NSTX

Structural Analysis of PF1, TF and OH Bus Bars

NSTX-CALC--55-01-00

November 22, 2013

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2013.11.22
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Peter Titus, Branch Head, Engineering Analysis Division

PPPL Calculation Form

Calculation # **NSTX-CALC-55-01-00** Revision # **00** WP: ENG-032

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

Perform Coupled Structural Electromagnetic and Thermal Analysis of PF1, TF, and OH bus bars

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

See attached report

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

See attached report

Calculation (Calculation is either documented here or attached)

See attached Report

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

Results for PF, TF and OH bus bars show that maximum values of stresses satisfy static structural design criteria. However in some local small areas maximum stress intensity in copper for PF1A, PF1B and TF bus bars is higher than fatigue design criteria of 125MPa. For PF bus bars additional reinforcement measures were proposed which may eliminate this high stresses. This is analyzed in detail in PF part of center stack analysis report. Maximum stress area for TF bus bar occurs in the area where conductor connection is assumed bonded. Actual bolted connection may allow more flexibility and reduce stress in the area.

Cognizant Engineer's printed name, signature, and date

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

Checker's printed name, signature, and date

Peter H. Titus

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Executive Summary

Three-dimensional numerical simulations of PF1, TF, and OH bus bars were performed using ANSYS coupled solver for simultaneous structural, thermal and electromagnetic analysis. Thermal and electromagnetic simulations supported structural calculations providing necessary loads and strains. Simulations were performed during design process to verify structural integrity. Several major changes were introduced in the design of the bus bars since the initial report was submitted.

Results for PF, TF and OH bus bars show that maximum values of stresses satisfy static structural design criteria. However in some local small areas maximum stress intensity in copper for PF1A, PF1B and TF bus bars is higher than fatigue design criteria of 125MPa. For PF bus bars additional reinforcement measures were proposed which may eliminate this high stresses. This is analyzed in detail in PF part of center stack analysis report. Maximum stress area for TF bus bar occurs in the area where conductor connection is assumed bonded. Actual bolted connection may allow more flexibility and reduce stress in the area.

Introduction

The NSTX Center Stack Upgrade requires new bus bars for PF, TF, and OH coils, these bus bars are affected by Lorentz force since they are placed in a strong magnetic field and carry currents of up to 130kA. Thermal strains impose additional load on the bus bars since temperature of the bus bars is elevated during operation.

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 following for room temperature conditions.

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

- PF1A, B, C upper and lower bus bars with flags supports and parts of coil assembly
- OH bus bar together with coaxial part
- TF bus bars with supports and parts of connecting structure
- NSTX PF coils modeled as SOURCE36 elements
- NSTX TF coils modeled as SOURCE36 elements within the center stack, and as SOLID5 elements at the periphery

Mathematical Model

Geometry

Design geometry

Details of the design model of the CS insert coil are presented on Fig.1. The model was designed using Pro/Engineer CAD software. Model and mesh of the parts 1,2,3,4 was provided by H. Zhang.

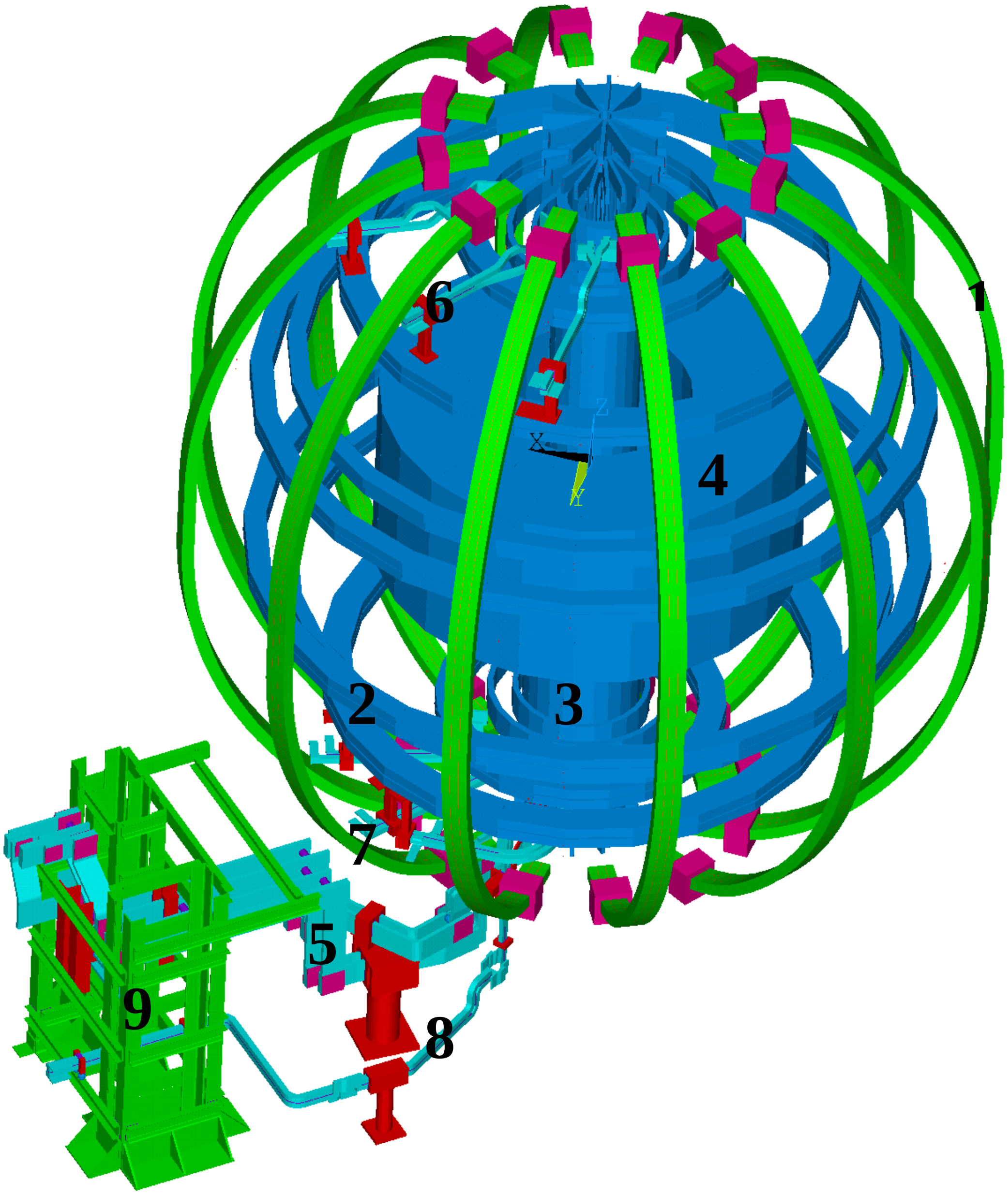


Fig1. Design model of the NSTXU coils and bus bars:
1. TF coils
2. PF coils
3. OH coils
4. Plasma
5. TF bus bars
6. Upper PF bus bars
7. Lower PF bus bars
8. OH bus bar
9. Support tower

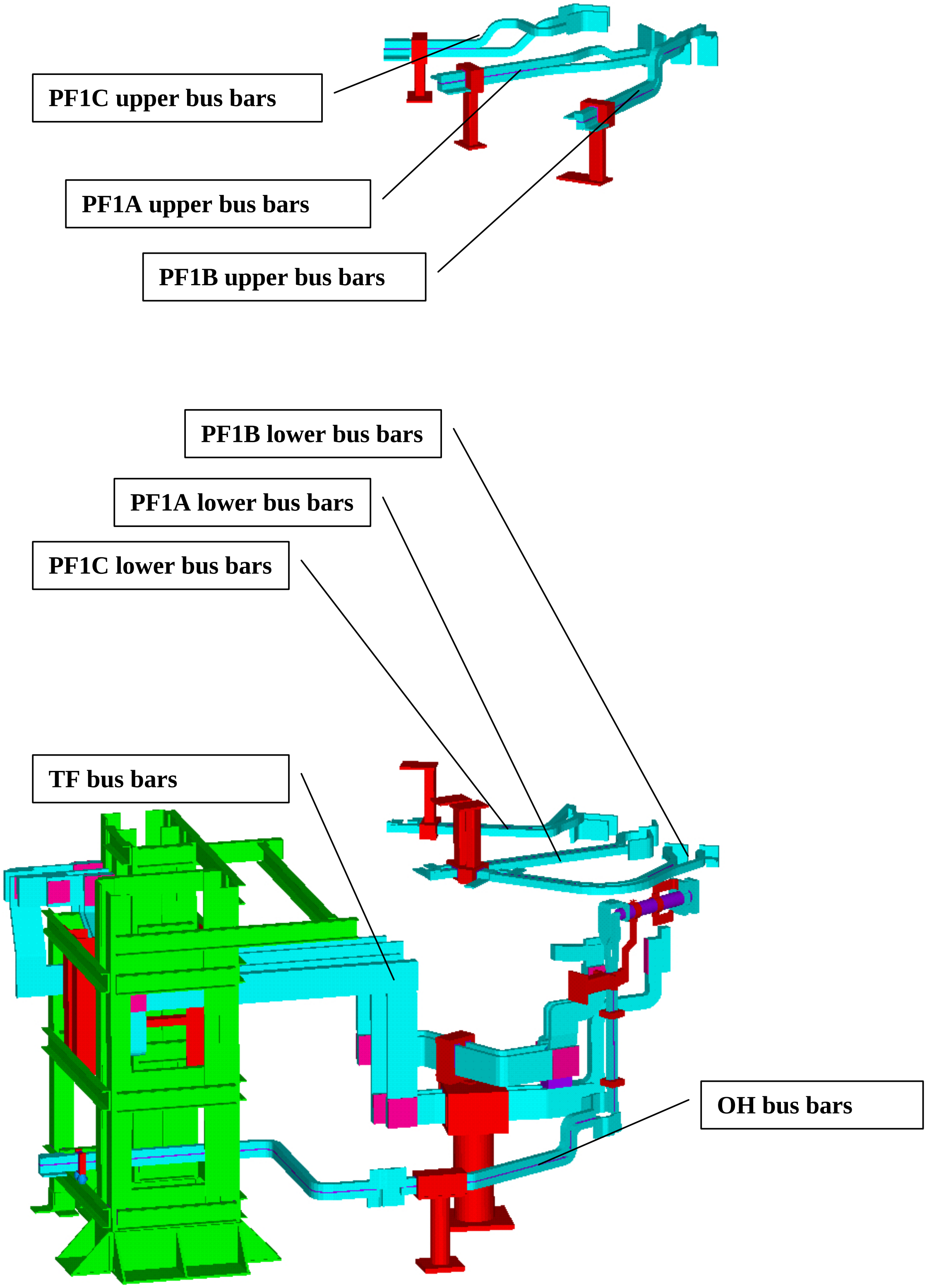


Fig 2.Bus bars

Bus bars analyzed in present investigation are presented on fig.2. PF bus bars were modeled together with a portion of the coils to insure proper loads on flags.

Geometry Simplification

Geometry simplification was performed using Pro/Engineer software mostly by deleting features in the original design model. Initial design geometry was simplified for the purpose mesh generation by removing some of the 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. Most of the 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 Pro/Engineer into Design Modeler via IGES file. Modifications of TF bus bar supports are shown on fig 3.

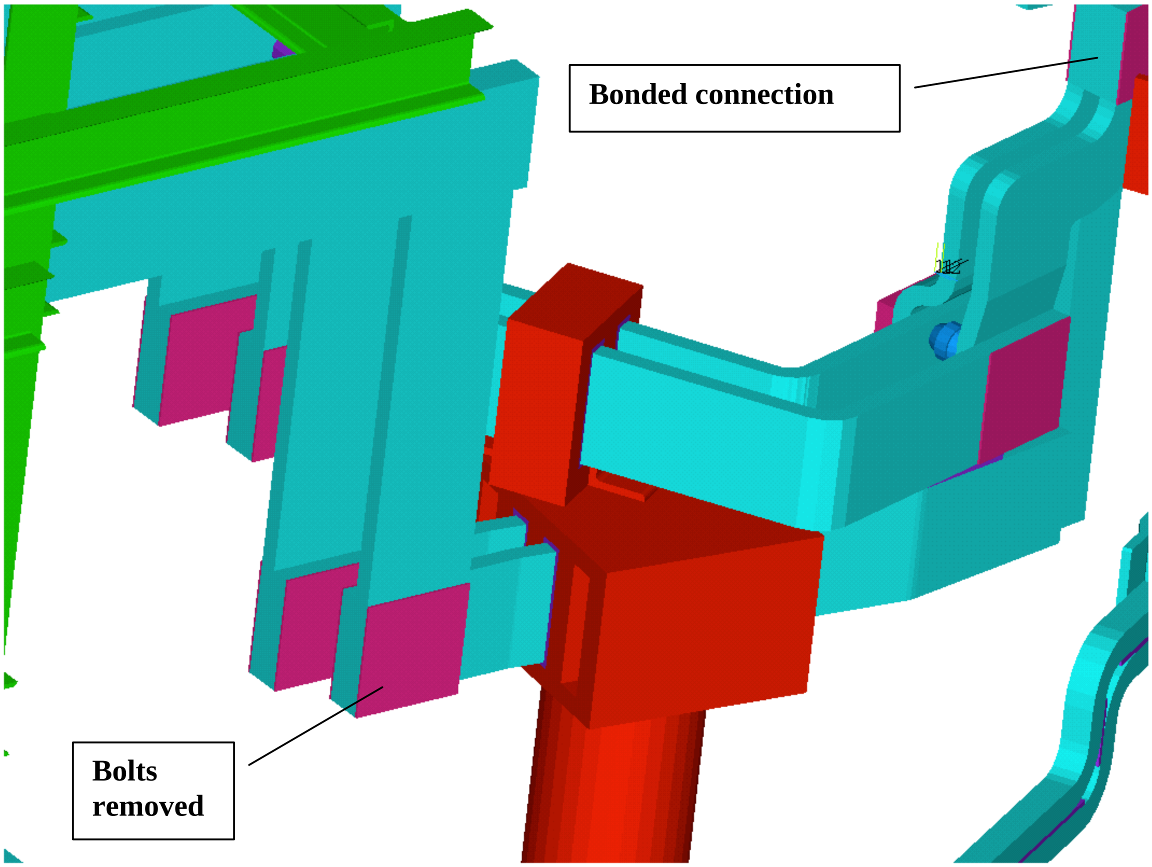


Fig 3 TF bus bar supports modification

Meshing

Elements used

ANSYS elements used to mesh the model are presented in Table 1. SOLID5 elements were used for model geometry meshing. SOLID5 elements allow simultaneous solution for coupled structural, thermal, and static electro-magnetic problem. The volumes that could not be measured with structural brick elements we meshed with unstructured mesh using SOLID 226 tetrahedral elements

Source elements were used to create external magnetic field.

