DUNE Near Detector Superconducting Magnet

Representing Fermilab TD, AD and PPD & ND
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Introduction

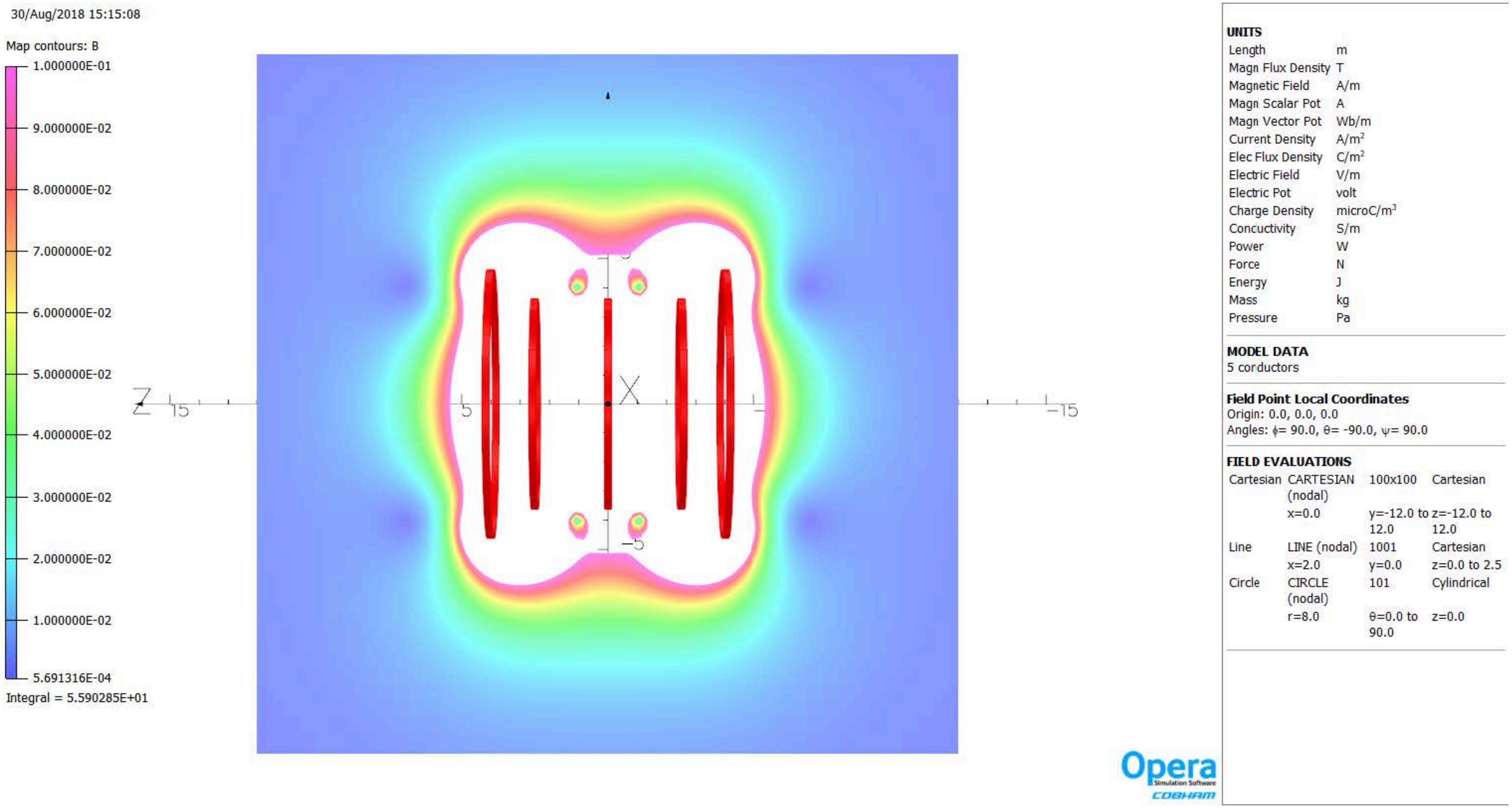
- During the DUNE near detector conceptual study, various magnet options (both NC and SC) were considered.
- The recommendations from the concept and approved by the EB was to build a new magnet
  - Still could be SC or NC
- At Fermilab we have been exploring a Helmholtz coil design following on experience from the Toroid system built for Class 12 at JLAB (& the configuration used by NA49/61/+
  - There are other appropriate approaches
- Our colleagues at BARC have been iterating on their original NC design (UA1-like), but now optimized for the new detector geometry
  - They are also participating in the SC design work
- I will review where we are with the SC design

Our approach

- Produce a conceptual design with ~ .5T central field with minimum material in the magnet system
- Go into enough detail so that we understand the cryogenic load, forces, weights, etc so we can understand the impact on the infrastructure and hall
  - Footprint
  - Power
  - Motion

SC magnet: Basic design

- 3 coils to provide field for the HPgTPC and two bucking coils to minimize the stray field.



UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Magn Vector Pot	Wb/m
Current Density	A/m^2
Elec Flux Density	C/m^2
Electric Field	V/m
Electric Pot	volt
Charge Density	microC/m^3
Concuctivity	S/m
Power	W
Force	N
Energy	J
Mass	kg
Pressure	Pa

MODEL DATA
5 conductors

Field Point Local Coordinates
Origin: 0.0, 0.0, 0.0
Angles: ϕ= 90.0, θ= -90.0, ψ= 90.0

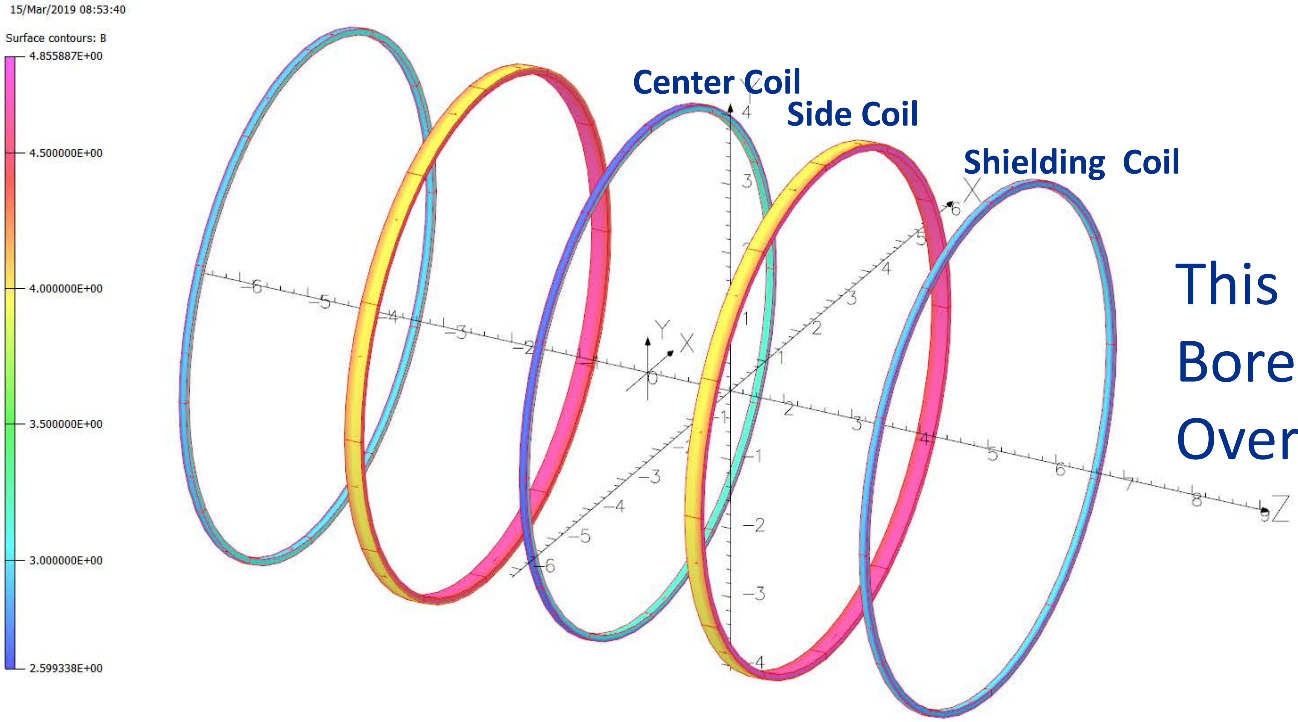
FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal) x=0.0	100x100 y=-12.0 to 12.0	Cartesian z=-12.0 to 12.0
Line	LINE (nodal) x=2.0	1001 y=0.0	Cartesian z=0.0 to 2.5
Circle	CIRCLE (nodal) r=8.0	101 θ=0.0 to 90.0	Cylindrical z=0.0

SC Magnet Design

- Recently when started underground hall conceptual design were raised several issues:
  - The proposed 5-coil magnet system with the two large shielding coils (>10 m diameter) may require a hall span that the rock cover will not support
- We investigated the magnet variant with identical center and shielding coils & move shielding coils further out
- It will simplify fabrication, transportation, and the final assembly.

