Design and manufacturing of three permanent magnet dipoles for FASER experiment

TE-MSC seminar

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Outline

- Introduction to FASER experiment
- Halbach array permanent magnets
- Design of FASER dipoles
- Samarium Cobalt material
- Assembly and measurements
- Installation in LHC
- Conclusion

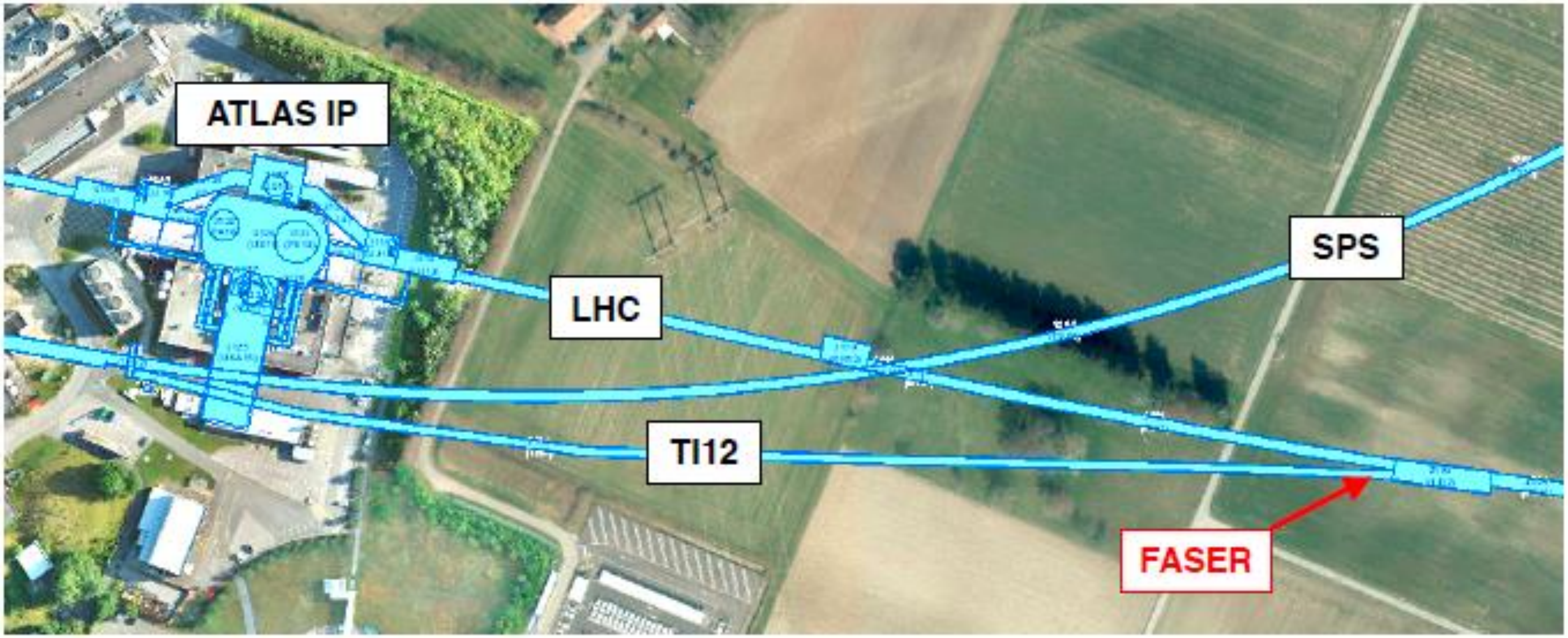
Introduction to FASER experiment

In March 2019, the CERN Research Board approved FASER, the ForwArd Search ExpeRiment (https://faser.web.cern.ch).

The idea is that some new, light and weakly interacting particles may be produced in large number during proton-proton collisions in LHC and may not be detected.

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.

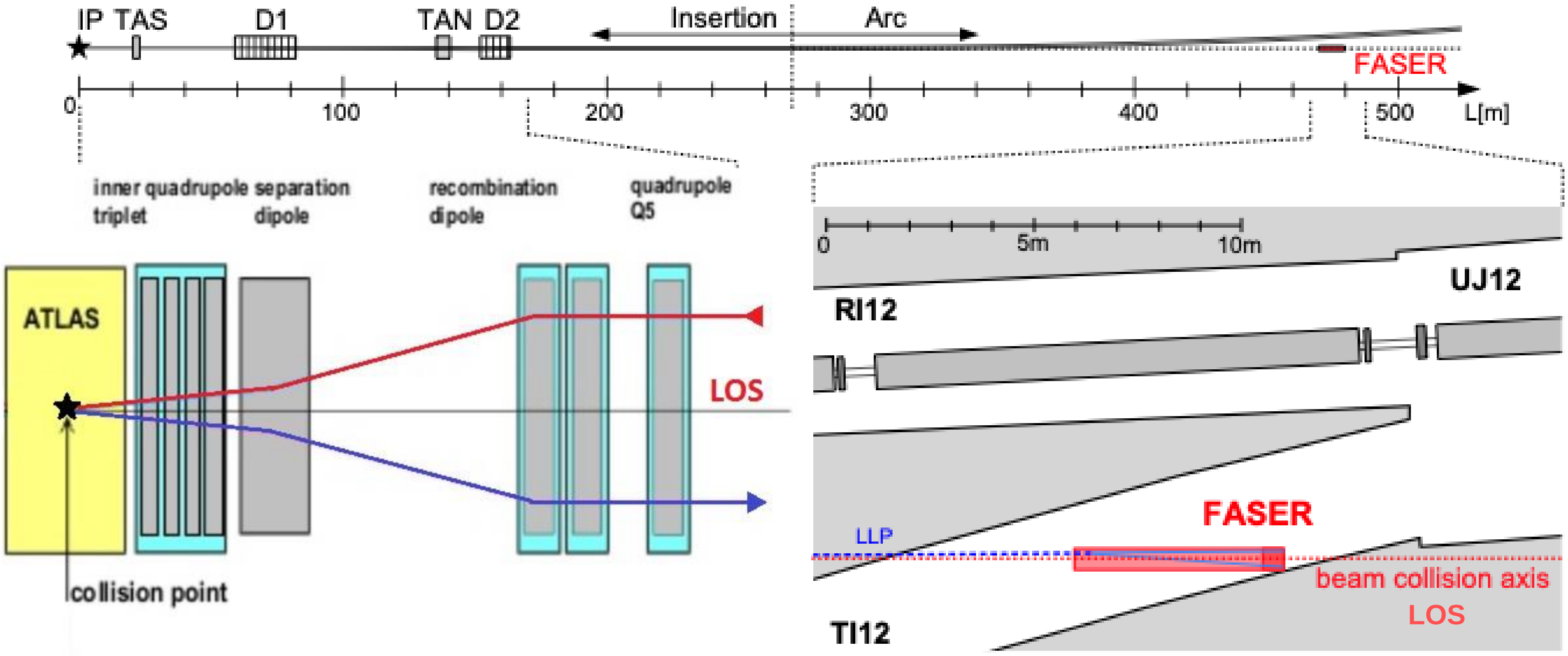
FASER has been designed to detect such potential events. It is located in LHC service tunnel TI12.



Introduction to FASER experiment

FASER will be situated along the beam *collision* axis line of sight (LOS)

- ~480 m from IP
- after beams start to bend
- a few meters from the LHC beamline

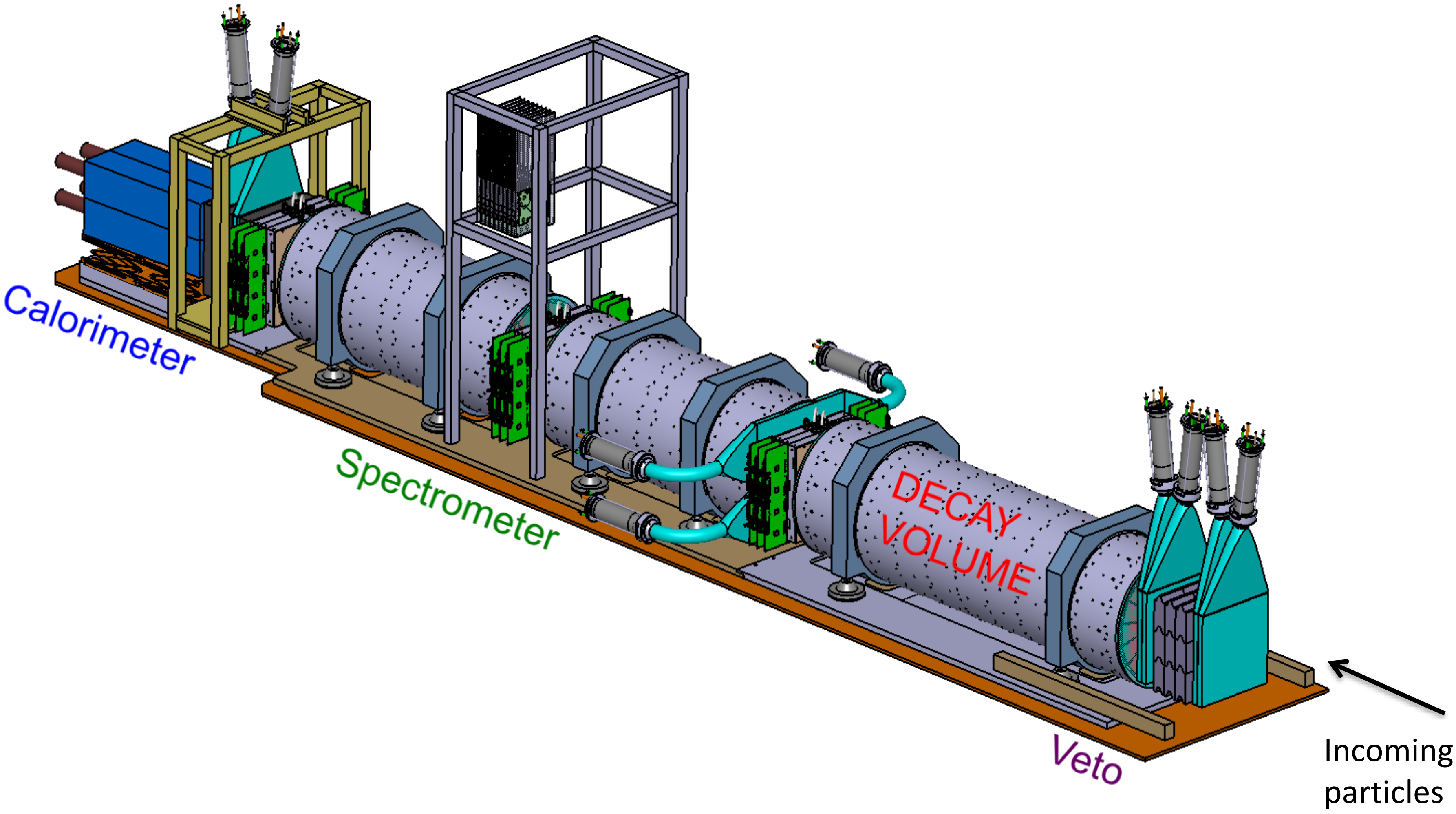


TI12 is a unused tunnel that intersects LOS 480m from IP1

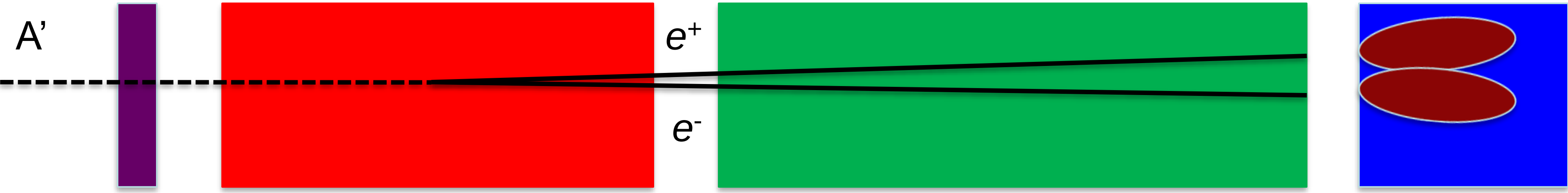
FASER detector

The detector consists of:

- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter



FASER detector



The detector consists of:

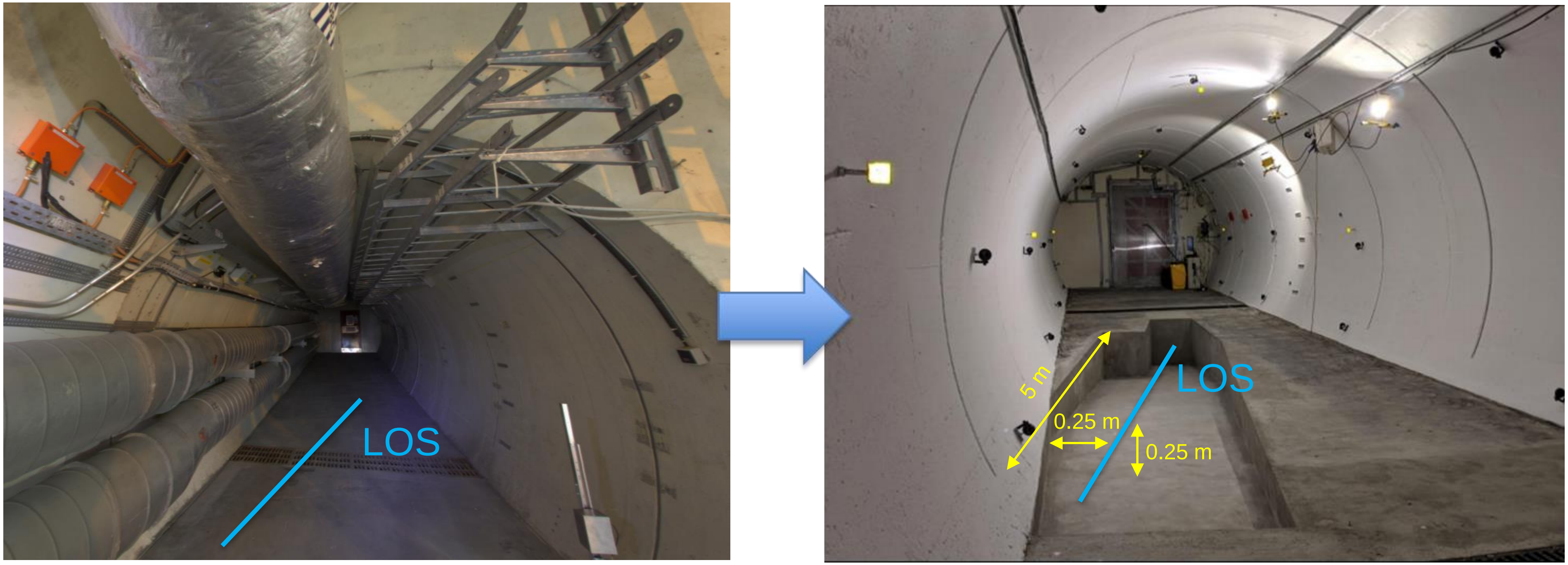
- Scintillator veto to suppress events with charged particles produced before Faser.

