PPPL Calculation Form - No: NSTXU-CALC-131-001

#

Calculation # NSTXU-CALC-131-001 Revision # 0 WP #, if any (ENG-032) 2254

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

The purpose of this calculation is to validate structural integrity of PF1C Lower coil terminal leads and coil bus bars including terminal stresses at lead sections of the PF1C Lower with the new design of filler blocks, support brackets and bus bar structure assembly.

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

ANSYS 18.2

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

[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] NSTX-U-SPEC-MAG-001-2 Specification for Inner PF coil conductor, M. Kalish, November, 2017

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

The 3D structural analysis models with conductor spiral winding, coil terminals and new bus bar assembly for each of the PF-1a, 1b and 1c coil are developed and used for the lead analysis. For PF-1c lower, the end of pulse condition is used where the maximum coil temperature of 50 C and a reference temperature of 22 C are used. The body force density cloud data extracted from the 3D MAXWELL magnetostatic analysis for the worst case EQ scenarios of #33 and #18 for PF-1c coils are mapped onto the spiral wound conductors, coil terminals and the bus bars in the structural analysis models. Linear structural analyses are performed for PF-1c lower where spiral winding of conductors is modeled but smeared properties are assumed as coil pack insulations. This report is to summarize the stress results from 3D calculation of coil terminal lead sections for the new design of the PF-1c lower.

Calculation (Calculation is either documented here or attached)

Please see attached main body of this document.

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

The results of this calculation show that maximum stress intensity of PF1C lower coil terminal leads is below the conductor fatigue design allowable of 160 MPa and thus acceptable.

Results of the numerical simulations show, that coil leads experience large values of local stresses due to magnetic forces and thermal expansion. The local stress intensity reaches 130MPa on the coil lead for scenario 18 at the point where coli lead is attached to the flag. Further reduction of the stress intensity can be achieved using fillets on the flag at lead attachment points. Brackets connecting flags to coil support structure improve strength of the connection, and are included in the analysis. Clamping of the in and out bus bar together is required to reduce the deformation and corresponding stress levels at the supports, and leads.

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

Yuhu Zhai Digitally signed by Yuhu Zhai
Date: 2018.09.10 12:48:03
-04'00'

Preparer's printed name, signature and date

Andrei Khodak Digitally signed by Andrei Khodak
Date: 2018.09.10 17:04:33
-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

Wenping Wang Digitally signed by Wenping Wang
Date: 2018.09.10 16:18:50 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of PF1C Lower Coil

NSTXU-CALC-131-001-0

3/21/2018

Andrei Khodak Digitally signed by Andrei Khodak Date: 2018.03.23 15:59:45 -04'00'

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Wenping Wang Digitally signed by Wenping Wang Date: 2018.03.28 10:35:35 -04'00'

Reviewed By
W. Wang

Steve Raftopoulos Digitally signed by Steve Raftopoulos Date: 2018.03.29 13:40:50 -04'00'

Approved By – Responsible Engineer
S. Raftopoulos

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	03/21/18	Initial Release	

NSTX-U Calculation Form

Purpose of Calculation:
Access Structural Integrity of PF1C lower coil including leads, and bus bars

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] NSTX-U-SPEC-MAG-001-2 Specification for Inner PF coil conductor, M. Kalish, November, 2017

Assumptions: See attached report

Calculation: See attached report

Conclusion: Calculated maximum stress intensity on PF1C lower coil leads is below requirement of 160 MPa.

Executive Summary

Three-dimensional numerical simulations of PF1C lower coil were performed using ANSYS Workbench static structural solver analysis. Thermal and electromagnetic simulations supported structural calculations providing necessary loads and strains. Simulations were performed during design process to verify structural integrity.

The following parts of the coil assembly are included in the analysis:

- PF1C lower coil including:
  - copper winding
  - epoxy-glass insulation block surrounding coil windings.
  - steel support structure
  - lead support bracket
  - flags
- PF1C lower bus bars including:
  - flags
  - copper bus bars
  - bus bar support bracket

EM analysis of NSTX coils was performed using ANSYS Maxwell (Y. Zhai) for four scenarios:

- 18
- 18 reverse TF
- 33
- 33 reverse TF

Results of EM analysis were imported as a tabulated distributed force density as ANSYS workbench external data. The force density data was validated using one-dimensional and three-dimensional ANSYS models (P. Titus, A, Brooks)

Temperature field was imposed according to the estimates related to the end of the pulse. Reference temperature of 22 ºC was used as an ambient temperature and temperature during assembly, of the device. Supporting brackets are fixed in places of attachment to other structures.

Results of the numerical simulations show, that coil leads experience large values of local stresses due to magnetic forces and thermal expansion. The local stress intensity reaches 130MPa on the coil lead for scenario 18 at the point where coli lead is attached to the flag. Further reduction of the stress intensity can be achieved using fillets on the flag at lead attachment points. Brackets connecting flags to coil support structure improve strength of the connection, and are included in the analysis. Clamping of the in and out bus bar together is required to reduce the deformation and corresponding stress levels at the supports, and leads.

1 Introduction

The NSTX Center Stack Upgrade Recovery requires structural assessment for PF coils, these bus bars are affected by Lorentz force since they are placed in a strong magnetic field and carry currents of up to 129kA. Thermal strains impose additional load on the coil and bus bars since temperature is elevated during operation.

2 Scope of this Report

This report provides assessment of the structural integrity of bus bars based on Finite Element Analysis (FEA). Simulations were performed for the elevated temperature conditions at the coil and bus bars, calculated for ambient temperature of 22 ºC.

The following parts of the coil assembly are included in the analysis:

- • PF1C lower coil including:
  - copper winding
  - epoxy-glass insulation block surrounding coil windings.
  - steel support structure
  - lead support bracket
  - flags
- PF1C lower bus bars including:
  - flags
  - copper bus bars
  - bus bar support bracket

3 Mathematical Model

3.1 Geometry

Details of the imported design model of the PF1C lower coil and bus bars are presented on Fig.1. The model was designed using Pro/Engineer CAD software.

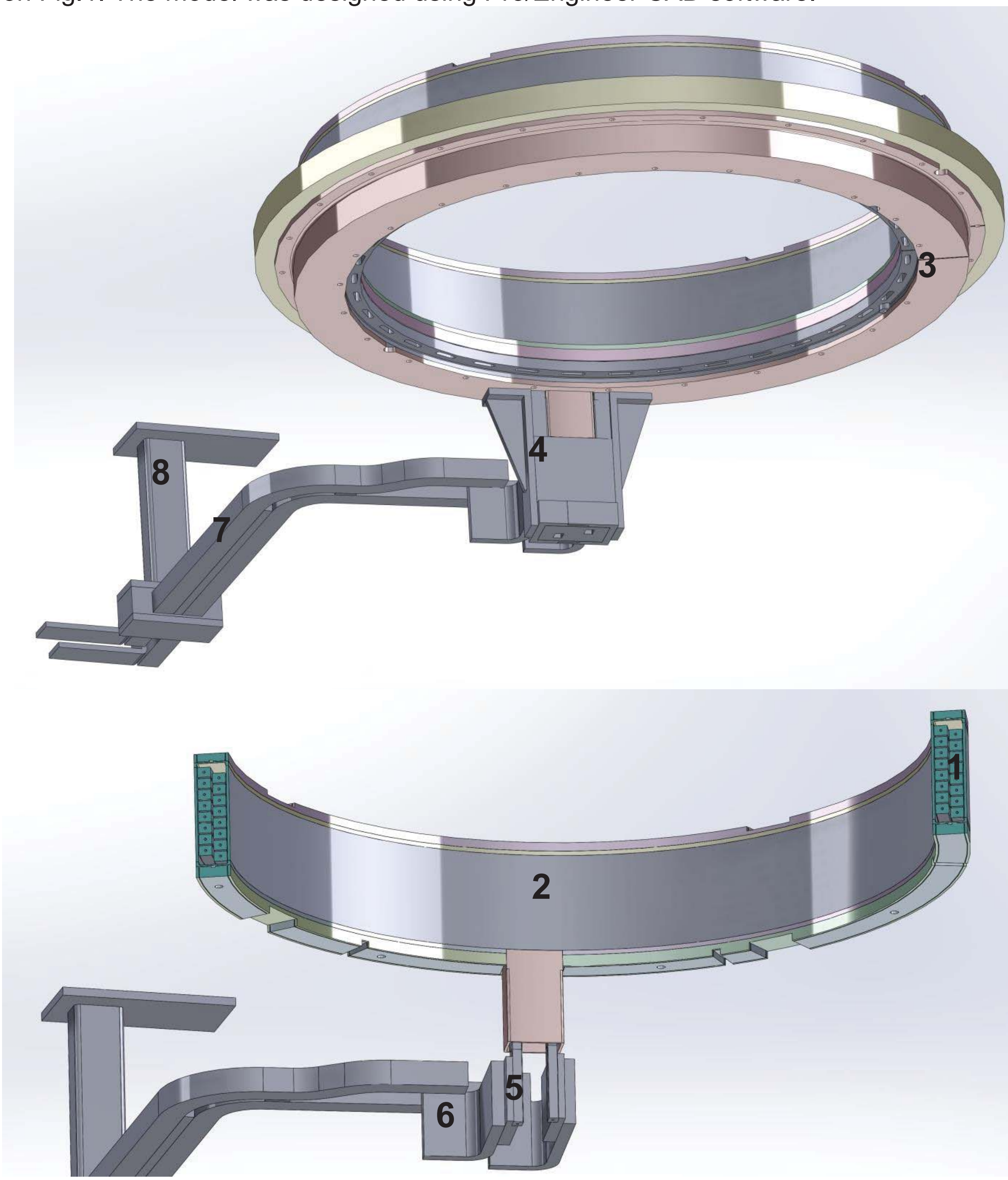


Fig 1. Design model of the NSTXU PF1C lower coil and bus bars: 1. coil windings; 2. epoxy glass insulation; 3. support structure; 4. coil lead support bracket; 5. coil flags; 6. bus bar flags; 7. bus bars; 8. bus bar support.

