PPPL Calculation Form - No: 2254-CALC-003

Calculation # NSTXU-CALC-131-10 Revision # 0 WP #, if any (ENG-032) 2254 ____

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

- To validate Coil Terminal and power cable Structural Support Design for Inner PF Coil Power Testing

Codes and versions: (List all codes, if any, used)

- ANSYS EMAG, MAXWELL

References (List any source of design information including computer program titles and revision levels.)

- See calculation report

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

- See calculation report

Calculation (Calculation is either documented here or attached)

- Calculation report attached

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

- Lorentz loads from self-fields for power testing of inner PFs are significantly lower than that for NSTX-U operations
- Coil terminal and cable support design is sufficient to react forces and moments for full power testing

Cognizant Individual (or designee) printed name, signature, and date

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2018.05.02 10:01:53 -04'00'

Preparer's printed name, signature and date

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2018.05.02 10:02:26 -04'00'

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

Checker's printed name, signature, and date

Art Brooks Digitally signed by Art Brooks Date: 2018.05.07 09:11:59 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Terminal Support Analysis for Inner PF Coil Power Testing

NSTXU-CALC-131-10 - Rev 0

April 30, 2018

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2018.05.03 14:32:26 -04'00'

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Approved By – Responsible Engineer
M. Kalish

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	4/30/18	Initial Release	Yuhu Zhai

Contents

1 Purpose of Calculation

The inner PF coils for NSTX-U recovery project are water-cooled solenoids fabricated from copper conductors with embedded central cooling channels. The coils, including three upper and lower pairs, denoted PF-1a, PF-1b and PF-1c, will be power tested to demonstrate design capability for pulse currents. The project is also obtaining prototype coils from four suppliers and the first prototype coil PPPL received will be power tested at the Field Coil Power Conversion (FCPC) building up to rated current and temperature prior to the production coil qualification and evaluation. The coils to be power tested will be installed on a Test Stand [5] located in the PF Reactor Enclosure of the FCPC building.

The purpose of this calculation is to 1) summarize the self-field generated from each inner PF coils when powered to their full currents; 2) report analysis results for the coil terminal support design based on EM loads from coil self-fields generated during power testing.

Different from the PF1A prototype coils [1], the inner PF design for the production coils [2-4] is based on the revised physics requirements defined in the NSTX-U General Requirements Document [6] and System Requirements Document for Magnet Systems [7-8].

The load specification for power testing, including stray field and its interactions with the nearby DC Current Limiting Reactor (CLR) and the concrete floor reinforcing bar (rebar) is documented in a separate calculation [9].

2 References

[1] PF1A Prototype Coil Assembly, E-DC11053
[2] PF1A Coil Assembly, E-DC11102
[3] PF1B Coil Assembly, E-DC11100
[4] PF1C Coil Assembly, E-DC11101
[5] PF Coils Test Stand Assembly, E-DC11061

[6] NSTX-U-RQMT-GRD-001-00 General Requirements Document, S. Gerhardt, December, 2017
[7] NSTX-U-RQMT-SRD-002-00 System Requirements Document Magnet Systems, S. Gerhardt, December, 2017.
[8] Inner PF coil design parameters, M. Kalish, February, 2018.
[9] Pulse Currents and EM Forces during Power Testing of Inner PF Coils, C. Neumeyer, April, 2018.
[10] 13-031010_CLN_01, Resistivity versus Contact Pressure, memo, C. Neumeyer.

3 Assumptions

ANSYS EMAG and MAXWELL models for inner PF coils are developed for extracting self-field electromagnetic forces for the design of prototype coil terminal connections. The MAXWELL magnetostatics analysis is performed for each of the PF1 coils to generate self-fields and Lorentz force distribution on the coil terminals. Structural analysis is performed to validate mechanical support design of the terminal connections. This report is to summarize results based on a simple plate-to-plate mechanical support design of the terminal flags.

3.1 Coil self-fields

- Use 2D axis-symmetric model (ANSYS EMAG) to generate self-field distribution
- Use 3D MAXWELL model with conductor spiral winding to obtain field distribution on coil terminals and flags connected to power cables
- Assume full rated current for each inner PFs in the self-field calculation

3.2 Coil terminal connection

- Use sub-modeling of prototype coil terminal assembly to validate support bracing design at terminal flags
- Concentrated forces from interaction of self-field and full current on coil leads are used for mechanical analysis
- Assume inlet water temperature 25^{o}C and bonded contact without friction is used
- Neglect thermal fatigue from cool down as only very few number of pulses used for power testing
- Assume perfect electrical contact at bolt joint connecting terminal flags and cable tabs but validate sufficient contact pressure (>3 ksi) in mechanical analysis

4 Calculation

Calculations are performed using ANSYS EMAG, MAXWELL and Workbench FEA tool.

4.1 Inner PF Coil Design

The global EM analysis models take input from the latest Kalish Coil Design Parameter data sheet [8]. The Equivalent Square Wave (ESW) for PF-1a is reduced at FDR from 2.1s to 1.9s due to conductor size change for tolerance control and to maintain the same maximum temperature. Table 1 shows the turns, current and ESWs for inner PFs.

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

Table 2 listed the coil design parameters [3], used as the input to establish the 2D axis-symmetric thermal analysis models. Figure 1 presents the inner PF-1a upper and lower coil pack assembly. The net weight of prototype and production coils is summarized in Table 3.

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 Coil Weight Summary

	Prototype	PF1A	PF1B	PF1C
Winding Pack (lb)	902	702	158	325
Sling support (lb)	n/a	271	73.5	0

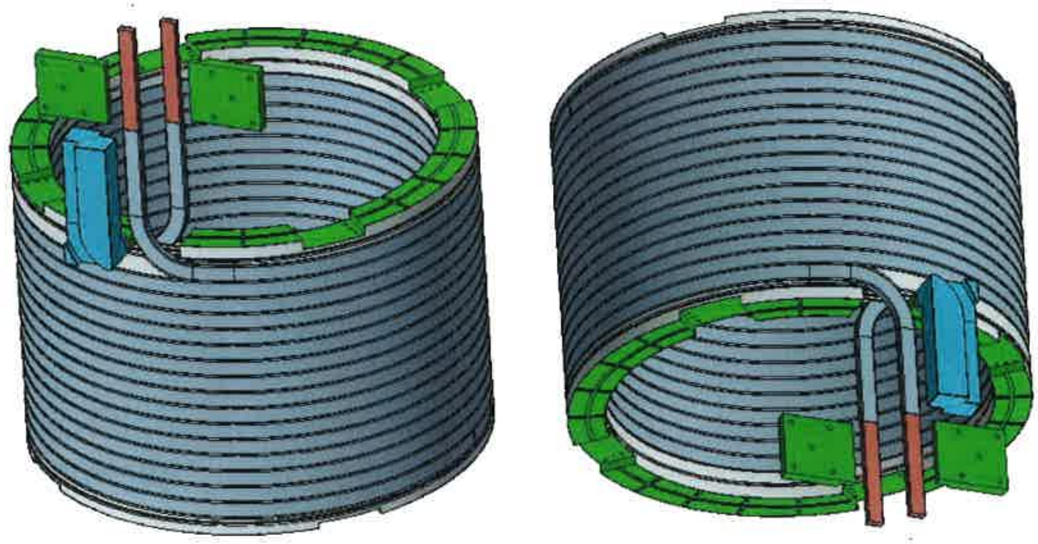

Figure 1 Inner PF Coil winding 1a upper (left) & 1a lower (right)

