Design study of the high gradient magnets for a future diffraction limited light source at MAX IV

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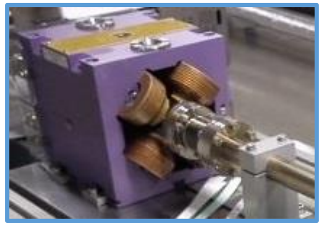
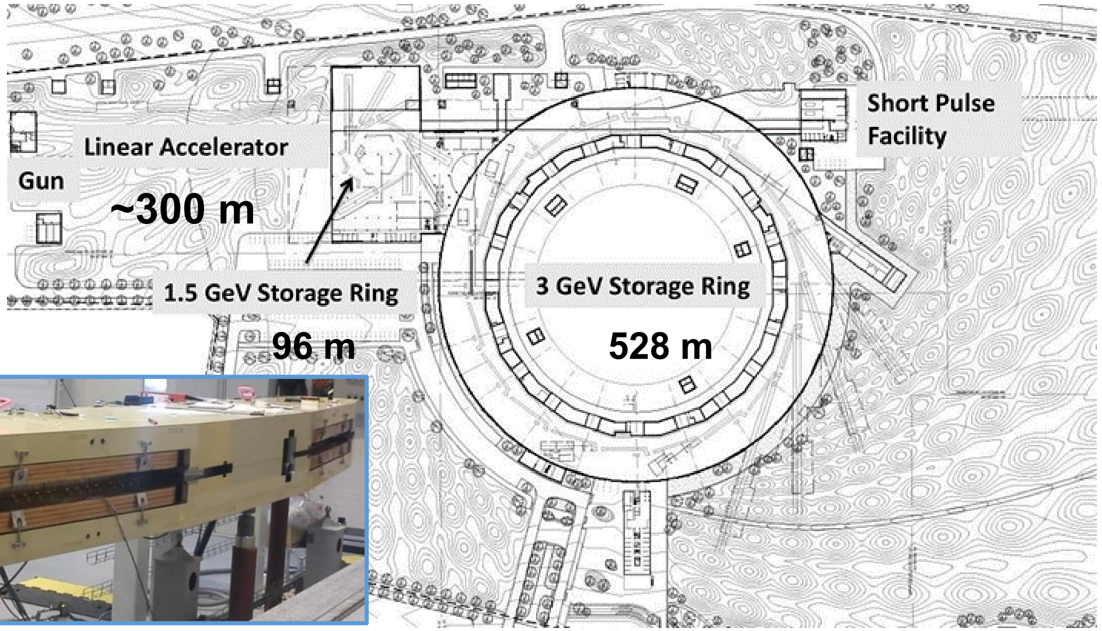
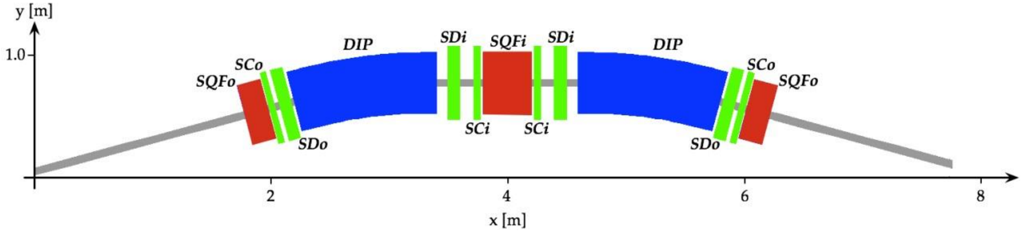
Introduction
The MAX IV magnets

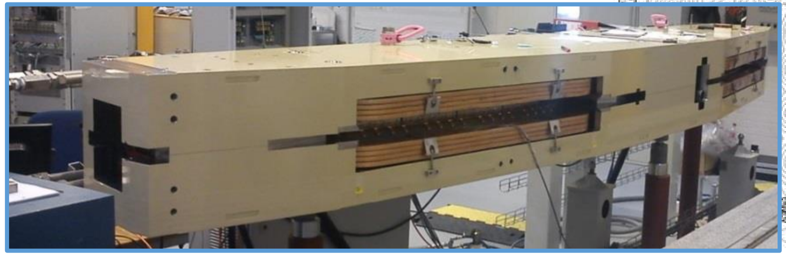
LINAC: various type of NC magnets, 112 magnets



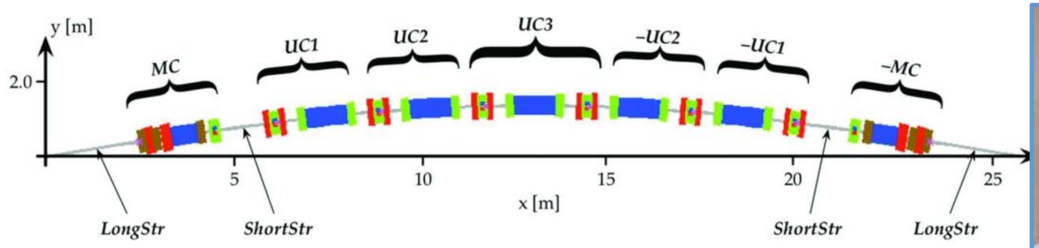


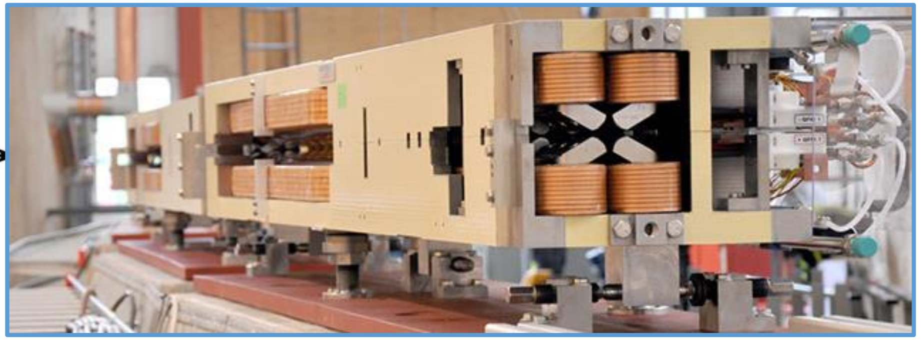
1.5 GeV lattice: 12 achromats, ”magnet block” concept, 156 magnets