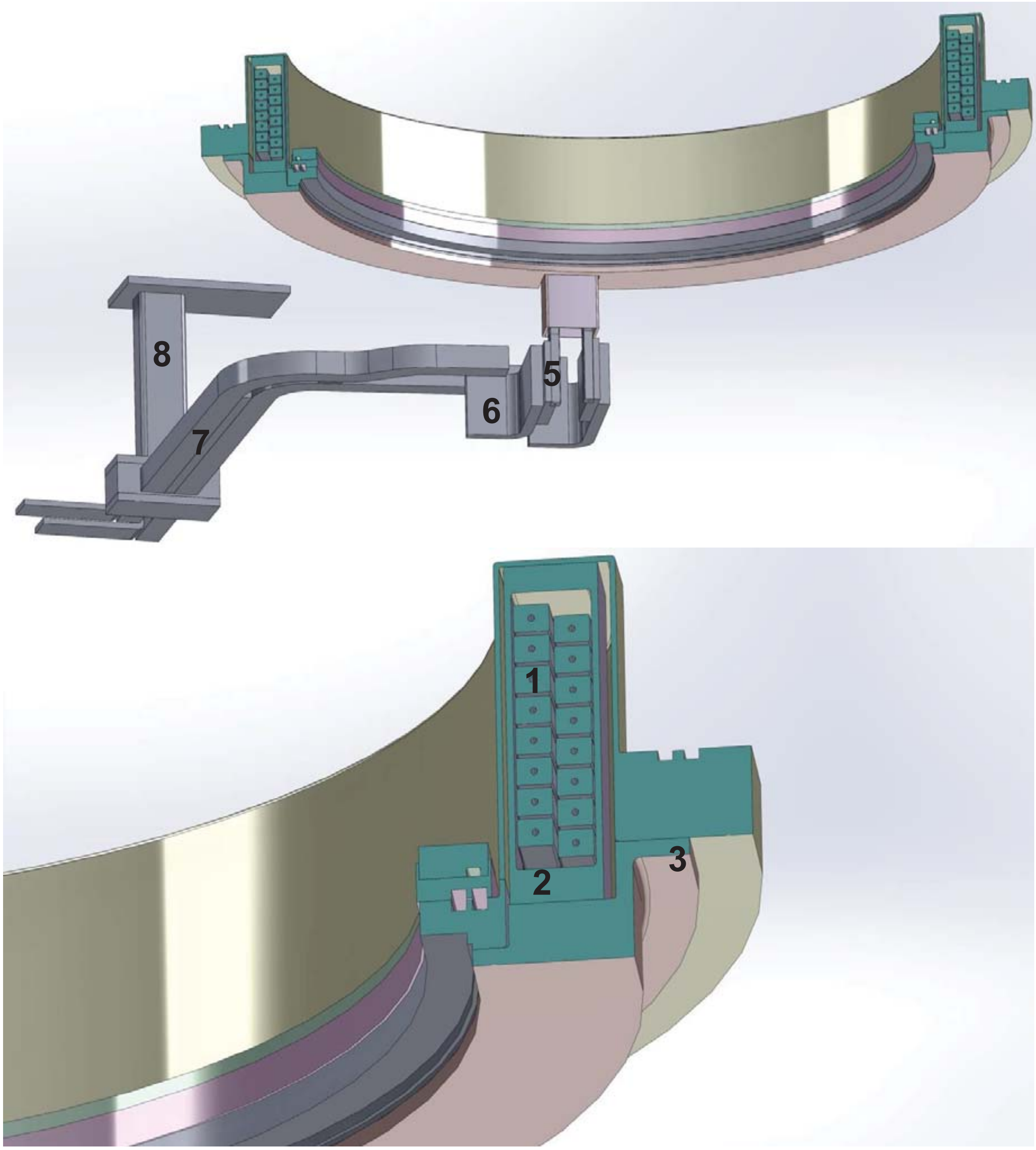


Fig 2. Analysis model of the NSTXU PF1C lower coil and bus bars: 1. coil windings; 2. epoxy glass insulation; 3. support structure; 4. coil lead support bracket; 5. coil flags; 6. bus bar flags; 7. bus bars; 8. bus bar support.

Model was imported into SolidWorks, and modified to eliminate gaps and perform geometrical simplifications. Initial design geometry was simplified for the purpose mesh generation by removing some mounting holes and fillets from the design. The effect of the fillets is only to reduce peak stresses (a beneficial trait) and their contribution to the global stiffness of the structure is negligible. Bolt connections of the bus bar supports were also removed and bonded connection was assumed.

The model was modified further using ANSYS Workbench Design Modeler software. Geometry was imported from Solidworks into Design Modeler via Parasolid binary file. Unified glass-epoxy block was created using Design Modeler software fill operation.

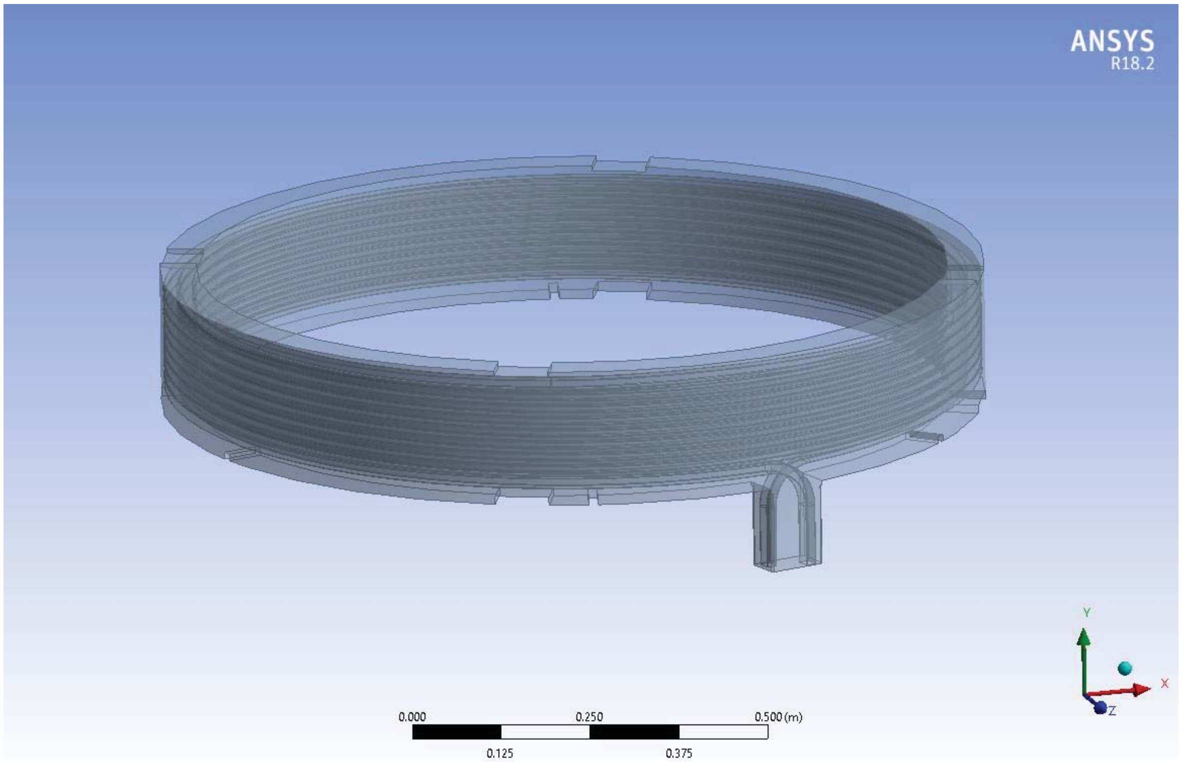
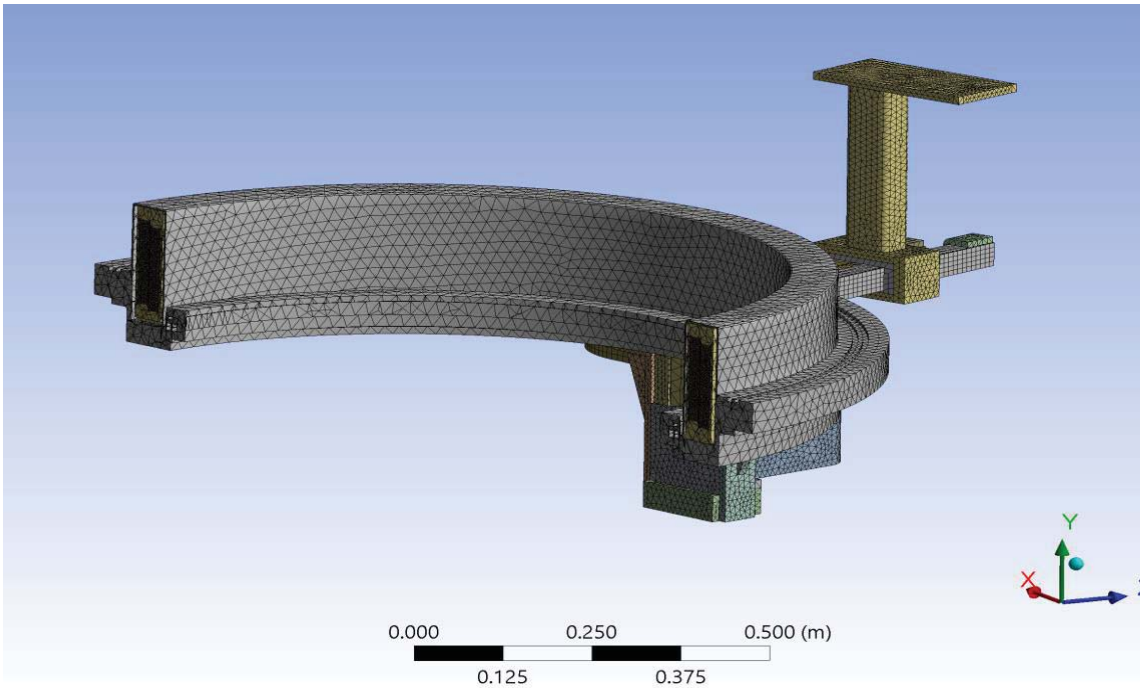


