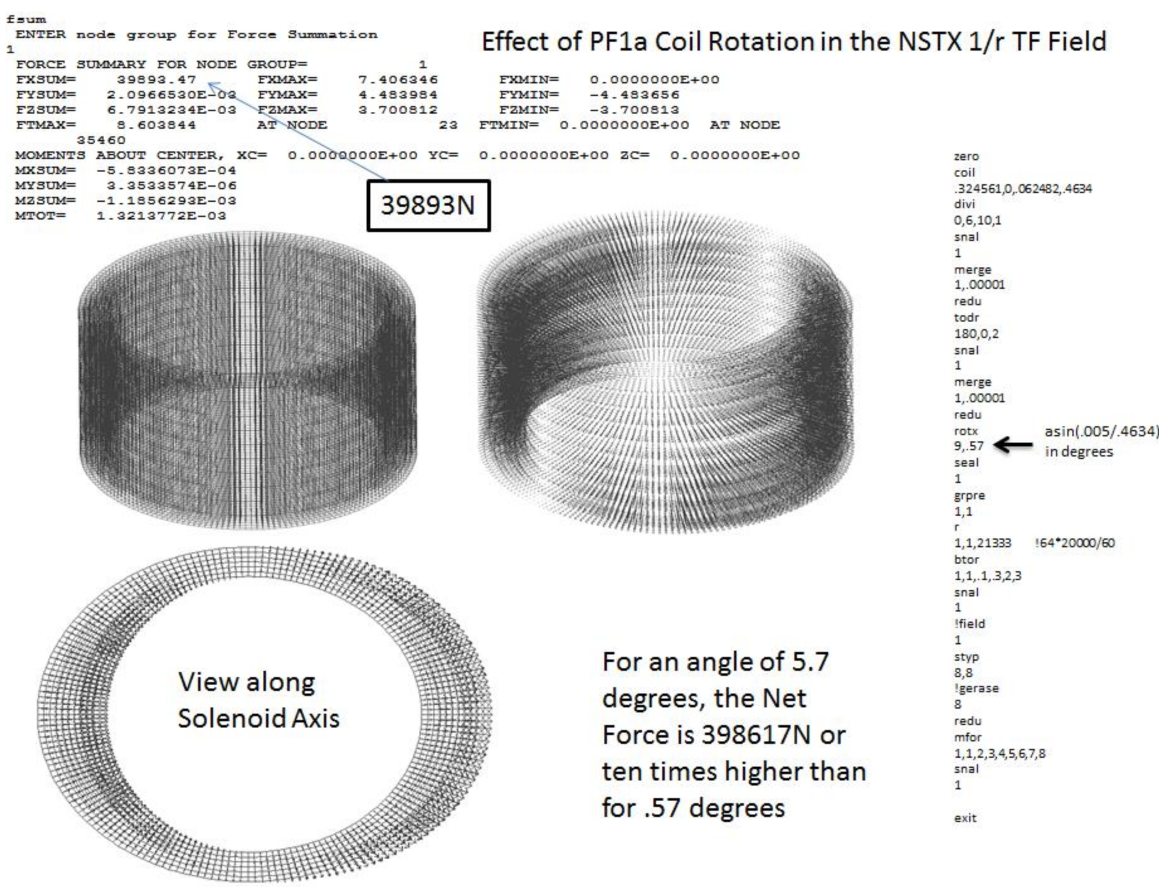


Figure 9.2.1 PF1a Coil Rotation about x in a Toroidal Field

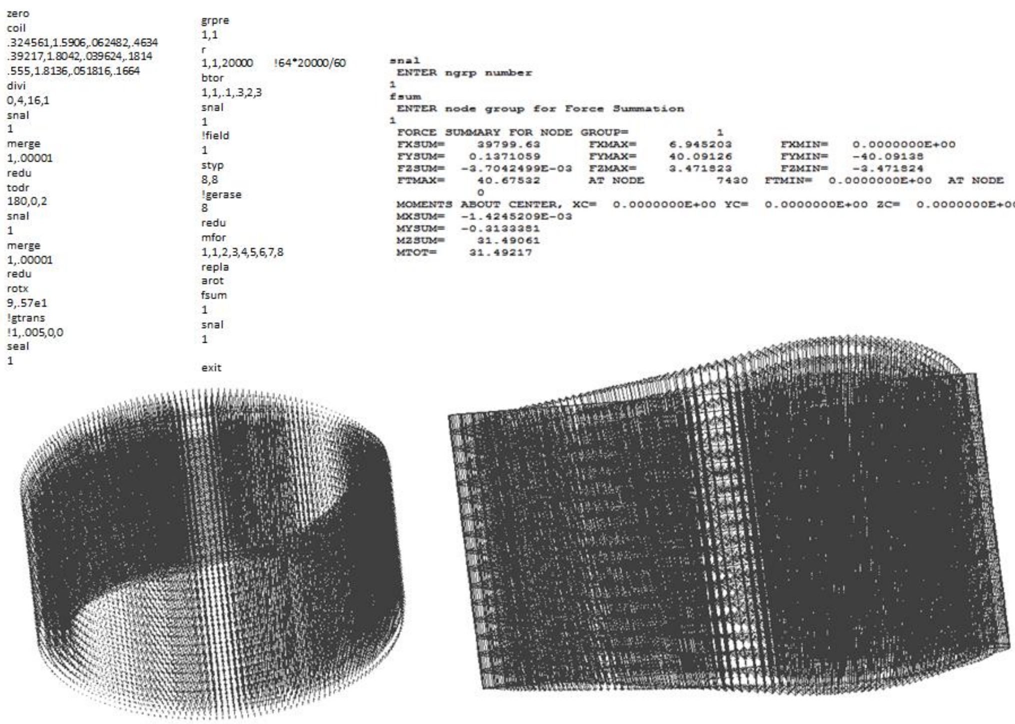


Figure 9.2-2 PF1a Coil Rotation about x in a Toroidal Field. The plots have a 5.7 degree Rotation so that it can be seen