4.2 Prototype and Production Coil Testing

A detailed procedure has been developed for a prototype coil technical evaluation. The coil evaluation includes power testing at the FCPC building on the same test stand used for the Stand Alone testing of NSTX-U Inner PF Coils. The test stand [5], however, is designed based on PF-1a replacement coils with mandrels. For the new prototype coil testing of bare coil (winding packs), a simplified design to mount the coil to test stand will facilitate easy fork-lifting and coil handling to the FCPC. Figure 2 shows the coil mounting design with a simple bolted tab connection of power cables to coil terminals without bus bar. The prototype and production coils with be tested with leads pointing upward, instead of downward used previously for the Stand Alone testing of NSTX-U PF1A. Other advantages of the new leads-up mounting scheme for coil testing include

- Minimize potential damage to coil pack and terminals during handling and testing
- Simple lift procedure developed with rigging only (three choked slings + pallet with blocks to forklift over to FCPC)
- Same design and procedure for testing of prototype and production coils, where sling assemblies with studs on PF1A and 1B will prevent mounting on flanges with leads pointing downward
- Consistency maintained for both prototype and production coil testing with easier inspection of coil terminal support blocks and cable connections

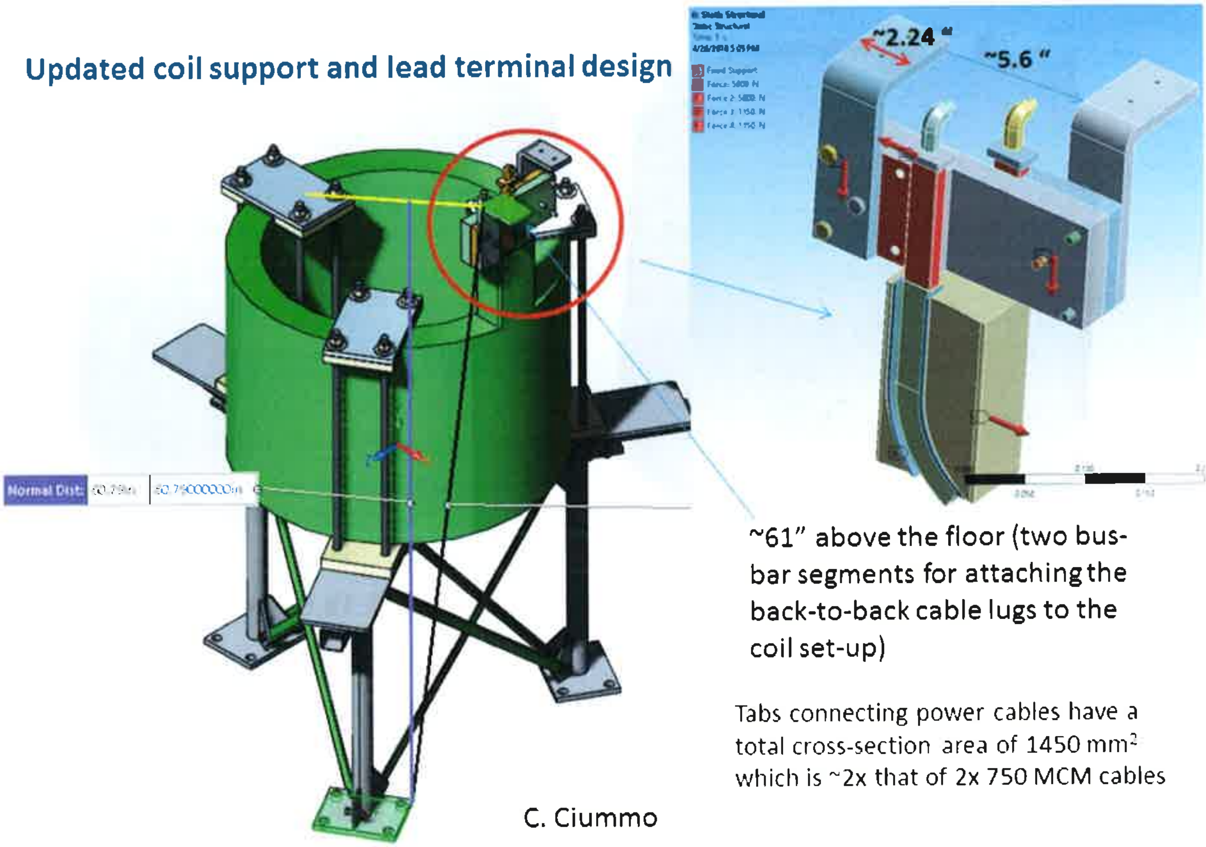

Figure 2 Test stand, prototype coil mounting and terminal connection to cables

The main disadvantage for the leads-up connection to power cables for testing is that existing cables in the FCPC test cell will need to be rerouted with additional design drawing changes, field works and procedure approval. We will need either move the existing cable tray from ceiling or implement additional cable support between the test stand and existing tray. A decision has been made to go with the leads-up connection while an easier solution for rerouting cable is shown in Figures 3 and 4. We will use existing unistrut insulated cable clamps to help position the cables in the back to back lug configuration for the final connection to the coil, coming off of the closest vertical members in the new support structure shown in Figure 3.

The net vertical forces on the prototype and production coils 1a and 1b is always downward, although there is a small net vertical force of ~168 lb launching load on the PF1C coil considering the eddy current force generated from interaction with the rebar [9]. The coils will be securely attached to the test stand which is bolted to the floor with 12 5/8" studs.