Fig 3 Unified glass-epoxy block

3.1 Meshing

Meshing was performed within ANSYS Workbench. Final mesh containing more than 2 million elements is presented on Figs 6, 7, and 8.



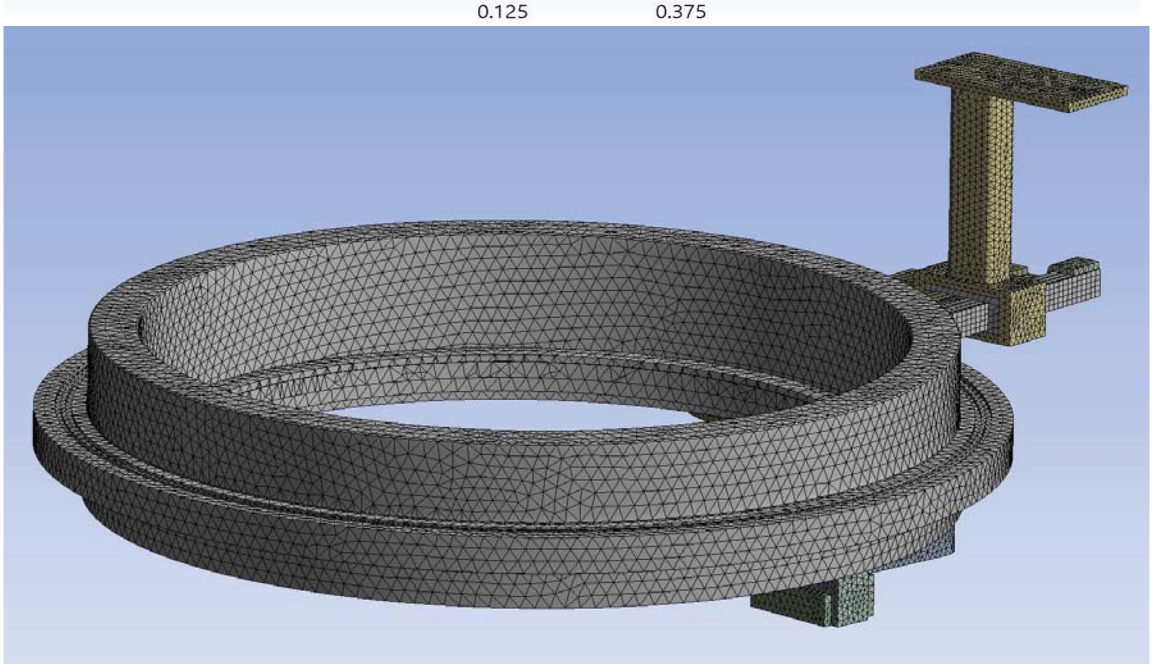


Fig 6 Mesh on PF1C lower coil structure

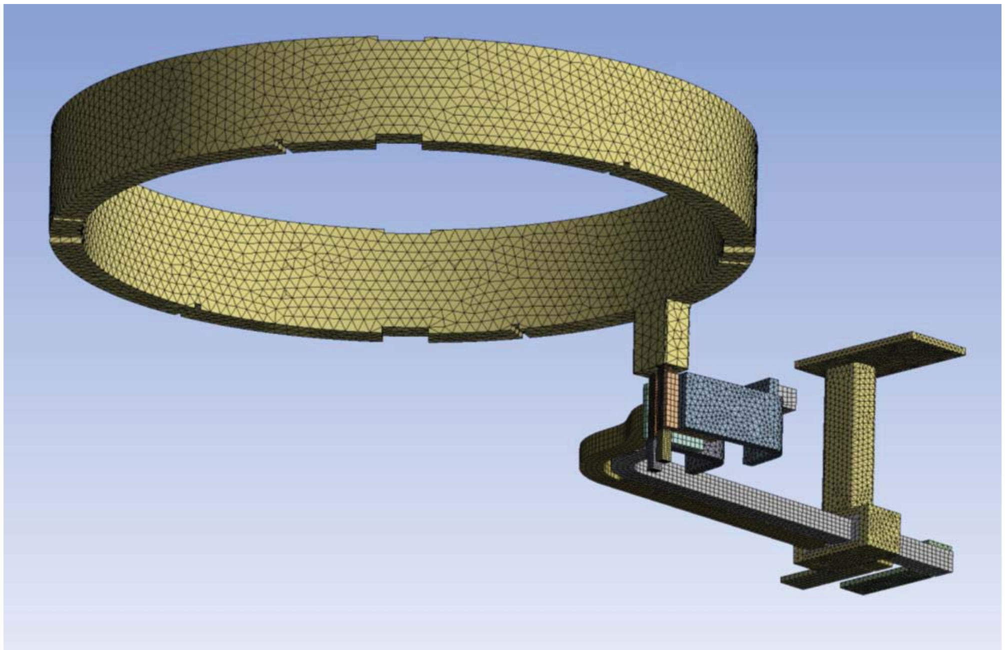


Fig 7 Mesh on PF1C lower coil insulation block

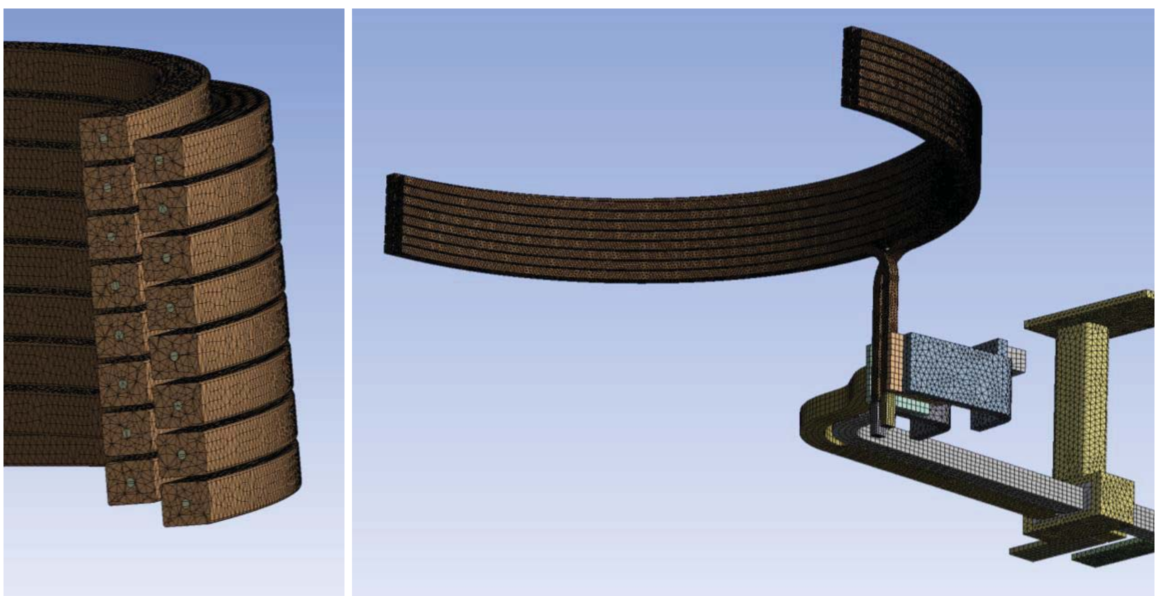


Fig 8 Mesh on PF1C lower coil conducting parts

3.2 Boundary Conditions and Loads

The model is fixed in all directions at the surfaces shown on fig 9. Supporting brackets are fixed in places of attachment to other structures.

