National **S**pherical **T**orus e**X**periment - **U**pgrade

NSTX-U

Summary of Loads for Inner PF Leads and Bus bars Analysis

NSTXU-CALC-133-28 - Rev 0

March 20, 2018

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2018.03.29 08:52:17 -04'00'

______________**Yuhu Zhai**_______________

Prepared By

Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.03.28 13:19:13 -04'00'

_____________**Peter Titus**_______________

Reviewed By

Michael Kalish Digitally signed by Michael Kalish Date: 2018.03.28 16:51:37 -04'00'

____________**Mike Kalish**_______________

Approved By – Responsible Engineer

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	3/20/18	Initial Release	Yuhu Zhai

NSTX-U Calculation Form

Purpose of Calculation: The NSTX-U inner PF coils are water-cooled copper solenoids fabricated from rectangular or square shaped conductors with embedded central cooling channels. The coils, consist of three upper and lower pairs, denoted PF-1a, PF-1b and PF-1c, are energized up to 20 kA for about 1-2 seconds during plasma operations and then cooled down with 12 ^{0}C cold water once every 1200 seconds. During machine operation the conductors in coil terminals (lead sections) will experience large Lorentz forces (30-50 kN/m) from 2-3 T toroidal magnetic fields as well as differential thermal stresses between coil leads and bus bars when coils are pulsed. This calculation is to summarize the input loads extracted from the worst case EQ scenarios used as input for each of the inner PF coil leads and bus bar analysis. The worst EQ scenarios for each coil are identified first based on the 2D scan of all 96 EQ scenarios and then the full 3D magnetostatics analyses of these worst scenarios are performed using ANSYS MAXWELL for each coil with the detailed spiral winding and new bus flags, support brackets and bus bar structures. The body force densities on the coils, coil terminals and bus bars are mapped onto the 3D structural analysis models. The summation of the Lorentz forces on each coil is compared with the load inventory defined in the DPSS and ~5% difference is generally found for the dominating loads. Both positive and reverse toroidal field cases under the worst EQ scenarios have been analyzed and reaction forces on the coil and the bus bars are extracted following NSTX-U General Requirements Document [1] and the System Requirements Document for Magnet Systems [2].

References:

[1] NSTX-U-RQMT-GRD-001-00 General Requirements Document, S. Gerhardt, December, 2017

[2] NSTX-U-RQMT-SRD-002-00 System Requirements Document Magnet Systems, S. Gerhardt, December, 2017.

[3] Inner PF coil design parameters, M. Kalish, February, 2018.

[4] NSTX-CRIT-0001-02 Structural Design Criteria, I. Zatz, January, 2016

[5] Inner PF Coil Thermal Analysis, NSTX-U-CALC-131-27, Y. Zhai, March 14, 2018.

[6] Inner PF Coil Electromagnetic Analysis, NSTX-U-CALC-133-23, Y. Zhai, March 9, 2018.

[7] Material Properties for Inner PF Coil FDR, MAG-180306-YZ-01, Y. Zhai, March, 2018.

Assumptions: *(Identify all assumptions made as part of this calculation.)*

The global 3D ANSYS MAXWELL models with detailed coil spiral winding, coil terminals and new bus bar assembly for each of the PF-1a, 1b and 1c coils are developed for extracting worst case electromagnetic forces in terms of elemental body force densities needed for the lead analysis. The MAXWELL magnetostatics analysis is then performed for each of the PF1 coils with conductor spiral winding, terminal flags and bus bars for that coil (while smeared coil pack was used for all other coils) as a complete conduction path for accurate mapping of the coil load distribution. The end of pulse condition is used where maximum coil temperature of 60 C, 90 C and 50 C for the PF-1a, PF-1b and PF-1c coils are prescribed for structural analysis of coil leads. The body force densities from the worst case EQ scenarios of #51, #33 and #18 for PF-1a, PF-1b and PF-1c coils are mapped onto conductors of the coil with spiral winding, coil terminals and bus bars in the subsequent structural analysis models. This report is to summarize the resultant input loads from the 3D MAXWELL calculation of each PF1 coil under the worst case EQ scenarios with detailed conductor spiral winding for the new design of the inner PFs.

Calculation: *(Calculation is either documented here or attached)*

Contents

1. Executive Summary

The inner PF coils for NSTX-U are installed to provide the poloidal field shaping and better controlling of plasma in the diverter region during machine operations. The inner PFs, fabricated from rectangular or square shape copper conductors with embedded central cooling channels, are designed to have 20,000 pulse cycles over the lifetime of machine operation as defined in the latest General Requirement Document [4]. The key design requirements include 1) all coil designs shall allow for operation of the toroidal field in either direction, and of the plasma current in either direction, 2) static EM loads are defined in the Design Point Spreadsheet which disruption loads are derived from the NSTX-U disruption analysis requirements 3) the maximum temperature for operations shall be below 100 ^{0}C. To this end, 3D magnetostatics analyses were performed based on the worst EQ scenarios selected from the 2D axis-symmetric models of PF-1a, PF-1b and PF-1c maximum fields, Lorentz forces and coil stresses. The 2D results show that maximum temperatures on the conductor when pulsed are 58, 90 and 48 ^{0}C for PF-1a, -1b and -1c coils respectively and the maximum radial fields on the inner PFs are ~2 T from the worst case EQ scenarios for each inner PF coils. The global 3D ANSYS MAXWELL models with detailed coil spiral winding, coil terminals and new bus bar assembly for each of the PF-1a, 1b and 1c coils are developed for extracting worst case electromagnetic forces in terms of elemental body force densities needed for the lead analysis. The MAXWELL magnetostatics analysis is then performed for each of the PF1 coil (with detailed spiral winding along with bus bar assembly as complete conduction path while a smeared coil pack was used for all other coils) for accurate mapping of the coil load distribution. The body force densities from the worst case EQ scenarios of #51, #33 and #18 for PF-1a, PF-1b and PF-1c coils are mapped onto conductors of the coil with spiral winding and bus bar assembly in the subsequent structural analysis models. Both positive toroidal field and reverse toroidal field cases of the worst EQ scenarios have been analyzed. This report is to summarize the resultant input loads extracted from 3D MAXWELL calculation of each PF1 coil with detailed conductor spiral winding for the lead analysis of the inner PFs.

