Status of the Coil Structure Design and Magnetic-Structural Analysis

Presented by X.R. Wang

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ARIES Meeting

PPPL, NJ

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Outline

- Review coil supporting structural design for ARIES-CS modular coils

- Report EM(Electromagnetic) analysis of the modular coils for EM loads:
  -Electric analysis for current densities;
  -EM analysis for magnetic flux density and magnetic forces.

- Report structural analysis of the structure responses from:
  -Coil supporting tube;
  -Bucking cylinder ring.

Main Challenges for Designing Coil Structures to Satisfy Both the Modular and Field-Period Maintenance Approaches

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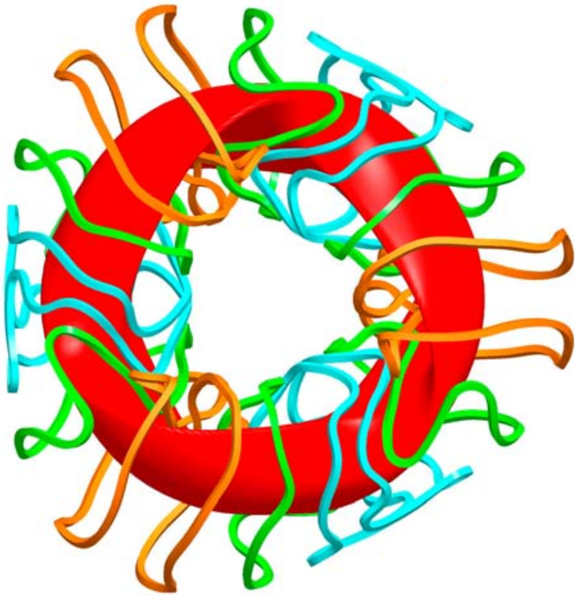
- How can the coil system be supported to react the centering force pulling the coil radially towards the center of torus? (up to 350 MN for SPPS stellerator)

- How can the force between neighboring coils acting in toroidal direction(out-of-plane force) be reacted?

- How can the weight of the "**cold**" coil system be transferred to the "**warm**" base structure of the reactor without excessive large heat ingress?



Three kinds of forces acting on the coils:

•Large centering forces pulling each coil towards the center of the torus;

•Out-of plane forces acting between neighboring coils inside a field period

•Weight of the cold coil system

Proposed Solution: Arrangement of All Coils of One Field-Period on a Supporting Tube

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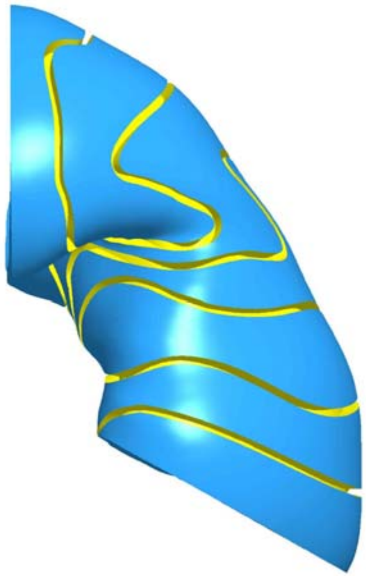

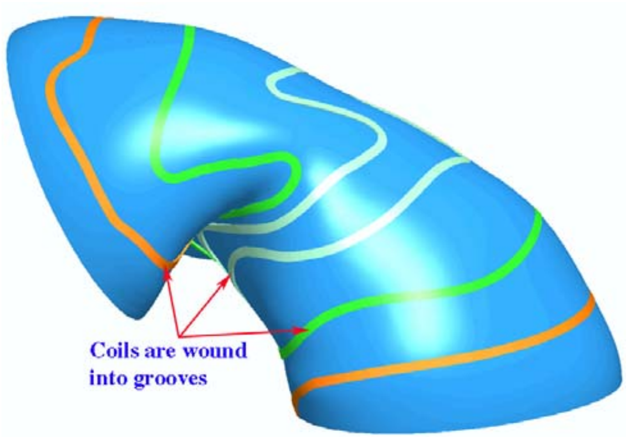

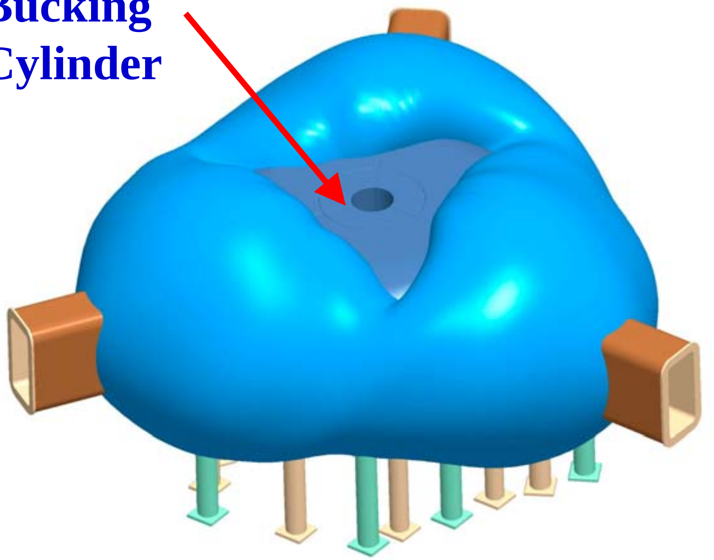

- **The Supporting Tube** is composed of inter coil structure, coil cases, and winding pack.
- All out-of-plane forces are reacted inside the field-period of the supporting tube.
- The centering forces are reacted by a strong bucking cylinder ring in the center of the torus.
- Weight of the cold supporting tube has to be transferred to foundation by ~3 long legs each field-period. The legs have to be long enough to keep the heat ingress by thermal conduction into the cold system in tolerable limit.
- At least 4 strong warm legs are needed in each field-period to support the weight of blanket/shields and transfer the weight to foundation.
- The entire coil system of a field period has to be enclosed in a common cryostat.

