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DUNE ND, 5-coil Magnet Baseline MPD Magnet Reference Design

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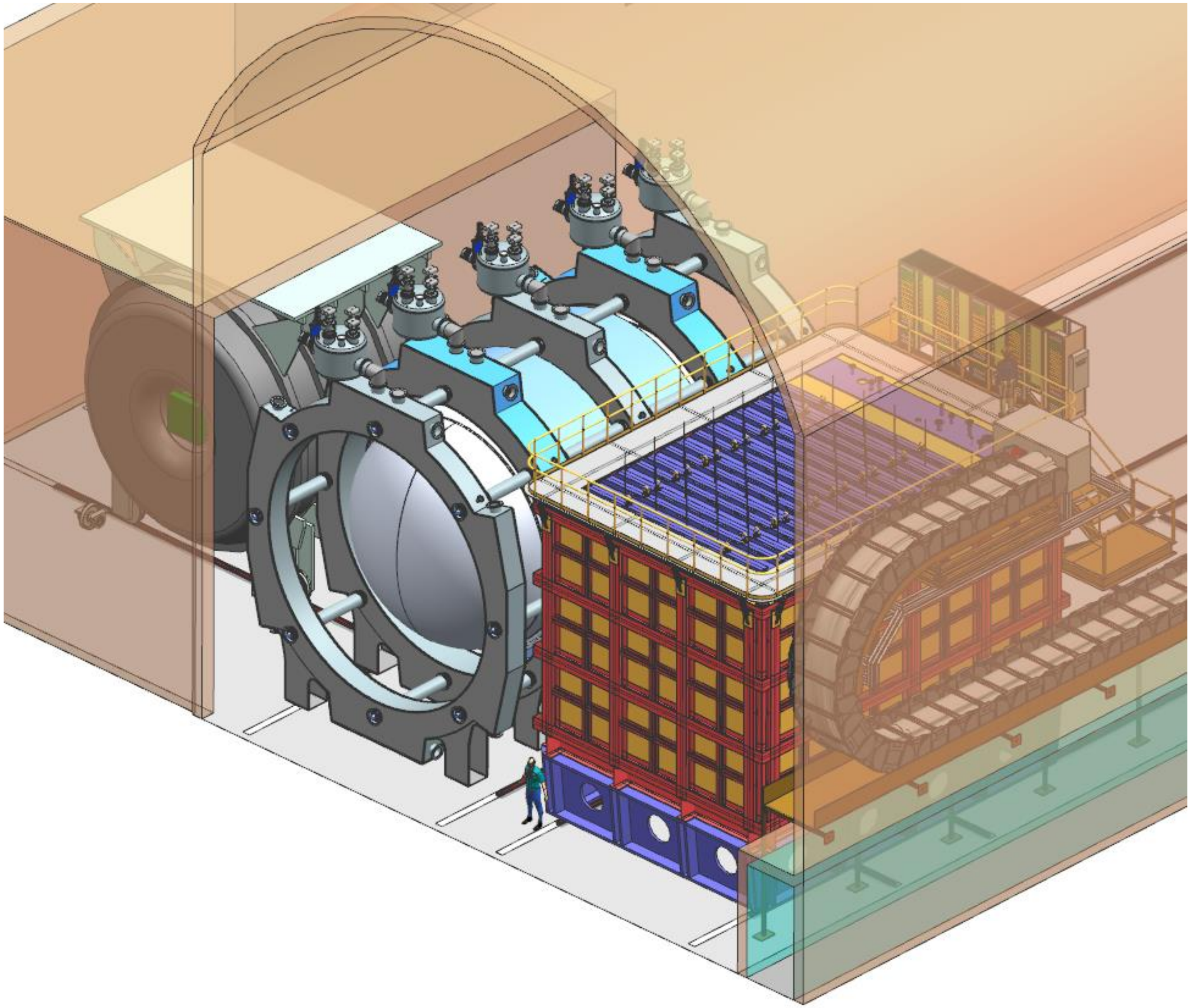
Outline

- Functional Requirement Specification
- Baseline design in ND hall
- CAD images of 5 coil design
- Coil structure
- Magnetic field
- Alternative design and yoke considerations
- Summary

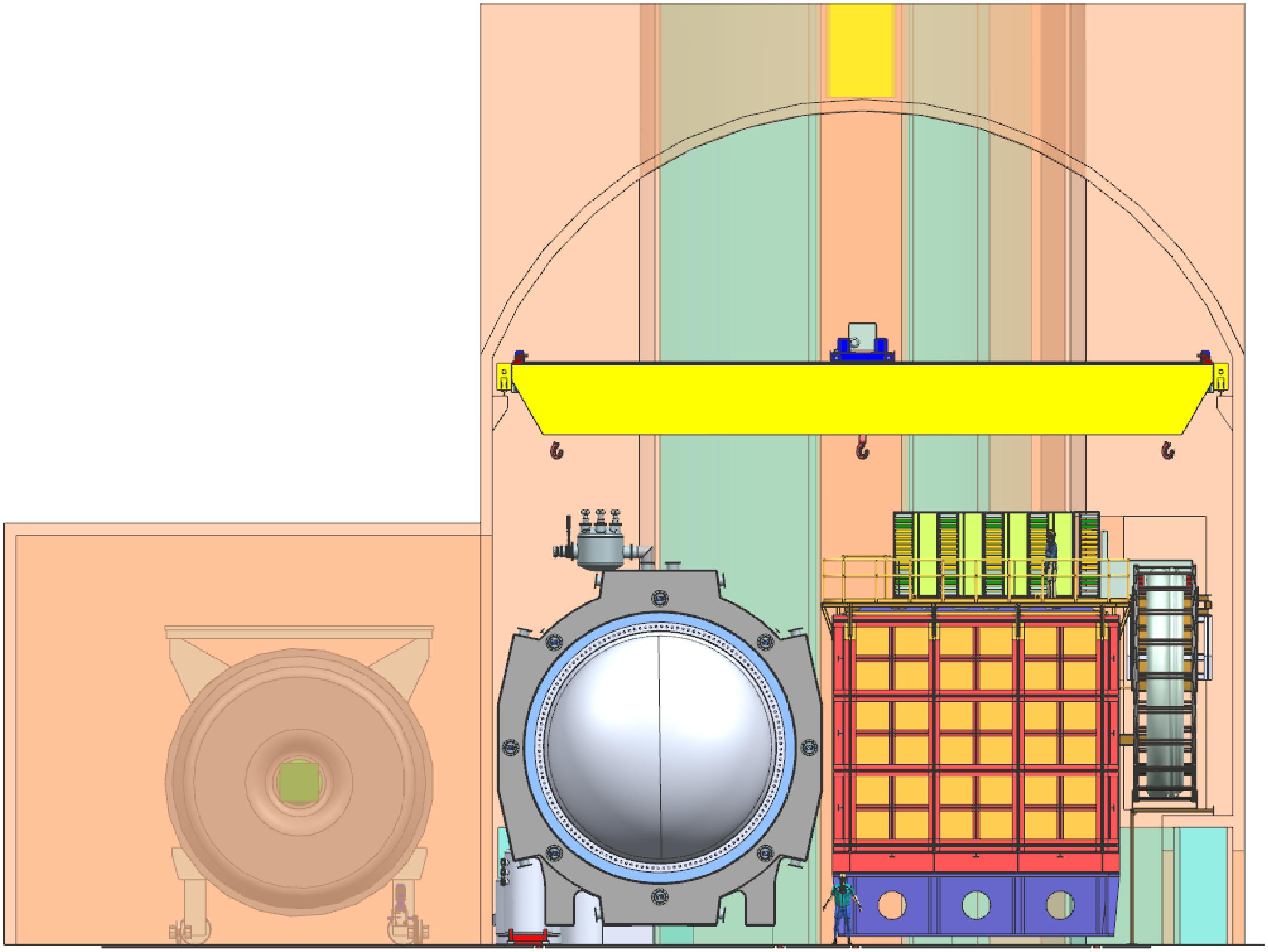
FSR: Summary

Parameter	Units	Value
Magnetic field configuration		Axial-Symmetric
Center peak field	T	0.5-0.7
Good field area diameter/length with the field homogeneity ± 10 %	m	4.0/4.0
The clear bore diameter for TPC	m	7.0
Maximum outer diameter	m	9.0
Maximum length	m	11.0
Superconductor type		NbTi
Preferable material for coils support structure		Aluminum
Superconducting coil operating temperature		≤ 5 K
Minimal distance between coil and strongback, helium piping to the cryostat wall	mm	200
Maximum coil deformation criterion	mm/m	1.7
Maximum vacuum jacket deformation criterion	mm/m	2
Positional Tolerance of the coils	mm	±5
Admissible bucking limit	MPa	120
Cooling source		Cryoplant

