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Theoretical Physics

Potential use of permanent magnets in experiments searching for light dark matter

Accelerating the Search for Disappearing Light Dark Matter – Workshop, Bonn, Germany
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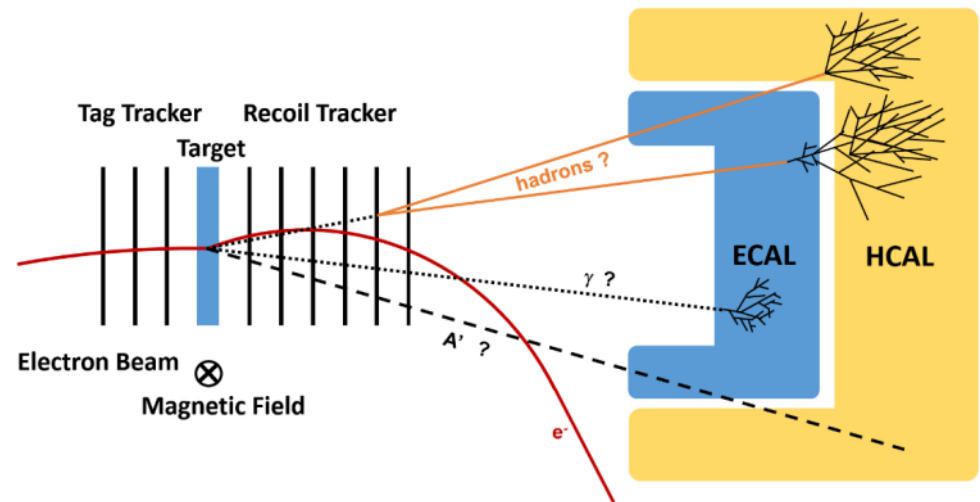
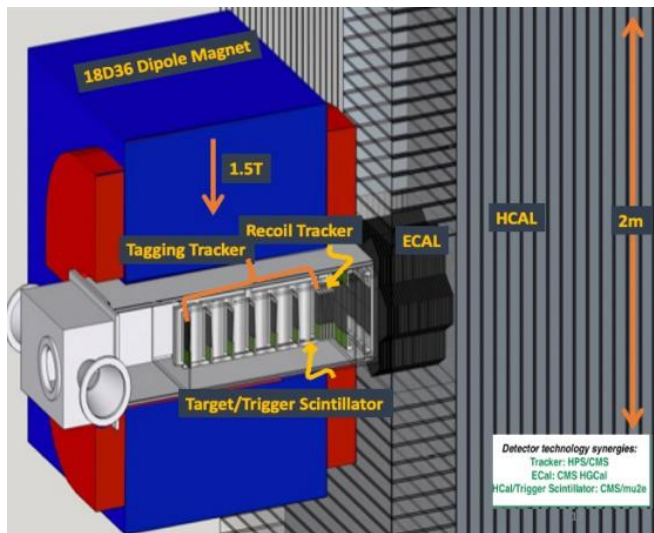


Outline

- ❖ Introduction to magnets required for experiments searching for light dark matter
- ❖ Normal conducting dipoles in experimental areas
- ❖ Permanent magnet-based designs
- ❖ Example of Faser dipoles
- ❖ Example of n-Tof dipoles
- ❖ Design proposal for Lohengrin experiment
- ❖ Conclusion

Dipole magnets to curve e^- beam in experiments searching for light dark matter

- Aperture dimensions compatible with integration of target and tracker elements.
- Field levels of 0.7 T (Lohengrin) to 1.5 T (LDMX).
- Length of 1 m to 1.5 m.
- Reasonable manufacturing and operating costs.



Pictured: layout of LDMX (left) and Lohengrin (right) experiments

Normal conducting dipoles in experimental areas

For decades, normal conducting magnets are largely used in experimental areas:

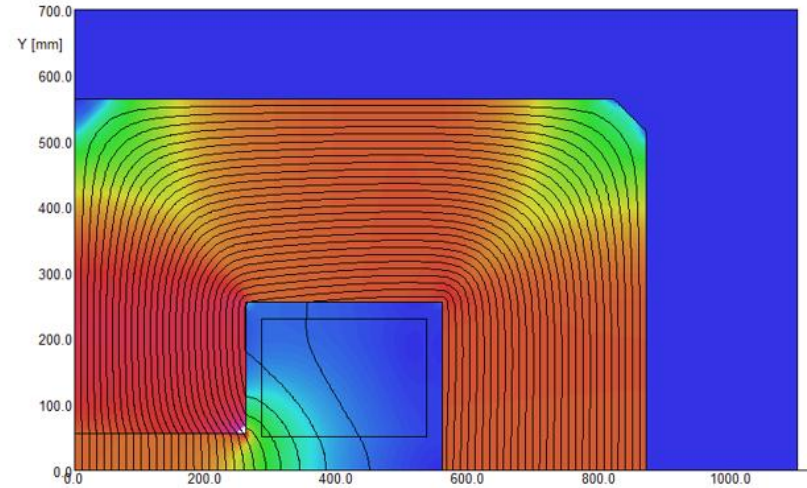
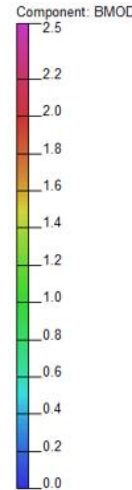
Pros:

- ❑ Well established technology.
- ❑ Equipment potentially available that could be re-used (magnets, power convertors, electrical and water networks).
- ❑ Reliable operation even in areas with high radiation levels.

Cons:

- ❑ High operational cost (especially for magnets operated in DC).
- ❑ Large and heavy magnets when large apertures are required.
- ❑ Field limited due to steel saturation.

Normal conducting dipoles in experimental areas



- ❑ Efficiency drops for fields higher than 1.6 - 1.7 T in the aperture due to steel saturation.
- ❑ Large aperture dipoles require large coils that enlarge cross-section.

Parameter	Value	Unit
Length	1000	mm
Aperture	110	mm
Pole width	520	mm
Central Field	1.65	T
Weight	17000	kg

Pictured: example of the laminated version of the M100 dipoles used in CERN East area

Alternative: super-ferric dipoles

While superconducting magnet designs are generally used when high field and/or large aperture are required, super-ferric designs could be an option for experimental area dipoles:

Pro:

- ❑ Reduction of operational cost (electricity).
- ❑ Manufacturing not as challenging as superconducting magnets.
- ❑ Could be feasible to integrate superconducting coils in existing dipole yoke.
- ❑ Reduction of dipole cross-section for large aperture dipoles.

Cons:

- ❑ Requires cryogenic infrastructure and dedicated operators.
- ❑ Field still limited due to steel saturation.
- ❑ More challenging than NC magnets in high radiation environment.

To consider: permanent magnet-based designs

Pros:

- ❑ Designs can be very compact.
- ❑ No extra-length required at the extremity to fit the coils.
- ❑ Could be easier to find space for detector components than in a NC magnet design.
- ❑ Reliability as there is no risk of electrical failure or water leaks.
- ❑ The operation of the magnet does not require any electricity.
- ❑ No need of power convertor neither electrical or water networks.

Cons:

- ❑ Limited field driven by permanent magnet blocks size.
- ❑ Fixed field.
- ❑ Fluctuation of permanent magnet material price.
- ❑ Assembly can be challenging for large magnets.