- 1.5m long decay volume (1 dipole) to start separation of e^+e^- pairs.

- 2m long spectrometer (2 dipoles, 3 tracking stations, 2 scintillators):
    - Timing information of the event in FASER and correlation with pp interaction in ATLAS.
    - Tracking of e^+e^- tracks to confirm they are originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP.

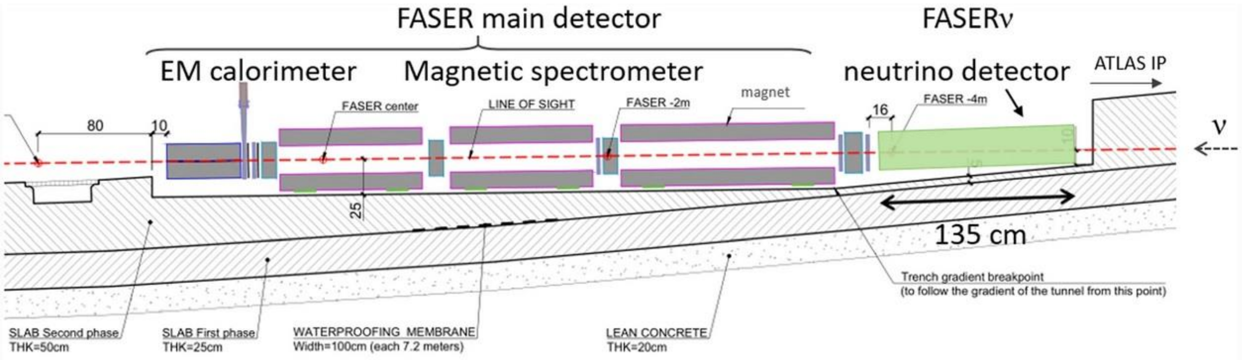
- EM calorimeter to stop high-energy electrons and photons, identify them, and measure their energies.

FASER in LHC TI12



TI12 tunnel has a slope:

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



Some permanent magnet dipoles for FASER experiment

Very tight constraints for the 3 dipole magnets:

- Several 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

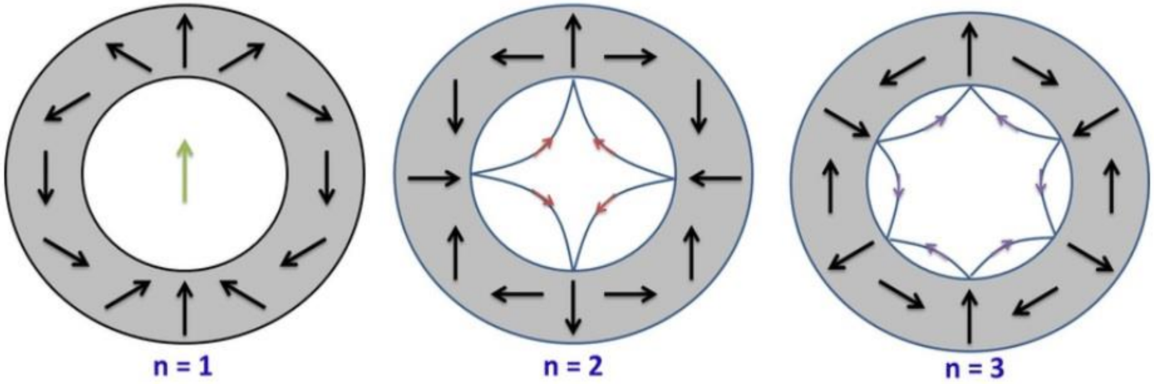
Parameter	Value	Unit
Number of dipoles	3 units (1 of 1.5 m long and 2 of 1 m long)	
Length	1000 and 1500	mm
Height from beam axis to floor	≤ 250	mm
Width from beam axis to tunnel structure (at the base)	≤ 250	mm
Aperture diameter	200	mm
Central field	0.55	T
Good field region (GFR) diameter	200	mm
Integrated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

Pictured: Klaus Halbach

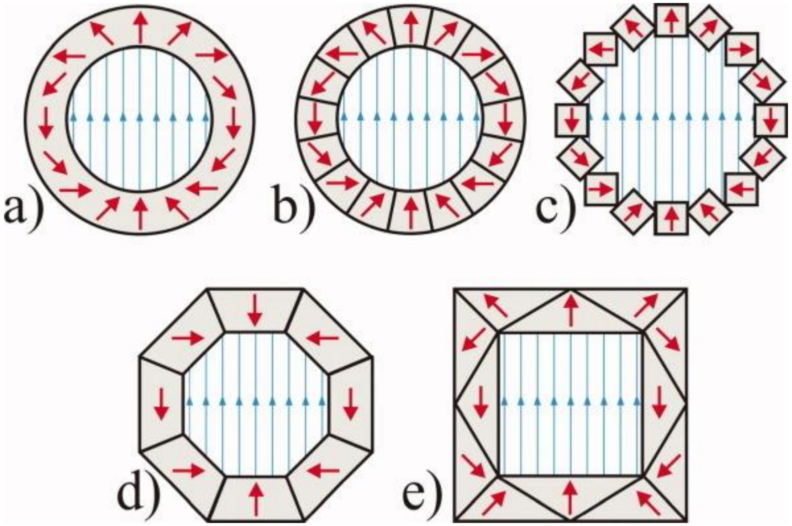


Pictured: Halbach designs, dipole (left), quadrupole (middle), sextupole (right)

A formula exists to approximate the field in a dipole:

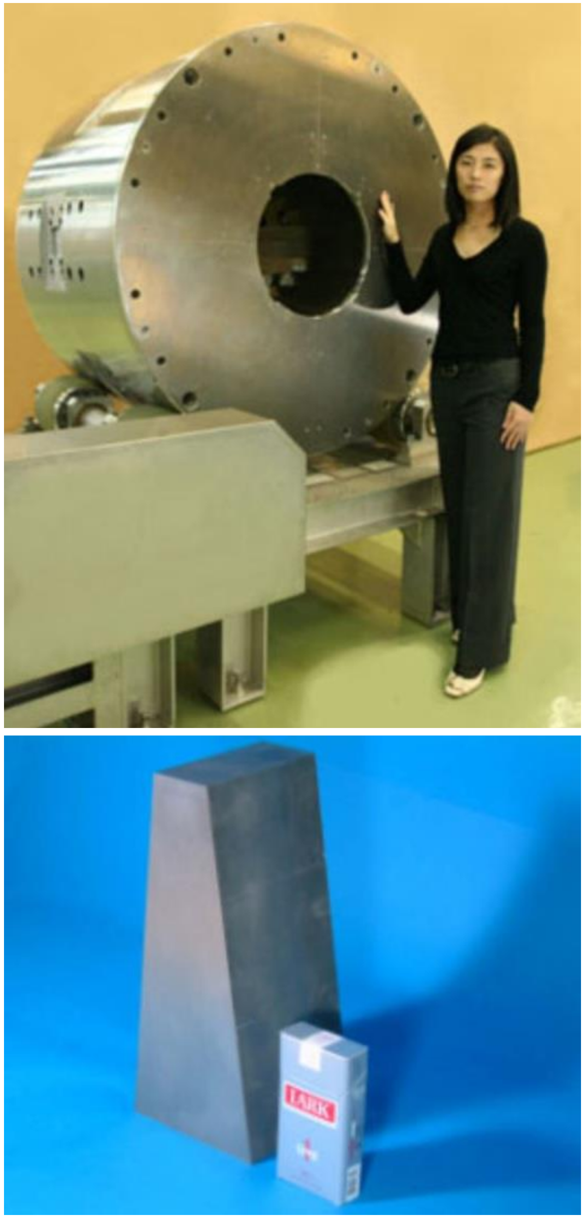
$$B = Br.\cos(\pi/M).Ln(R/r)$$

Where Br is the remanent field, M is the number of segments, R is the outer radius and r the inner radius. This formula works for a long dipole made of a perfect ring (type a or b).

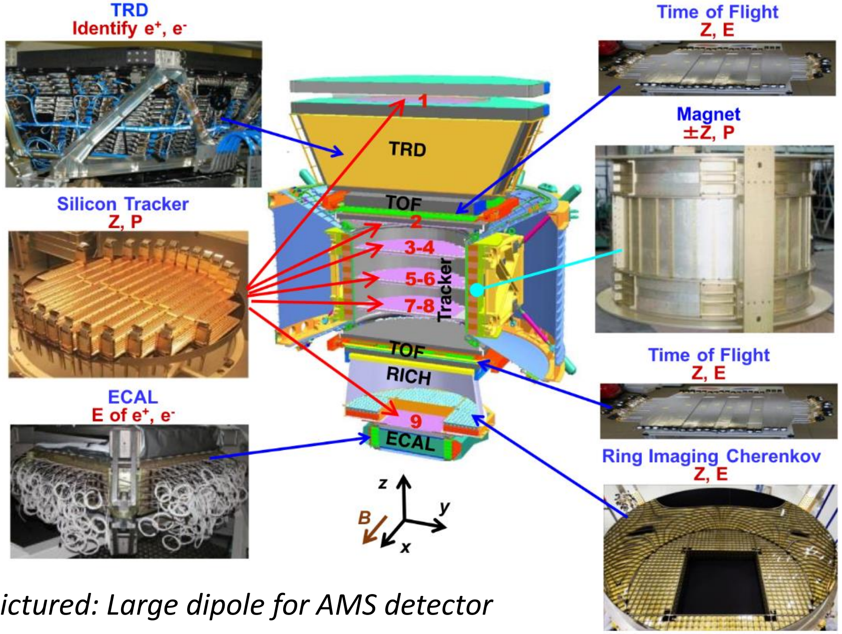


Pictured: different arrays of dipoles

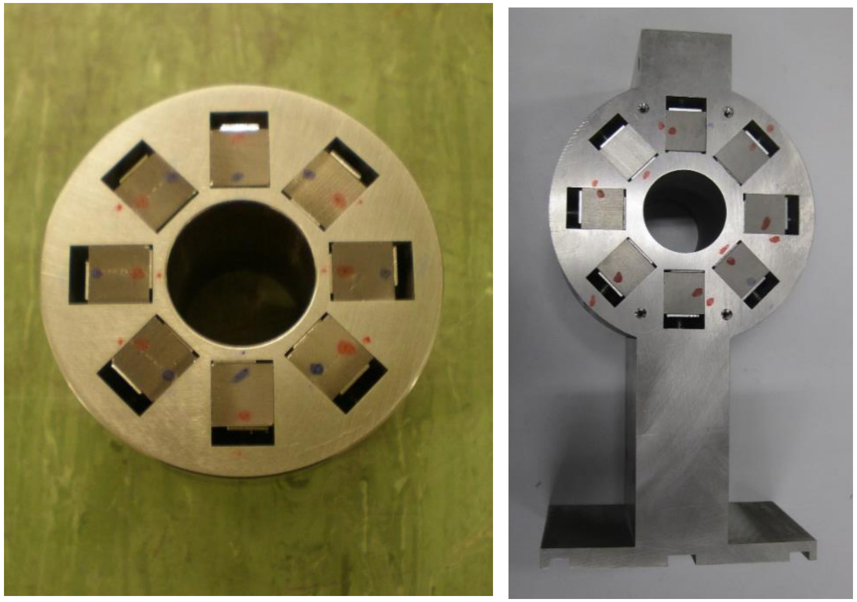
Some Halbach array magnets produced in the past



