Разработка магнитов для ускорителей заряженных частиц и физических установок

Обзорный семинар

(в связи с перевыборами на должность старшего научного сотрудника)

А.С. Ворожцов

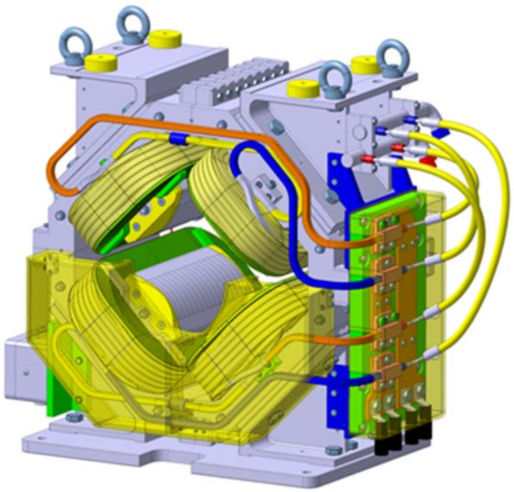
List of projects 2013-2018

- Compact Linear Collider (CLIC)
- New H- linear accelerator LINAC 4
- High resolution spectrometer DIRAC
- MedAustron - centre for ion-therapy and research
- Proton Synchrotron (PS) transfer line upgrade
- AWAKE- plasma wakefield acceleration
- Watt balance Mark II Experiment
- 3GeV ring upgrade of Synchrotron Light Source, MAX IV Lab
- ATLAS upgrade

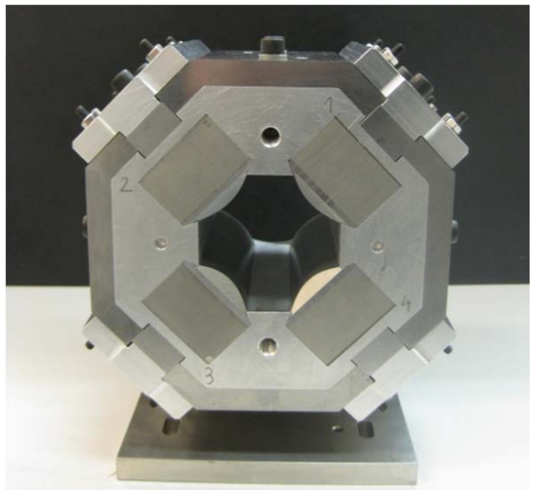
Magnets for accelerators

Iron dominated (Dipoles, Quadrupoles, Sextupoles, Combined Function Magnets etc.)

NC Electromagnets



Permanent magnets



Hybrid magnets

Field of expertise:

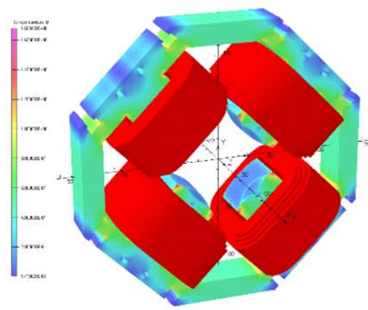
- Magnet design: 2D/3D FEM modeling, engineering parameters(electric, hydraulic etc.)
- Cost estimate
- Documentation for tender (Technical Specification, Spec. Drawings, Technical questionnaire, etc.)
- Control of the manufacturing process (Contract follow up)
- Acceptance tests / Magnetic measurements

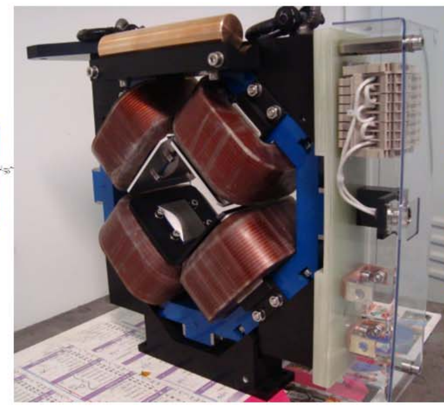
Plasma Wakefield Acceleration Experiment (AWAKE)