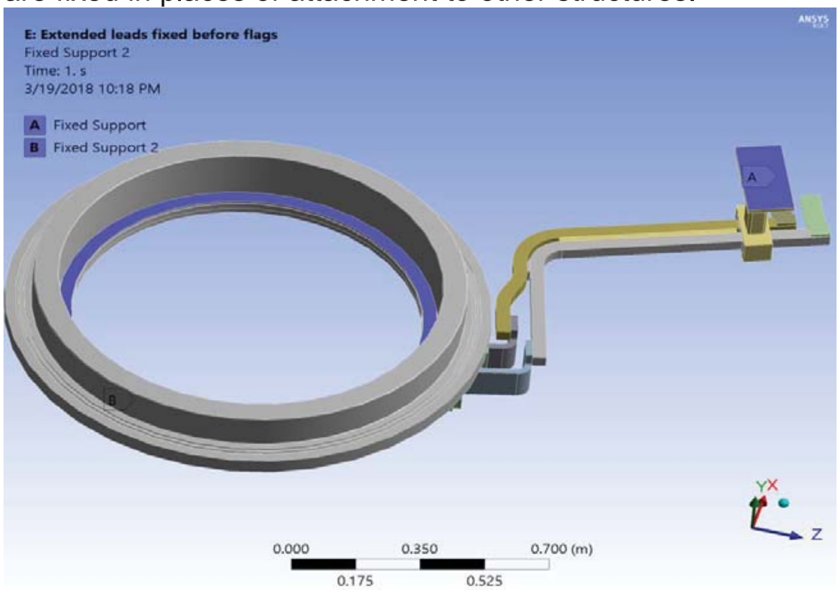


Fig 9 PF1C lower coil constraints

Contacts between epoxy block and copper coil windings are presented on fig 10. For the most part the coil and insulation block are bonded together, leads however have frictionless contact with epoxy reflecting Kapton inserts.

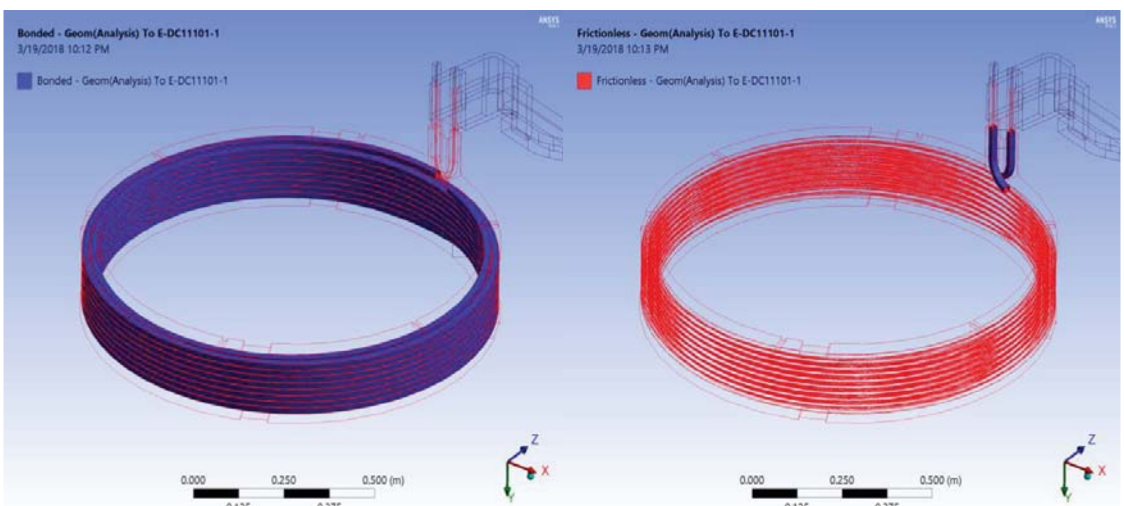
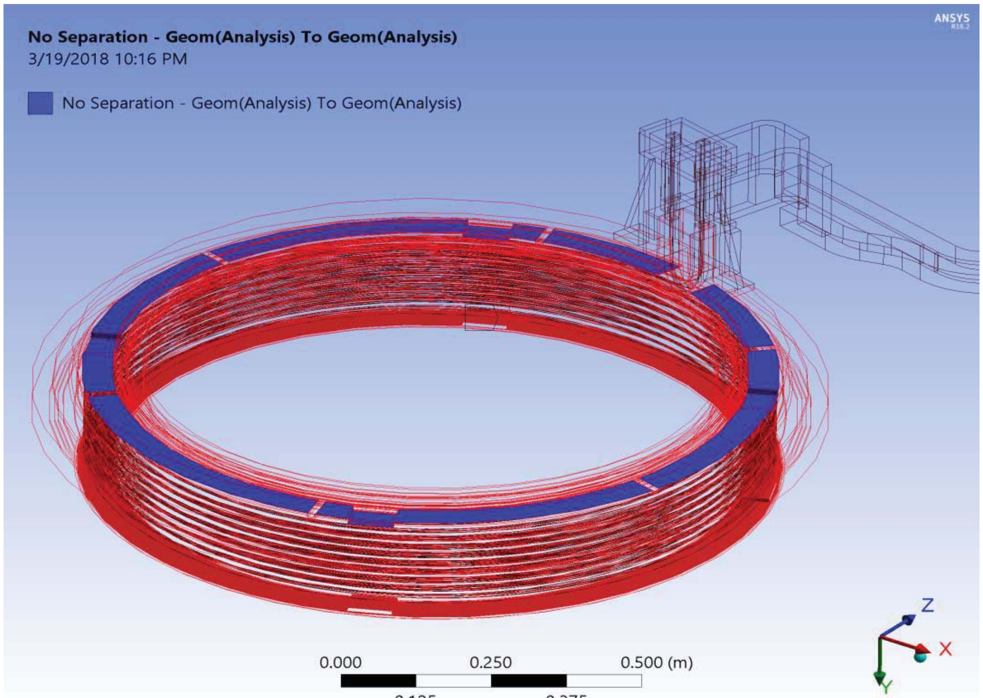


Fig 10 PF1C lower coil constraints

No separation conditions are imposed between epoxy block and structure and between bus bar and support brackets, allowing thermal expansion, while keeping coil centered.



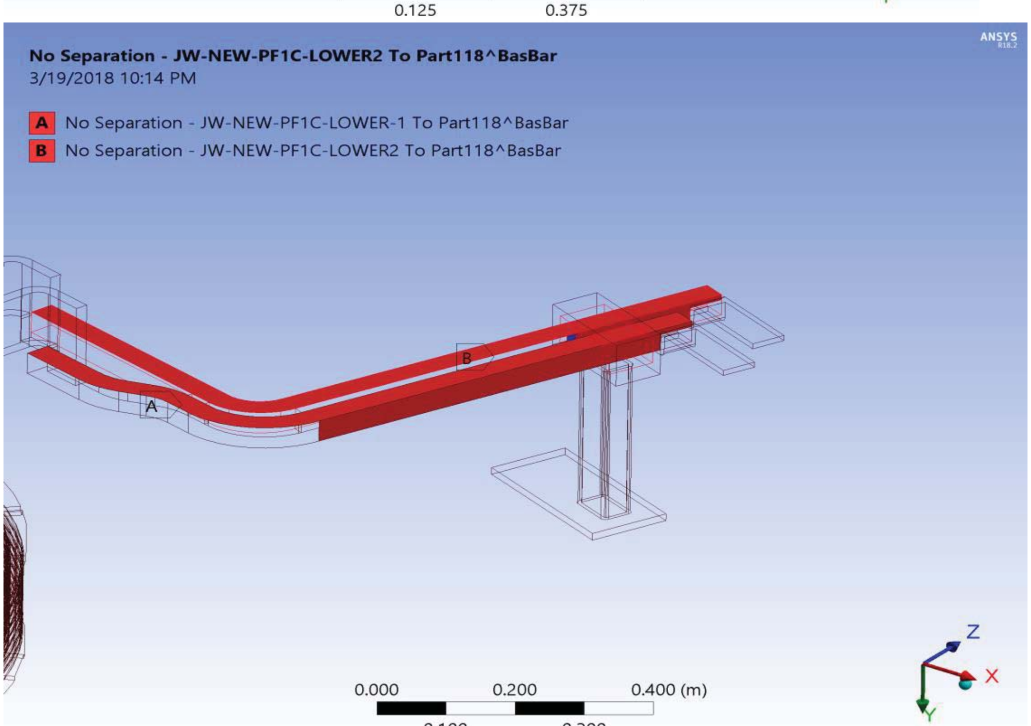


Fig 11 PF1C lower coil no separation contacts

Thermal load on the coil is presented on fig 12. Coil temperature is set to 50ºC as a conservative assumption for the end of the pulse condition. Temperature is linearly reduced to 12ºC towards the tips of the coil leads where Joule heating is absent and 12ºC coolant is supplied. Bus bars are not water cooled and thermally insulated from the ambient air by electrical insulation wrap. Conservative estimate 50ºC was set on the bus bars as well.