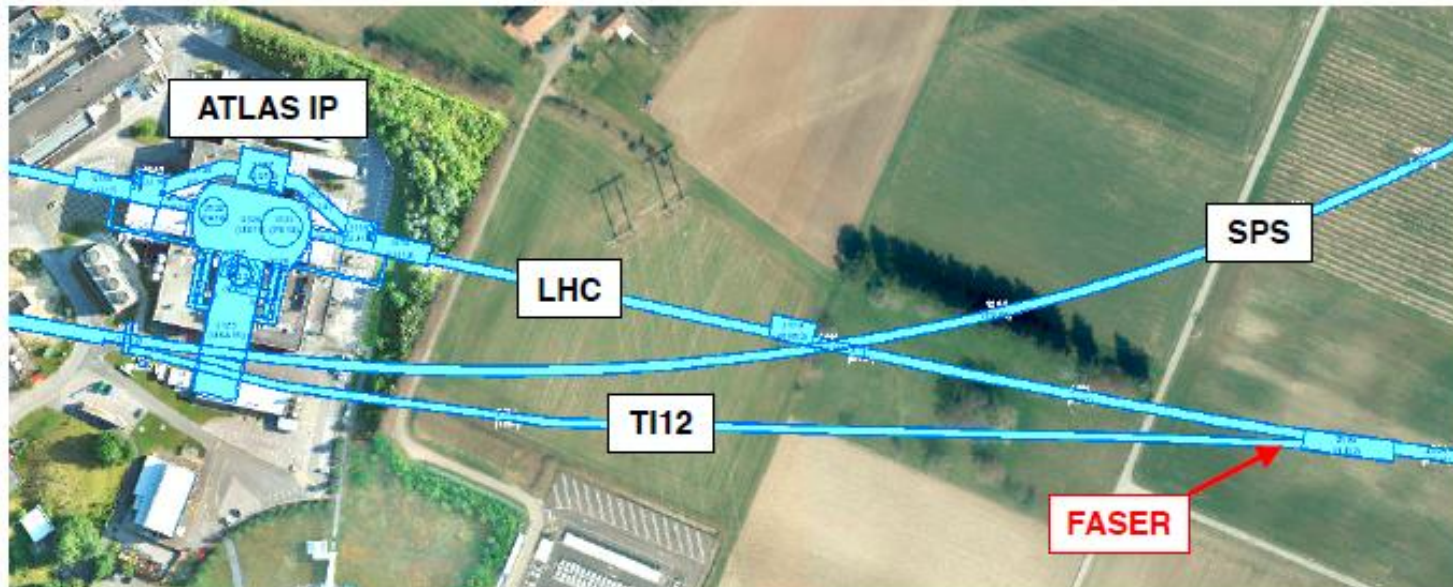
Example of Faser dipoles



Pictured: Faser detector installed next to ATLAS in LHC

Introduction to FASER experiment

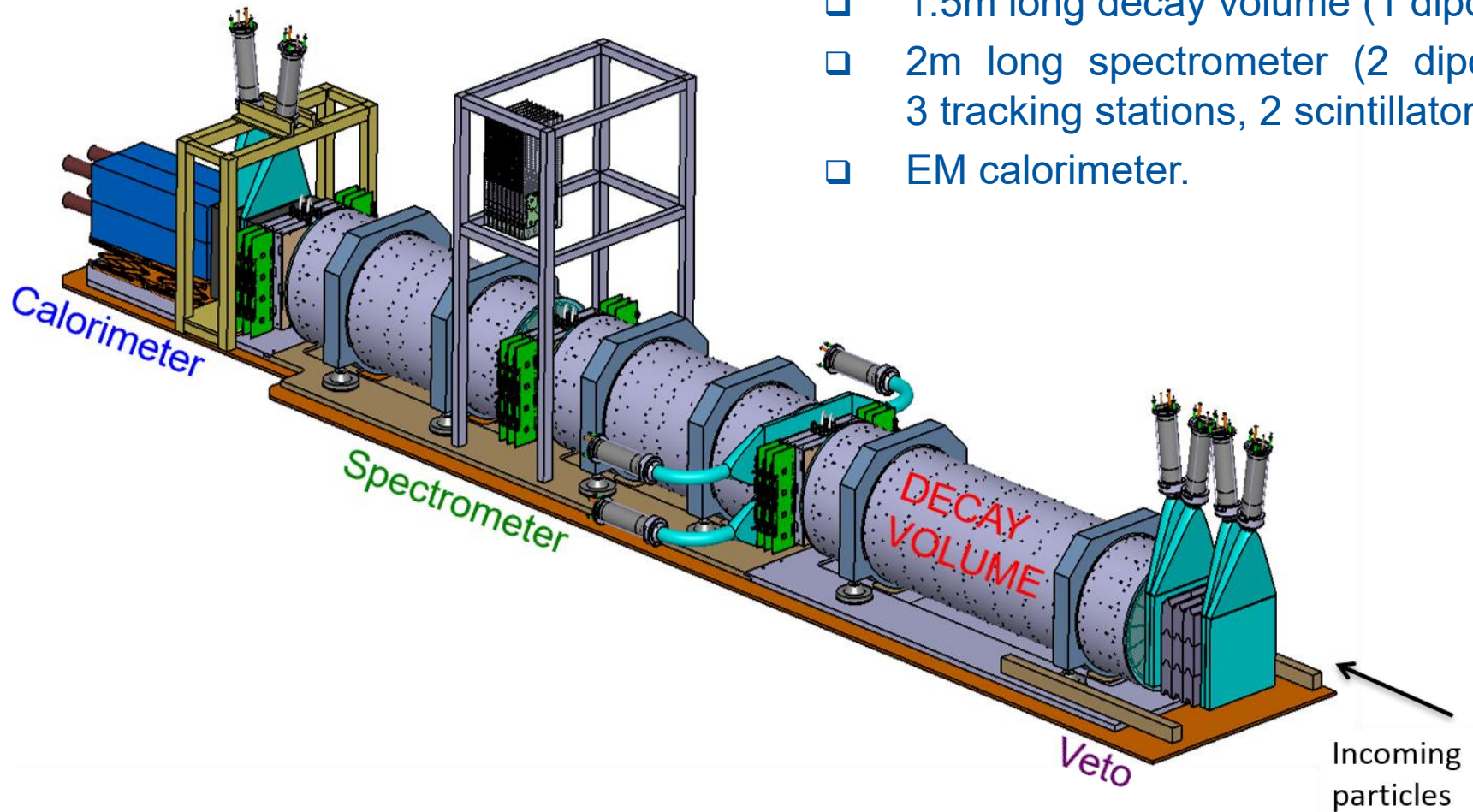
- ❑ FASER, the ForwArD Search ExpeRiment (<https://faser.web.cern.ch>) was installed in LHC service tunnel TI12 and is running since 2022.
- ❑ It is designed to detect potential light and weakly interacting particles that could be produced parallel to the proton beamline during the proton-proton collisions in ATLAS experiment.
- ❑ These long-lived particles would follow the collision axis direction without interaction with magnetic field and then after few hundred meters decay to standard model particles, for example, electron-positron pairs.
- ❑ Located along the beam collision axis line of sights (LOS) at 480 m from IP.



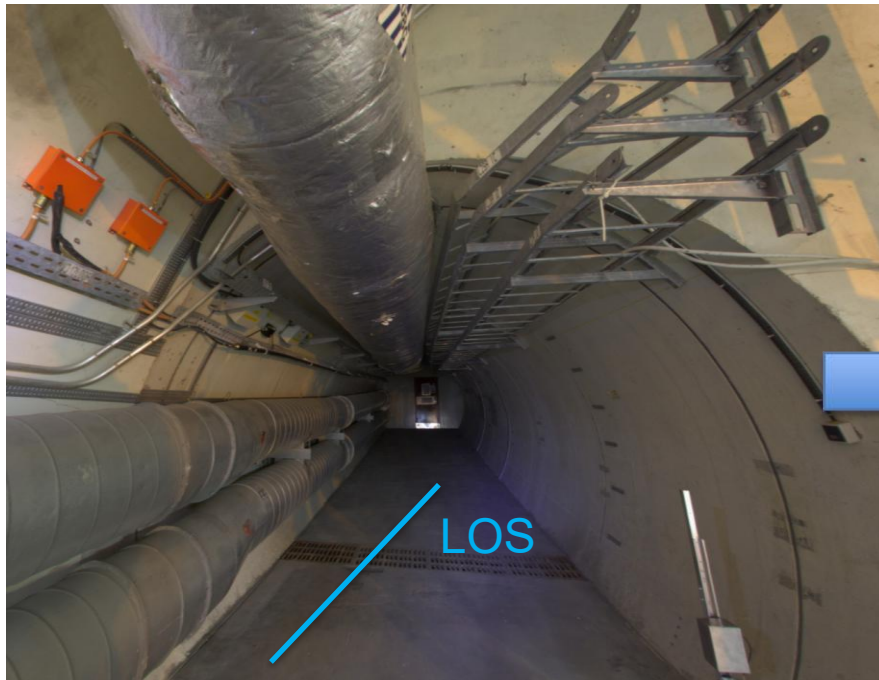
FASER detector

The detector consists of:

- ❑ Scintillator veto.
- ❑ 1.5m long decay volume (1 dipole).
- ❑ 2m long spectrometer (2 dipoles, 3 tracking stations, 2 scintillators).
- ❑ EM calorimeter.

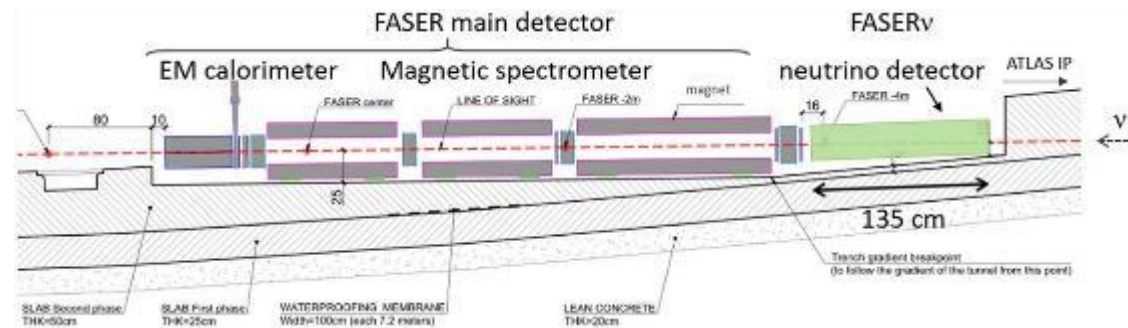


FASER in LHC TI12 tunnel



TI12 tunnel has a slope:

- ❑ Need excavation to align FASER with the LOS.
- ❑ Excavation limited due to tunnel structure.