3 GeV ring lattice: 20 achromats, ”magnet block” concept, 1320 magnets

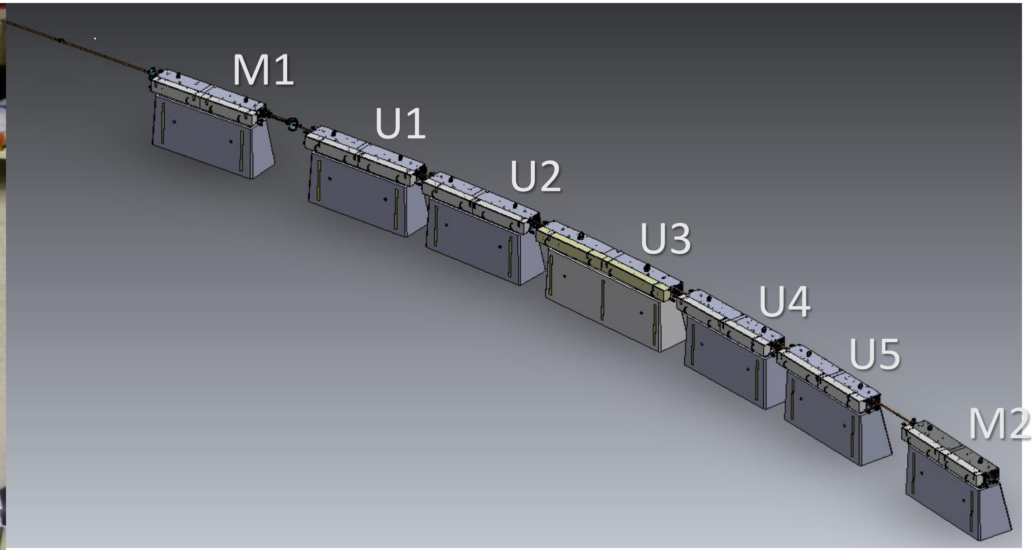




courtesy of M. Johansson

“Magnet block” concept 3 GeV Ring

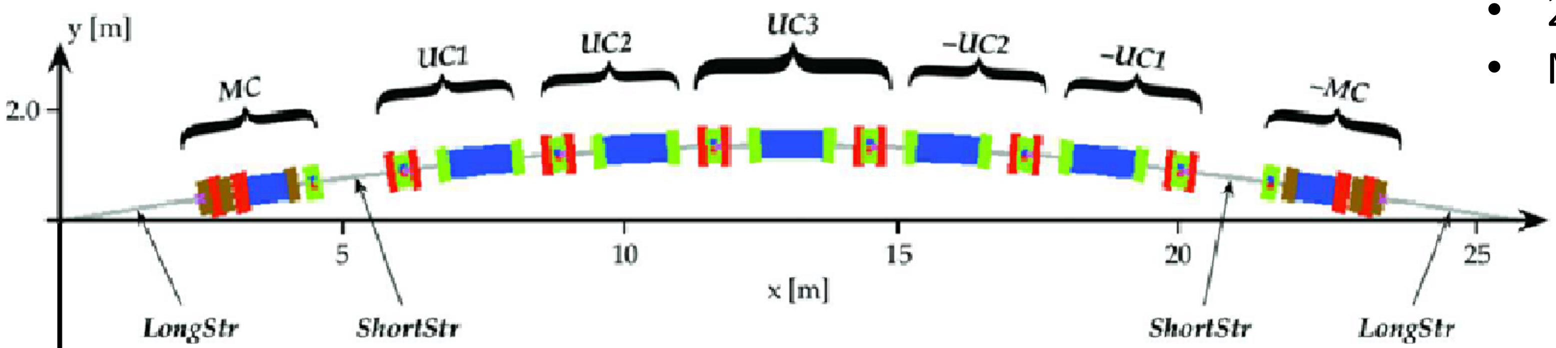
- The main structural parts of the magnet blocks are the yoke bottom and yoke top halves. Material: Armco low carbon steel.
- Gradient dipole pole, quad. and corrector pole roots machined out of the block, pole tips mounted over the coil ends.
- 6pole and 8pole magnet halves mounted into guiding slots in yoke block.
- Half-yoke cross section = 350 x 128 mm
- Lengths = ~ 2.3 m (M1, M2), ~ 2.4 m (U1-U5), ~ 3.4 m (U3)
- Weights = ~450 kg (M1, M2), ~490 kg (U1,…), ~620kg (U3)
- Magnet aperture= Ø25 mm, total power consumption ~300 kW.



courtesy of M. Johansson

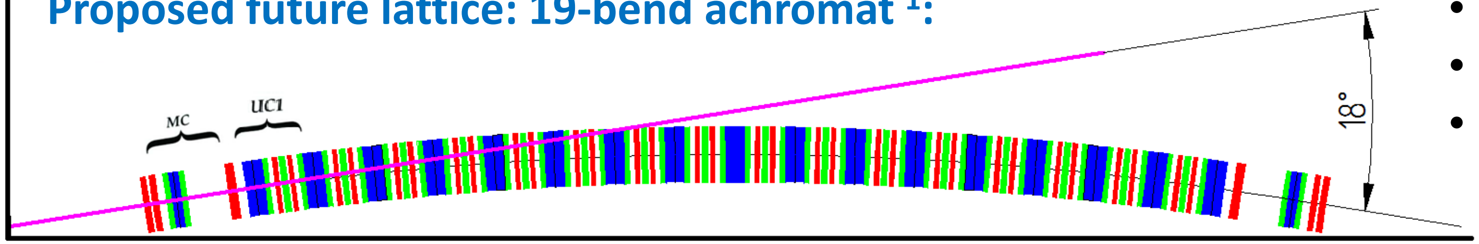
3 GeV ring lattice layout

Existing lattice: 7-bend achromat:



- Five unit cells and two matching cells.
- 20 achromats x 7 cells = 140 cells total
- Min. magnet aperture Ø= 25 mm

Proposed future lattice: 19-bend achromat [1]:

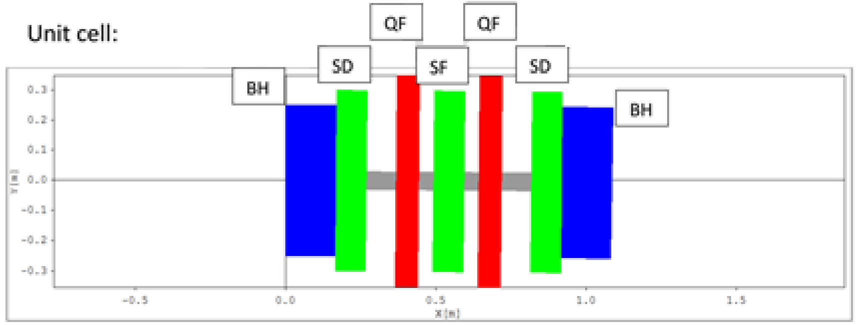


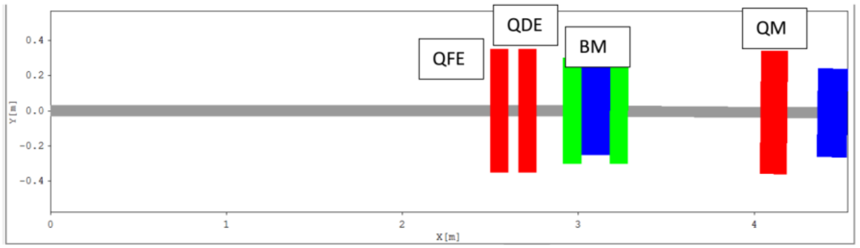
- 17 unit cells and two matching cells.
- 20 achromats x 19 cells = 380 cells total
- Min. magnet aperture Ø= 11 mm

- Achromat length = 26.4 m
- Ring circumference = 26.4 x 20 = 528 m

[1] Future Development Plans for the MAX IV Light Source: pushing further towards higher brightness and coherence. Pedro Fernandes Tavares, Johan Bengtsson and Åke Andersson. MAV IV Laboratory, Sweden

3 GeV ring magnets for the new lattice





Quadrupole	Magnetic Length [m]	Gradient [T/m]	Pole Tip Field [T] Rbore=5.5 mm
QF	0.075	219	1.2
QM	0.15	183	1
QFE	**0.1**	**234**	**1.29**
QDE	0.1	-198	1.1