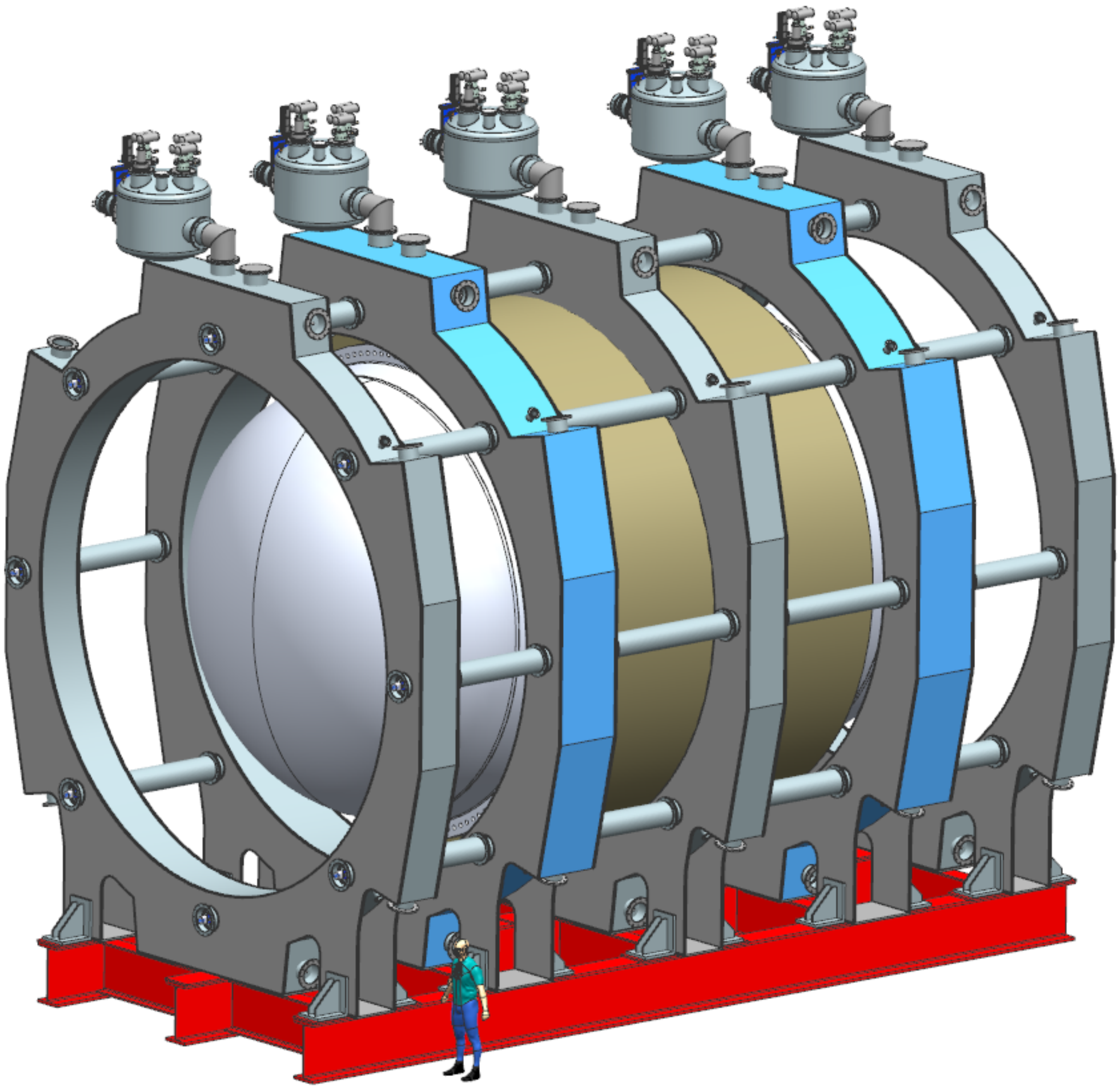
Baseline design in ND hall



Baseline design in ND hall



CAD images of 5 coil design



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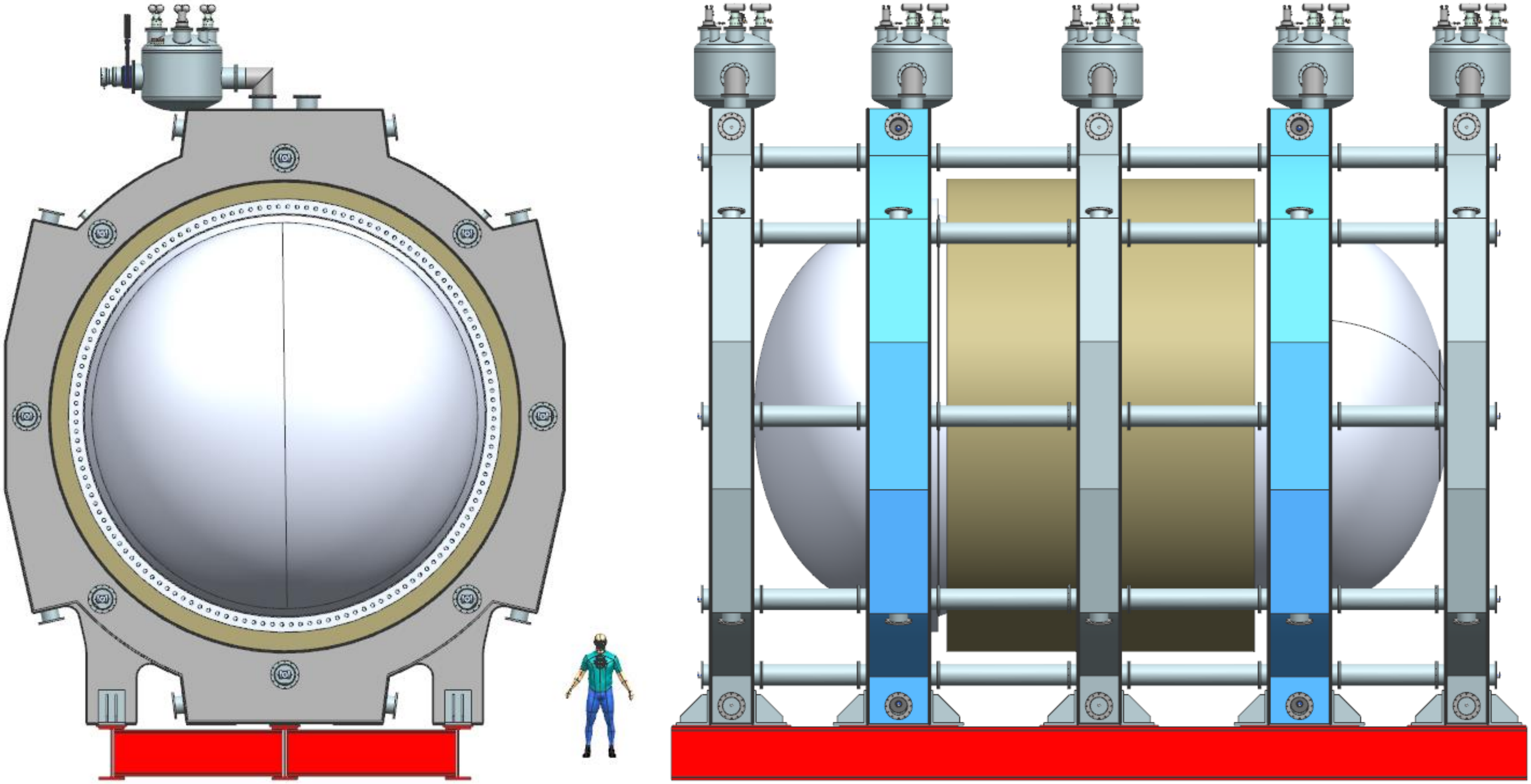
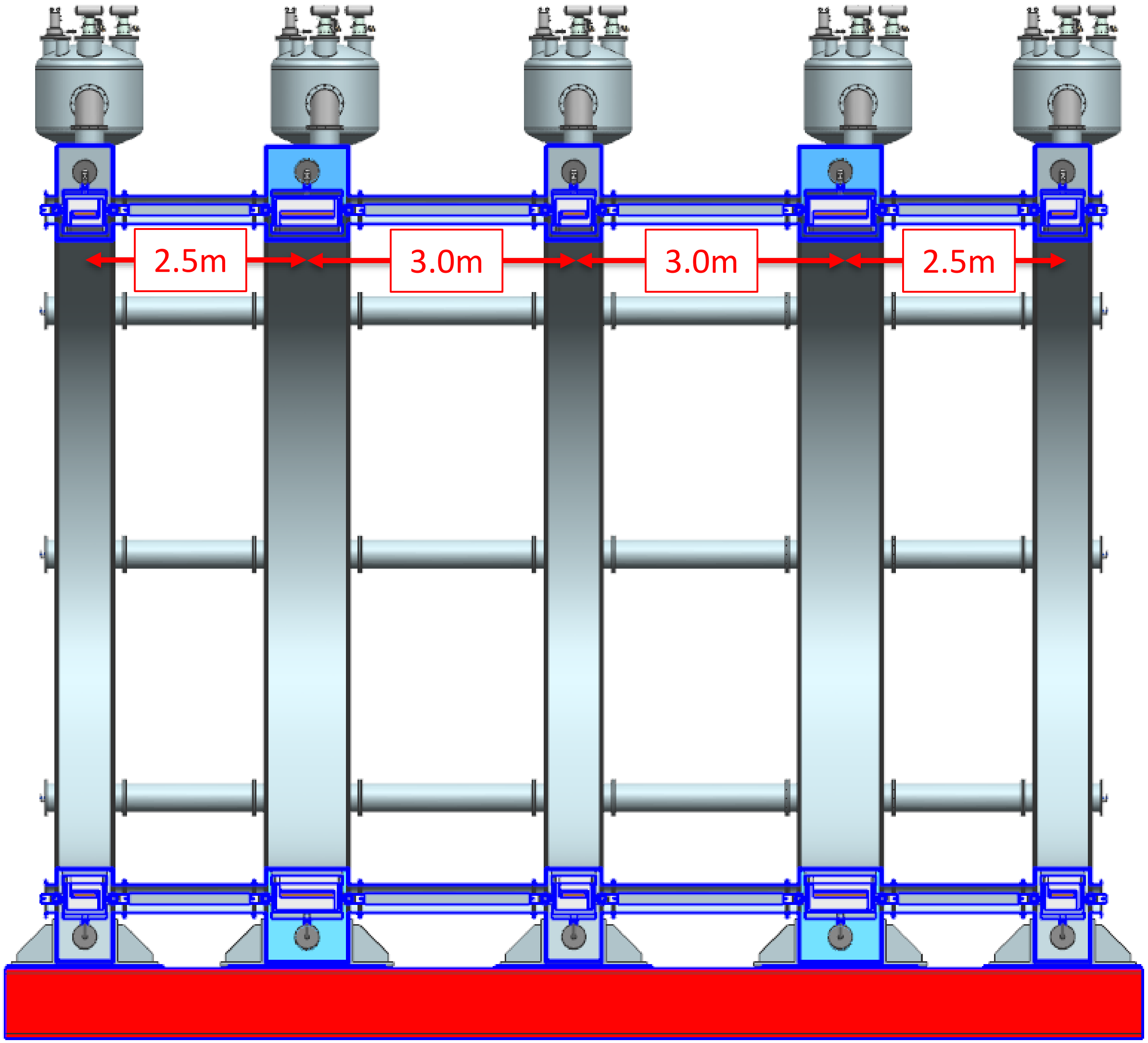
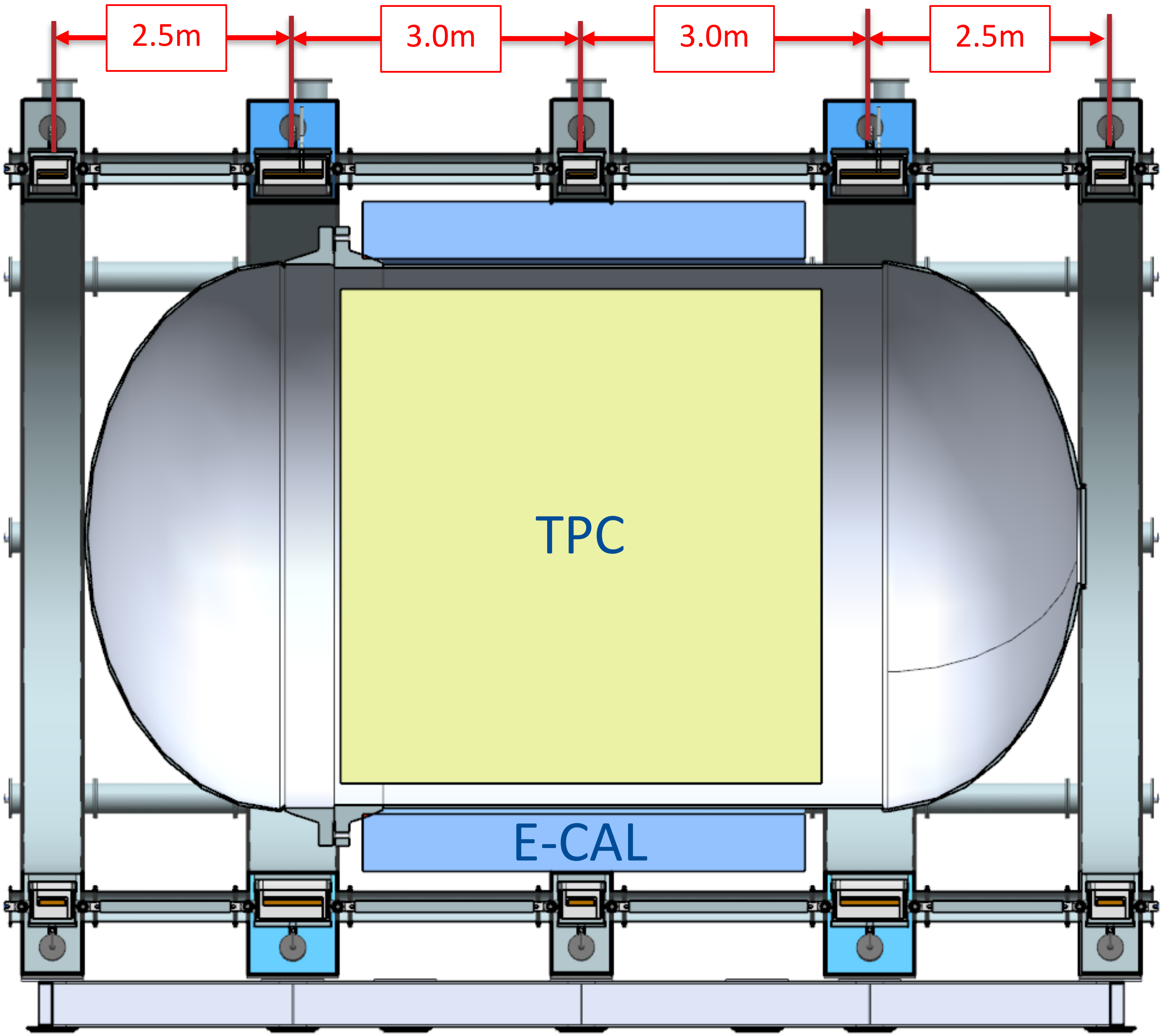