Tight constraints for the magnets

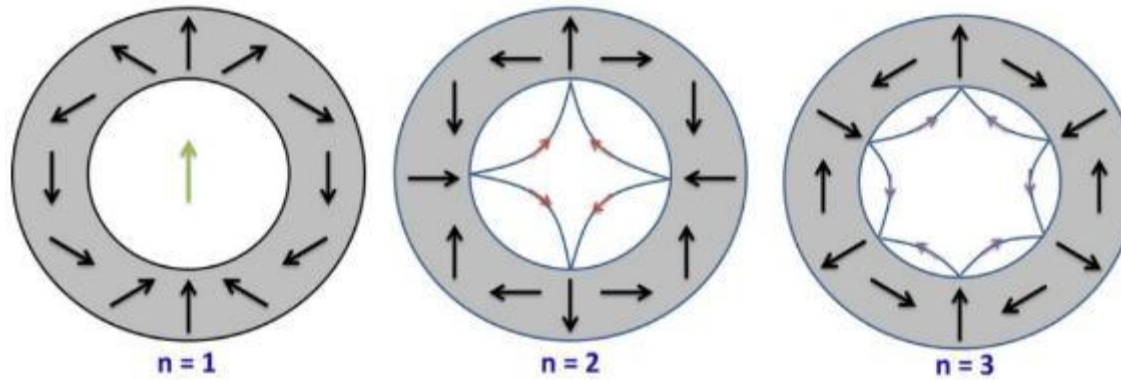
- ❑ Space constraints due to civil engineering structure.
- ❑ Large aperture with significant field.
- ❑ Limit the impact on general infrastructure (power supply, different networks).
- ❑ Budget compatible with FASER project.

Parameter	Value	Unit
Number of dipoles	3 units (1 of 1.5 m long and 2 of 1 m long)	
Length	1000 and 1500	mm
Height from beam axis to floor	≤ 250	mm
Width from beam axis to tunnel structure (at the base)	≤ 250	mm
Aperture diameter	200	mm
Central field	≥ 0.55	T
Good field region (GFR) diameter	200	mm
Integrated field homogeneity in GFR	± 5	%

A design based on permanent magnets (Halbach array) was retained because it is very efficient to produce a high and homogeneous field with a compact design.

Halbach array

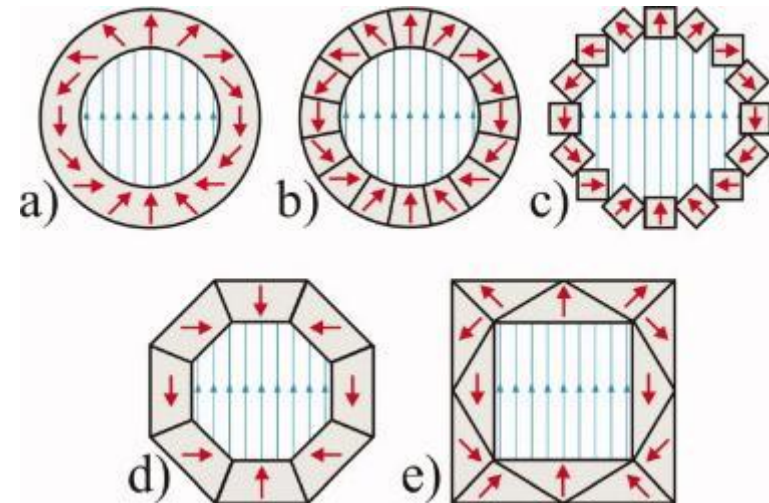
The physicist Klaus Halbach imagined in the 1980s some arrays to design magnets used in particle accelerators.



A formula exists to approximate the field in a dipole (valid for type a or b in right picture):

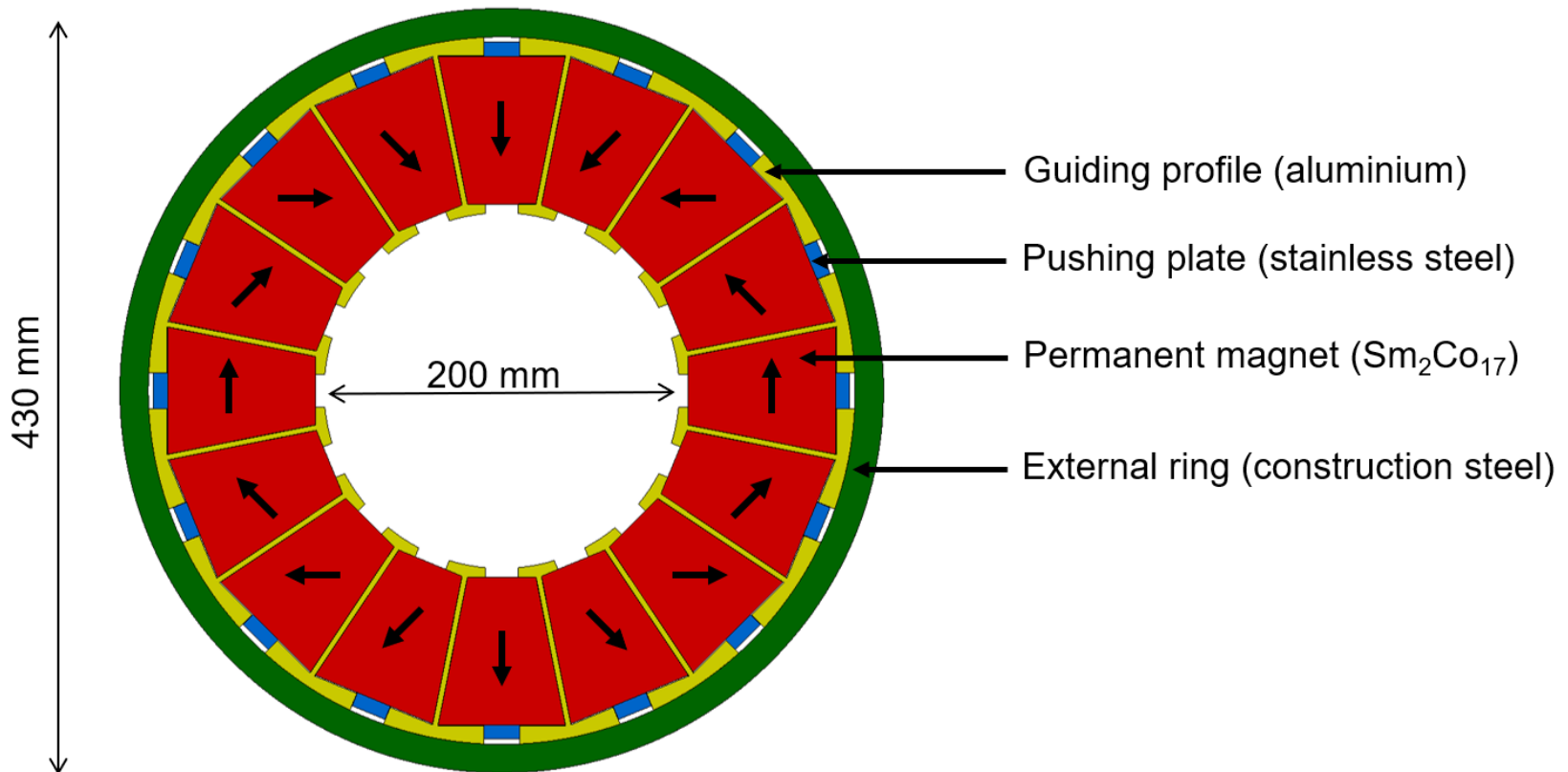
$$B = B_r \cdot \cos(\pi/M) \cdot \ln(R/r)$$

B_r: remanent field; *M*: number of segments; *R*: outer radius;
r: the inner radius.