Sextupole	Magnetic Length [m]	Gradient [T/m^2]	Pole Tip Field [T] Rbore=5.5 mm
SF	0.1	33592	1
SD	0.1	19729	0.6

Gradient Dipole	Magnetic Length [m]	Bending angle	B_0[T]	G [T/m]
Unit cell	0.3333	1°	0.52	-70.1
Matching cell	0.16667	0.5°	0.52	-30

QFE quadrupole

Requirements and constrains

- Magnet aperture Ø ≥ 11 mm
- Field gradient = 234 T/m
- Pole field= 1.29 T (Max. value for the conventional quadrupole 1 T ÷ 1.1 T)
- Magnetic length =100 mm
- Tuning range: ± 3 %
- Good field region Ø= 6 mm
- Integrated Grad. Homogeneity $\Delta\int Gdz/\int Gdz$: < (± few units of 10^{-4})
- Overall magnet height × width: ≤ (256 × 350 - existing magnet block dimensions)
- The top half-yoke shall be easy to demount to allow the installation of the vacuum chamber
- "Magnet block" concept similar to the existing MAX IV R3 ring

QFE
magnet design options

✗ **“Halbach “ type Permanent Magnet Quadrupole**

- Strength adjustment : Mechanical (double ring, etc.)
- Closed ring structure: issue with the synchrotron light extraction
- Not applicable for the “Magnet Block” concept

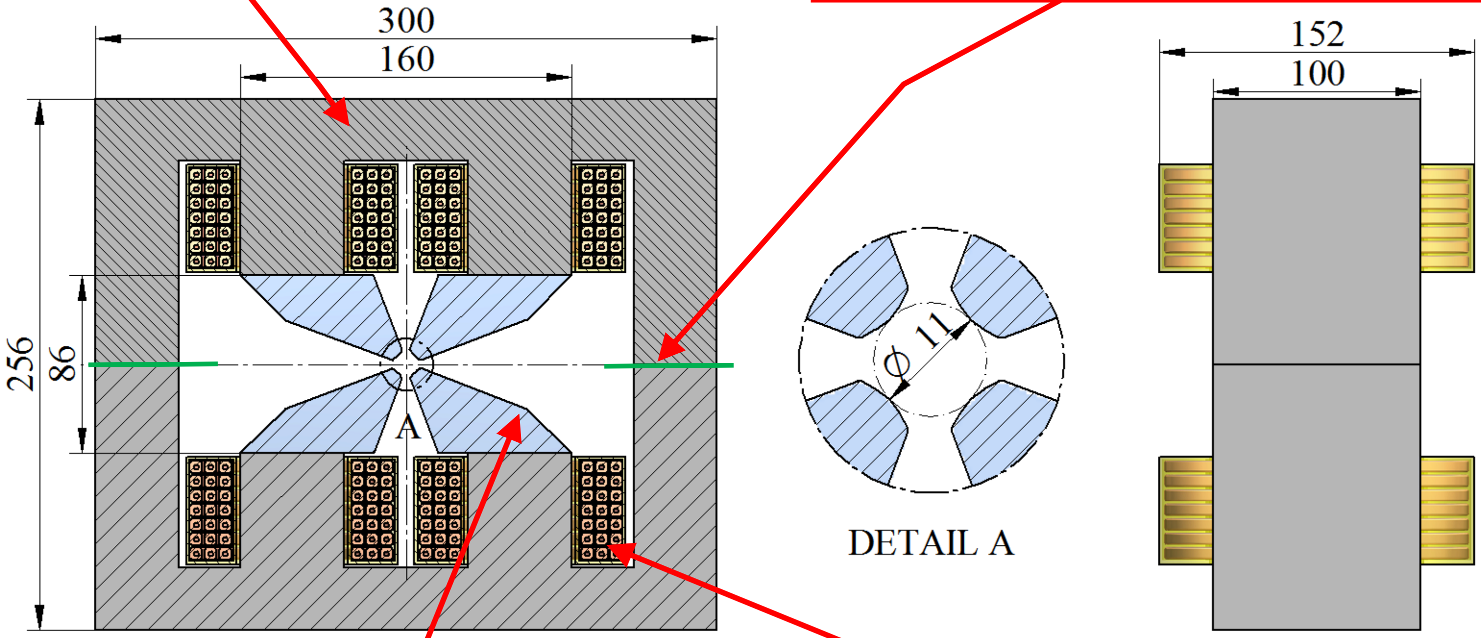
✓ **Conventional electromagnet**

✓ **Hybrid (Combination of the permanent magnet and trim coils)**

Conventional electromagnet

"Magnet block" concept:
Pole root machined out from the half yokes. Material: ST1010 or Armco

Pole profile shape and alignment:
Precise machining of the matting surface, pole profile machining in situ