2. Inner PF Coil Design

The coil geometry and conductor dimension of the global EM analysis models are taken from the latest Kalish Coil Design Parameter data sheet [3]. To ensure a self-consistent coil alignment with consideration of assembly and positional tolerances of components, the PF-1a conductor width was reduced by 1 mm since inner PF PDR so to increase the inner bore size by 8 mm (4 mm on each side), and cooling hole size is reduced from 0.225” to 0.185” accordingly so to maintain the same width from the hole edge to the conductor outer side edge for fatigue crack propagation of 1mm minimum detectable flaws. The Equivalent Square Wave (ESW) for PF-1a is reduced accordingly from 2.1s to 1.9s so to maintain the same maximum temperature with the conductor modification as shown in Table 1.

Table 1 – Inner PF Physics Requirements

	PF-1a	PF-1b	PF-1c
No. of turns	61	20	16
Max current (kA)	19.67	20	20.25
ESW time (s)	1.9	1.0	1.4

Tables 2-3 listed the coil design parameters and the inner PF conductor dimensions [3], used as the input to establish the 2D axis-symmetric thermal analysis models. Figure 1 presents the typical structural analysis models of inner PF-1a and PF-1b upper and lower assembly in the polar region of NSTX-U. The structural models are used for the 3-D lead analysis.

Table 2 – Inner PF Coil Design Parameters

		MK PF Coil Sizing 02-01-18					
		PF1A (")	**PF1B** (")	**PF1C** (")	**PF1A** (mm)	**PF1B** (mm)	**PF1C**
R center	r_0=	**12.81**	15.44	21.85	325.374	392.176	554.99
Z center	z_0=	62.62	71.03	71.4	1590.548	1804.16	1813.56
Coil ID	ID=	**23.03**	29.32	41.66	585	745	1058
Coil OD	OD=	28.21	32.44	45.74	717	824	1162
Width	w=	**2.59**	1.56	2.04	58.1152	31.9532	44.1452
Height	h=	18.44	7.17	6.94	468.376	174.447	168.605

Table 3 – Inner PF Conductor Dimension

Conductor	PF1A (")	PF1B	PF1C	PF1A (mm)	PF1B	PF1C
Width	**0.481**	0.54	0.78	12.2174	13.716	19.812
Height	0.98	0.5	0.61	24.892	12.7	15.494
hole	**0.185**	0.146	0.146	4.699	3.7084	3.7084

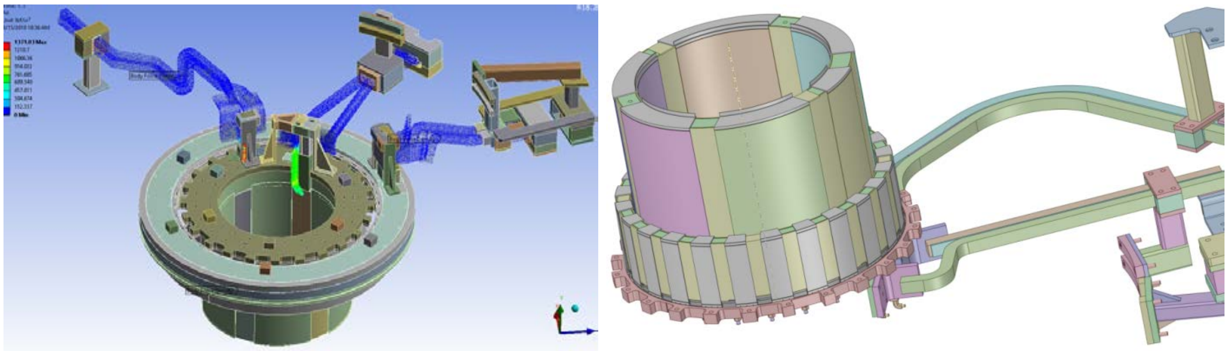


Figure 1 Structural Analysis Models for PF1a & 1b upper (top) and lower (bottom)

3. Procedure for Coil Lead Analysis

A procedure has been developed for coil leads and bus bar analysis, which includes the following steps

- Setup structural environment in 3D models with coil spiral winding for the leads to be analyzed. Implement the new design of the filler blocks at coil terminals, bus flags and bus bars.
- Import Lorentz forces in the form of body force densities from the worst case scenarios and prescribe maximum conductor temperatures on coil packs, leads and bus bars for static structural analysis
- Perform 3D EM and structural analysis for both positive and reverse toroidal field cases for the selected scenarios for each PF1 coils
- Check consistency throughout all lead analysis for each inner PFs

4. Worst Case EQ Scenarios

Three-dimensional magneto-static analysis models were developed for each of the upper and lower PF1-a, PF1-b and PF1-c coils as shown in Figure 2 below. The 3D EM models include conductors of spiral winding, coil leads, bus flags and bus bar assembly. Figure 2 also showed the static magnetic field distribution in the vertical plane, as well as the detailed coil spiral winding used for the lead analysis.

