Magnets Technology for Axion Helioscopes

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2. Accelerator Magnets
3. Detector Magnets
4. Other Possibilities
5. Tooling
6. Towards a IAXO Magnet
7. An Initial Concept
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Introduction

Figure of Merit (FOM)

- In order to determine the needs from a next generation helioscope, we define a figure of merit.
- The magnet parameters of an axion helioscope sensitivity are: The magnetic field B, the magnet's length L and the area picked up by optics devices A.
- These parameters appear in the sensitivity to the axion coupling as $f_M = B^2 L^2 A$.
- CAST's magnet parameters have the values:

$$B = 9 \text{ T}, \;\; L = 9.26 \text{ m}, \;\; A = 2 \times 15 \times 10^{-4} \text{m}^2$$

- CAST's magnet FOM (MFOM) is $f_M^{CAST} \approx 21 \text{ T}^2 \text{m}^4$.

Introduction

Figure of Merit (FOM)

- IAXO’s goal is to improve the sensitivity to the axion-photon coupling constant by at least one order of magnitude (matching DOE criterion).
- Hence, the magnet FOM (MFOM) of IAXO should be increased by a factor of ~ 300, relative to the CAST MFOM.
- When using NbTi superconducting cables, the magnetic field is constrained to < 10 T.
- The magnet’s length is taken to be 20 m, in order to allow the magnet to rotate and follow the sun.
- The parameter that can yield the most significant enhancement is the magnet’s aperture (cross-section area).

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Accelerator Magnets

Scaling Up a Dipole Magnet

- The straightforward option is to scale up an accelerator dipole magnet to have the required aperture.
- Setting an increase by a factor of 100 for the MFOM shows that, when accounting the present magnetic field and length of CAST, the aperture of the dipole should be made of a single 618 mm bore, or a pair of twin 436 mm bores.
- Enlarging the dipole's aperture results in an increase of the stress acting on the coils by a factor of ~10. Current existing mechanic systems can support stress of up to ~ 200 MPa.
- The solution: Increasing the quantity of superconductor to distribute the Lorentz forces over a larger area. Going with a 618 mm aperture to 200 MPa will require a coil ~ 4 times wider than the LHC dipole (i.e. a 120 mm wide coil).

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Accelerator Magnets

Impacts of a Large Aperture

- Putting more layers of cables will increase the overall mass, volume and costs of the magnet.
- A massive and large iron yoke will be needed in order to enclose the magnetic flux, minimize the stray fields and support the system mechanically.
- For a 9 T, 618 mm bore magnet, the needed iron yoke is ~ 1.4 m wide. This sets an overall diameter of about 4 m for the magnet system.
- The iron alone will weight ~ 45 tones (current CAST dipole weighs 40 tones).
- Designing a dipole magnet for a next generation helioscope will require additionally the design and manufacture of completely new tooling machines. This adds significantly to the costs of such a project.

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HEP Detector Magnets

Characterization

- A different approach can be to scale down an existing model of a detector magnet such as ATLAS or AMS.
- These magnets are characterized by a very large volume, compared to accelerator magnets. Hence, detector magnets store an enormous amount of energy.
- The magnet's protection requires the use of Al stabilizer around the superconductor. In the entire cable, the ratio between NbTi to Al is typically around 1:25.
- Detector Magnets do not require an iron yoke.
- The aperture which counts in the MFOM is determined by the area covered by x-ray focusing optics.

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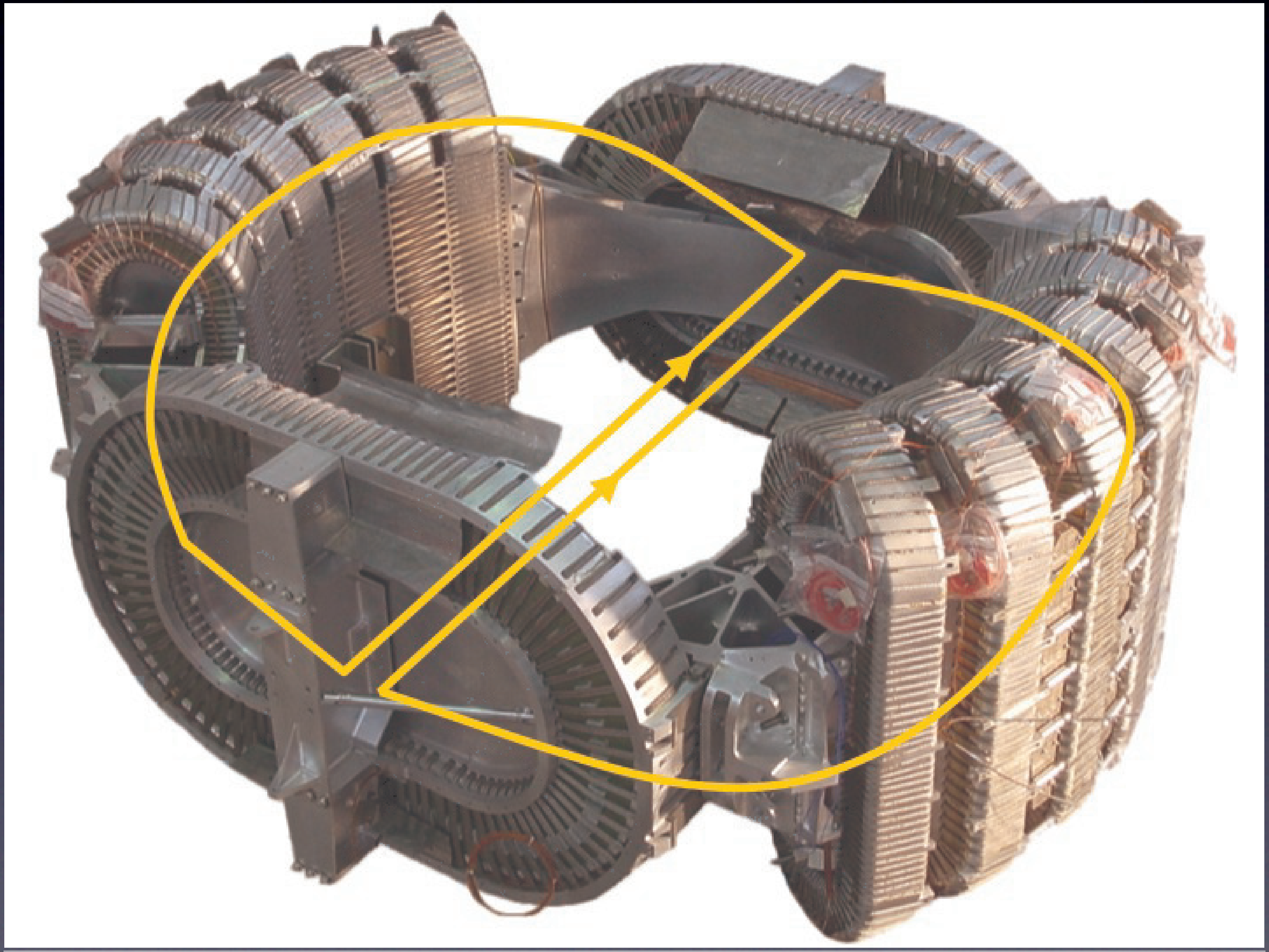
HEP Detector Magnets