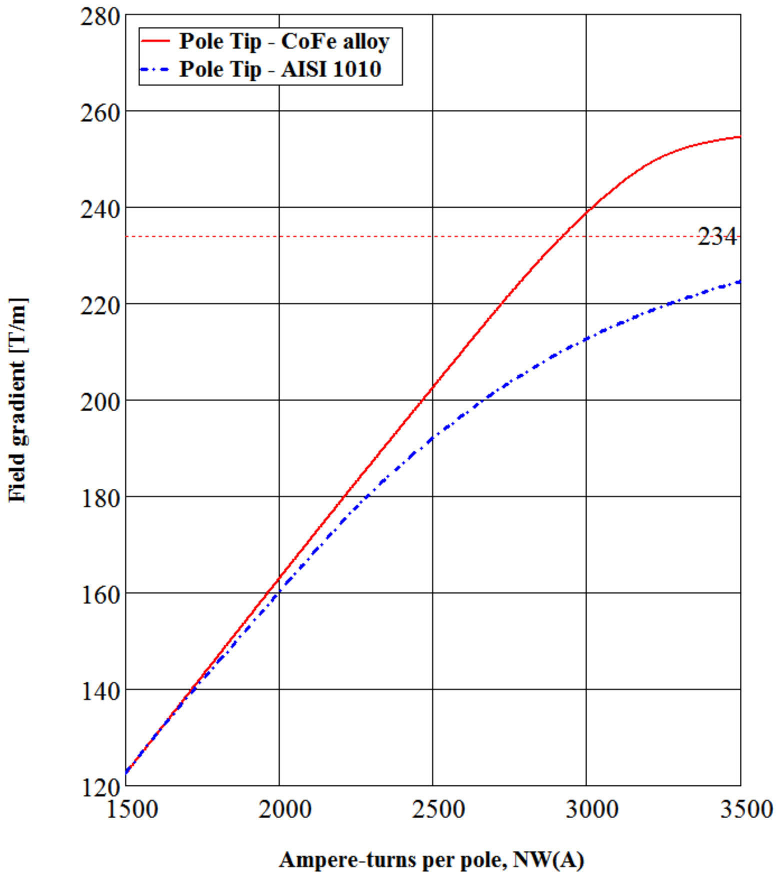


Pole Tip (separate pieces)
Material: Cobalt Iron alloy, Bs=2.35 T

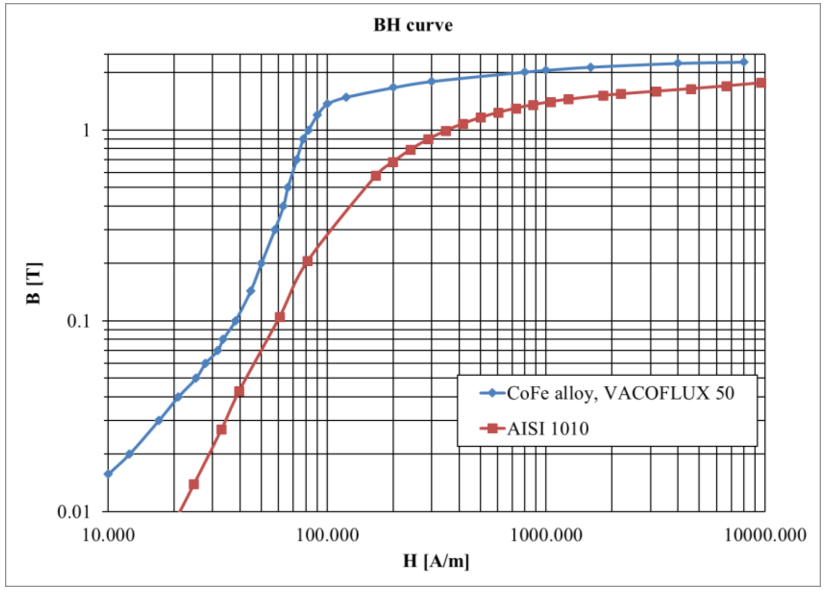
4 water cooled coils

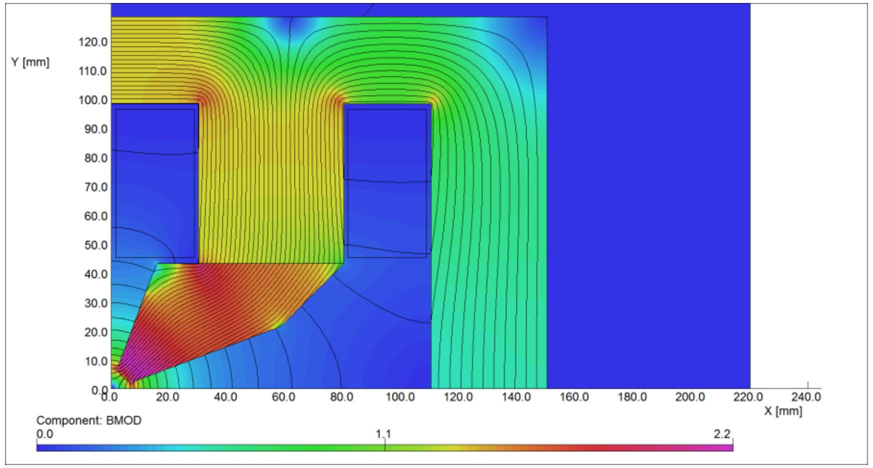
Main parameters		
Magnet		
Overall dimensions	300 x 256 x 152	mm³
Half return yoke mass (length 100 mm)	17.8	kg
Total magnet mass	52	kg
Coil		
Number of turns / coil	21	
Conductor dimensions	6 x 6 Ø 2.5	mm
Nominal current I_{nom} @234 T/m	140	A
Current density @ I_{nom}	4.6	A/mm²
Resistance @ 20°C	18.2	mΩ
Total power consumption	358	W
Voltage	2.6	V
Cooling parameters		
Cooling circuits / magnet	2	
Coolant velocity	1.1	m/s
Cooling flow	0.3	L/min
Pressure drop	1.6	Bar
Temperature rise	8	K

Conventional electromagnet



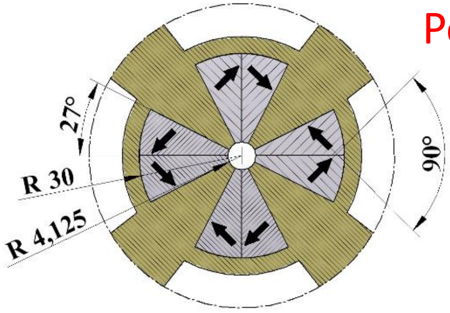
- Pole Tip (CoFe alloy):
  - Gnom.=234 T/m at I=139.5 A (NW=2930 A)
  - Pole field=1.29 T
  - Magnet efficiency η=96.4 %
  - Possible to achieve Gmax.=250 T/m I=154 A, η=93.1 %
- Pole Tip (AISI 1010):
  - G=210 T/m at I=139.5 A, (234 T/m @210 A, η=64 %)
  - Pole field=1.15 T
  - Magnet efficiency η=86.6 %

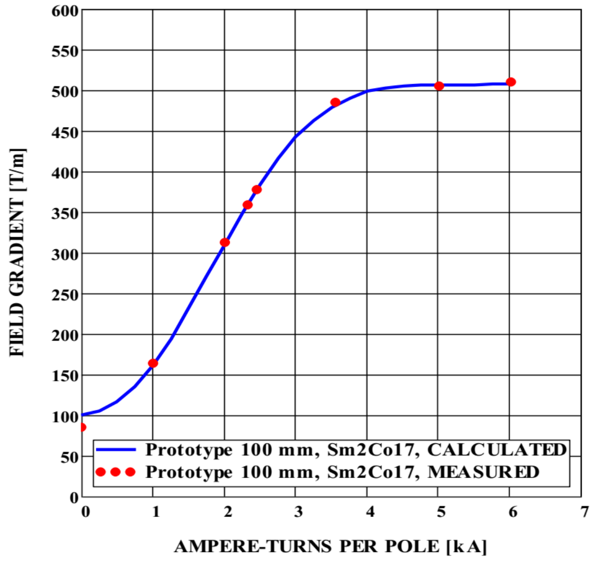




Electromagnet with Sm_2Co_{17} inserts
"Laced" quadrupole[1]

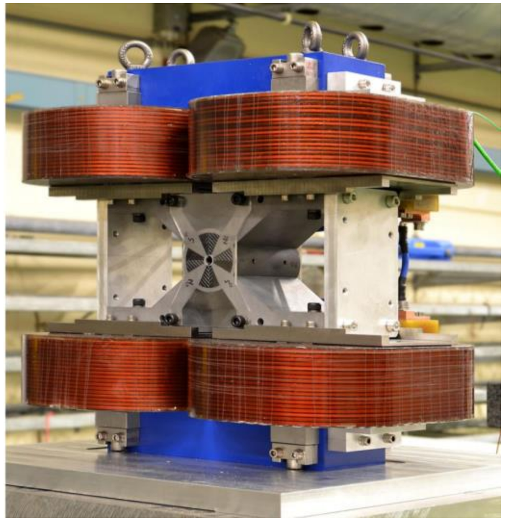
- A conventional iron dominated quadrupole is at the basis
- Rare earth permanent magnet material placed between the iron poles.
- The magnetic flux due to the permanent magnets is directed to cancel the part of flux produced by the coils which does not contribute to the field gradient in the magnet aperture
- Reduces the saturation effects in the iron pole
- Max. field gradient ~ 35 % larger than in a conventional quadrupole.