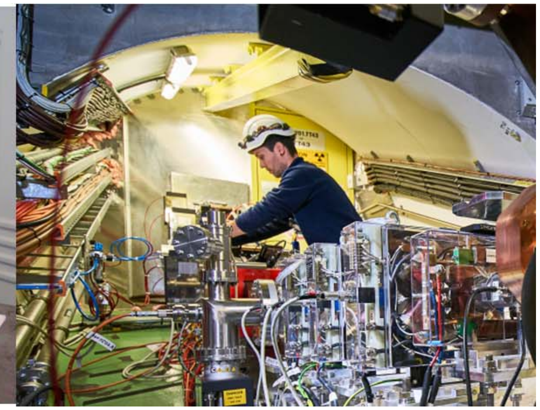
The AWAKE collaboration at CERN successfully accelerated electrons for the first time using a wakefield generated by protons zipping through a plasma. The electrons were accelerated by a factor of around 100 over a length of 10 metres: they were externally injected into AWAKE at an energy of around 19 MeV and attained an energy of almost 2 GeV (200 MV/m). Aim is 1 GV/m.

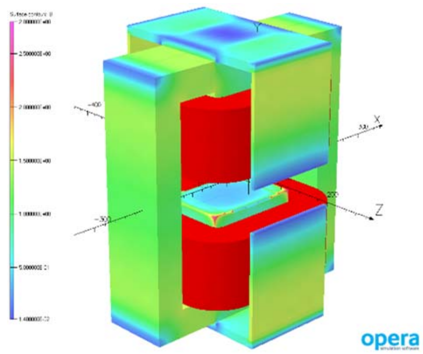
Design & Production follow up

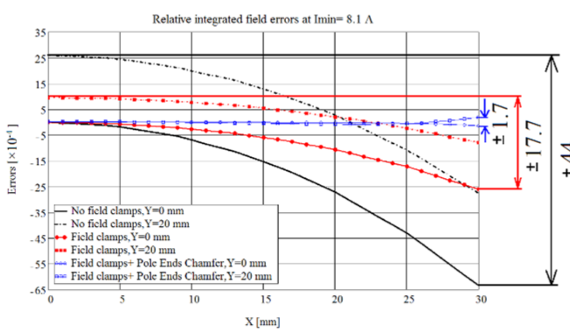
- H/V correctors
- Quadrupole
- Dipole

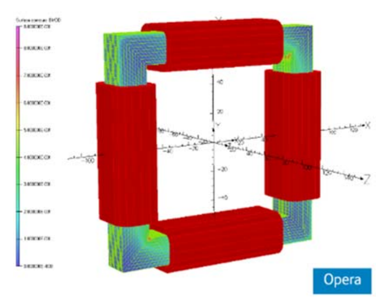


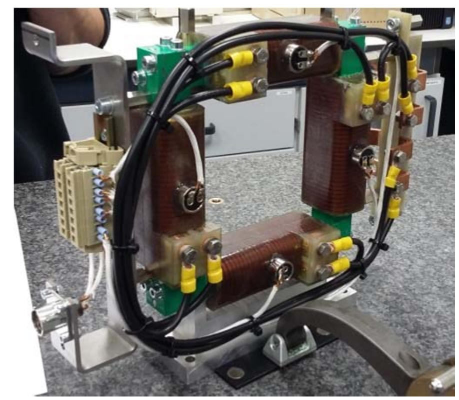










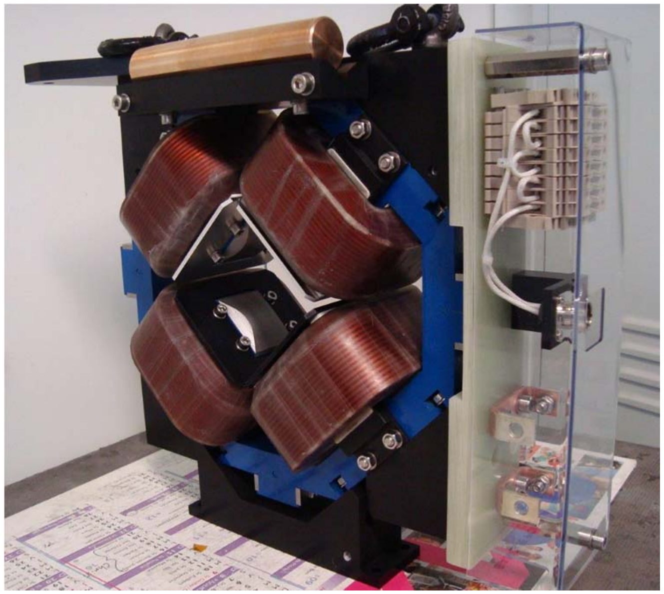


An example of a magnet design/ follow-up /tests : Quadrupole magnet

Functional specification (requirements and constrains)