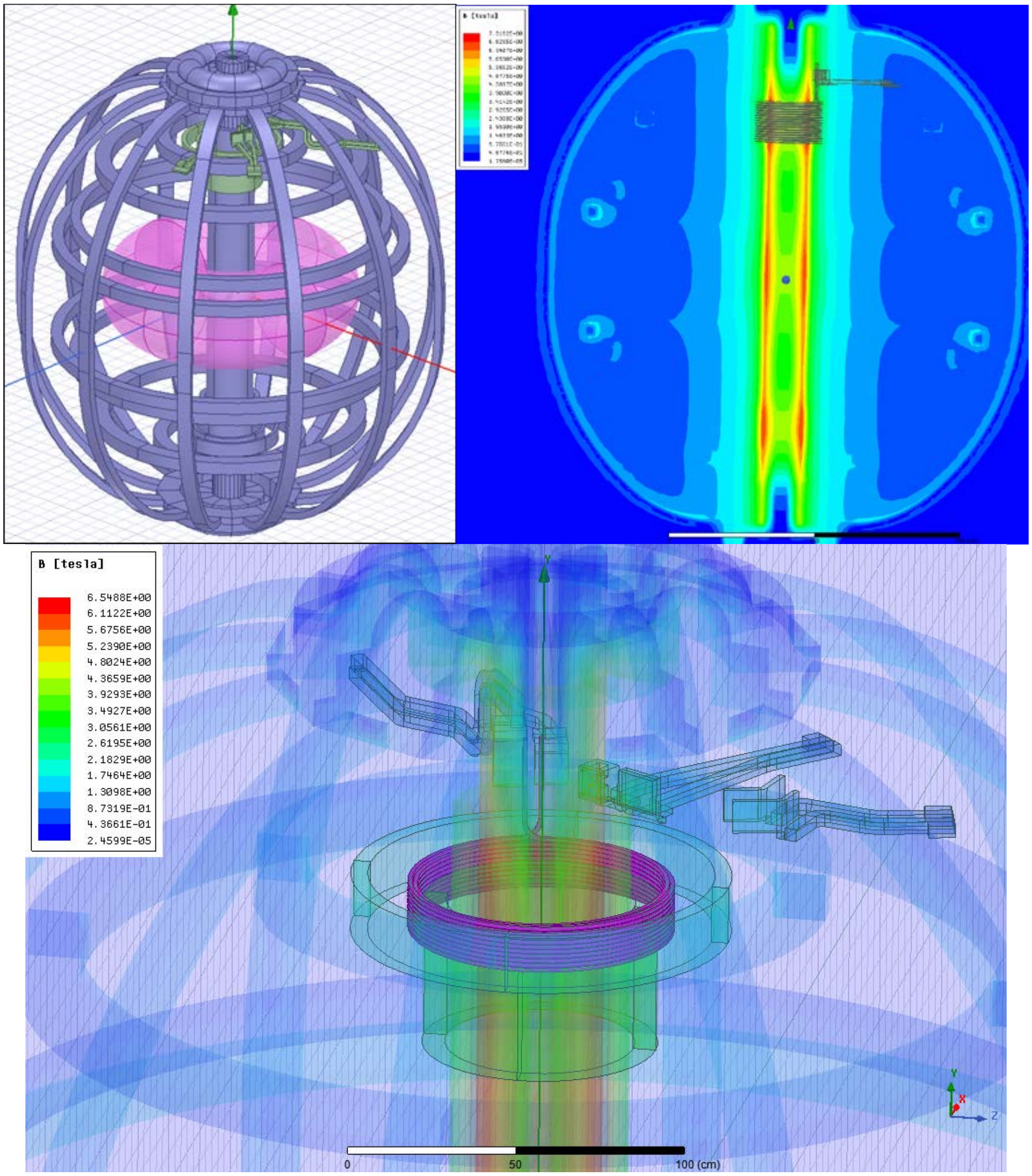


Figure 2 Global Magneto-static Analysis Models for upper inner PFs (left) and Magnetic Field Distribution for EQ #51 (right)

Table 4 – Maximum Total Magnetic Fields for Inner PFs

	PF-1a	PF-1b	PF-1c
EQ scenarios	1, 51	1, 33	18, 33
Maximum current (kA)	20	20	20
Local max B Fields (T)	2.5	3.3	3.2

The worst case EQ scenarios are selected based on the 2D scan of all 96 scenarios defined in DPSS for inner-PF coil current requirements [7]. The equilibrium scenarios of #51, #33 #18 define the maximum magnetic fields on the coil leads and full currents on coils and bus bars. Figures 3-5 present the radial field distribution on the upper inner PFs for the selected EQ scenarios. Both positive and reverse toroidal field cases are analyzed using 3D ANSYS MAXWELL and detailed structural models for leads and bus bars. Other assumptions used for lead analysis include 1) insulations are bonded to the conductors without delamination and linear elastic behavior is used for copper without yielding, 2) coil packs in 3D structural analysis have no thermal conduction with coil support structure, 3) maximum temperature of conductors at end of pulses is prescribed as defined in the 2D thermal analysis.