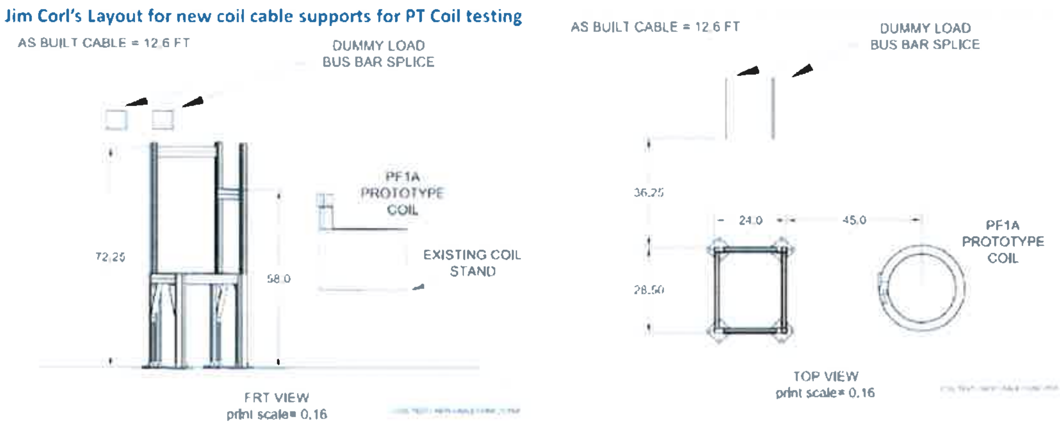

Figure 3 Layout for new cable support to connect coil on Test stand to cables

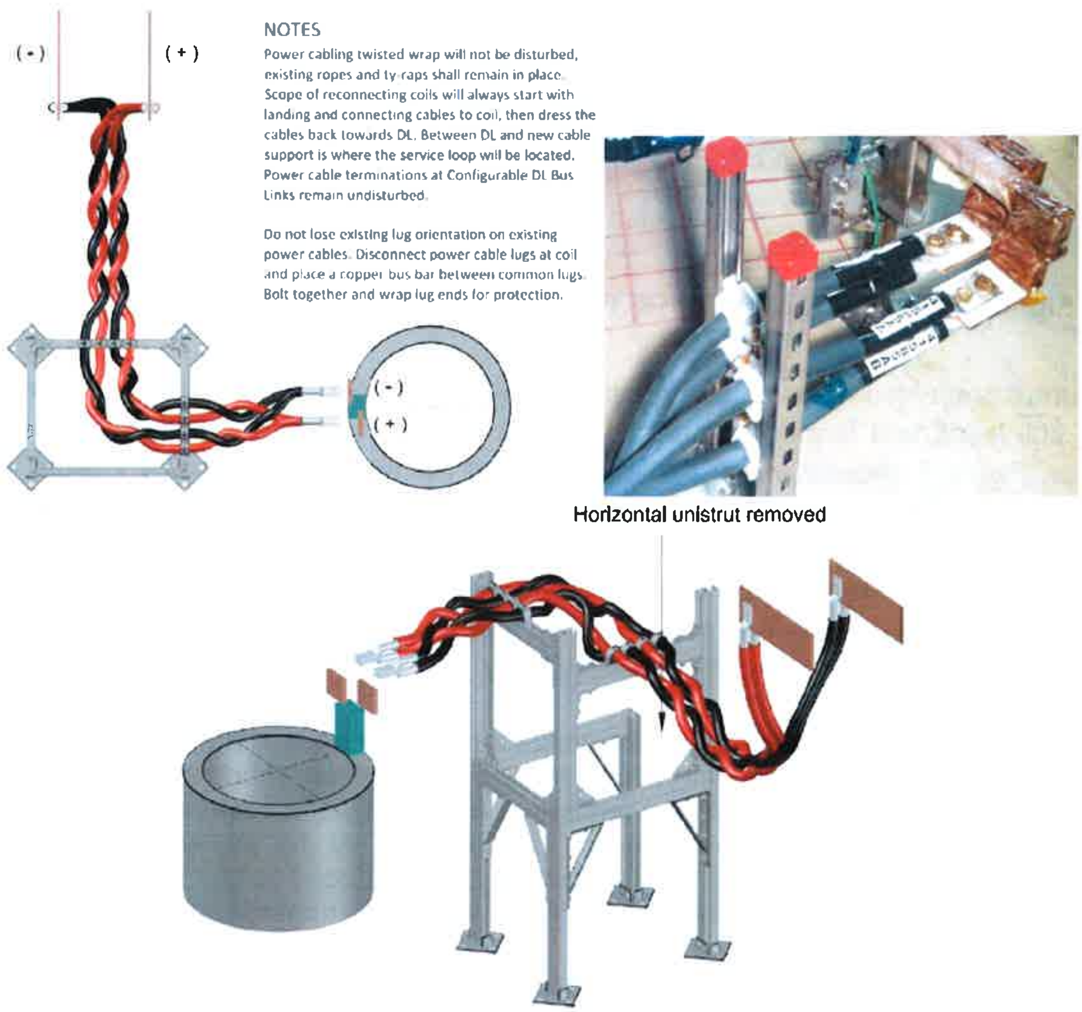

Figure 4 Cable support + terminal connection to 750 MCM power cables (Corl)

4.3 Analysis Models

The 3D magneto-static analysis models were developed during inner PF FDR for each of the upper and lower PF1-a, PF1-b and PF1-c coils as shown in Figure 5 below. The 3D EM models include conductors of spiral winding, coil leads, terminal flags and bus bar assembly. Also shown in Figure 5 is typical magnetic field distribution in the vertical plane, as well as the detailed coil spiral winding used for the lead analysis.

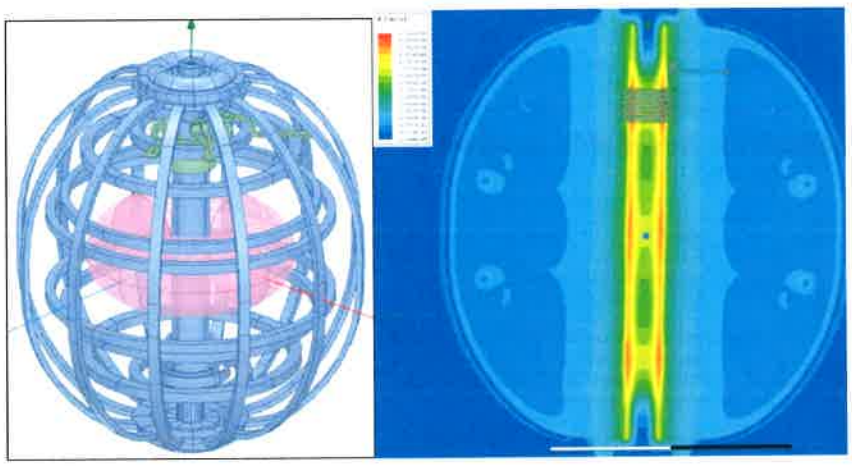

Figure 5 EM Model for inner PF FDR (left) and Field plot from EQ #51 (right)

Figure 6 presented details of the magnetic self-field generated from full current around the coil leads and terminals flags, as well as the detailed field directions at the coil leads. Figure 7 showed the self-field direction at the terminal flags (<0.5 T radial field and <0.5 T vertical field). Table 4 presented a summary of the maximum self-fields at rate currents for each inner PFs. Figure 8 presents the Lorentz force distribution on the coil terminals and the potential torque on terminal flags. Figures 9-17 presented the self-field distribution (total, vertical and radial) on the coil winding pack from the 2D analysis models for PF-1a, PF-1b and PF-1c respectively.

The stray field at the cable support frame shown in Figure 4 is about 300 G (0.6 meter away from the coil outer diameter). To minimize the loop current during power testing, the lower back horizontal unistrut is removed. Under the worst case condition, assume that the dB/dt is the maximum that can be produced by the power supplies and if running with the full 2kV power supply. The maximum induced voltage is limited to be a few volts. All four cables will be encompassed with white nautical rope to constrain its movement.