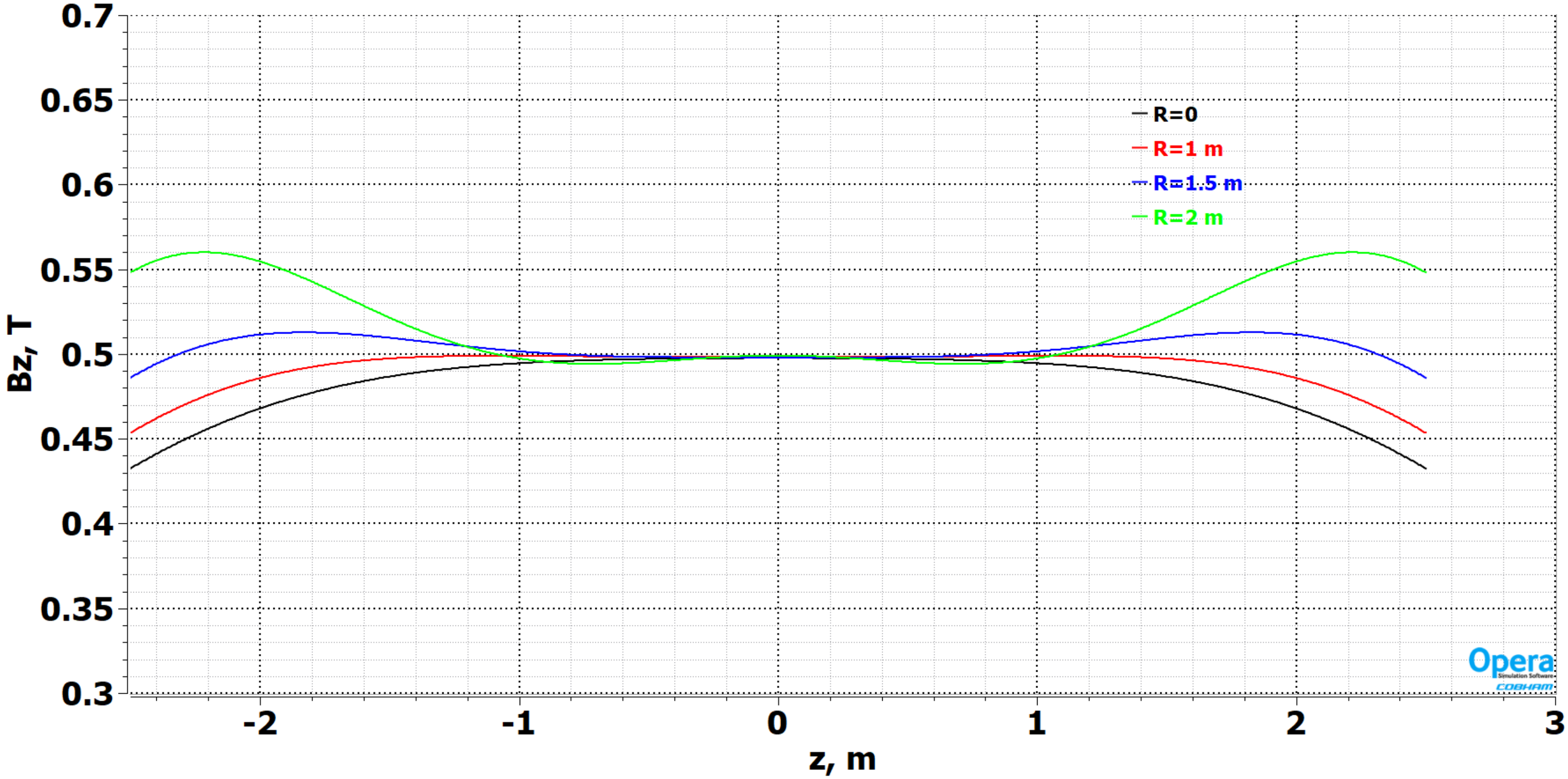
5 Coils Magnet System



This is a big magnet
Bore =7m
Overall L=10m

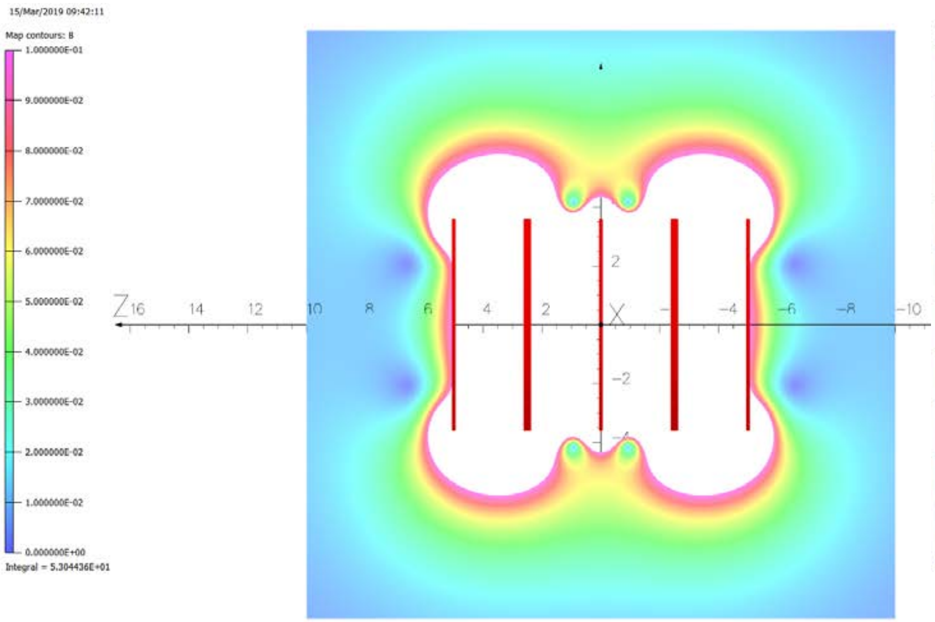
- Peak coil fields: 3.3 T (center), 4.9 T (side) 3.2 T (shield).
- Forces Fz : 0.0 (center), - 5.9 MN (side), 2.7 MN (shield).
- Side coils at 2.5 m, shielding coils placed at 5 m from the magnet center in Z.
- All coils have the same inner radius 3.5 m and outer radius 3.59 m.
- Center and shielding coils are identical and have the same number of ampere-turns.