9.3 PF1a Stacked 50 Degree Worst Transitions Load Interaction with the TF Field

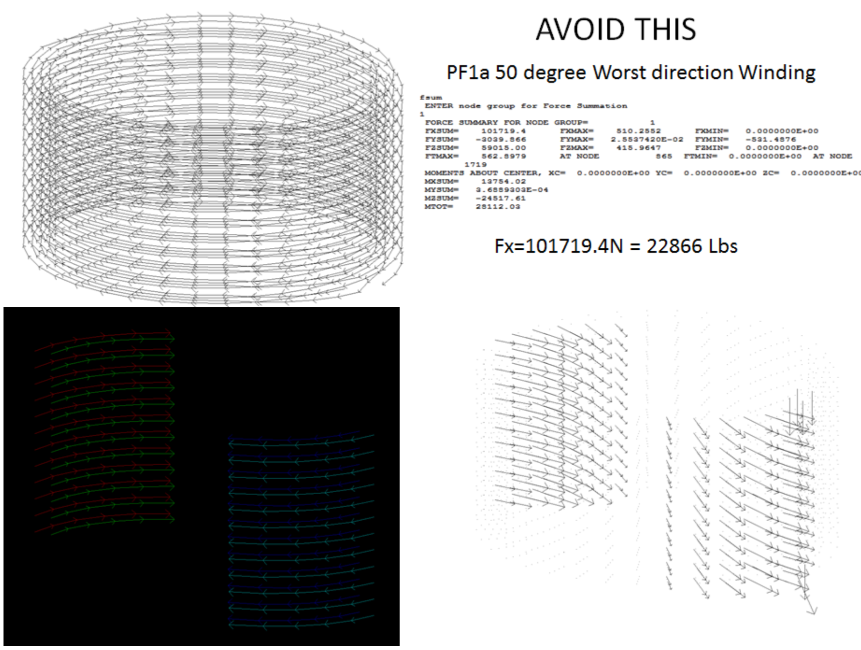


Figure 9.3 Loads from a “Bad” Transition LAYOUT

9.4 Pf1A Helix Loads Interaction with the TF Field

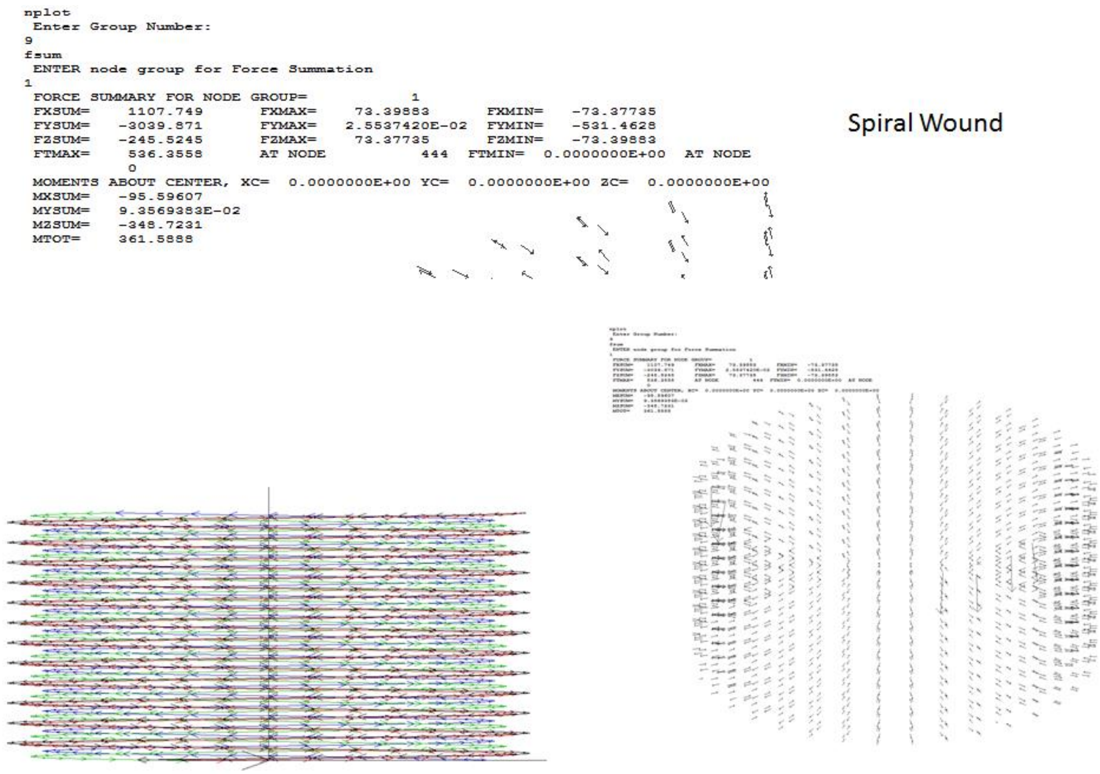
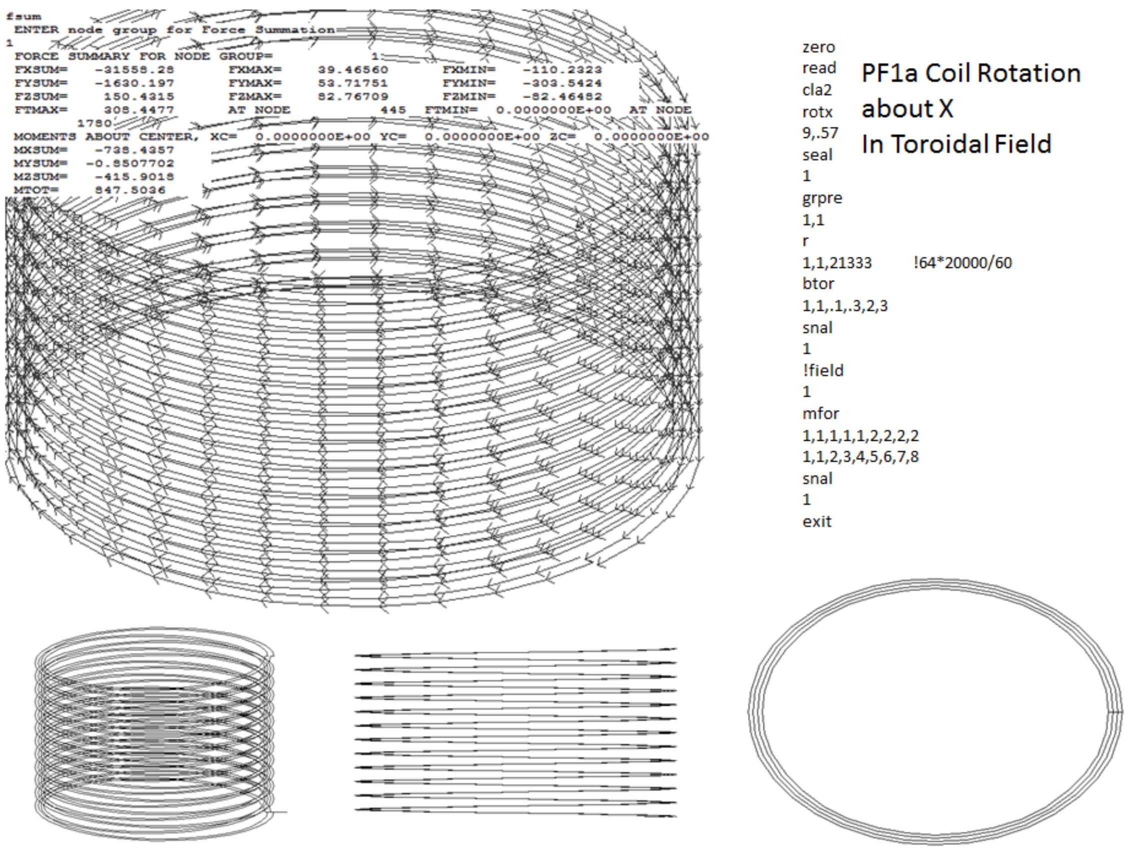


Figure 9.4-1 Loads resulting from a Helically Wound PF1a Coil in a TF Field

The net loads for the helically wound coil are FX=1107N, Fy=3039N and Fz=-245N. Compared with the 50 degree transitions, that yielded 101719 N the helical winding is attractive from a net load standpoint. Field quality much better for the helical winding. The helical winding was chosen for the design of the coils because of both the net load effect on the sling supports and the better field quality.



9.5 PF1a Loads due to 5mm translation with respect to the Poloidal Field (EQ51)

PF1a Upper 5mm EQ #1 5mm error in PF1a Lateral Position

```
fsum
 ENTER node group for Force Summation
5
 FORCE SUMMARY FOR NODE GROUP=             5
 FXSUM=   -902.5580      FXMAX=    19.17772      FXMIN=   -13.90260
 FYSUM=    115.9059      FYMAX=    19.68298      FYMIN=   -26.06915
 FZSUM=   0.2985721      FZMAX=    8.549595      FZMIN=   -8.550179
 FTMAX=    26.96187      AT NODE         31859  FTMIN=  0.0000000E+00  AT NODE
       31680
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=  0.0000000E+00
 MXSUM=   0.4880727
 MYSUM=   7.4504777E-03
 MZSUM=    748.7533
 MTOT=    748.7535
```

srel
5,5
snel
5,5
gtrans
5,.005,0,0,0
field
5

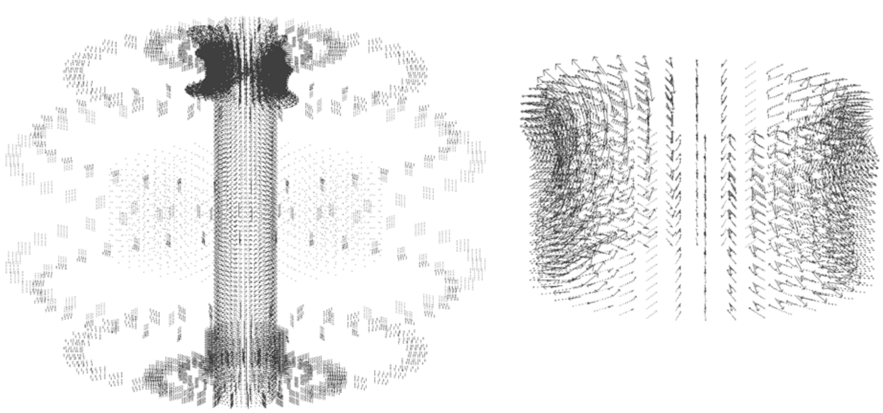


Figure 9.5-1 PF1aU Interaction with the PF Field

The Net Load Due to the interaction with the PF field is -902.6N

10.0 PF1b
10.1 PF1b 180 Degree Opposite Side
10.2 PF1b Error Field Stacked 180 Degree Transitions

Two PF1b coils are overlayed – One with stacked 180 degree transitions, and the other an "ideal" coil with only circular current vectors