Pictured: 10 Tons dipole produced by Shin-Etsu



Pictured: Large dipole for AMS detector

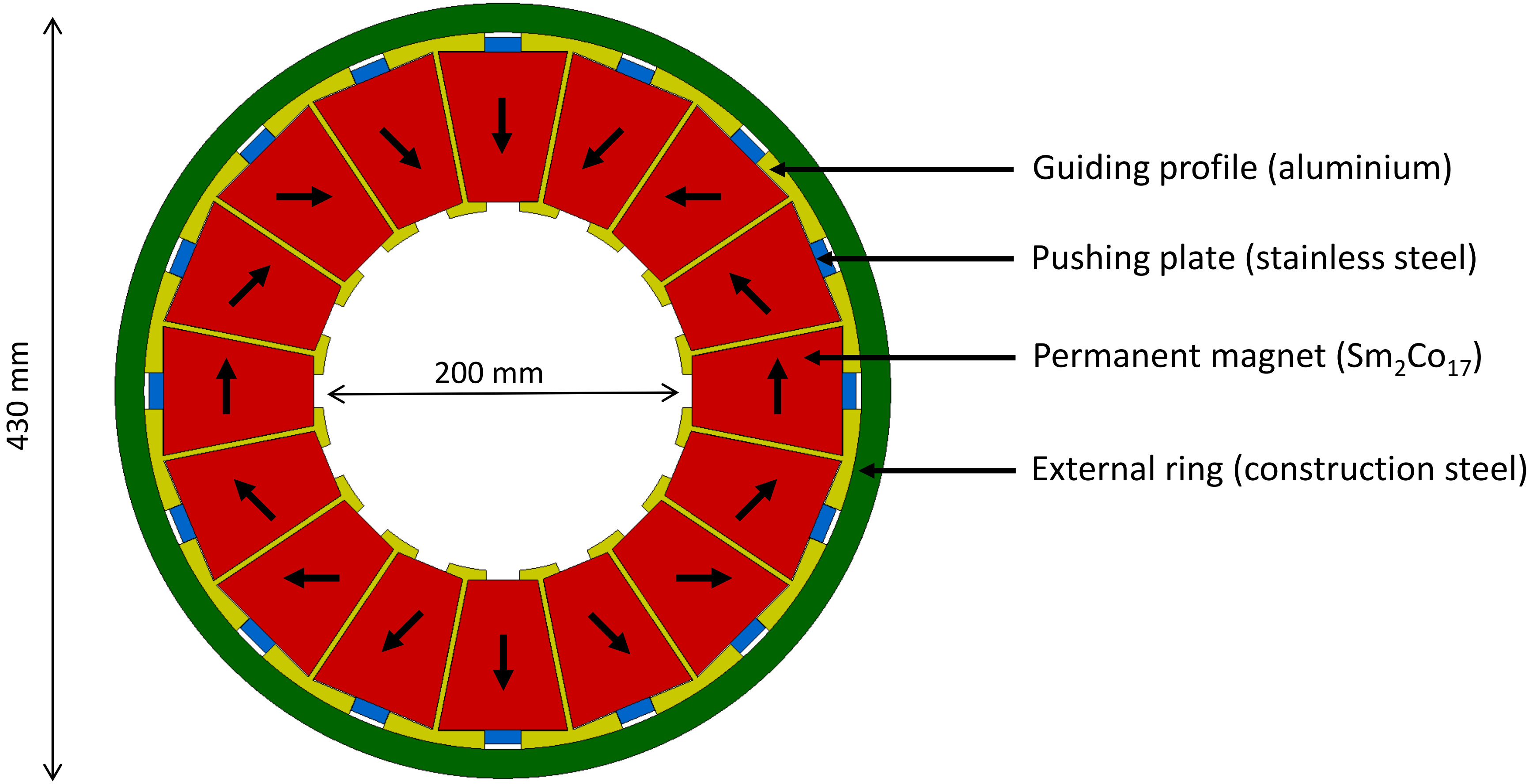


Pictured: quadrupoles for Linac4 DTL and CCDTL

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.



Guiding profile (aluminium)

Pushing plate (stainless steel)

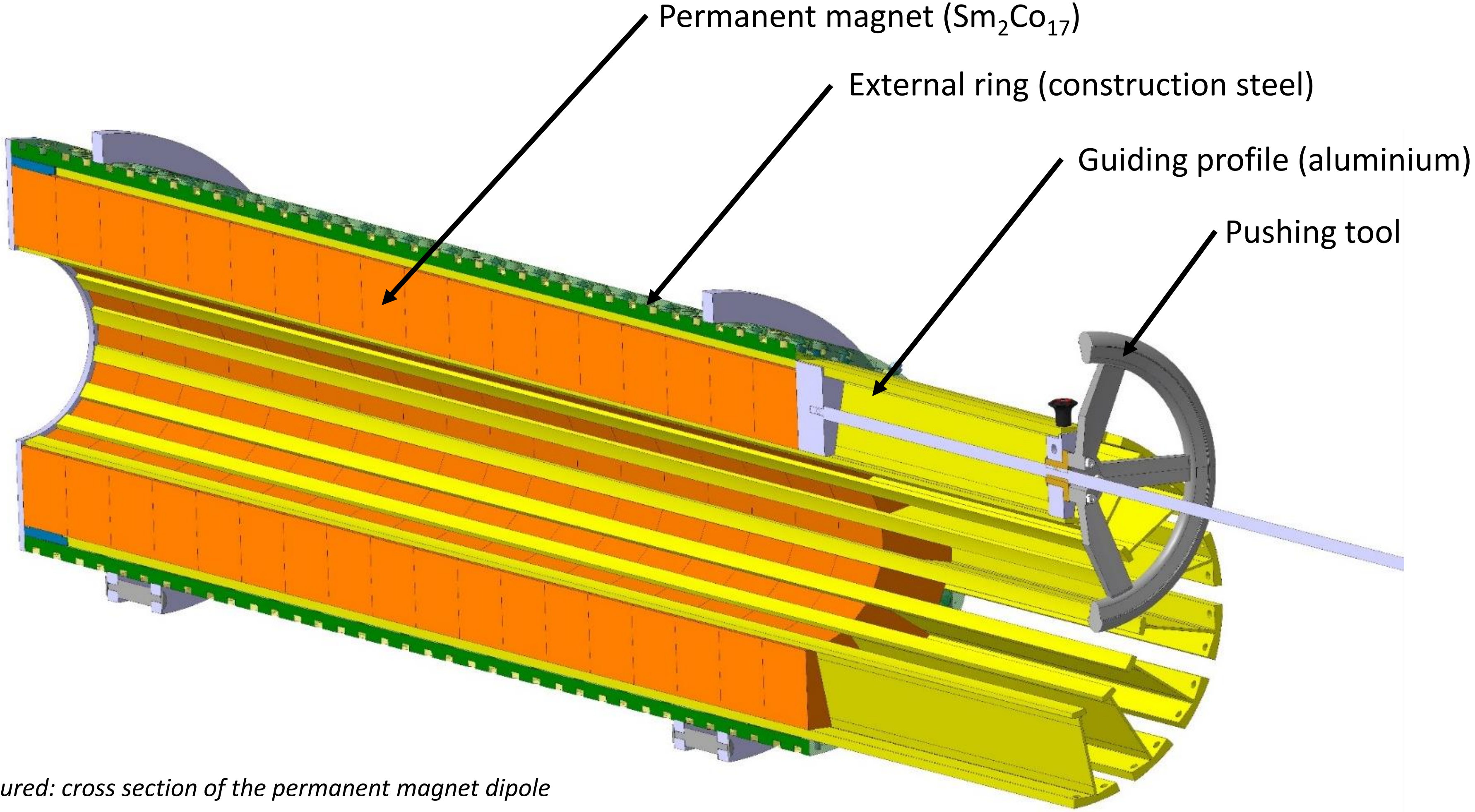
Permanent magnet (Sm_2Co_{17})

External ring (construction steel)

Pictured: layout of the permanent magnet dipole

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.



Permanent magnet (Sm_2Co_{17})

External ring (construction steel)

Guiding profile (aluminium)

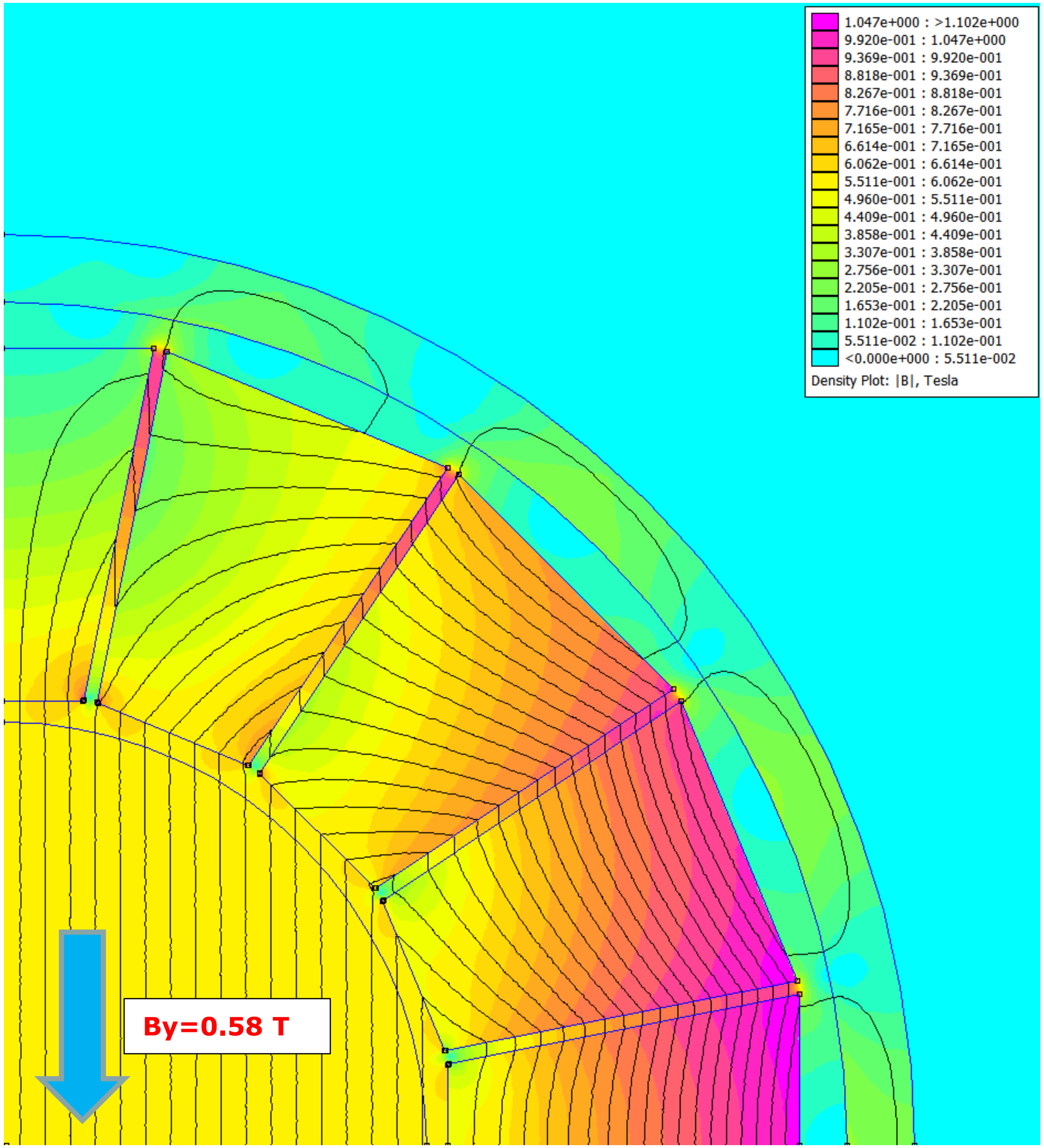
Pushing tool

Pictured: cross section of the permanent magnet dipole

2D magnetic design

- The main variable parameters for this design are:
  - The outer radius
  - The number of blocks
  - The space between blocks
  - The magnet blocks shape

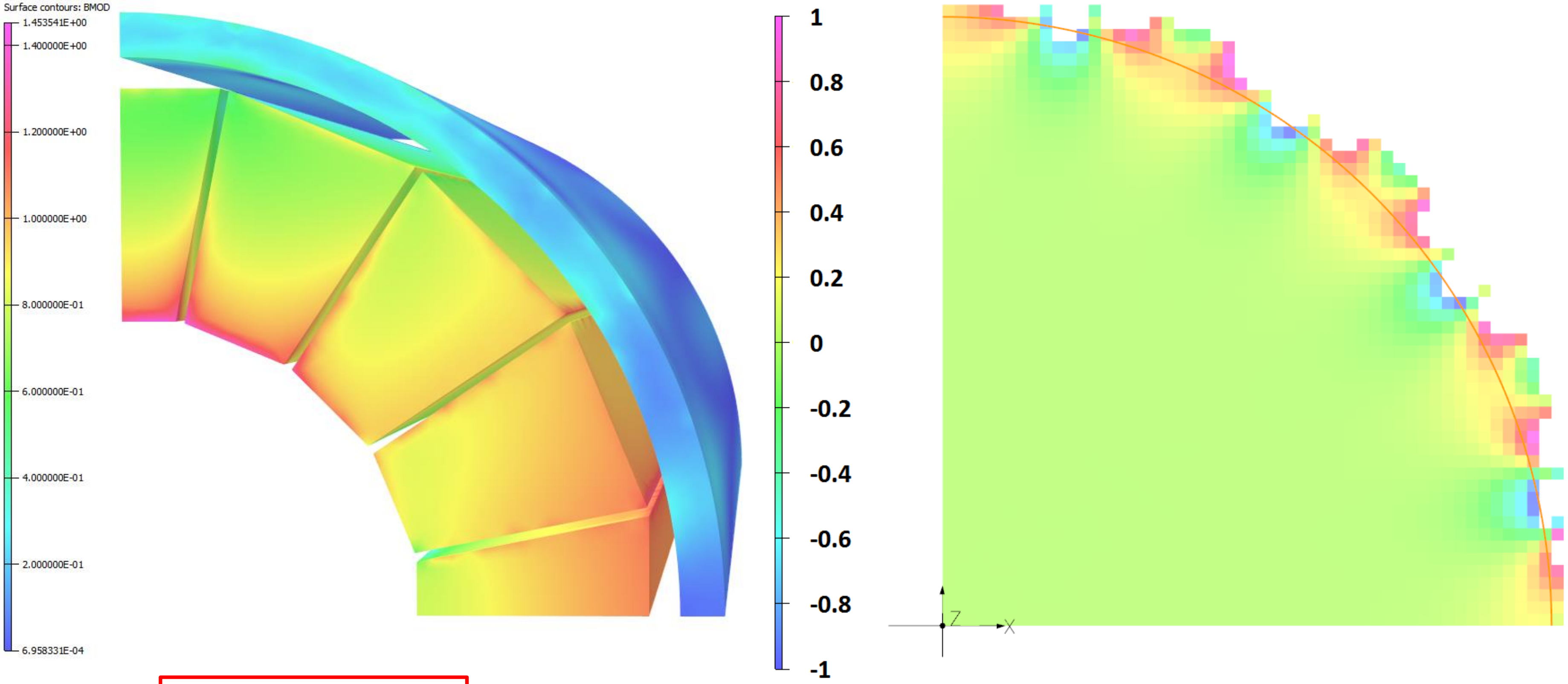
- The thickness of guiding profiles (i.e. space between blocks) has a significant incidence on field quality.