CAD images of 5 coil design

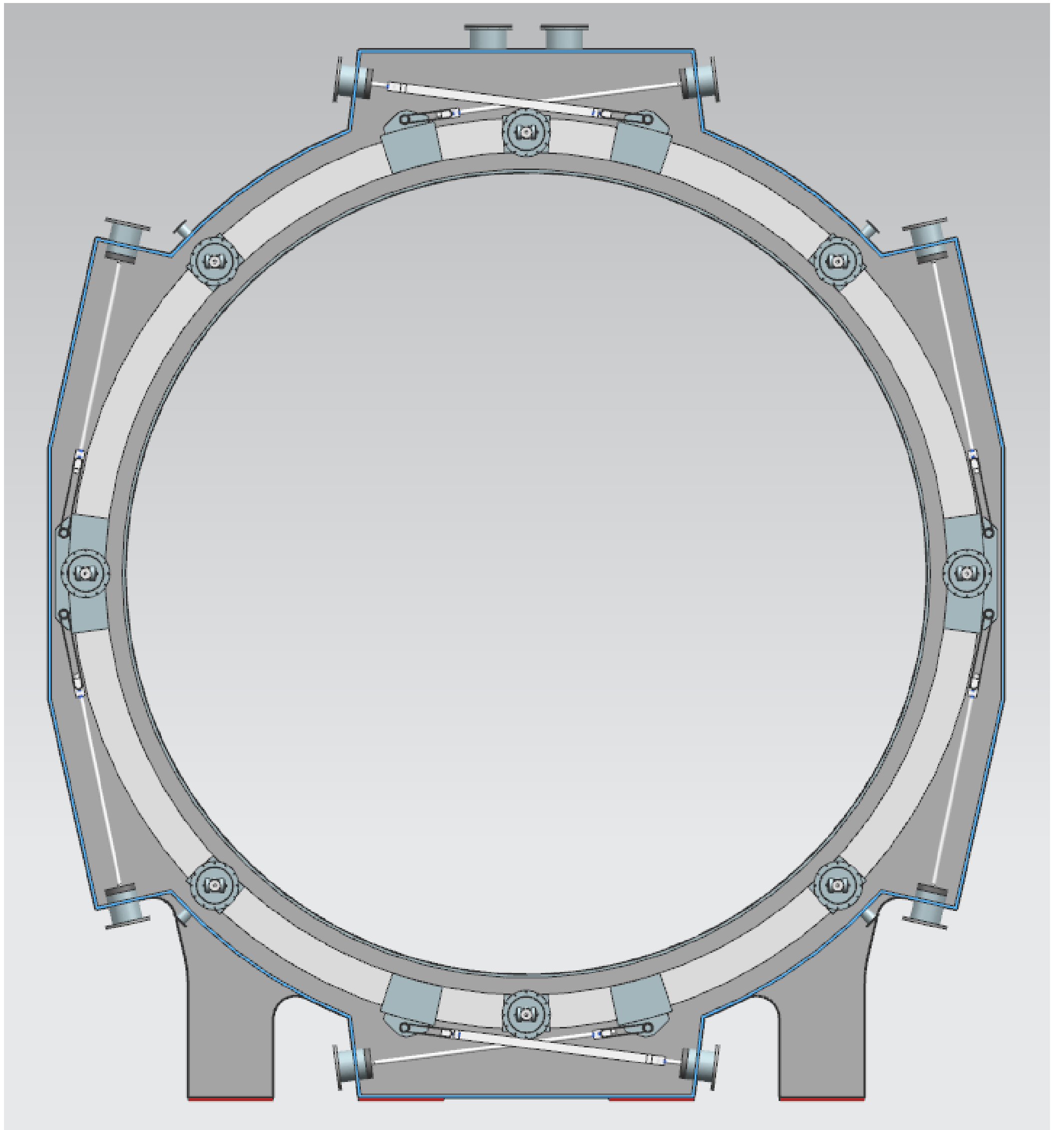


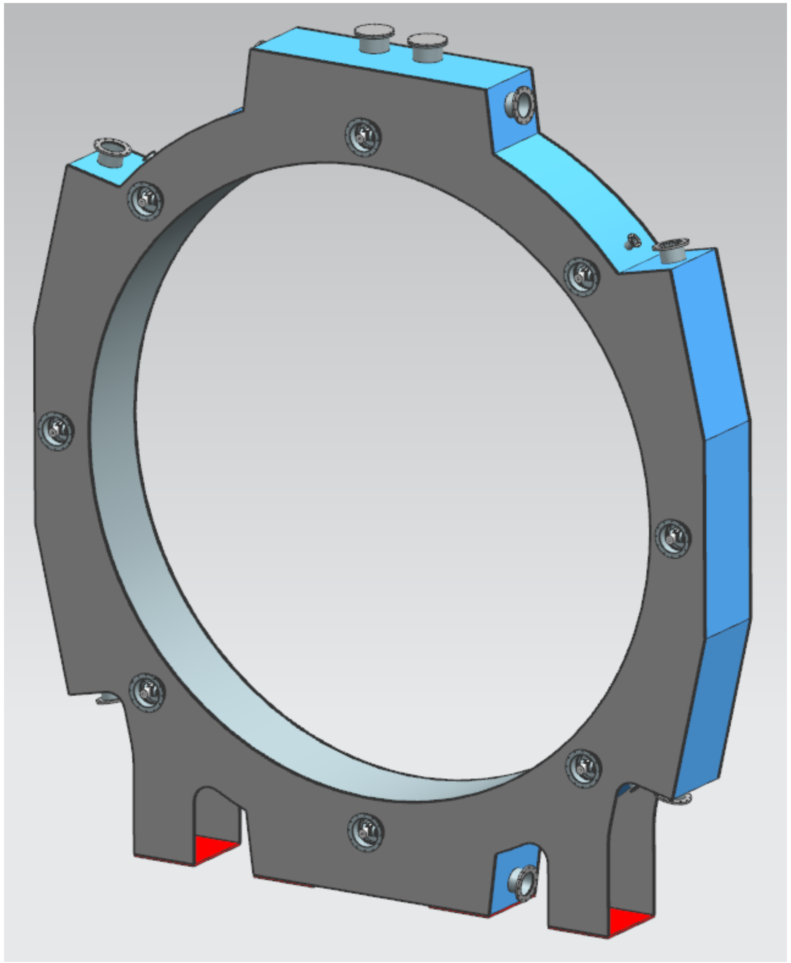
Baseline Development Model: Design Parameters



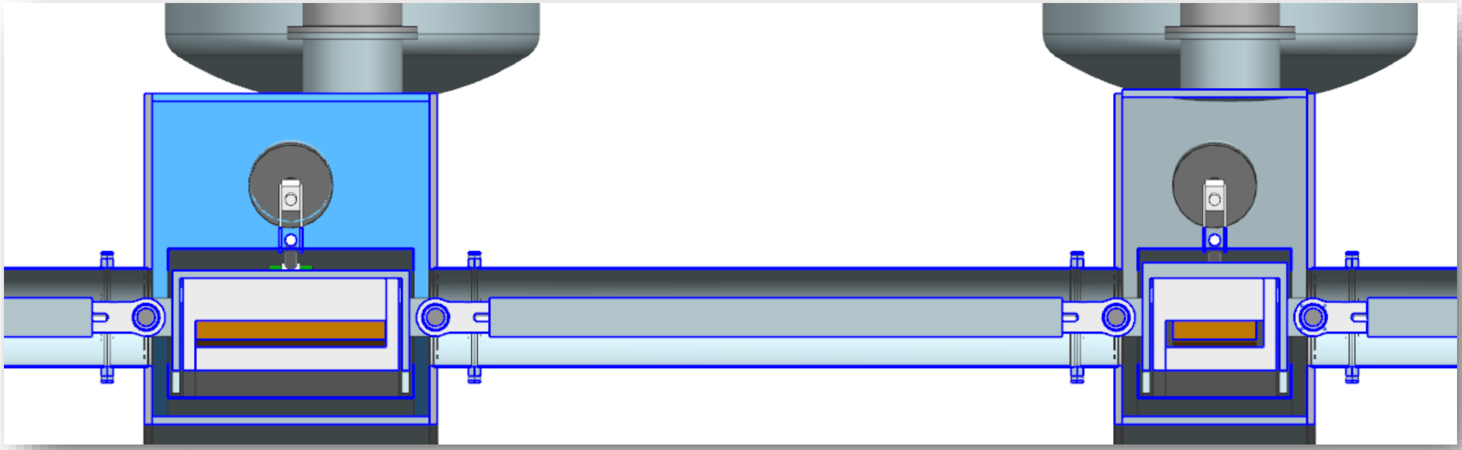
Coil Dimensions
- OD: 7724 mm
- ID: 7600 mm
- Width (x3): 270 mm
- Width (x2): 616 mm