Table 1 Elements used in the FE Model

Element Type	Nodes	Name	Used in the Mesh of
3-D Coupled Solid	8	SOLID5	Majority of parts
3-D Structural Solid	4	SOLID226	Parts with unstructured mesh
Source	2	SOURCE36	External Magnetic Field

Geometry split into blocks

SOLID5 ANSYS elements require using sweep method for meshing. Thus, the model has to be split into blocks that can be swept. The model was split within ANSYS Classic. Splitting of the model into blocks does not introduce any additional geometrical simplifications into model, and was used exclusively for meshing simplification Example of the geometry split into multiple blocks is presented on Fig 4.

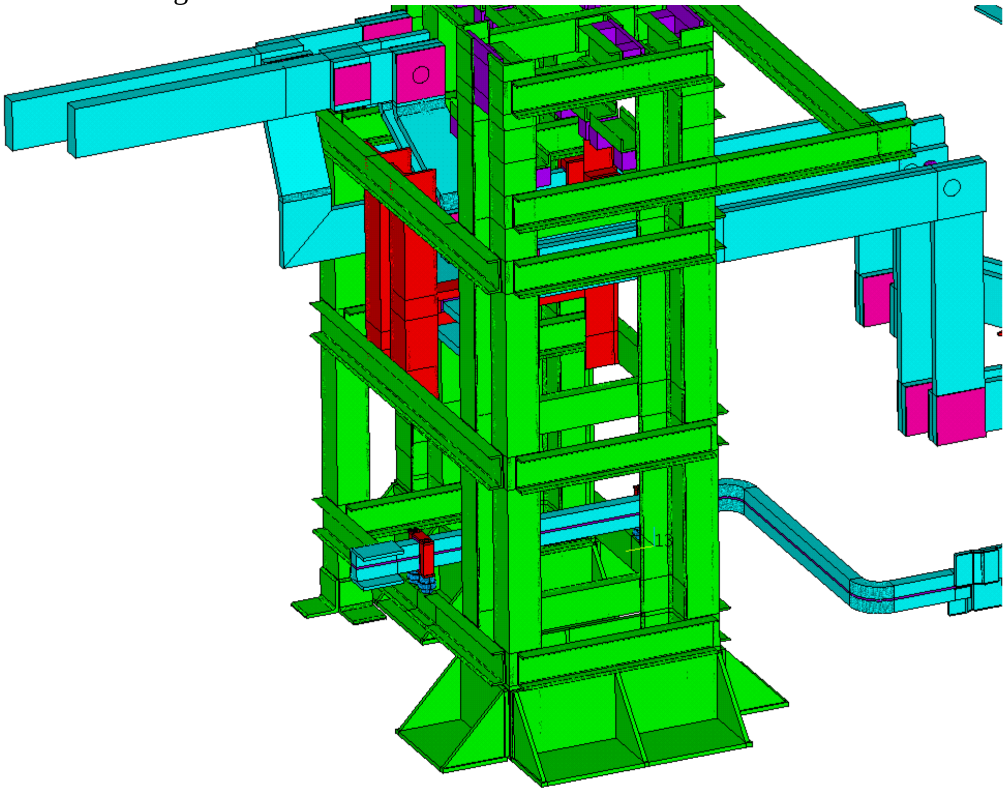


Fig 4 Splitting of TF bus bar model allowing hexahedral sweep meshing

Meshing

Meshing was performed within standalone version of ANSYS. Final mesh containing 378981 elements is presented on Fig 6, 7, and 8.

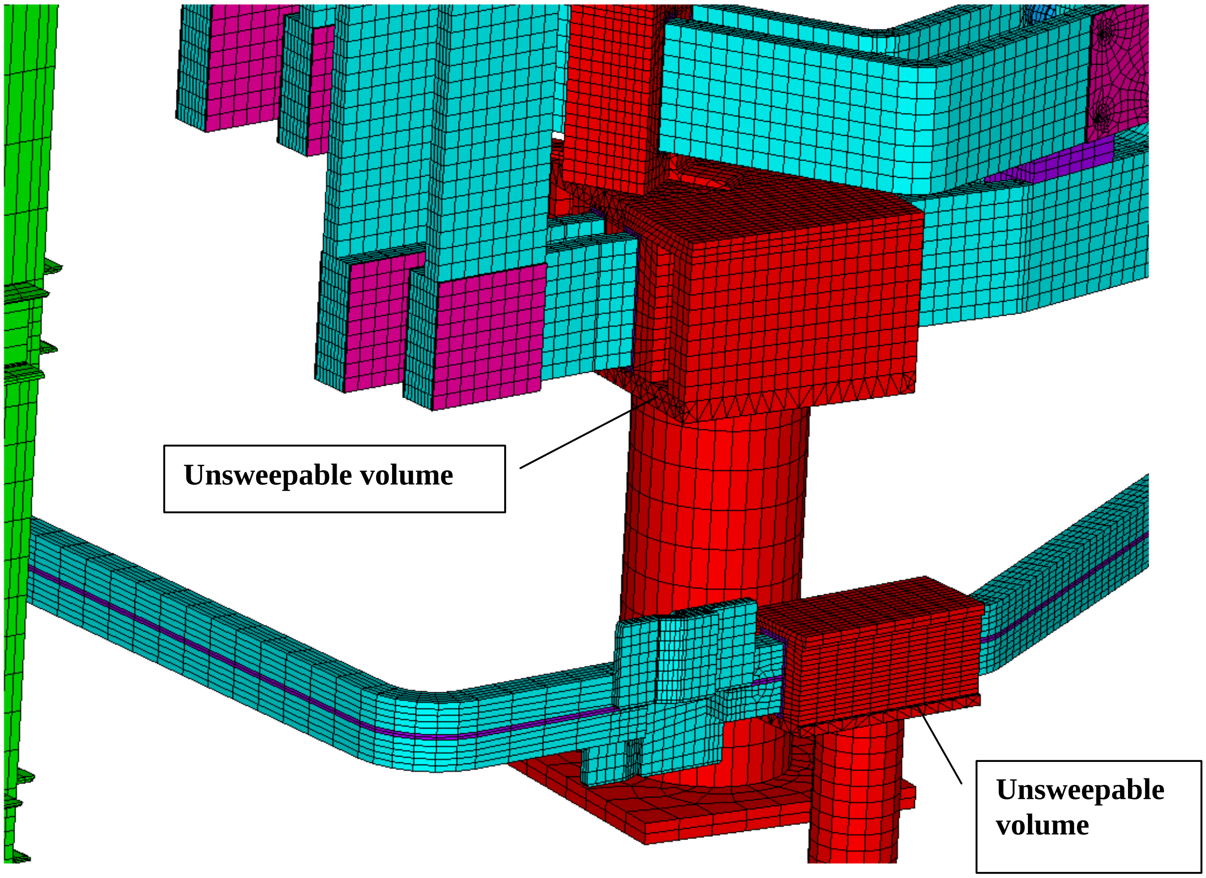


Fig 6 Mesh for TF bus bars

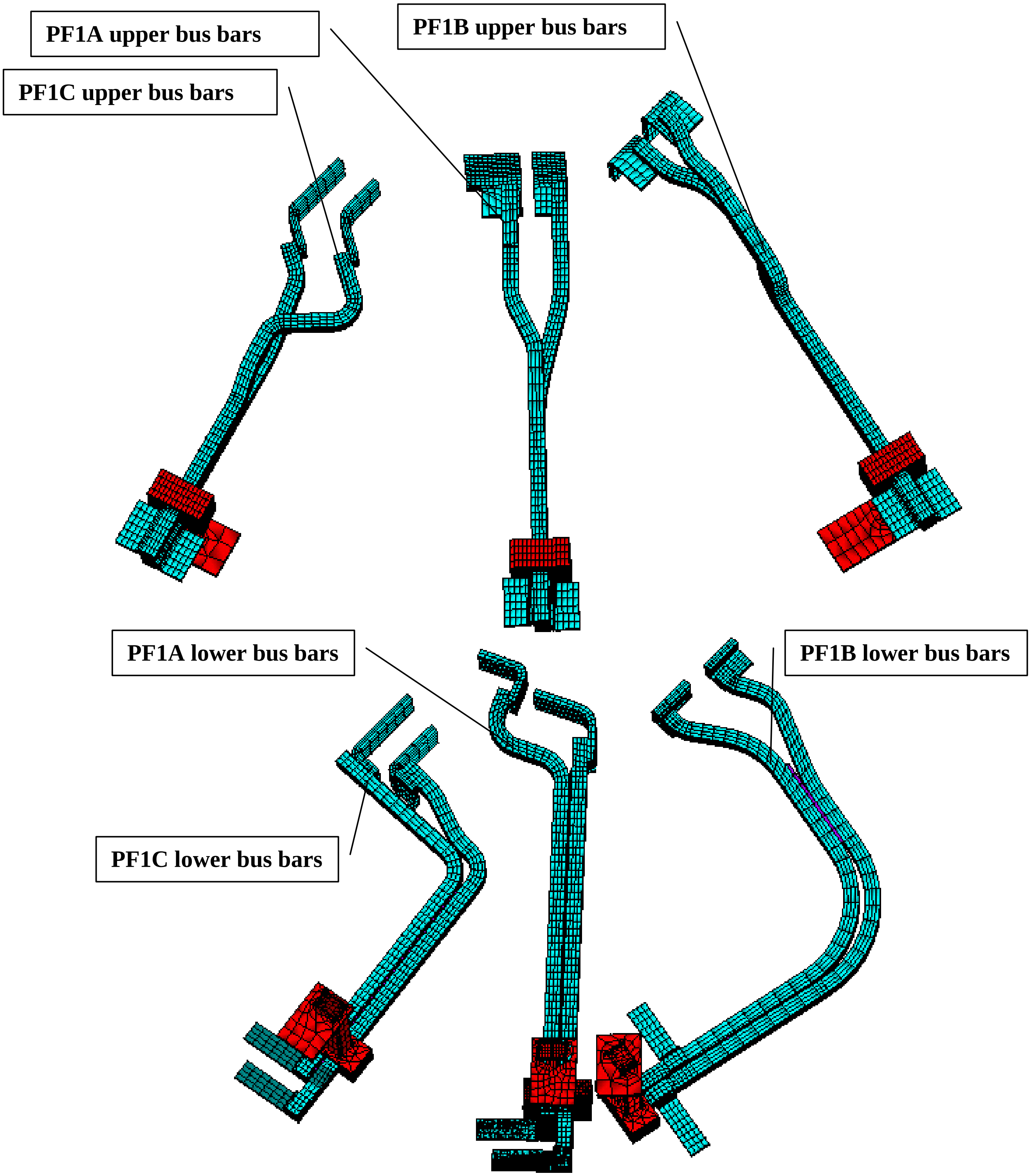


Fig 7 Mesh for PF bus bars

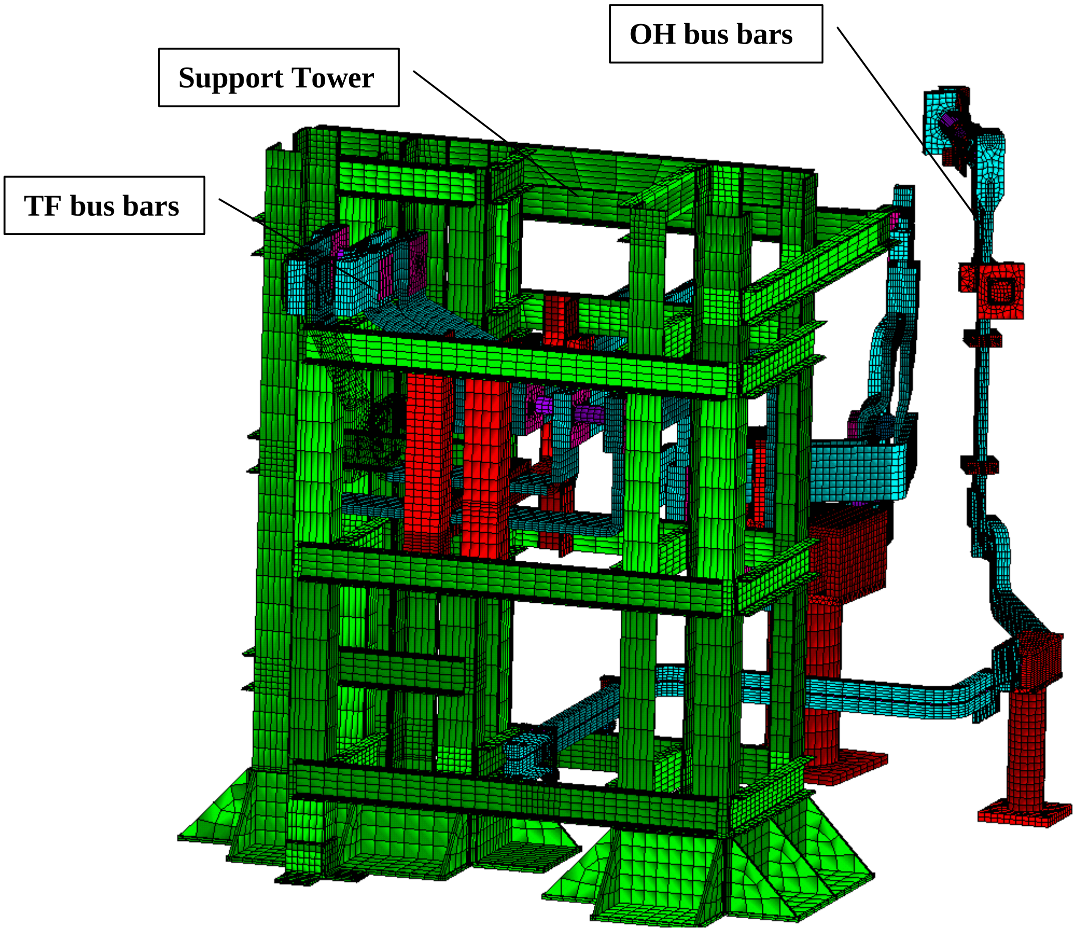


Fig 8 Mesh for TF and OH bus bars with support tower

Boundary Conditions and Loads

Structural boundary conditions

The model is fixed in all directions as shown on fig 9. Supporting brackets are fixed in places of attachment to other structures. Both ends of the OH bus bars are fixed, as well as outer ends of the TF bus bars. Inner TF bus bar directly connected to outer portion of the TF coil (see fig 9). The other TF bus bar is fixed at center stack connection. Most of PF bus bars are fixed at the flags with no displacement. Positive vertical displacement of 1 cm is imposed on PF1A, and PF1B flags. Analysis of center stack thermal expansion was provided by A. Brooks. Outer ends of PF bus bars are not fixed since they are attached to flexible connectors.