By=0.58 T

Pictured: Field distribution Bmod (T) in the dipole

3D magnetic design (model of 1500 mm long)

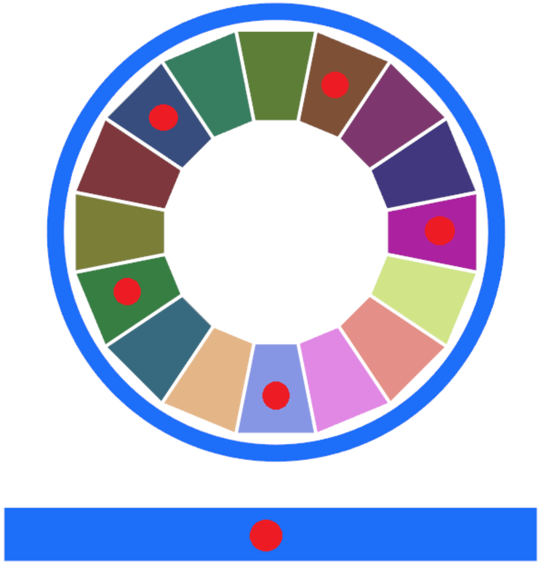


∫Bydl=0.87 T.m

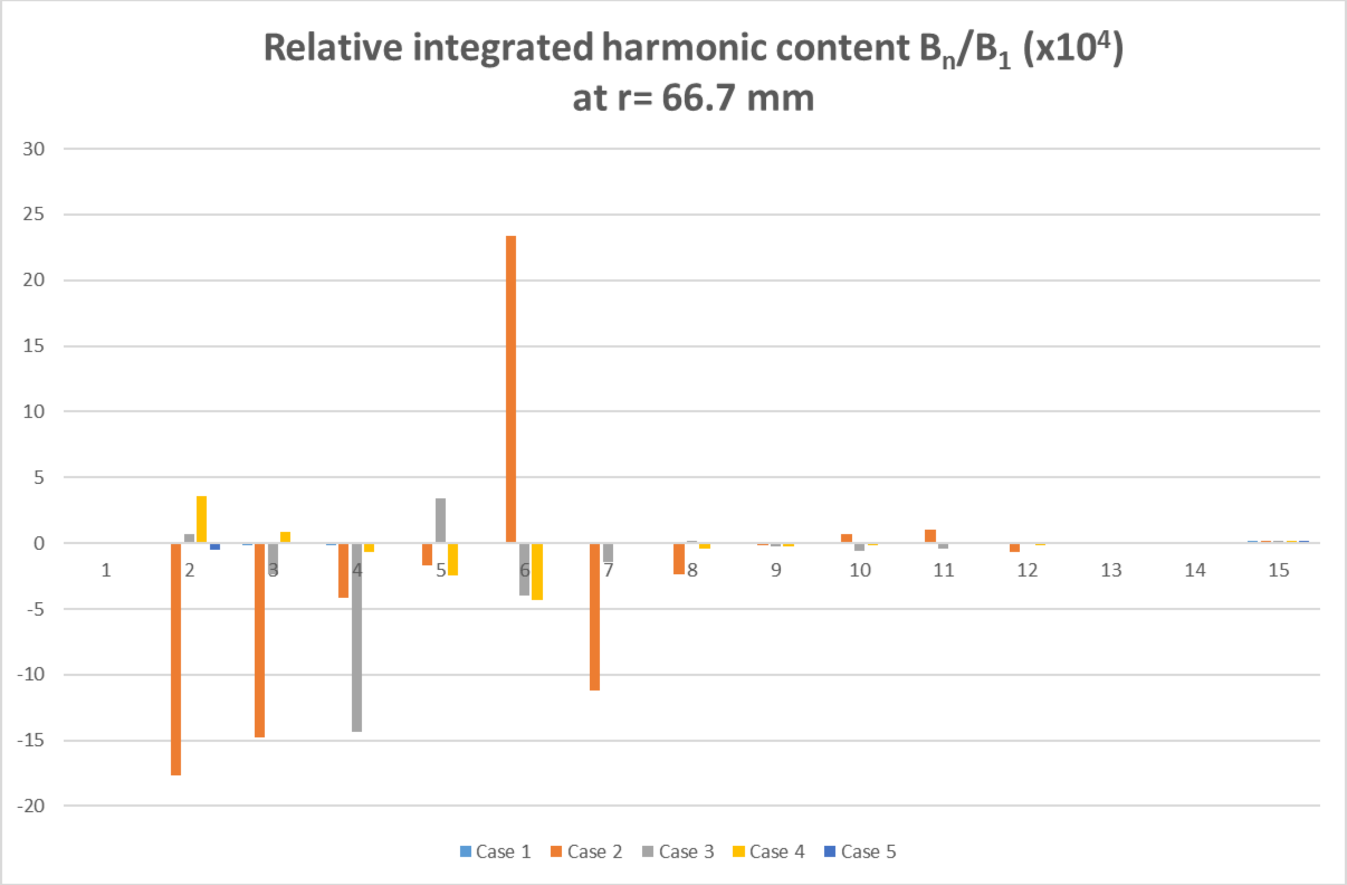
∫Bydl homogeneity (%) inside a radius of 100 mm

Pictured: Field distribution Bmod (T) and ∫Bydl integrated field homogeneity in the dipole

Effects of PM blocks imperfections and external structure on field quality



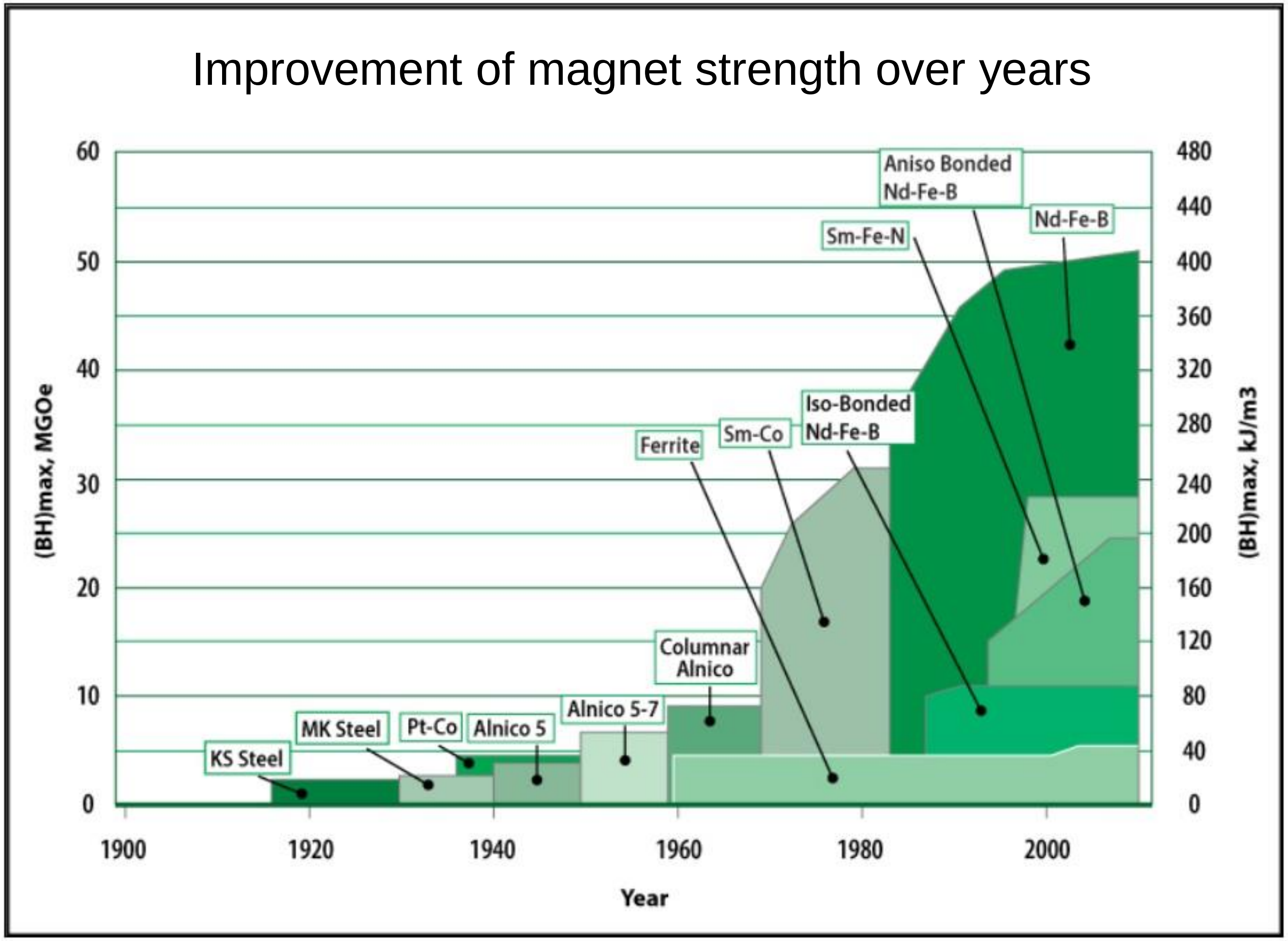
- Case 1: Ideal case
- Case 2: Misalignment of magnetization direction of 5° on 5 lines of magnets
- Case 3: Positioning error of 0.5 mm on 5 lines of magnets
- Case 4: Deviation of magnetic characteristics by +/- 2% on 5 blocks
- Case 5: Presence of a 5 cm thick steel plate located 5 cm under the magnet



Why Samarium Cobalt?

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

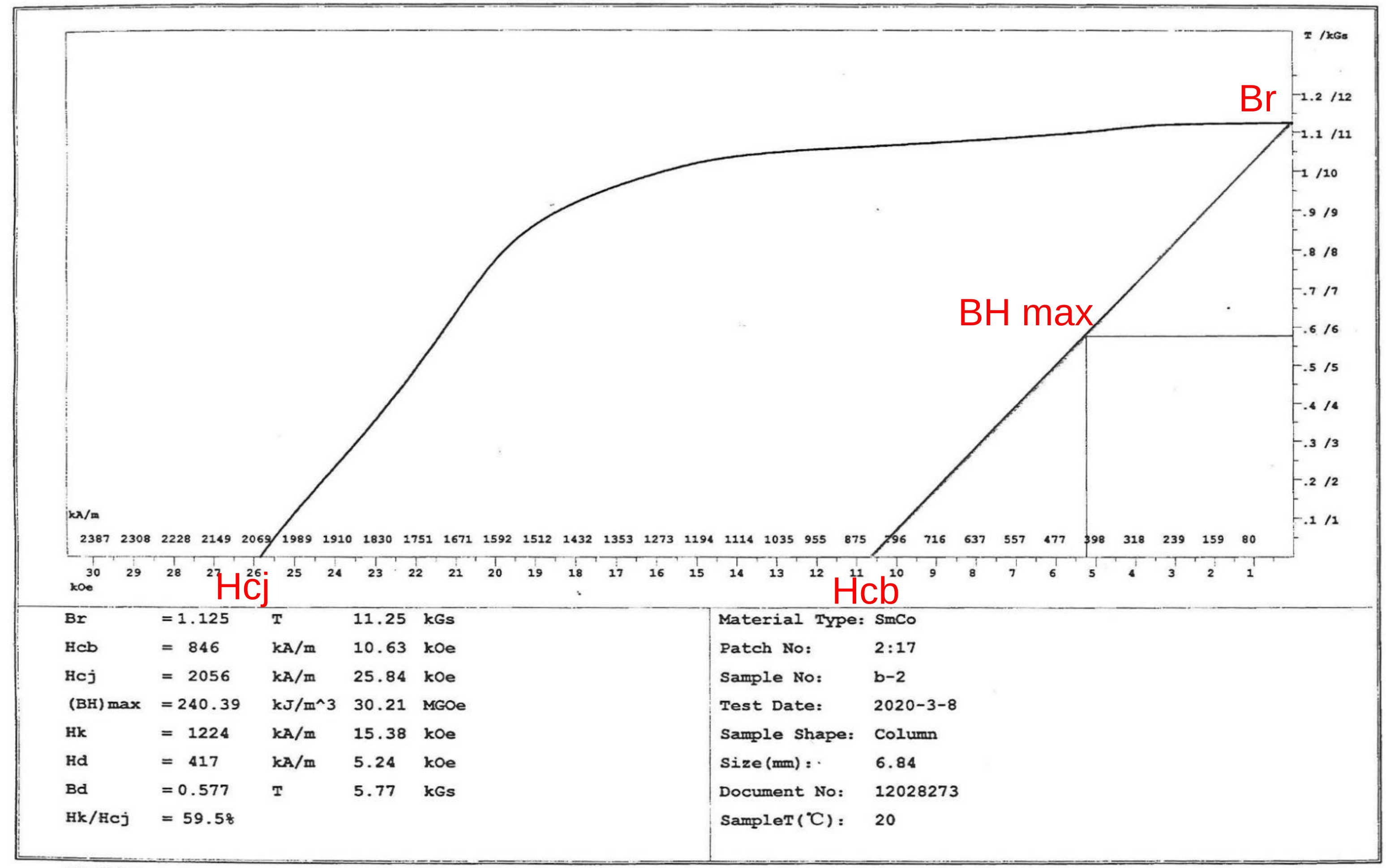
- SmCo has a small temperature coefficient: -0.035%/°C.
- SmCo has a good radiation resistance.
- SmCo has an acceptable corrosion stability even without protective coating.



Why Samarium Cobalt?