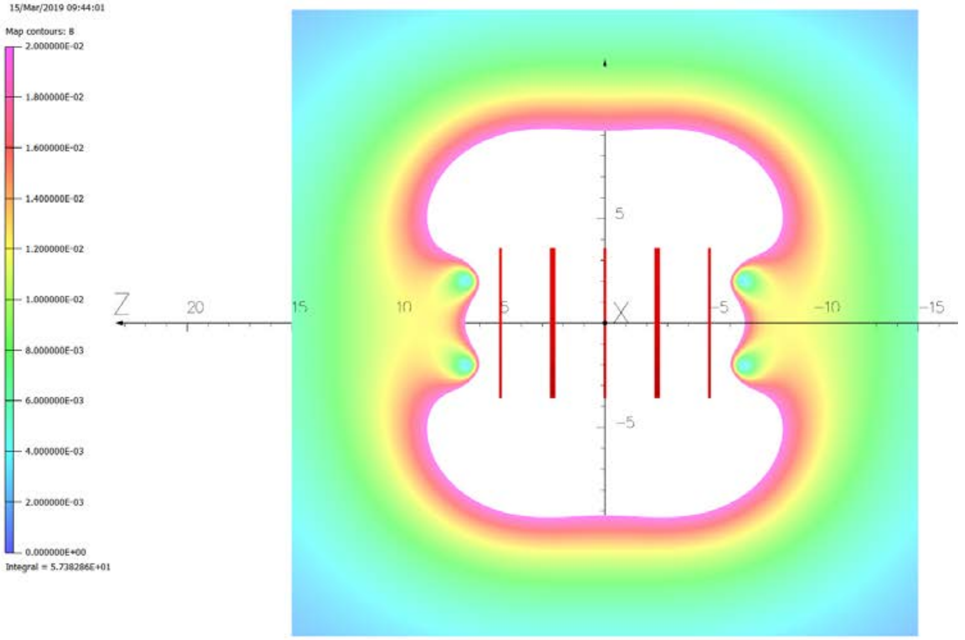
Bz Field in the Magnet Bore



- The center field is 0.5 T at coil total currents: 0.84 MA (center and shield), 2.1 MA (side).

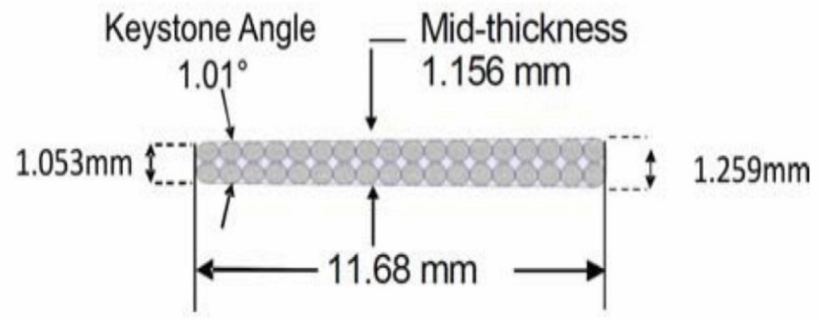
Magnet Fringe Field





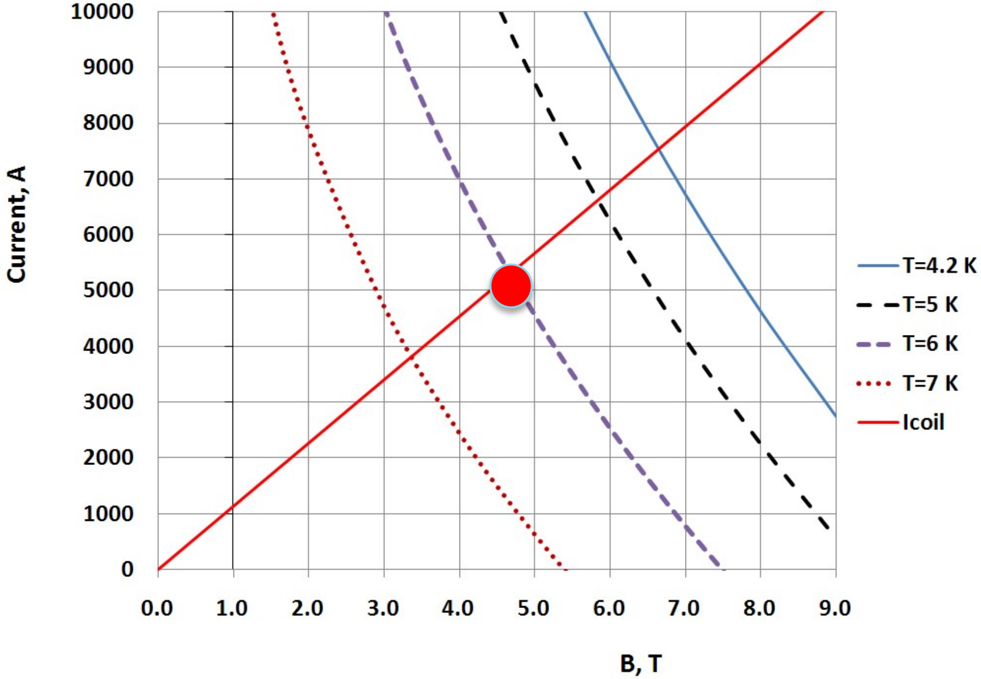
- ➢ Fringe fields less than 0.1 T (left) 0.02 T (right) shown as zone maps.

NbTi Cable in Channel Superconductor



NbTi cable

NbTi cable in Cu channel



Cable short sample parameters

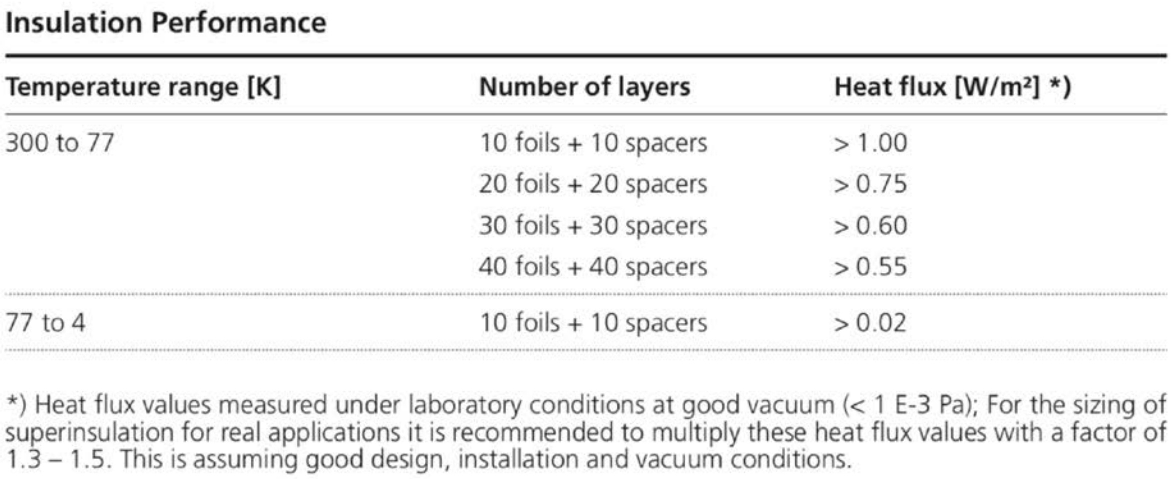
SSC type NbTi Rutherford cable. Dimensions with copper channel and insulation 2.8 mm x 20.3 mm. This cable was used for JLAB TORUS coils.