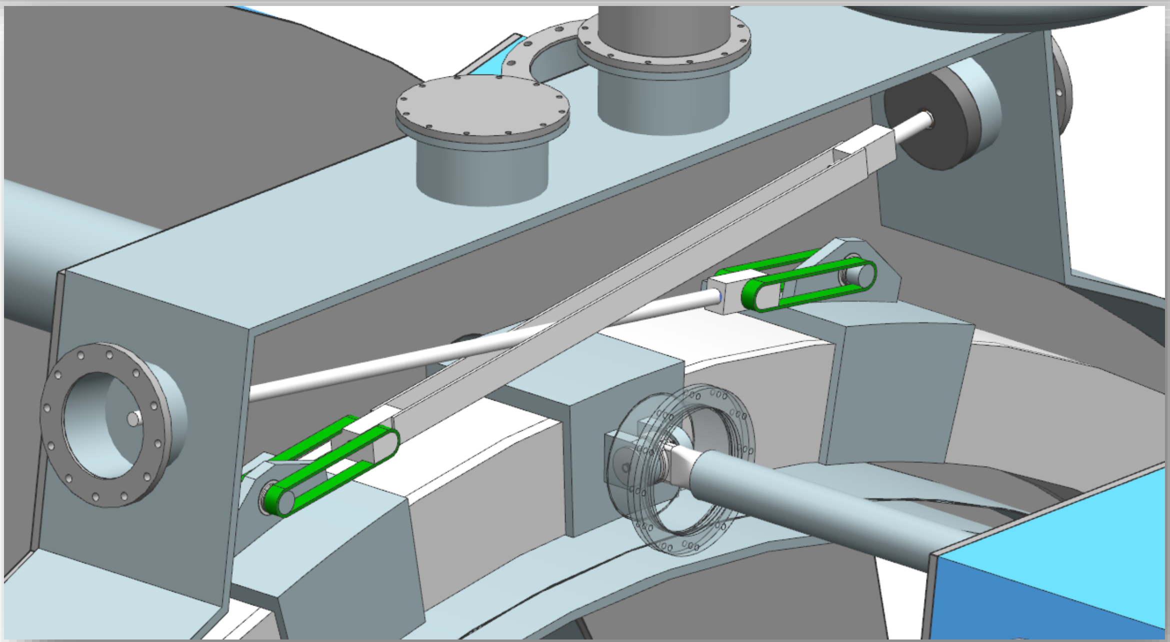
Side Coil CAD Development Model



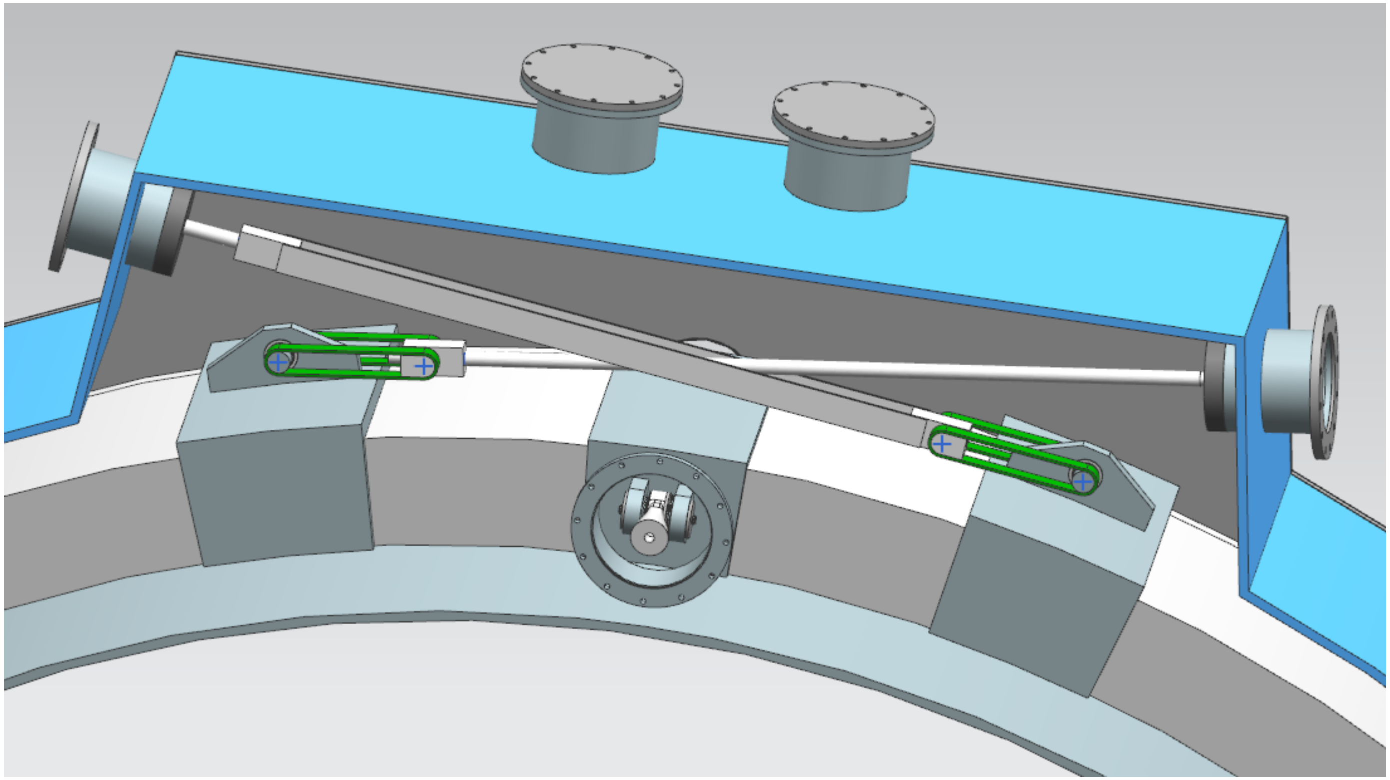


Baseline Development Model – *Cold* Stabilizing Rods

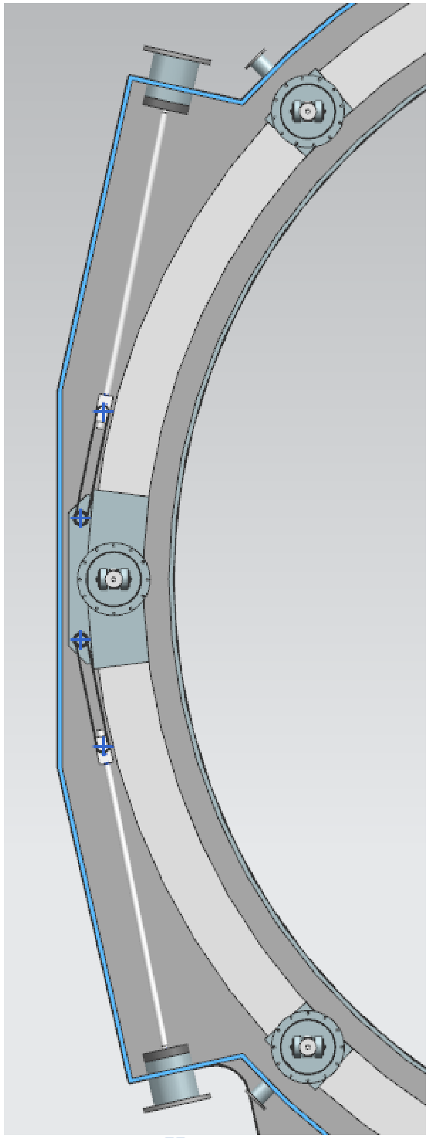




Typical Support Rod Concepts



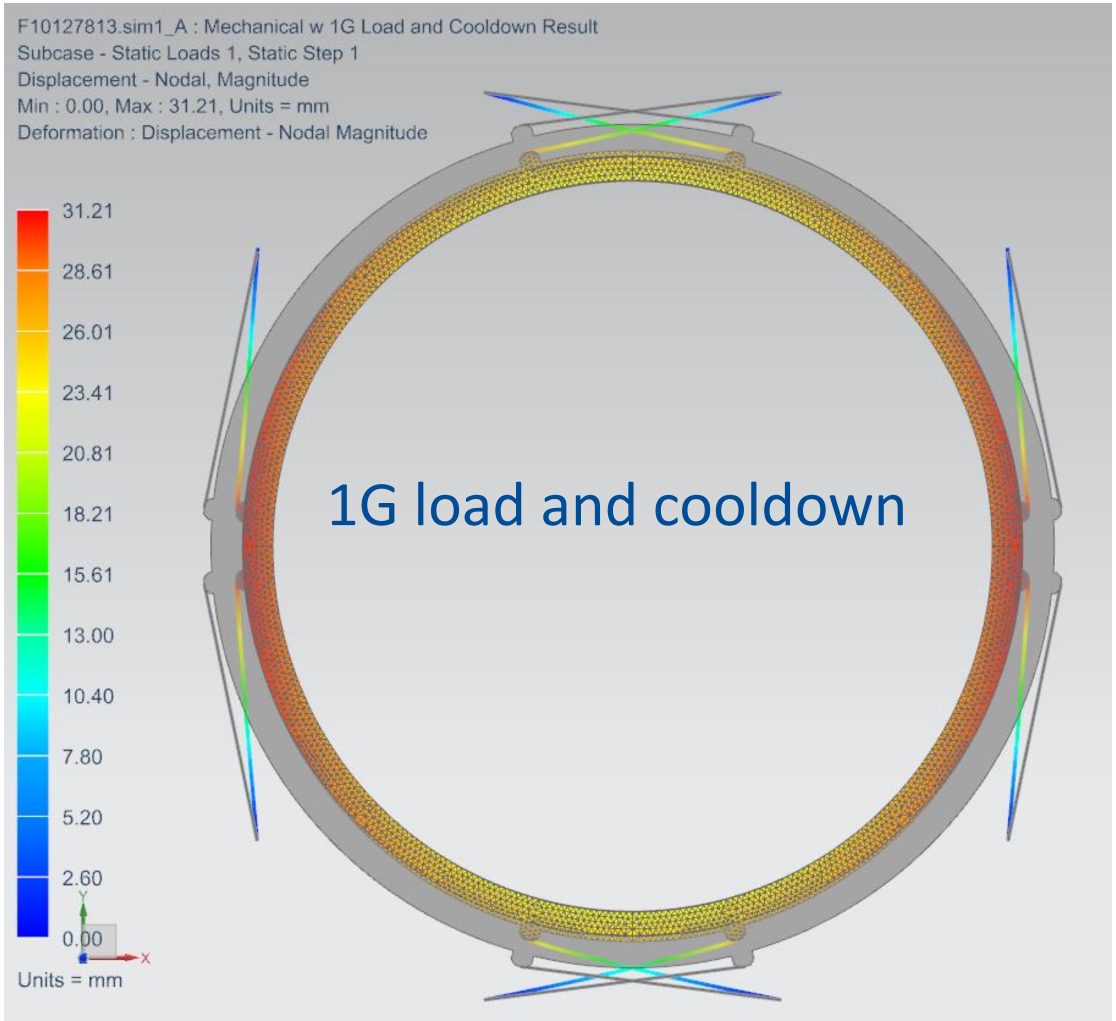
Side-to-Side Support Rods



Vertical Support Rods

Mechanical structure analysis: Analysis Approach

All of this in detail with Don in "Mechanical Design Issues"

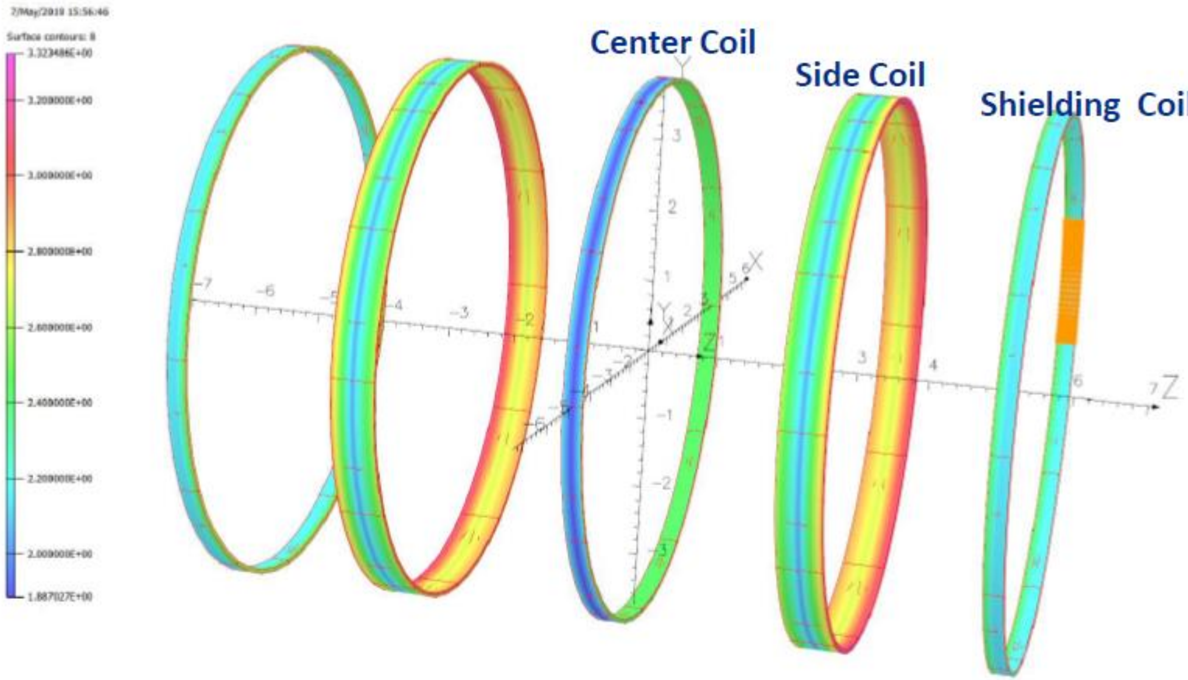


Five Coils Field (CDR)

Parameter	Units	Center coil	Side coil	Shield coil
Number of coils		1	2	2
Coil ampere-turns	MA	1.08	2.46	1.08
Coil peak field	T	2.53	3.32	2.72
Coil inner radius	m	3.8	3.8	3.8
Coil outer radius	m	3.862	3.862	3.862
Coil width along	m	0.27	0.616	0.27
Coil position in Z	m	0	3.0	5.5
Lorentz force in Z	MN	0	8.17	4.49

Stored energy 109 MJ, coil peak field 3.3 T, center field 0.5 T

Baseline Development Model: Design Parameters



Peak coil fields: 2.53 T (center), 3.32 T (side) 2.72 T (shield).

Total stored energy 109 MJ

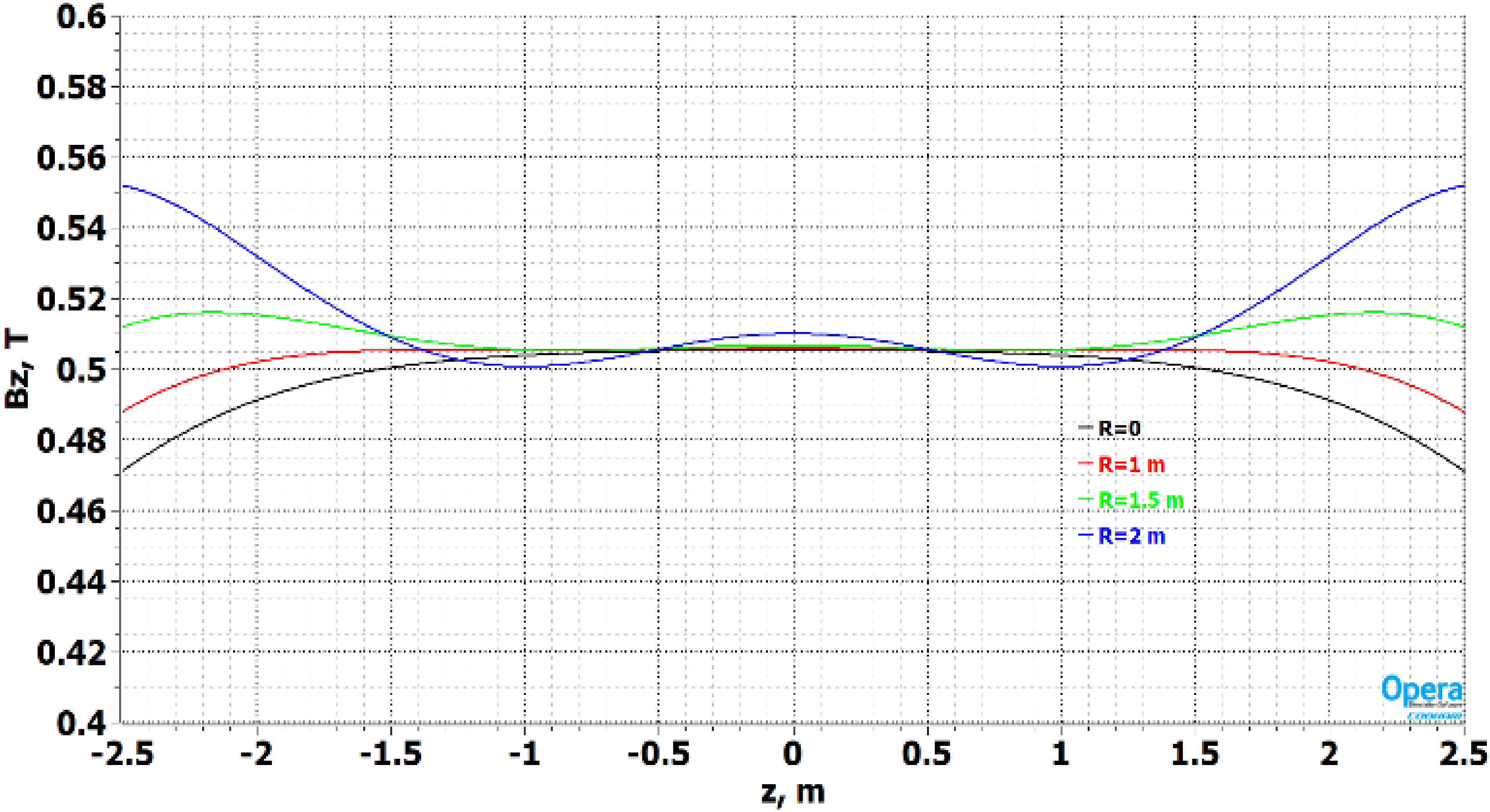
Forces Fz : 0.0 (center), - 8.2 MN (side), 4.5 MN (shield).

Side coils at 3.0 m, shielding coils placed at 5.5 m from the magnet center in Z.

All coils have the same inner radius 3.8 m and outer radius 3.862 m.