The following material was selected to fulfils the design constraints and minimize the size of the dipole:

- Material with high energy product (≈30 MGOe).
- High remanent field Br≥1.11 T and coercivity Hcb ≥830 kA/m.
- High intrinsic coercivity Hcj ≥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



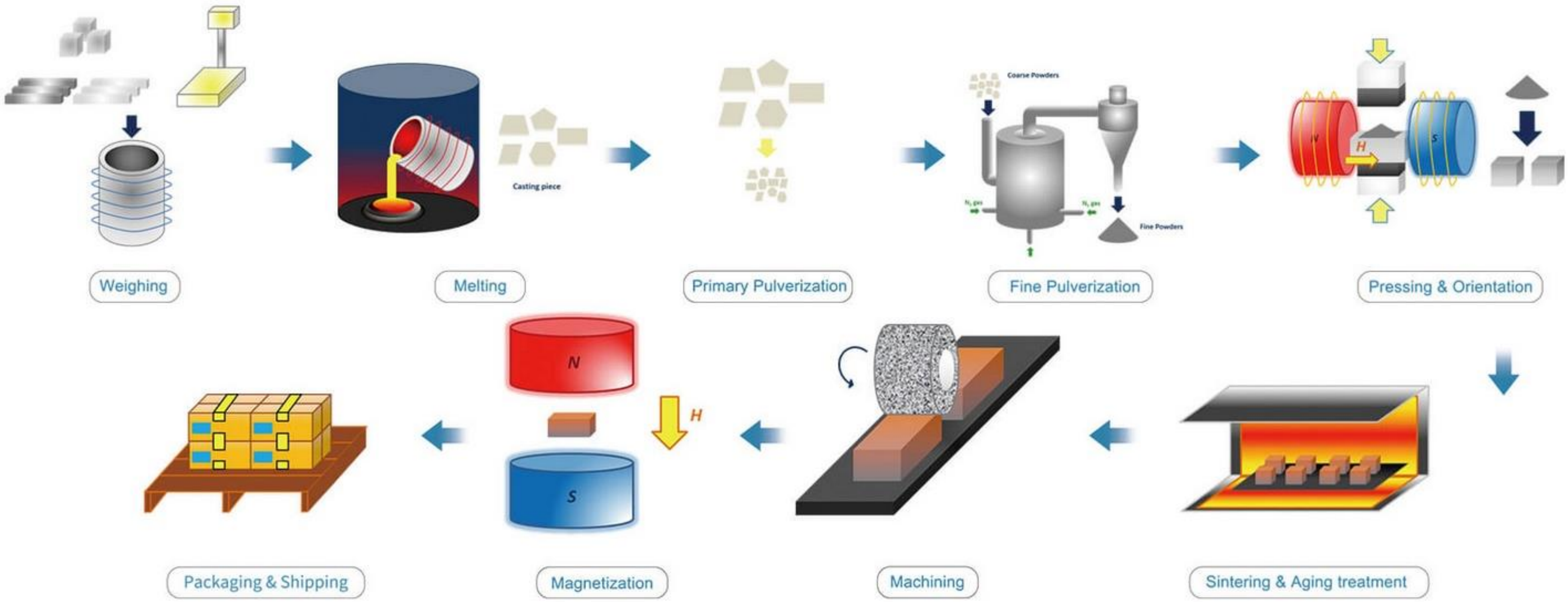
Br	= 1.125	T	11.25	kGs
Hcb	= 846	kA/m	10.63	kOe
Hcj	= 2056	kA/m	25.84	kOe
(BH)max	= 240.39	kJ/m^3	30.21	MGOe
Hk	= 1224	kA/m	15.38	kOe
Hd	= 417	kA/m	5.24	kOe
Bd	= 0.577	T	5.77	kGs
Hk/Hcj	= 59.5%			

Material Type: SmCo
Patch No: 2:17
Sample No: b-2
Test Date: 2020-3-8
Sample Shape: Column
Size(mm): 6.84
Document No: 12028273
SampleT(℃): 20

AUTOMATIC HYSTERSIGRAPH MODE AMT-4 SJ LTD.

Pictured: BH curve of the material delivered

Manufacturing Process of Sintered Samarium Cobalt magnets



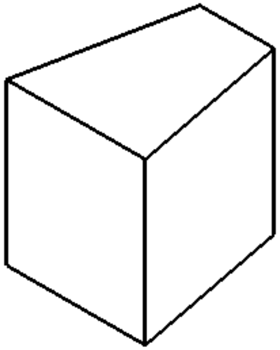
- As Faser magnet blocks are big, an additional isostatic pressing is required (after pressing & orientation operation) in order to get the material density.

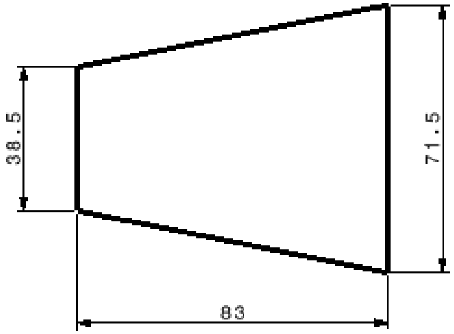
- The BH curve is controlled on some samples after sintering.

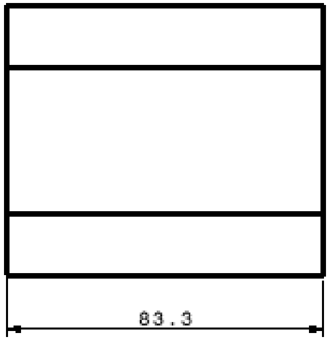
- During final magnetization the magnet blocks will be magnetized following the easy axis defined during Pressing and Orientation operation (it cannot be changed!).

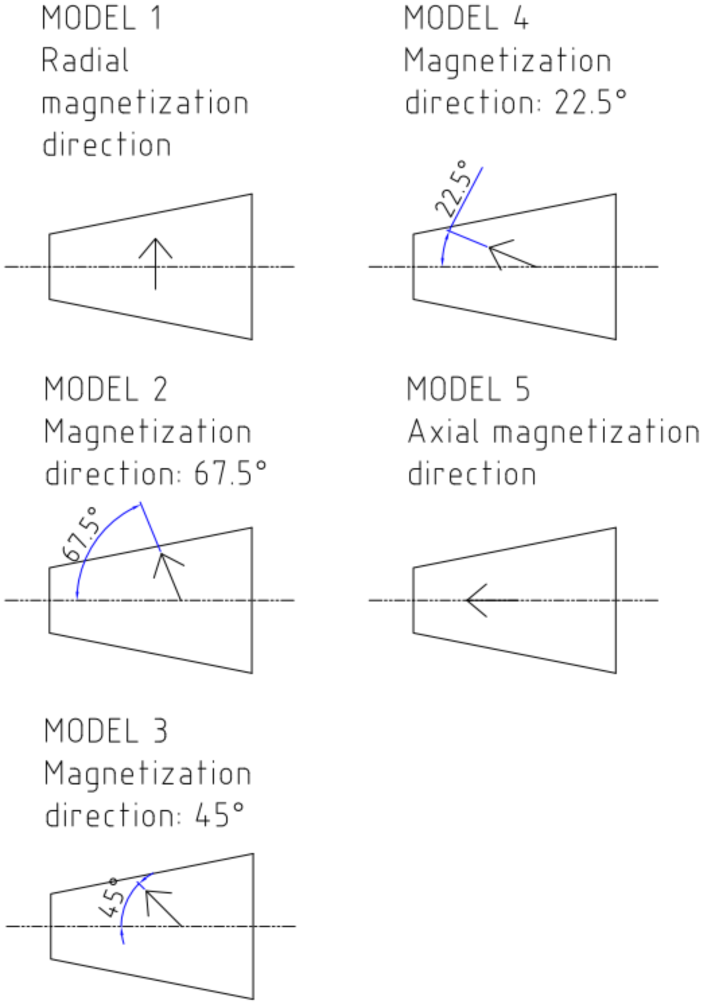
Permanent magnet blocks

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.





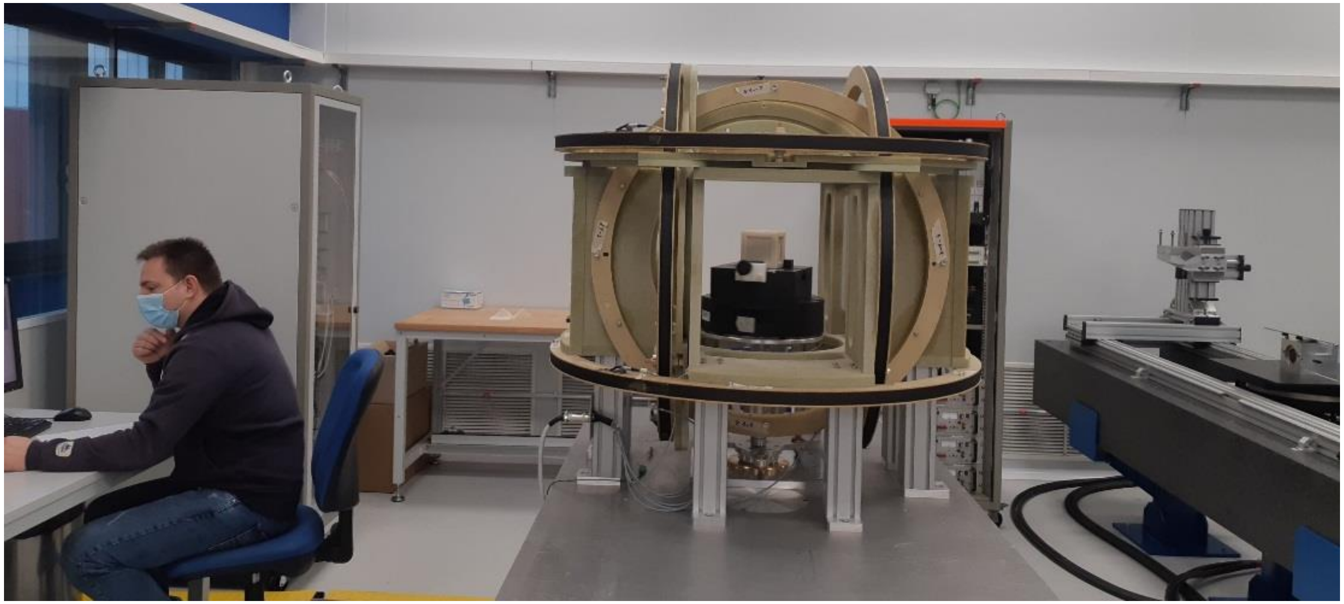




Pictured: shape and magnetization direction of the blocks

Permanent magnet blocks measurements at CERN

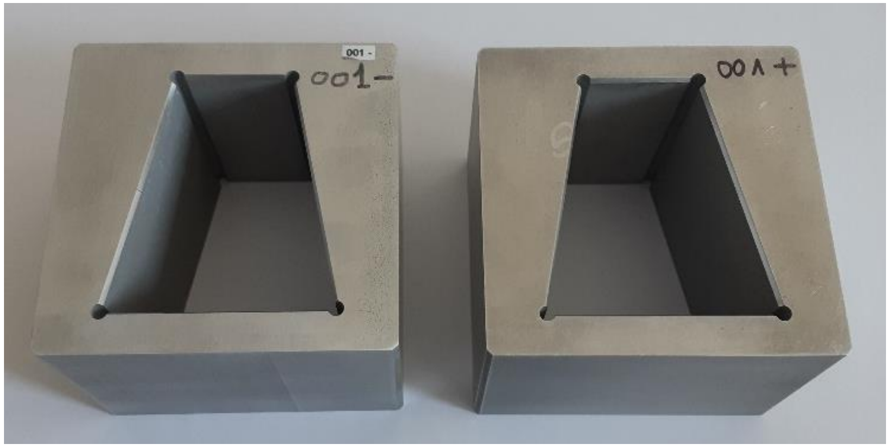
The magnetic moment of the 672 permanent magnet blocks were measured for their 3 axis with our colleagues from TE-MSC-MM using an Helmholtz coil.



Pictured: 3D Helmholtz coil

$$M_{mag} = \frac{Br.V}{\mu_0}$$

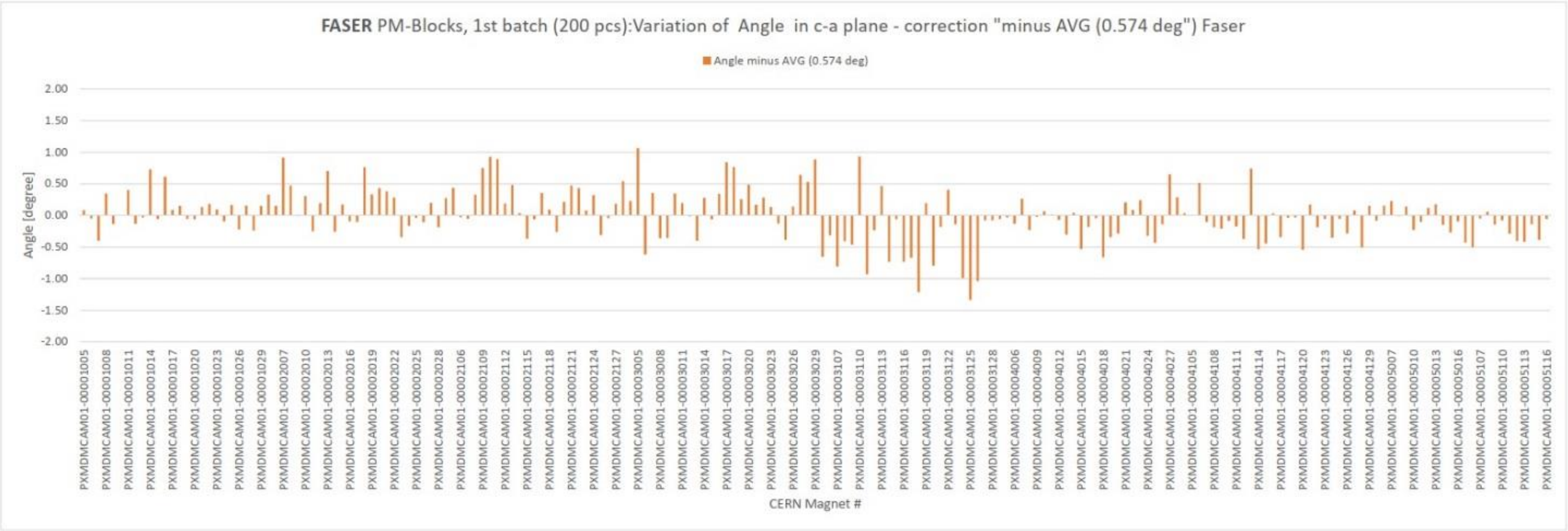
The dimensions of the blocks were checked using GO-NOGO gauges.