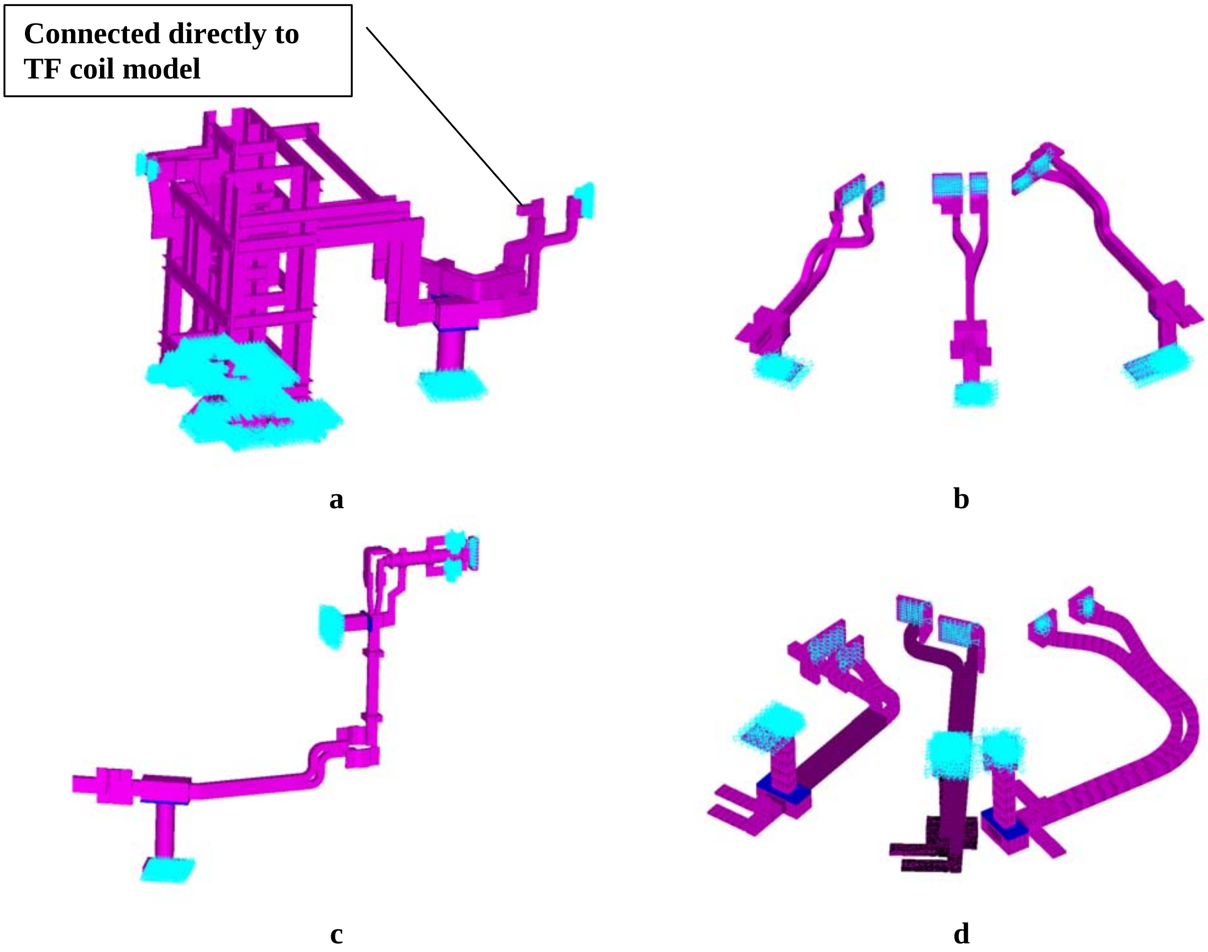


Fig 9 Structural boundary conditions a) TF bus bars; b) Upper PF bus bars c) OH bus bar; d) Lower PF bus bar

Thermal Load

Constant temperature boundary conditions are summarized in table 2. Cooling channels of TF and OH buses are presented on fig 10.

Table 2 Constant temperature boundary conditions

Part	Side	Temperature
OH bus bars	outer	40 ºC
	center stack	40 ºC
	cooling channels	20 ºC
TF bus bars	outer	50 ºC
	outer TF coil	50 ºC
	center stack	40 ºC
	cooling channels	20 ºC
PF bus bars	outer	40 ºC
	center stack	100 ºC
Bus Bar supports	fixed points	35 ºC

Reference temperature of 20 ºC was used for thermal strain calculation, as a temperature during assembly, of the device. Heat transfer conditions were imposed on the all external walls with film coefficient of 7 and ambient temperature of 35 ºC

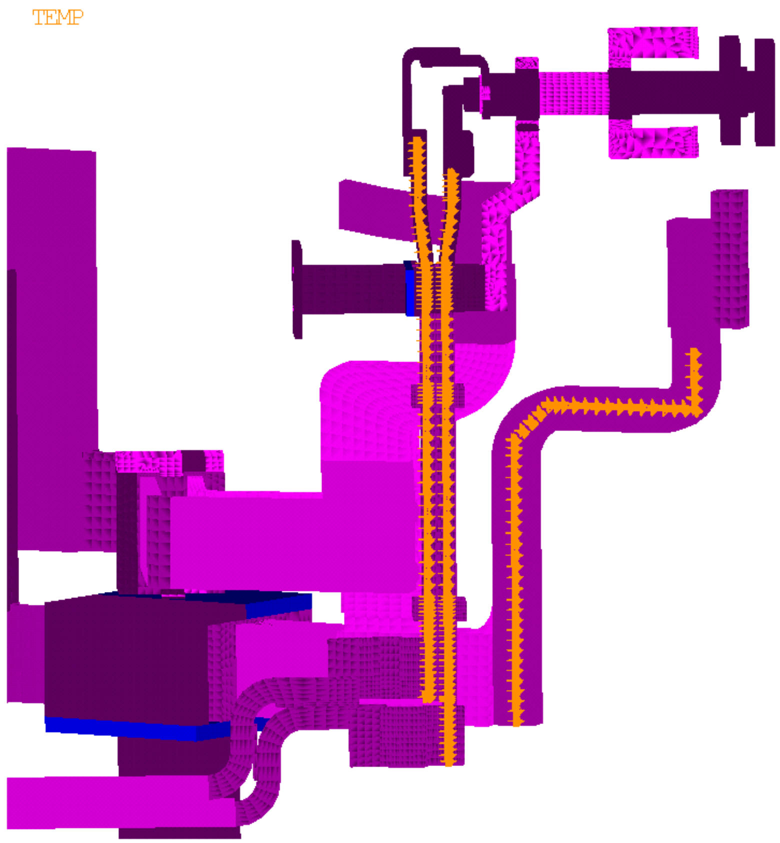


Fig 10 Cooling channel walls at 20 °C or OH and TF bus bars

With this boundary conditions heat transfer problem was resolved including Joule heat on the conductor parts. However resistivity of copper was assumed 150 times lower to model 8s pulse every 20 minutes.

Electric Boundary Conditions

Electrical boundary conditions were imposed on the opposing ends of the each bus bar cable, to simulate constant electrical current flow. At one end constant voltage level of zero was imposed, while on the other end constant current level corresponding to the coil and scenario is imposed. The current direction in bus bars is chosen in consistence with correspondent coil current direction. Scenario 72 was chosen to obtain current values. In this scenario all PF1 coils are charged at maximum values, and higher values are also imposed on PF4 and PF5 coils creating strong magnetic field. Currents used to charge coils and corresponding bus bars are presented in table 3:

Table 3

Coil	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH	TF
Current [kA]	18.3	13	15.9	15	-16	-16	-34	-16	15	15.9	13	18.3	-24	130

External magnetic Field

External to bus bars magnetic field was generated using SOURC36 elements for PF and OH coils and inner parts of TF coil, outer legs of TF coils were meshed using SOLID5 elements as shown fig. 12. The model was provided by Han Zhang. The values of the parameters used for source elements are summarized in the table 4. They correspond to the Scenario 72 and create external field presented on fig. 12. Axial field of more than one Tesla is assumed conservative approximation of all the scenario effects on the bus bars.

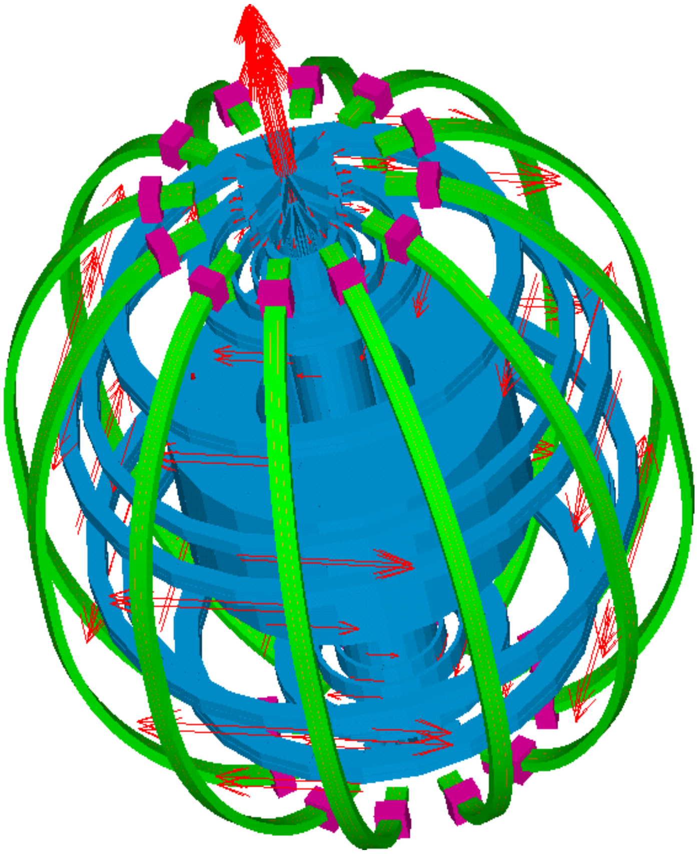


Fig 11 External magnetic field creating elements

Table 4 Magnetic field source element properties

Coil	**R (center)**	**dR**	**Z (center)**	**dZ**	**nR**	**nZ**	**Turns**
	(cm)	**(cm)**	**(cm)**	**(cm)**			
OH (half-plane)	24.2083	6.9340	106.0400	212.0800	4.0	110	442
PF1a	32.4434	6.2454	159.0600	46.3296	4.0	16	64
PF1b	40.0380	3.3600	180.4200	18.1167	2.0	16	32
PF1c	55.0520	3.7258	181.3600	16.6379	2.0	10	20
PF2a	79.9998	16.2712	193.3473	6.7970	7.0	2	14
PF2b	79.9998	16.2712	185.2600	6.7970	7.0	2	14
PF3a	149.4460	18.6436	163.3474	6.7970	7.5	2	15
PF3b	149.4460	18.6436	155.2600	6.7970	7.5	2	15
PF4b	179.4612	9.1542	80.7212	6.7970	2.0	4	8
PF4c	180.6473	11.5265	88.8086	6.7970	4.5	2	9
PF5a	201.2798	13.5331	65.2069	6.8580	6.0	2	12
PF5b	201.2798	13.5331	57.8002	6.8580	6.0	2	12