Center and shielding coils are identical and have the same number of ampere-turns

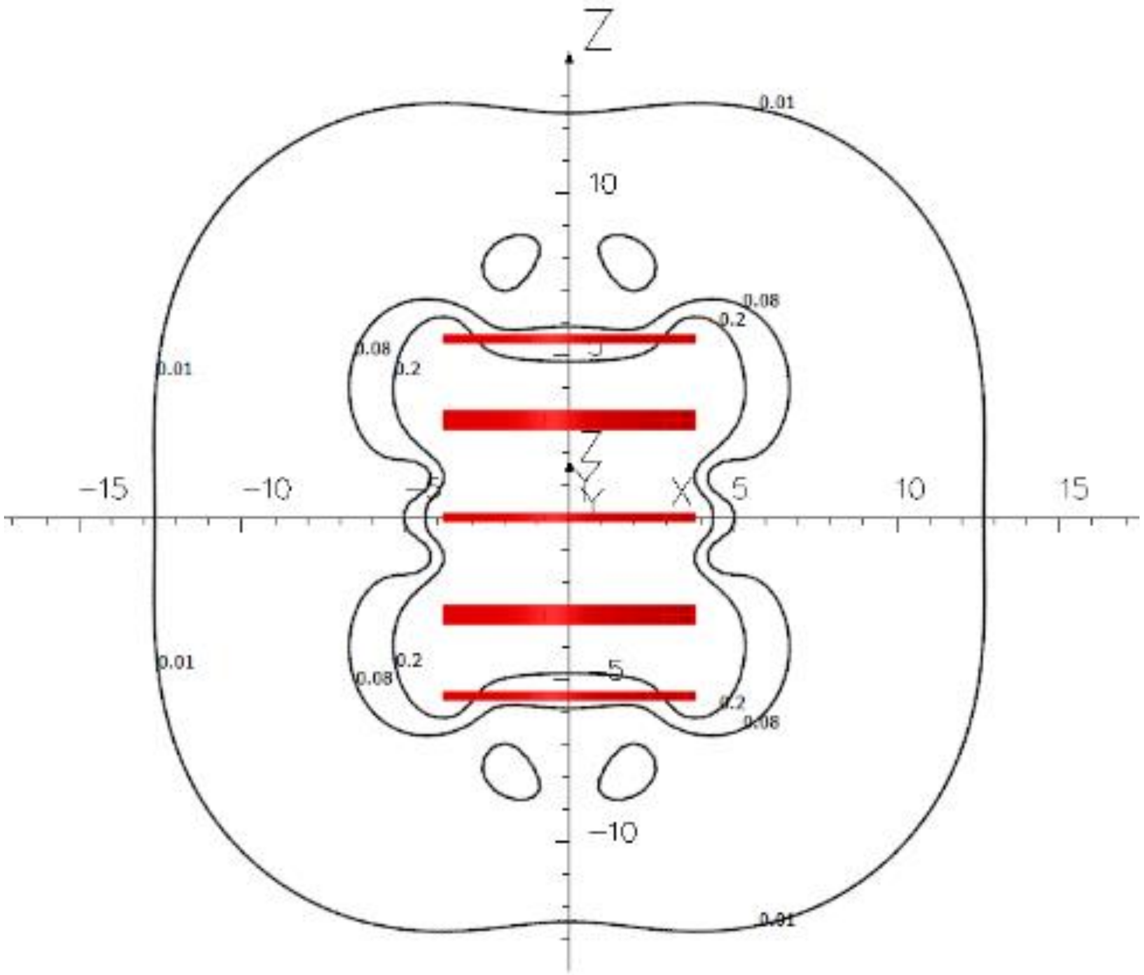
Five Coils Field (CDR)



Stored energy 109 MJ, coil peak field 3.3 T, center field 0.5 T

Fermilab

Five Coils Field (CDR)



Stored energy 109 MJ, coil peak field 3.3 T, center field 0.5 T

Baseline Development Model: Design Parameters

Coils	N	Iw MA	Bmax T	Rin m	Rou m	Zc m	Width m
Center	1	1.08	2.53	3.8	3.862	0	0.27
Side	2	2.46	3.32	3.8	3.862	3.0	0.616
Shield	2	1.08	2.72	3.8	3.862	5.5	0.27
Total	5	8.16	-				

*Coil dimensions for the 10 kA operating current and without support structure.

N – number of coils;

Iw- coil ampere-turns;

Bmax – peak field on the coil;

Rin, Rou – inner and outer coil radiuses;

Zc – coil center distance;

Width – coil width.

Baseline Development Model: Design Parameters

Lorentz Forces

N	Coil	Iw MA	Fz MN	Iw MA	Fz* MN	Iw MA	Fz** MN
1	Shield	1.08	-4.491	0	0	1.08	-0.647
2	Side	-2.46	8.17	-2.46	4.327	0	0
3	Center	-1.08	0	-1.08	-0.404	-1.08	2.908
4	Side	-2.46	-8.17	-2.46	-8.476	-2.46	-6.446
5	Shield	1.08	4.491	1.08	4.552	1.08	4.186

N – coil number;

Iw- coil ampere-turns;

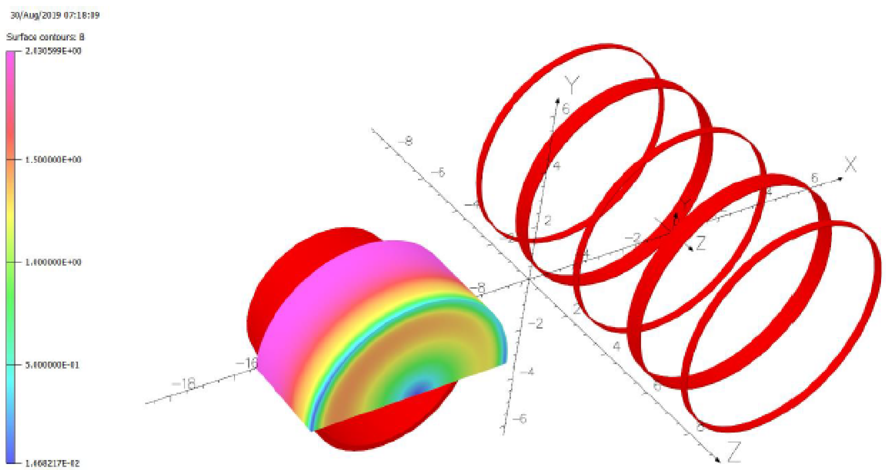
Fz – Lorentz force on the coil when all coils powered;

*Fz – Lorentz force on the coil when all coils powered besides one shield coil;

**Fz – Lorentz force on the coil when all coils powered besides one side coil;

Baseline Development Model: Design Parameters

ND and KLOE Magnets Interaction



N	Coil	Iw MA	Fz MN	Fx kN
1	Shield	1.08	-4.39	-160
2	Side	-2.46	8.29	14
3	Center	-1.08	0	476
4	Side	-2.46	-8.29	14
5	Shield	1.08	4.39	-160
KLOE	Solenoid	-2.17	0	- 7.1

KLOE iron is saturated up to 2 T at the nominal operational center field 0.6 T.

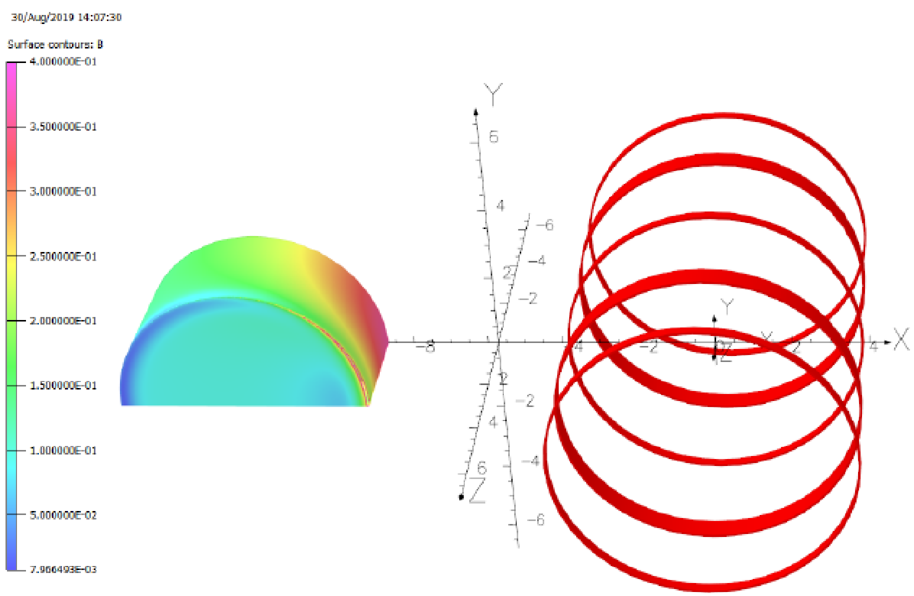
Horizontal force between magnets (on ND coils) is 183 kN.

Horizontal force on KLOE solenoid is – 7.1 kN.

Fermilab

Baseline Development Model: Design Parameters

ND and KLOE Magnets Interaction



N	Coil	Iw MA	Fz MN	Fx kN
1	Shield	1.08	-4.38	-164
2	Side	-2.46	8.28	23
3	Center	-1.08	0	485
4	Side	-2.46	-8.28	23
5	Shield	1.08	4.38	-164
KLOE	Solenoid	0	0	0

KLOE iron max field from ND is 0.4 T at zero current in KLOE solenoid.

Horizontal force between magnets (on ND coils) is 202 kN.

Horizontal force on KLOE solenoid is zero.

Field summary

Parameter	Units	CDR
Center field	T	0.5
Coil ID	m	7.6
Distance between coils	m	N/A
Total ampere-turns	MA	8.16
Stored energy	MJ	109

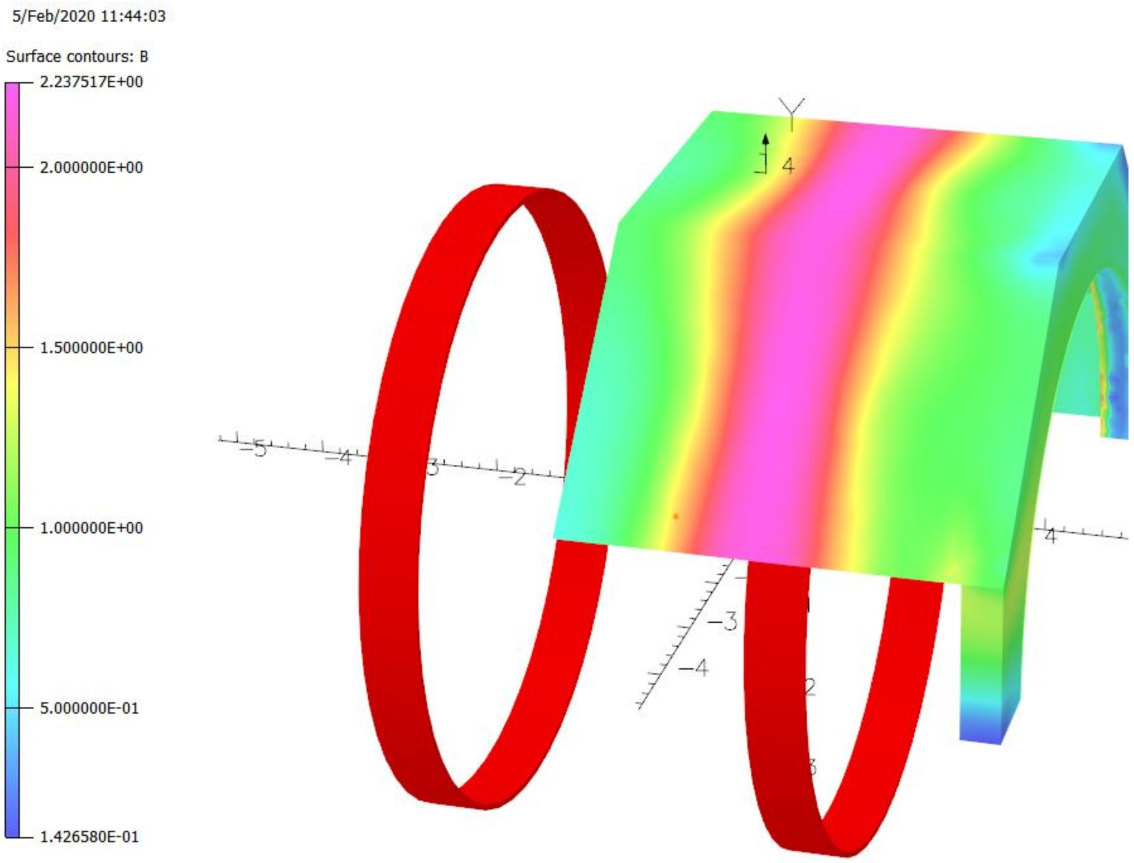
CDR- 5 coils, no iron yoke.

Alternative design and yoke considerations

- To evaluate the influence of a partial return yoke, three variants were analyzed
- We removed the center and shielding coils, keeping only the two relevant coils (Helmholtz like). This will change the center uniformity wrt to the 5 coil case presented earlier.
  - Case V1 – simply remove the three coils
    - Yoke thickness 0.4 m, length 8.8 m, distance between coil centers 4 m
  - Case V2 – decrease coil distance to match TPC dimension
    - Yoke thickness 0.4 m, length 8.8 m, distance between coil centers 3.6 m
  - Case V3 – reduced tracker volume
    - Yoke thickness 0.4 m, length 5 m, distance between coil centers 3.6