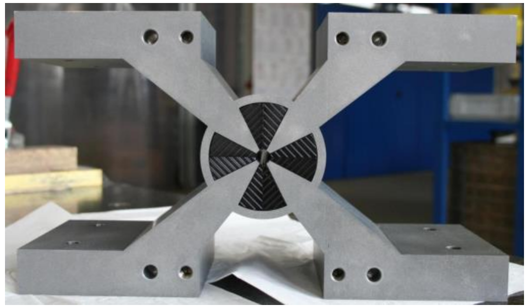




Final Focus Quadrupole Model for CLIC [2]

Pole field > 2 T

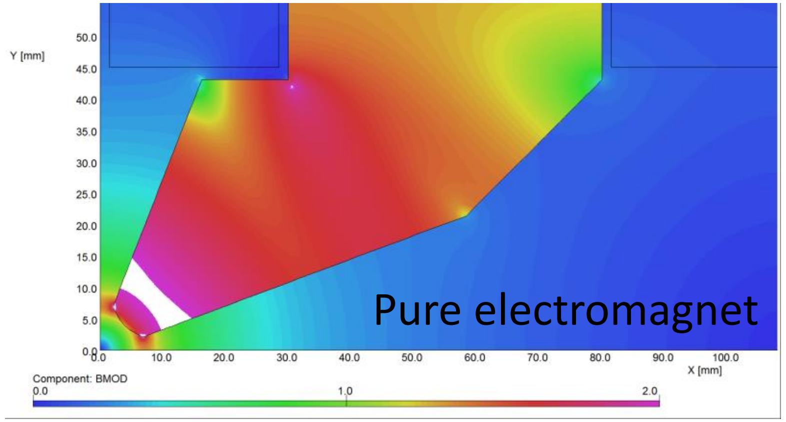


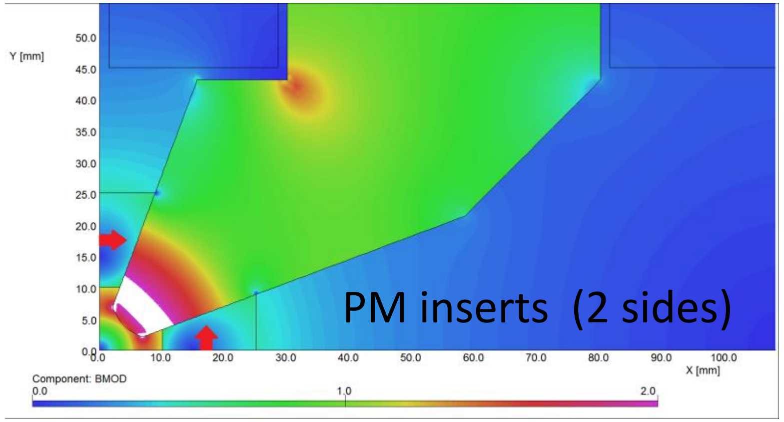


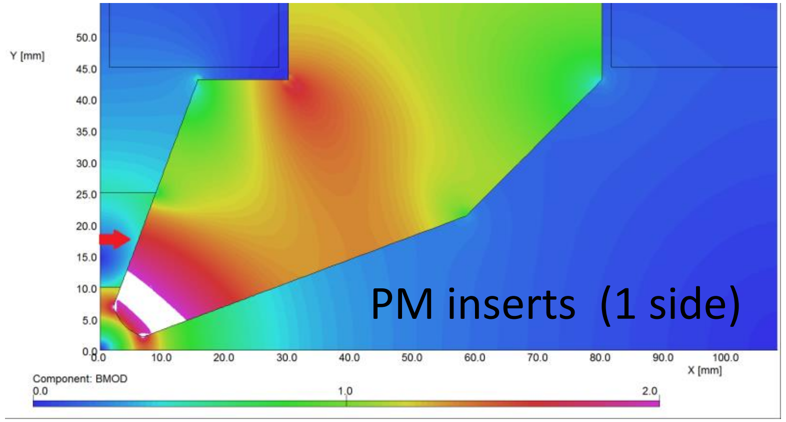
[1] K. Halbach, 'Magnet Innovations for Linacs', Proceedings of "1986 Linear Accelerator Conference", SLAC-R-303, Linac86-105, TH2-1.

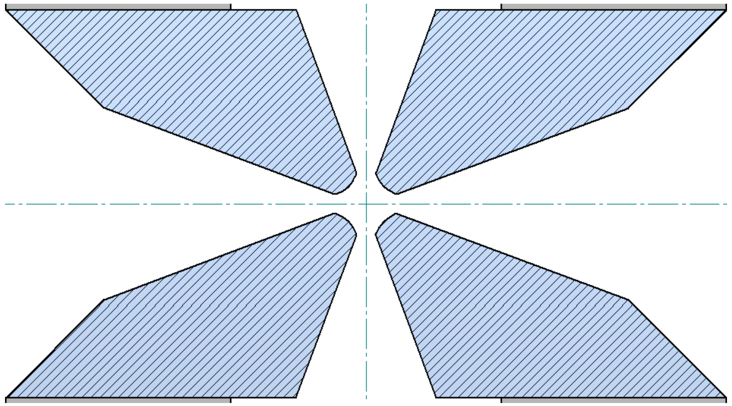
[2] A. Vorozhtsov, M. Modena, D. Tommasini, 'Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC', MT-22