Electromagnetic and Structural Analyses of the ARIES-CS Coils

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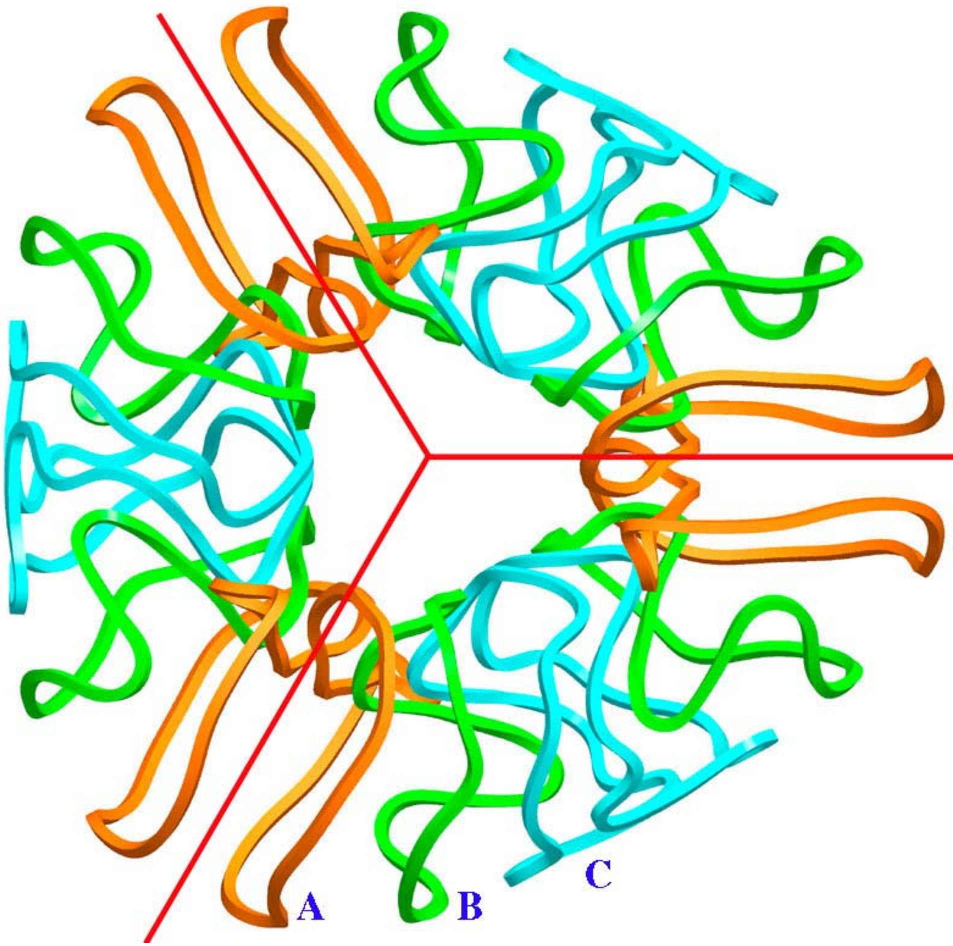
- The EM(electromagnetic) analysis to calculate magnetic flux density and magnetic forces in the modular coils.
- The structural analysis to evaluate the structural responses of the coil supporting tube and bucking cylinder.
- Considering threefold cyclic symmetry(three field-period), only the coils within a 120-degree region (one field-period) will be simulated.