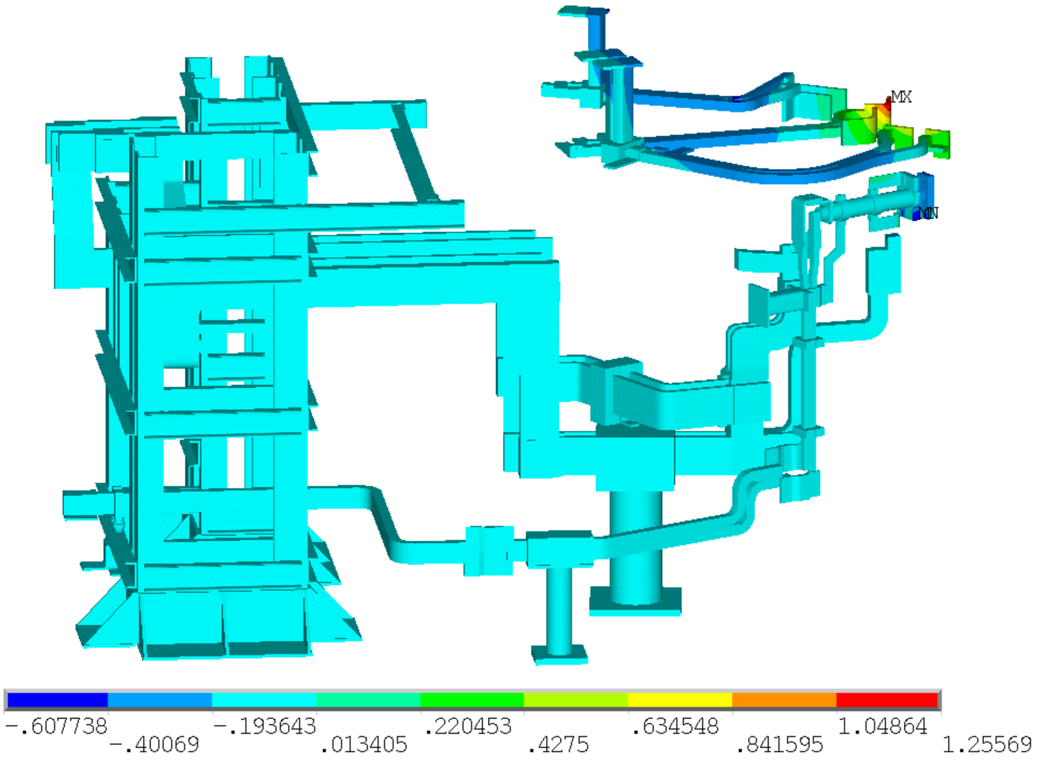


Fig 12.a Axial component of external magnetic field

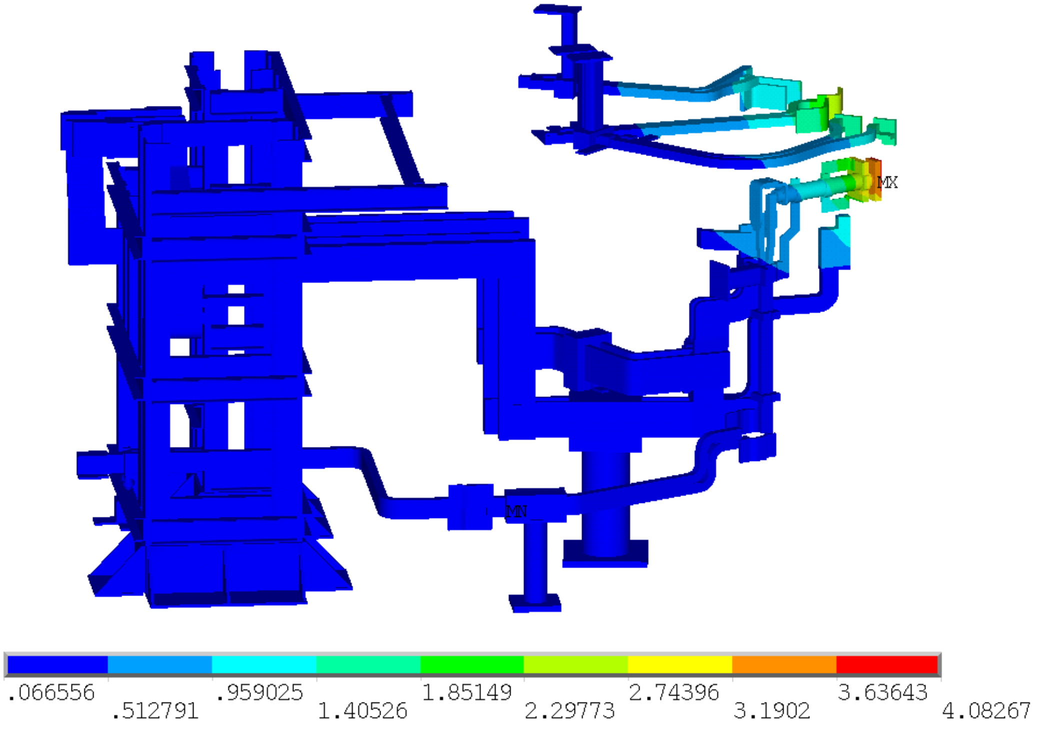


Fig 12.b Toroidal component of external magnetic field

Material properties for bus bar analysis model

Conductors

Material: copper.
Material is isotropic with elastic modulus of 120GPa and Poisson ratio of 0.33.
Thermal conductivity is 385[W/(mK)].
Thermal expansion coefficient is $1.64 \cdot 10^{-5}$[1/K] at 293K.
Temperature dependent electrical resistivity is presented in table 5. Value used in analysis was 150 times less assuming 8s pulse in 20 min interval

Table 5 Copper conductor electrical resistivity

Temeprature°C	273	293	393
r_{Cu} [Ωm]	1.49E-08	1.62E-08	2.28E-08
r_{Cu} [Ωm] used in analysis	9.91E-11	1.08E-10	1.52E-10

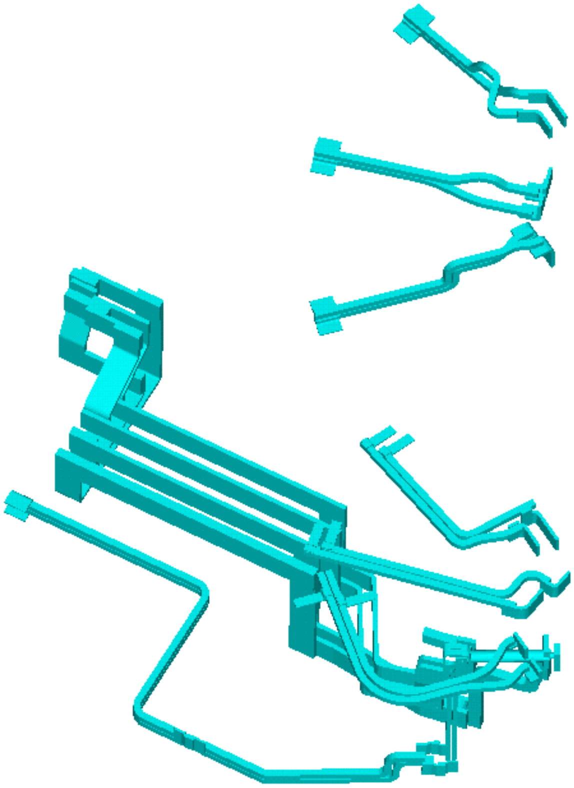


Fig 13 Copper conductors

Insulation

Material: G10.
Material is isotropic with elastic modulus of 20GPa and Poisson ratio of 0.33.
Thermal conductivity is 0.288 [W/(mK)].
Thermal expansion coefficient is $0.99 \cdot 10^{-5}$[1/K] at 293K.
Electrical resistivity is $1.673 \cdot 10^{+6}$ [Ohm·m]

Fig 14 Insulation

Support Hardware

Material: steel.
Material is isotropic with elastic modulus of 190GPa and Poisson ratio of 0.33.
Thermal conductivity is 25[W/(mK)].
Thermal expansion coefficient is $1.60 \cdot 10^{-5}$[1/K] at 293K.

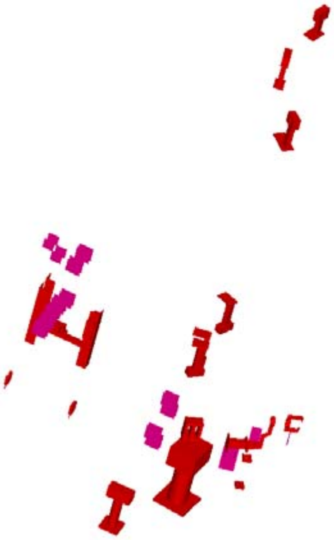


Fig 15 Supporting Hardware

Insulating Inserts

Material: insulating plastic.
Material is isotropic with elastic modulus of 20GPa and Poisson ratio of 0.
Thermal conductivity is 0.288 [W/(mK)].
Thermal expansion coefficient is $1.6\cdot10^{-5}$[1/K] at 293K.
Electrical resistivity is $1.673\cdot10^{+6}$ [Ohm·m]

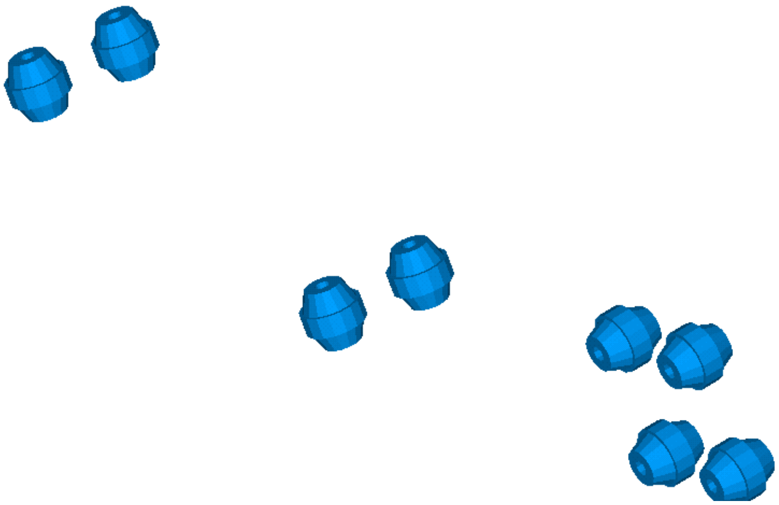


Fig 16 Insulating inserts

Compressible Insertsor PF1A upper and PF1B upper supports

Material: insulating plastic.
Material is isotropic with elastic modulus of 150MPa and Poisson ratio of 0.49
Thermal conductivity is 0.288 [W/(mK)].
Thermal expansion coefficient is $0.99\cdot10^{-5}$[1/K] at 293K.
Electrical resistivity is $1.673\cdot10^{+6}$ [Ohm·m]

Fig 17 Compressible inserts

Support Tower

Material: Aluminum 6061
Material is isotropic with elastic modulus of 68.9GPa and Poisson ratio of 0.33.
Thermal conductivity is 167 [W/(mK)].
Thermal expansion coefficient is $2.36 \cdot 10^{-5}$[1/K] at 293K.
Electrical resistivity is $3.99 \cdot 10^{-8}$ [Ohm·m]

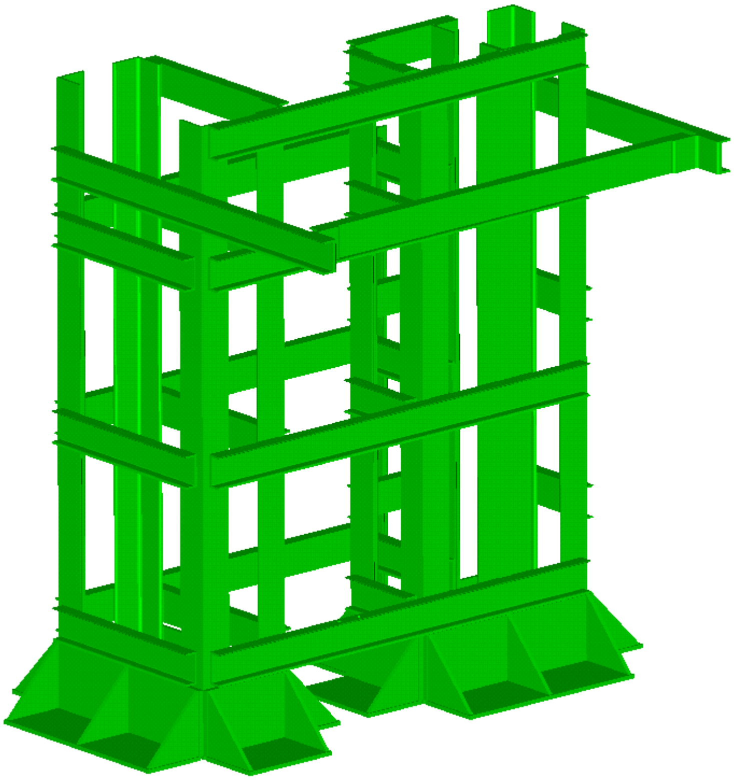


Fig 18 Supporting Tower

Simulation Results

PF Upper Bus Bars

PF1A Upper Bus Bar

Stress intensity and displacements on PF1A upper bus bar are presented on Fig. 19