AMS II



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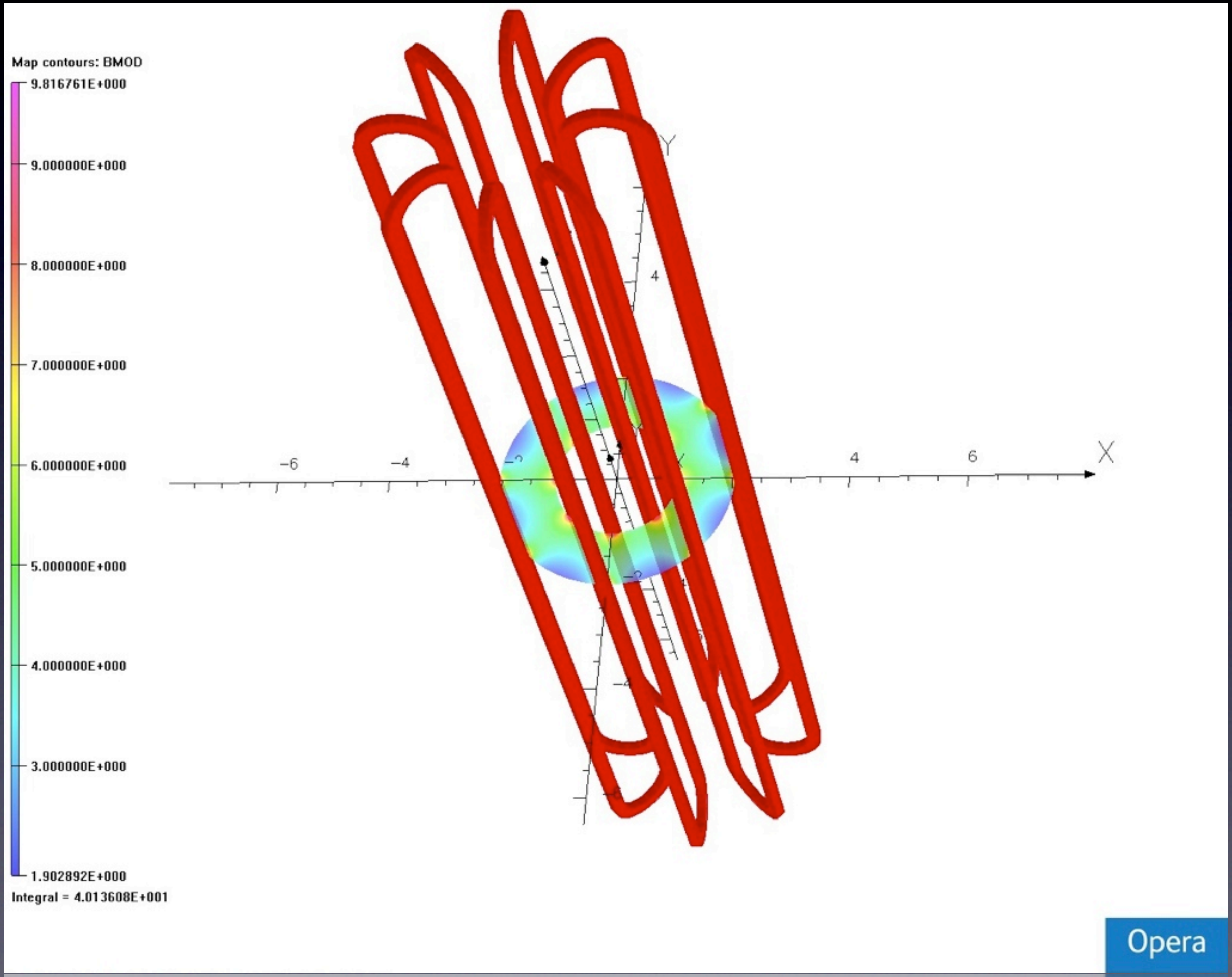
HEP Detector Magnets

Toroid Magnet - An Illustration



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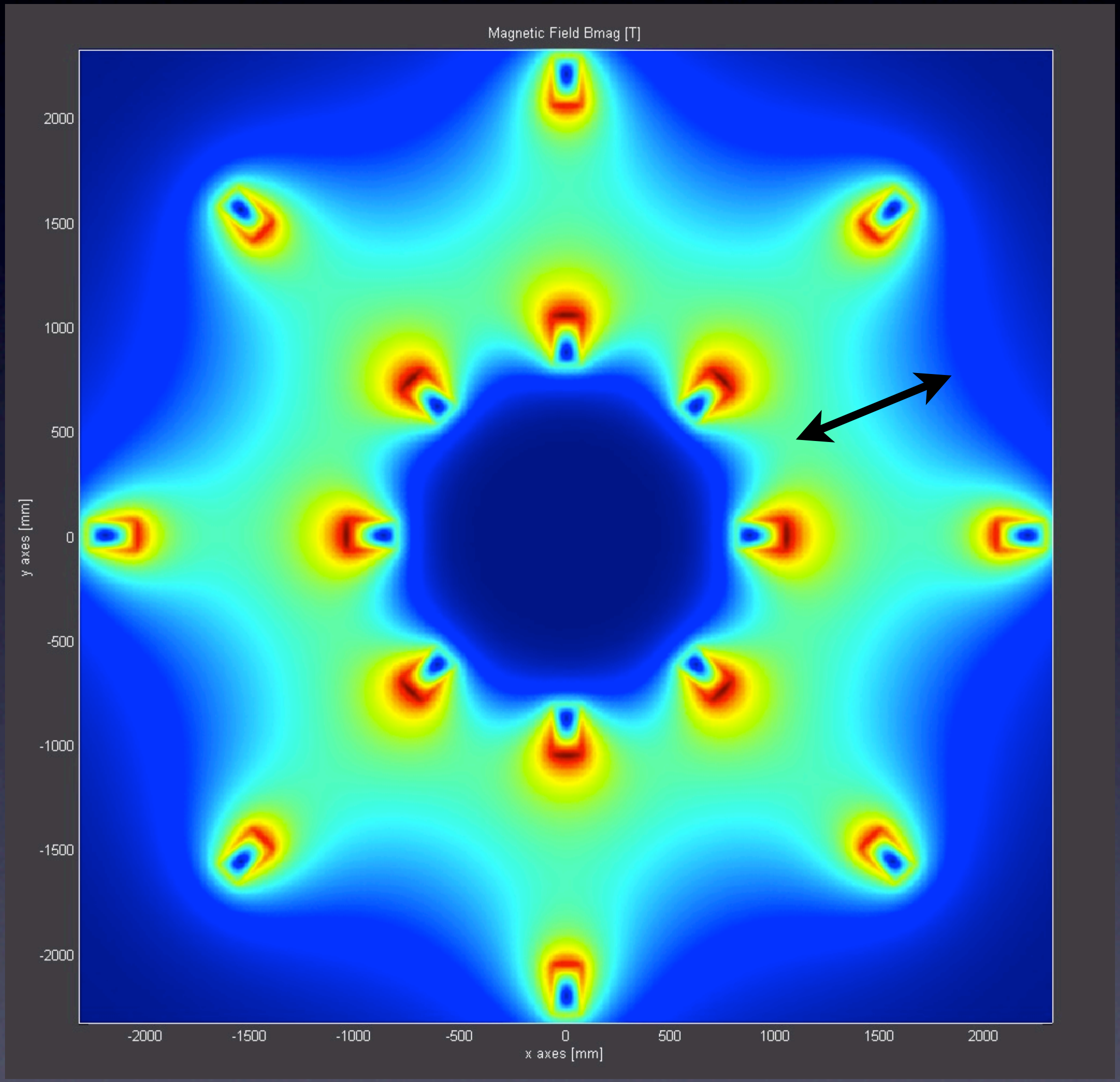
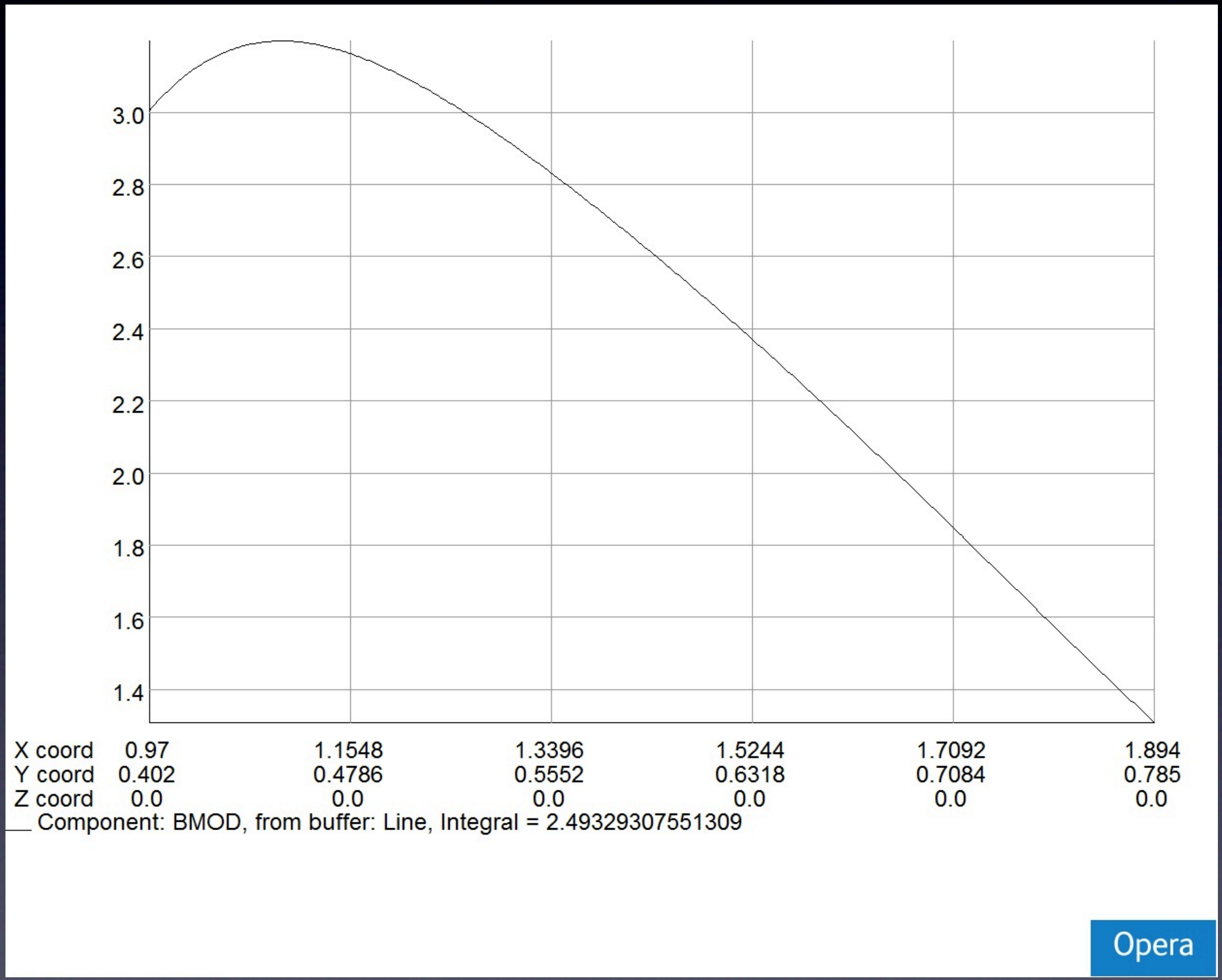
HEP Detector Magnets