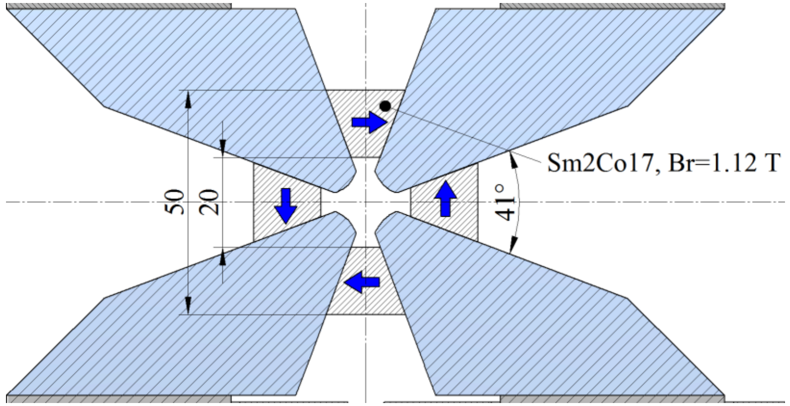
Electromagnet with Sm_2Co_{17} inserts

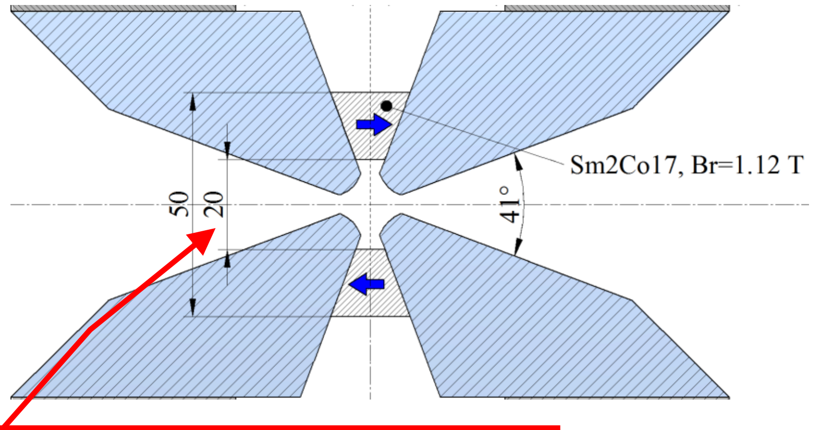






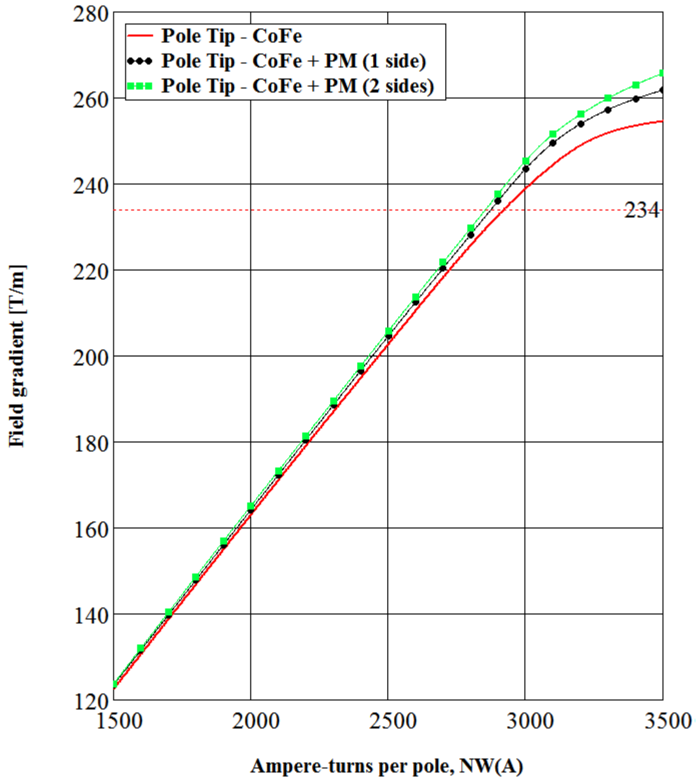


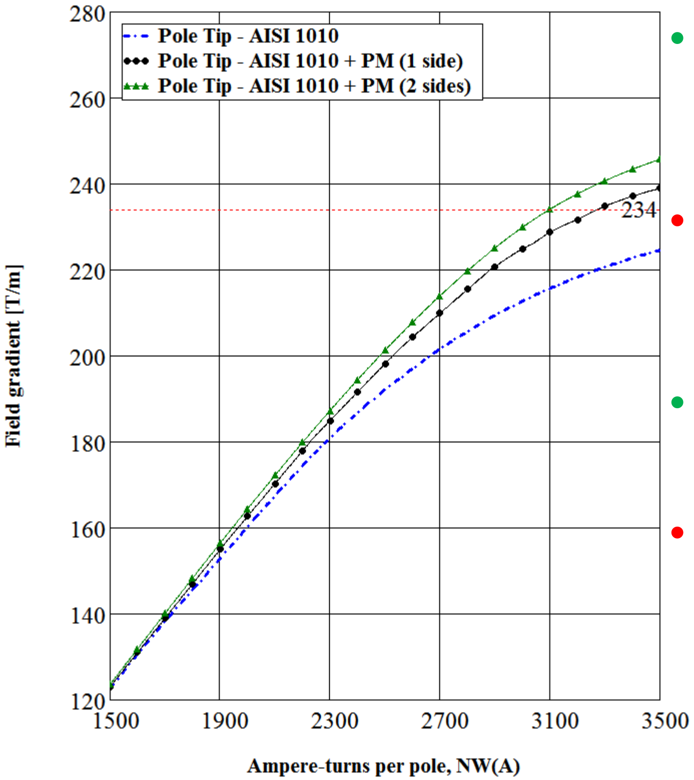




20 mm: Min. permissible value
Field quality reduction due to the field asymmetry

Electromagnet with the Sm_2Co_{17} inserts

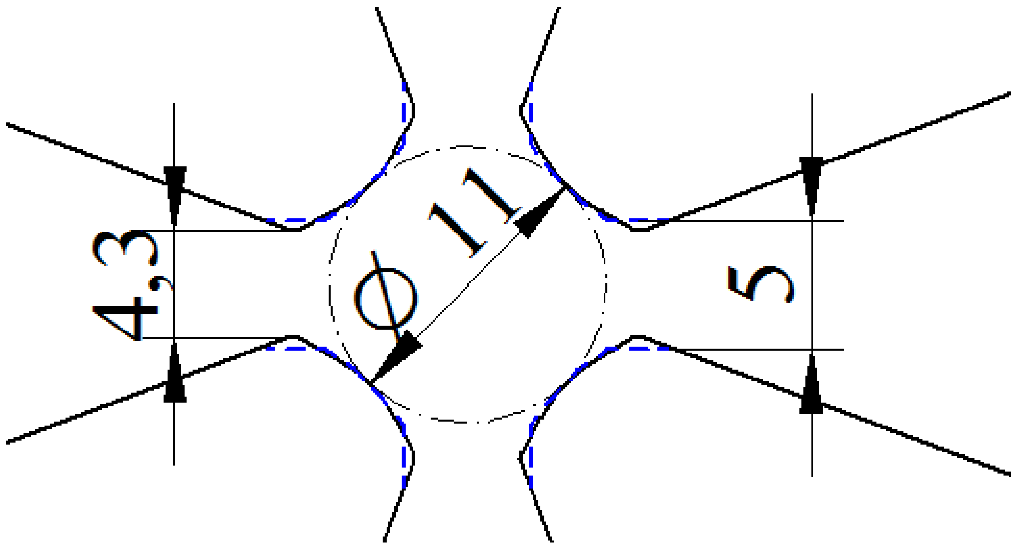




- Reduce the saturation of the Pole tip & Pole root & Return yoke: give a possibility to decrease the overall dimensions of the magnet.
- Not efficient for CoFe Pole tip @234 T/m, but extend the linear part of the excitation curve, possible to achieve the higher level of the gradient
- Significant improvement for 1010 pole, but CoFe solution gives better result even without PM inserts
- Cost of the CoFe raw material ≤ cost of the Sm_2Co_{17} PM blocks / magnet

Pole material&Configuration	CoFe	CoFe+PM(1side)	CoFe+PM(2 sides)	AISI 1010	AISI 1010+PM(1 side)	AISI 1010+PM(2 sides)	units
Number of turns / coil	21	21	21	21	21	21	
Nominal current I_{nom} @234 T/m	140	137	136	210	156	148	A
Current density @ I_{nom}	4.64	4.52	4.50	6.96	5.16	4.88	A/mm²
Total power consumption	358	341	336	805	442	396	W
Magnet efficiency η	96.4	96.7	96.8	64	86	90.1	%