FEA Model for EM Analysis

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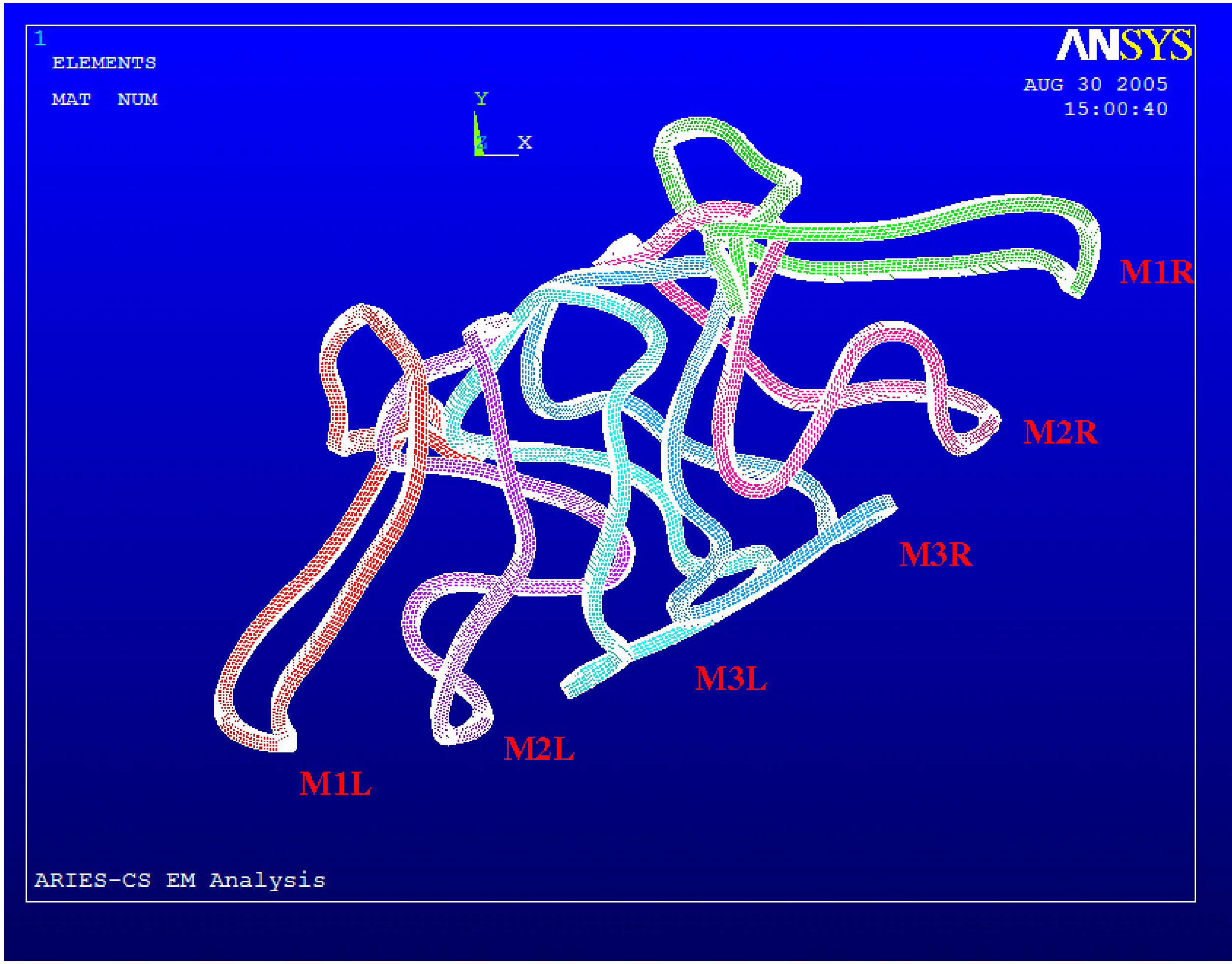
- Geometry of the modular coils are imported from Pro/E CAD modeling.
- The 6 coils are meshed by nearly 30000 Hexahedral elements and 45000 nodes.
- ANSYS SOLID5 is used in magnetic model, and the DOF including Ux, Uy, Uz, TEMP, VOLT, and MAG.



Example Results of EM Analysis: Current Density Distribution

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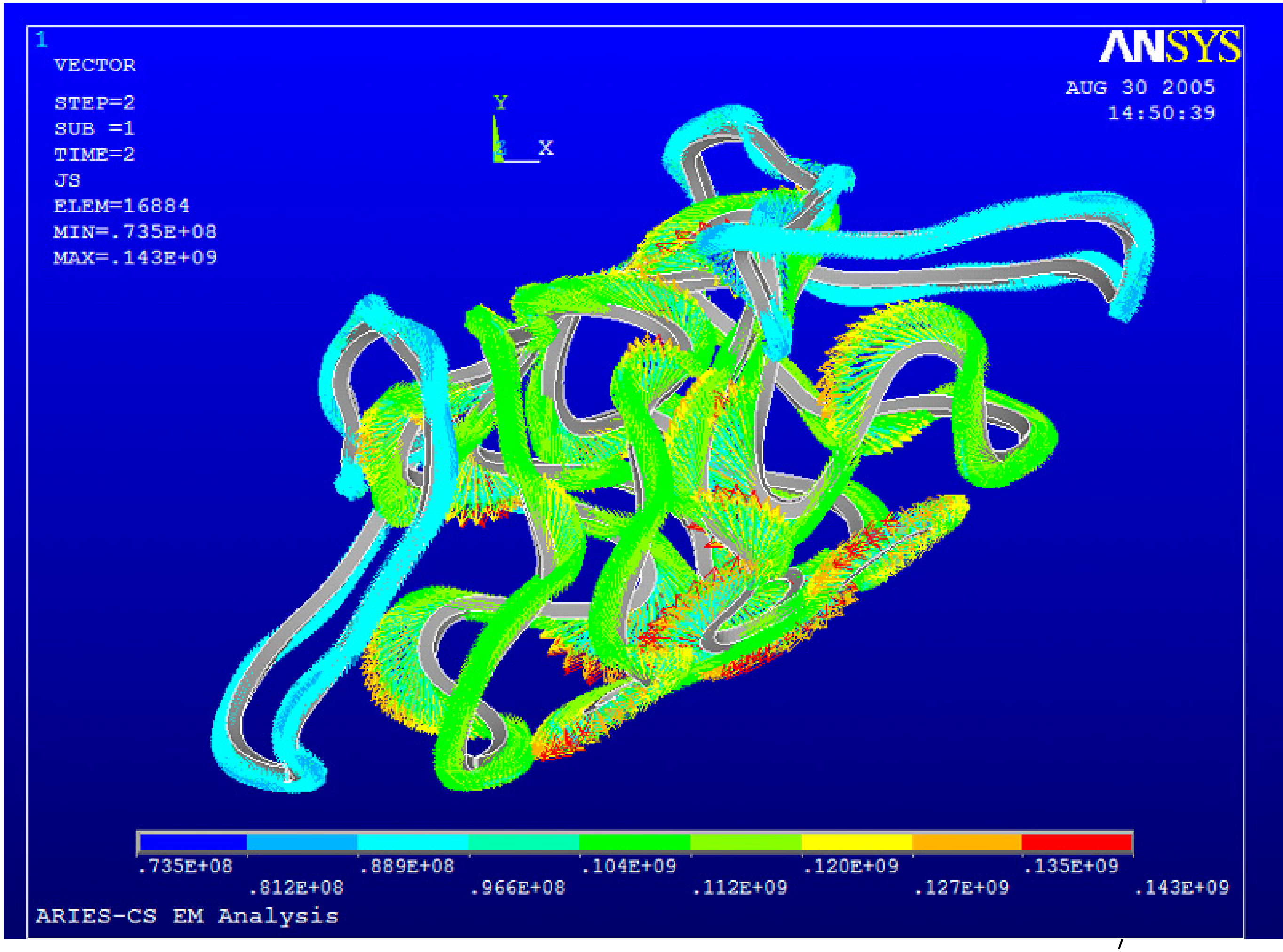
- Current density distributions are generated with electric analysis.
- The direction of currents is assumed to be the same in all modular coils.
- ***Example of currents: M1=10.1MA, M2=12.2MA, M3=12.2MA.***
- Plasma current is not included in the magnetic model.