Toroid Magnet - An Illustration





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$$B_{avg} \approx 2.5\ \mathrm{T}$$

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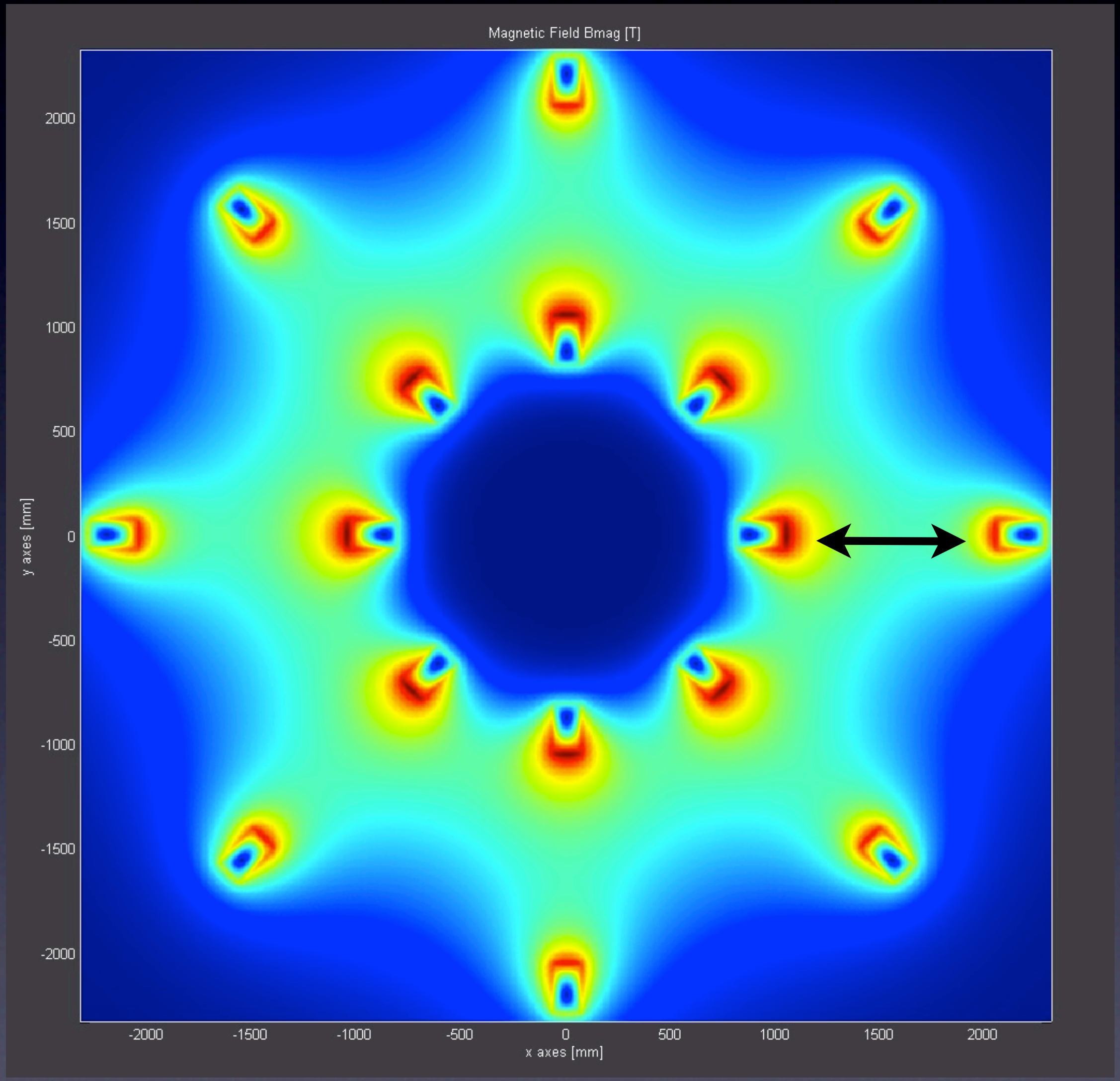
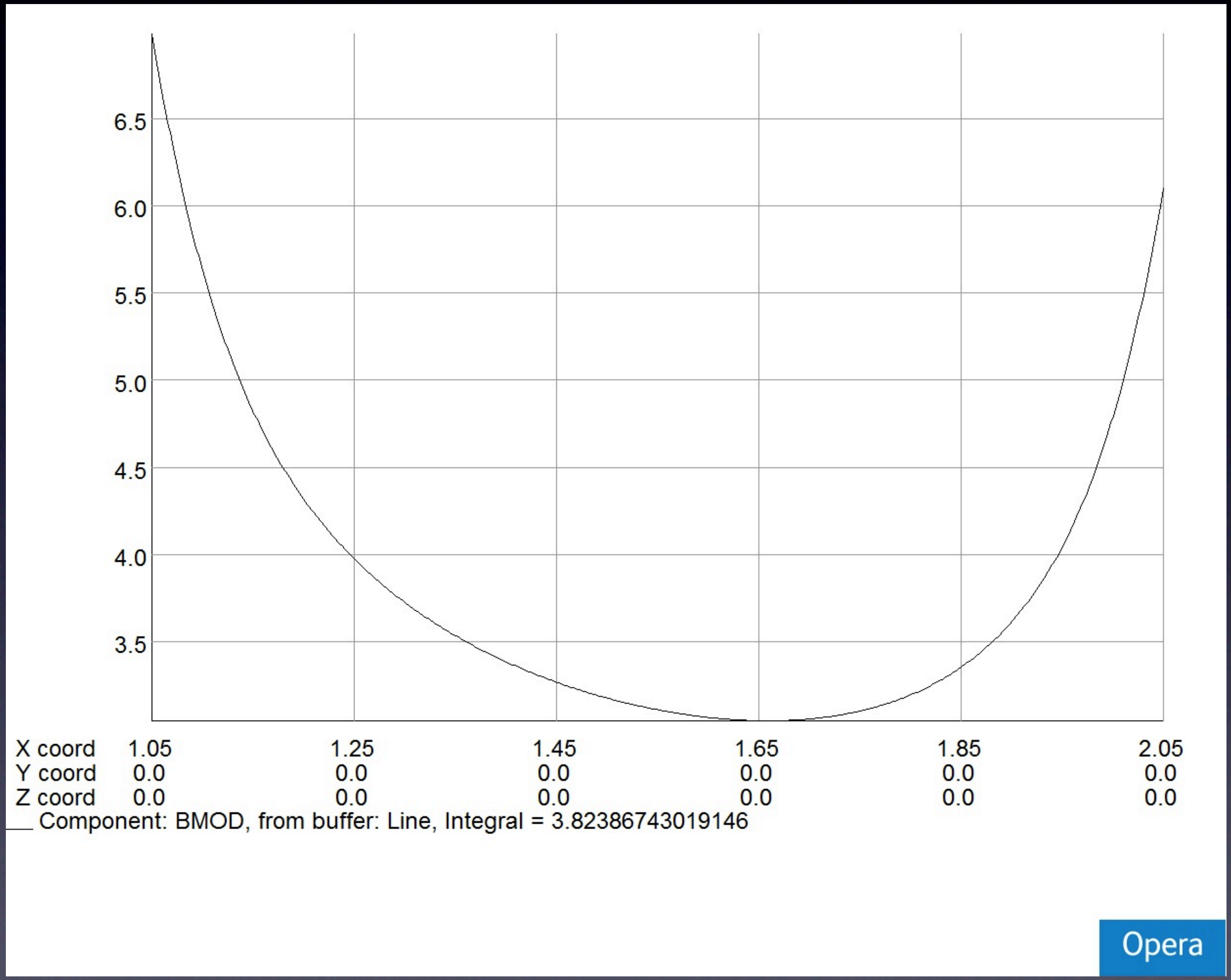
HEP Detector Magnets

Toroid Magnet - An Illustration





Component: BMOD, from buffer: Line, Integral = 3.82386743019146

$$B_{avg} \approx 3.8 \text{ T}$$

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Other Possibilities

- A solenoid magnet is the easiest to design and manufacture. However, the required solenoid will not be transparent to x-ray photons.
- Using a Nb3Sn superconductor.
- Since we essentially combine the detector and accelerator magnets doctrines, the major efforts will focus on the mechanical engineering of such a magnet. The new magnet will have to stretch the limits of the design factors.