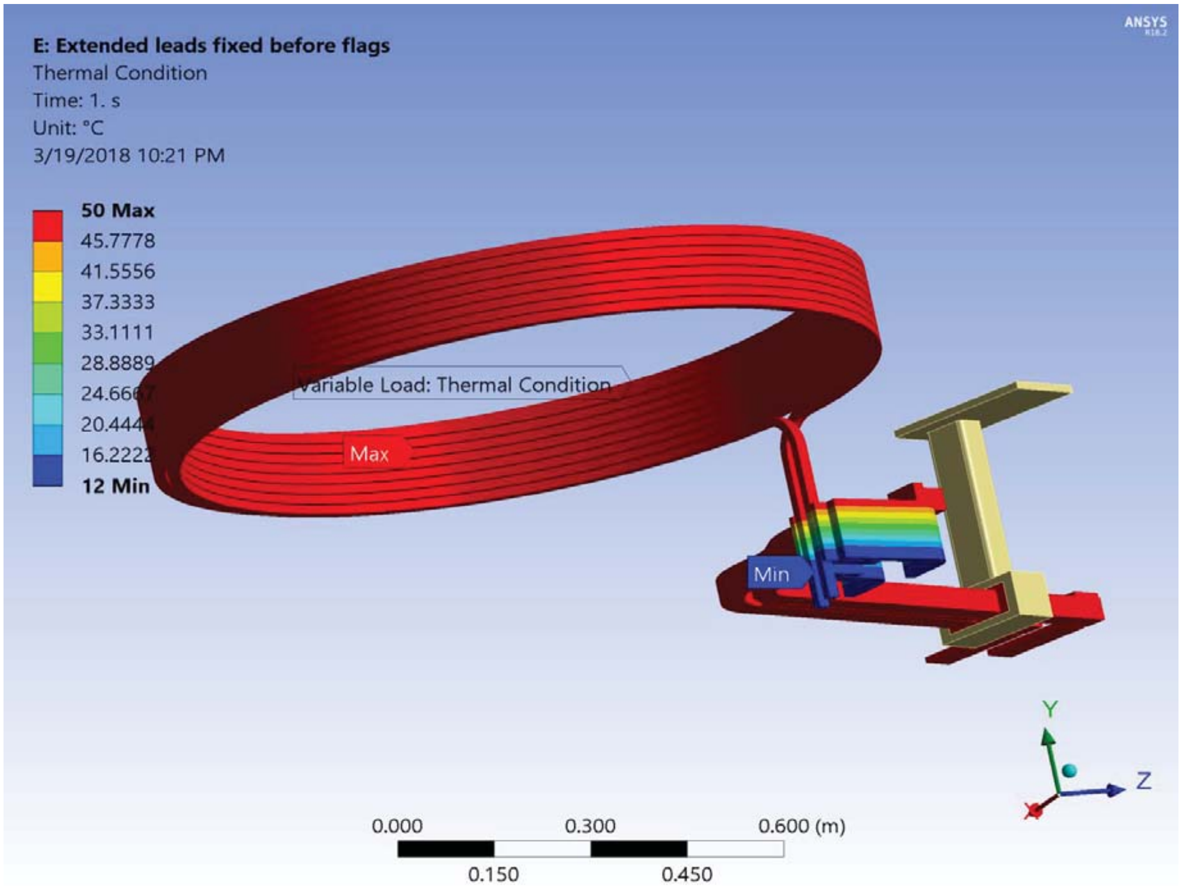


Fig 12 PF1C lower coil thermal load

Electro-magnetic force load was imported from Maxwell analysis using cloud data via external data workbench option as shown on fig 13.

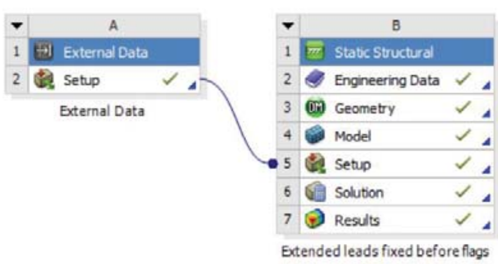


Fig 13 Electro-magnetic force input set-up

Separate data sets were used for coil and bus bar data. Validation of the body force transfer was performed using analysis of the data for the coil and each bus-bar separately. Note that Maxwell model did not include cooling channel, inside the coil, whereas structural model has cooling channel included. Effect of the loss of the cooling channel portion was assessed, and found to be around 5%. Results for external forces for the case 18 direct are presented on figures 14-17. For structural analysis portion of the electro-magnetic force interpolated on the cooling channel region was included, by simulating cooling channel with the material with the same properties as coil except Young modulus, which was assumed hundred times lower.

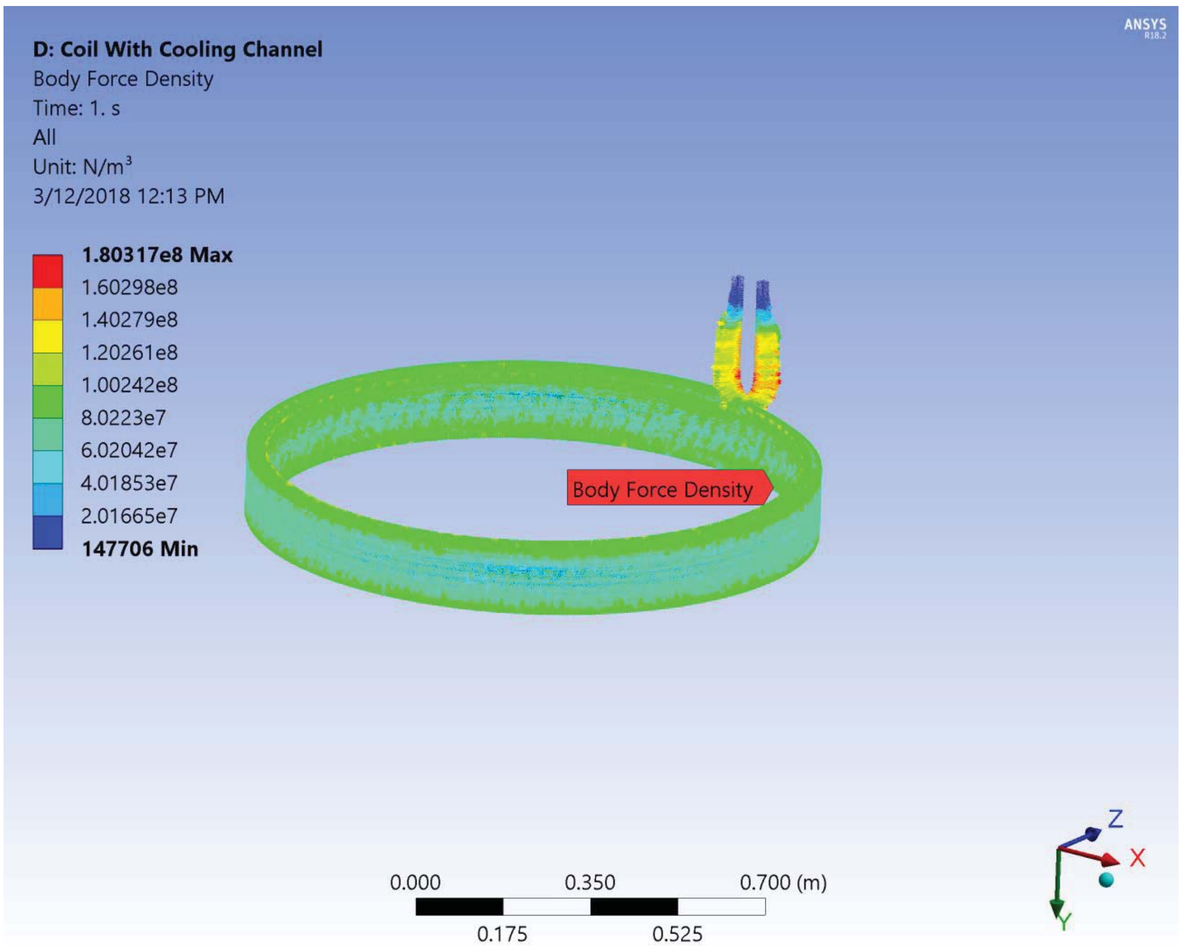


Fig 14. Body Force on coil. Cooling channel filled. Scenario 18 direct

	X:	Y:	Z:	Total:
Force Reaction [N]	**-421.54**	**-19601**	**764.32**	**19620**
Moment Reaction [N]	**332.31**	**94.866**	**75.176**	**353.67**