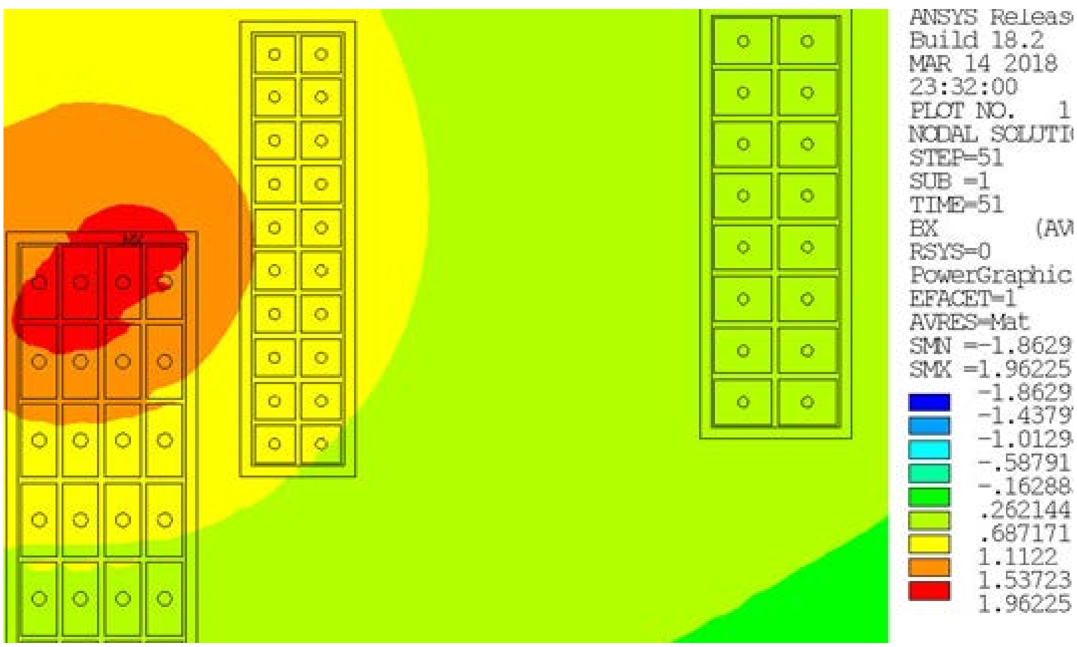


Figure 3 Radial field from EQ #51 (2 MA circular plasma) – worst for PF-1a Leads

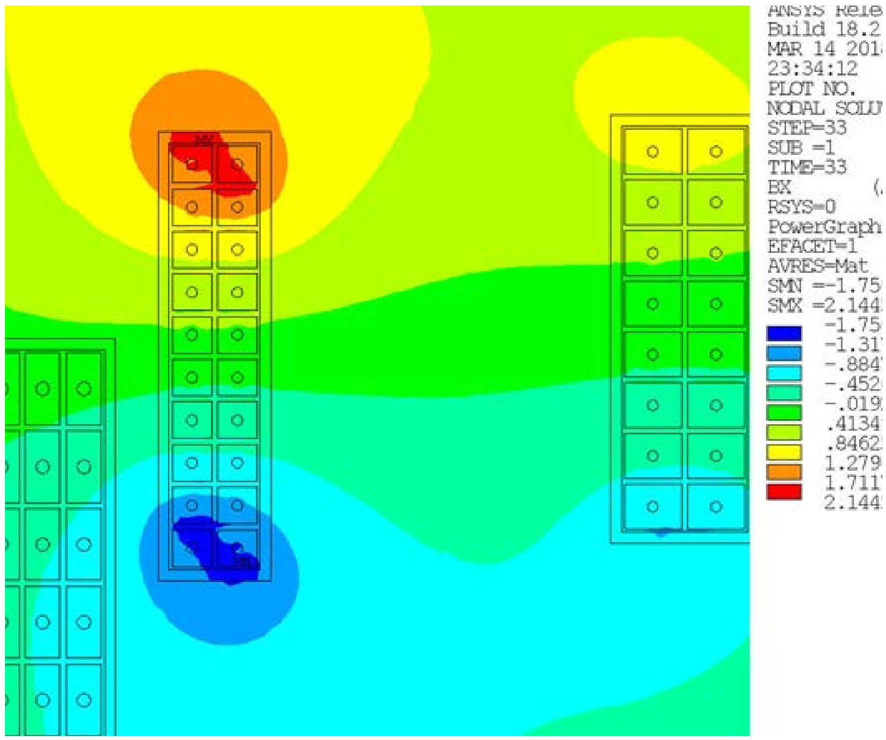


Figure 4 Radial field from EQ #33 (2 MA circular) – worst for PF-1b Leads

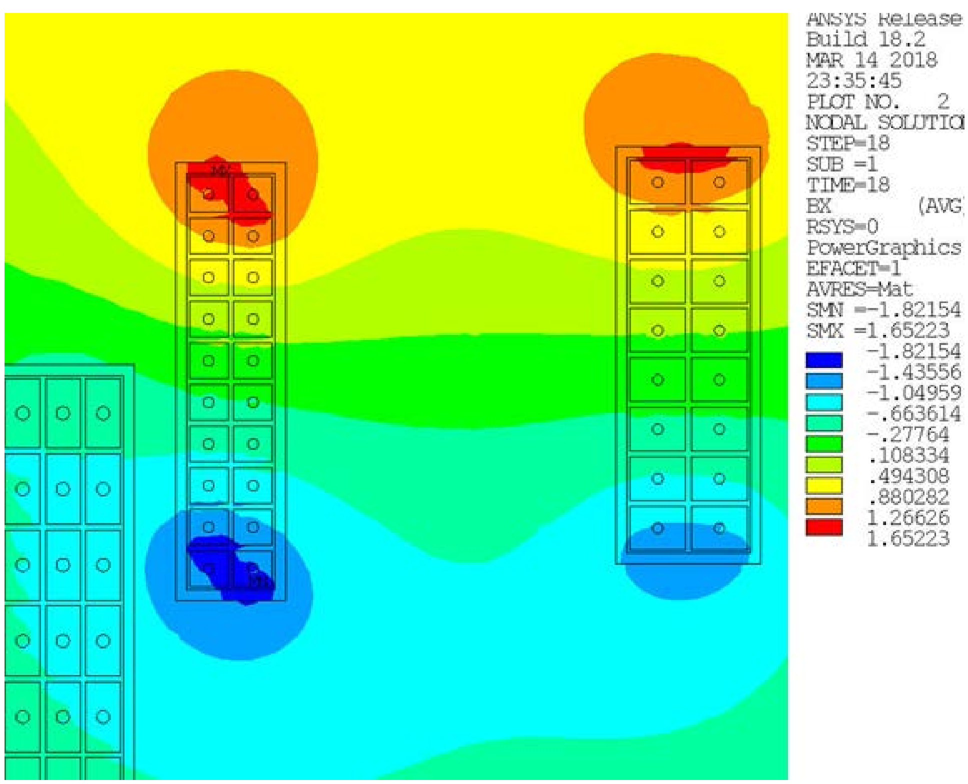


Figure 5 Radial field from EQ #18 (2 MA circular) – worst for PF-1c Leads

5. EM Results

When the inner PFs are energized, the conductor will be pulsed up to ~20 kA for about 1-2 seconds. The conductor and insulation will experience fatigue stress and strain, but thermal stress during cool down dominates the fatigue evaluation for the conductor and stress due to Lorentz loads dominates fatigue evaluation for coil leads. During normal operation, the equivalent square wave (ESW) time of PF-1a, -1b and -1c coils is 1.9, 1.0 and 1.4 seconds respectively. The net forces on inner PF coils extracted from the 3D MAXWELL models are comparable with the DPSS as shown in Table 5 below.