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Tooling

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Tooling


BABCOCK NOELL NUCLEAR GmbH
BEAM
B
Endschalter nicht berühren!


Large Magnet F

6 Towards a IAXO Magnet

Towards a Concept

- The first step towards designing an initial concept of IAXO's magnet is to optimize its geometrical lay-out in order to obtain a high figure of merit for the proposed experiment.
- The MFOM is determined by the integral $\int B^2(x,y)dxdy$.
- The integration is performed over the open area covered by the x-ray optics being used.
- The IAXO group has decided to use 8 x-ray telescopes with a diameter of 600 mm and an inner blind spot of 100 mm.

Towards a IAXO Magnet

Geometrical Lay-Out Optimization

- In order to carry out the integration, the telescopes' center point coordinates need to be determined.
- In the $\hat{\theta}$ direction there are two principal options for the telescopes' positioning, which we shall refer to as the "behind" and the "between" options.
- In practice, these two options represent two different approaches:

1. Field dominated.
2. Area dominated.

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Towards a IAXO Magnet

Geometrical Lay-Out Optimization

- The $\hat{r}$ coordinate of the telescopes' center should be minimized in order to enhance the MFOM.
- The minimal radial position is limited by the following (impractical) value $r_{min} = R_{det}/\sin(\theta/2)$.
- When the positioning of the telescopes is fixed, one can perform the integration over a disc with radius R_{det} centered at (R_{cen}, θ).

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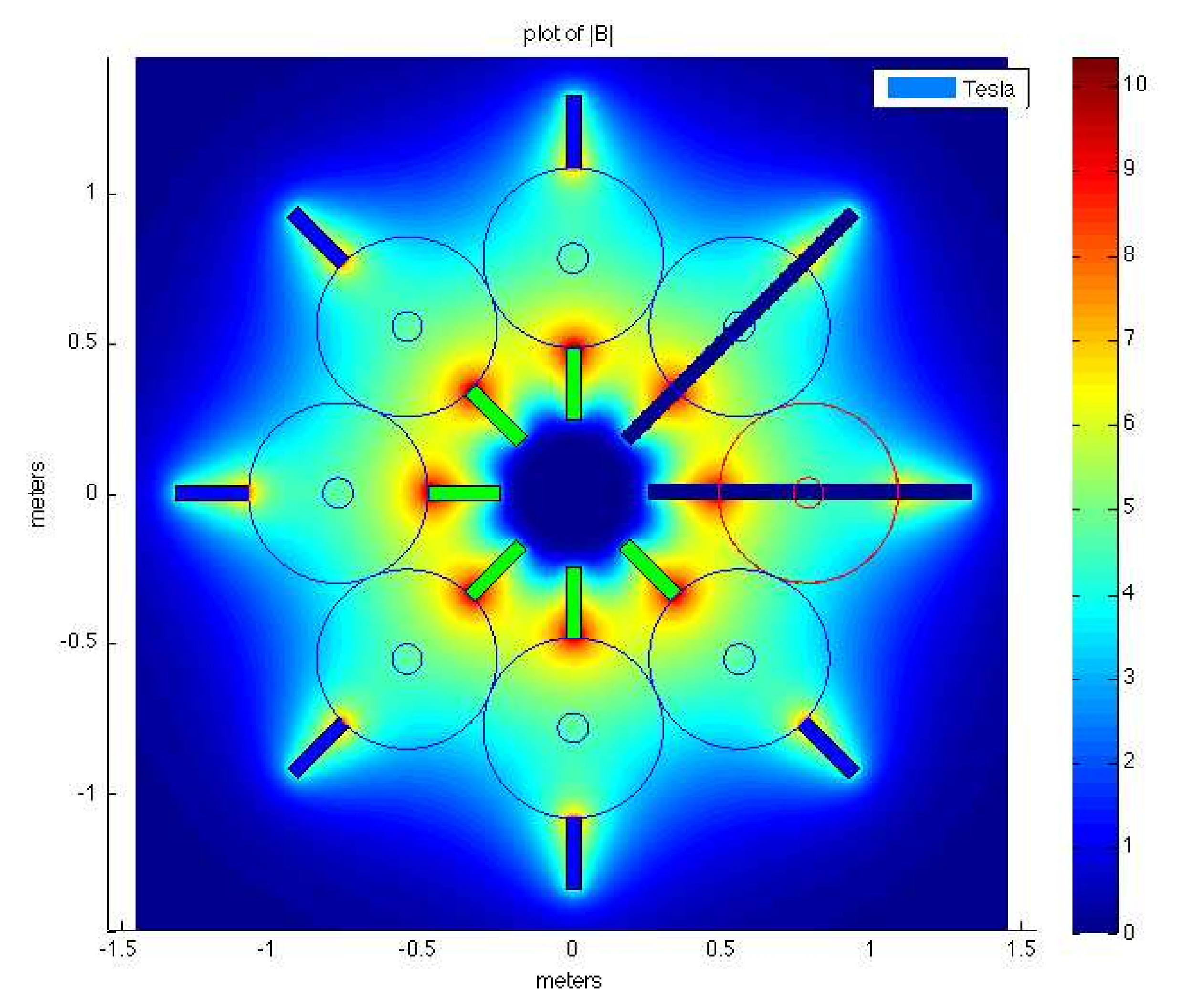
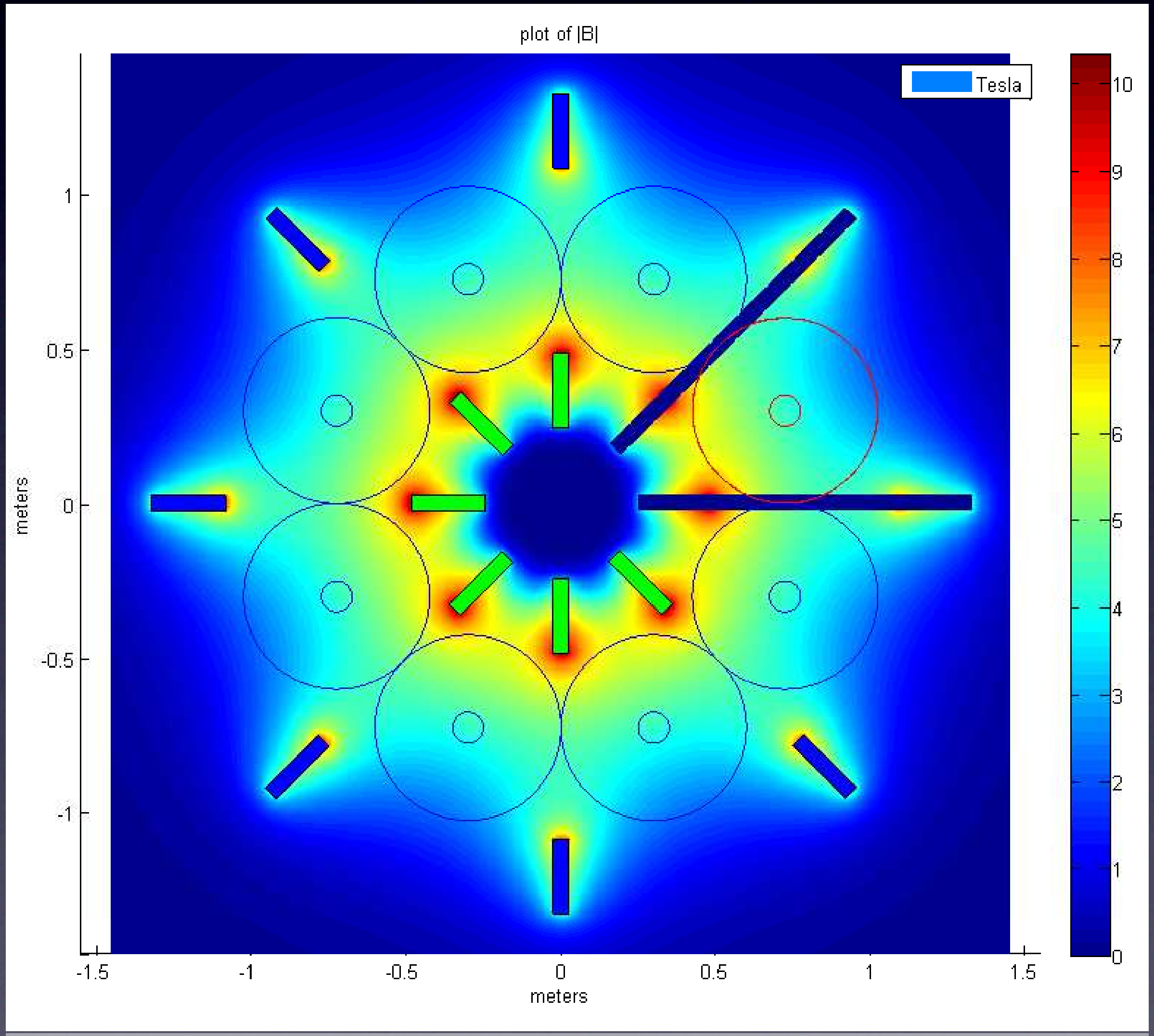
Towards a IAXO Magnet