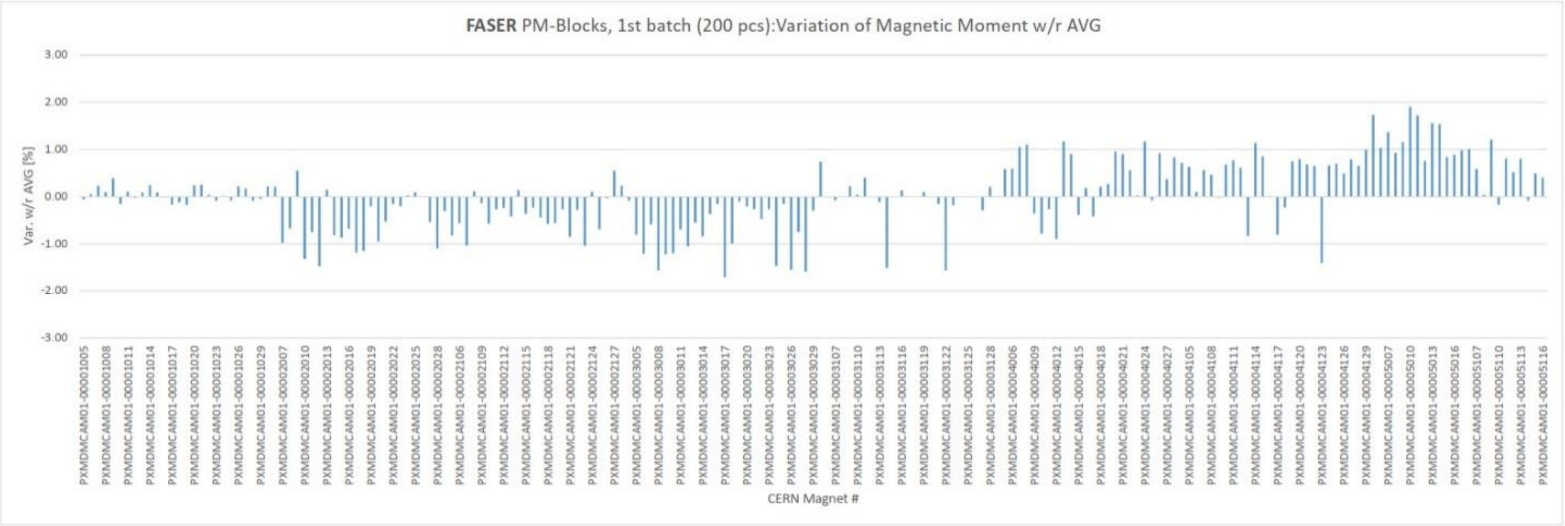


Pictured: Dimensional check of the blocks with GO-NOGO gauges

Permanent magnet blocks measurements at CERN

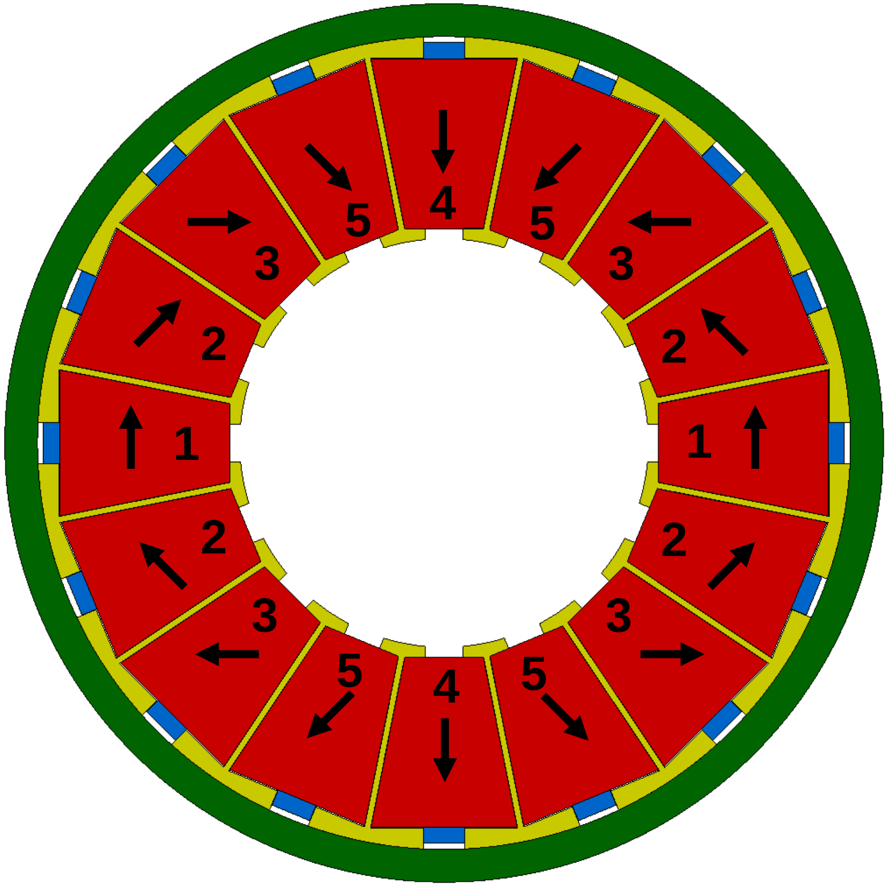
The delivered permanent magnet blocks were of very good quality with a moment homogeneity within +/- 2% and a maximum deviation of the easy axis angle of 1.5°. All dimensions were within tolerances.





Pictured: deviation of easy axis angle and magnetic moment homogeneity for 1^{st} batch of magnets

Dipole assembly



Pictured: assembly sequence

- The magnetic forces between blocks are not constant during assembly.

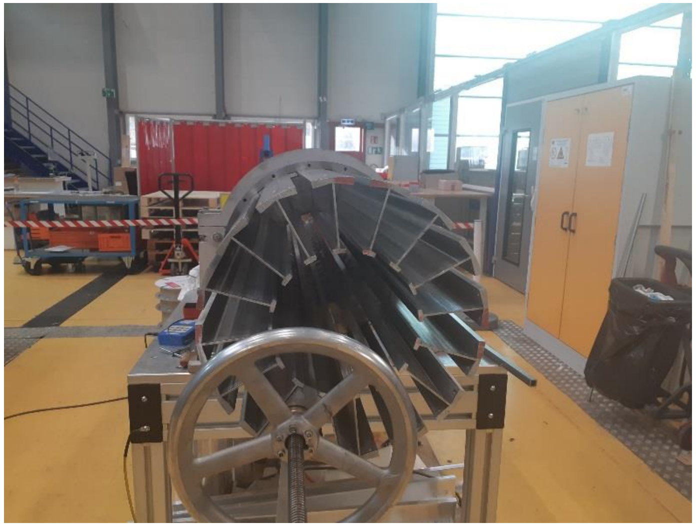
- Their amplitude and even their direction change depending which magnet block is installed.

- The forces (attraction or repulsion) is comprised between 800 N and 2000 N for each permanent magnet blocks.

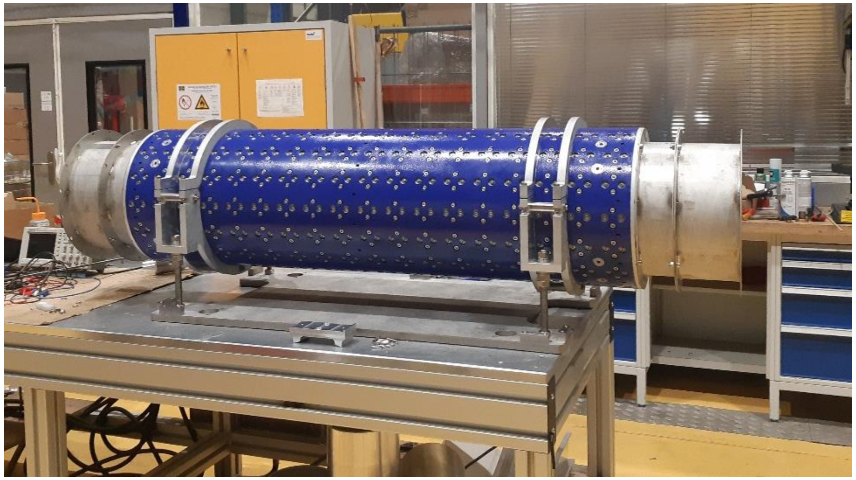
- An assembly sequence was defined in order minimize these forces and have a stable structure.

Dipole assembly

Assembly of the dipole yoke including steel ring and aluminium profiles



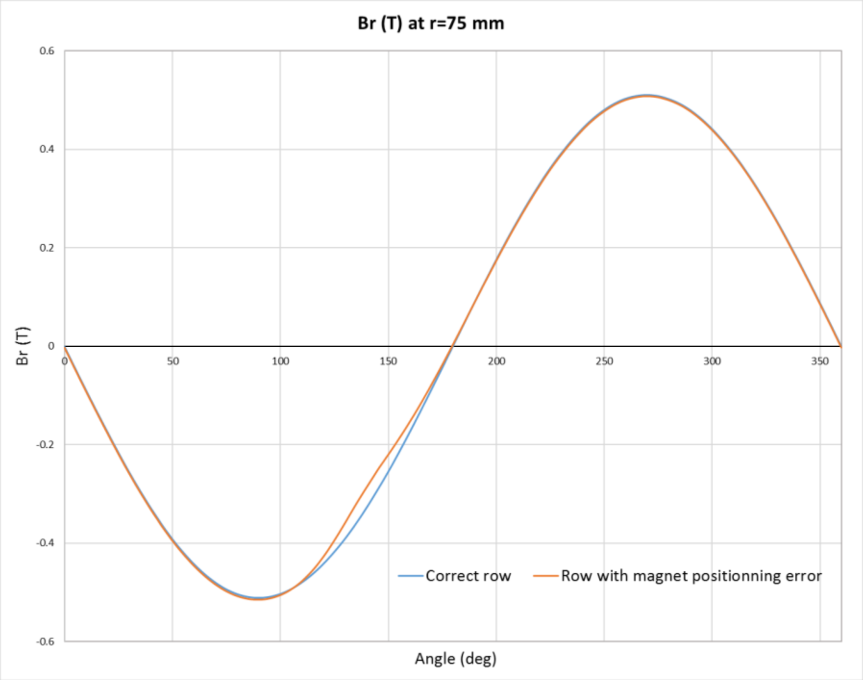
Insertion of each permanent magnet blocks row after row (one row comprises 16 magnet segments). The 1 m long dipole has 12 rows and the 1.5 m long dipole has 18 rows.



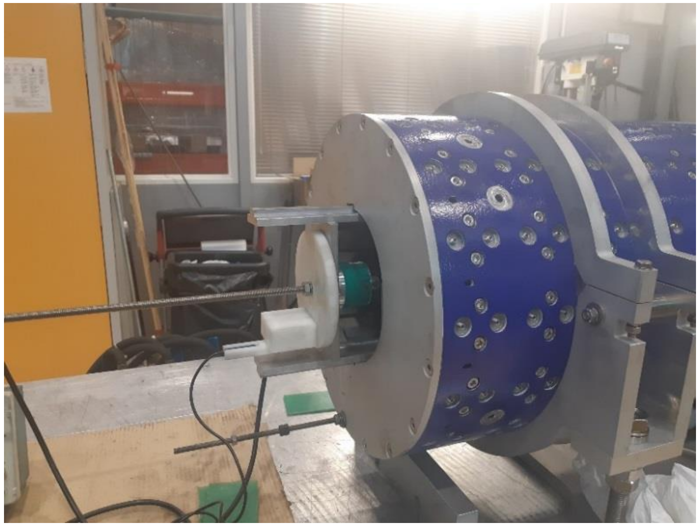
Cutting of the extra length of the aluminium profiles and installation of protection covers to create a physical barrier to the magnetic field

Measurements during assembly

- Even if the polarity of each magnet block is checked several times before to insert it inside the dipole yoke, we identified a potential risk of polarity or block positioning error which maybe discovered only at the final measurement of the dipole.
- We developed together with TE-MSC-MM a system to measure the Br after each row completion. Due to magnet symmetry, the measured value of the first and last row assembled shall be identical. If an error is detected we have the chance to correct it immediately.