Table 5 – Maximum Total Magnetic Fields for Inner PFs

		Vertical Force (klbf)		
	EQ#18	DPSS	MAXWELL	%
2 MA	PF1AU	-44.46	-44.23	-0.52
circular	PF1BU	17.29	17.96	3.88
plasma	PF1CU	-4.18	-3.6	-13.88

With Plasma

PF1U Coil Vertical Force (lbf) vs Current Scenario

Coil/CS#	**18**	**33**	**51**
PF1A	-4.449E+04	1.016E+04	-4.948E+04
PF1B	1.760E+04	-4.159E+04	0.000E+00
PF1C	-3.891E+03	-2.613E+04	0.000E+00

Magnetic Fields and Body Forces

The magnetic field distribution on the PF-1a upper and PF-1b lower conductors and bus bars are shown in Figure 6 below for the worst case EQ scenarios (EQ #51 and #33). Figure 7 presents the detailed volume force density on the conductors and bus bars of PF-1a upper. The plot clearly indicated conductor in the solenoid is under clamping force and bulged out in the mid-plane, which is the typical behavior of solenoid magnets when energized.

The volumetric force densities for each 3D magnetostatics analysis of the worst case EQ scenarios (both positive and reverse toroidal field cases) for the inner PFs have been extracted from MAXWELL calculators and saved as the database for inputs to the static structural analysis of the coil leads and bus bars. The data are saved in a typical format of (x, y, z, Fx, Fy, Fz) and can be directly imported in ANSYS external data for structural analysis.

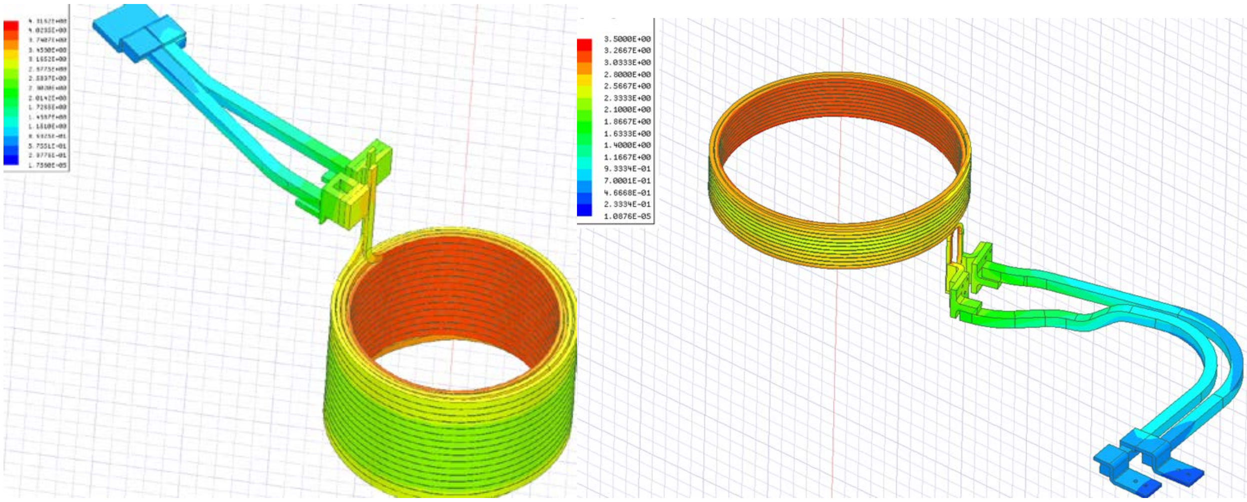


Figure 6 Magnetic fields on PF-1a upper (#51) and PF-1b lower (#33) conductors

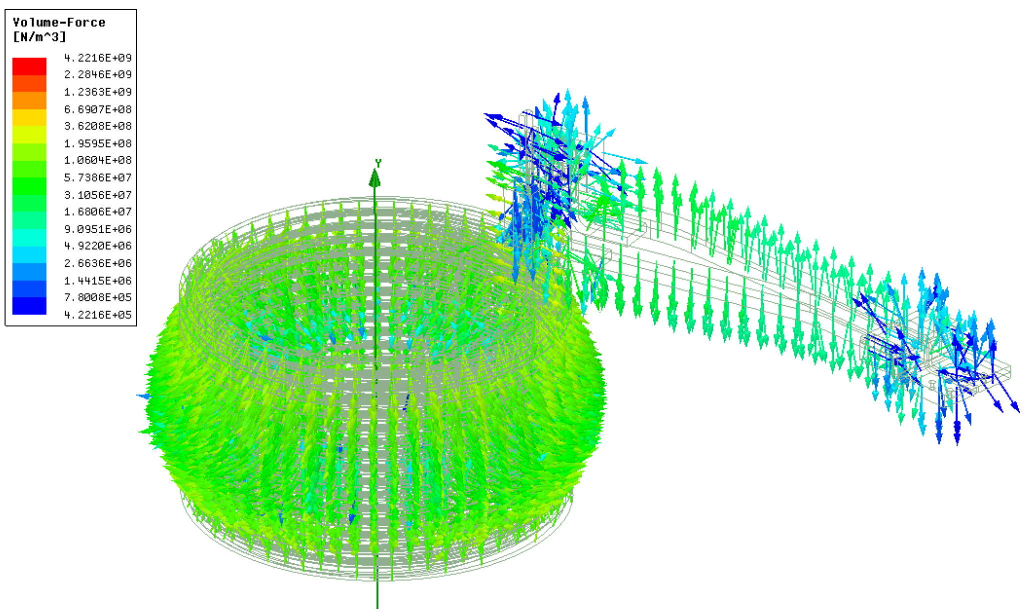


Figure 7 The body force density in PF-1a coil winding and bus bars

The volumetric body force density on the conductor and bus bars for the PF-1b lower is shown in Figure 8. The force density distribution shows very similar behavior of solenoid magnets when energized. The force density on the coil terminals is also clearly shown in Figure 8, where higher force density is expected from interaction with the significant toroidal fields. Table 6 presents the maximum local radial, vertical as well as the toroidal fields on each of the inner PF coils and coil terminals. Note that the toroidal fields can switch sign and both positive and reverse toroidal field cases are analyzed for the coil leads for each inner PFs.