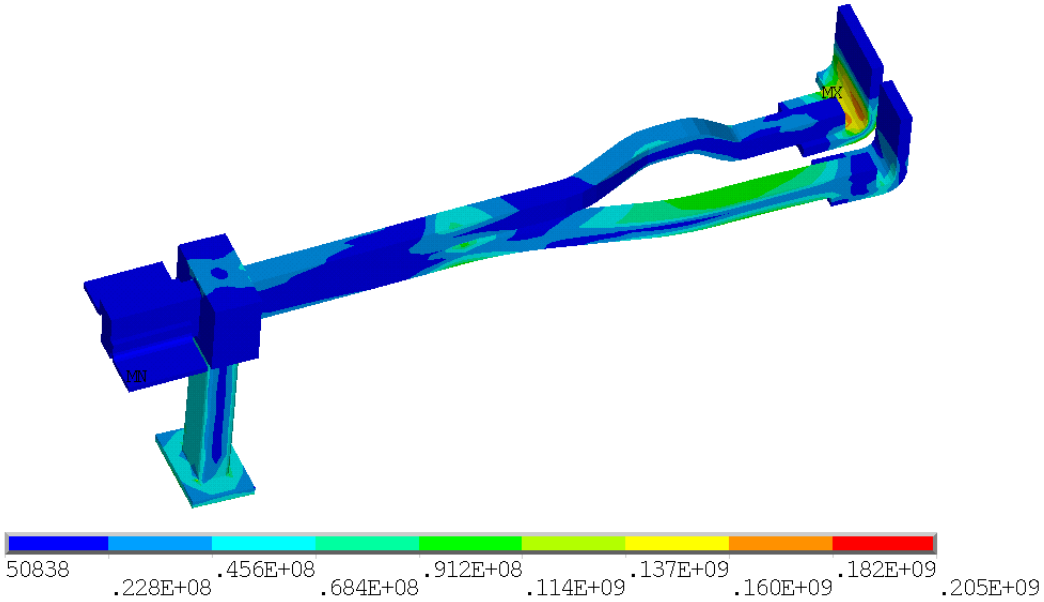


Fig 19.a Stress intensity

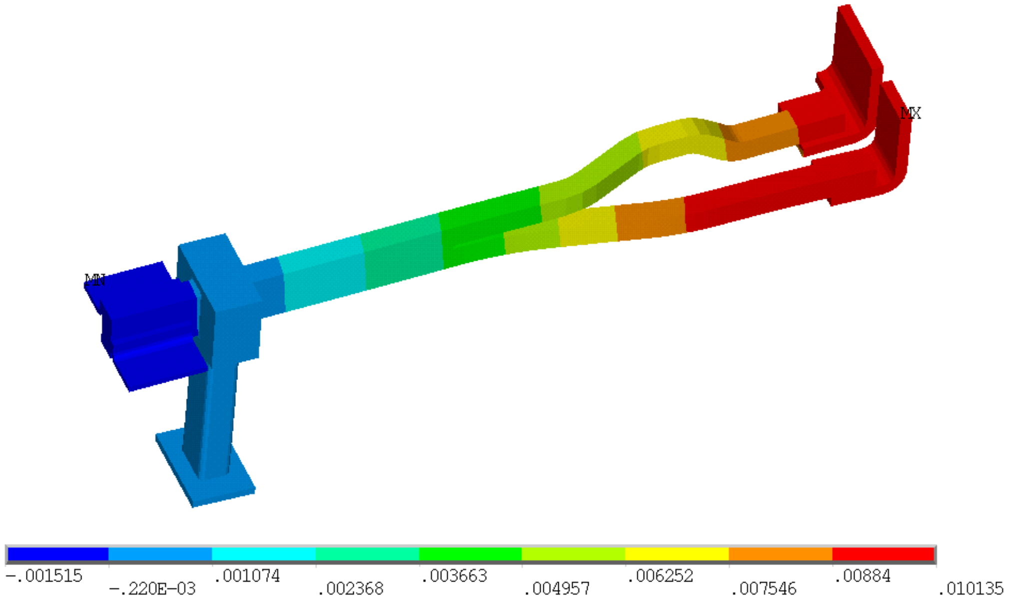


Fig 19.b Vertical Displacement

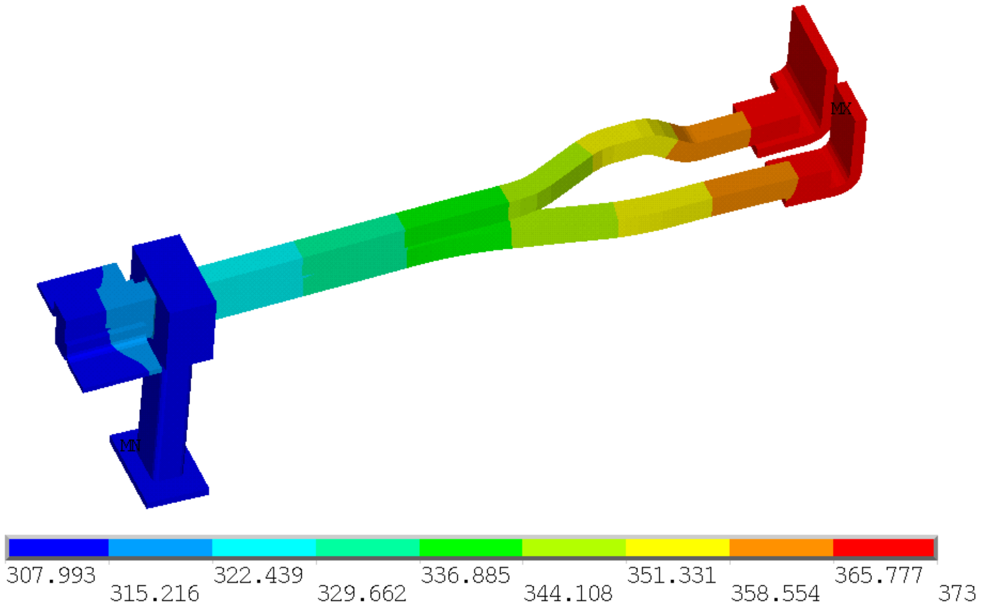


Fig 19.c Temperature

PF1B Upper Bus Bar

Stress intensity and displacements on PF1B upper bus bar are presented on Fig. 20

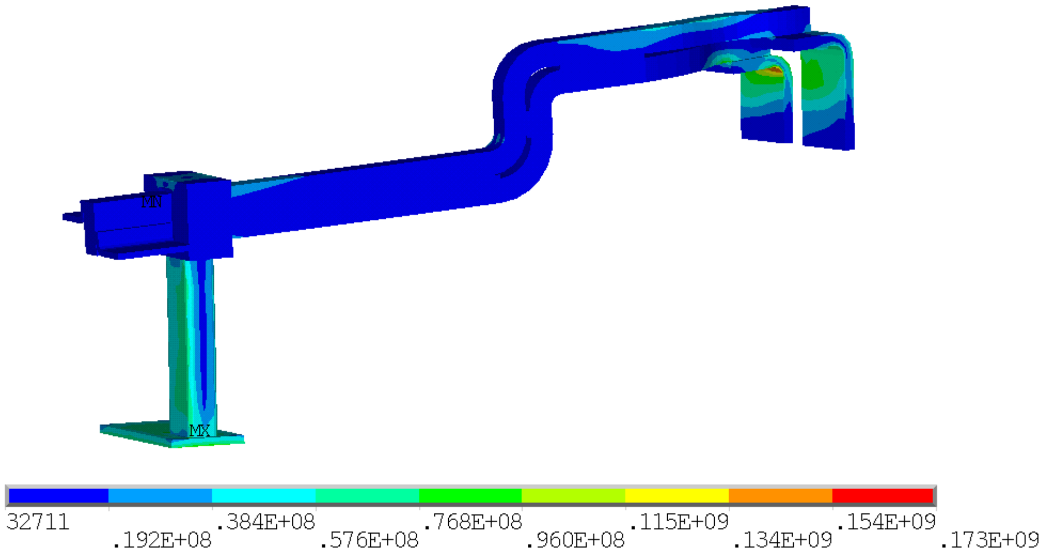


Fig 20.a Stress intensity

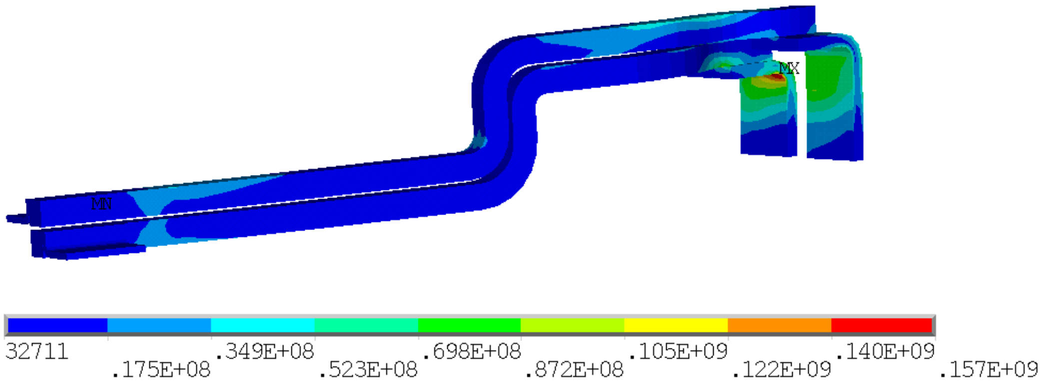


Fig 20.d Stress intensity in copper conductor

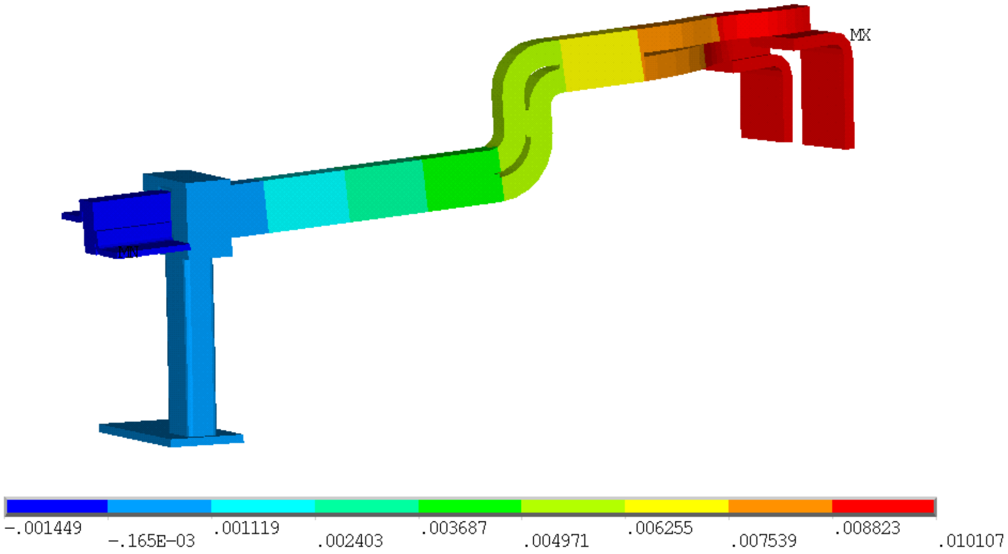


Fig 20.b Vertical Displacement

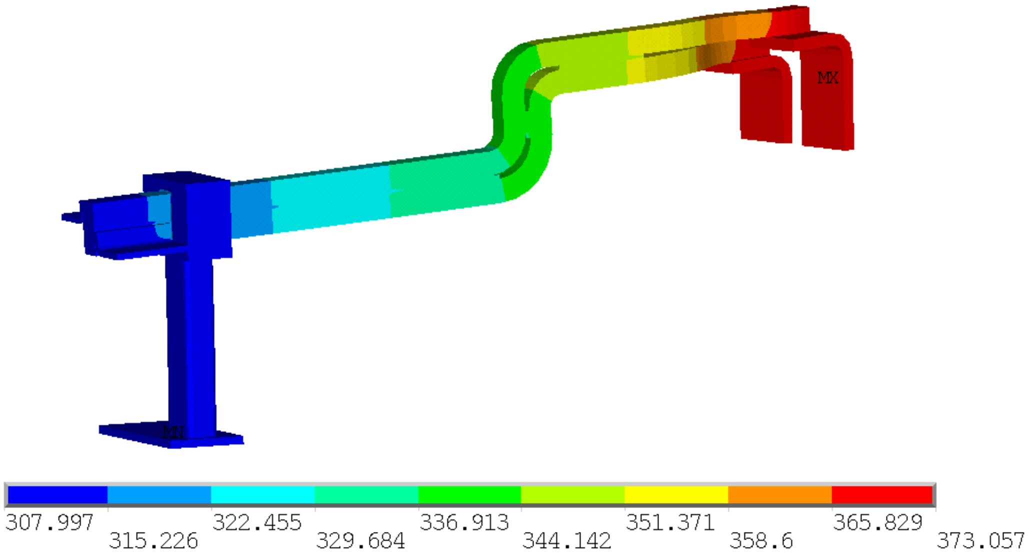


Fig 20.c Temperature

PF1C Upper Bus Bar

Stress intensity and displacements on PF1C upper bus bar are presented on Fig. 21