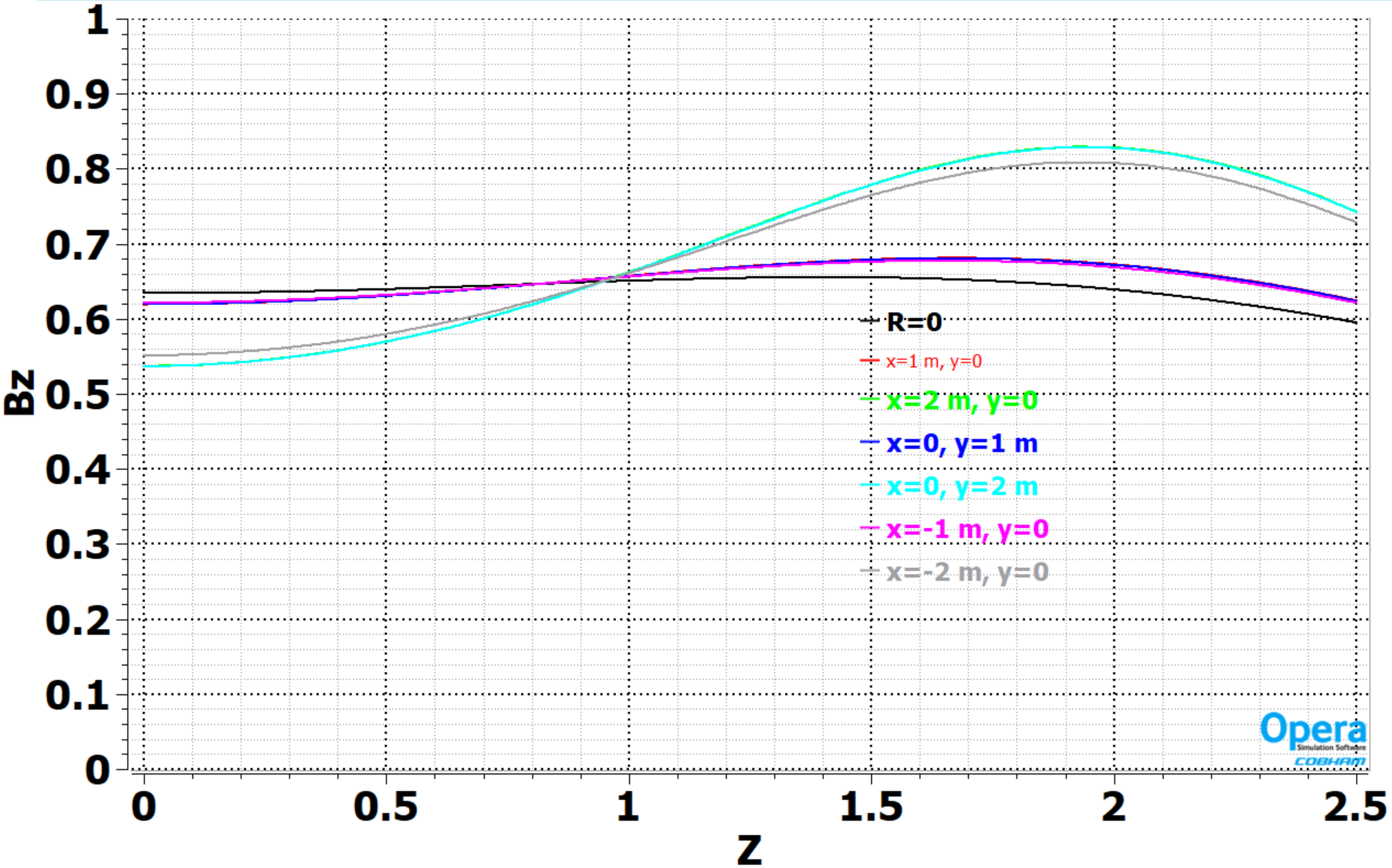
*Actual yoke would be smaller, as only three layers of 15 cm thick iron are within the 40 cm volume.

Two Coils with Octagonal Yoke (V1)



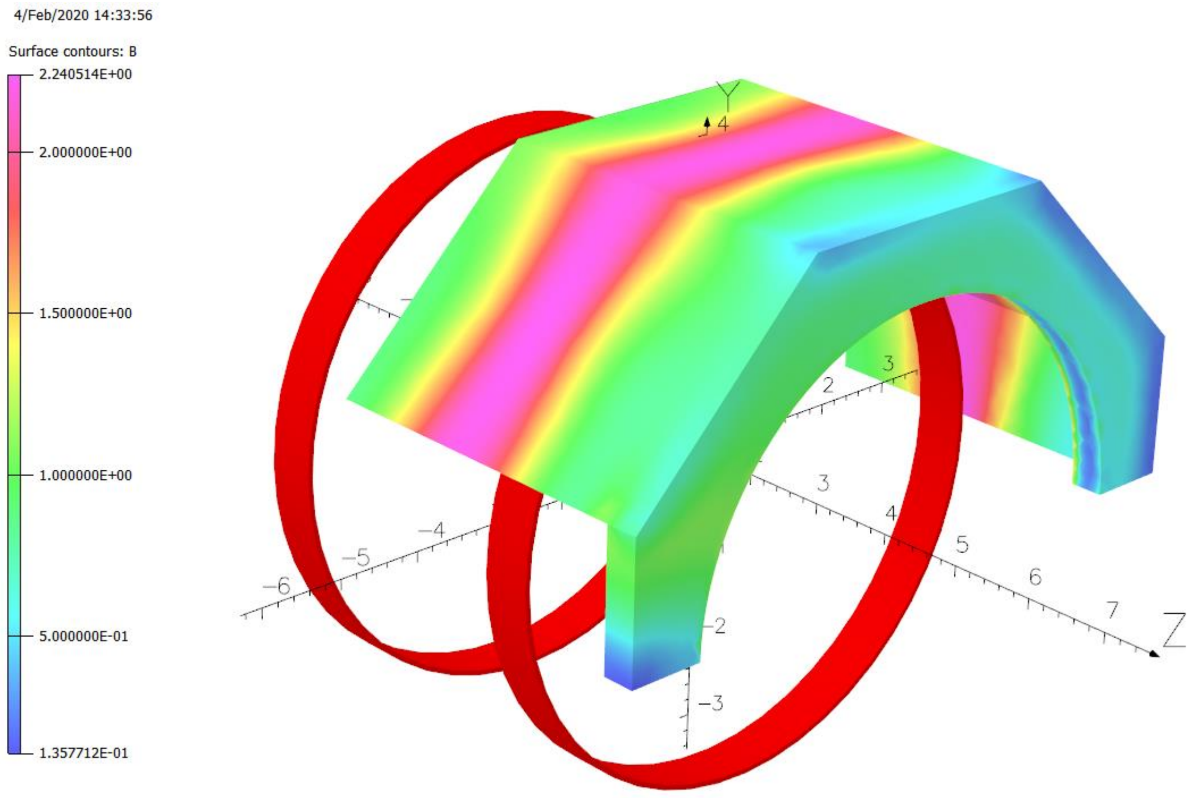
Yoke thickness 0.4 m, length 8.8 m, distance between coil centers 4 m.

Bz Field in the Magnet Bore (V1)



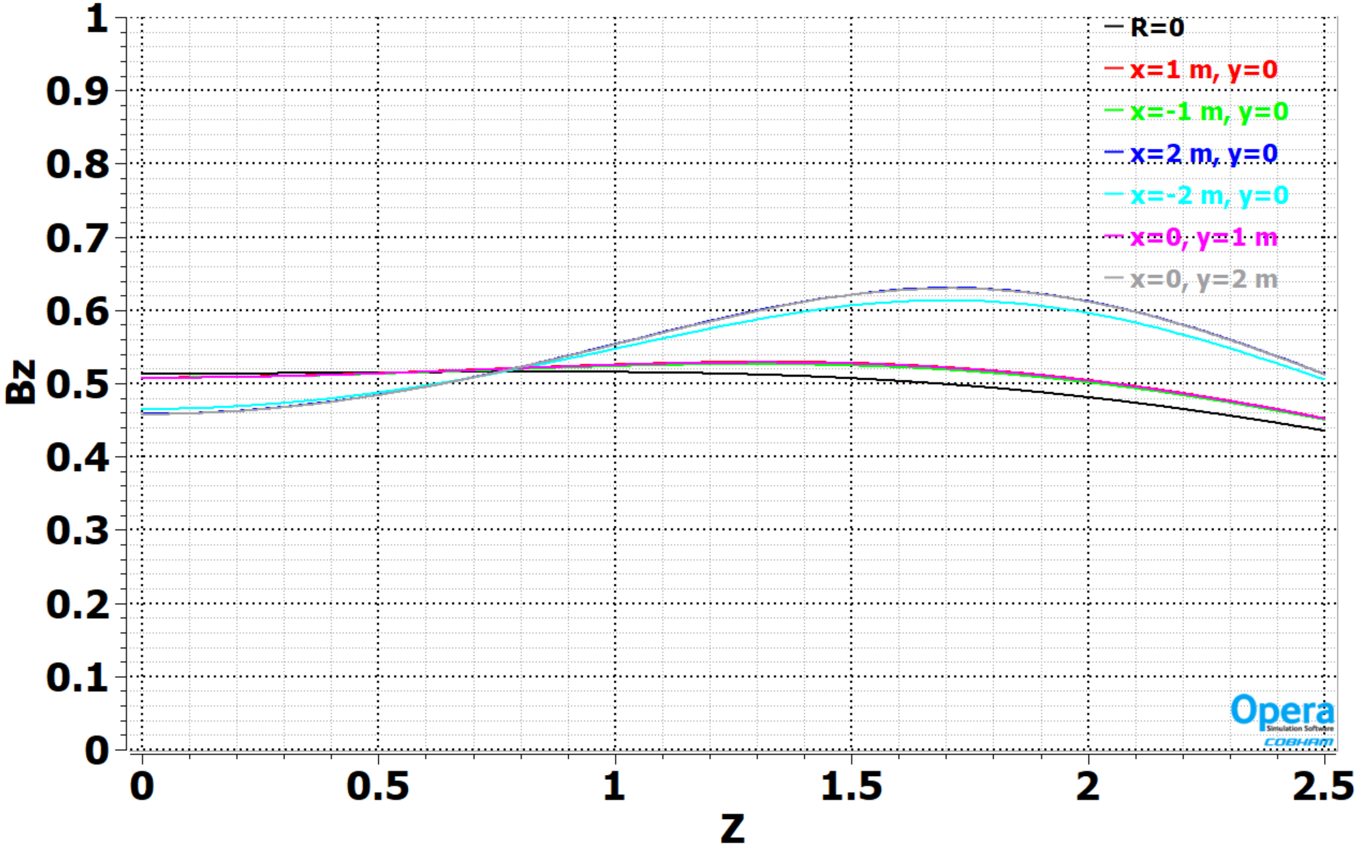
Fields for X-Z and Y-Z planes for 0, 1 m, 2 m distances from the central axis Z. Between coil centers 4 m.

Two Coils with Octagonal Yoke (V2)



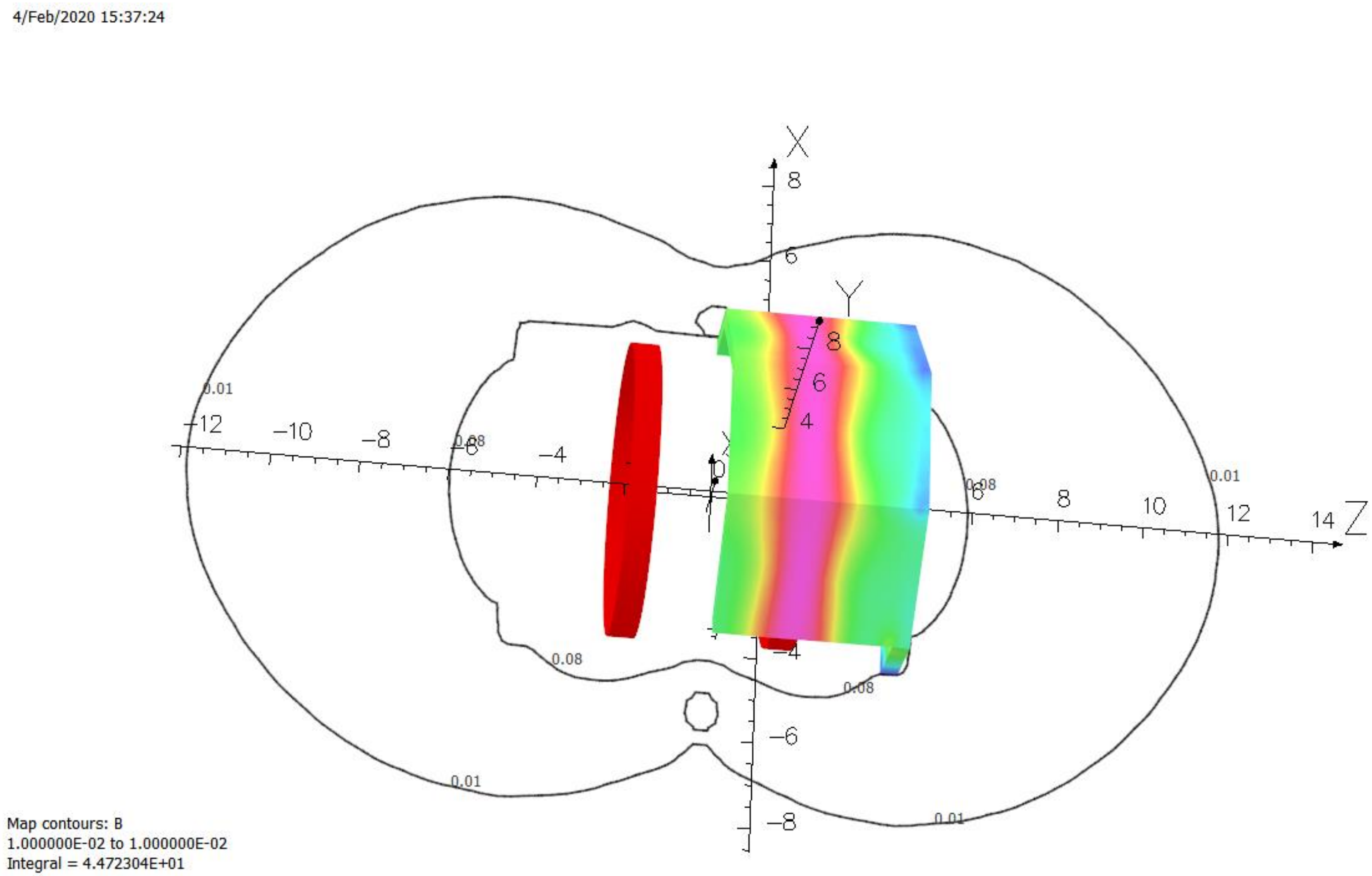
Yoke thickness 0.4 m, distance between coil centers 3.6 m.
Iw=1.76 MA.