Pole profile study / Field quality



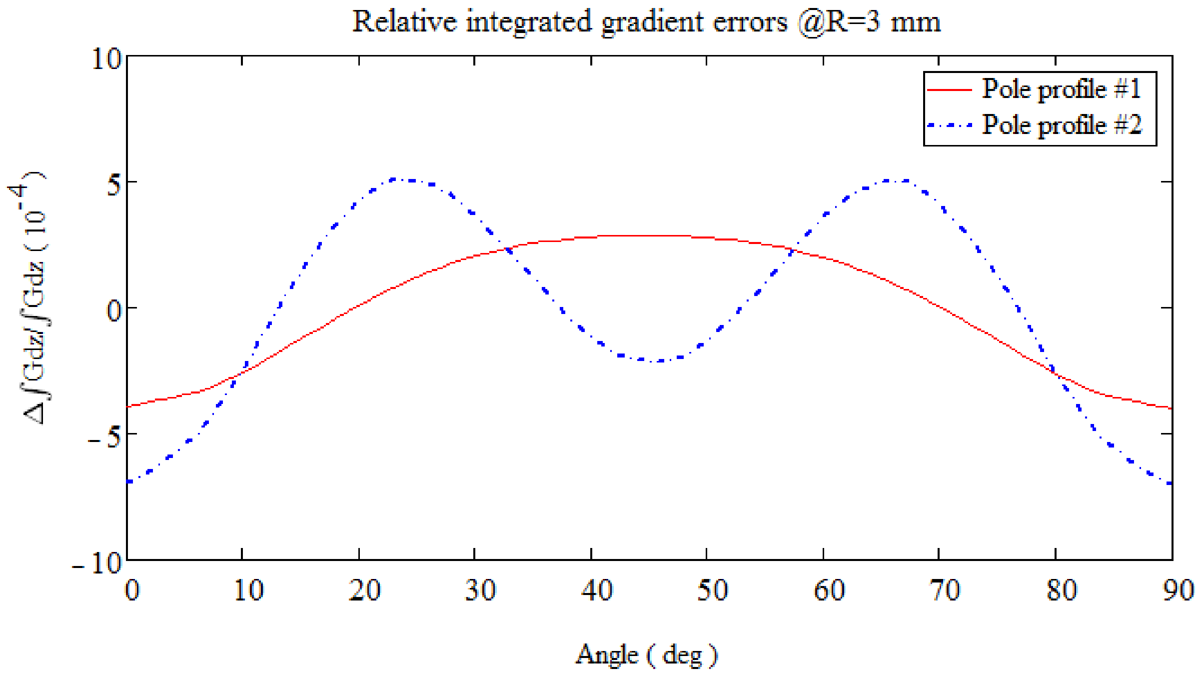
— Profile #1 (V gap= 4.3 mm)

---- Profile #2 (V gap=5 mm)

5 mm - Min. vertical gap (Existing MAX IV R3 magnets)

Normal relative field components b_n [10^{-4}] @R3 mm

Harm. #	Profile #1		Profile #2	
	2D	***Integrated***	***2D***	***Integrated***
4	0.02	0.05	0.03	0.1
6	0.34	-3.4 (pole chamfer required)	1.35	-2.5
10	-0.61	-0.6	-5.04	-4.7

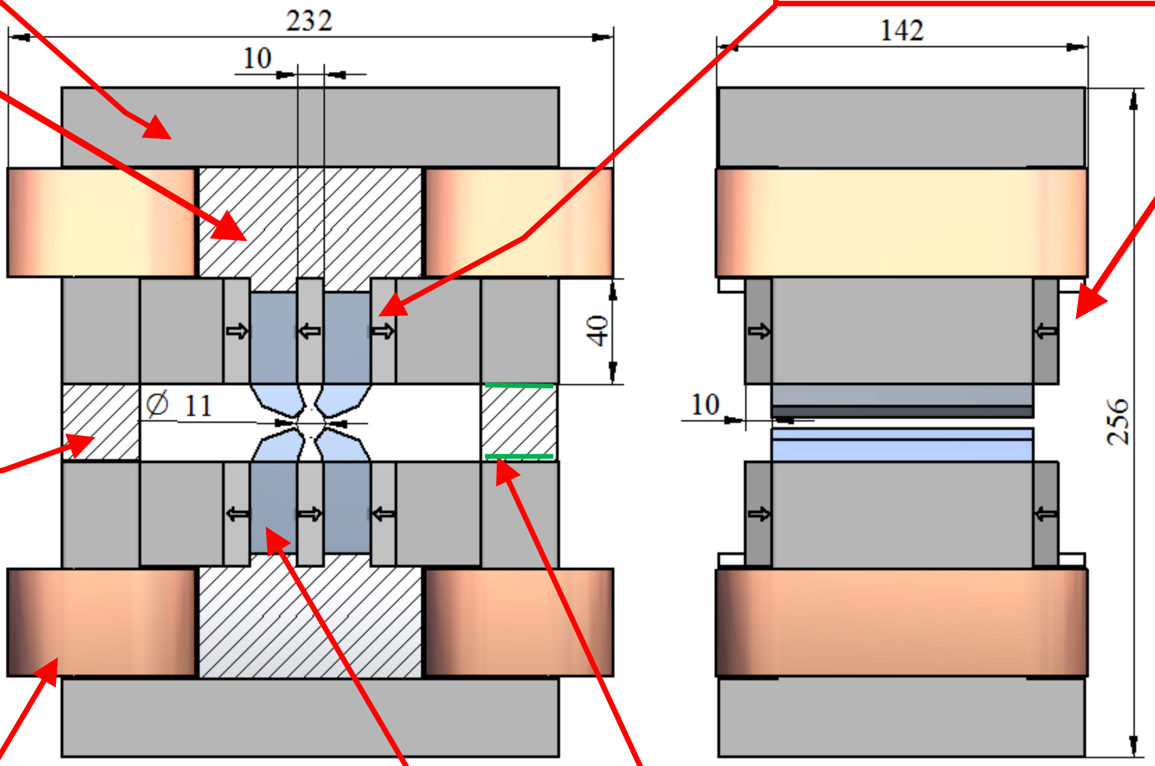


QFE magnet design
Hybrid magnet

"Magnet block" concept:
Return yoke machined out from the half yokes. Yoke shape: figure of "8" to reduce the magnetic forces between 2 halves

Permanent magnet blocks:
Sm2Co17, Br=1.12 T, HcB=844 kA/m
100x40x10(6 units) & 20x40x10(8 units)

Non-magnetic spacers



4 air cooled trim coils

Pole Tip (separate pieces)
Material: Cobalt Iron alloy, Bs=2.35 T

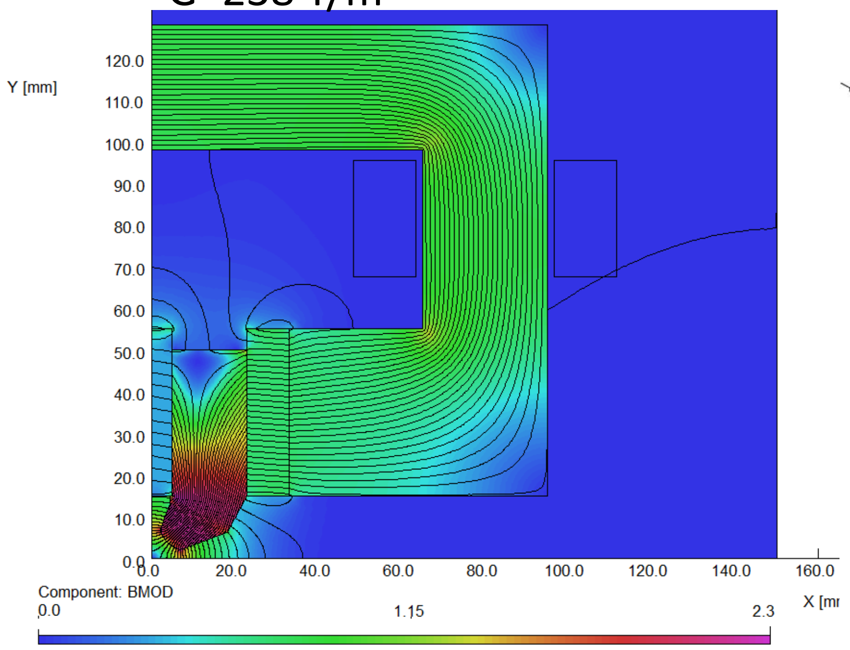
Pole profile shape and alignment:
Precise machining of the matting surface, pole profile machining in situ (1st assembly without PM)