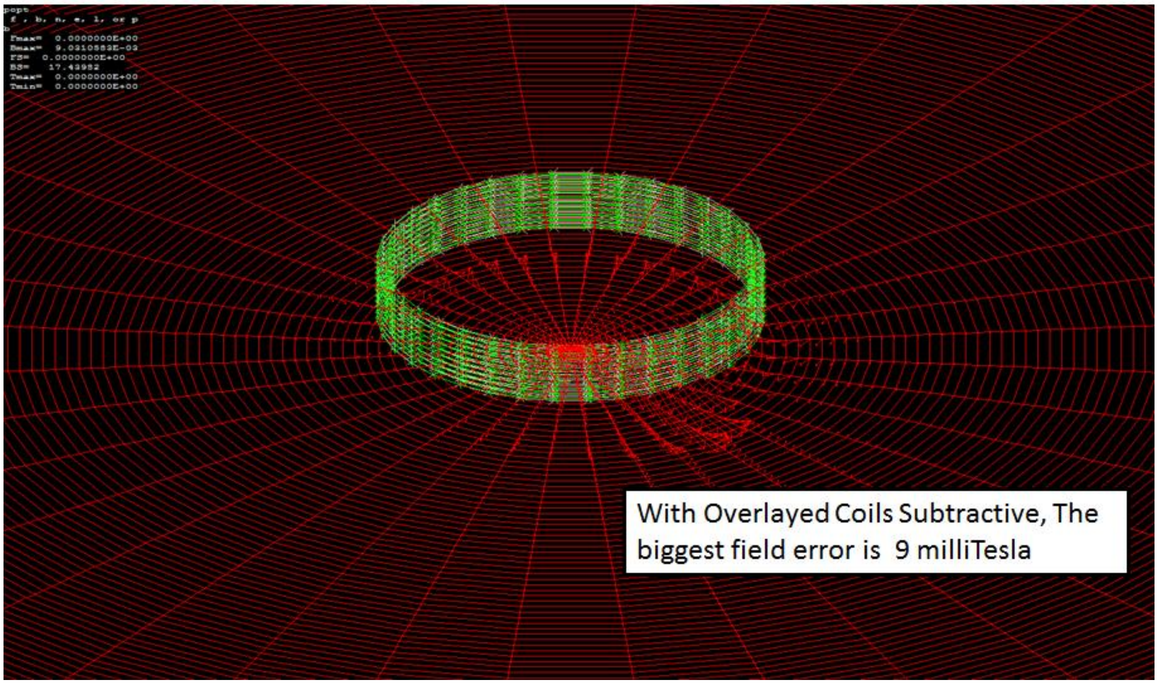
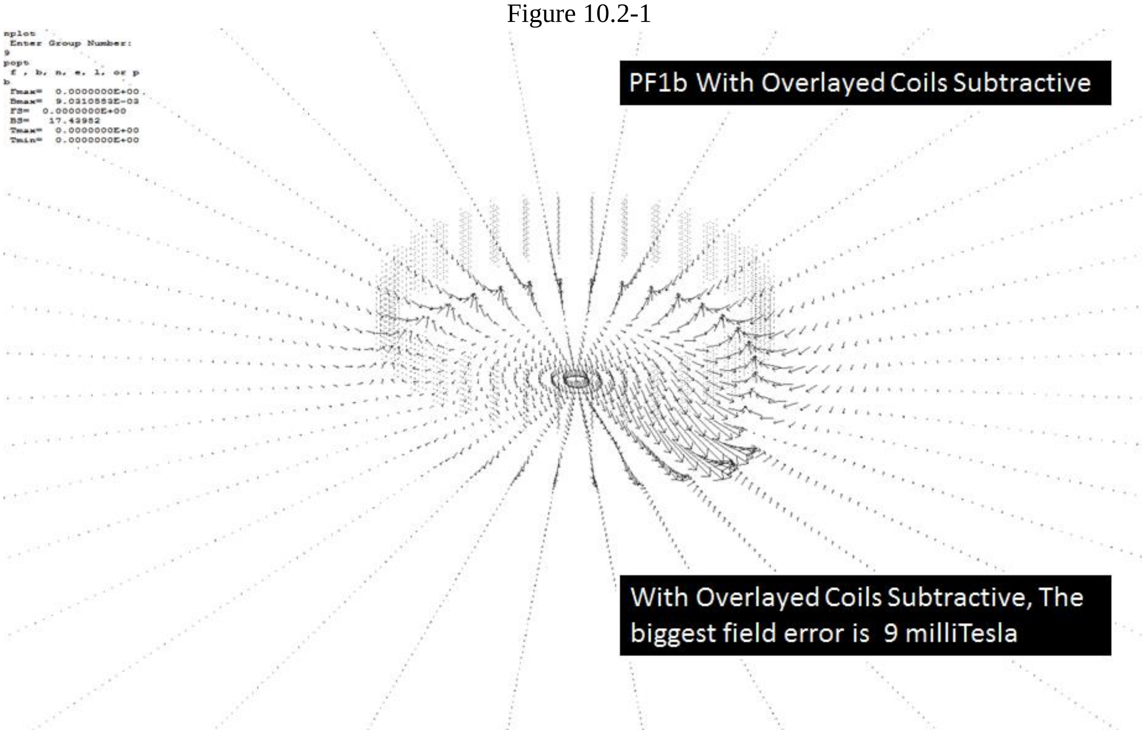
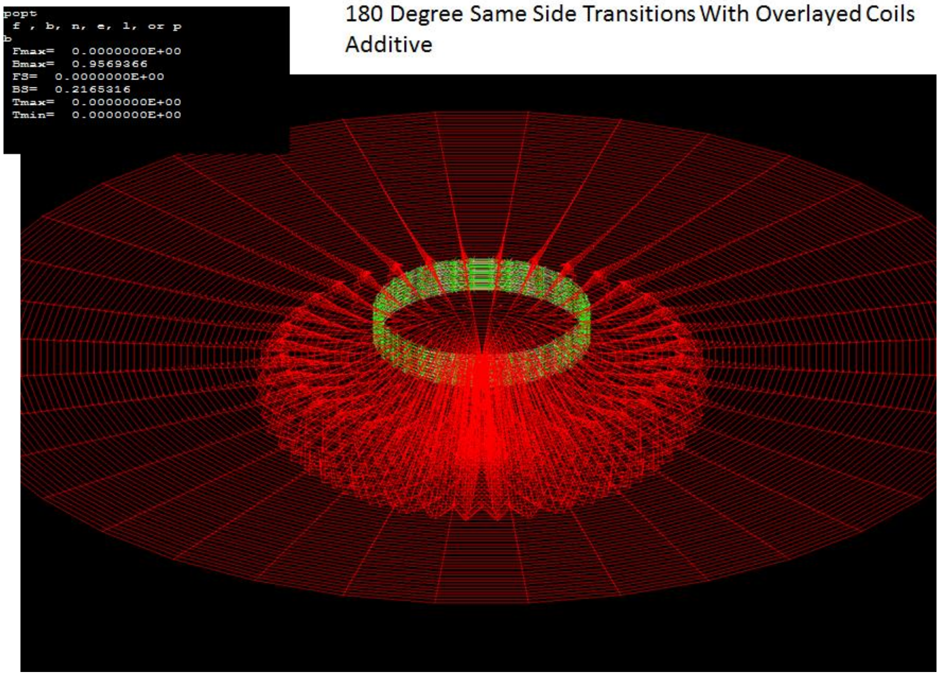
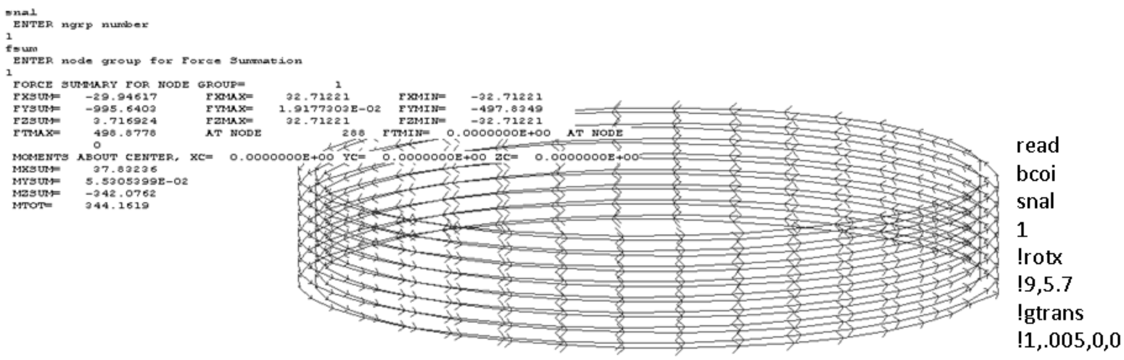