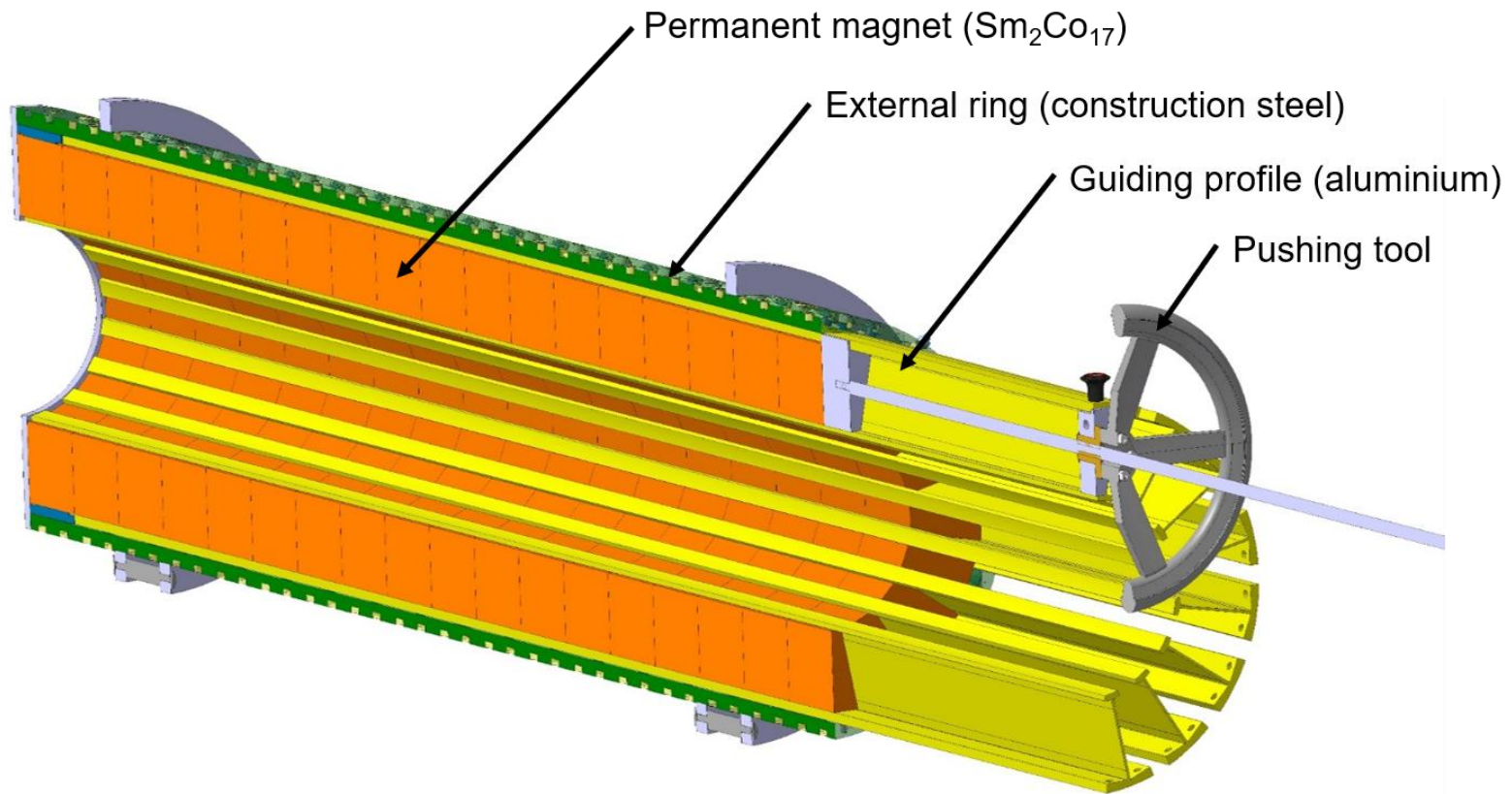
FASER dipole general view

- Often the assembly of magnets based on Halbach array is critical due to strong magnetic forces and the permanent magnet blocks are glued together.
- For FASER dipoles a novel design was proposed with an external ring made of construction steel holding some guiding profiles used to insert the permanent magnet blocks.

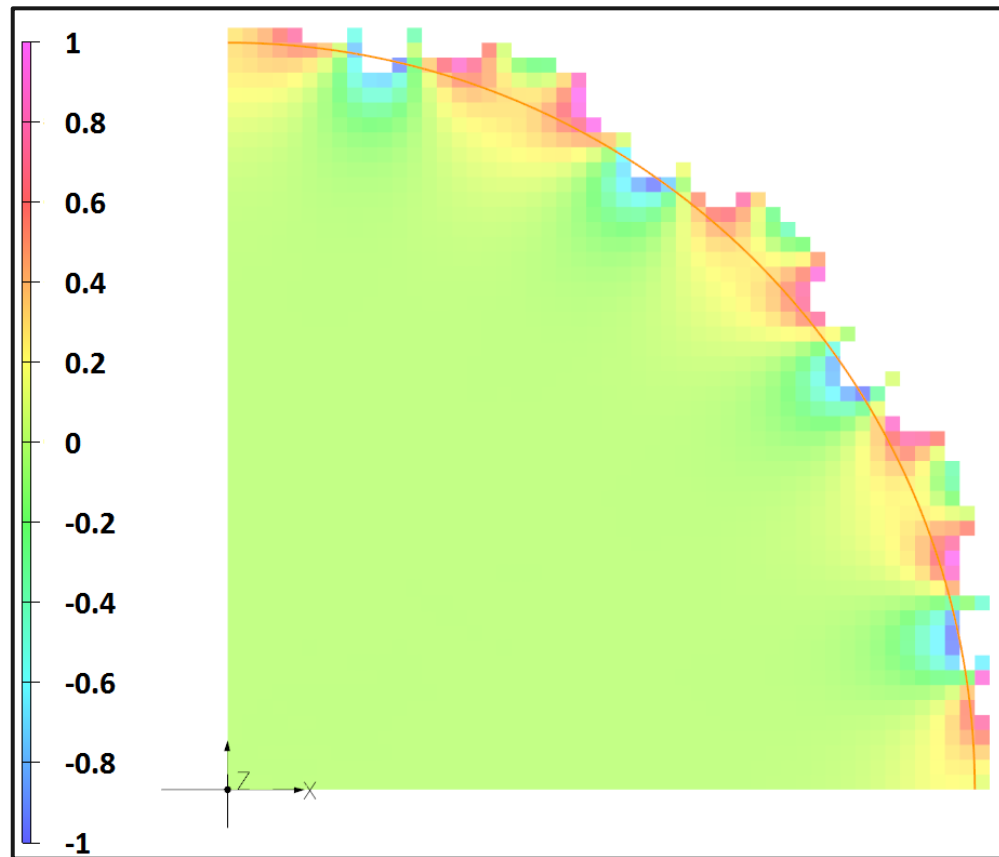
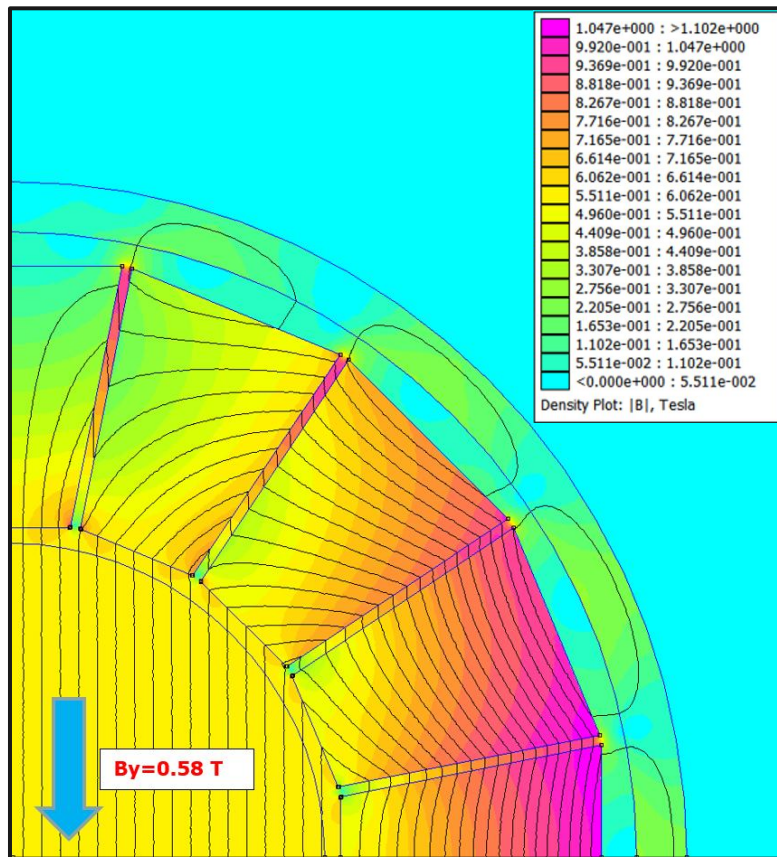


FASER dipole general view

- ❑ The aluminium profiles are used to guide the permanent magnet blocks during assembly.
- ❑ At the end of the assembly the extra length of the aluminium profiles (outside the yoke) is cut.



Magnetic design

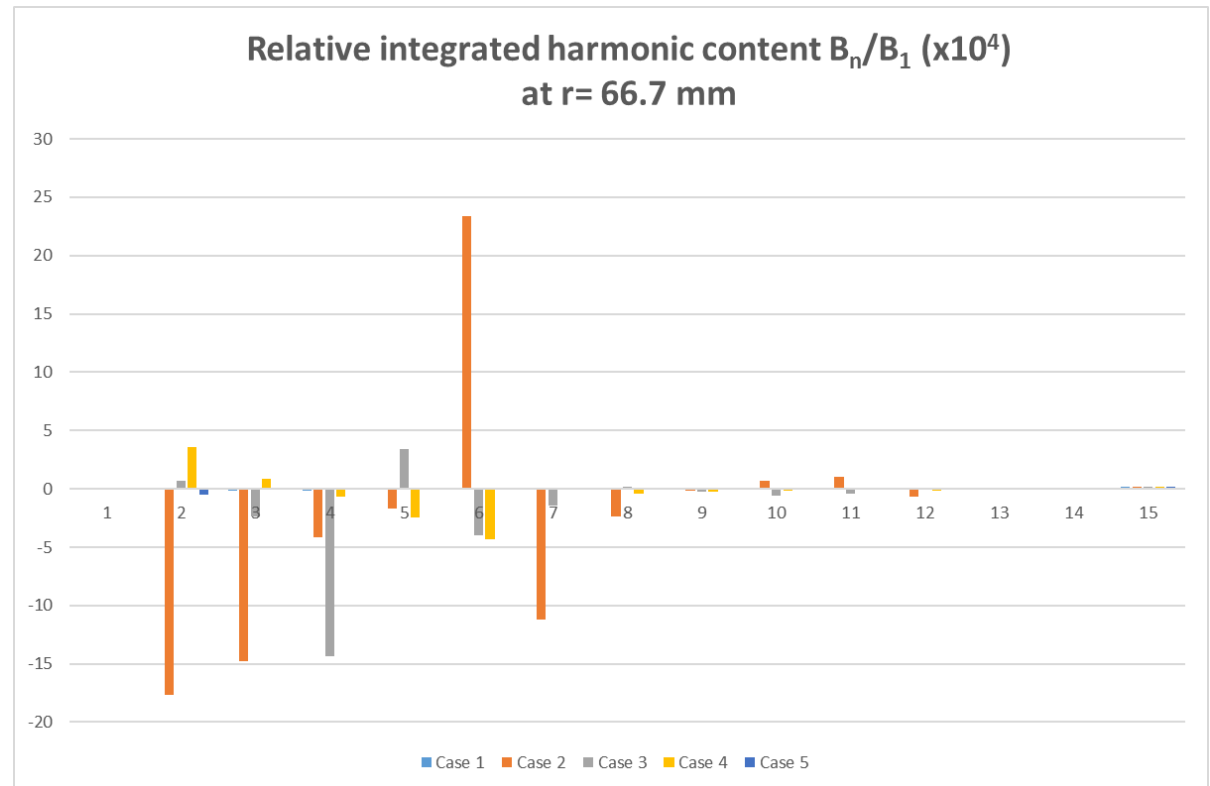


Pictured: 2D field distribution (left) and integrated field homogeneity in % inside a radius of 100 mm (right)