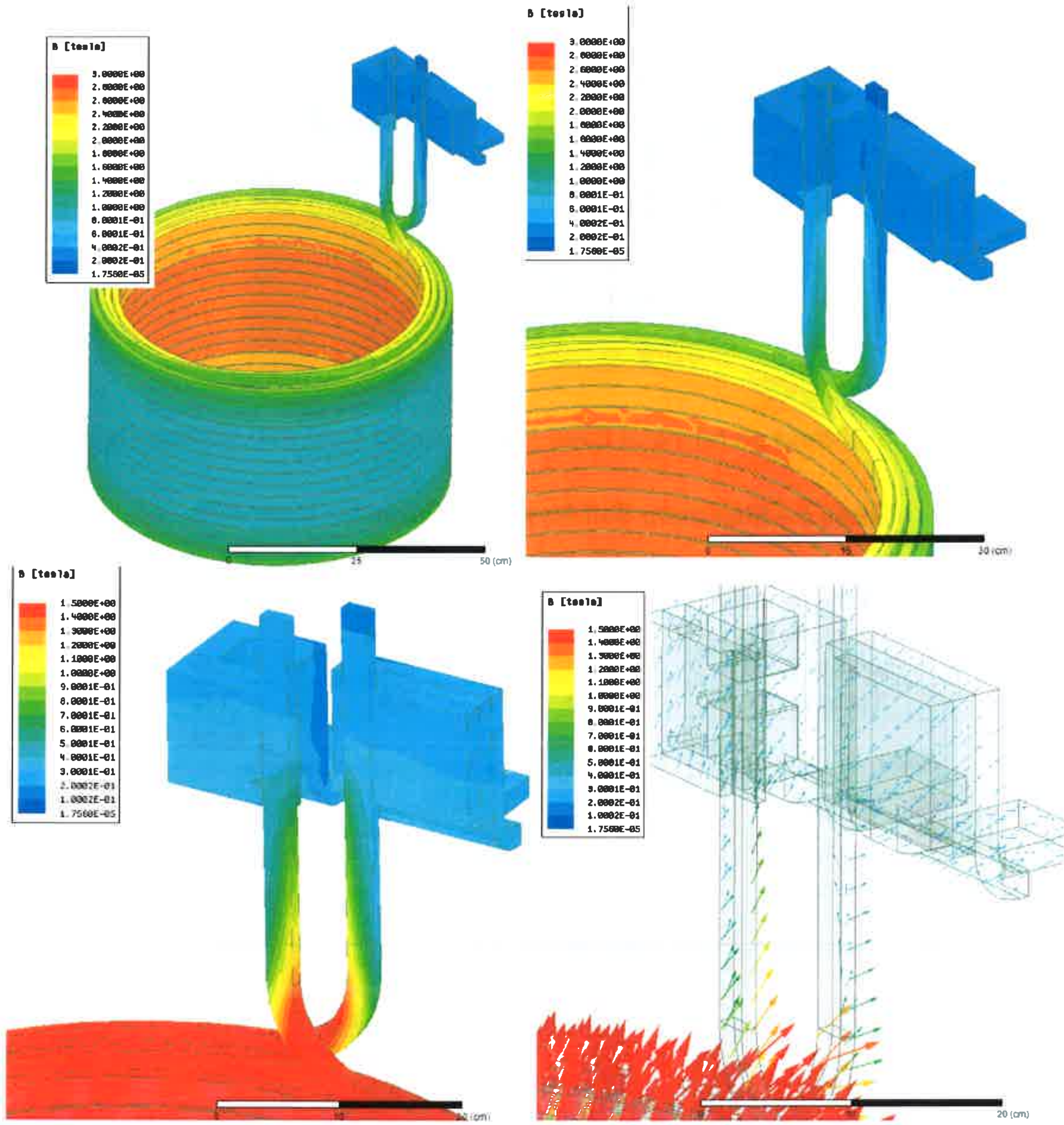

Figure 6 Self-field on PF1A (top) at full current and on coil terminals (bottom)

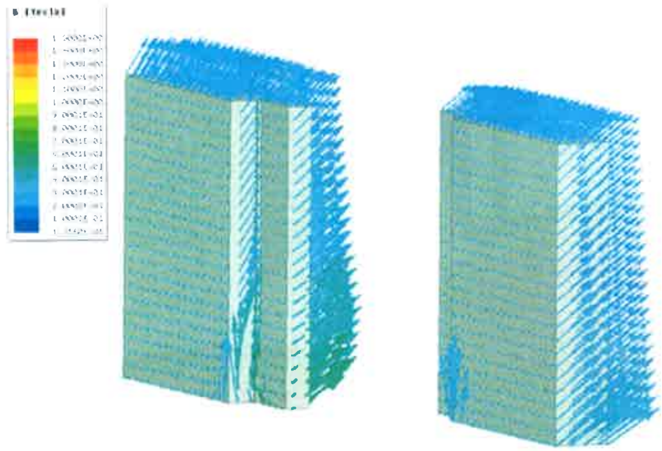

Figure 7 Self-field on terminal flags (<0.5 T radial field and vertical field)

Table 4 – Maximum Self Magnetic Fields for Inner PFs

	PF-1a	PF-1b	PF-1c
Rated current (kA)	19.67	20	20.25
Radial B_r (T)	2	2	1.5
Vertical B_z (T)	3.1	2.2	1.6
Total B (T)	3.1	2.3	1.6