Figure 10.2-1

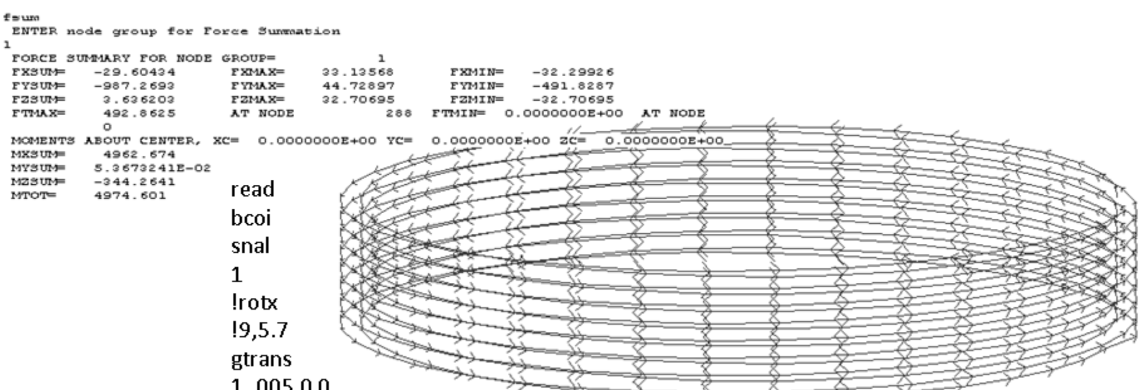




10.3 Helix in a TF field - No Translation



10.4 PF1b Helically Wound in a TF Field 5mm Translation

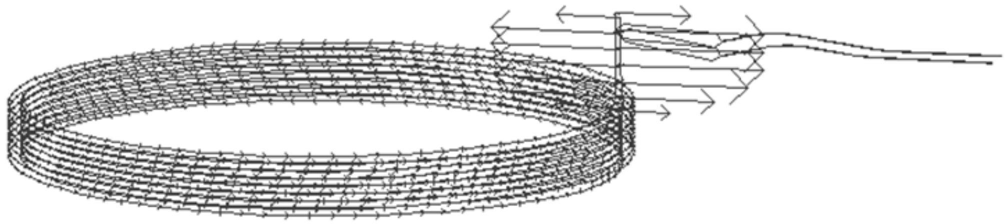


10.5 PF1b Circular Winding in a TF Field 5mm Translation

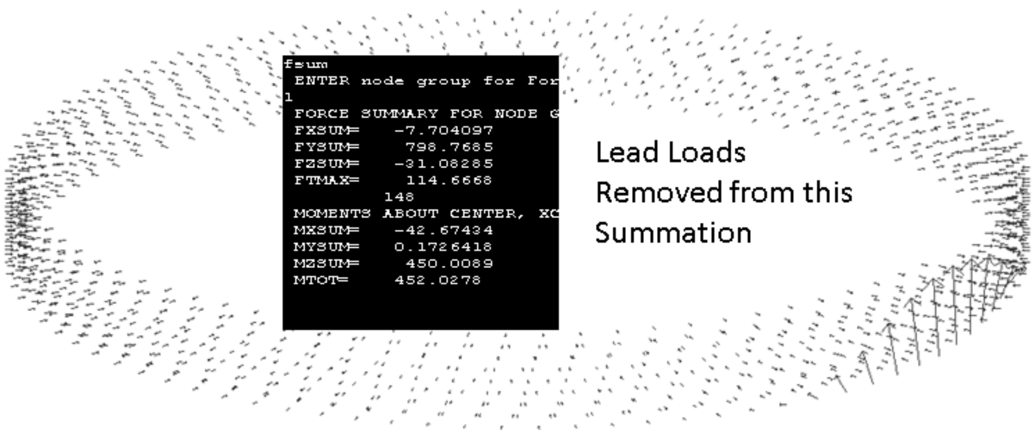
10.6 PF1b Circular Winding in a TF Field 5.7 degree Rotation

11.0 PF1c

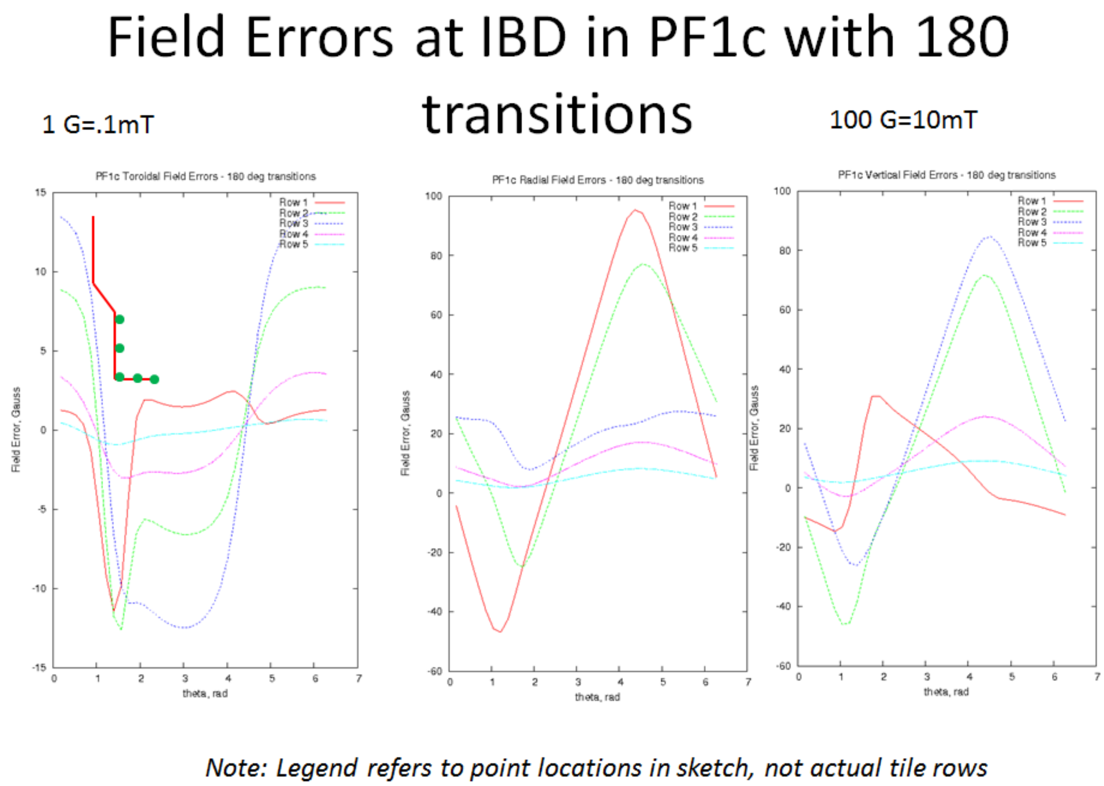
11.4 Loads on PF1c with a Helical Winding



PF1c U Loads Due to Spiral Winding in a TF Field



11.0PF11 with 180 Degree Transitions



12.0 PF1a Bus

12.1 PF1aL Error at the Inner Horizontal Divertor

13.0 PF1b Bus

13.1 Error at the Inner Horizontal Divertor

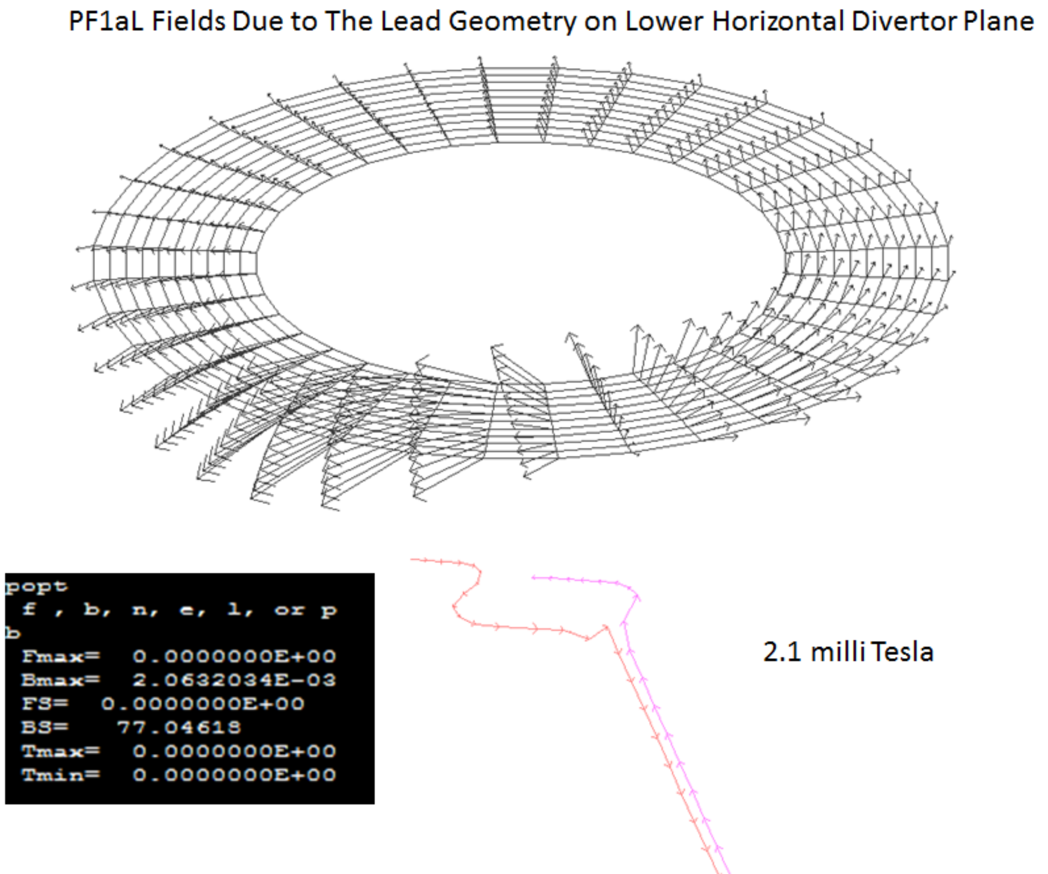


Figure 13.1-1 PF1aL Fields Due to The Lead Geometry on Lower Horizontal Divertor Plane

14.0 PF1c Bus

18.0 TF Error – Misalignment of the divertor flange with respect to the TF field

If the TF itself is misaligned with respect to the divertor flange, then the field lines will not intersect the divertor tiles uniformly around the circumference of the inner divertor. In this analysis the TF field is computed on the surface of the divertor flange with it tilted and nominally orthogonal to the TF axis. The two results are subtracted to calculate and plot only the deviation.