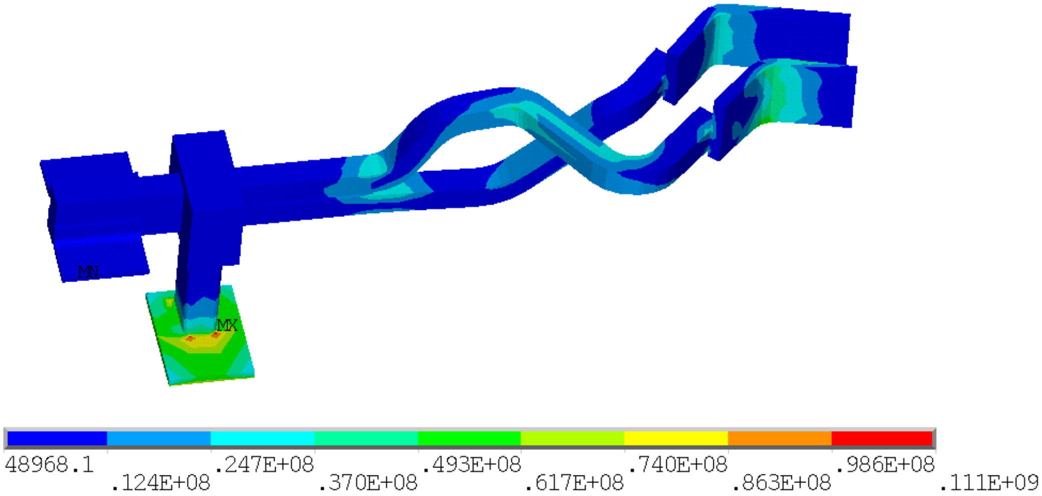


Fig 21.a Stress intensity

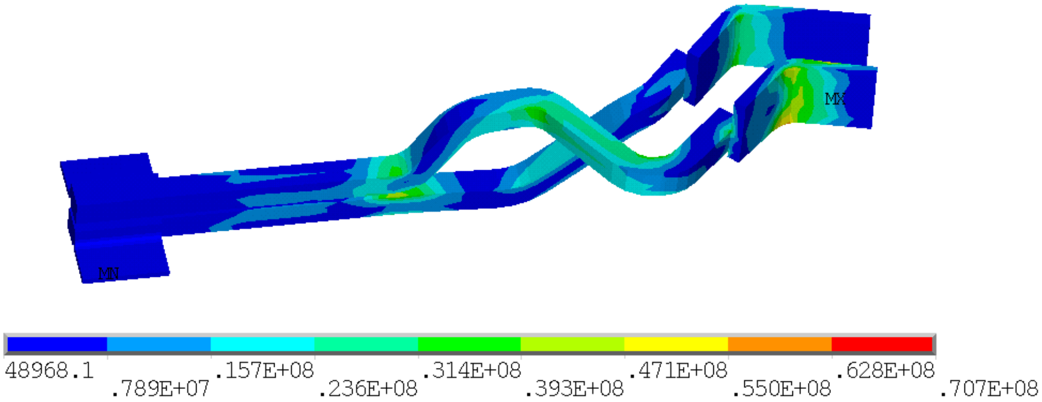


Fig 21.d Stress intensity in copper conductor

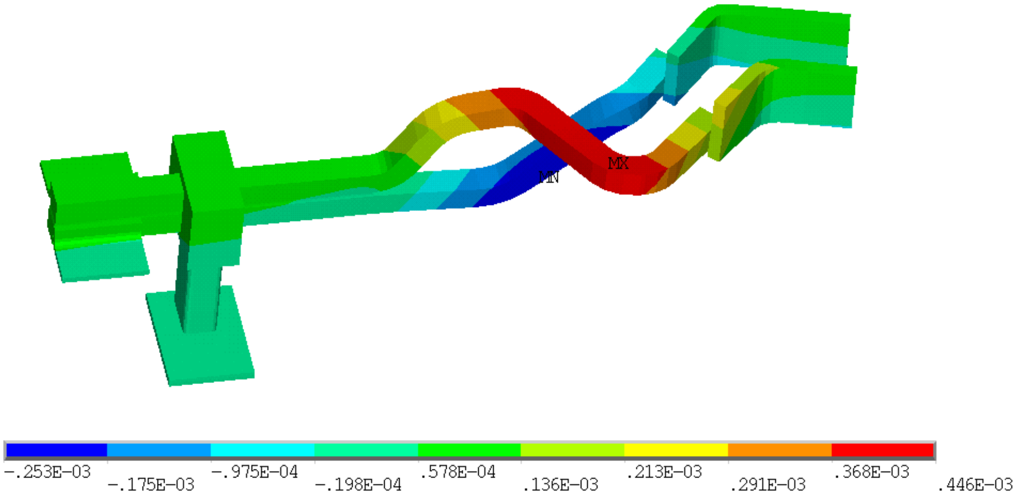


Fig 21.b Vertical Displacement

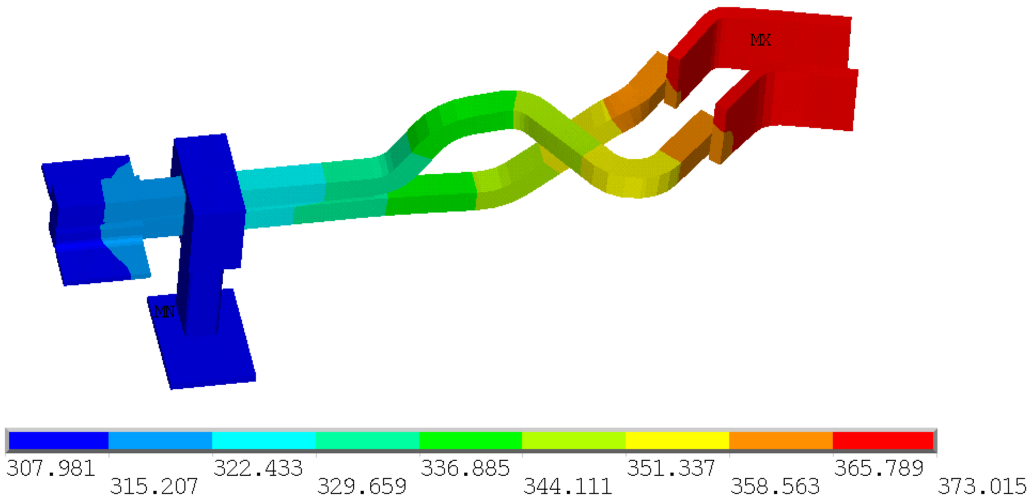


Fig 21.c Temperature

PF Lower Bus Bars

PF1A Lower Bus Bar

Stress intensity and displacements on PF1A lower bus bar are presented on Fig. 22

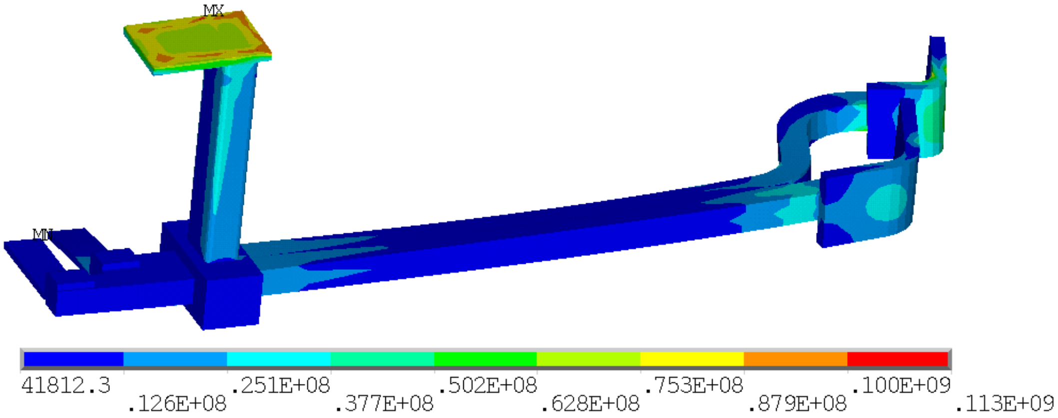


Fig 22.a Stress intensity

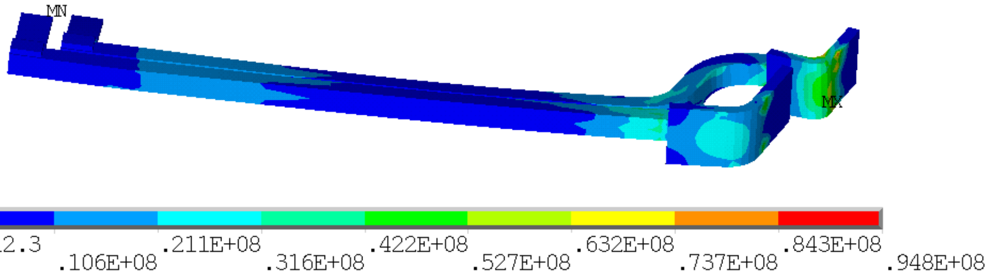


Fig 22.d Stress intensity in copper conductor

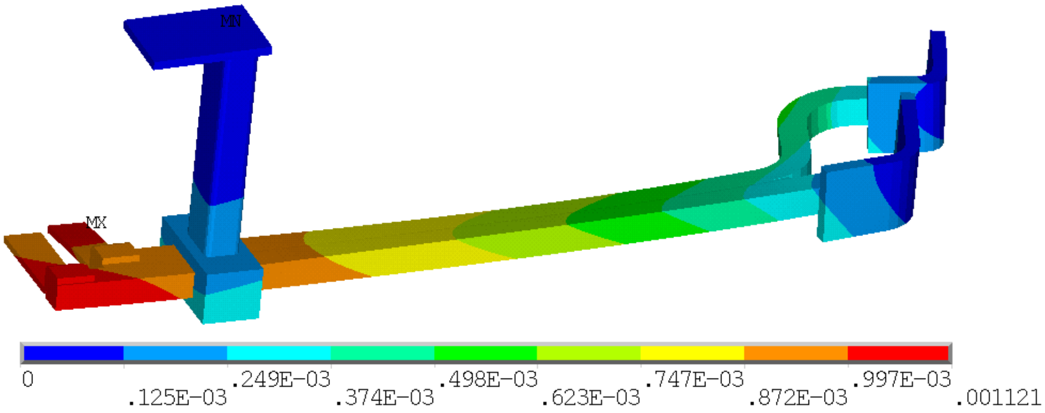


Fig 22.b Displacement

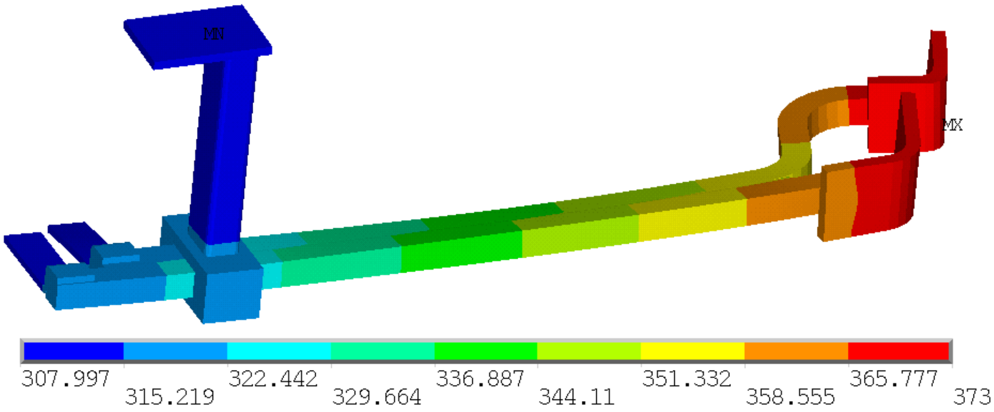


Fig 22.c Temperature

PF1B Lower Bus Bar

Stress intensity and displacements on PF1B lower bus bar are presented on Fig. 23

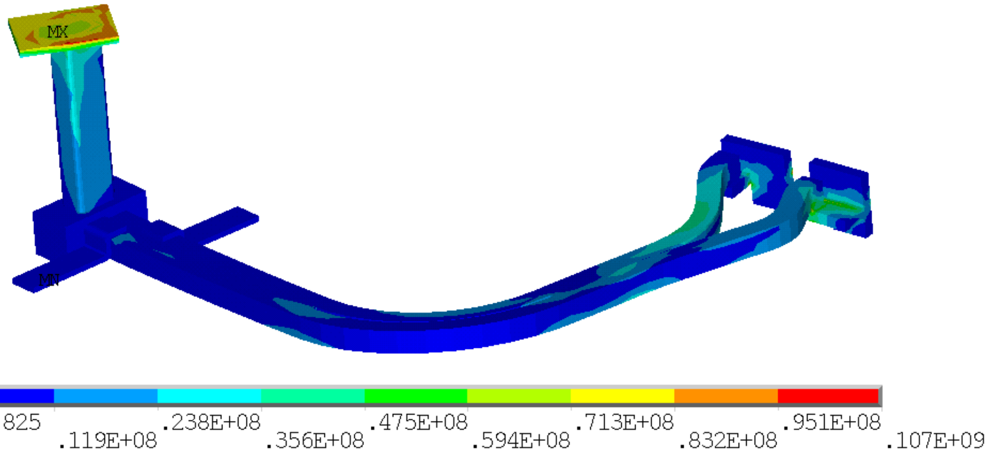


Fig 23.a Stress intensity

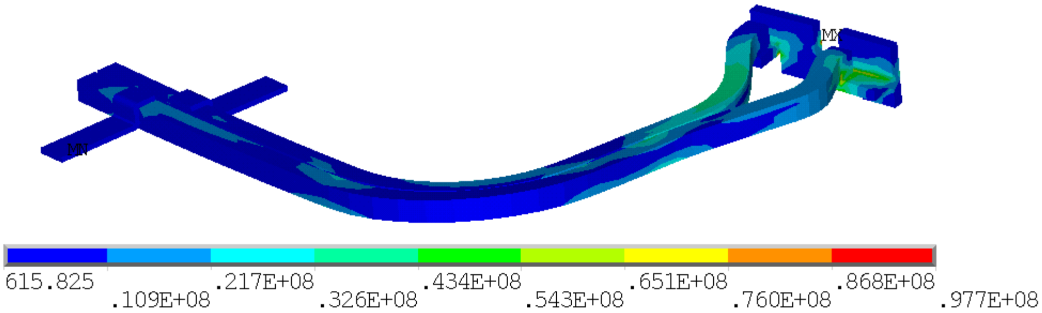


Fig 23.d Stress intensity in copper conductor

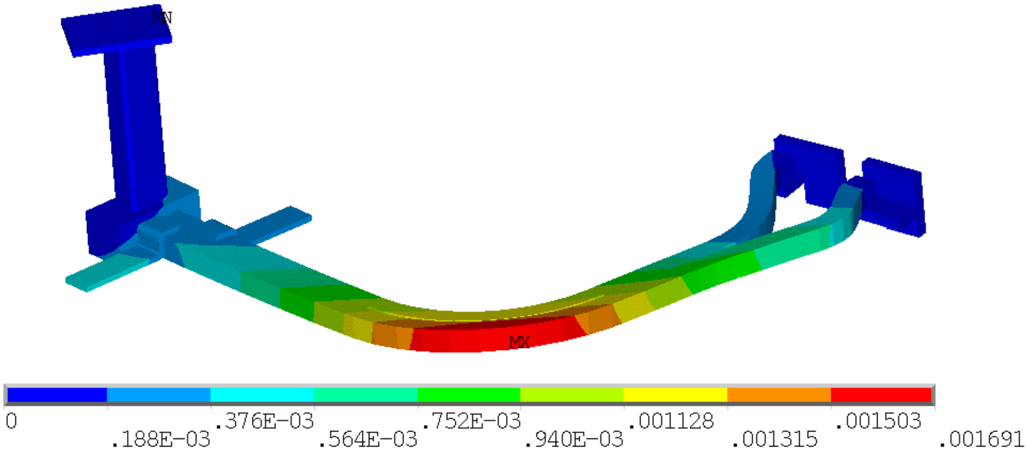


Fig 23.b Displacement

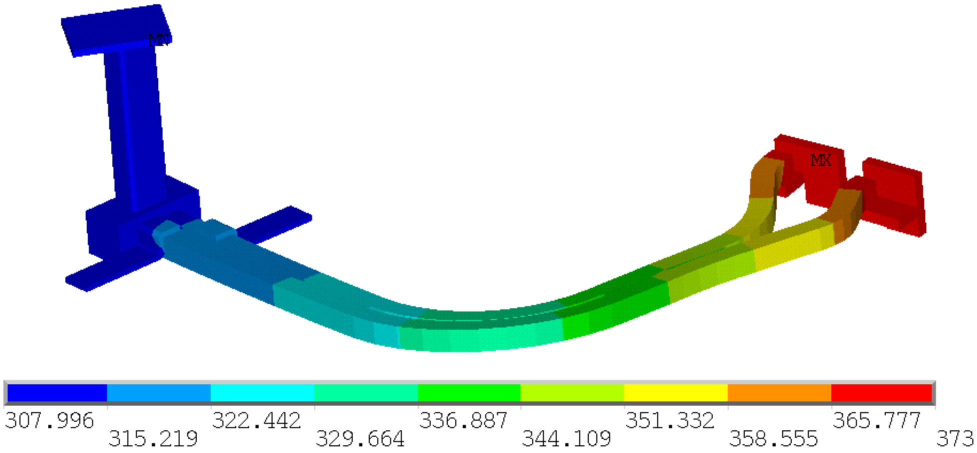


Fig 23.c Temperature

PF1C Lower Bus Bar

Stress intensity and displacements on PF1C lower bus bar are presented on Fig. 24