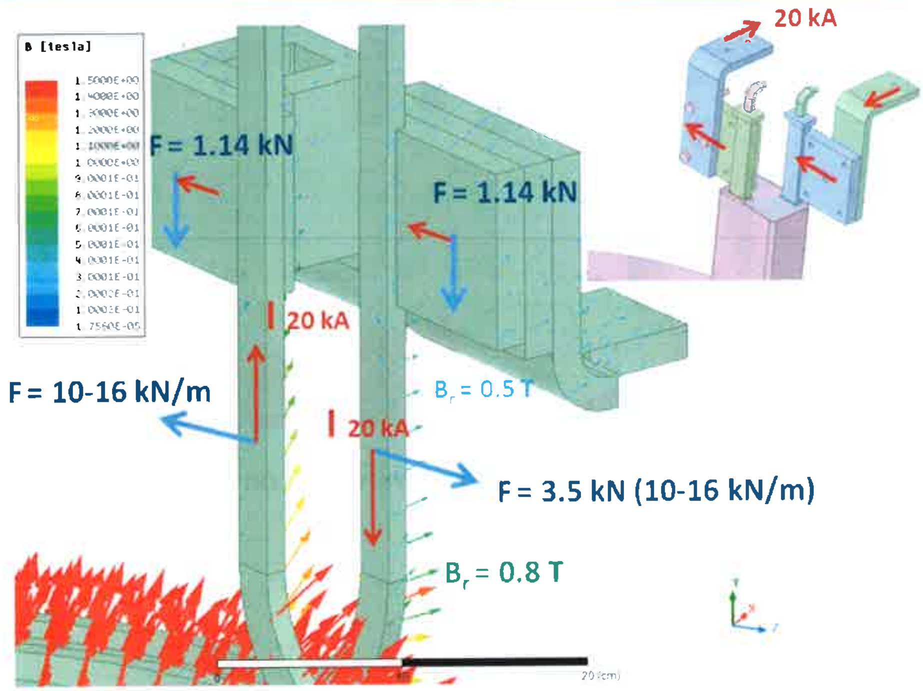

Figure 8 Lorentz forces from self-field on PF-1a terminals and terminal flags

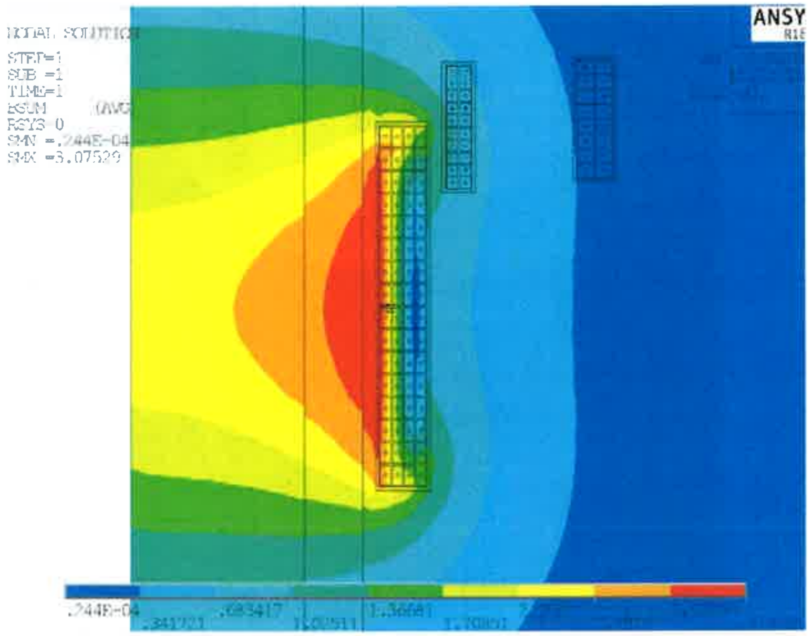

Figure 9 Total self-magnet field (20 kA full current) for PF-1a coil testing

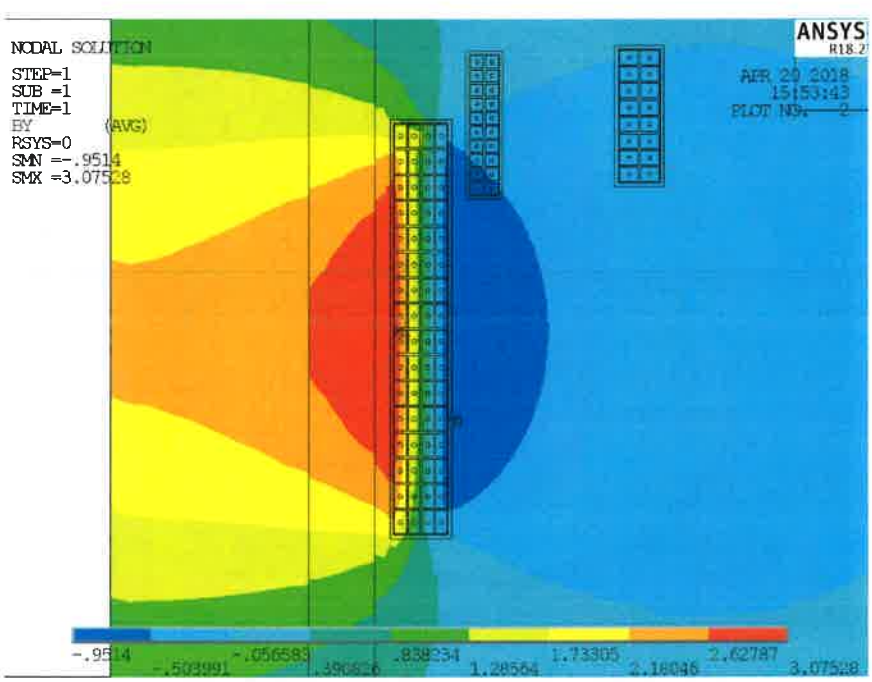

Figure 10 Vertical field distribution (20 kA full current) for PF-1a power testing