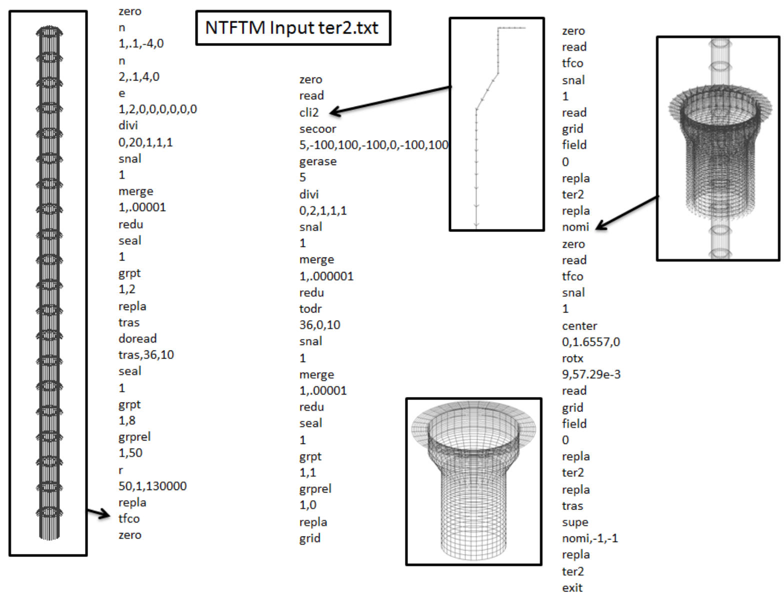


Figure 18.0-1 Input to the TF Error Field Calculation

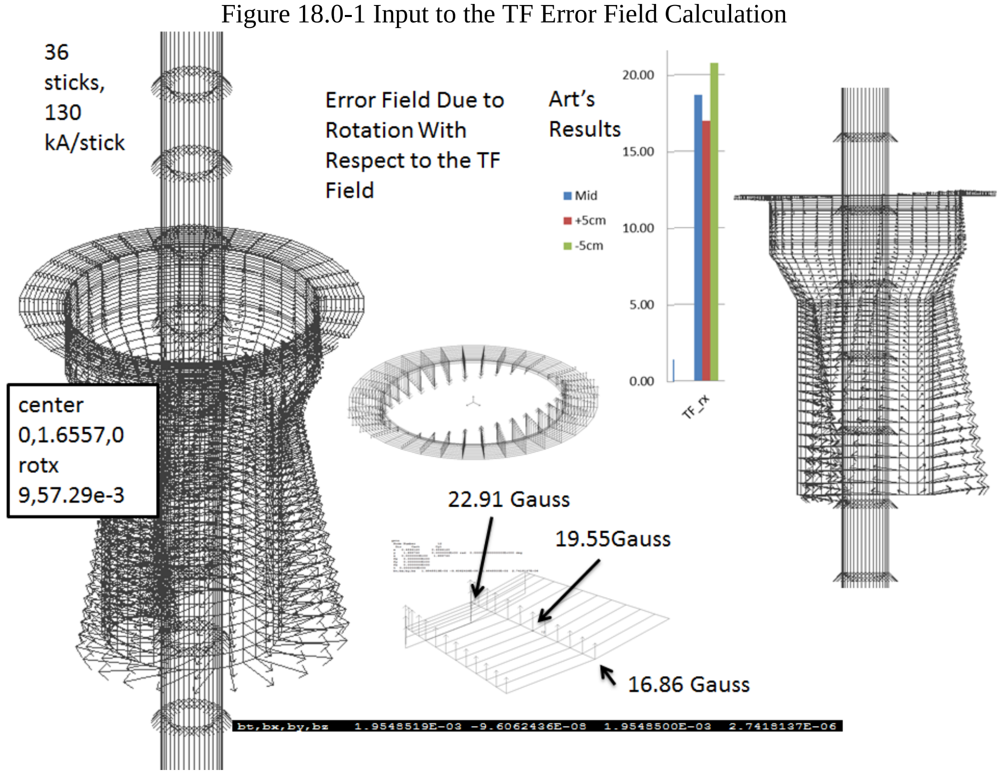


Figure 18.0-2 Results of rotation of the Casing with Respect to the TF Field by 1 milli-radian

19.0 OH

19.1 Field Error due to 1 mm shift in x

19.2 Field error due to rotation

19.3 Field Error Due to Growth and Shrinkage of the OH Coil

The top of the OH and field moves downward by .3 inches during a typical shot. This will move the field lines near the divertor area and change the incident angle. As of Rev 0 of this calculation, the field errors from this have not been quantified.

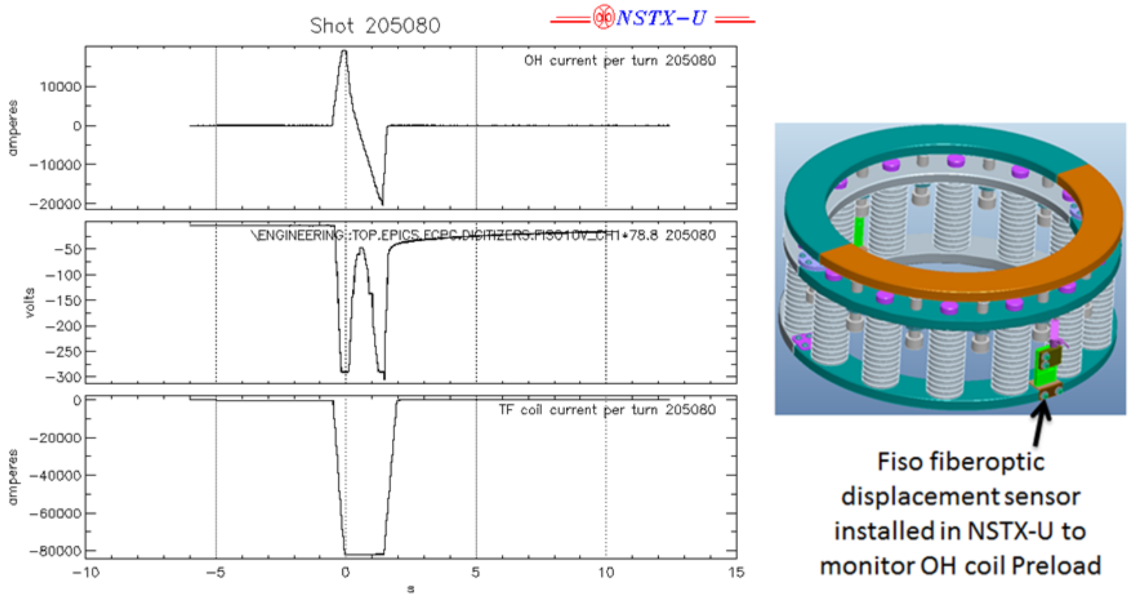
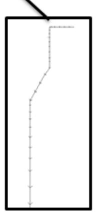
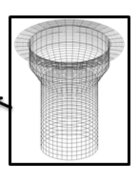


Figure 8.1-1 Measured OH Motions

20.1 Error due to PF1a Shift

```
zero
read
cli2
secoor
5,-100,100,-100,0,-100,100
gerase
5
seal
1
divi
1,2,1,1
snal
1
merge
1,.00001
redu
todr
36,0,10
snal
1
merge
1,.00001
redu
seal
1
grpt
1,1
grprel
1,0
repla
grid
```





```
zero
coil
.324561,1.5906,.062482,.4634      !PF1a
.39217,1.8042,.039624,.1814
.555,1.8136,.051816,.1664
.2421,0,.0694,4.2605    !OH
divi
0,4,16,1
snal
1
merge
1,.00001
redu
!exit
todr
90,0,4
snal
1
merge
1,.00001
redu
seal
1
grprel
1,1
r
1,1,10000        !Arts Normailzed Current
rcur
1,1,2,3,4,5,6,7,8
redu
snal
1
merge
1,.00001
redu
```

NTFTM Input aerr.txt

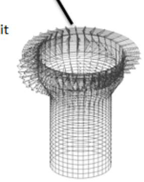
```
repla
veca
snal
1
seal
0
read
grid

field
0
styp
8,8
gerase
8
redu
repla
nomi

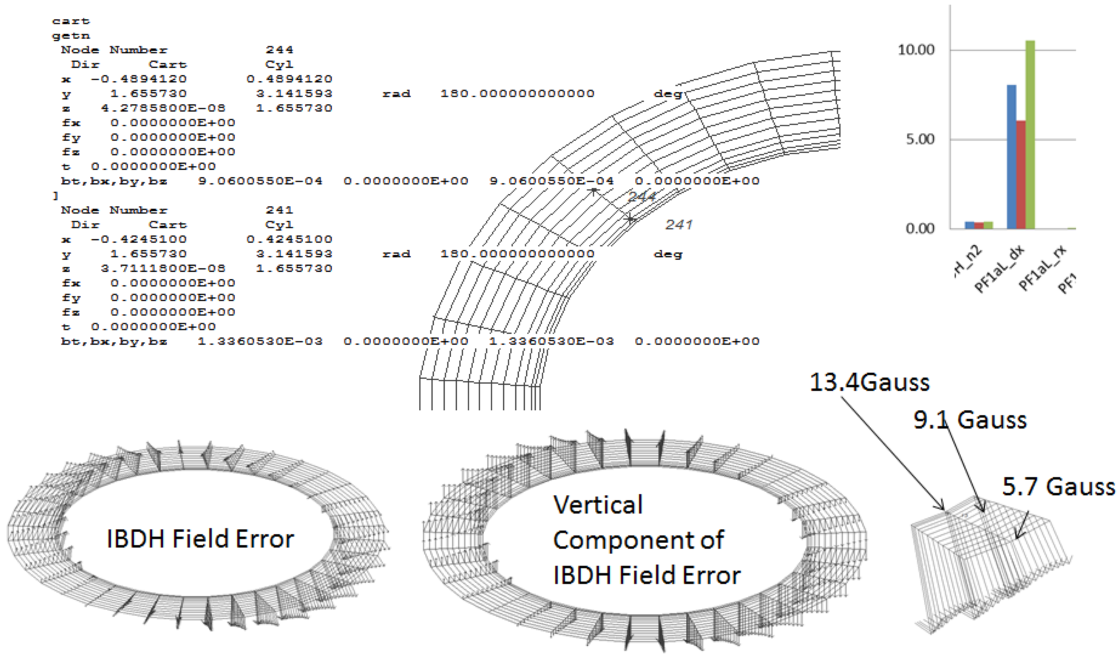
zero
read
veca
snal
1
center
0,1.5906,0
!rotx
!1,57.295e-3
gtrans
1,.001,0,0
seal
1
snal
1
read
grid
```