Main parameters		
Magnet		
Nominal field gradient	234	T/m
Tuning range	-6 / + 5	%
Overall dimensions	232 x 256 x 142	mm³
Total magnet mass	40	kg
Magnetic force between the 2 half-yokes	30	kg
Trim Coil		
Number of turns / coil	60	
Conductor dimensions	3 x 4	mm
Max. current I_{max}	16	A
Current density @ I_{nom}	1.3	A/mm²
Total power consumption	15	W

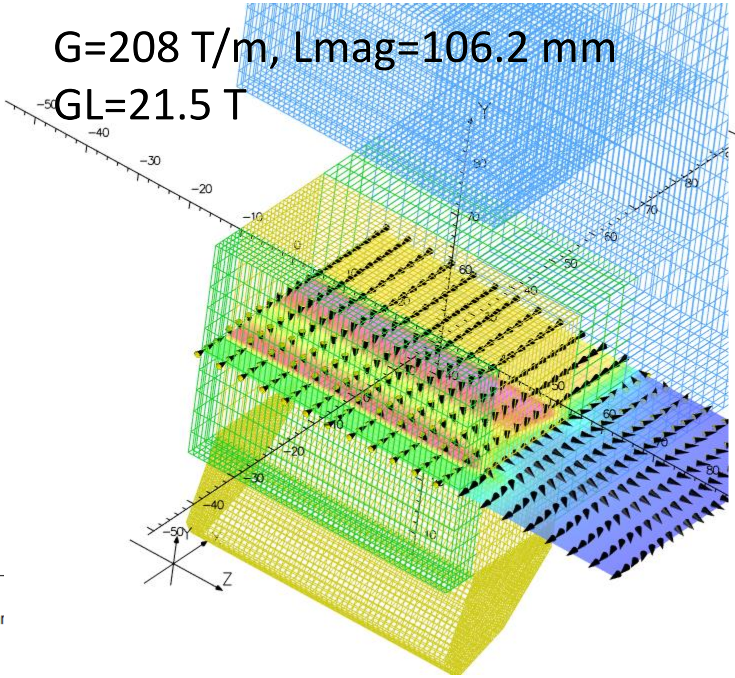
QFE Hybrid magnet
2D & 3D modelling

Permanent magnet blocks at each end of the poles to prevent the flux leakage : 20x40x10 (8 units)

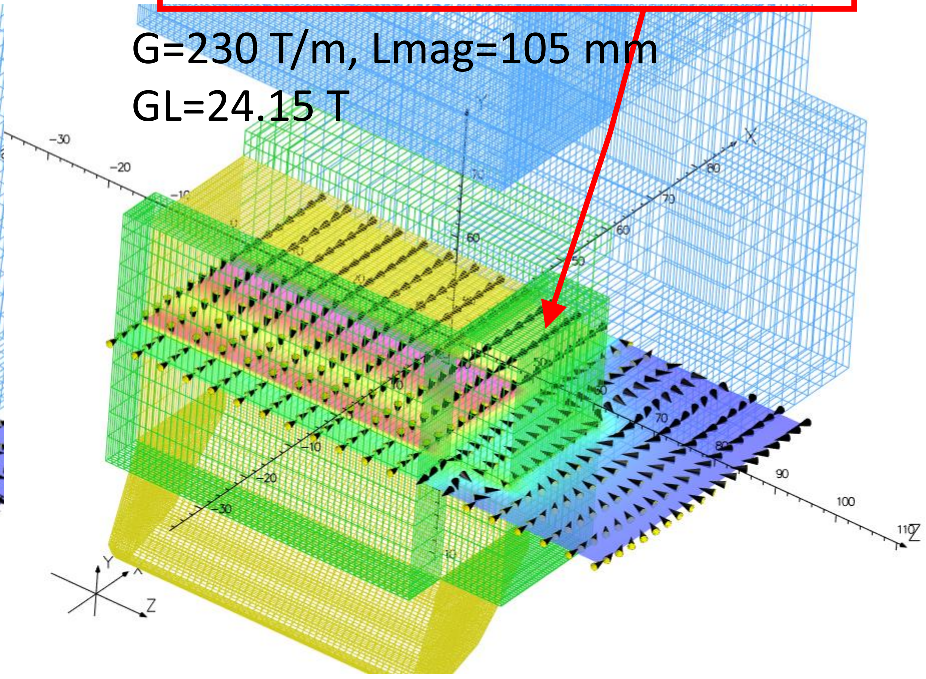
G=238 T/m



G=208 T/m, Lmag=106.2 mm
GL=21.5 T



G=230 T/m, Lmag=105 mm
GL=24.15 T



PM imperfections:

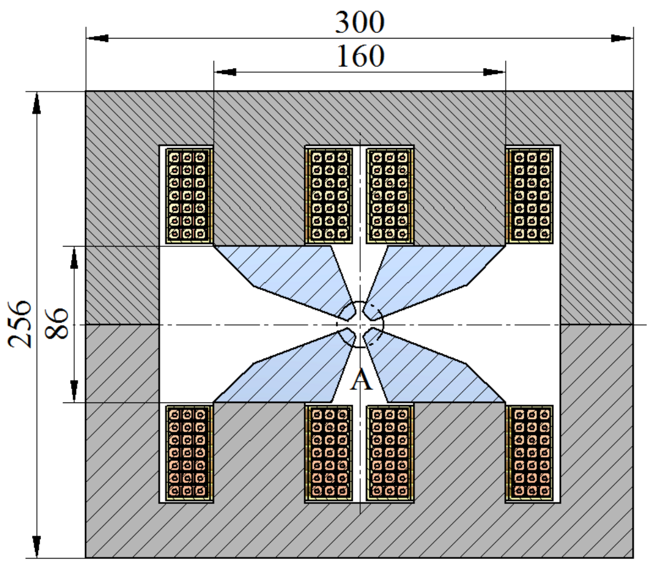
1. Direction of magnetization error ± 3%:

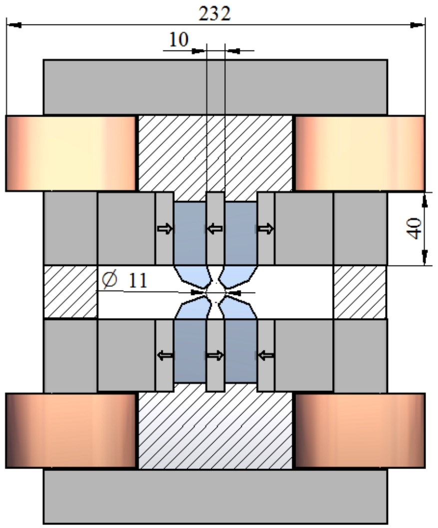
   The effect on a field quality / strength is negligible

1. Br & HcB variations from typical to min. values Br(1.12 T ↔ 1.09 T) , HcB (844 kA/m T ↔ 820 kA/m):

   Field strength variation of ± 1.5 % (25 % of the trim coils capability)

QFE Magnet design





Magnet type	Pros	Cons
Pure electromagnet	• Less complicated manufacturing / assembly	• Large power consumption (running cost) • Vibration induced by the water cooling
Hybrid magnet	• Low power consumption • Compact solution ?	• Assembly difficulties (magnetic forces) assuming the magnet block concept • Large capital cost (permanent magnet material)

Thank you for your attention !