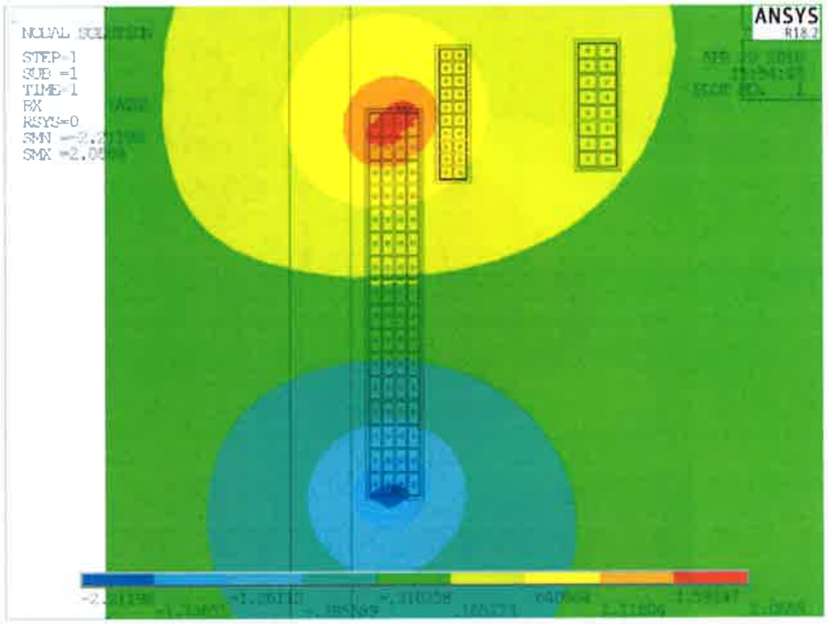

Figure 11 Radial field distribution (20 kA full current) for PF-1a power testing

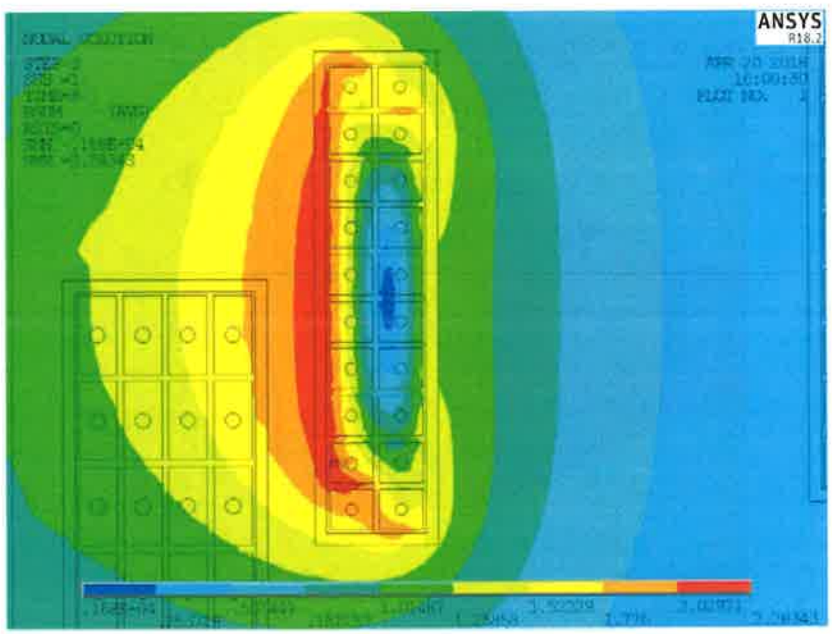

Figure 12 Total self-magnet field (20 kA full current) for PF-1b coil testing

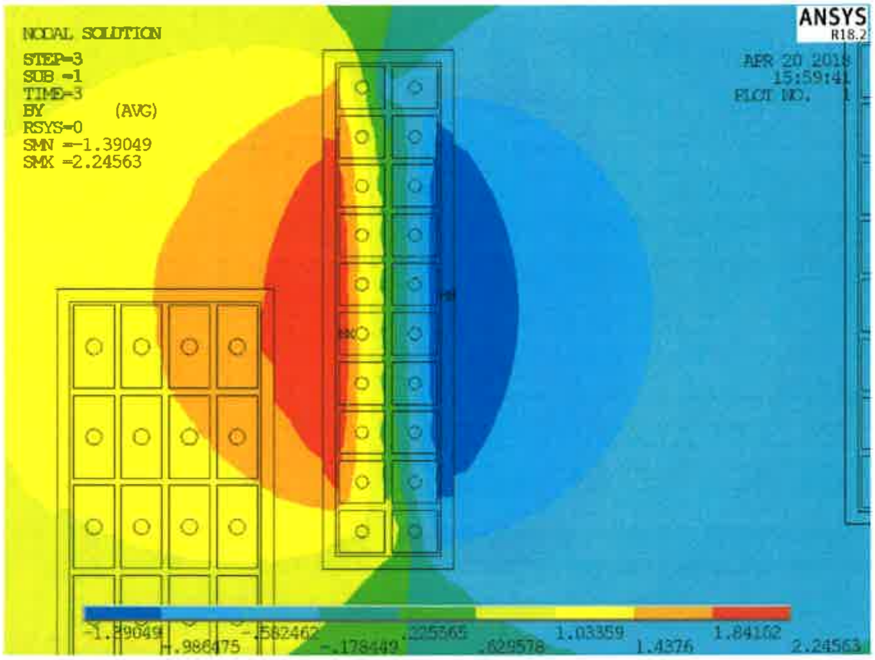

Figure 13 Vertical magnet field (20 kA full current) for PF-1b coil testing

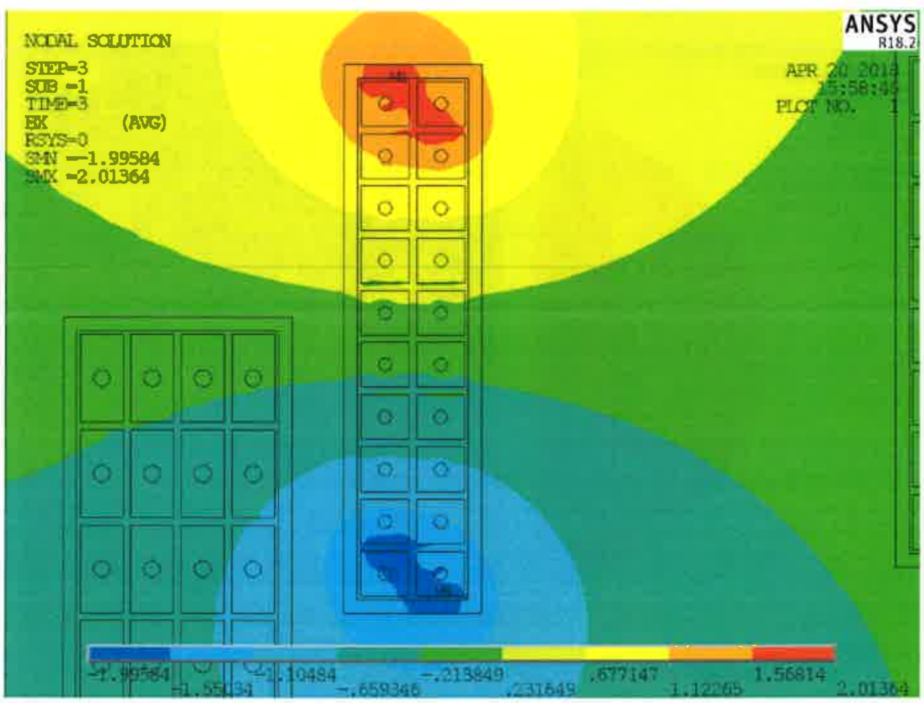

Figure 14 Radial self-magnet field (20 kA full current) for PF-1b coil testing

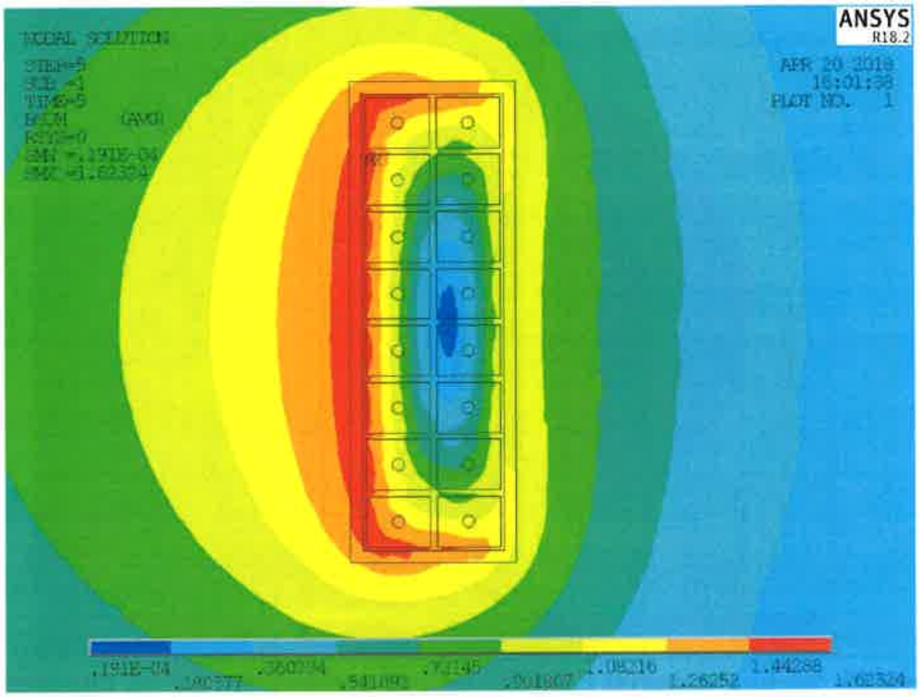

Figure 15 Total self-magnet field (20.25 kA full current) for PF-1c coil testing

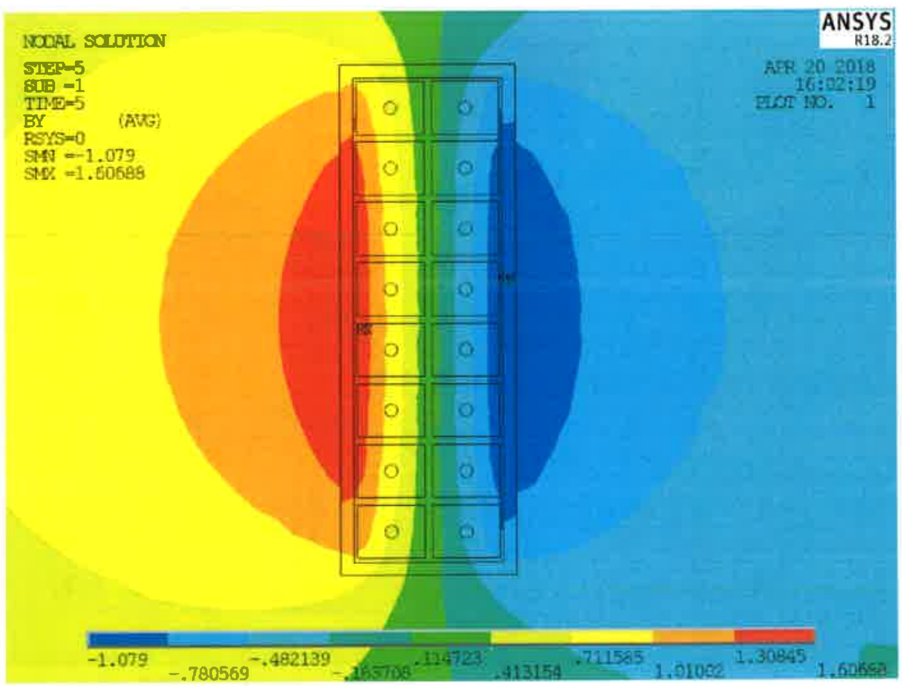

Figure 16 Vertical self-magnet field (20.25 kA full current) for PF-1c coil testing

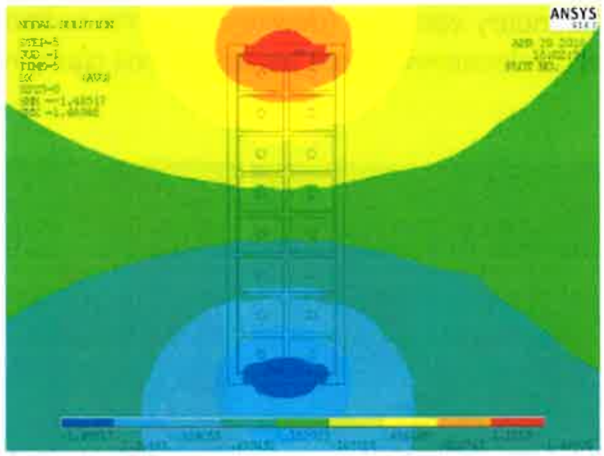

Figure 17 Radial self-field (20.25 kA) for PF-1c coil testing

4.4 Terminal Flags and Cable Connections

The coil will be mounted onto the test stand and connected to the power cables. With the absence of a significant background toroidal field (>2.5 T) during operation, self-field generated Lorentz forces on coil terminals and flags for power testing are significantly lower than that for machine operation. To this end, a much simpler support design is used to connect soft cables to coil terminals without bus bars. A simple flat G10 block from plate-to-plate is used for bracing of the terminal flags. The flat tab plates will be silver plated copper conductor to minimize contact resistance and ensure the bonding with the power cables. The flab tabs are connected to the 2x 750 MCM cables with bolt joint to ensure >2 ksi sufficient contact pressure over the joint area [10]. In addition, Believille washers are used to ensure a tight joint with thermal cycling during power testing (6 cycles for prototype coil and 20 cycles for production coils). The cables are coming down from tray above as shown in Figures 3-4.