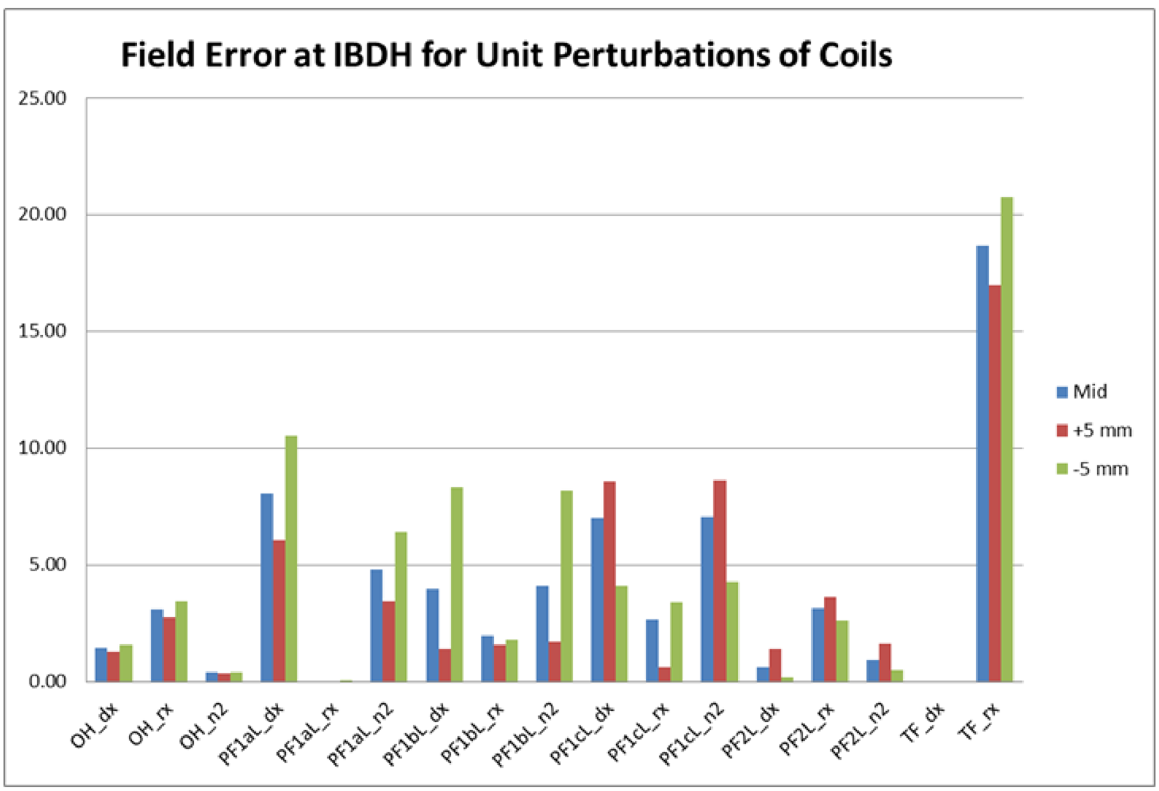
```
field
0
styp
8,8
gerase
8
redu
repla
garb
supe
nomi,-1,-1
repla
aerr
exit
zero

!mfor
8,1,1,1,1,2,2,2,2
1,1,2,3,4,5,6,7,8
repla
aerr
fsum
1
snal
1
exit
```