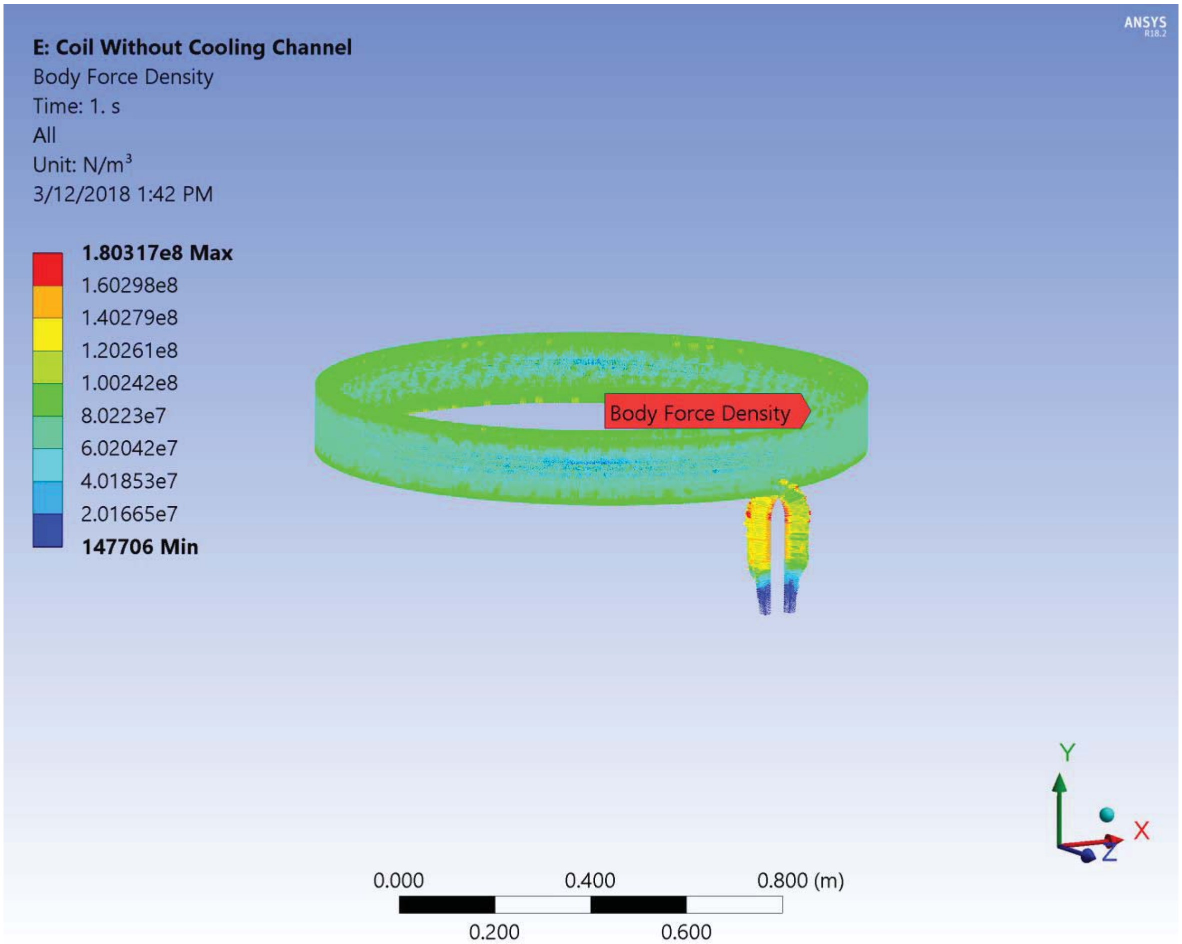


Fig 15 Body Force on coil. Cooling channel empty. Scenario 18 direct

	X:	Y:	Z:	Total:
Force Reaction [N]	**-385.29**	**-18864**	**769.62**	**18883**
Moment Reaction [N]	**306.79**	**94.356**	**87.659**	**332.73**

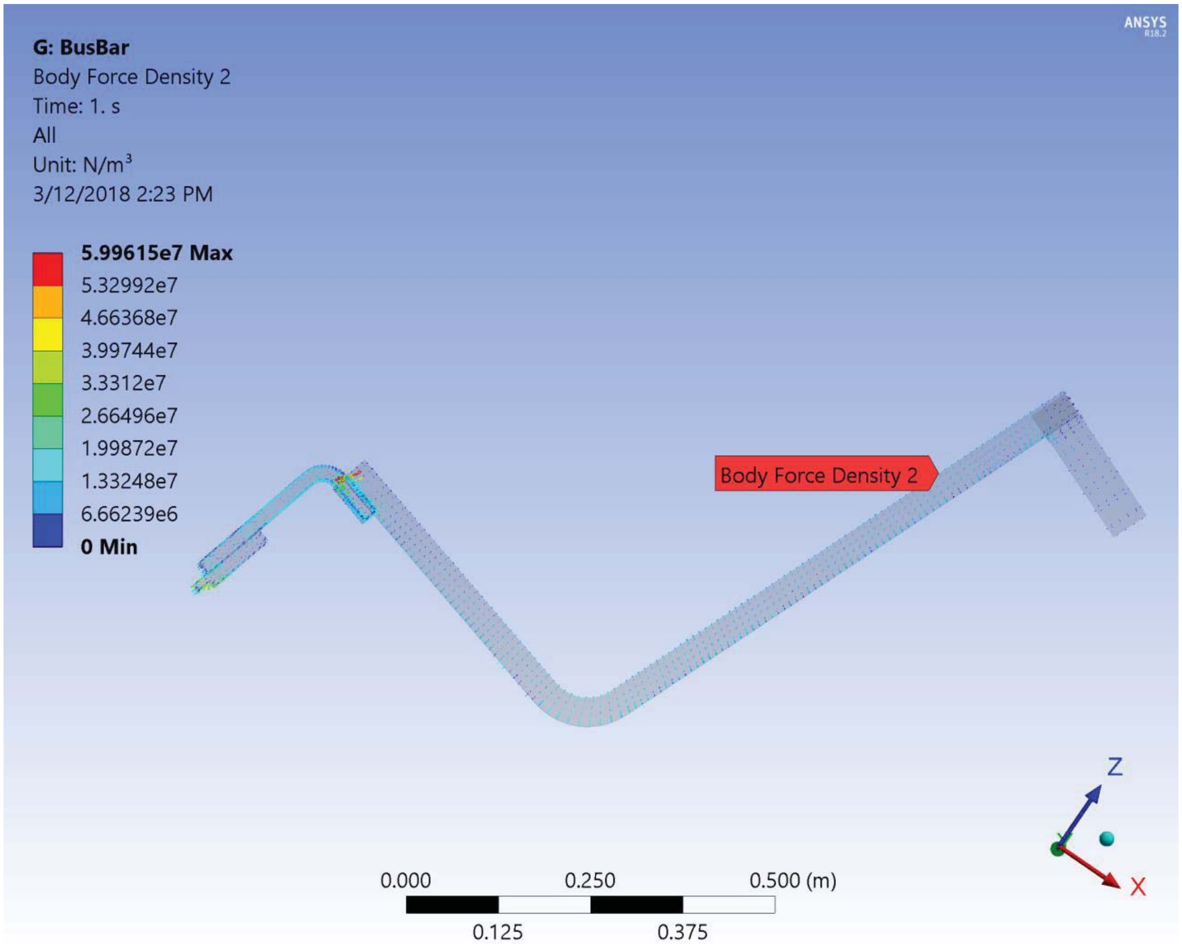


Fig 16 Body Force on bus bar 1. Bus attached to concave side of the flag. Scenario 18 direct

	X:	Y:	Z:	Total:
Force Reaction [N]	**3484.6**	**23557**	**-5108.2**	**24355**
Moment Reaction [N]	**-455.07**	**1373.6**	**1676.5**	**2214.6**

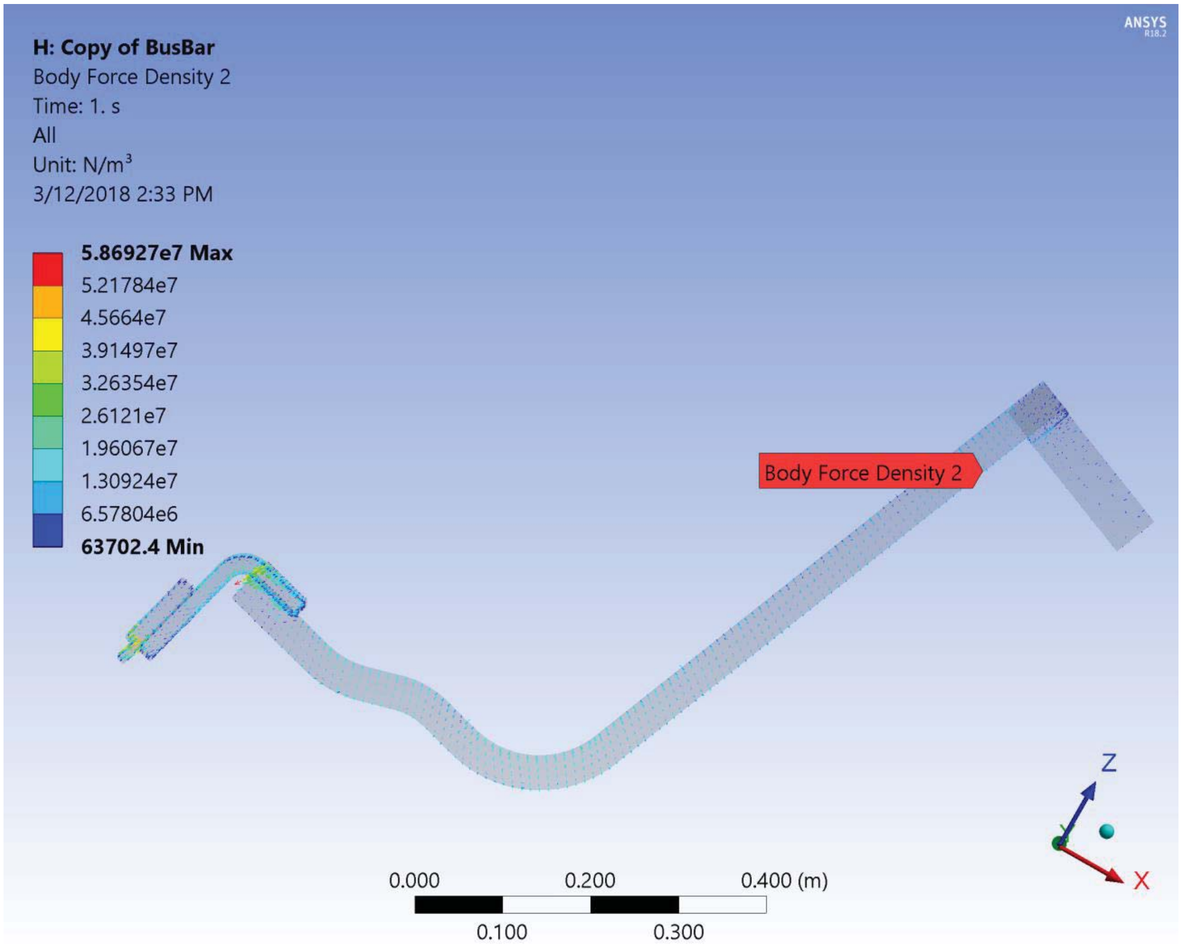


Fig 17 Body Force on bus bar 2. Bus attached to concave side of the flag. Scenario 18 direct Force Reaction [N] X: Y: Z: Total:

-2731.1 -21935 4832.2 22627

Moment Reaction [N] X: Y: Z: Total:

-208.42 -977.99 -1200.9 1562.7

3.3 Material properties for bus bar model

Material properties from NSTX database were used:

<u>Conductors</u>
Material: copper.
Material is isotropic with elastic modulus of 110GPa and Poisson ratio of 0.34.
Thermal expansion coefficient is $1.8\cdot10^{-5}$[1/K] at 293K.