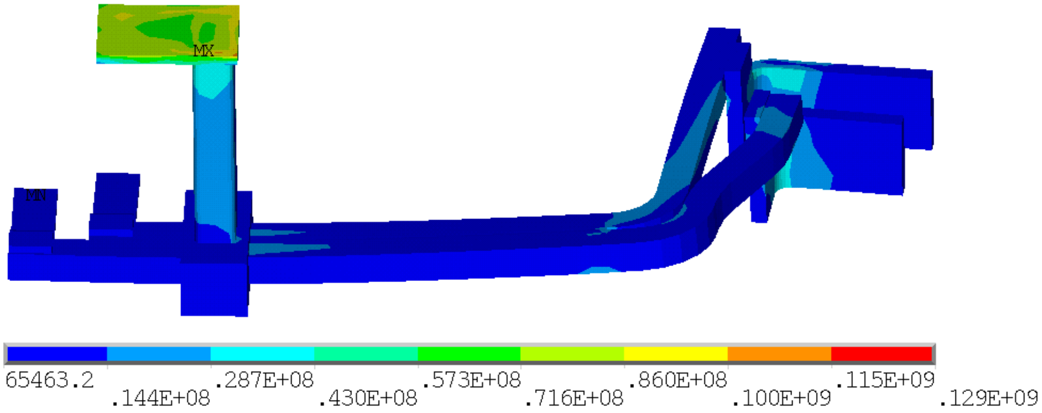


Fig 24.a Stress intensity

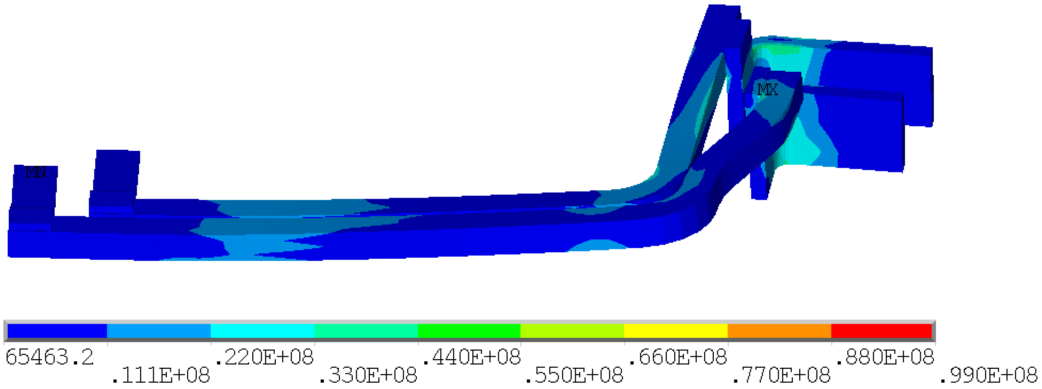


Fig 24.d Stress intensity in copper conductor

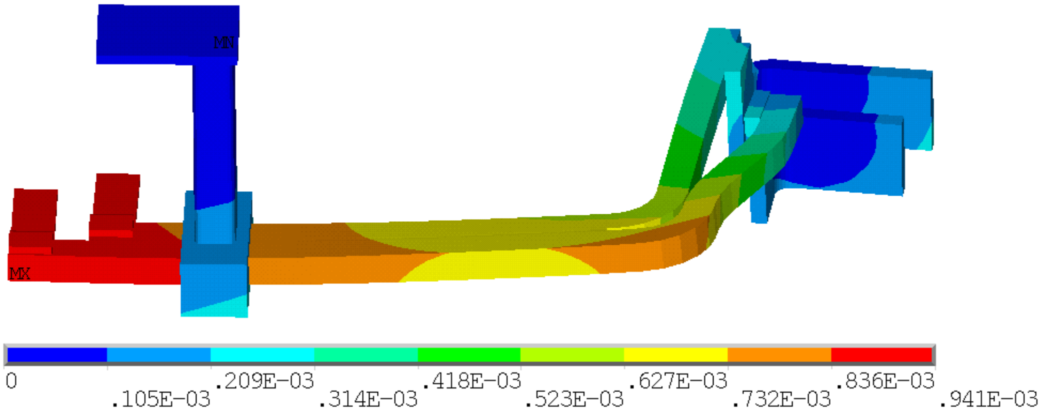


Fig 24.b Displacement

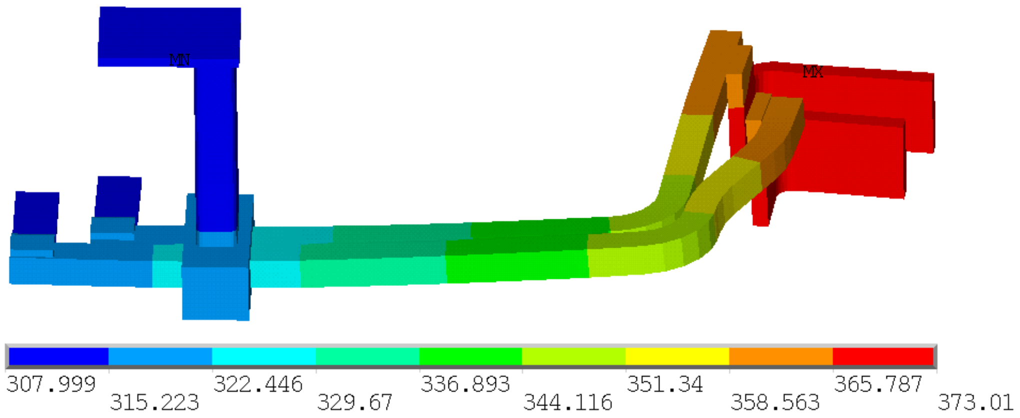


Fig 24.c Temperature

TF Bus Bars

Stress intensity and displacements on TF bus bars are presented on Fig. 25. Figures 25.b and 25c. show additional measures proposed to reduce stress intensity and displacement.

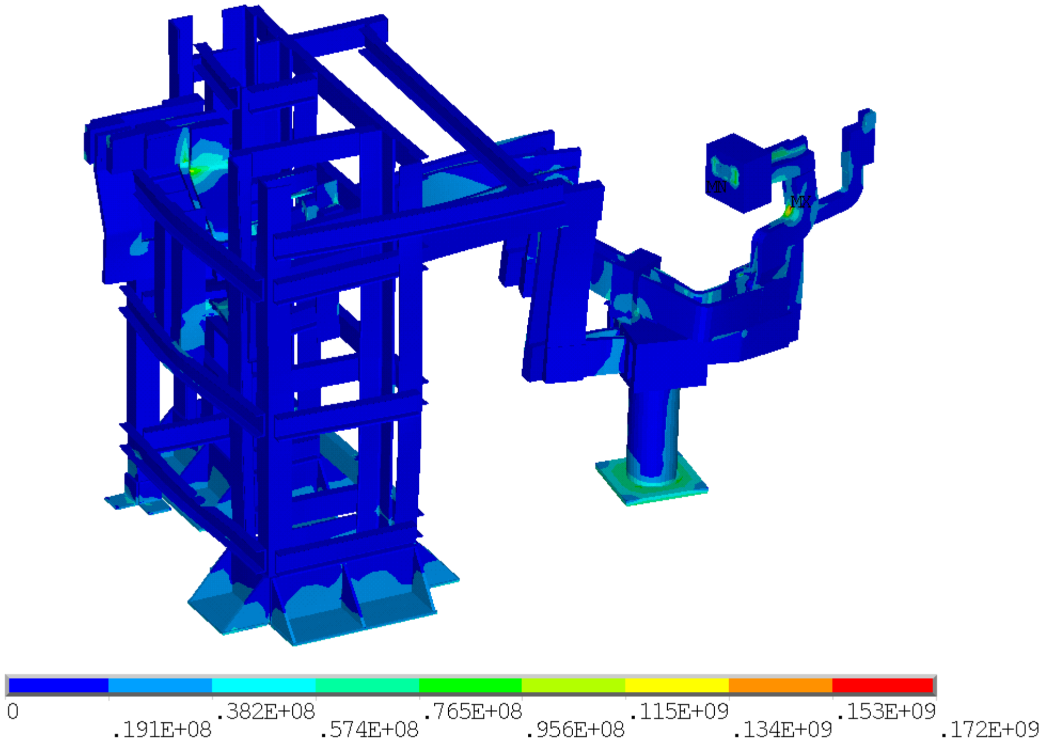
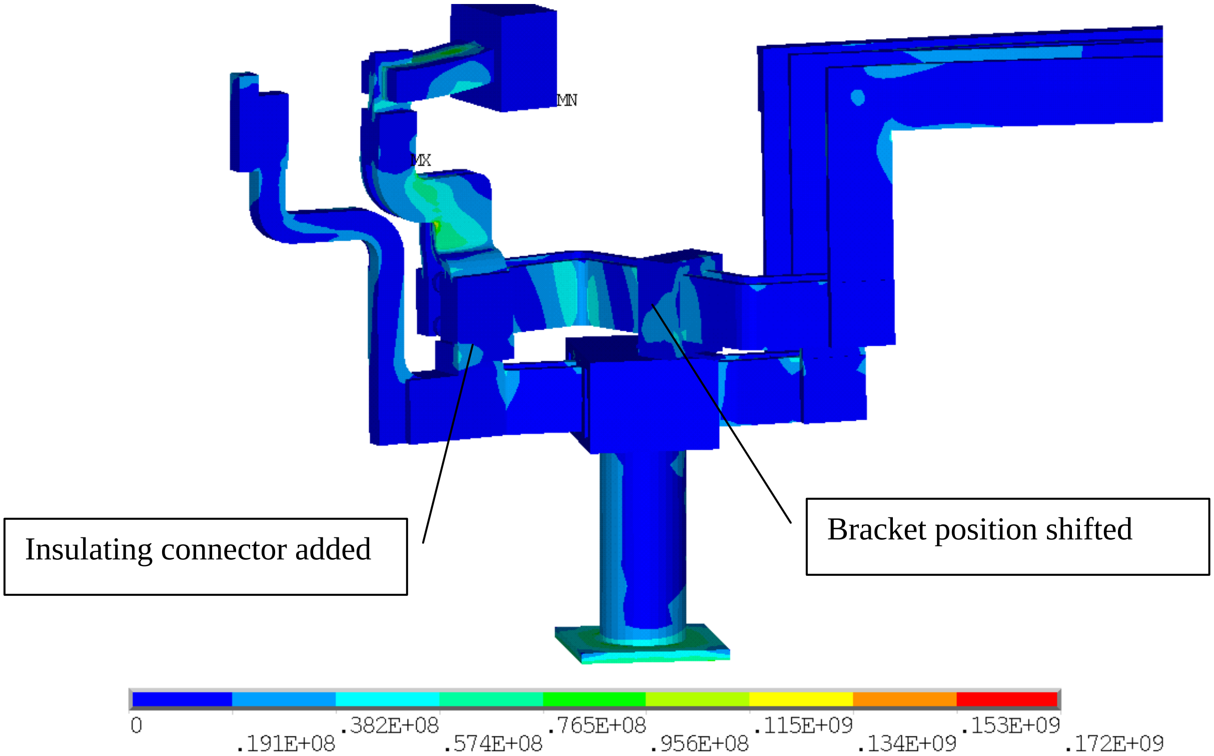