Example Results of EM Analysis: Magnetic Flux Densities

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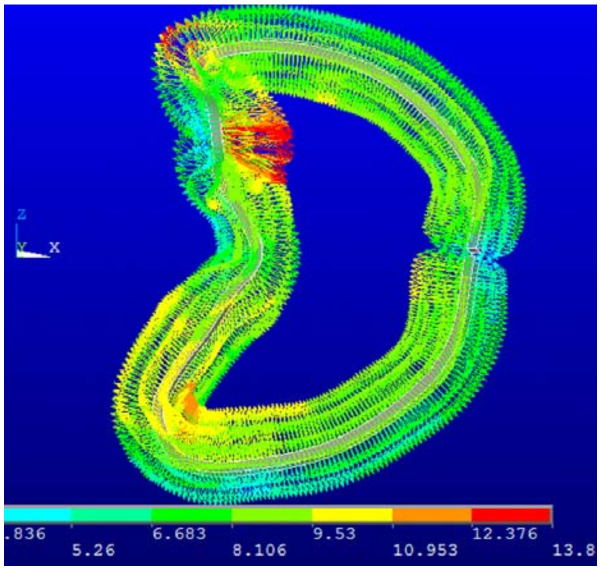
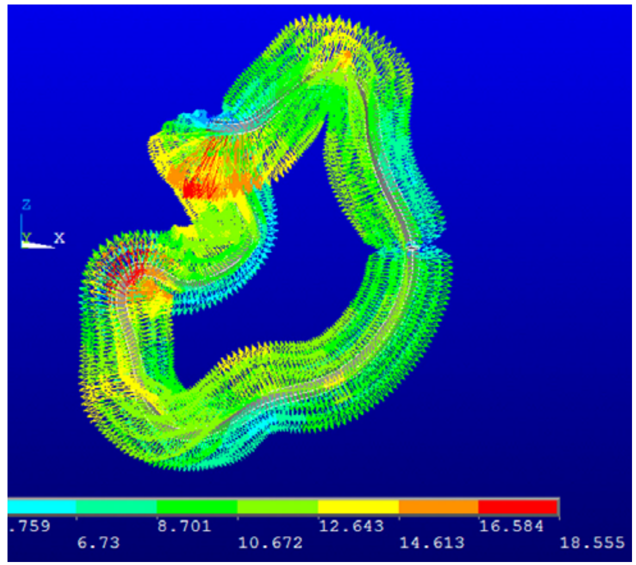
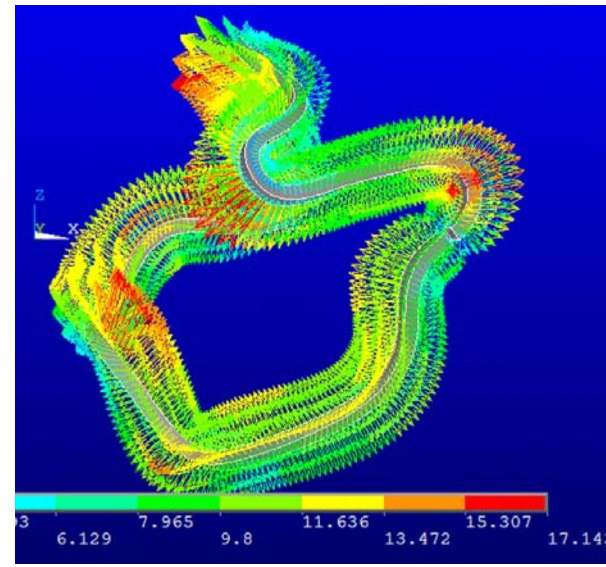


M1



M2



M3

- Local maximum magnetic flux densities were found in the modular coils where there are small bend radiuses of curvatures at winding pack.
- The local maximum magnetic flux density in the modular coils are: B(M1)=13.8 T, B(M2)=18.6 T, and B(M3)=17.1 T.
- Average magnetic flux density B(M1)~9.5T, B(M2)~11.6T, and B(M3)~10.7T