<u>Insulation</u>
Material: G10.
Material is isotropic with elastic modulus of 11.721GPa and Poisson ratio of 0.12.
Thermal expansion coefficient is $1.49\cdot10^{-5}$[1/K] at 293K.

<u>Support Hardware</u>
Material: steel.
Material is isotropic with elastic modulus of 193GPa and Poisson ratio of 0.31.
Thermal expansion coefficient is $1.7\cdot10^{-5}$[1/K] at 293K.

<u>Bracket Inserts and cooling channel</u>
Material: copper with low elastic modulus
Material is isotropic with elastic modulus of 1.1GPa and Poisson ratio of 0.34.
Thermal expansion coefficient is $1.8\cdot10^{-5}$[1/K] at 293K.

4 Analysis Results

4.1 Scenario 18 direct TF current

Stress Intensity is presented on Fig 18. Maximum stress intensity on coil leads is 150 MPa below than required 160MPa.

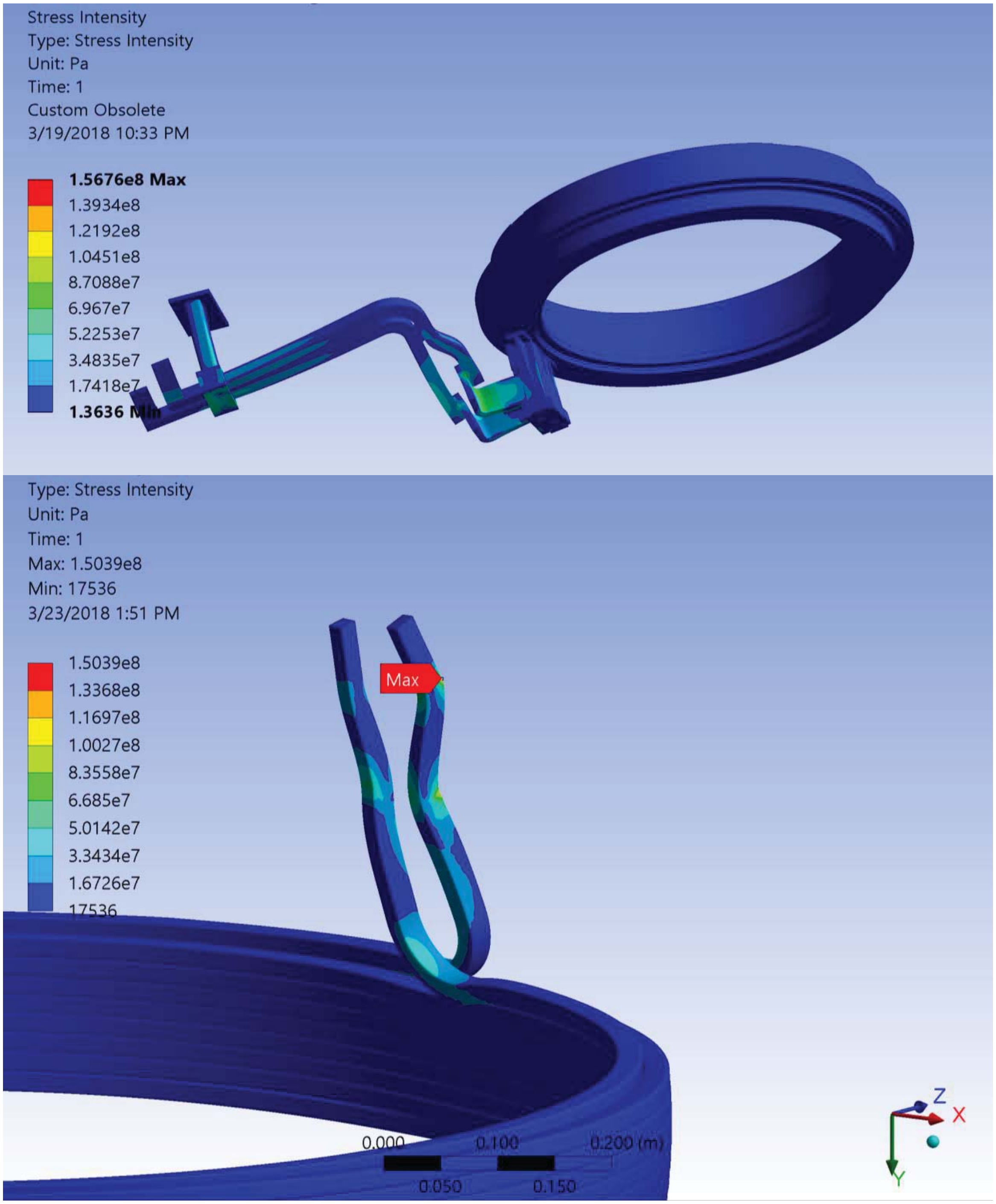


Fig 18 Stress intensity on PF1C lower coil for scenario 18 direct TF current. Maximum stress intensity on coil leads is 150 MPa.

4.2 Scenario 18 reverse TF current

Stress Intensity is presented on Fig 19. Maximum stress intensity on coil leads is 104 MPa below required 160MPa.

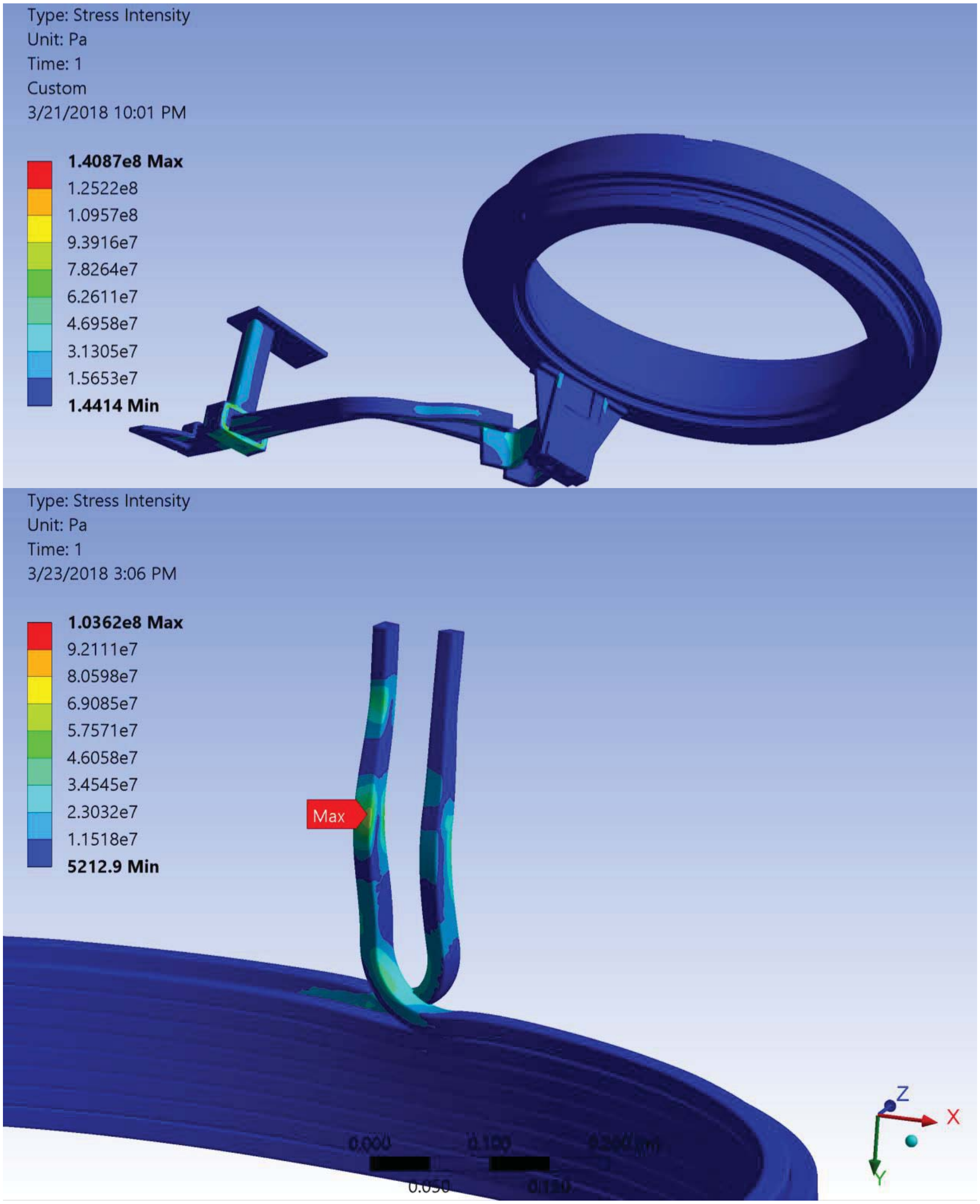


Fig 19 Stress intensity on PF1C lower coil for scenario 18 reverse TF current. Maximum stress intensity on coil leads is 104 MPa.