Geometrical Lay-Out Optimization





6 Towards a IAXO Magnet

Normalization

- In order to make the integration results, or the MFOMs obtained from them, comparable, one should choose a normalizing method.

- A method which will be useful for our case is to constraint the electromagnetic parameters of each magnet configuration such that all magnet configurations are "on the critical surface".

- For Nb-Ti, the linear approximation of the critical current density is given by $J_c = d(B_{c2} - B)$.

- From the latter, we can find the intersection point of the given load-line with the critical surface to be

$$J_c = \frac{\kappa d B_{c2}}{1 + \kappa d \gamma}$$

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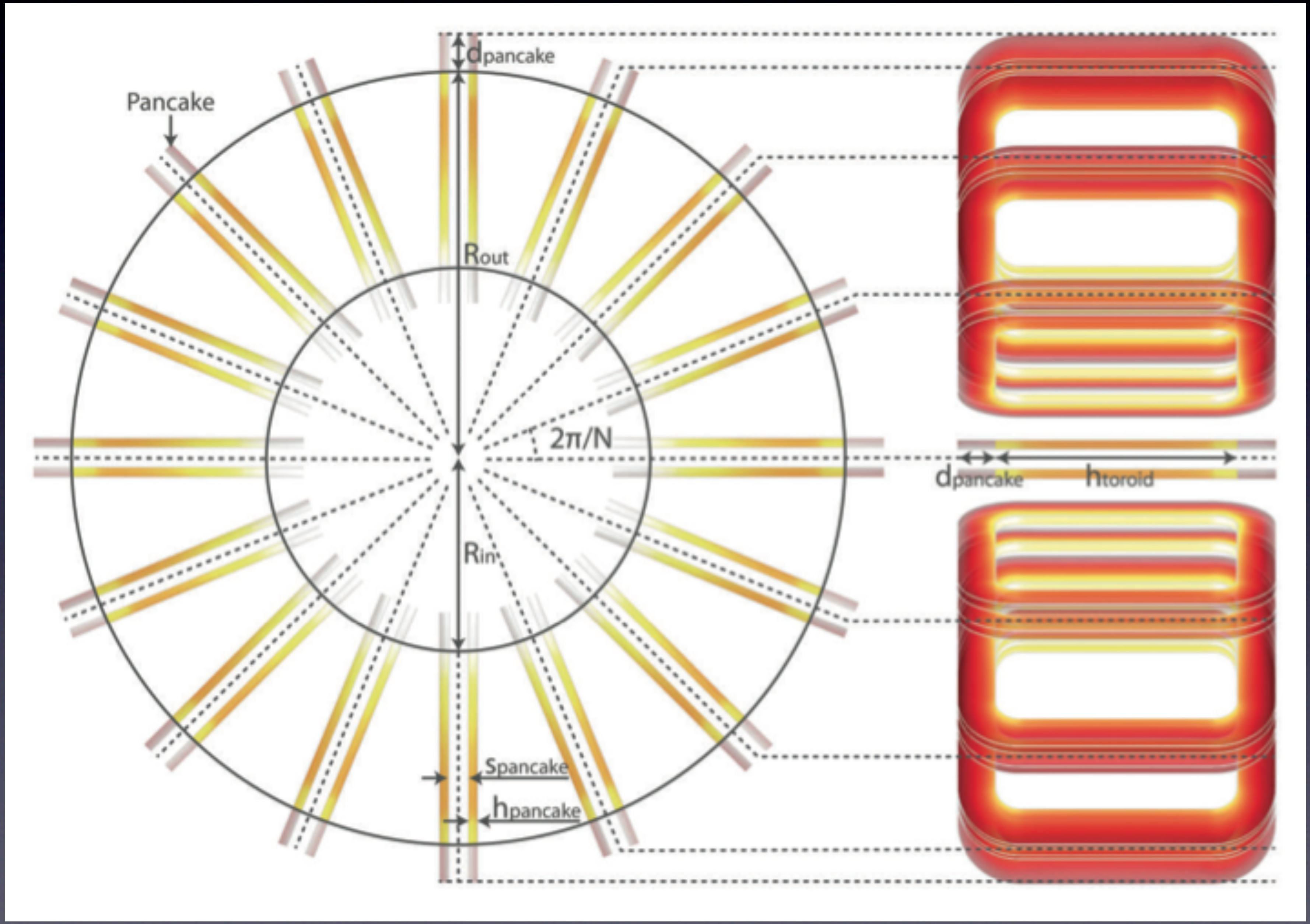
Towards a IAXO Magnet

Toroid Set of Parameters



Towards a IAXO Magnet

Results - Behind Option

- The results presented here are calculated with $N = 8$ and $R_{cen} = 1100$ mm
- The MFOM will be higher when using a thinner coil so that the open aperture is larger $2 \times h_{pancake} + s_{pancake} = R_{spot}$.
- The use of the thinner, two single pancakes cable, increases the MFOM by 12% relative to a thicker, two double pancake cable.
- Then, the "behind" option yields a maximal MFOM of ~990 relative to the current CAST MFOM with radii $R_{in} = 920\text{mm}$ and $R_{out} = 1300\text{mm}$.

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Towards a IAXO Magnet

Results - Between Option

- The "between" option shows that a maximum exist for R_{in} only, where the MFOM is increasing as R_{out} increasing.
- The maximum is at $R_{in} = 850 \text{ mm}$.
- Setting $R_{out} = 1850 \text{ mm}$, the MFOM is ~1140 times better than CAST.
- The between option gives a ~15% gain compared to the behind option.
- ***Important to remember:*** These results are obtained from the ***critical*** magnetic field.