Example Results of EM Analysis: Magnetic Forces in M1's

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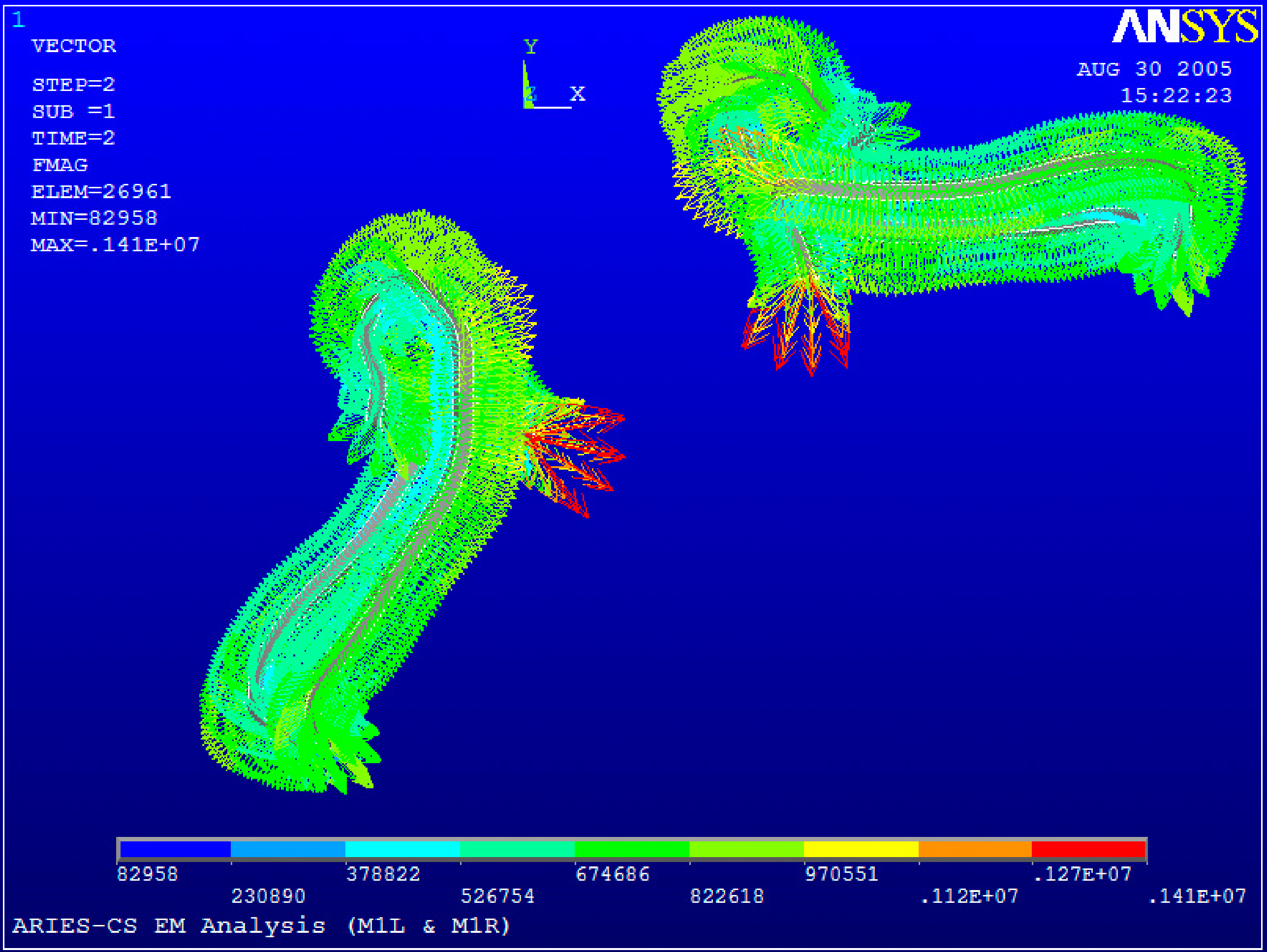
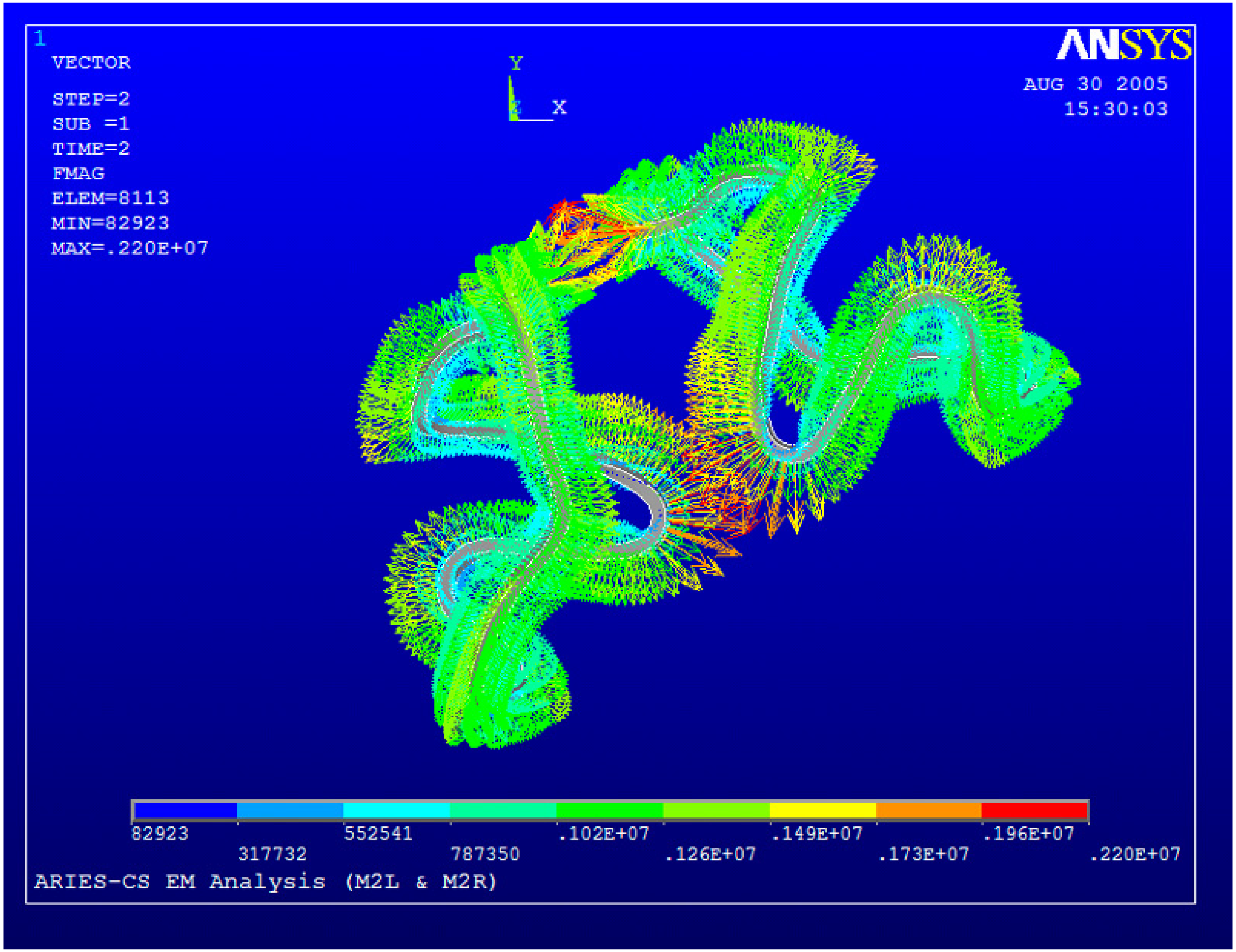
- The nodal forces vector plot shows a full symmetry for the pair of coils from the top view.