4.3 Scenario 33 direct TF current

Stress Intensity is presented on Fig 20. Maximum stress intensity on coil leads is 136 MPa below required 160MPa.

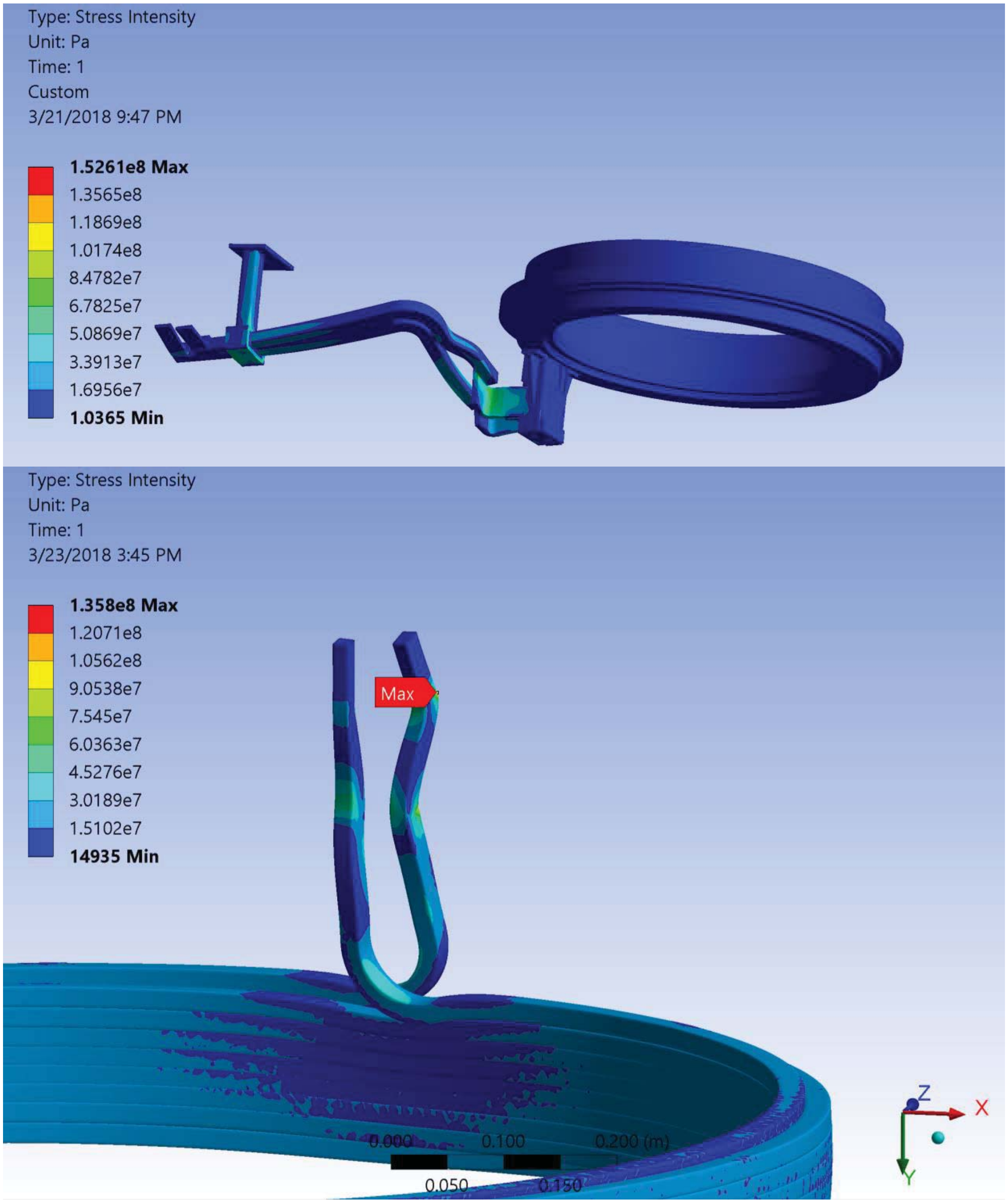


Fig 20 Stress intensity on PF1C lower coil for scenario 33 direct TF current. Maximum stress intensity on coil leads is 136 MPa.

4.4 Scenario 33 reverse TF current

Stress Intensity is presented on Fig 21. Maximum stress intensity on coil leads is 155MPa below required 160MPa.

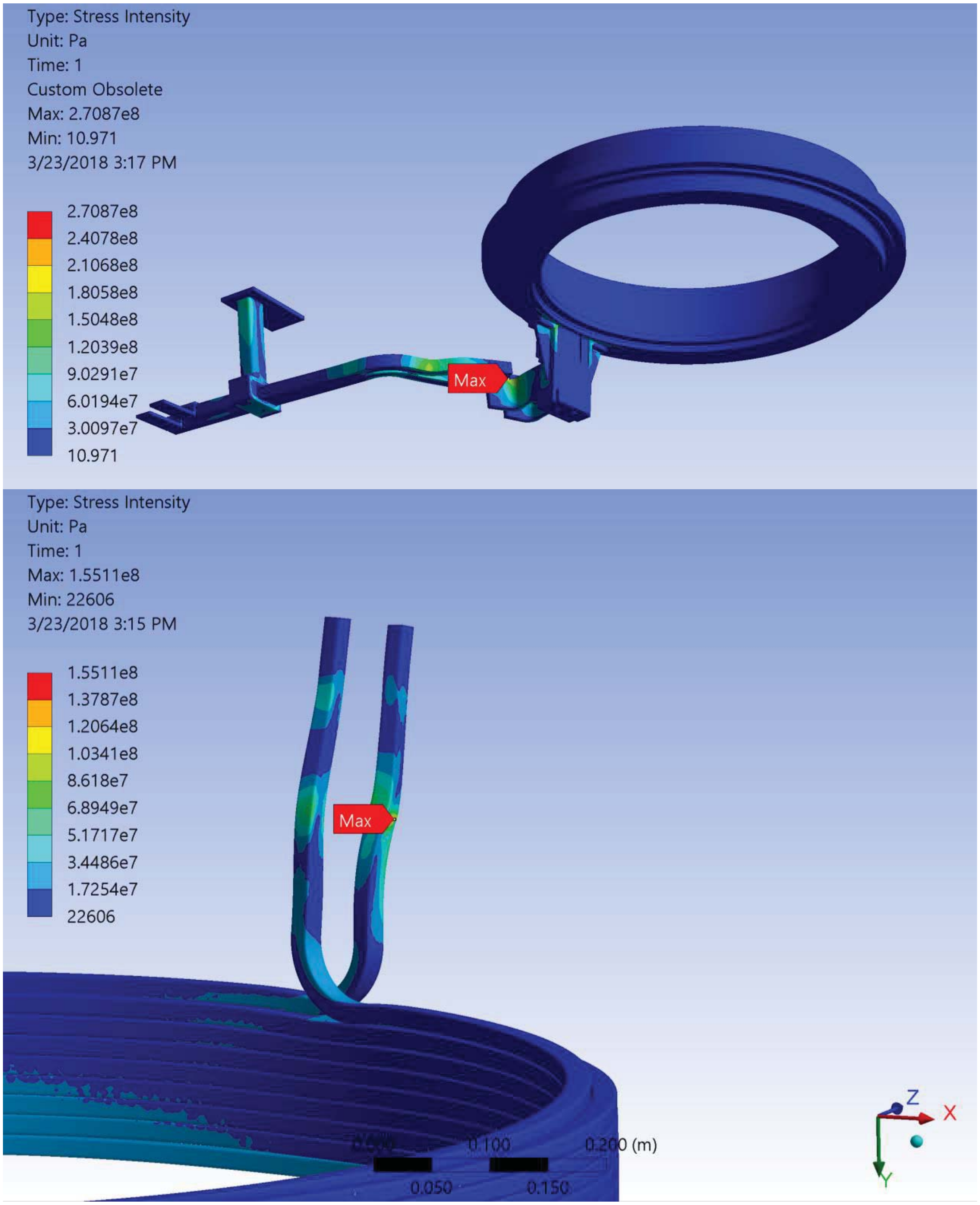


Fig 21 Stress intensity on PF1C lower coil for scenario 33 reverse TF current. Maximum stress intensity on coil leads is 155 MPa.

5 Summary

Maximum stress intensity on PF1C lower coil leads is below requirement of 160 MPa.

Scenario	*Max Stress Intensity [MPA]*	*Max Stress Intensity requirement [MPa]*
18 direct TF current	150	160
18 reverse TF current	104	160
33 direct TF current	136	160
33 reverse TF current	155	160

Maximum value of stress intensity on the leads occurs close to flag connection and can be further reduced by using fillets on the flags, in the area of leads attachment.

Additionally bracket can have extended opening for leads allowing them to expand radially.

Bus bars in the analysis are assumed bonded to each other, and must be attached to each other during assembly to avoid excessive stress.

Flags need to be separated from the bracket metal parts by solid insulation blocks.