- For an operating current of 5000 A (●), peak field 4.9 T and 5 K temperature, the cable will have 50 % margin in current for the heaviest loaded side coils.

Preliminary heat load estimate based on 5 coils

Assumptions

- Surface area of coldmass and thermal shield calculated
- Multiplied by MLI mfg heat flux data with 1.5x safety factor
- 77 K – 4 K assumed 10 layers at 0.03 W/m^2
- 300 K – 77 K assumed 40 layers at 0.825 W/m^2



Insulation Performance

Temperature range [K]	Number of layers	Heat flux [W/m²] *)
300 to 77	10 foils + 10 spacers	> 1.00
	20 foils + 20 spacers	> 0.75
	30 foils + 30 spacers	> 0.60
	40 foils + 40 spacers	> 0.55
77 to 4	10 foils + 10 spacers	> 0.02

*) Heat flux values measured under laboratory conditions at good vacuum (< 1 E-3 Pa); For the sizing of superinsulation for real applications it is recommended to multiply these heat flux values with a factor of 1.3 – 1.5. This is assuming good design, installation and vacuum conditions.

Heat load

- Coldmass (all 5 coils)
  - Surface area 179 m^2
  - 77 K to 4.7 K thermal radiation 5.4 W
    - Support conduction to room temp likely to be several times this….
    - Also will have HTS power lead heat load 15 W at 10 kA
  - 42.3 tonne (assumed to be aluminum)
- Thermal shield (all 5 coils)
  - Surface area 281 m^2
  - 300 K to 77 K thermal radiation 232 W

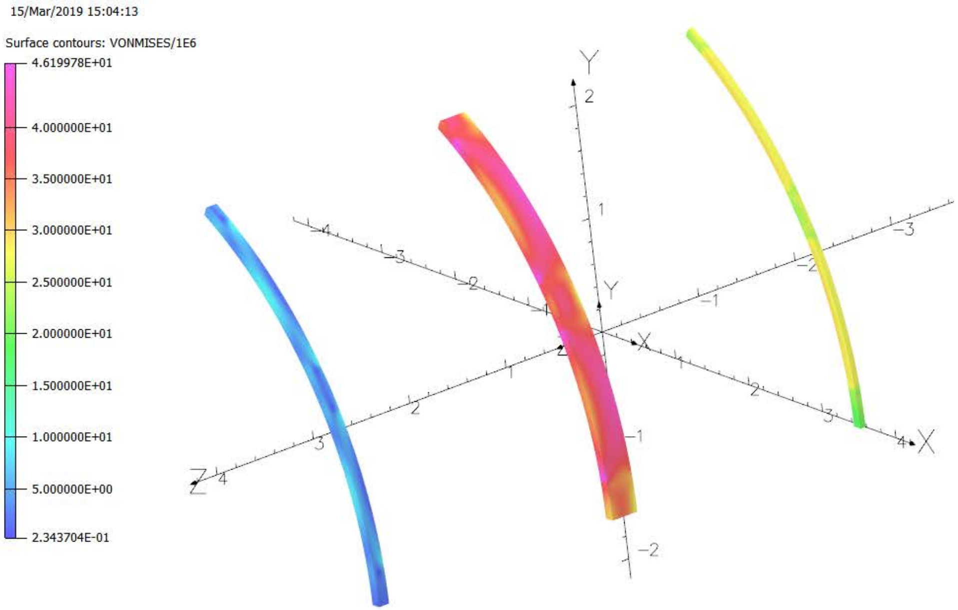
Combined Magnetic and Stress Analysis

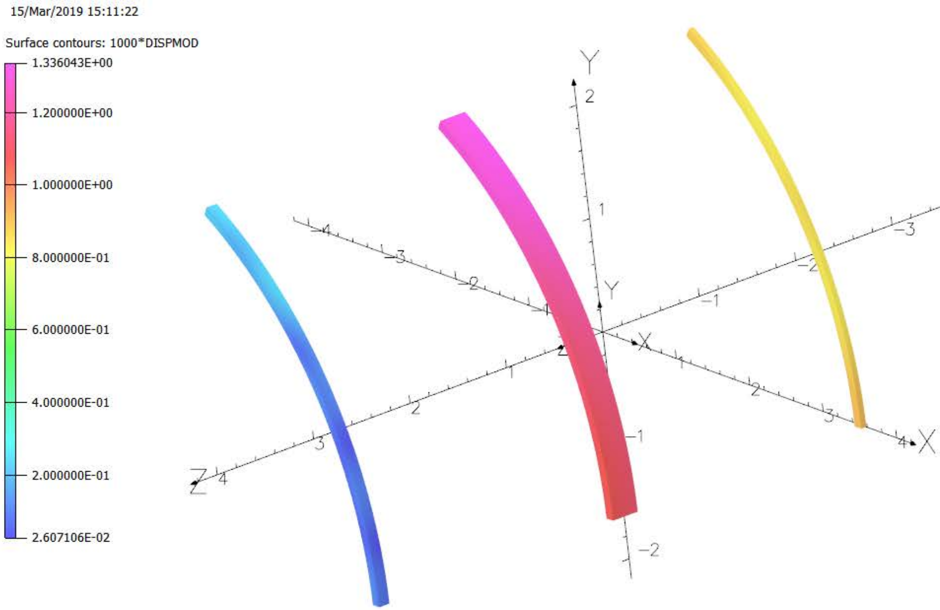
The goal of preliminary mechanical analysis is to investigate:

- Is it possible to make 5 coils cold mass support structure capable withstand MegaNewtons of Lorentz Forces applied to these coils and support structure?
- What is the level of stresses and deformations?
- If an aluminum support structure material is acceptable?
- How many support bars between coils needed in an azimuthal direction?

It should be noted that the cold mass support structure should not occupy the magnet bore, has minimum weight and surface area. At least, must be more cost efficient than cylindrical cryostat.

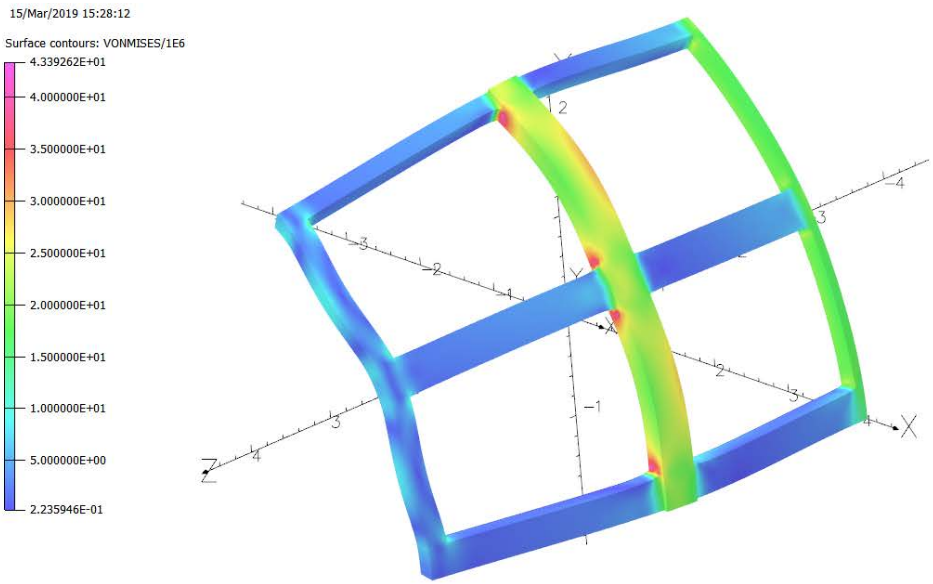
Coils Stresses and Deformations

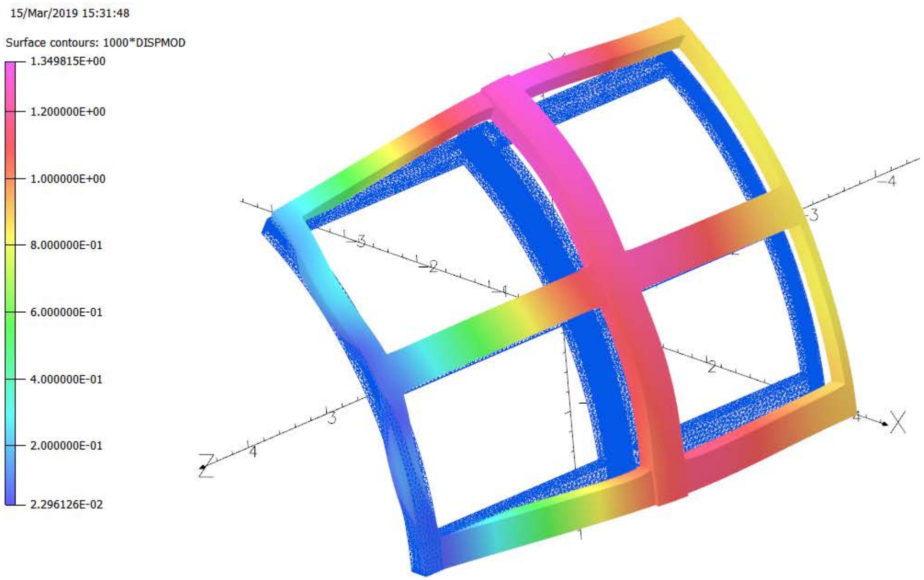




Maximum von Mises stress in side coils is 46.2 Mpa (left), displacement 1.34 mm (right).

Al Case Stresses and Deformations





There were investigated two variants: 6 and 12 equally azimuthally distributed longitudinal bars to intercept forces between coils.
The 6 bars version has large deformations. 12 bars version is shown.
Maximum aluminum support case von Mises stress 43.4 Mpa (left), displacement 1.35 mm (right).