Bz Field in the Magnet Bore (V2)



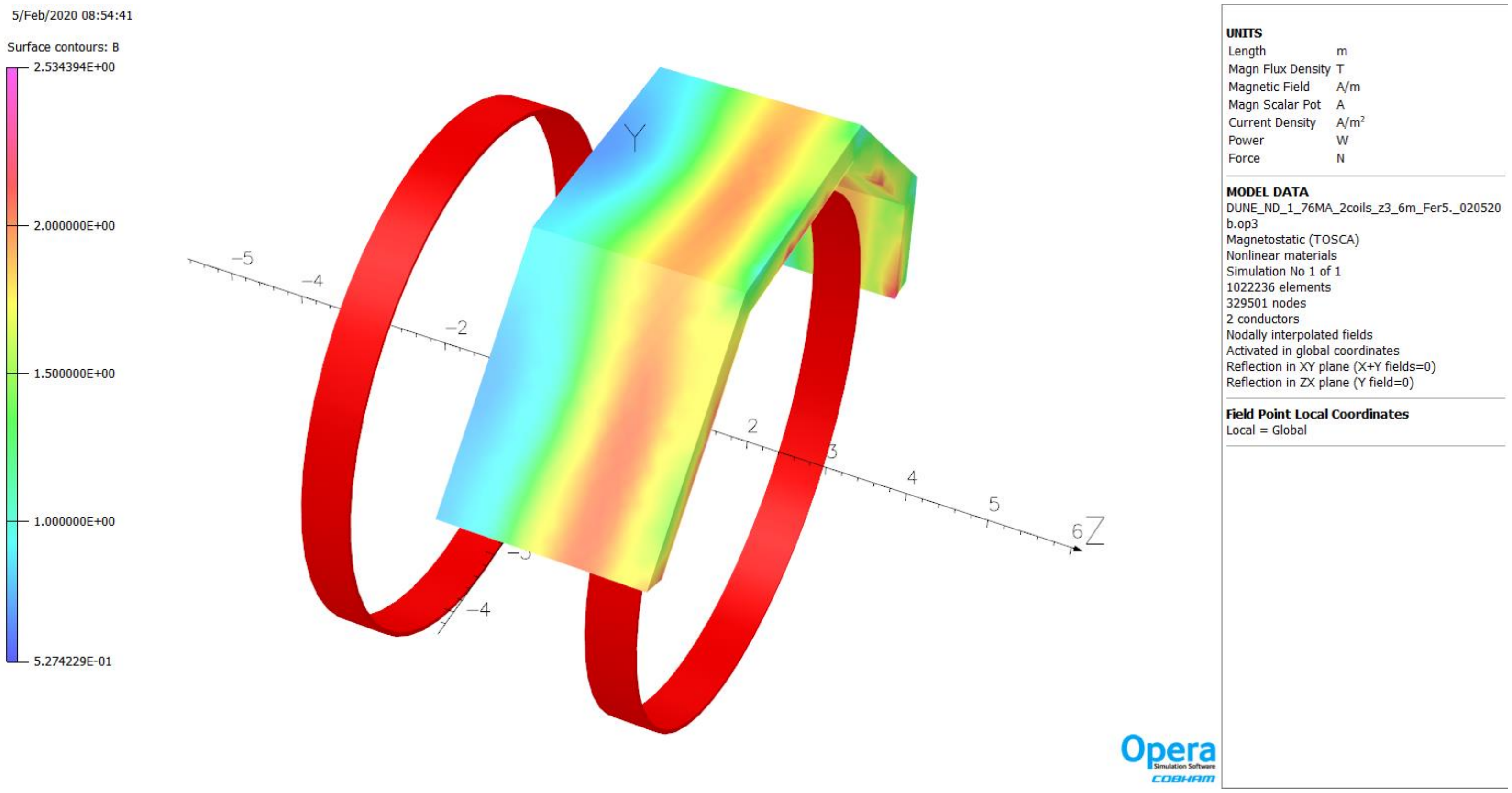
Fields for X-Z and Y-Z planes for 0, 1 m, 2 m distances from the central axis Z. Between coil centers 3.6 m. Iw=1.76 MA. Bcoil=2.2 T, Fx=23 kN, Fz=-2 MN, W=52 MJ.

Fringe Field (V2)



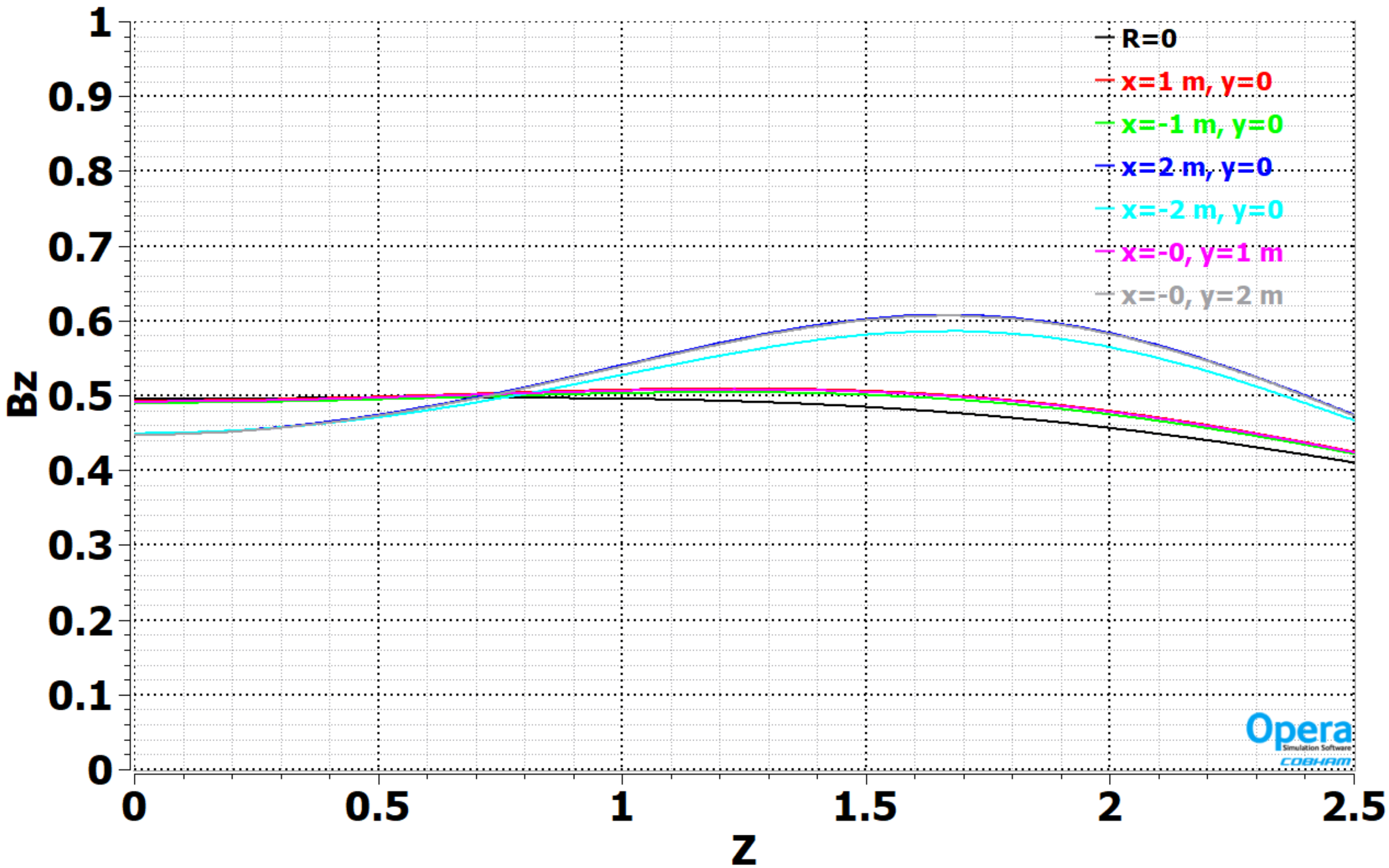
Field on lines: 0.08 T, 0.01 T

Two Coils with 5 m Yoke (V3)



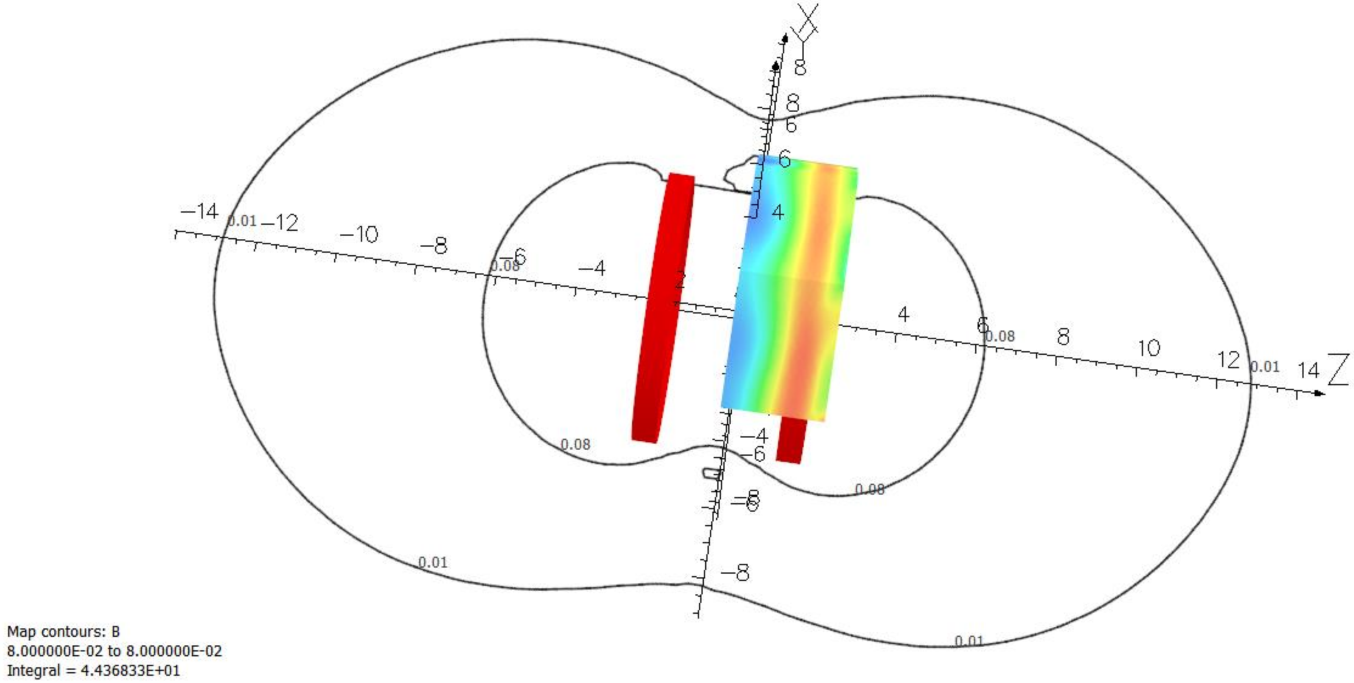
Yoke thickness 0.4 m, distance between coil centers 3.6 m. Iw=1.76 MA, yoke length 5 m.

Bz Field in the Magnet Bore (V3)



Fields for X-Z and Y-Z planes for 0, 1 m, 2 m distances from the central axis Z. Between coil centers 3.6 m, yoke length 5 m, weight 350 tons. Iw=1.76 MA. Bcoil=2.4 T, Fx=1.33 MN, Fz=-3.7 MN, W=50 MJ.