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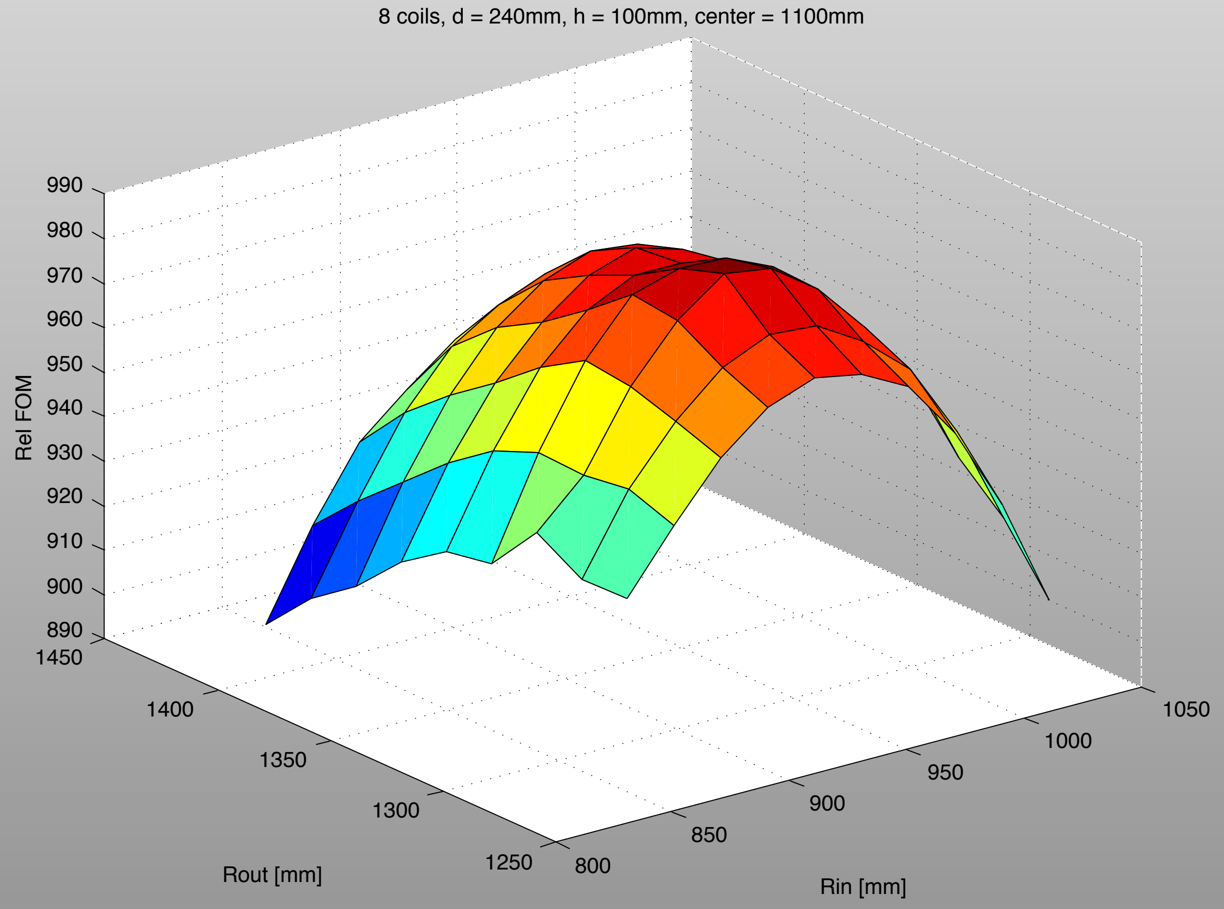
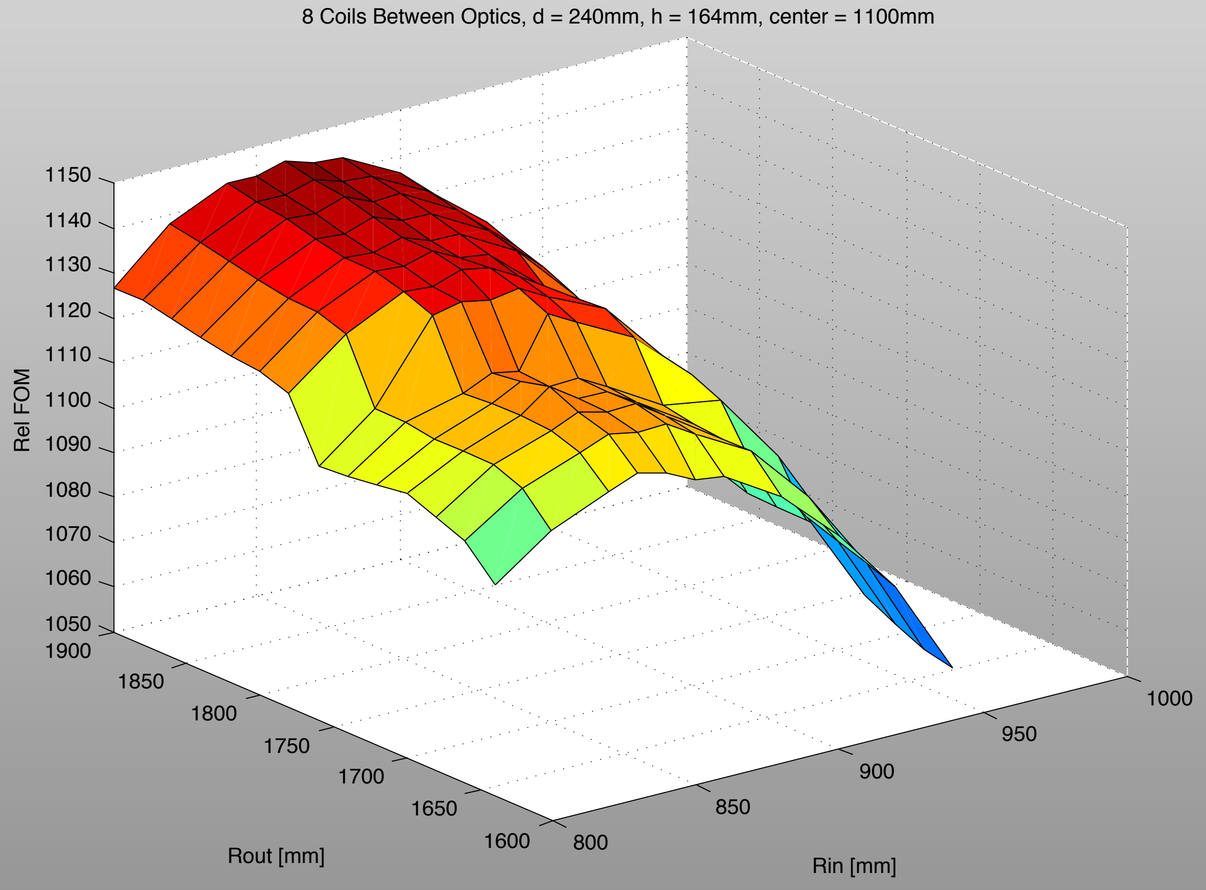
Towards a IAXO Magnet

Results - Graphs



“Behind”



“Between”

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An Initial Concept

Initial and Plausible to Manufacture

- The study of the geometrical optimization of the MFOM may lead us to suggest a basic initial design concept that will address all the physics requirements from the magnet while relying on known and familiar engineering solutions.
- This allows to present a magnet design which is expected to be plausible to manufacture.
- The basic initial design concept of the IAXO magnet supports the decoupling of the magnet system from the rest of the systems which are taking part in the experiment.
- This basic design will also allow for open bores in between the magnet's coils, in accordance with the geometrical study, which will simplify the use of physics experimental instrumentation.