Pictured: Computed Br (ideal case vs error during assembly)



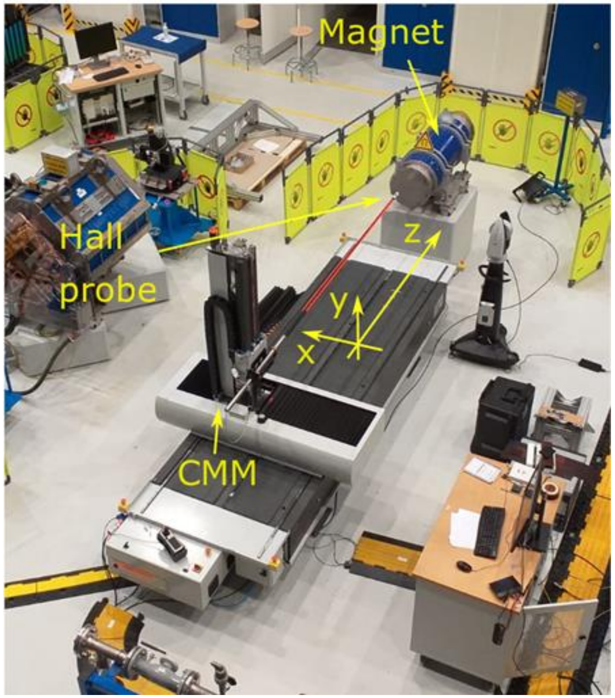
Pictured: system with angular encoder and Hall probe connected to an oscilloscope to check Br inside the dipole aperture

Measurements of the assembled dipole

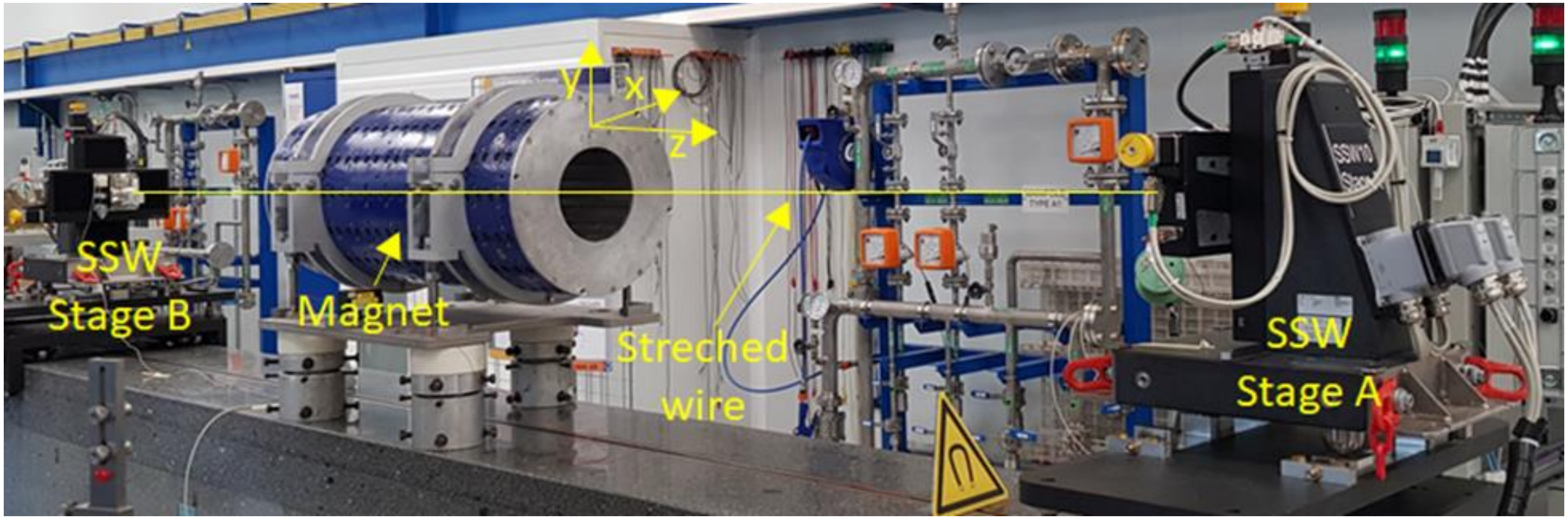
- The field integral and the multipole analysis was measured on the stretched wire bench.

- A mapping of the dipole aperture was done with the field mapper.

- When integrating the values measured with the mapper along the dipole length, it fits perfectly with the measurements done with the stretched wire.



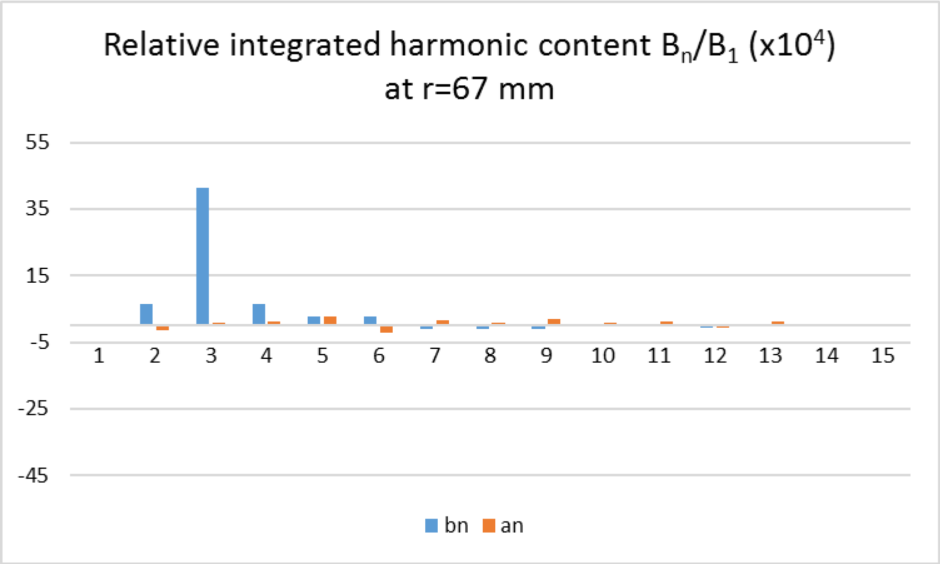
Pictured: Field mapper

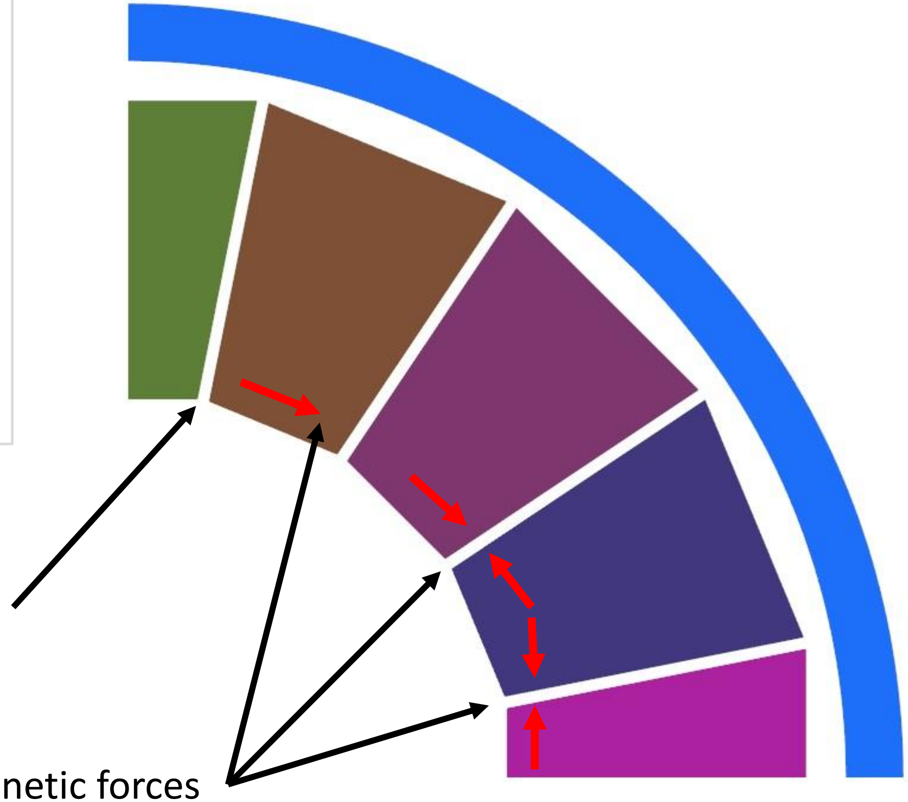


Pictured: Stretched wire bench

Measurements of the assembled dipole

During harmonic analysis, we observe a b_3 component which is larger than the designed value. It is not problematic in our case as we are still much lower than requirements.
This is due to forces during assembly which create some small gaps between the magnet blocks.





Small gap inducing b_3

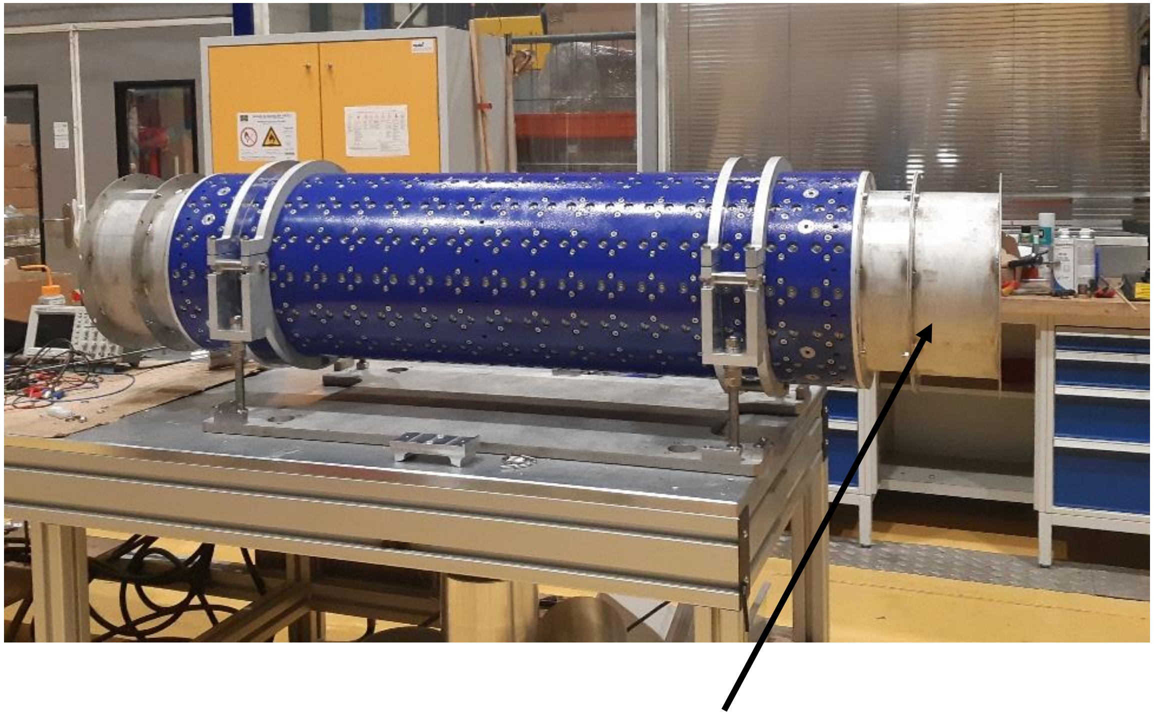
Strong magnetic forces

Protection covers

- For safe handling and work activities in the vicinity of the dipole, during the transport and installation, some protection covers were installed at each extremities.

- Only after the dipoles are installed and fixed to the supporting structure, the covers can be removed to leave space for the detector.

- The covers are here to create a physical barrier and avoid to approach a ferromagnetic tool close to the magnet but are not related to protection of persons which has restrictions to magnetic fields exposure higher than 0.5 mT.



Protection covers

DANGER!

RESTRICTED ACCESS

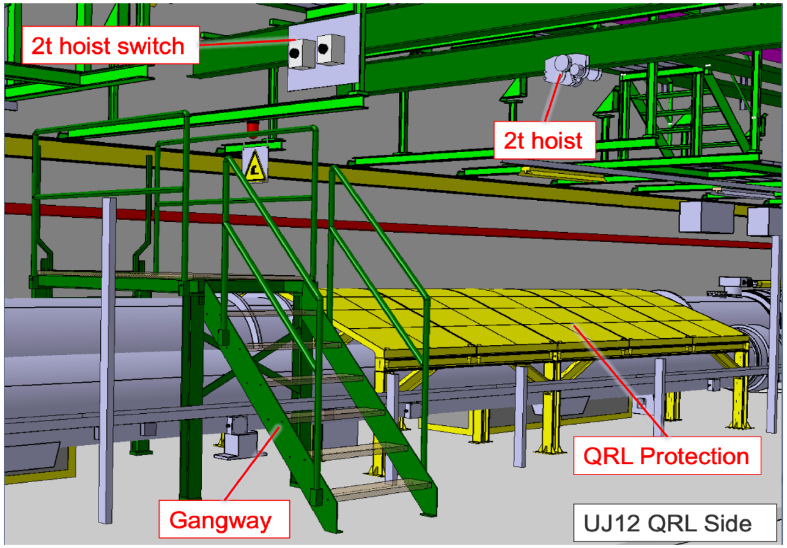
STRONG MAGNETIC FIELD

The Magnet is Always On!

- **NO CARDIAC PACEMAKERS OR IMPLANTABLE CARDIOVERTER DEFIBRILLATORS (ICDs)**
  Persons with certain metallic, electronic, magnetic, or mechanical implants, devices, or objects may not enter this area. **Serious injury may result.**

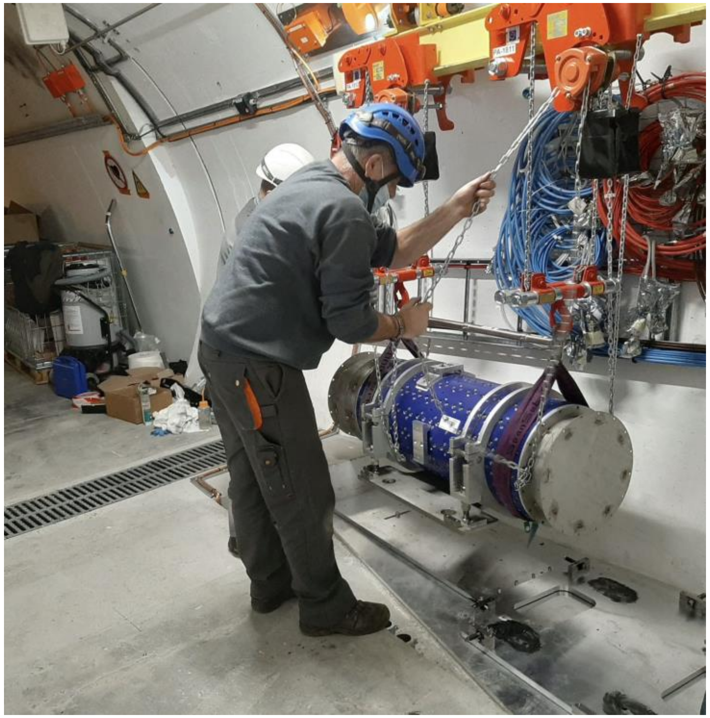
- **NO LOOSE METAL OBJECTS**
  Objects made from ferrous materials must not be taken into this area. **Serious injury or property damage may result.** Electronic objects such as hearing aids, cell phones, and beepers may also be damaged.