Effects of PM blocks imperfections and external structure on field quality



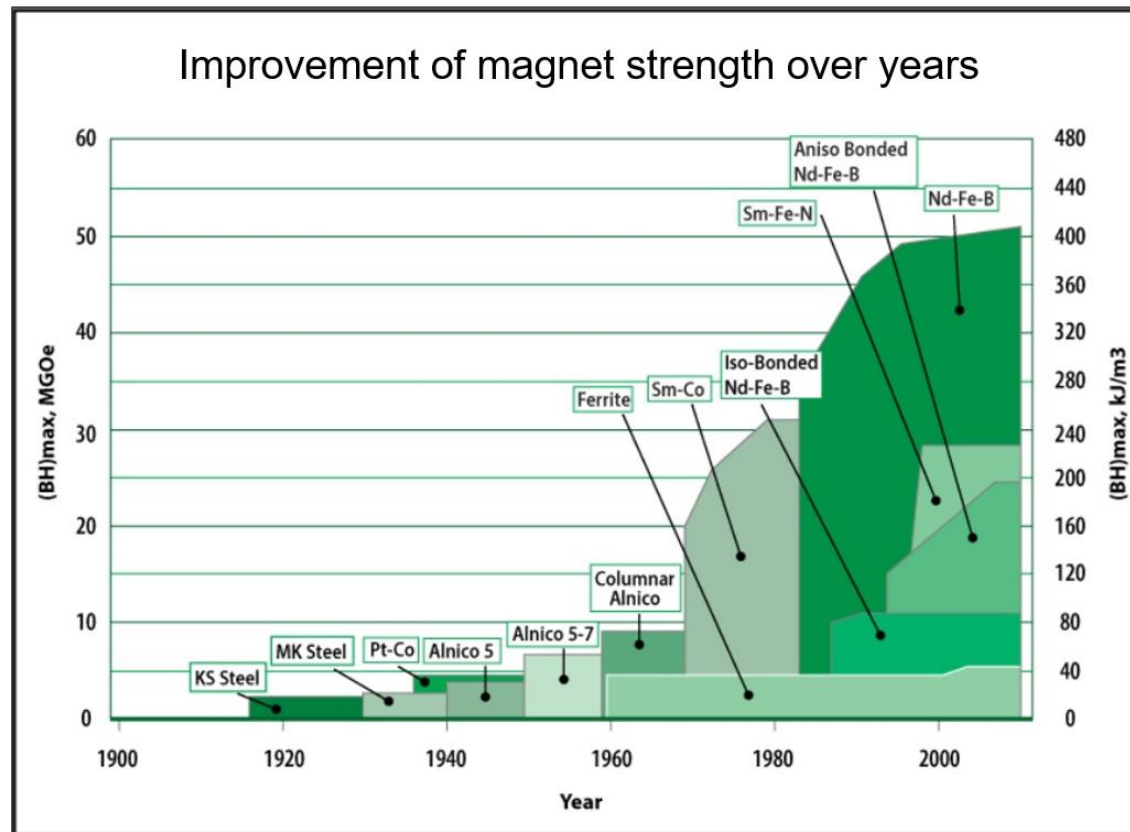
- Case 1: Ideal case
- Case 2: Magnetization direction misaligned by 5° on 5 lines
- Case 3: Positioning error of 0.5 mm on 5 lines
- Case 4: Deviation of magnetic characteristics by $\pm 2\%$ on 5 lines
- Case 5: 50 mm thick steel plate located 50 mm under the dipole



Why Samarium Cobalt?

Neodymium (NdFeB) magnets have higher magnetic characteristics (remanence, coercivity) than Samarium Cobalt (SmCo) magnets but in our case the SmCo has some advantages:

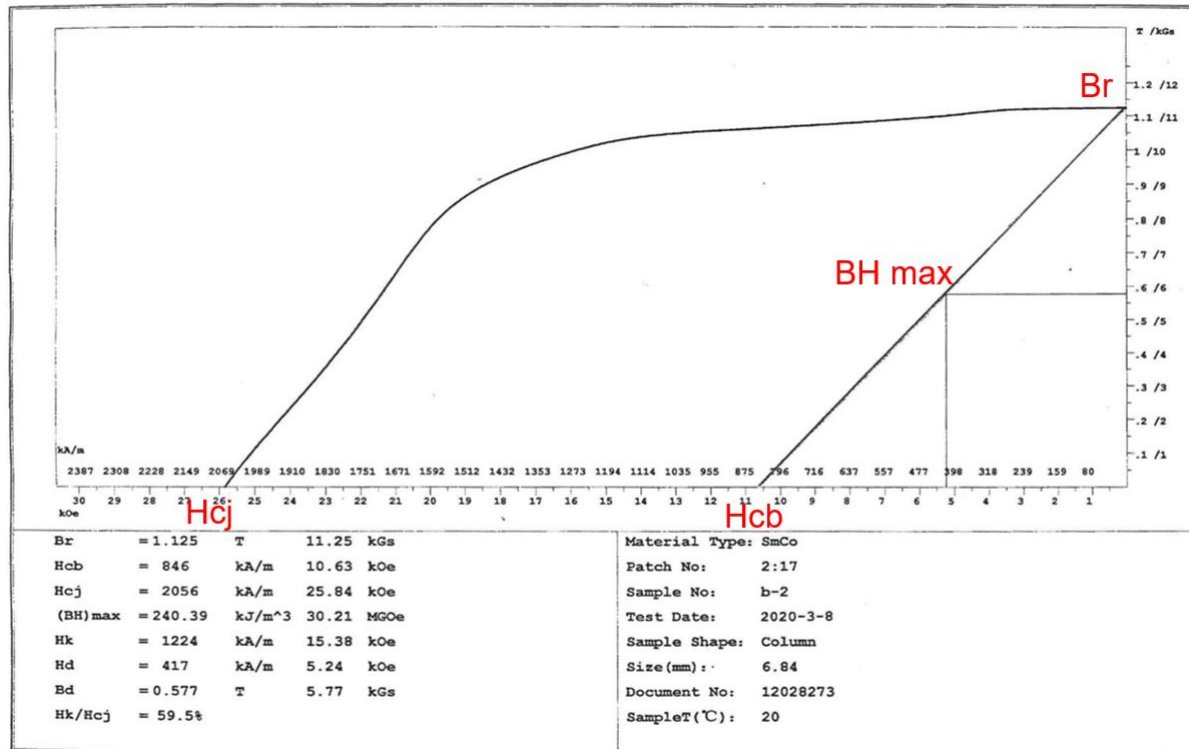
- ❑ SmCo has a small temperature coefficient: $-0.035\%/^{\circ}\text{C}$.
- ❑ SmCo has a good radiation resistance.
- ❑ SmCo has an acceptable corrosion stability even without protective coating.



Material characteristics

The following material was selected to fulfils the design constraints:

- ❑ Material with high energy product (≈ 30 MGOe).
- ❑ High remanent field $Br \geq 1.11$ T and coercivity $H_{cb} \geq 830$ kA/m.
- ❑ High intrinsic coercivity $H_{cj} \geq 1990$ kA/m to avoid any risk of demagnetization.
- ❑ ± 5 deg maximum error of easy axis orientation.
- ❑ Mechanical tolerance of the blocks: ± 0.1 mm.

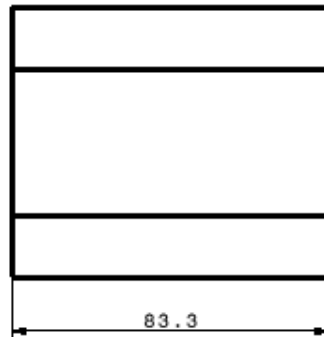
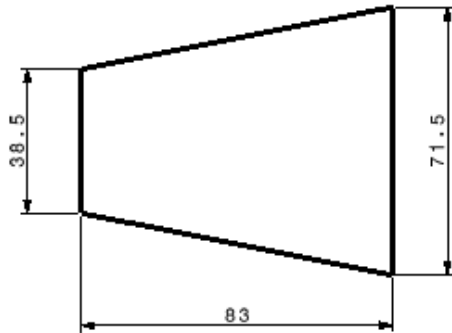
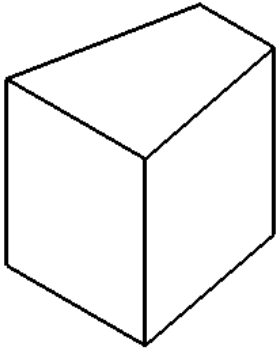


Pictured: demagnetization curve of PM material used for Faser

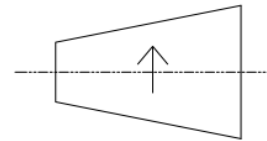
AUTOMATIC HYSTERSIGRAPH MODE AMT-4 SJ LTD.