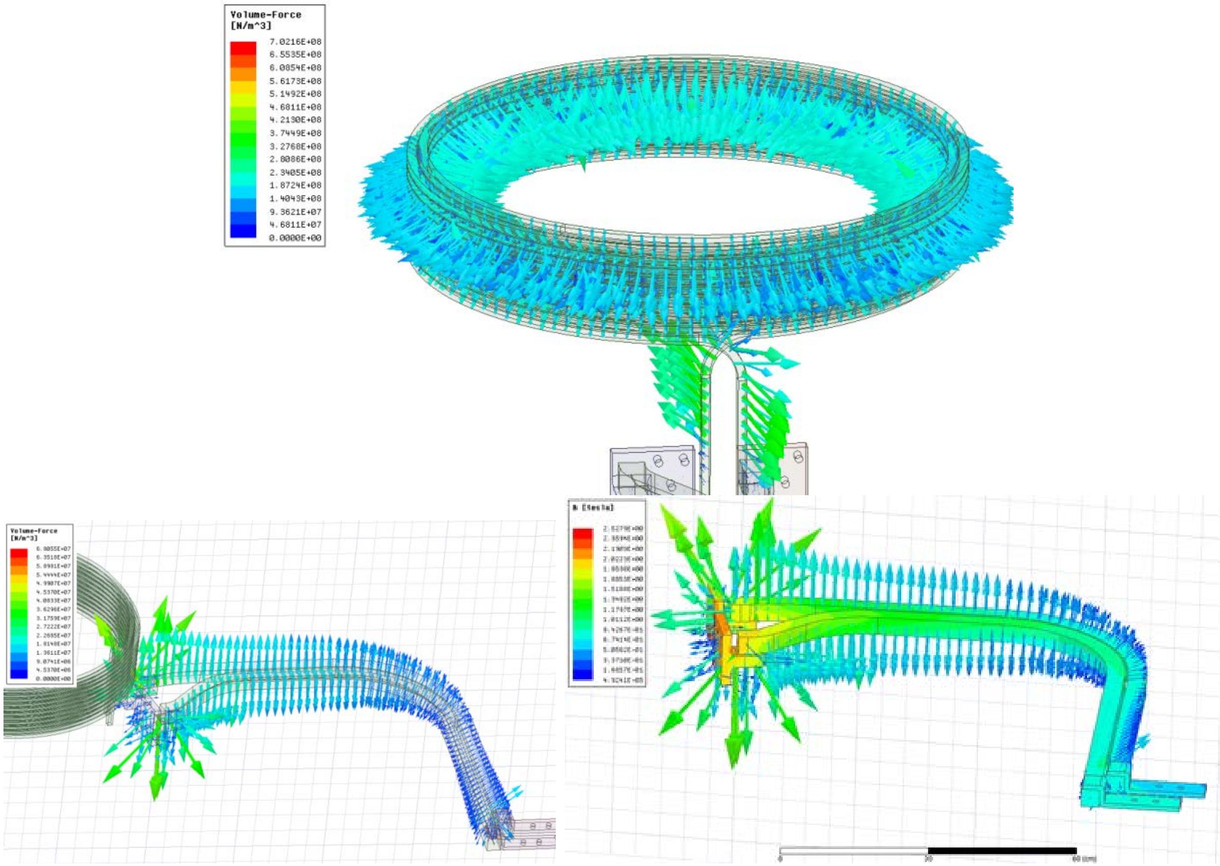


Figure 8 Volume body force on conductor and bus bars of PF-1b lower - EQ #33.

Table 6 – Maximum Fields on Inner PF Coils

	PF-1a	PF-1b	PF-1c
Worst EQ #	51	18, 33	18
Radial B_r (T)	2	2.1	1.7
Vertical B_z (T)	2.5	2.2	1.1
Toroidal B_t (T)	2.9	2.4	1.7

Mapping of Elemental Body Force Density

A typical format of the body force density as input to the structural analysis is shown below. All input files are assembled and stored on the google drive folder. Figure 8 presents the body force densities mapped onto the structural models for the PF-1a and PF-1b upper assembly and the PF1b lower assembly. Figure 8 clearly shows the higher force density on the coil terminals as result of the impact from the toroidal field which is quite significant for the coil terminals.