Coil Support Structure Initial Design

Minimum Requirements

- Using generic aluminum and steel yields with SF of 2
  - Allowable stress of 145 MPa for steel
  - Allowable stress of 138 MPa for aluminum
- Calculated minimum required area to prevent failure
  - Without any cross supports, welds, bolts , etc.
  - Final mass will be larger

Steel

- Shield to Side
  - Area = 0.015 m^2
  - Mass = 181.841 kg
- Side to Center
  - Area = 0.047 m^2
  - Mass=938.136 kg

Aluminum

- Shield to Side
  - Area = 0.016 m^2
  - Mass = 64.565 kg
- Side to Center
  - Area = 0.049 m^2
  - Mass = 333.098 kg

Minimum Requirements Cont.

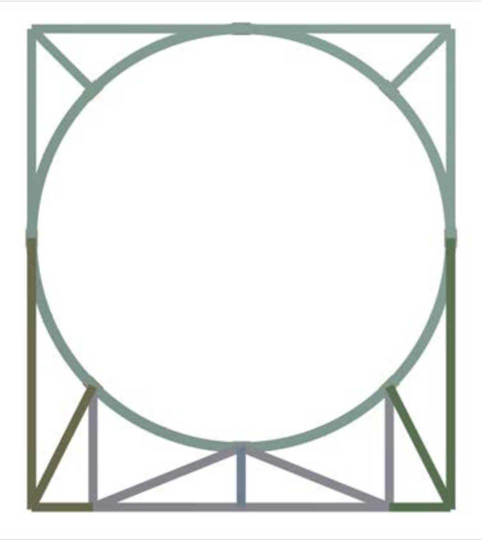
- Coil will apply pressure on support structure
  - Pressure on Side Coil is about 1.196 MPa
  - Pressure on Shield Coil is about 1.186 MPa
- Assuming density of copper for Coil
  - Side Coil is about 12,750 kg (125,100 N)
  - Shield Coil is about 1,385 kg (13,580 N)
- Design for thermal contraction is critical
  - Very early estimates show
    - Cross bracing will shrink 0.023 m in either direction (0.046m total)
    - Diameter of ring will shrink about 0.033 m

Inner Frame Initial Design (Space Frame)

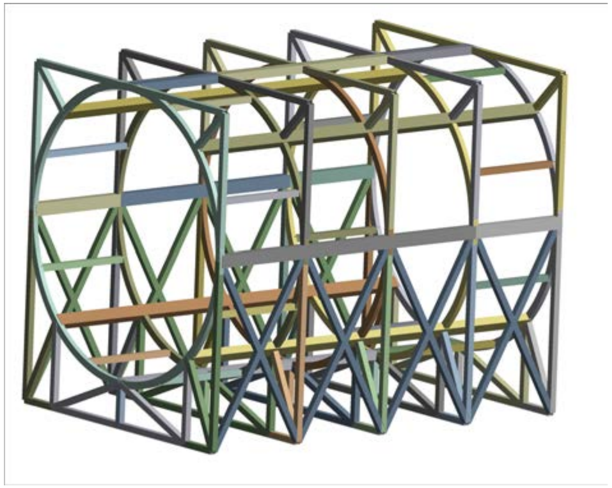
5 Separate frames to be connected by cross bracing

- Made of mostly hollow structural tubes
- Minimizing deformation will be more important than stress
- Line body simulations used to perform initial sizing and structural analysis
  - Future iterations will reduce deformation and mass