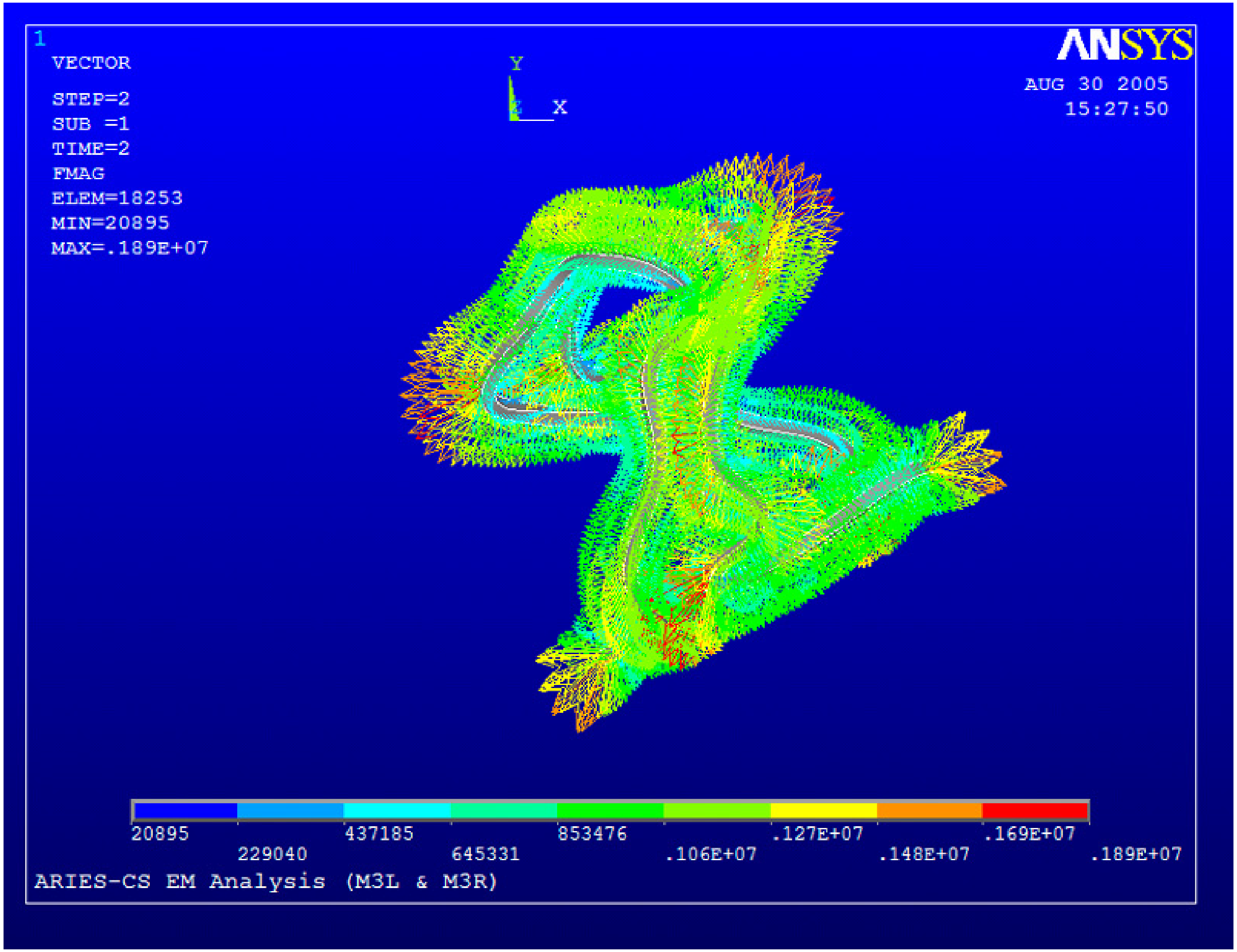
- The maximum magnetic forces are found in the modular coils where there are small bend radiuses of curvatures at winding pack.