Permanent magnet blocks

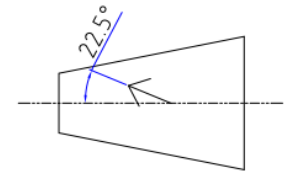
672 trapezoidal permanent magnet blocks with 5 different magnetization directions are necessary for the production of the 3 dipoles. This represents 2130 kg of magnets.



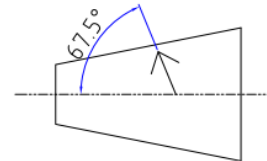
MODEL 1
Radial
magnetization
direction



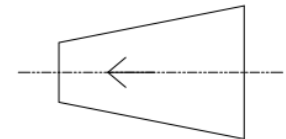
MODEL 4
Magnetization
direction: 22.5°



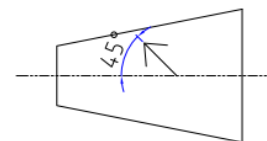
MODEL 2
Magnetization
direction: 67.5°



MODEL 5
Axial magnetization
direction



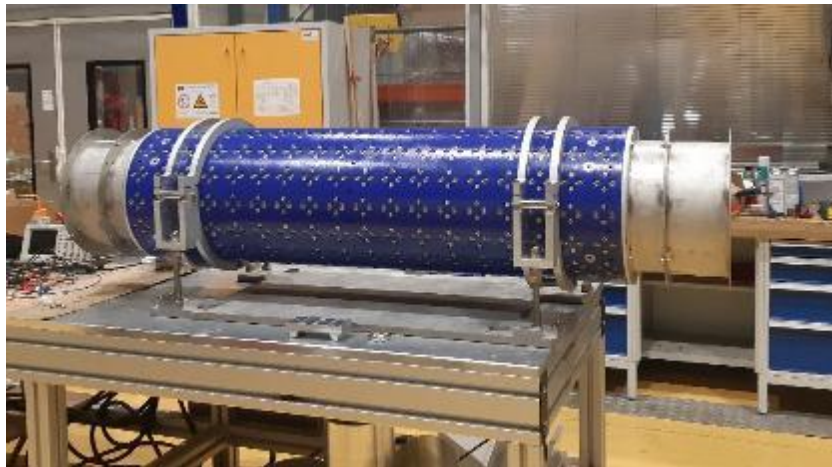
MODEL 3
Magnetization
direction: 45°



Dipole assembly



Assembly of the dipole yoke including steel ring and aluminium profiles.



Cutting of the extra length of the aluminium profiles and installation of protection covers to create a physical barrier to the magnetic field.

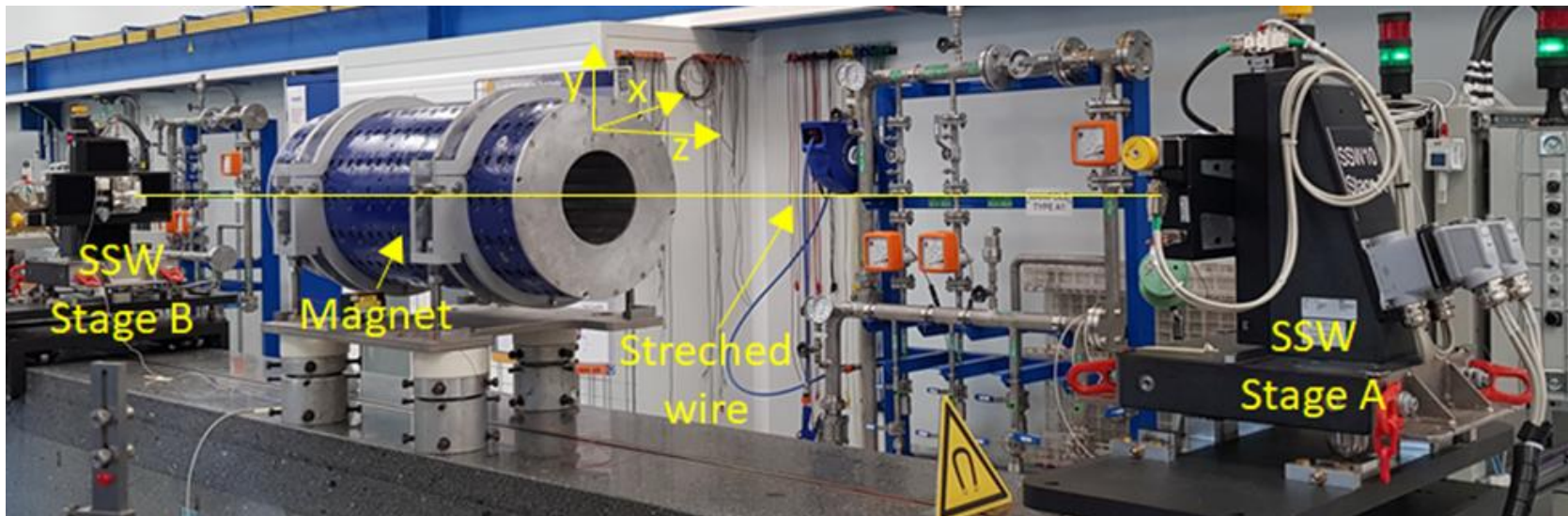
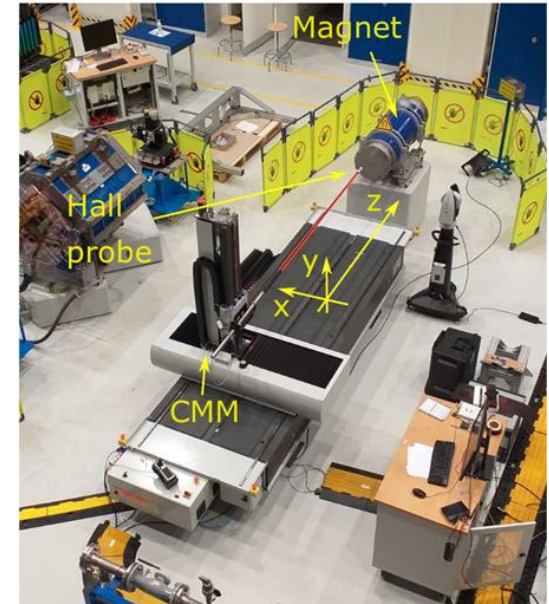


Insertion of each PM blocks (16 segments per row). 12 rows for the 1-m long version and 18 rows for the 1.5-m long version.



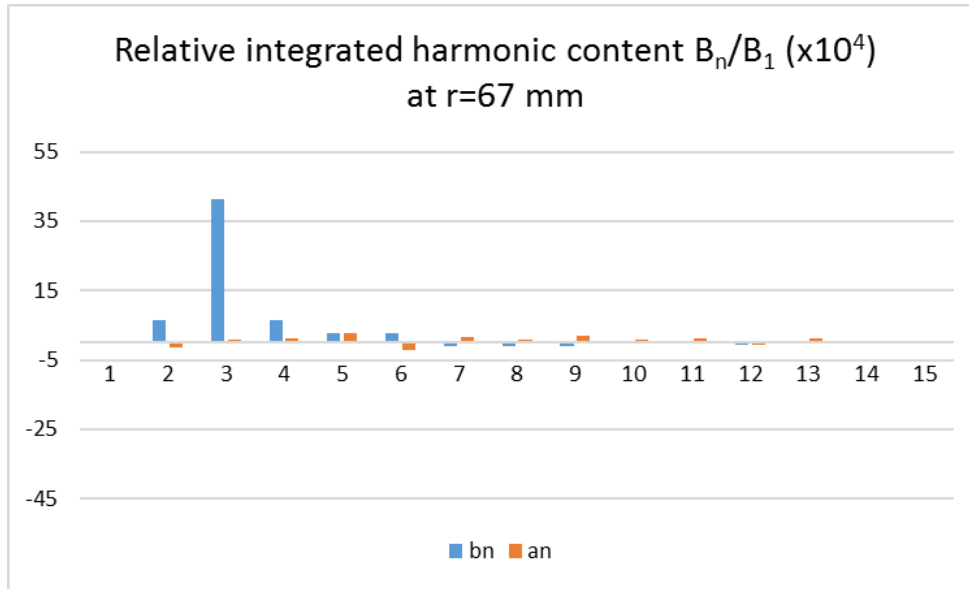
Magnetic measurements

- ❑ The field integral and the multipole analysis was measured on the stretched wire bench.
- ❑ A mapping of the dipole aperture was done with the field mapper.
- ❑ Perfect fit between stretched wire measurements and integrated values from field mapper measurements.