X (m)	Y (m)	Z (m)	Fx (N/m^3)	Fx (N/m^3)	Fx (N/m^3)
-5.76E-01	-1.85E+00	1.02E-02	6.25E+07	4.03E+07	8.34E+05
-5.66E-01	-1.84E+00	1.00E-02	2.66E+07	3.02E+07	7.10E+05
-5.76E-01	-1.84E+00	1.02E-02	6.46E+07	2.82E+07	4.96E+05
-5.66E-01	-1.85E+00	7.52E-03	2.49E+07	4.24E+07	1.05E+06
-5.56E-01	-1.84E+00	9.85E-03	-9.39E+06	2.02E+07	5.86E+05
-5.66E-01	-1.84E+00	1.00E-02	2.86E+07	1.81E+07	3.72E+05
-5.56E-01	-1.84E+00	7.35E-03	-1.11E+07	3.24E+07	9.25E+05
-5.76E-01	-1.84E+00	1.02E-02	6.66E+07	1.60E+07	1.58E+05
-5.66E-01	-1.84E+00	7.52E-03	2.69E+07	3.03E+07	7.11E+05
-5.56E-01	-1.85E+00	4.84E-03	-1.27E+07	4.46E+07	1.26E+06

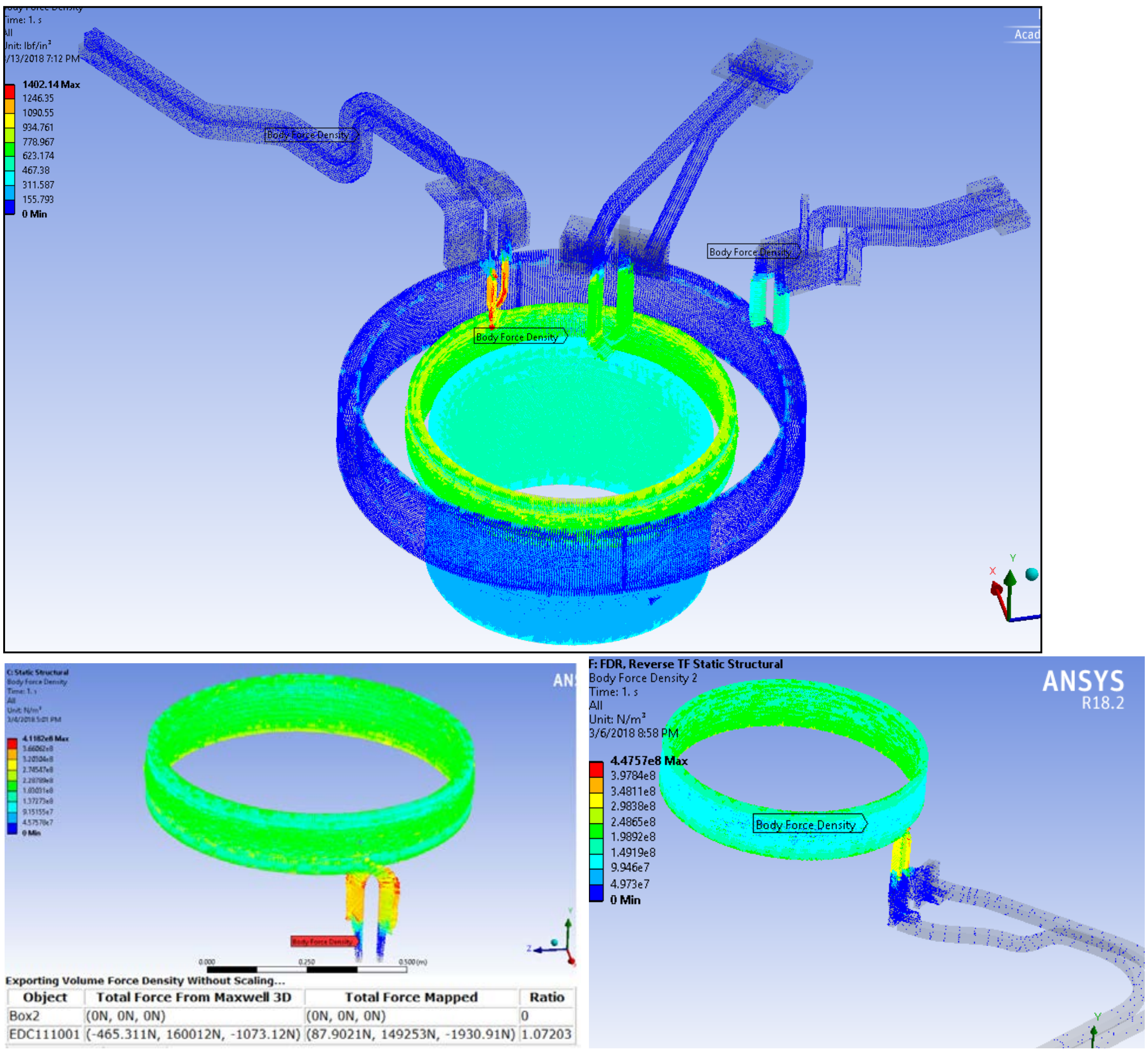
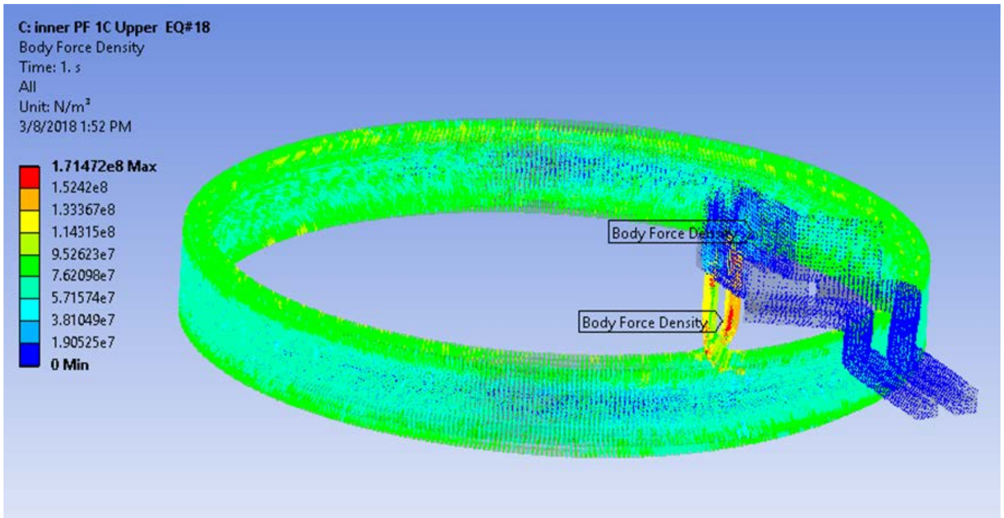
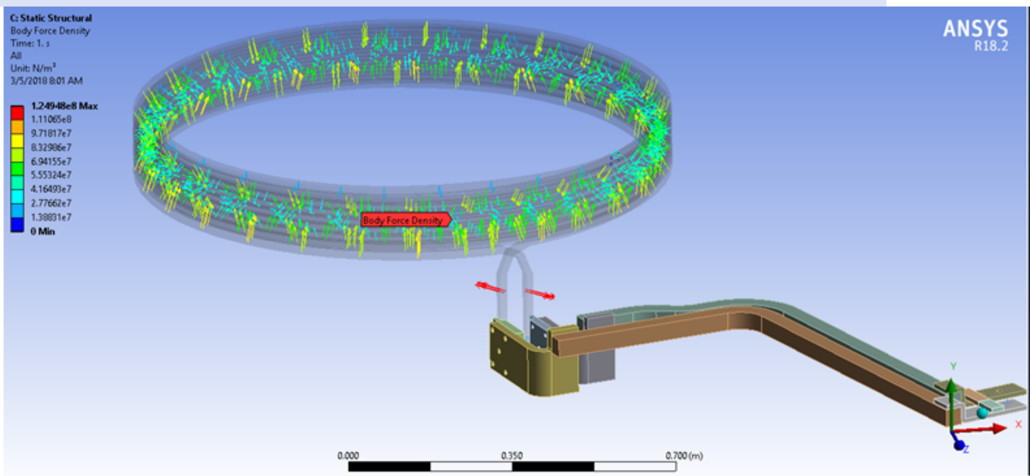