Example Results of EM Analysis: Magnetic Forces in M2's



Example Results of EM Analysis: Magnetic Forces in M3's



Example Results of EM Analysis:Net Forces in the Modular Coils

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	F_r, MN	F_θ, MN	F_z, MN
M1R	-76.7	-24.6	5.9
M1L	-76.7	24.6	-5.9
M2R	-222.9	-73.6	101.9
M2L	-222.9	73.6	-101.9
M3R	125.6	-57.1	125.1
M3L	125.6	57.1	-125.1
Sum of all 6 coils	-348	0	0

Structural Analysis

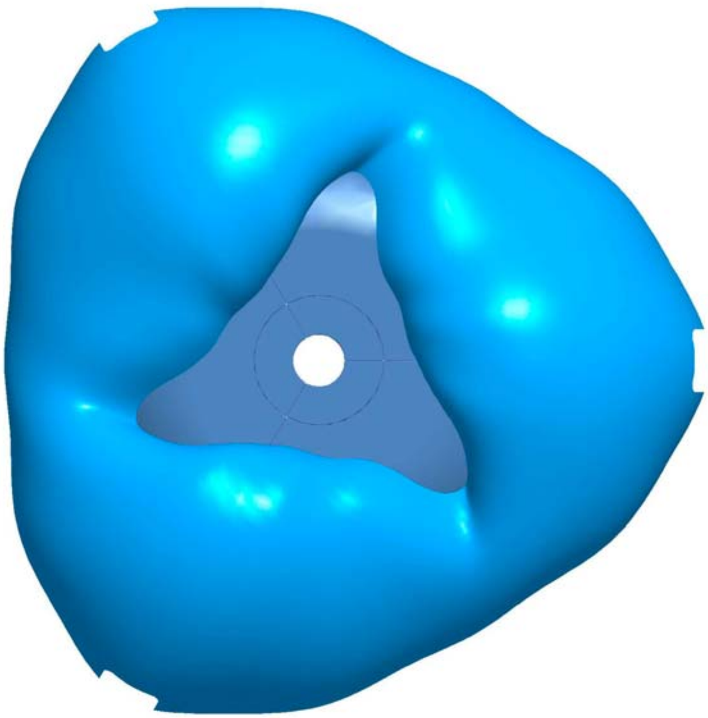
- An ANSYS FEA model for the structural analysis consists of the modular coils, the supporting tube with grooves, and the bucking cylinder ring.

- The nodal forces obtained from EM analysis will be applied in the structural analysis to evaluate:

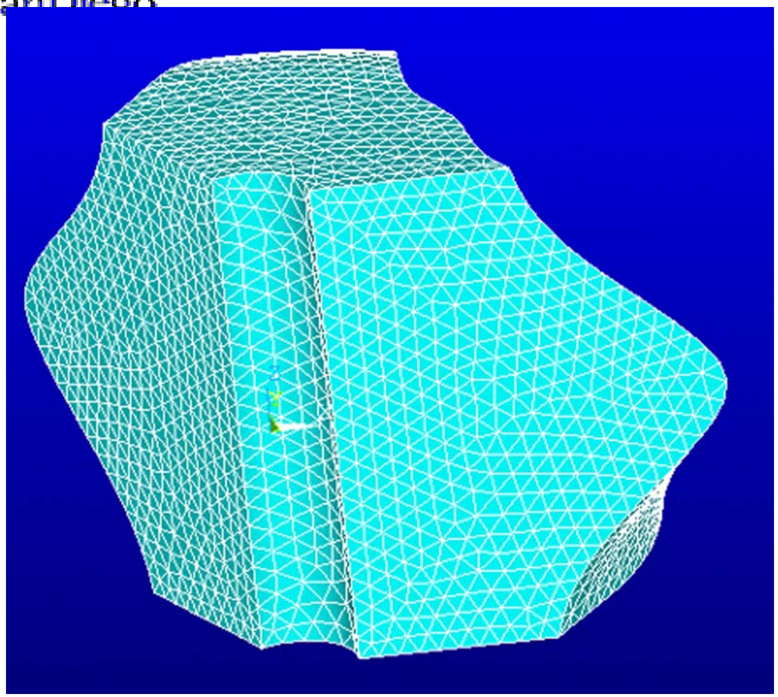
  -structural response of the supporting tube;

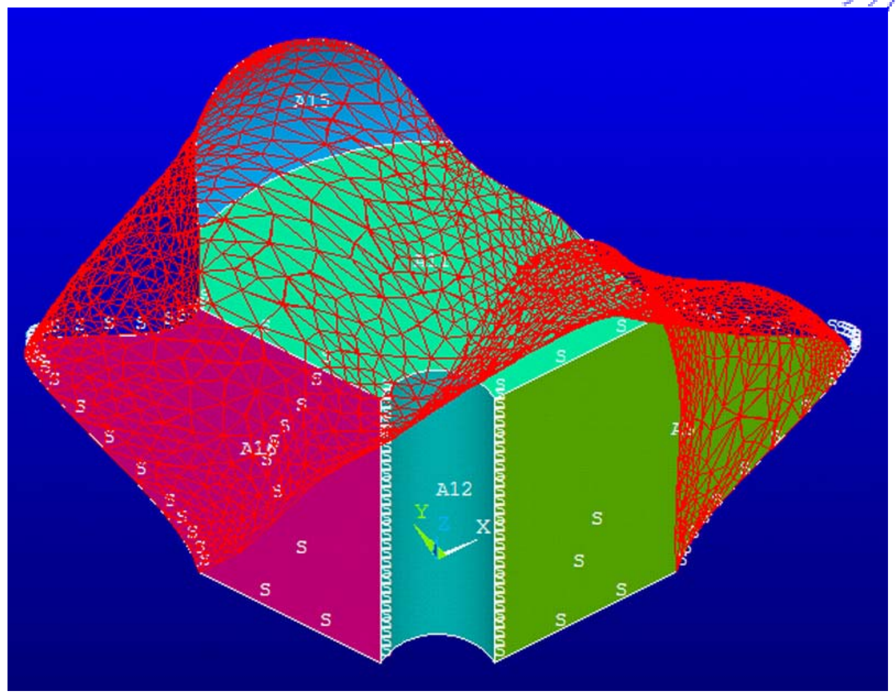
  -structural response of the bucking cylinder.