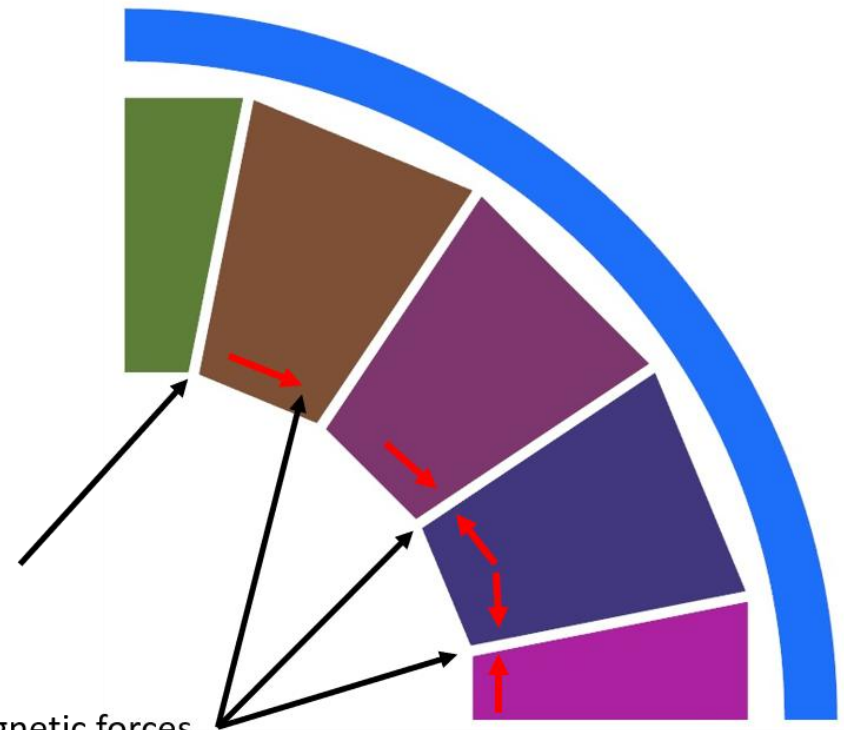
Magnetic measurements

On harmonic analysis, we observed a b_3 component which is larger than the designed value. It is not problematic for Faser detector, but it shall be taken in consideration for other projects. It is due to forces during assembly which create some small gaps between the magnet blocks.



Small gap inducing b_3

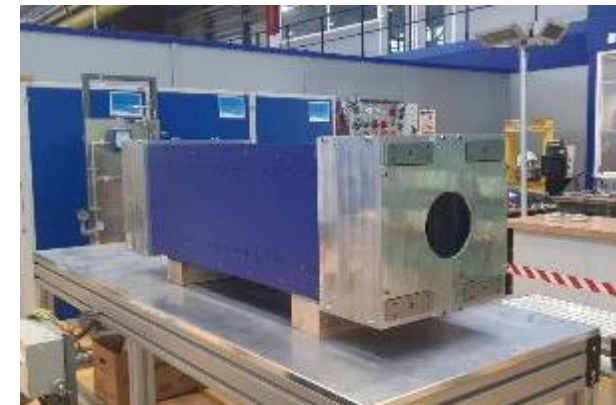
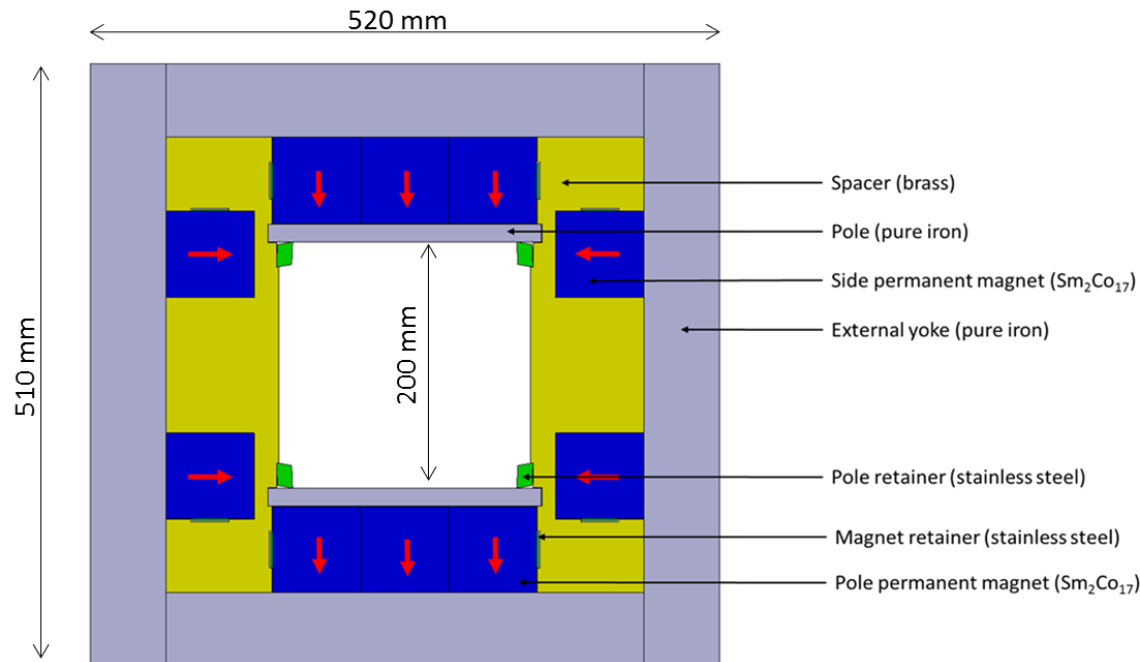
Strong magnetic forces



Example of nTof dipoles

A separator dipole installed after nTof spallation target was designed to replace a M200 normal conducting magnet (30 tons – 40 kW), mainly to save energy.

Parameter	Value	Unit
Length	1540	mm
Aperture	200	mm
Central Field	0.39	T
Weight	2600	kg