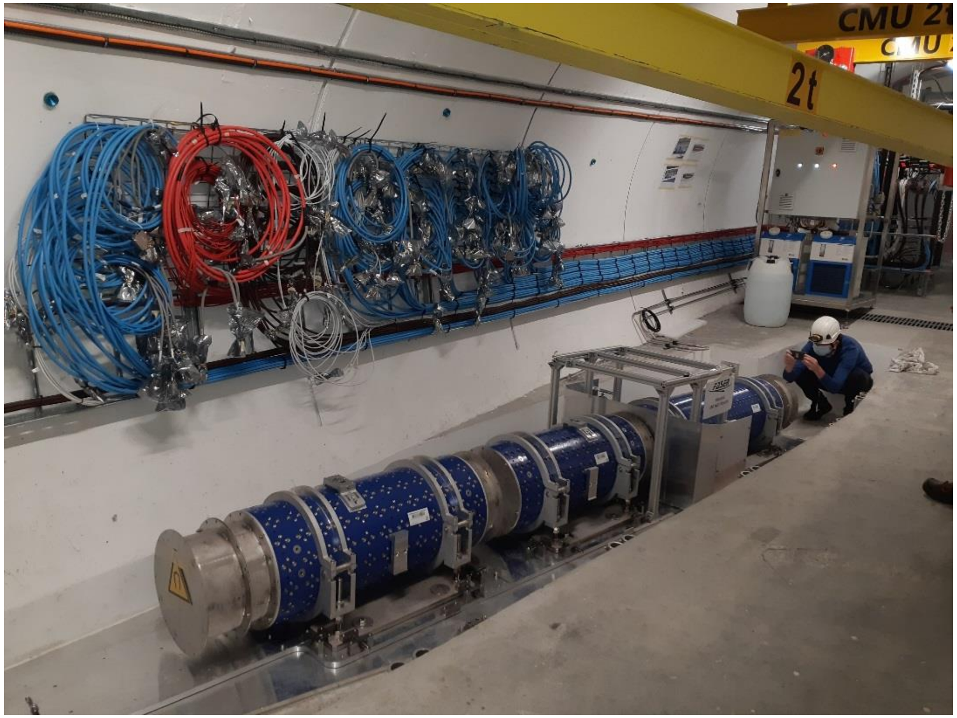
Installation in LHC



- A protection was installed on the top of QRL and LHC magnets.

- A new crane was installed over FASER experiment.

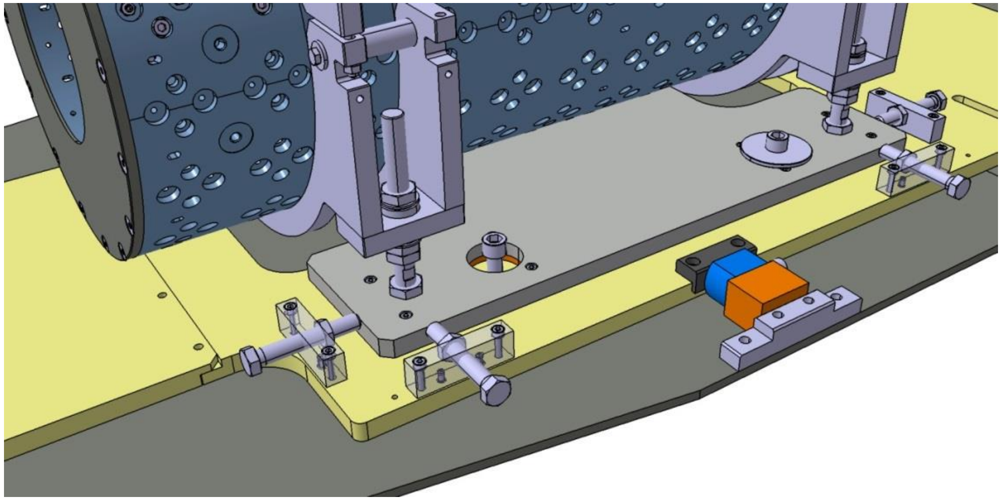


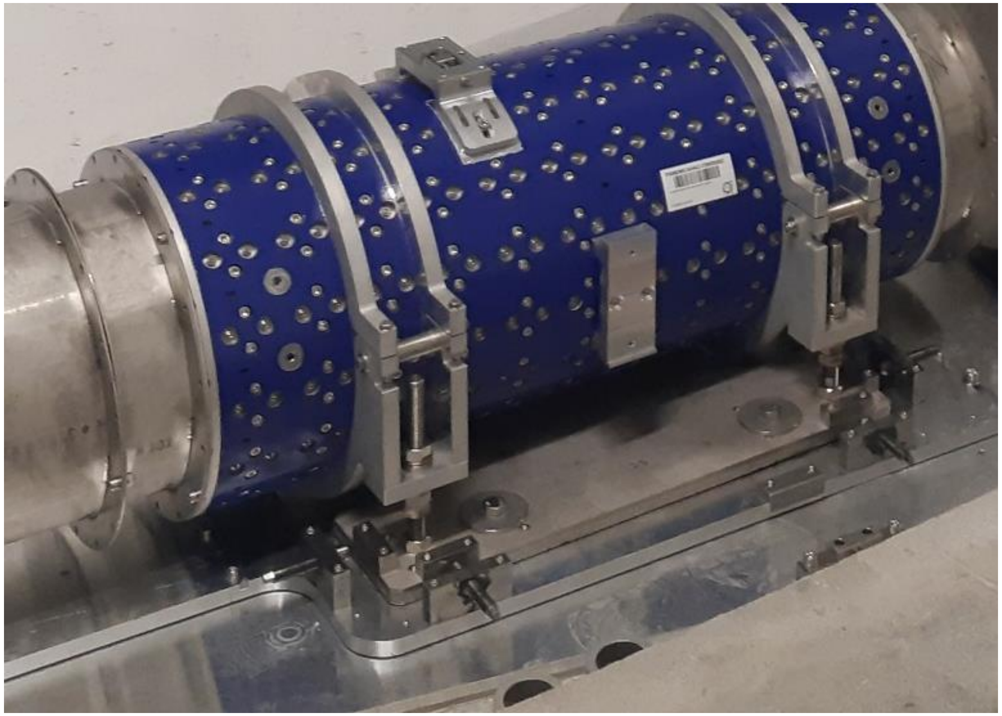


Installation in LHC: alignment

- A supporting and alignment system was designed to align the dipoles with respect to the beam *collision* axis line of sight (LOS).

- The whole detector can also be trimmed in case the ATLAS crossing angle change.





Installation in LHC

Parameter table

Magnet	**Short model**	**Long model**	**Unit**
Type	Dipole	Dipole	
Aperture diameter	200	200	mm
Length	1000	1500	mm
Outer diameter	430	430	mm
Mass (including support)	914	1331	kg
Yoke			
Steel type	Construction steel	Construction steel	
Iron length	1000	1500	mm
Permanent magnets			
Permanent magnet material	Sm_2Co_{17}	Sm_2Co_{17}	
BH max	32	32	MGOe
Mass of permanent magnet	606	909	kg
Magnetic field			
Nominal field at the centre	0.576	0.576	T
Nominal integrated field	0.584	0.87	T.m
Magnetic length	1014	1510	mm
GFR radius	100	100	mm
Integrated field homogeneity in GFR	≤ ± 3	≤ ± 3	%

Conclusion

- The design based on permanent magnets was probably the most relevant to meet the tight constraints of FASER especially in term of available space, large aperture with significant field, budget and limited impact on the LHC infrastructure.

- This solution is cost efficient as the budget for the 3 permanent magnet dipoles is probably a bit cheaper than normal conducting magnets, then there is no power supply, electric cable, cooling network and no running cost.

- FASER was a great opportunity to gain some experience in design and assembly of large Halbach array magnets.

- Some other projects based on permanent magnets were also recently made at CERN such as a large dipole for nTof and 2 high tunable gradient quadrupoles for the AD target area (see additional slides).

- Permanent magnet technology could also be interesting for some medical DC applications (reliability, no services nor maintenance needed).

- Do not hesitate to contact us, we are always open to new challenges!

Many Thanks to all the persons who contributed to this project, in particular:

Jamie Boyd
Frank Cadoux
Romain Ferriere
All EN-MME team
All TE-MSC-MM team
All TE-MSC-NCM team
Davide Tommasini

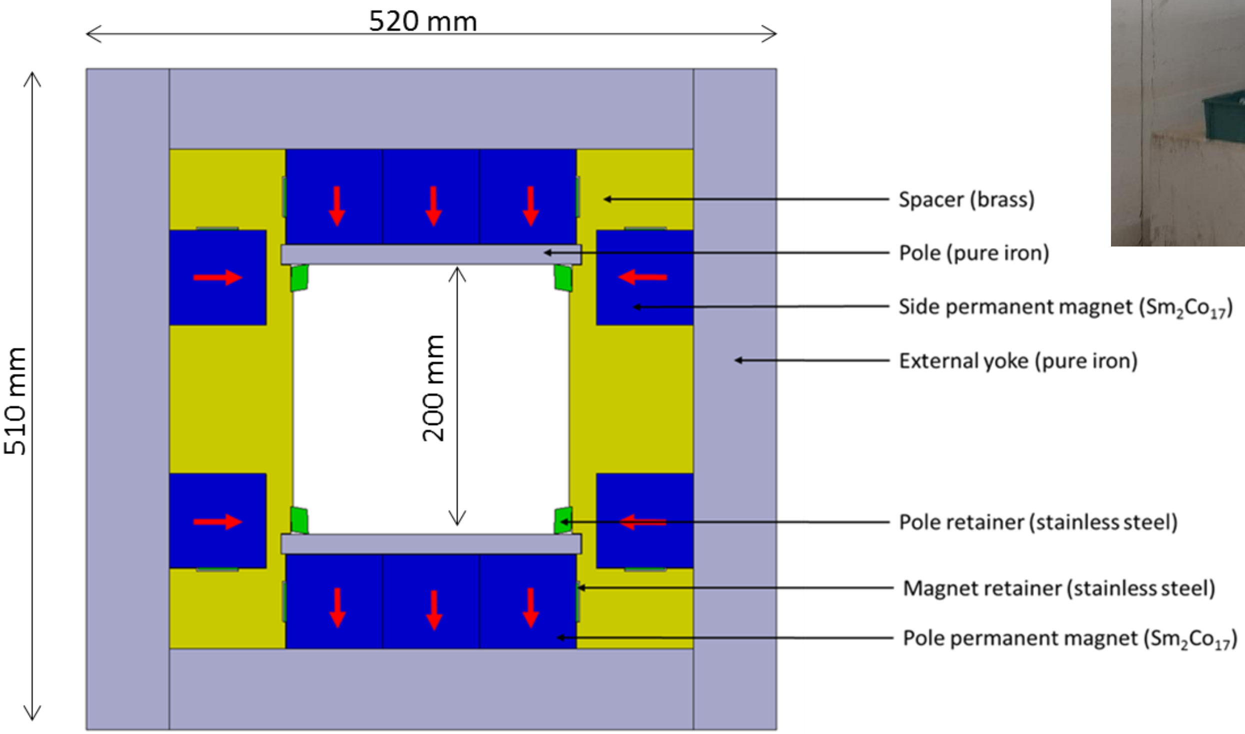
Thank You.

Additional slides

Permanent magnet for nTof EAR2

A separator dipole to replace a M200 resistive magnet (30 tons – 100 kW) in nToF EAR1, to save energy.

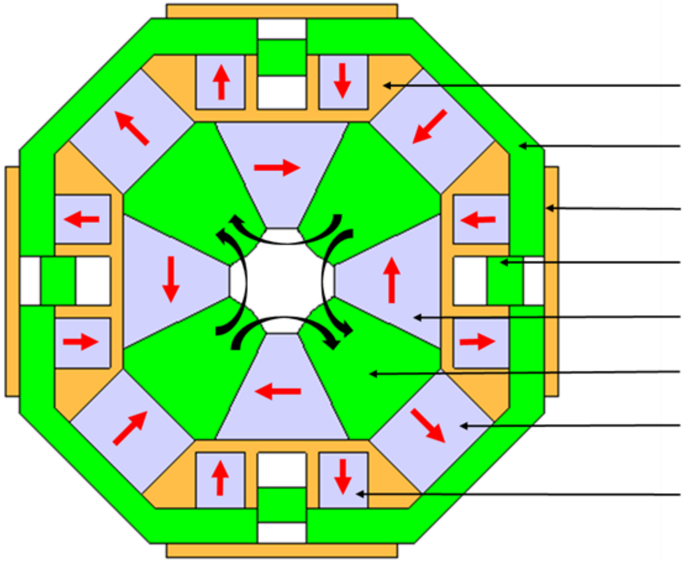
Parameter	Value	Unit
Length	1540	mm
Aperture diameter	200	mm
Central field	0.39	T
Magnet weight	2600	kg
Permanent magnet weight	626	kg



Permanent magnets for AD target area

2 quadrupoles to replace resistive magnets in AD target area, to improve reliability.

Parameter	Value	Unit
Number of magnets	2 units	
Length	1092	mm
Aperture diameter	60	mm
Central gradient	50	T/m
Magnet weight	1100	kg
Permanent magnet weight	800	kg



Frame (stainless steel)

External yoke (pure iron)

External plate (stainless steel)

Adjustable shunt (pure iron)

Trapezoidal permanent magnet (Sm_2Co_{17})

Pole (pure iron)

Rectangular permanent magnet type 1 (Sm_2Co_{17})

Rectangular permanent magnet type 2 used only in the high gradient quadrupole version (Sm_2Co_{17})