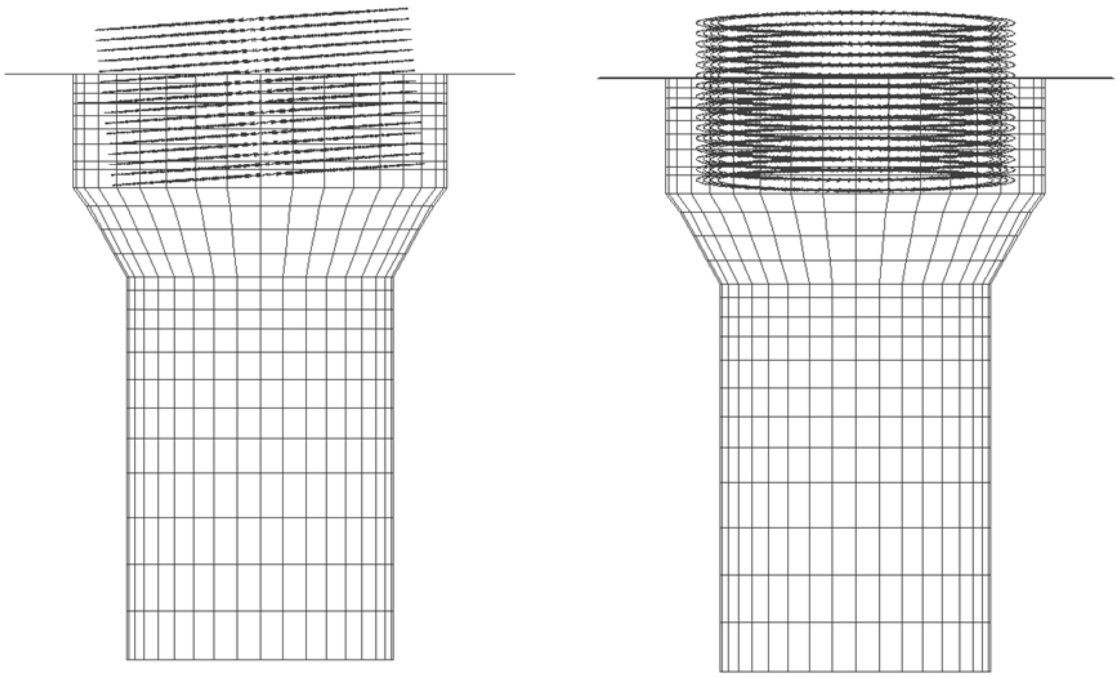


Field Error Due to Translation of PF1a by 1mm



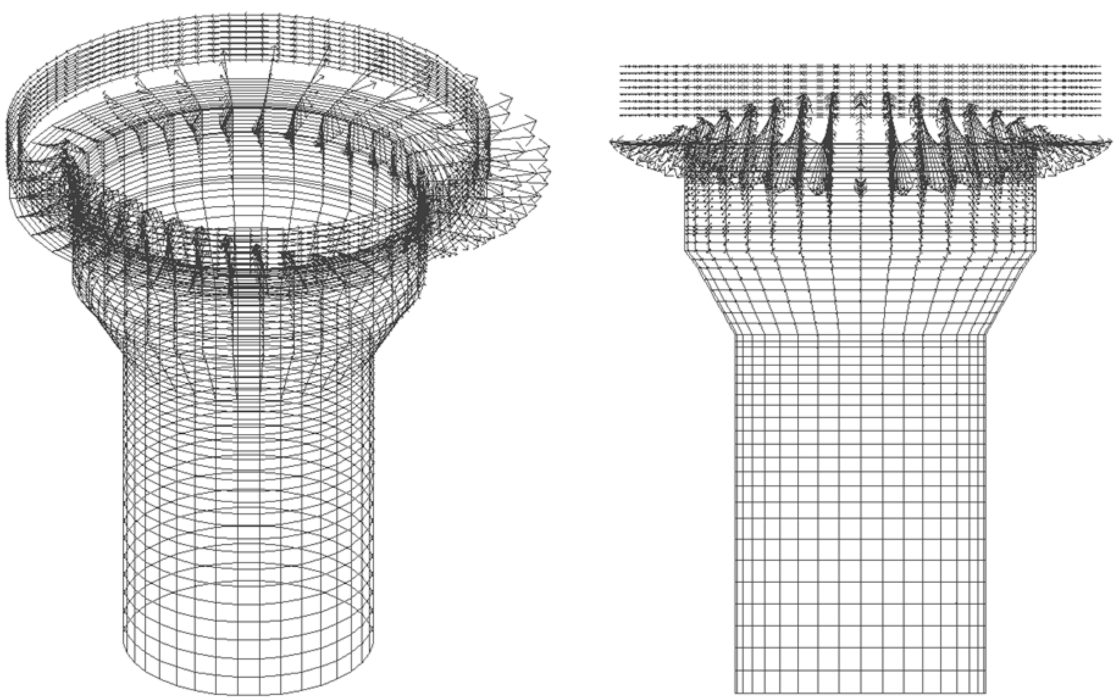


20.2 Error due to PF1a Tilt

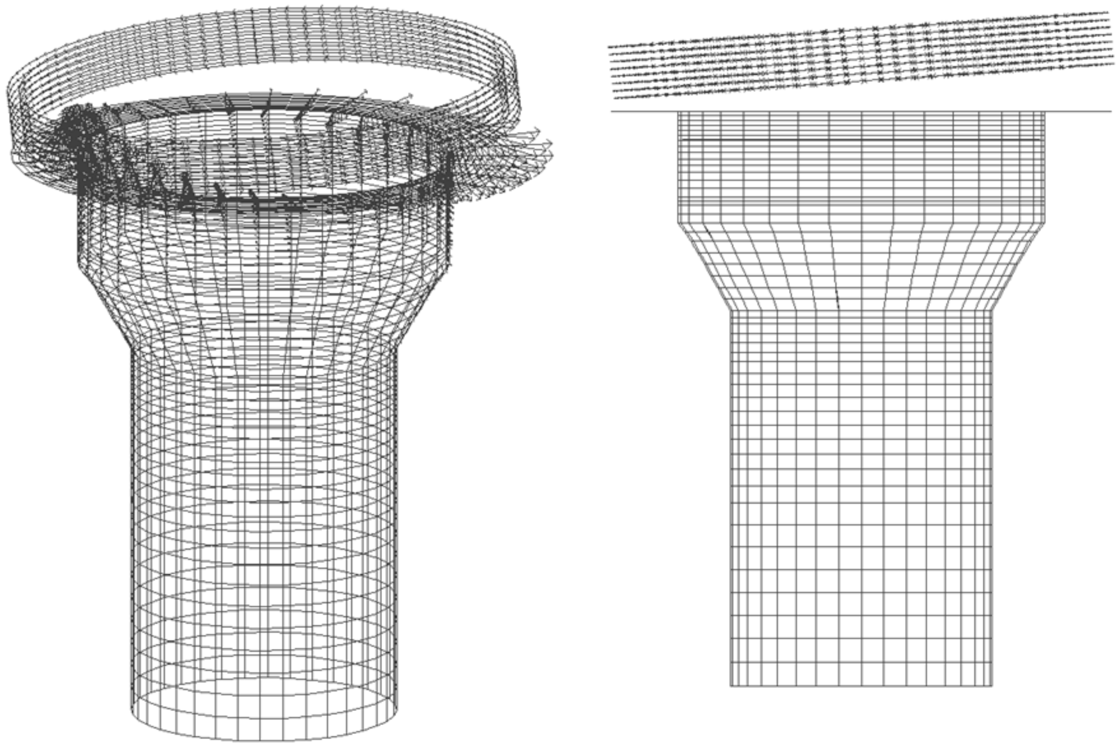


20.3 PF1al Leads Error Field

22.1 PF1c Shift



22.2 PF1c Tilt



22.3 Field Error Due to the PF1cU Leads

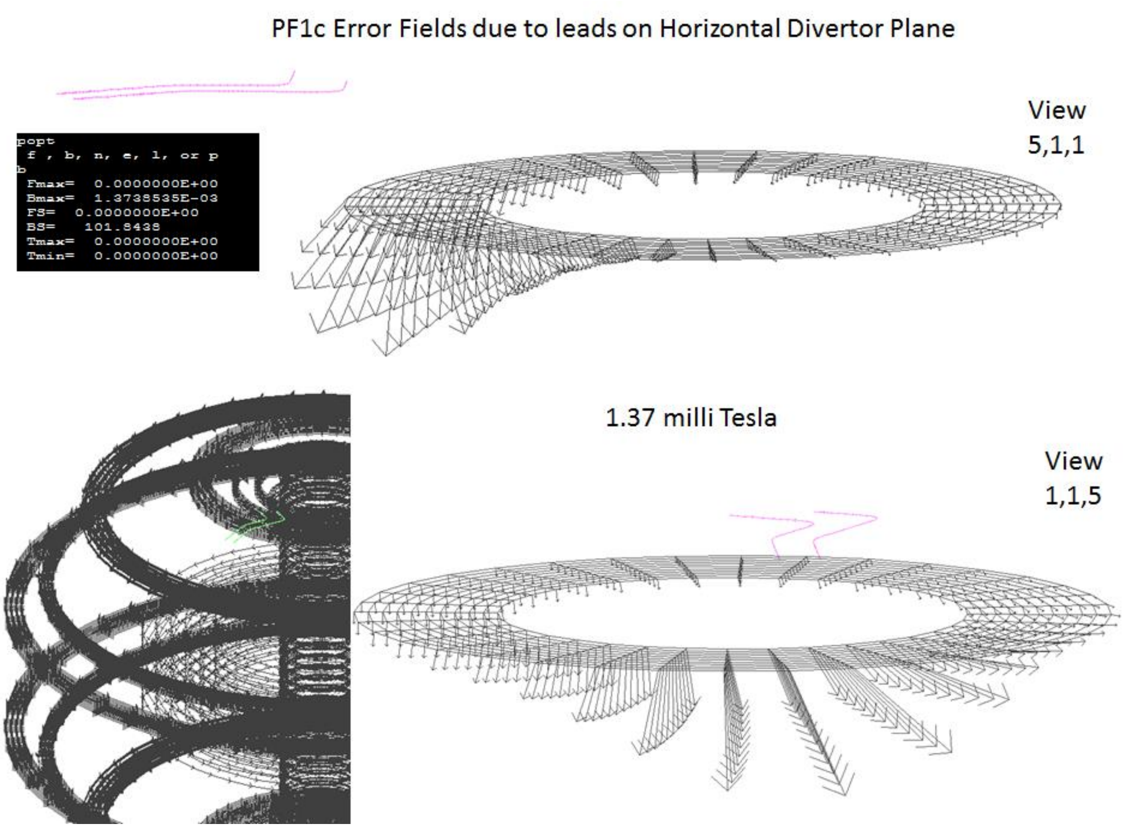


Figure 14.1- PF1c Error Fields due to leads on Horizontal Divertor Plane

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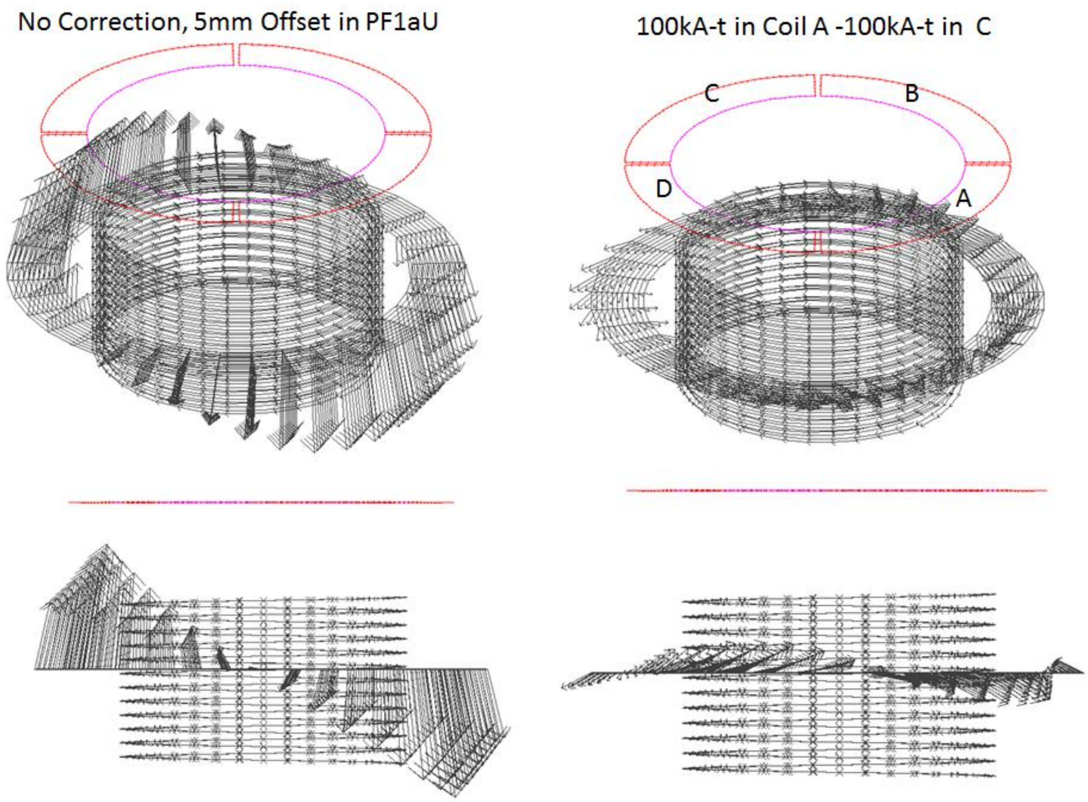
Figure 10.1-2 Load deflection of the 225 degree C sample

23.0 Possible Field Correction Coils

The uncertainties in coil positions are effecting the coil and tile design progress. There may be a fall back/contingency plan to implement correction coils if needed after the coils, coil supports, and tile supports are built - and maybe after some run period. - Or maybe never if we can hold the tolerances. Power them with the SPA's?? Mount them off the PF2 Clamps?