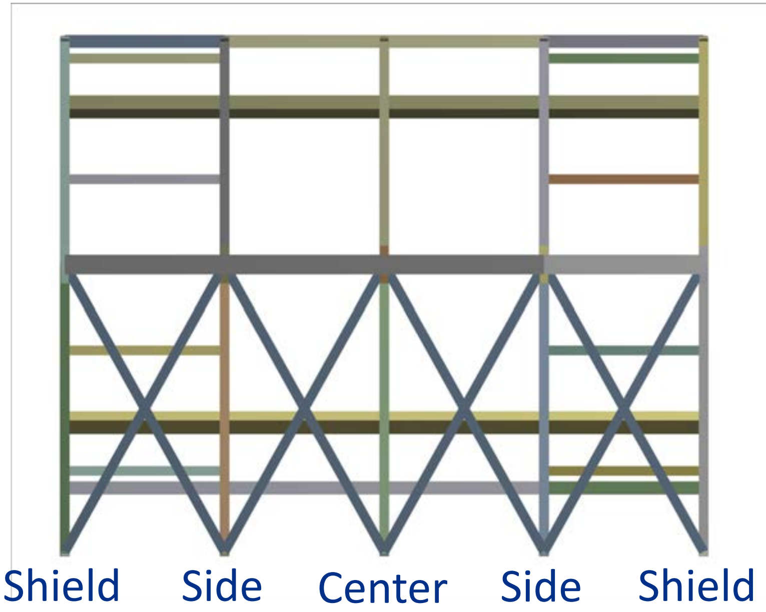
Front View



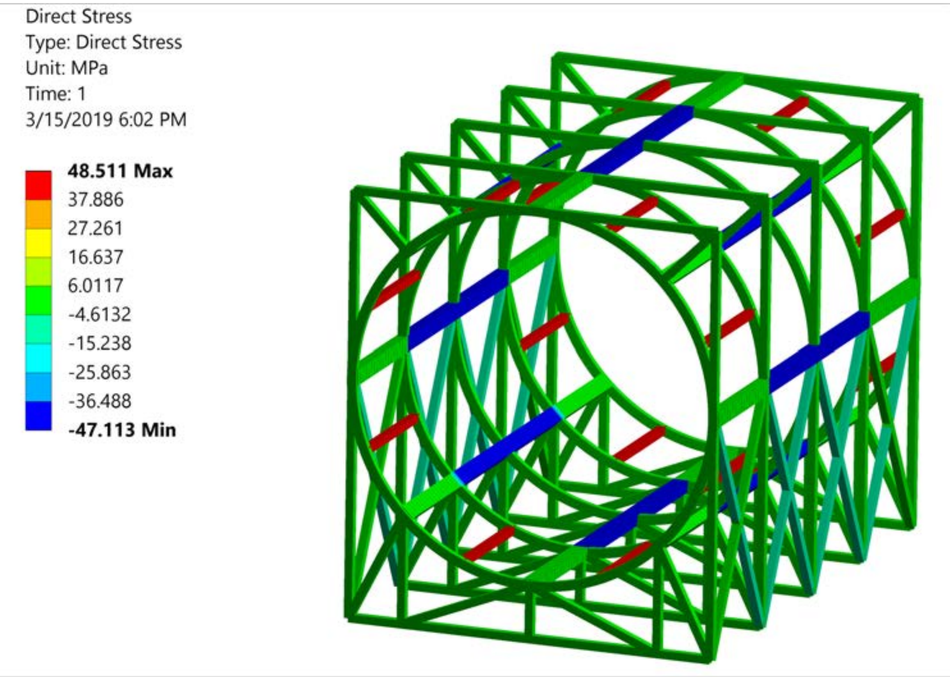
Iso. View

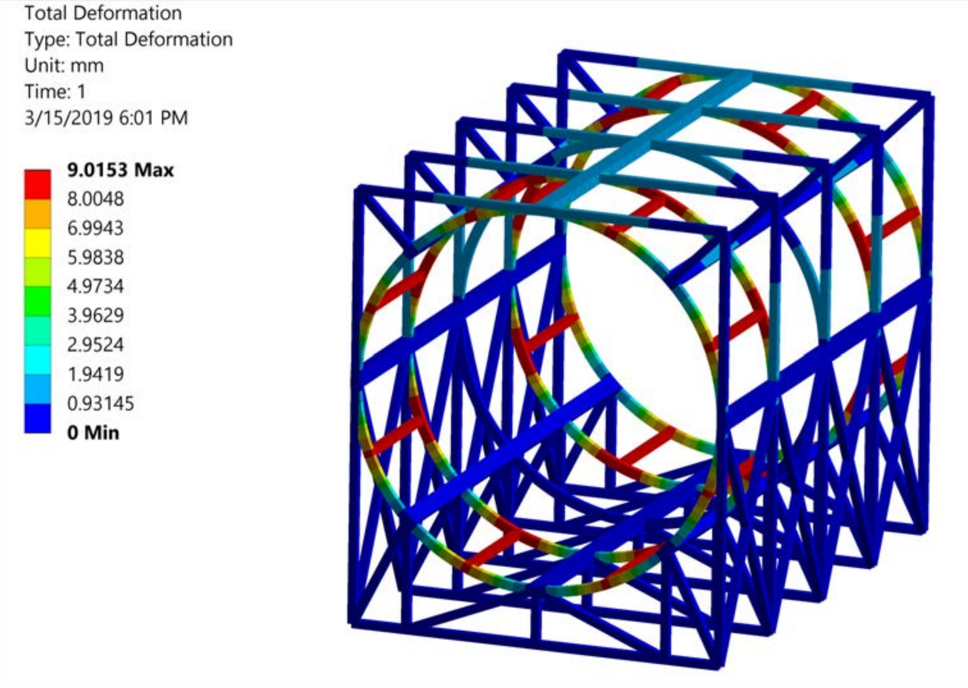


Side View



Simulation Results





Summary

- Deformation limit will drive the design of the structure
  - Currently aiming for 2mm
    - Finial limit will be set by magnet simulations
- Stress in structure less than allowable
  - 48.1 MPa
    - Will be reduced by reducing deformation
- Edits to structure, methods of connection, etc. still needed.
- Due to size of structure, thermal contraction will be an important design consideration

Magnet System Parameters

Parameter	Unit	Value
Magnet bore field	T	0.5
Number of coils		5
Coils inner diameter	m	7.0
Center/Shield coils ampere-turns	MA	0.84
Side coils ampere-turns	MA	2.1
Coil center/side peak fields	T	3.3/ 4.9
Stored energy	MJ	99.4
Fz Lorentz force on side coils	MN	5.9
Fz Lorentz force on shield coils	MN	2.7
Max coil/case stress	MPa	46.2
Max coil/case displacement	mm	1.35
Max magnet system diameter	m	8.0
Max magnet system length	m	11.0
Total cold mass weight	ton	52.1

Summary

- Preliminary magnet system conceptual design showed that it is possible to design system with the same coils outer diameter.
- Three of the five coils can be identical.
- The fringe field from the system is rather high, but local field shielding for the field sensitive equipment could be added.
  - Work in progress
- The mechanical design with 5 coils having identical ID and OD and 10 m distance between shield coils looks reasonable.
- The center and shield coils are identical and have 0.84 MA,

  side coils have 2.1 MA.
- Coils and aluminum case stresses and deformations are acceptable.
- There are 12 longitudinal bars equally distributed with 30 deg.

  between them. They occupy 20 % of azimuthal space.
- The mechanical design will be updated by including cold mass weight support structures and possible accidental forces caused by coil failures.

Conclusion

- We have arrived at what looks to be a reasonable preliminary design for a “self-shielded” Helmholtz coil concept.
- The SCHC design has a number of advantages
  - Low mass to reduce backgrounds from ν interactions in non-active material
  - Open structure
  - Low power
  - Manageable stray fields.
- The final design, however, will be determined/developed by the organization/company that delivers the system.
- This is just a start and just one of potentially a number of viable superconducting solutions.