Fringe Field (V3)



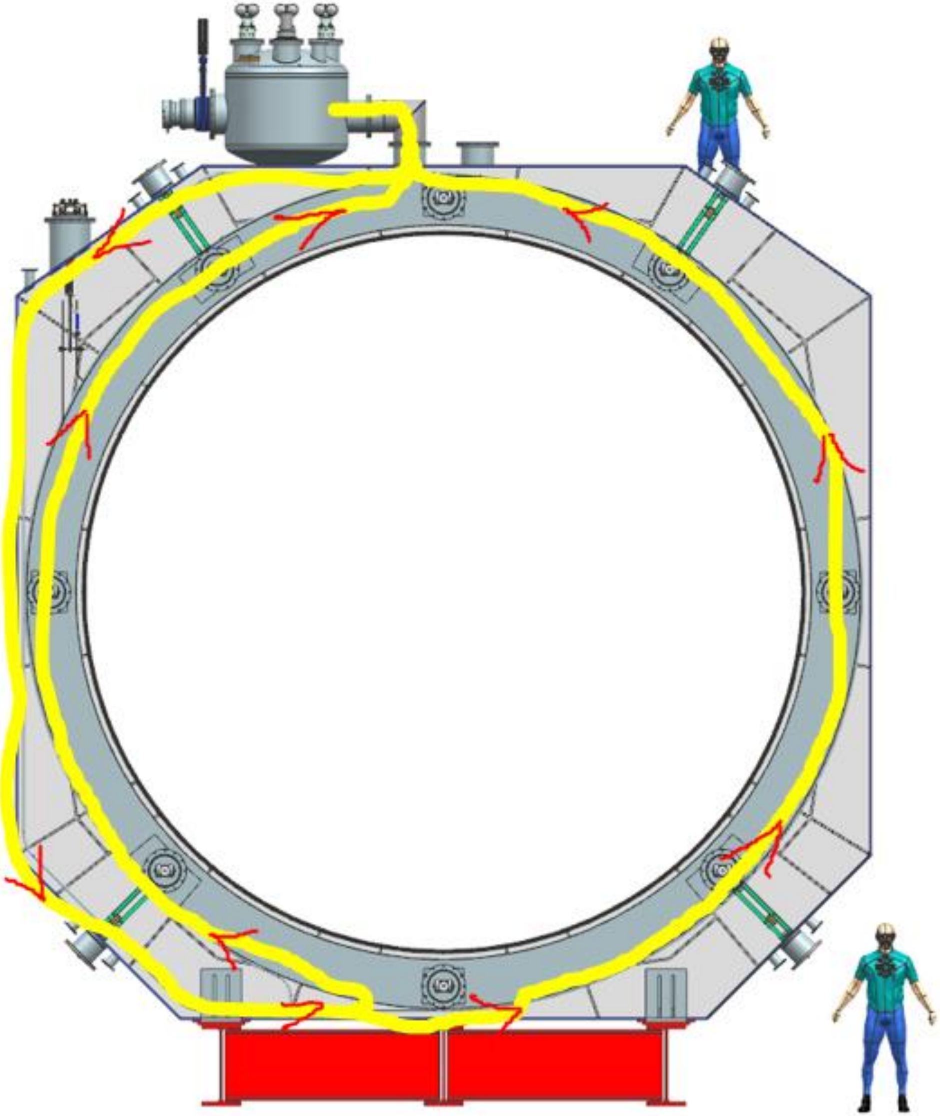
Field on lines: 0.08 T, 0.01 T

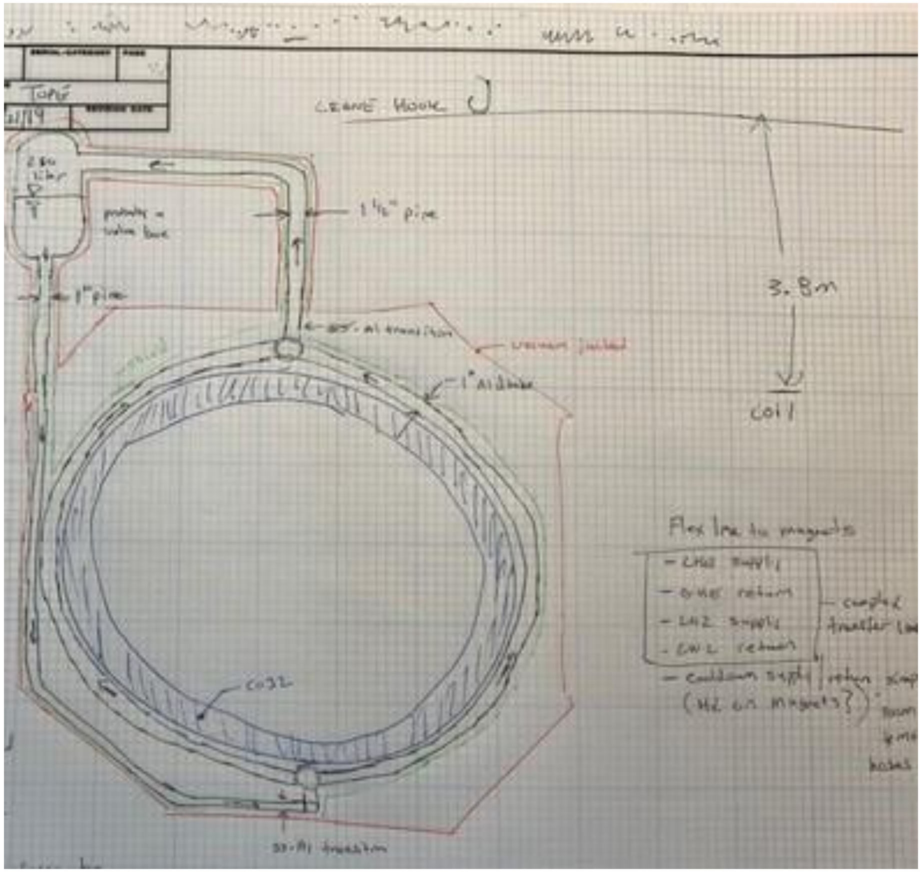
Variants Comparison

Parameter	Units	CDR	V1	V2	V3
Center field	T	0.5	0.5	0.5	0.5
Coil ID	m	7.6	6.6	6.6	6.6
Distance between coils	m	N/A	4	3.6	3.6
Total ampere-turns	MA	8.16	3.52	3.52	3.52
Stored energy	MJ	109	52	52	50
Coil force in z	MN	N/A	1.3	2	3.7
Iron width/height/thickness	m	N/A	8/8/0.4	8/8/0.4	8/8/0.4
Iron length	m	N/A	8.8	8.8	5
Iron weight	ton	N/A	705	705	350

CDR- 5 coils (no iron) , V1-V3 – 2 coils variants with the iron yoke.

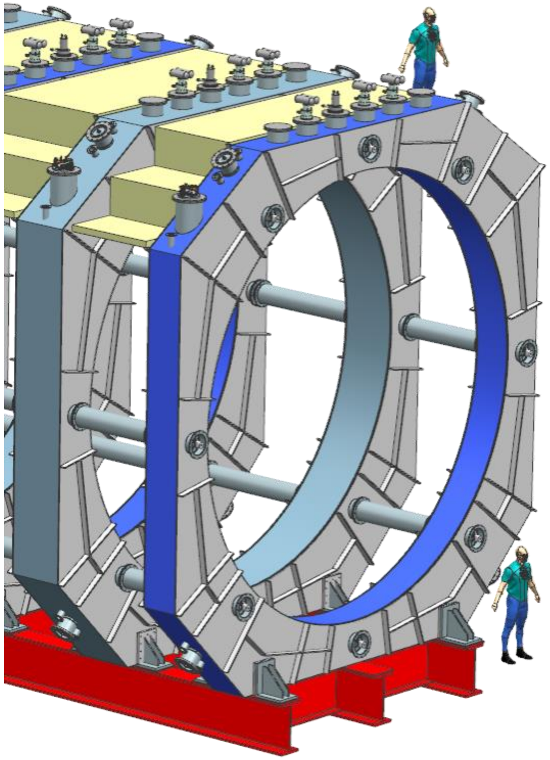
Thermosyphon System – being considered





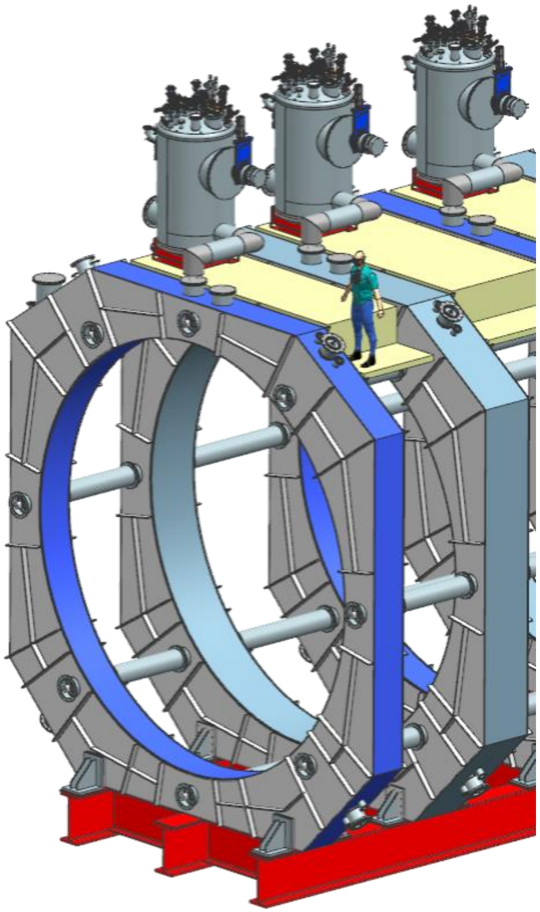
Cooling tubes - conduction with coil bobbin

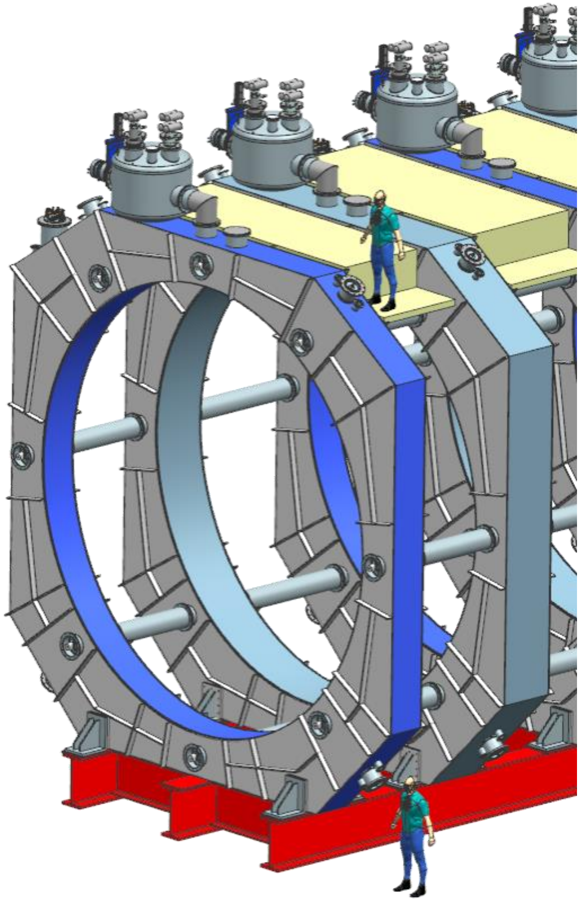
Cryogenic Systems under Consideration



Direct cooling using Cryo-Coolers

Typical Feedcans connected to a Cryo-plant





Hybrid design using Cryo-Coolers

Summary

- A conceptual design was developed for the cold mass cryostat and coil support
- The baseline design coil support is optimized to provide even shrinkage, uniform field and minimal material for particles crossing between the MPD and ArgonCube
- The cryogenic feedbox based on past experience is added to the layout, more details will be needed in the future
- A partial yoke compromised from the outer tracker will not have much influence on the field, as the three relatively thin iron plates are quickly saturated, especially near the coils

BackUp

FSR: Assumptions, Interfaces and Constraints

a) Engineering, design and procurement of the DUNE ND magnet (DNM) could be accomplished by collaboration between Fermilab, INFN (Italy) and BARC, India.

b) Necessary buildings, civil structures and utilities (electrical power, cooling water) are available prior to the installation of the DNM and CP.

c) The DNM and the associated CP is expected to operate for a lifetime of at least 20 years.

d) The DNM coils are made from Superconductor material.

e) The DNM is a yoke-free magnet, using a modified Helmholtz coil design with five coils, two main coils (B), a center coil for field uniformity (C) and two flux return coils (A). The DNM field is arranged along the Z-axis in the order of A B C B A.

f) The DNM field is symmetric around the Z-axis and vertical center plane.

g) A closed loop system will be used to provide the cooling water.

h) Building and civil structures offer restricted geometry. The D-shaped shaft has a clear shaft diameter of 7.8 m, however considering the full 11 m diameter shaft rectangular objects with larger dimension can be lowered down the access shaft.

i) The DNM can be assembled in the detector hall.

j) The DNM and its supports will be placed on a platform structure that allows travel perpendicular to the beam direction. The platform can be moved for installation purposes to the location of the fork lift truck in Figure 1.

k) To fulfill the physics requirements, there has to be a minimal amount of radiation lengths in between LArTPC and HPgTPC. Careful selection of materials and design is needed to minimize backgrounds.

l) There is no weight limit on the DNM.

m) There is no anticipated need for non-destructive removal of the magnet after operation.

n) The DNM cool down shall take less than 15 days with the a maximal allowable gradient of 100 K over the coils..

o) The DNM will use Helium conduction cooling.

p) The thermal shield cooled by GHe to 50 K or LN2 to 80 K.

FSR: Requirements

a) Project Key Performance Parameters and Physics Requirements listed in the DUNE CDR shall be met.

b) The DNM shall be built such that no quench is needed to reach operating current

c) The DNM coil support and strongback should hold all forces between coils, considering:

   a. failure of a single or multiple coils
   b. quench
   c. misalignment
   d. thermal contraction
   e. gravitational support
   f. hoop stresses

d) The DNM cryostat vacuum shall be at 10^{-5} mbar or better.

e) The DNM shall be capable of 50 thermal cycles between operating temperature and room temperature without performance loss.

f) The DNM needs to allow space such that the HPgTPC can be inserted into the coil package along the z-axis from one end.

g) The DNM must allow clear space between the inner bore and the platform to place support feet for the HPgTPC, e.g. this space is not allowable for DNM structures and DNM infrastructure.

h) The DNM vacuum jacket design shall be in accordance to FESHM chapter 5033.

i) Structural supports between the DNM vacuum jacket and cavern shall be in accordance with FESHM chapter 5100.

j) Piping within the DNM shall be in accordance with FESHM chapter 5031.

k) If the DNM contains a beam window it shall be in accordance with FESHM Chapter 5033.1

l) Assembly of the DNM in the detector hall shall be in accordance with FESHM Chapter 10110.

m) The DNM cryogenic distribution needs to allow travel of platform with magnet. perpendicular to the beam direction.

n) The DNM power distribution needs to allow for travel with the platform perpendicular to the beam direction.