- Beam Optics
- Vacuum
- Power Supply
- Alignment /Support / Installation

Units to be produced	11 + (1)	Installed + (spare)
Electron beam energy range	10 – 20	MeV
Full aperture Ø	≥ 70	mm
Integrated field gradient range	0.01(10% margin) – 0.18(20% margin)	T
Effective length	70	mm
Good field region radius	20	mm
Integrated field gradient quality $\Delta\int Gdz/\int G_{(0,0,z)}dz$	< ±40	units
Operational mode	DC	
Overall magnet length	≤ 200	mm
Overall magnet width x height	< 400	mm
Power converter current / voltage	< 10 / < 10	A / V

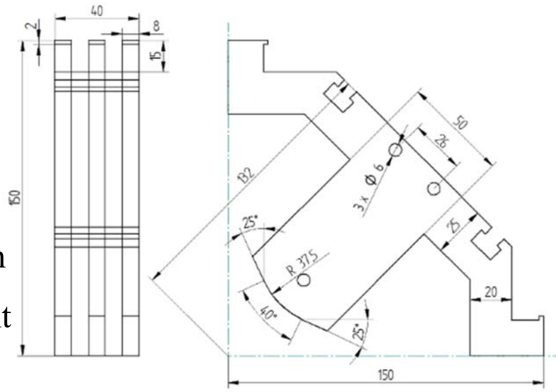


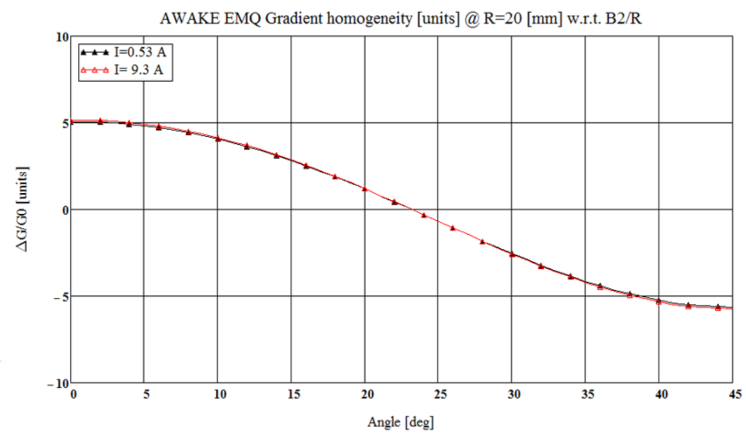
Electromagnetic design / FEM modeling / preliminary mechanical design

- Aperture R=35 mm, Leff=70 mm => B'(0)=(0.14 – 2.57) => NI,
- Coil (water / air cooled)=> Copper conductor(VonRoll) => Nw/pole (Current, Voltage)
- Yoke material low Hc(residual field, Bpole(min)=50 Gauss) / (solid / laminated)
- Yoke length

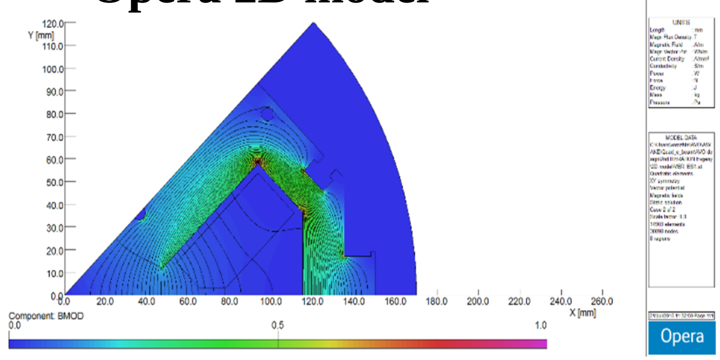
2D modelling:

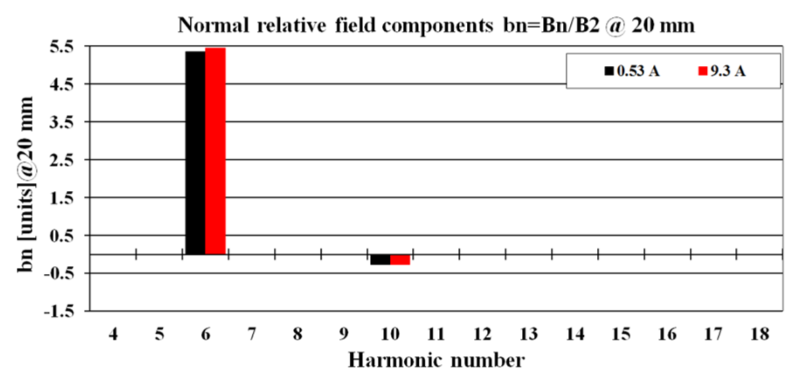
- Pole profile optimization
- Coil position optimization
- Yoke cross-section optimization
- Harmonic analysis / 2D gradient homogeneity inside GFR





Opera 2D model

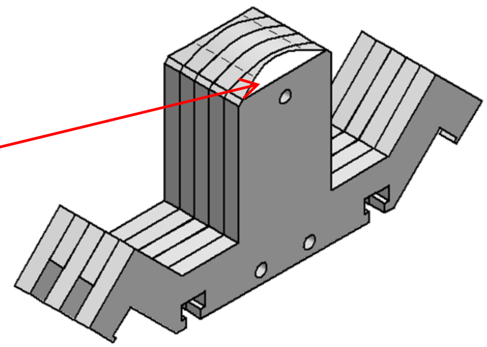


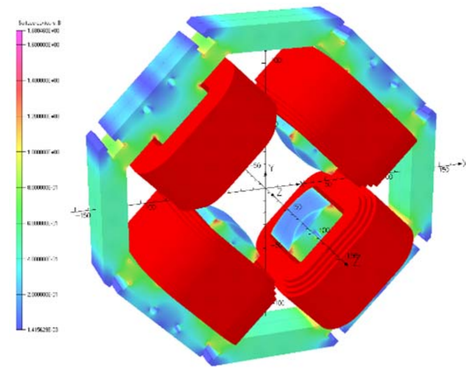


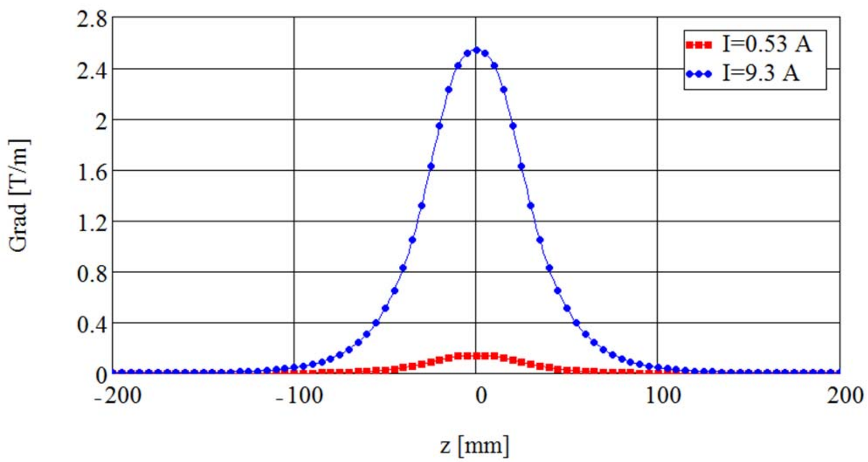
3D modelling / optimization

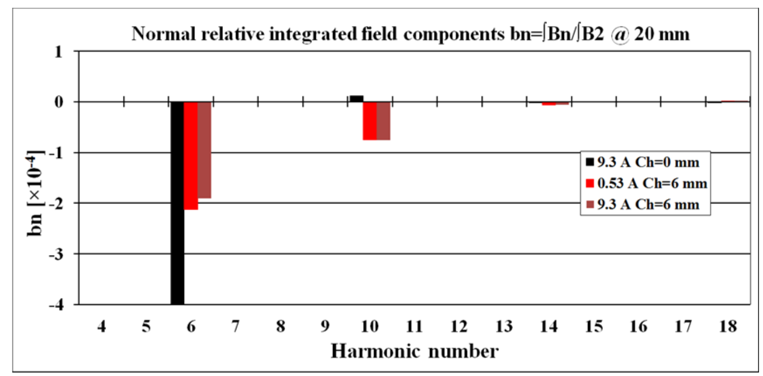
3D modelling :