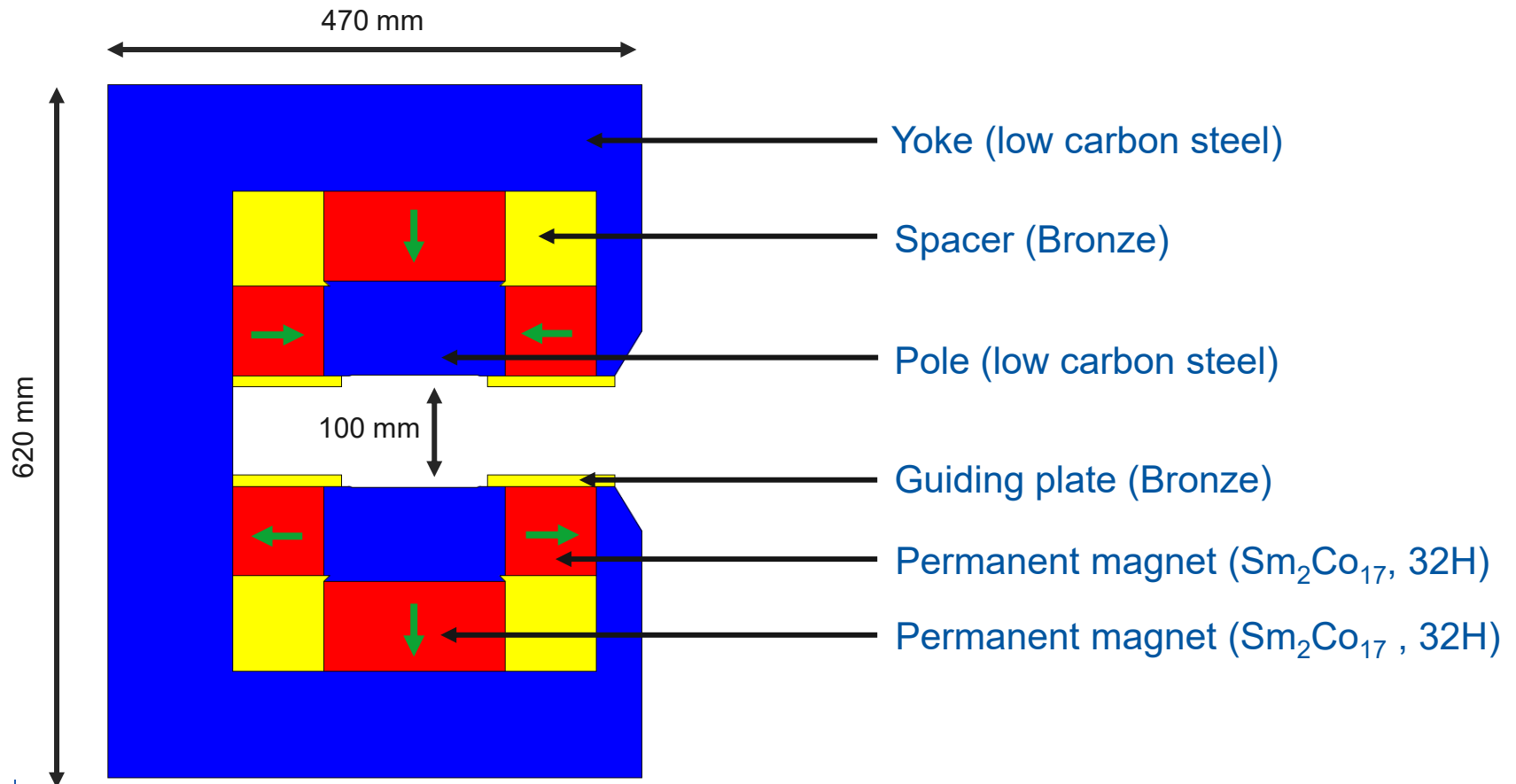


Dipole for Lohengrin experiment: requirements

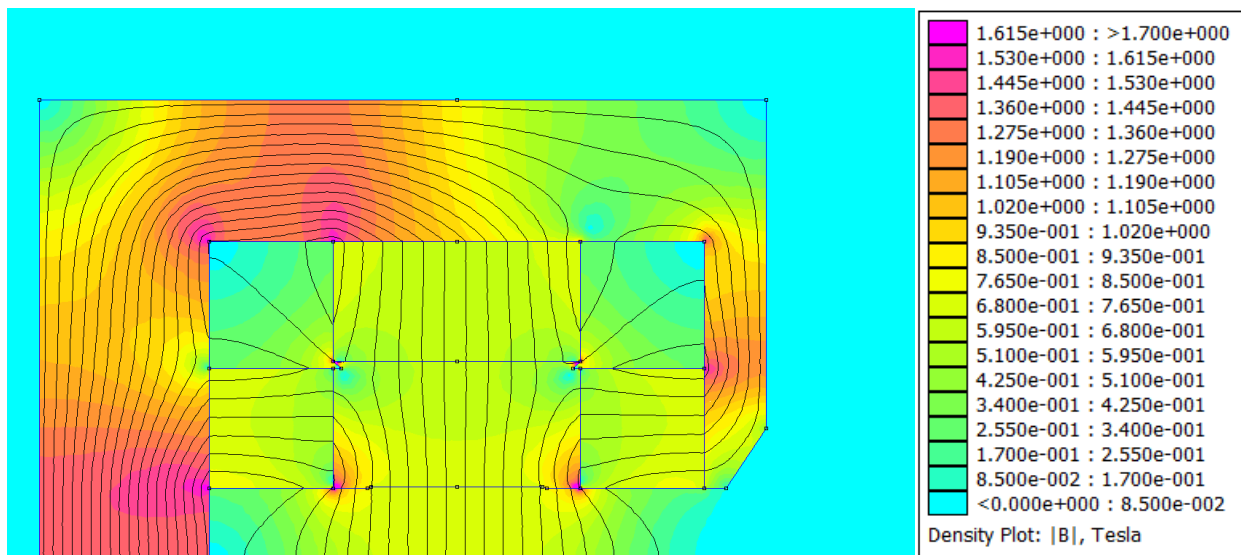
- ❑ Dipole aperture height of 100 mm.
- ❑ Integrated field of 1 T.m.
- ❑ Overall length of 1.5 m.
- ❑ Opening on one side of the aperture with a height of 30 to 50 mm such as low energy electrons generated in the target are deflected towards this gap.
- ❑ Ideally some free space available in middle plane on side opposite to opening to leave large angle for particle emitted from target.
- ❑ Desired to have a permanent magnet-based design.
- ❑ Field mapping of the whole aperture with a precision of about 1% in a grid of 1 x 1 x 1 mm.
- ❑ Required field homogeneity?

Proposed design: general view

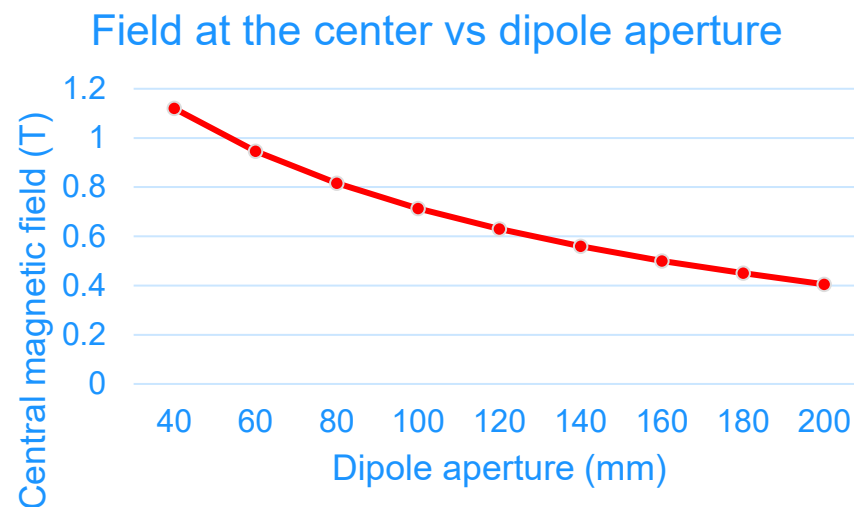
- ❑ A C-shape iron dominated dipole is proposed (design used in low-emittance storage rings).
- ❑ The opening leave space to instal tracker and target elements.
- ❑ The low carbon steel pole smooth possible irregularities of permanent magnet blocks.
- ❑ PM blocks limited to 80 x 80 x 80 mm to stay within reasonable available dimensions.



Magnetic design

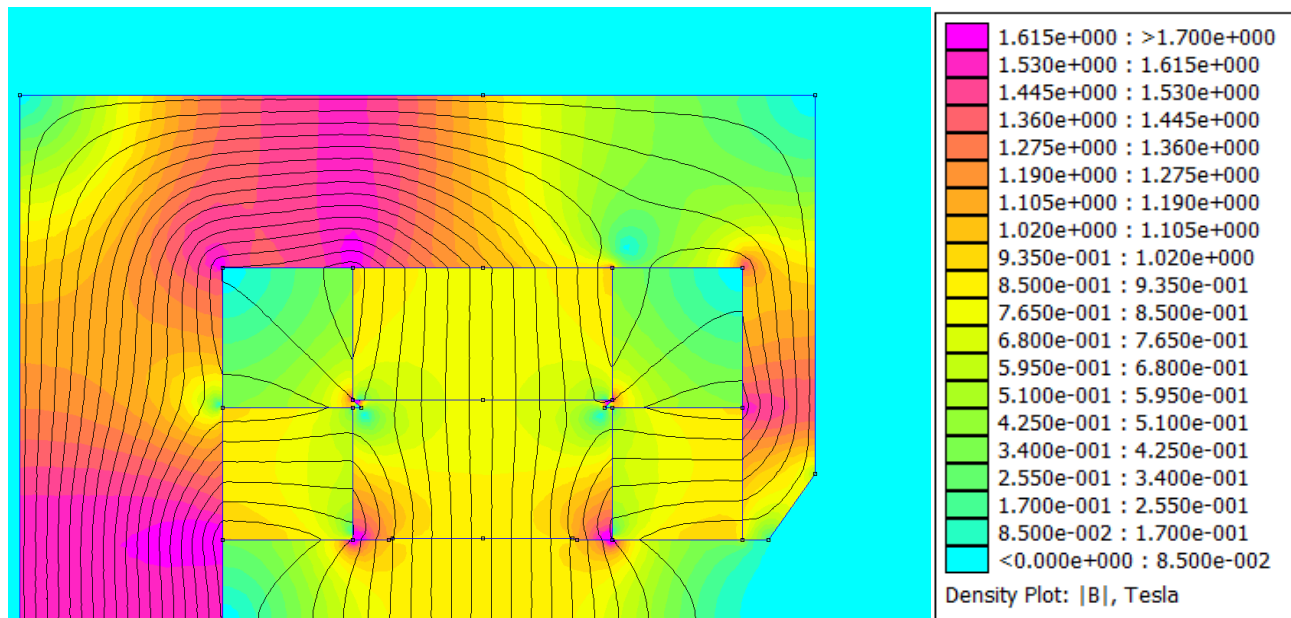


Parameter	Value	Unit
Length	1500	mm
Aperture	100	mm
Central Field	0.71	T
Field integral	1.1	T.m
Field homogeneity ($r = 50$ mm)	+/- 2	%
Weight	3100	kg
PM weight	650	kg



If we replace SmCo magnets by NdFeB

- ❑ Model solved with N48SH grade (high intrinsic coercivity).
- ❑ Potential 25% increase of the magnetic field with respect to SmCo.
- ❑ 0.9 T instead of 0.71 T for a 100 mm aperture dipole.
- ❑ Need to know integrated dose expected on permanent magnets to evaluate potential risks of demagnetization.
- ❑ NdFeB has higher temperature dependence than SmCo ($-0.12\%/^{\circ}\text{C}$).
- ❑ Potentially difficult to magnetize such large blocks with standard magnetizer.



Dipole cost estimation

Parameter	Cost (euro)
Permanent magnet blocks (~ 650 kg)	60000
Low carbon steel (~ 3000 kg)	10000
Bronze (~ 600 kg)	15000
Machining	20000
Assembly tooling	10000
Design, assembly and magnetic measurements	25000
Contingency	10000
TOTAL COST ESTIMATE	150000

Conclusion

- ❑ Permanent magnet-based designs, a good solution for experimental areas:
 - Flexibility of designs
 - Cost efficiency
 - Reliability
- ❑ The dipole design proposed for Lohengrin experiment appear to meet all initial requirements.
- ❑ Possibility with the same design to introduce a quadrupolar component with a hyperbolic pole profile.
- ❑ Field homogeneity ($\pm 2\%$) can be improved by enlarging the poles.
- ❑ Field strength can be higher by replacing SmCo magnets by NdFeB provided that integrated radiation dose stay sufficiently low.



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