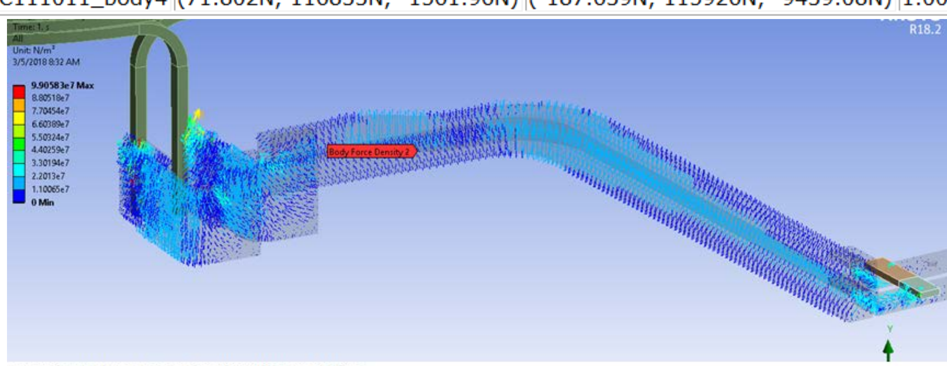
Figure 9 Mapped force densities for PF-1a, 1b upper assembly and PF-1b lower





Exporting Volume Force Density Without Scaling...

Object	Total Force From Maxwell 3D	Total Force Mapped	Ratio
Box2	(0N, 0N, 0N)	(0N, 0N, 0N)	0
EDC111011_body4	(71.802N, 116833N, -1561.96N)	(-187.639N, 115926N, -9439.08N)	1.00459



Exporting Volume Force Density Without Scaling...

Object	Total Force From Maxwell 3D	Total Force Mapped	Ratio
Box2	(0N, 0N, 0N)	(0N, 0N, 0N)	0
JWPF1CLOWER1BUSFLAG	(-390.138N, 3363.89N, -1629.96N)	(-381.566N, 3383.37N, -1624.52N)	0.996229
JWNEWPF1CLOWER2	(-3730.41N, -15670.4N, 4920.93N)	(-3727.78N, -15659.6N, 4918.95N)	1.00066
JWPF1CLOWER2BUSFLAG	(-294.811N, -5216.82N, 1774.65N)	(-297.711N, -5207.71N, 1760.05N)	1.00239
EDC14724	(554.404N, 1668.05N, 384.135N)	(557.029N, 1680.2N, 385.674N)	0.993152
EDC14724_1	(-555.141N, -1752.91N, -632.248N)	(-555.715N, -1734.27N, -630.528N)	1.00892

Table 7 – Typical Ratio of Total Load Mapped from EM to Structural

	PF-1a	Pf-1b	PF-1c
Ratio of Total Load Mapped	1.05	1.07	1.005

As part of the validation of load mapping, the typical ratio of total load mapped from MAXWELL EM solver to the ANSYS static structural model is shown in Table 7, where a close to 100% of volumetric body forces has been mapped onto the structural models.

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

3D magnetoststic analyses have been performed for the inner PF coils PF-1a, -1b and -1c using ANSYS MAXWELL models with detailed spiral winding of each PF1 coils, coil terminals as well as bus bars as a full conduction path, but smeared coil pack for other coils. The analyses performed based on the worst case EQ scenarios selected from a 2D scan of all 96 scenarios defined in the DPSS. The maximum local magnetic fields for each of the inner PFs have been extracted and worst case EQ scenarios for the coil lead and bus bar analysis are identified. Both positive and reverse toroidal field cases have been performed for each of the worst case scenarios to ensure we capture the worst loading and resultant stress for the coil leads in the structural analysis.

The main conclusions include

1. *A consistent procedure has been developed for the analysis of coil leads and bus bars with the new design of bus bar assembly for each inner PFs. The procedure worked effectively in terms of load transfer for qualifying the coil design at the terminal support and bus bar interfaces.*

2. *2D scan of all 96 EQ scenarios shown the worst case scenarios are #51, #33 and #18 for the inner PF 1a, 1b and 1c respectively.*

3. *The maximum radial and toroidal fields for the inner PFs are ~2-3 T in the coil terminals for the worst case EQ scenarios.*