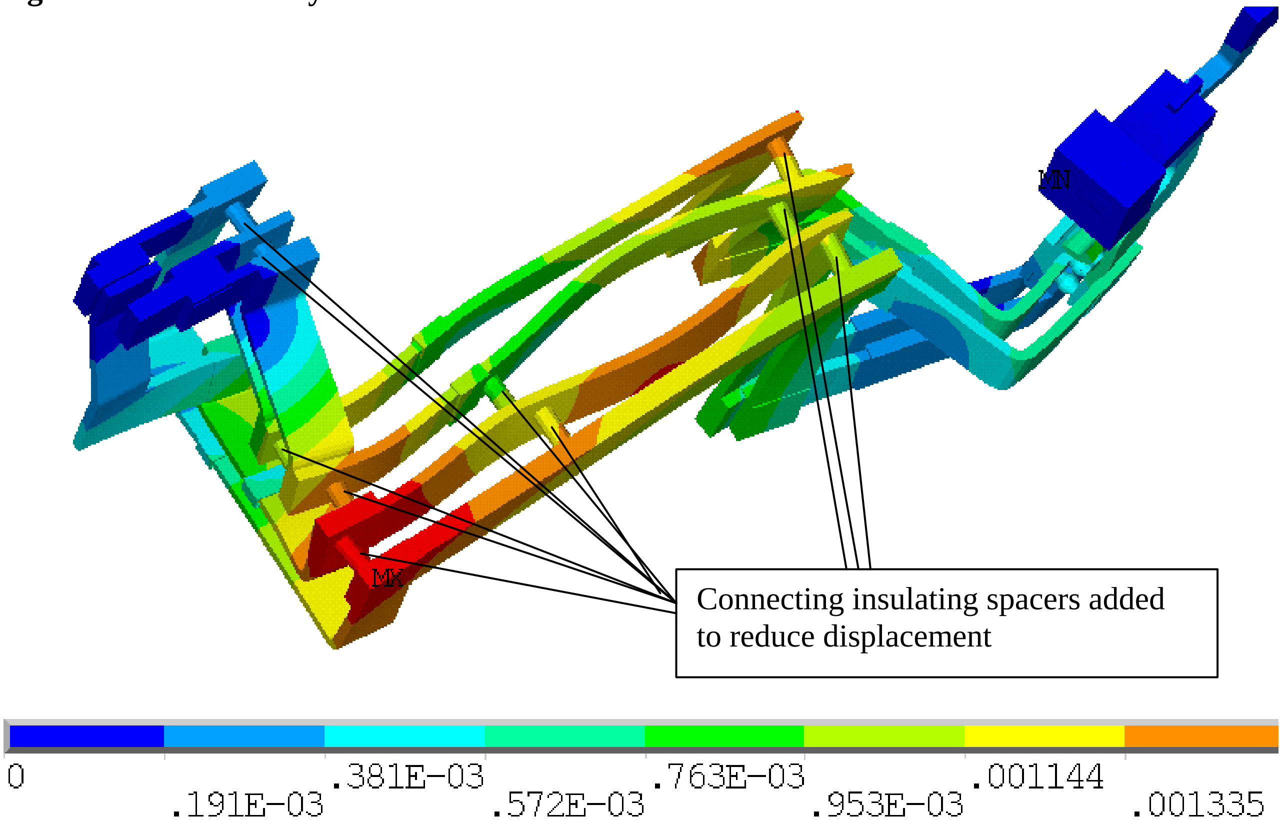
Fig 25.a Stress intensity



Insulating connector added

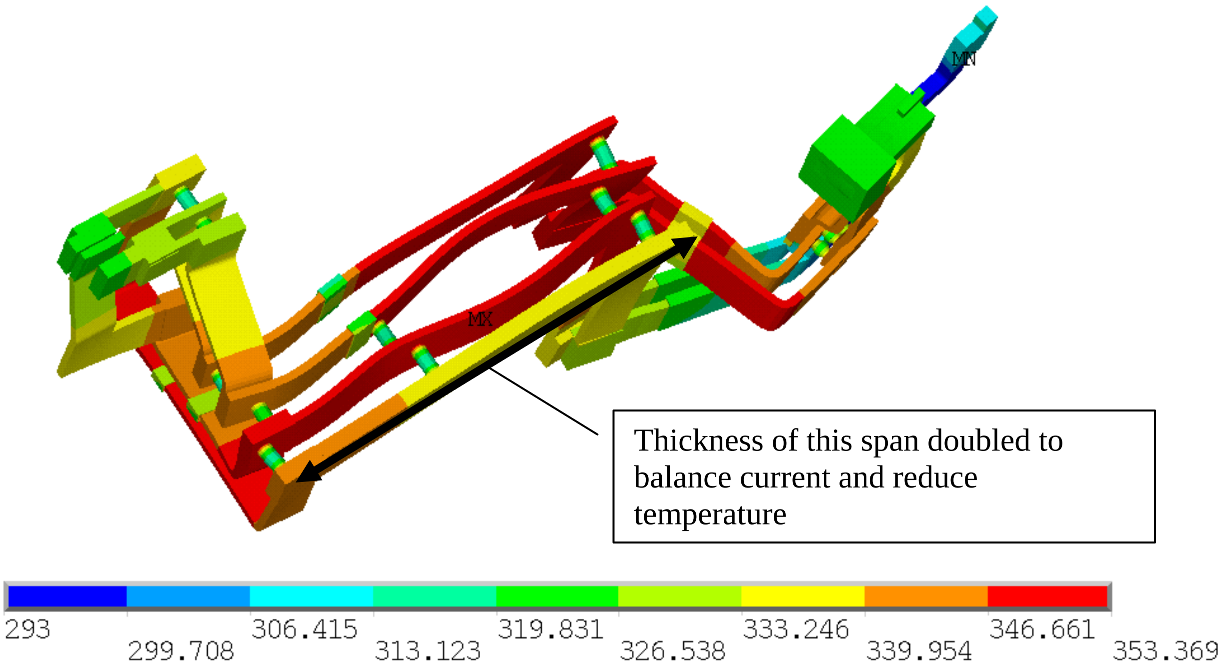
Bracket position shifted

Fig 25.b Stress intensity



Connecting insulating spacers added to reduce displacement

Fig 25.c Displacement



Thickness of this span doubled to balance current and reduce temperature

Fig 25.c Temperature

OH Bus Bars

Stress intensity and displacements on OH bus bars are presented on fig. 26

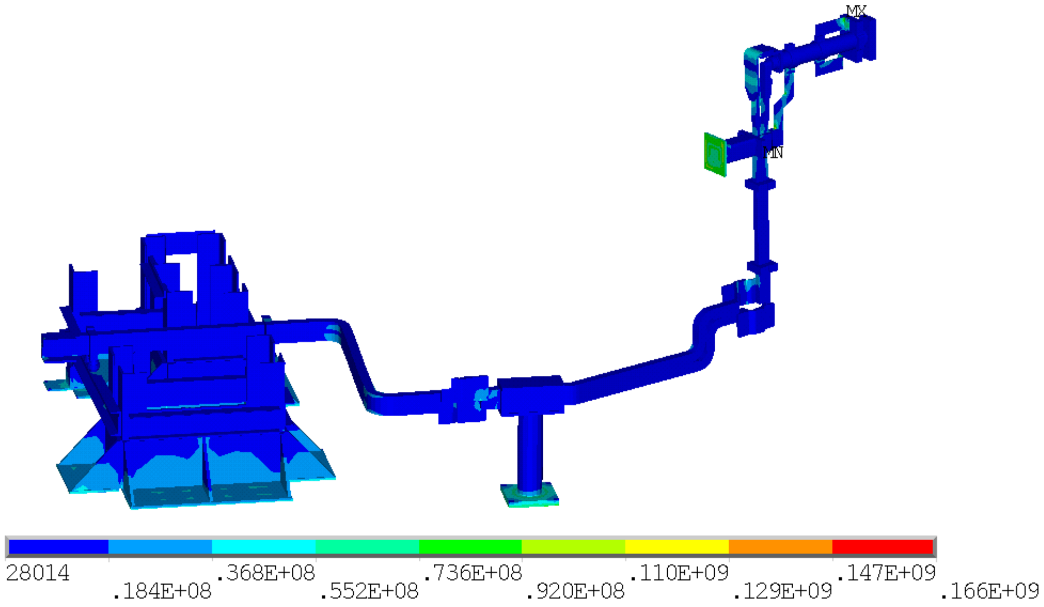


Fig 26.a Stress intensity

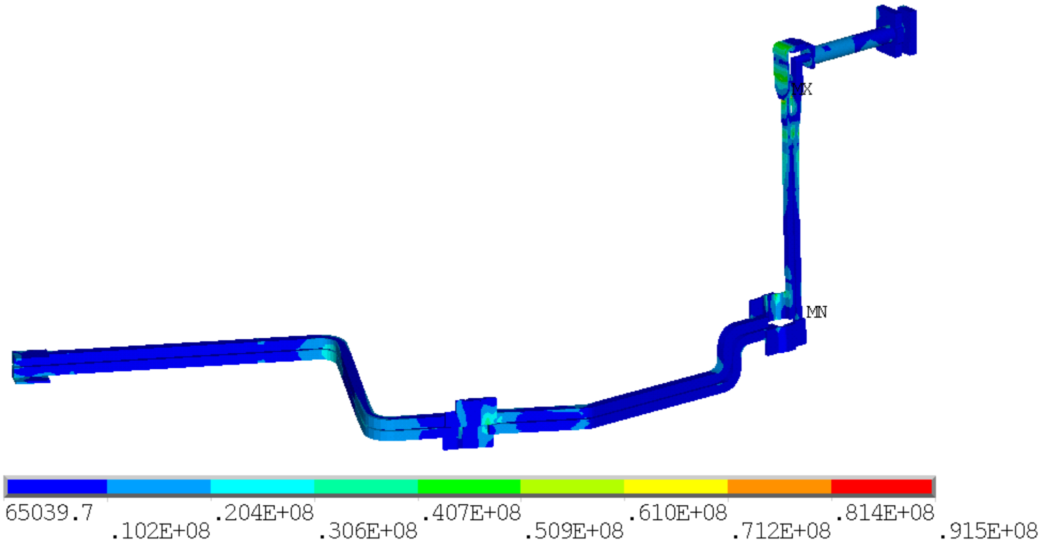


Fig 26.b Stress intensity in copper conductor

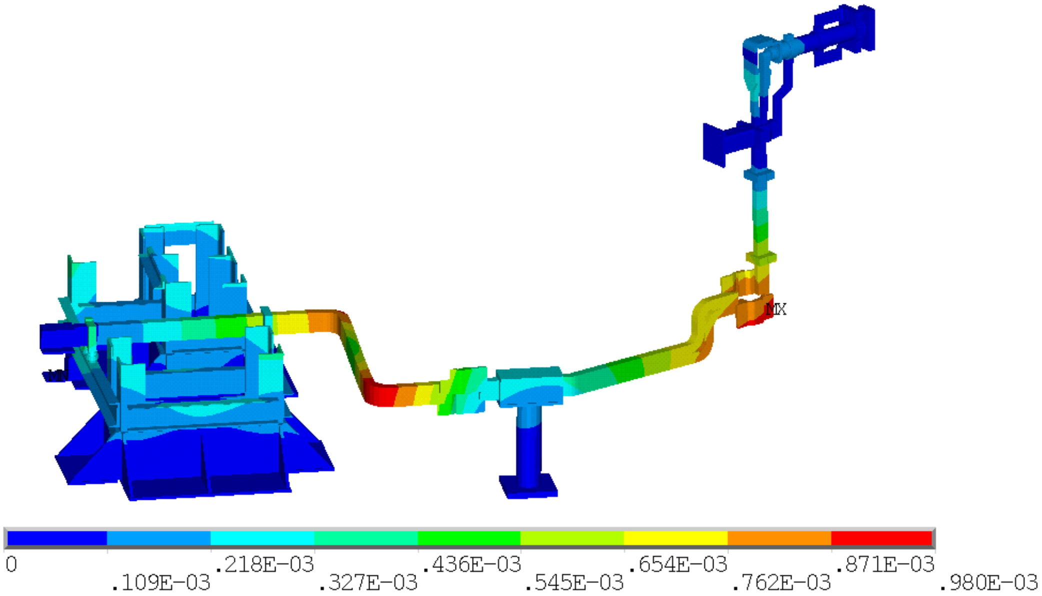


Fig 26.c Displacement

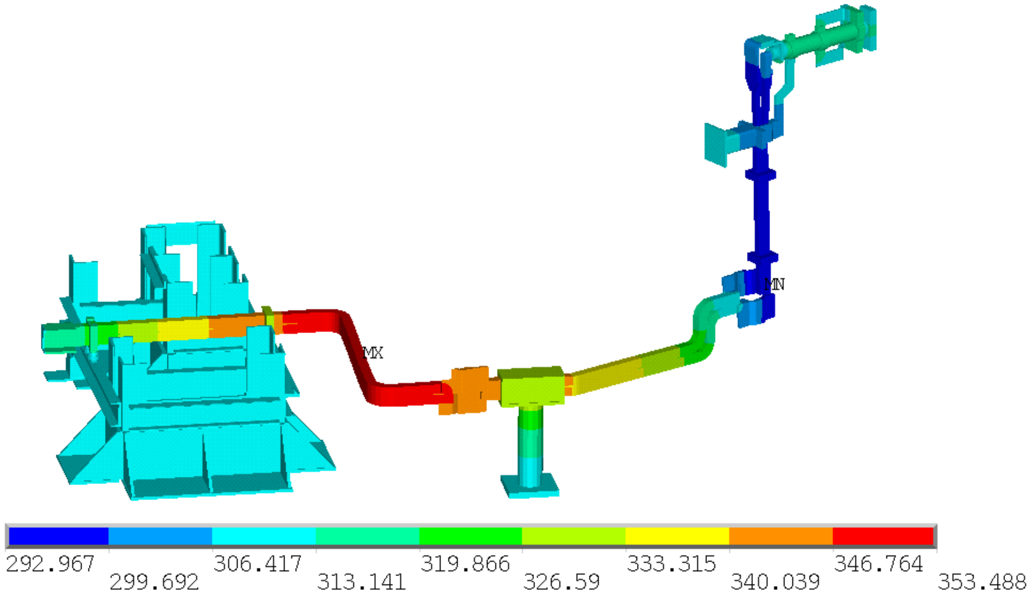


Fig 26.d Temperature

Conclusions

Results for PF, TF and OH bus bars are presented in Table 5 show that maximum values of stresses satisfy static structural design criteria.

However maximum stress intensity in copper for PF1A, PF1B and TF bus bars is higher than fatigue design criteria of 125MPa. The areas of elevated stress are very small.

Table 5 Stress intensity in bus bars

Coil connected to BusBar	*Max Stress Intensity [MPA]*	*Max Stress Intensity in copper conductor [MPa]*
PF1A upper	205	205
PF1B upper	173	157
PF1C upper	111	71
PF1A lower	113	95
PF1B lower	107	98
PF1C lower	129	99
TF	172	172
OH	166	92

For PF bus bars additional reinforcement measures were proposed which may eliminate this high stresses. This is analyzed in detail in PF part of center stack analysis report [3].

Maximum stress area for TF bus bar occurs in the area where conductor connection is assumed bonded. Actual bolted connection may allow more flexibility and reduce stress in the area.

Based on initial calculations insulated connectors are added between TF bus bars to reduce deflection.

Ground support of the TF bus bars was shifted to

The thickness of the strait section of one of the TF bus bars was doubled to balance the electric current between two parallel bus bars, and correspondingly reduce maximum temperature.

Reactions on bolts and brazing joints will be analyzed in the next version of the report.

References

[1] http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html Dated 2 - 17- 2009 (reference for Design Currents)

[2] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz

[3] WBS 1.1.3 Structural Analysis of the PF1 Coils Leads and Supports, Rev1 NSTX-CALC-133-01-01
Prepared By: Leonard Myatt, Reviewed by A. Zolfaghari, and Rev1, prepared by A.Zolfaghari, , Cognizant Engineer: Jim Chrzanowski
(Reference for Ali's detailed modeling of PF1b Upper Lead)

[4] WBS 1.1.1 Plasma Facing Components, Global Thermal Analysis of Center Stack – Heat Balance NSTX-CALC-11-01-00 Prepared By: Art Brooks, Reviewed by: Han Zhang, Cognizant Engineer: Jim Chrzanowski
(Reference for vertical expansion of center stack)

[5] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD Revision 0 March 30, 2009 Prepared By: Charles Neumeyer NSTX Project Engineering Manager