Appendix A

EMAILS

Jan 29 2018 from Art Brooks:
Peter,

I've scaled my results to 5 m and 20 kA to compare with you:

	Fx, N		Mx, N-m	
	Pete	Art	Pete	Art
OH	468,345	519,020	235,423	259,510
PF1a	39,893	35,814	20,037	17,907
PF1b	12,507	11,742	6,290	5,871
PF1c	100,129	9,394	5,031	4,697

They all look close except for pf1c which I believe you are of by a factor of 10. I noticed in all the others the Fx and Mx differ by a factor of 2.
Art

Appendix B
True Basic Code to Generate Coil Winding Patterns

```
dim x(4,10000),y(4,10000),z(4,10000),mat(10000),real(10000)
!   Coil specs
let transtype=6

let drcoil=.2
let nlayers=4
let Rcoil=.324561
let Zcoil=0

if transtype=1 then
let PFname$="pf1Au Replacement"
let make=4
let trans=0
let Rcoil=.324561
let Zcoil=0
let drcoil=.062482
let dzcoil=.4634
let nlayers=4
let nlayerturns=12
let l1transs =1
let l1transe =5
let l2transs =8
let l2transe =12
let l3transs =15
let l3transe =19
let l4transs =22
let l4transe =26
end if

if transtype=2 then
let PFname$="pf1Au Replacement"
let make=4
let trans=0
let Rcoil=.324561
let Zcoil=0
let drcoil=.062482
let dzcoil=.4634
let nlayers=4
let nlayerturns=12
let l1transs =1
let l1transe =5
let l2transs =1
let l2transe =5
```

```
let l3transs =1
let l3transe =5
let l4transs =1
let l4transe =5
end if

if transtype=3 then
let PFname$="pf1Au Replacement"
let make=4
let trans=0
let Rcoil=.324561
let Zcoil=0
let drcoil=.062482
let dzcoil=.4634
let nlayers=4
let nlayerturns=12
let l1transs =1
let l1transe =5
let l2transs =1
let l2transe =5
let l3transs =18
let l3transe =22
let l4transs =18
let l4transe =22
end if

if transtype=4 then
let PFname$="pf1Au Replacement Worst Loading"
let make=4
let trans=0
let Rcoil=.324561
let Zcoil=0
let drcoil=.062482
let dzcoil=.4634
let nlayers=4
let nlayerturns=12
let l1transs =1
let l1transe =5
let l2transs =18
let l2transe =22
let l3transs =1
let l3transe =5
let l4transs =18
let l4transe =22
end if
```

```
if transtype=5 then
let PFname$="pf1Au Replacement Spiral Wound"
let make=4
let trans=0
let Rcoil=.324561
let Zcoil=0
let drcoil=.062482
let dzcoil=.4634
let nlayers=4
let nlayerturns=12
let l1transs =0
let l1transe =36
let l2transs =0
let l2transe =36
let l3transs =0
let l3transe =36
let l4transs =0
let l4transe =36
end if

if transtype=6 then
let PFname$="pf1bu Replacement "
let make=2
let trans=0
let Rcoil=15.51/39.37
let Zcoil=0
let drcoil=1.56/39.37
let dzcoil=7.21/39.37
let nlayers=2
let nlayerturns=10
let l1transs =0
let l1transe =18
let l2transs =0
let l2transe =18
let l3transs =0
let l3transe =36
let l4transs =0
let l4transe =36
end if

!let nlayerturns=12
let condz=dzcoil/nlayerturns
let condr=drcoil/nlayers

!let outfile$="d:\nstx\csu\bellows\tras.txt"
let outfile$="d:\nstx\csu\magnetic sta\tras.txt"
```

```
when error in
unsave outfile$
use
end when
OPEN #3: name outfile$, create new
if make>0 then
!    Layer 1
let rlayer=rcoil -drcoil/2+condr/2
for t=1 to nlayerturns
for th=1 to l1transs-1
let theta=theta+10
let n=n+1
let mat(n)=1
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t-1)
next th
for th=l1transs to l1transe-1
let theta=theta+10
let n=n+1
let mat(n)=1
let real(n)=1
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t-1)+condz*(th-l1transs)/(l1transe-l1transs+1)
next th
for th=l1transe+1 to 36
let theta=theta+10
let n=n+1
let mat(n)=1
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t)
next th
next t

!    Transition 1
for th=1 to trans/10
let theta=theta+10
let n=n+1
let mat(n)=1
let real(n)=10
let x(1,n)=(rlayer+condr/(trans/10)*(th))*cos(pi*theta/180)
let z(1,n)=(rlayer+condr/(trans/10)*(th))*sin(pi*theta/180)
```

```
let y(1,n)=condz*(nlayerturns)
next th
end if

If make >1 then

!    Layer 2
let rlayer=rlayer+condr
for t=1 to nlayerturns
for th=1 to l2transs-1
let theta=theta+10
let n=n+1
let mat(n)=2
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t-1)
next th
for th=l2transs to l2transe -1
let theta=theta+10
let n=n+1
let mat(n)=2
let real(n)=2
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t-1)-condz*(th-l2transs)/(l2transe-l2transs+1)
next th
for th=l2transe+1 to 36
let theta=theta+10
let n=n+1
let mat(n)=2
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t)
next th
next t


!    Transition 2

for th=1 to trans/10
let theta=theta+10
let n=n+1
let mat(n)=2
let real(n)=10
```

```
let x(1,n)=(rlayer+condr/(trans/10)*th)*cos(pi*theta/180)
let z(1,n)=(rlayer+condr/(trans/10)*th)*sin(pi*theta/180)
let y(1,n)=0
next th
end if
 If make>2 then

!    Layer 3
let rlayer=rlayer+condr
for t=1 to nlayerturns
for th=1 to l3transs-1
let theta=theta+10
let n=n+1
let mat(n)=3
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t-1)
next th
for th=l3transs to l3transe
let theta=theta+10
let n=n+1
let mat(n)=3
let real(n)=3
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t-1)+condz*(th-l3transs)/(l3transe-l3transs+1)
next th
for th=l3transe+1 to 36
let theta=theta+10
let n=n+1
let mat(n)=3
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=condz*(t)
next th
next t
!    Transition 3
for th=1 to trans/10
let theta=theta+10
let n=n+1
let mat(n)=3
let x(1,n)=(rlayer+condr/(trans/10)*th)*cos(pi*theta/180)
let z(1,n)=(rlayer+condr/(trans/10)*th)*sin(pi*theta/180)
let y(1,n)=condz*(nlayerturns)
```

```
next th
end if

if make>3 then
!    Layer 4
let rlayer=rlayer+condr
for t=1 to nlayerturns
for th=1 to l4transs-1
let theta=theta+10
let n=n+1
let mat(n)=4
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t-1)
next th
for th=l4transs to l4transe
let theta=theta+10
let n=n+1
let mat(n)=4
let real(n)=4
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t-1)-condz*(th-l4transs)/(l4transe-l4transs+1)
next th
for th=l4transe+1 to 36
let theta=theta+10
let n=n+1
let mat(n)=4
let real(n)=10
let x(1,n)=(rlayer)*cos(pi*theta/180)
let z(1,n)=(rlayer)*sin(pi*theta/180)
let y(1,n)=nlayerturns*condz-condz*(t)
next th
next t
end if


print #3: "zero"
print #3: "type"
print #3: "8"
for i=1 to n
print#3: "n"
print #3: i;",";x(1,i);",";y(1,i);",";z(1,i)
print#3: "mat"
print#3: mat(i)
```

```
print#3: "real"
print#3: real(i)
print#3: "e"
print #3: i;",";i+1;",0,0,0,0,0,0"
next i
print #3: "erla"
print #3: "repla"
print #3: "clay"
print #3: "exit"

set window -.5,.5,-.2,.8
print "theta type="; thetatype
print "Rz= "; coilr
plot 0,0;1,0
plot 0,0;0,1
for i=1 to n
set color mat(n)
plot x(1,i),z(1,i);
call arrow(x(1,i),z(1,i),x(1,i+1),z(1,i+1))
next i
!plot x(1,i-1),z(1,i-1)

get key kinp

clear
plot 0,0;.8,.3
plot 0,0;0,1
plot 0,0;-.3,-.8
for i=1 to n
if mat(i)=1 then set color "blue"
if mat(i)=2 then set color "green"
if mat(i)=3 then set color "red"
if mat(i)=4 then set color "black"
!plot x(1,i)*.8,z(1,i)*.3+y(1,i);
!if mat(i)>1 then
call arrow(x(1,i)*.8,z(1,i)*.3+y(1,i),x(1,i+1)*.8,z(1,i+1)*.3+y(1,i+1))
pause .01
!end if
next i
plot x(1,i-1),z(1,i-1)
get key kinp
clear
plot 0,0;1,0
plot 0,0;0,1
for i=1 to n
if mat(i)=1 then set color "blue"
```

```
if mat(i)=2 then set color "green"
if mat(i)=3 then set color "red"
if mat(i)=4 then set color "black"
!plot x(1,i),y(1,i);
call arrow(x(1,i),y(1,i),x(1,i+1),y(1,i+1))
next i
plot x(1,i-1),z(1,i-1)


SUB arrow (a1,b1,a2,b2)
 LET a3=a1+.8*(a2-a1)+.1*(b2-b1)
 LET b3=b1+.8*(b2-b1)-.1*(a2-a1)
 LET a4=a1+.8*(a2-a1)-.1*(b2-b1)
 LET b4=b1+.8*(b2-b1)+.1*(a2-a1)
plot a1,b1;a2,b2
plot a3,b3;a2,b2
plot a2,b2;a4,b4
 END SUB
end
```