Figure 18 presents the detailed sub-model used for analysis of the terminal connection. To ensure sufficient current transfer, the flat tabs used to connect the terminals to power cable are selected to have a cross section area of 724 x 2 = 1450 mm^2 , which is more than 2x of the 2 750 MCM cable cross section areas (760 mm^2). The analysis model includes the break out section of the conductor from the coil winding pack, the G10 support block for the terminal leads, terminal flags and the flat plate to plate connector block (G10), as well as the tabs for bolting the power cables. The Lorentz forces of 5 kN to push apart the two vertical leads of the conductor are applied on the surface of the conductor, in addition to the vertical downward force of ~1.15 kN applied onto the terminal flags. Bonded contact connection is used throughout the structural analysis. 22 C ambient is used on the mechanical parts for the calculation. A detailed finite element mesh is also shown in Figure 18 (right panel). The model has a prescribed ~0.03 mm vertical displacement boundary condition (downward) at the bottom of the terminal G10 block (resultant vertical displacement of coil pack from coil clamping force during power testing).

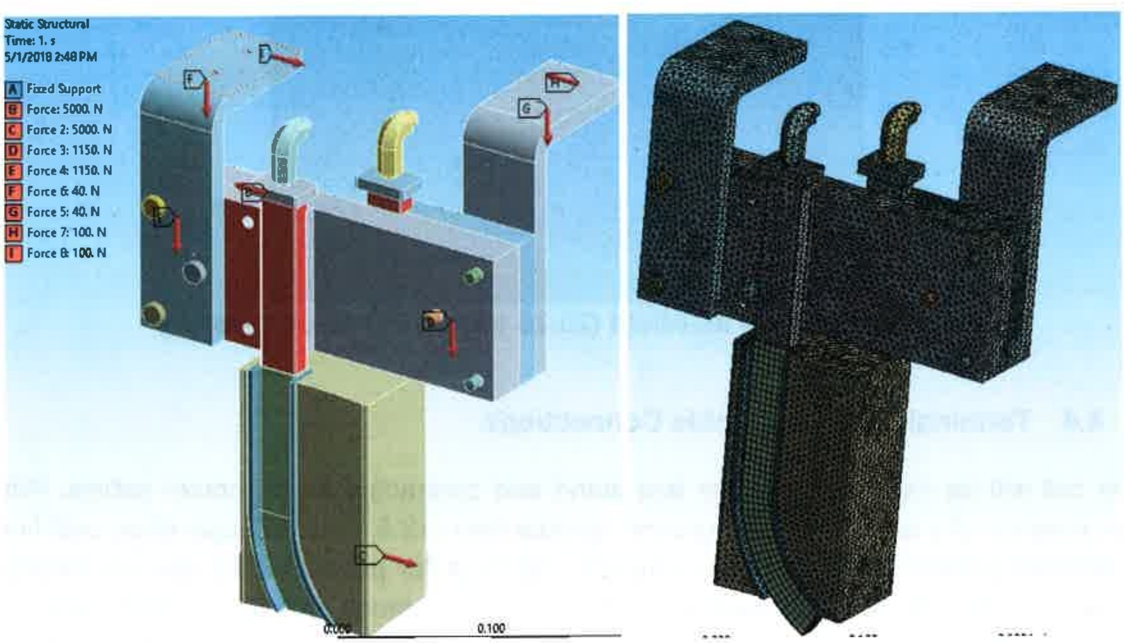

Figure 18 Analysis model for structural validation of terminal connections

Figures 19-20 show the total deflection and equivalent stress distribution on the assembly of the terminal connection. The maximum stress on the conductor at terminals during full power testing is less than 30 MPa, which is much lower than the design stress fatigue allowable of 160 MPa. Figure 20 also shows the stress distribution on the G10 blocks, where the peak on the block is below 20 MPa, also much lower than the >100 MPa allowable for G10.