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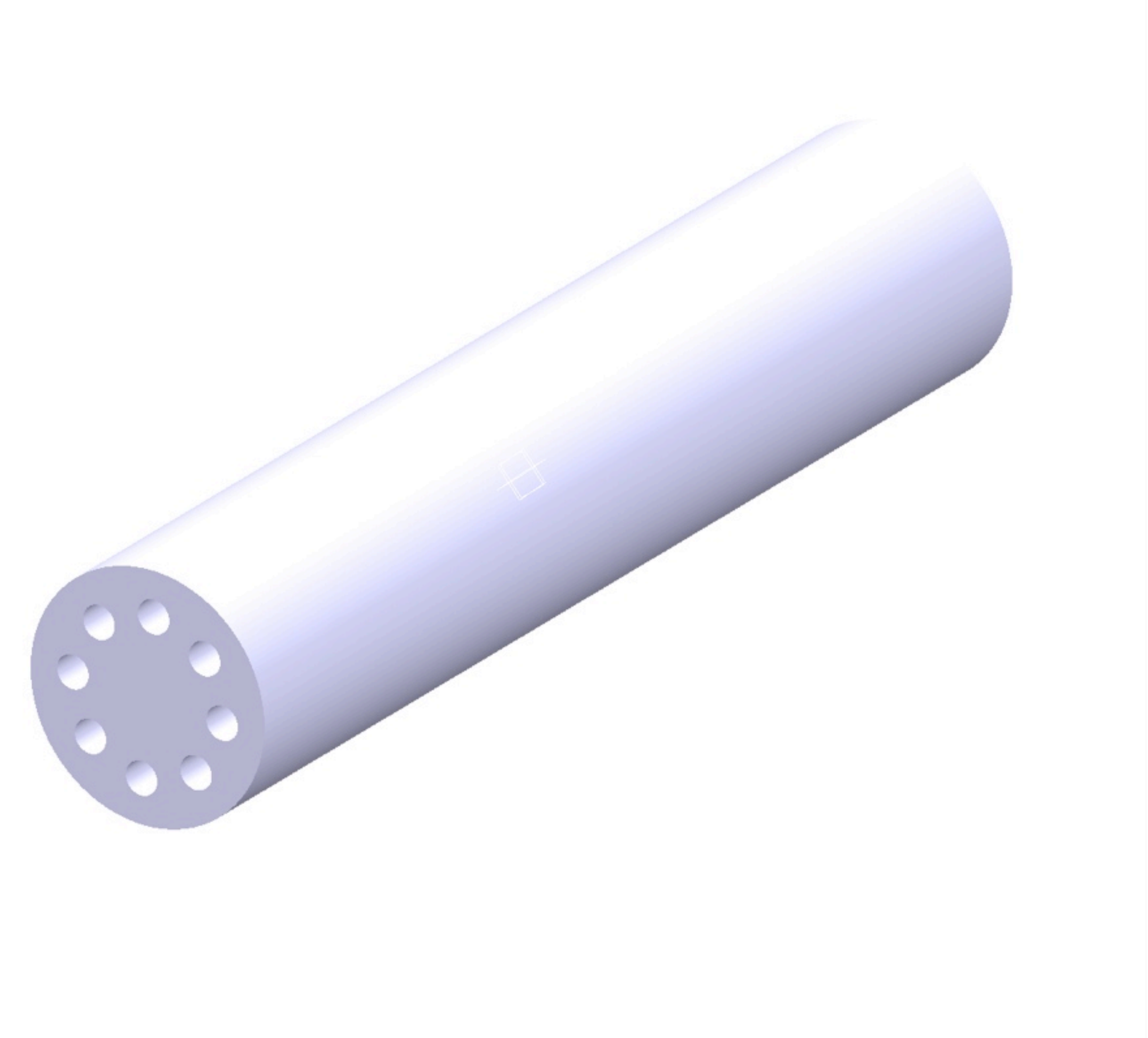
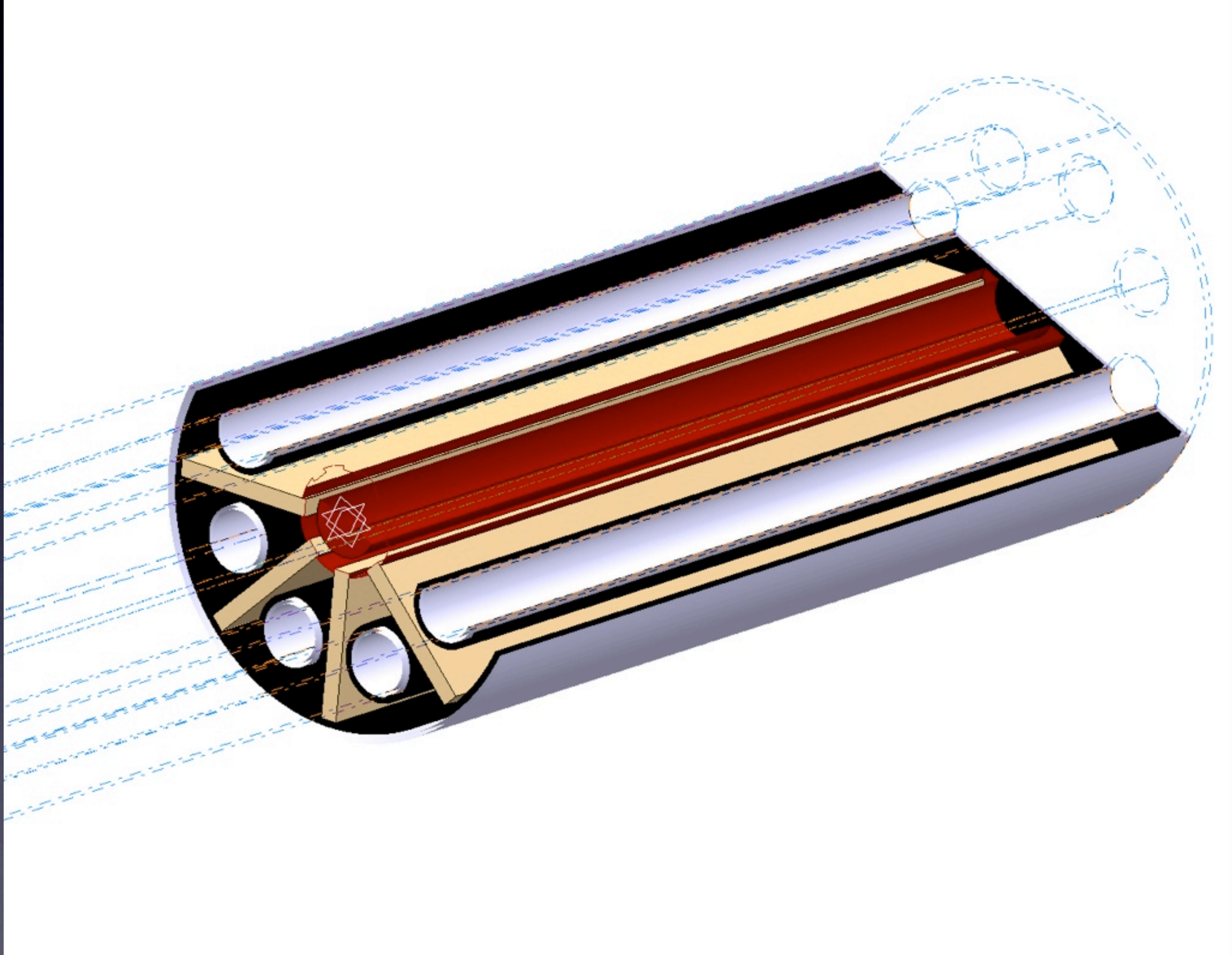
An Initial Concept