- ***Can we make an simple estimation to determine the stresses in the bucking cylinder caused by a net centering force from the modular coils before the final phase?***



Structural Analysis of the Bucking Cylinder





- The geometry of the bucking cylinder is imported from Pro/E.
- The contact area between the coil supporting tube and the bucking cylinder is calculated by Pro/E, S=117.5 m^2 for one field-period.
- The pressure on the bucking cylinder surface caused by the centering forces is about ~3 MPa.

Material Properties Used in ANSYS Structural Model*

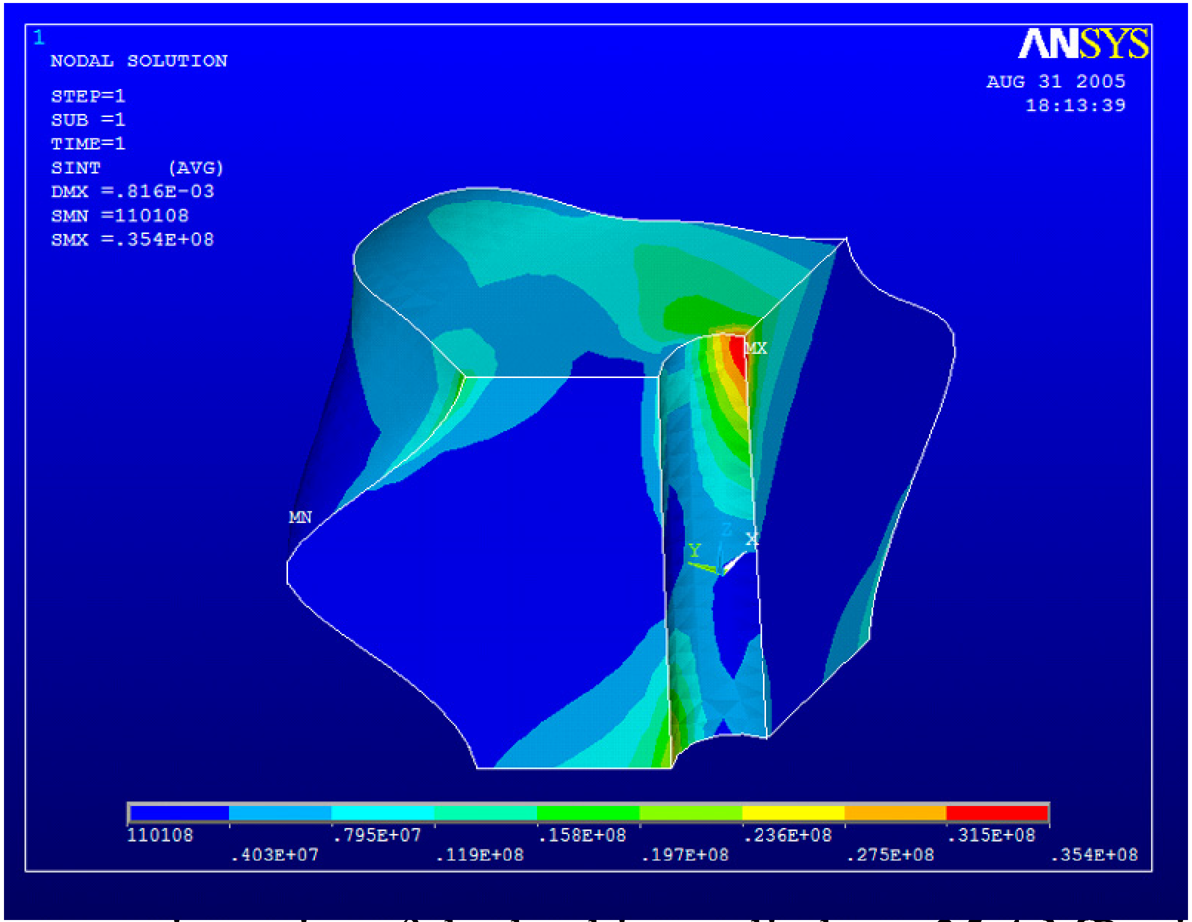
Material	316 SS cold worked
Average ultimate strength	745 MPa at 473 K
Average yield strength	670 MPa at 473 K
Modulus of elasticity	1.94×10^5 MPa
Poisson's ratio	0.3
Design stress	446 MPa at 473 K

- 316 SS is assumed to be the material of the both coil supporting tube and bucking cylinder to be operated at the cryogenic temperature.

- Mechanical properties at 473 K used as conservative assumption.

*** Data from SPPS Report**

Example of the Structural Analysis Results for Bucking Cylinder



- The maximum stress intensity of the bucking cylinder, ~35.4 MPa, is far less than the design stress of 466 MPa.
- The material amount of the bucking cylinder can be reduced by increasing the inner radius or opening some holes in it.

Summary

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- The maximum magnetic flux densities were found in the modular coils where there are small bend radius of curvatures at the winding pack.
- The results of EM analysis show that both the net vertical and toroidal forces of the 6 modular coils inside one field-period are zero, and there is only the net centering force with a magnitude of 348 MN.
- The maximum stress intensity at the bucking cylinder is far less than the design stress, therefore, we can reduce the material amount of the bucking cylinder by increasing the inner radius or opening some holes in it.
- The analysis confirms that the transfer of the centering forces between coil supporting tube and bucking cylinder is not possible between "cold" and warm element (Contact pressure of ~ 3 MPa by fare too high for any thermal insulator). The entire support structure has to be operated at cryogenic temperature.

Future Work

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- ***Plasma current(~3.35 MA) should be included in the magnetic model.***
- ***The structural analysis including the modular coils, coil supporting tube and bucking cylinder needs to be performed to evaluate the stress responses of the coil supporting tube and to decide the thickness of the supporting tube by applying the nodal forces directly from EM analysis results.***