Table 5 – Equivalent Stress on Terminal Assembly - Power Testing

Peak Stress	**Conductor**		**G10**		**Bolt**
	Allowable	Power Test	Allowable	Power Test	Power Test
MPa	**50**	30	150	20	4.1

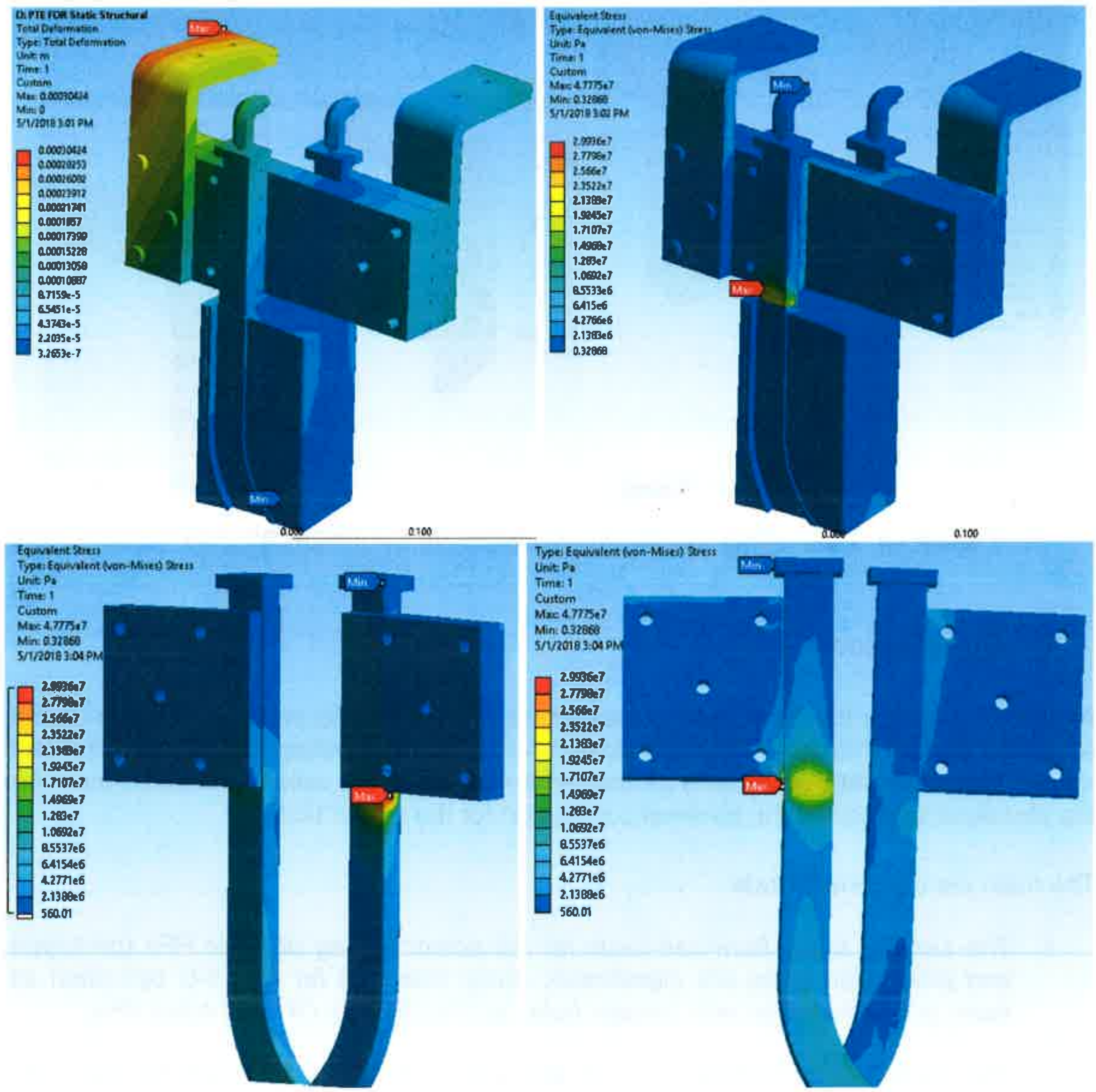

Figure 19 Deflection and stress distribution on coil terminal connections

There is a net twisting load on the flat tabs connecting to the power cable as result of cable current interaction with the vertical stray field. The stray field at the flat tab is <0.1 T and the horizontal force on each tab is 0.1 kN. There is also a section of the cable to be supported from the frame to the terminals. The net weight of the two cables for each terminal is less than 40 N. Note that in Table 4 the peak stress under the terminal flags is a bending stress and it is below the yield strength of fully annealed copper as result of brazing between the leads and the terminal flags.

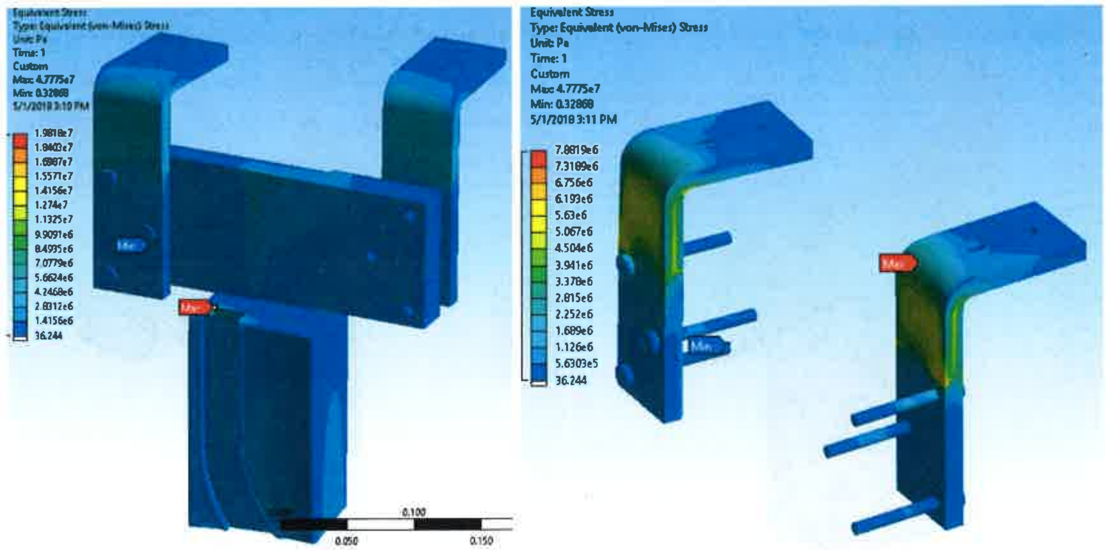

Figure 20 Equivalent stress on coil terminal connections (<20 MPa)

5 Conclusion

Analysis results for the full current pulses on the prototype coils provide validation of the simplified terminal structural support design for coil power testing mounted on the test stand. Magneto-static analysis is performed for the inner PF coils to extracted input for the structural analysis of the terminal connection for the power testing.

The main conclusions include

1. *The Lorentz loads from self-fields for full power testing of inner PFs (prototype and production coils) are significantly lower than that for NSTX-U operation as there is no interaction with toroidal fields and fields from OH and other PFs.*

2. *The simplified coil terminal support design is sufficient for full power testing and it can facilitate easy mounting and handling of coils on the test stand for testing.*

3. *The structural support for coil terminal and power cable connection will adopt the same design principle presented here for both the prototype and production coil testing but mounting for production coils (PF-1b and PF-1c) will be adjusted accordingly with minimum additional effort.*