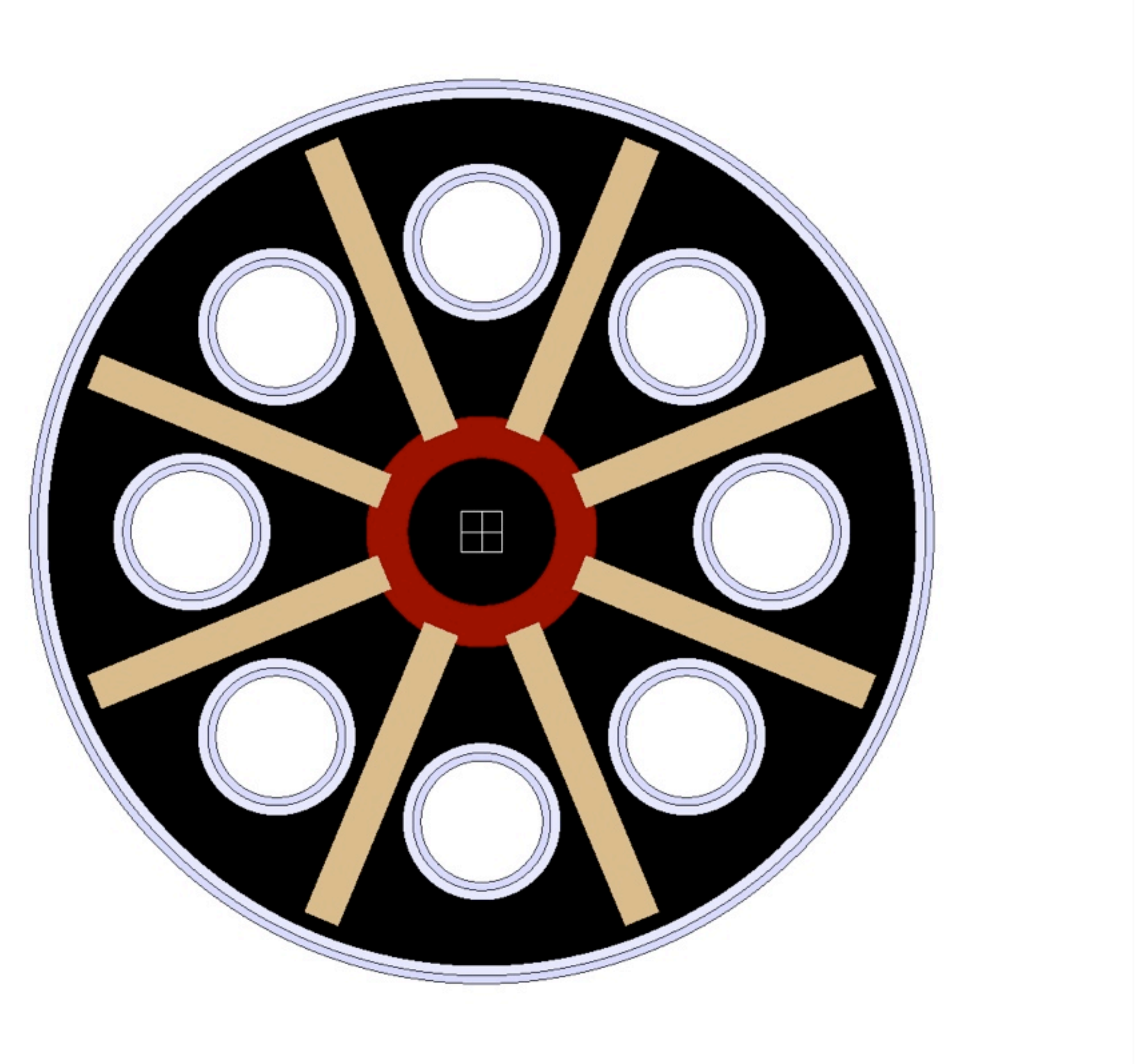
An Initial Concept

Side Cross Section



An Initial Concept

Front Cross Section



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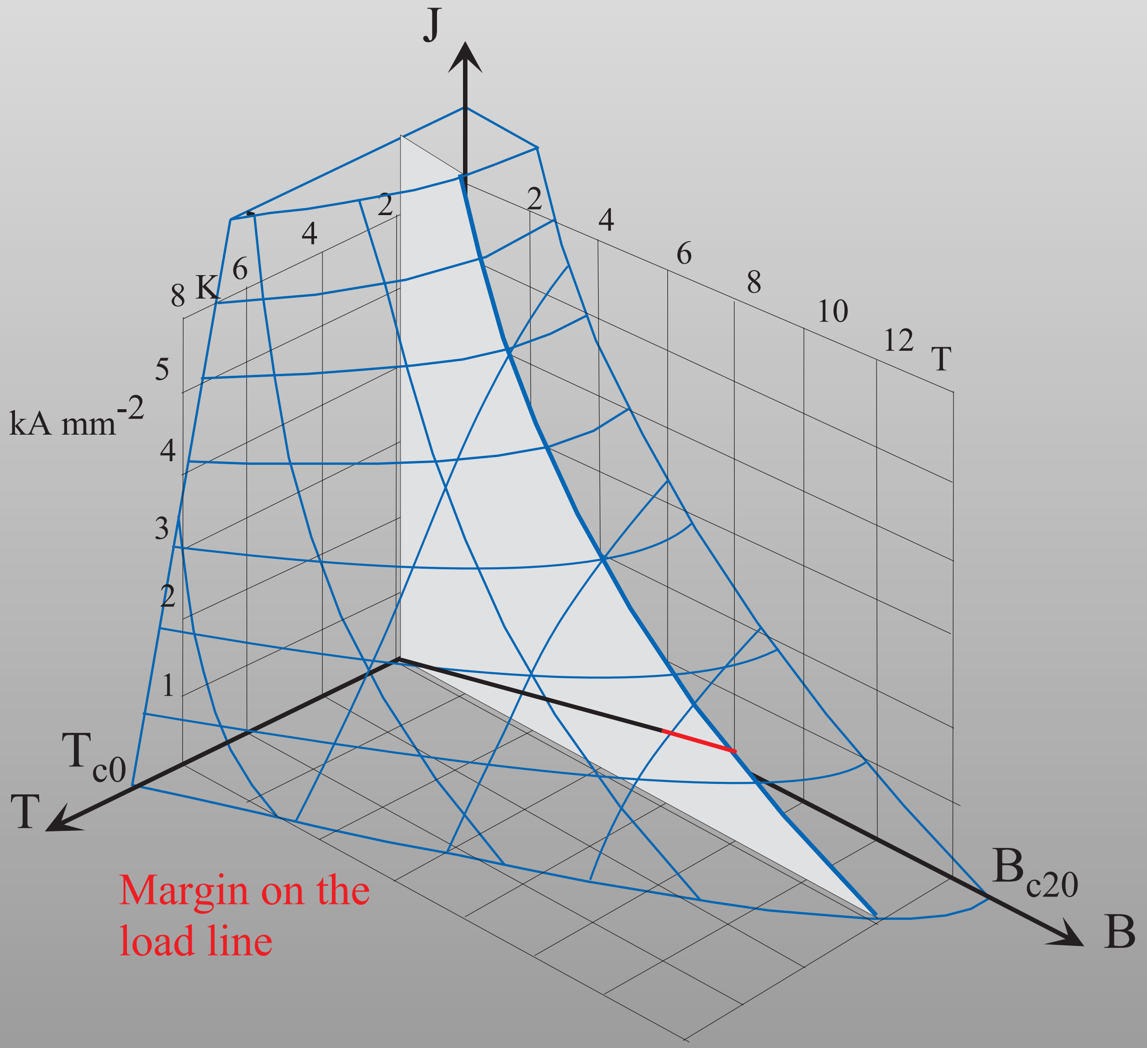
An Initial Concept

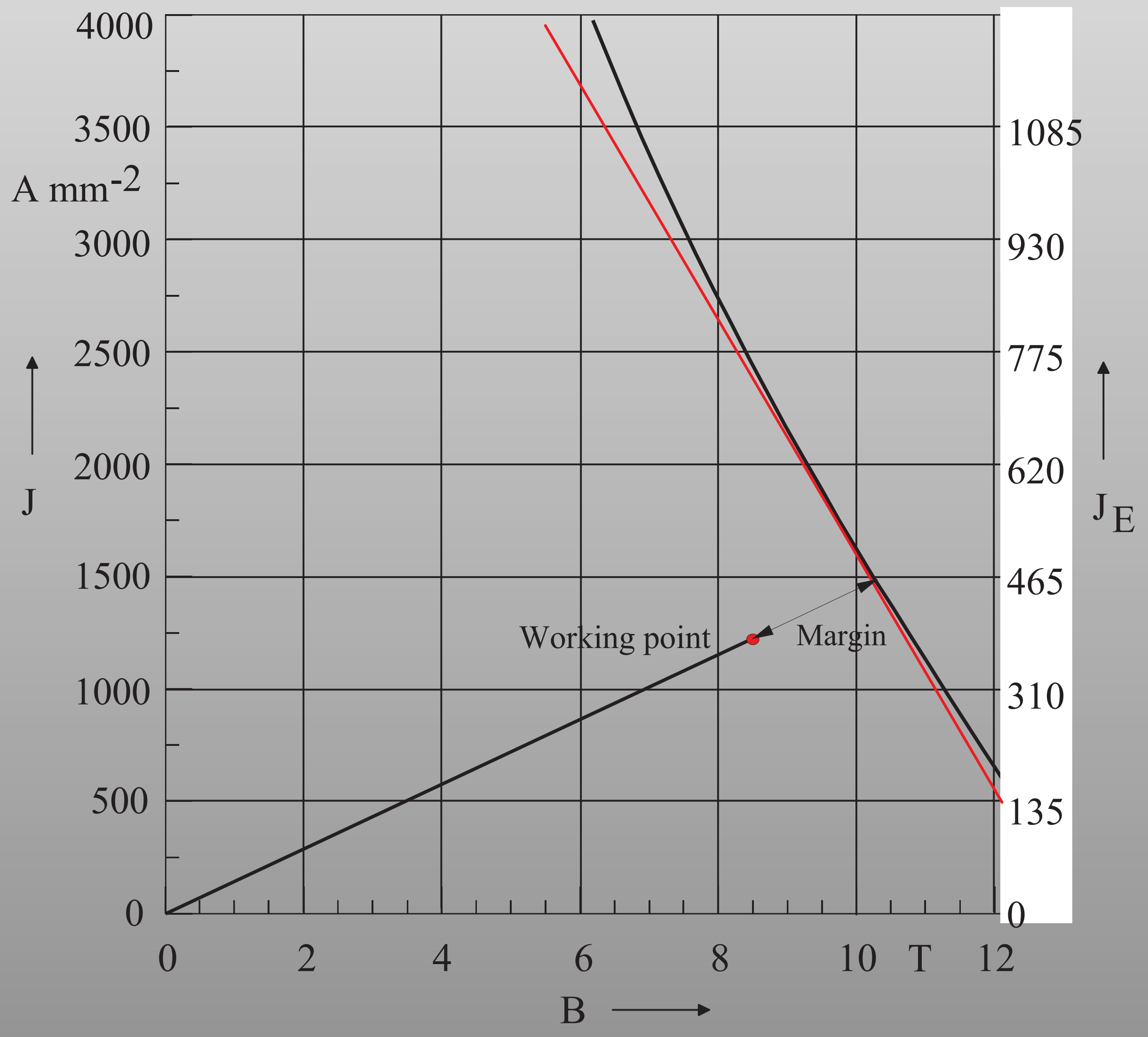
Vessel Bores

- The basic concept presents a coil casing, a cylindrical support for the magnetic forces, a thermal shield and a vacuum vessel.
- The expected mass is ~330 tones with stored energy of ~350 MJ.
- An important point is the location of the open bores in between each pair of coils: The magnet needs to be separated from these holes by a cryostat and a thermal shield in order to keep it in its individual vacuum and to protect it from thermal radiation.
- In the initial proposed design R_{cen} is increased to 1430 mm, which results in a $\sim 30\%$ decrease in the MFOM.

8 Concluding Remarks

Operational Margin





Courtesy of Stephan Russenschuck

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Concluding Remarks

Initial Concept - Summary

Rin	1.05 m
Rout	2.05 m
Rcen	1.43 m
Length	20 m
Bc	9.8 T
Jc	116 A/mm^2
Average Field in Bores (Bc)	4 T
Relative MFOM	770
Stored Energy (Bp = 0.5*Bc)	350 MJ
Mass	330 Tones

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Concluding Remarks

An Open Discussion