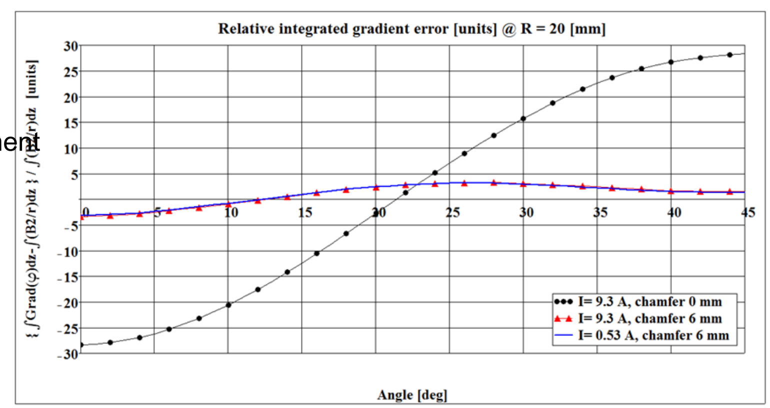
- Integrated field / field gradient
- Pole ends chamfer profile optimization
- Harmonic analysis(integrated field)
- Magnetic length
- Update of the electrical parameters











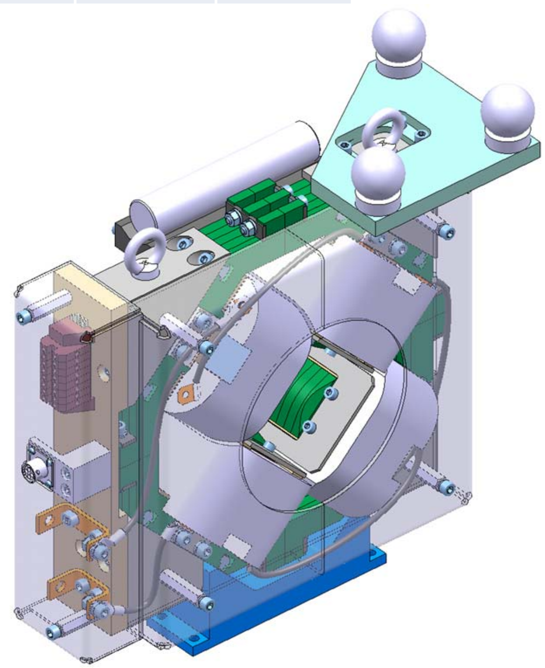
$$Error\ @\ r = 20mm = \frac{\int G_{r=20}(\phi,z)dz - \int \frac{B_2(z)}{r}dz}{\int \frac{B_2(z)}{r}dz}$$, where B_2 - main quadrupole field component

From Electromagnetic design =>
Mechanical design / Technical Specification

Main Parameters / Mechanical Tolerances / 3D mechanical model => Specification drawings=> Technical Specification

Parameter	Value	Unit
BASIC		
Number of magnets	12	
Nominal field gradient	2.54	T/m
Aperture diameter	70	mm
FIELD QUALITY (for information only)		
Integrated field gradient range ∫Gdl	0.01 – 0.18	T
Magnetic length	71.8	mm
Good field region diameter	40	mm
Integrated gradient homogeneity Δ∫Gdl / ∫Gdl	$< \pm 5 \cdot 10^{-4}$	
ELECTRICAL PARAMETERS		
Nominal current I_{nom}	9.3	A
Maximum current I_{max}	10	A
Current density at I_{max}	1.2	A/mm²
Dissipated DC power at I_{nom}	34	W
Resistance at 20°C	391	mΩ
Inductance	48.1	mH
Voltage on magnet U_{nom} (DC)	3.64	V
COOLING		
Cooling method	Air, natural convection	
DIMENSIONS AND WEIGHT		
Yoke length	40	mm
Overall length	~156	mm
Overall width	~395	mm
Overall height	~342	mm
Total magnet mass	~ 23	kg

Parameter	Value	Unit
Number of coils per magnet	4	
Number of pancakes per coil	1	
Number of turns per coil	138	
Conductor length per coil	~43	m
Conductor size on copper	3.0 × 2.8	mm × mm
Conductor edge rounding radius	0.5	mm
Min. conductor insulation thickness	0.06	mm
Max. conductor size with insulation	3.2 × 3.0	mm × mm
Ground insulation thickness	1.5	mm
Electrical resistance per coil at 20°C	98 ± 1	mΩ



Technical Specification

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Technical Specification

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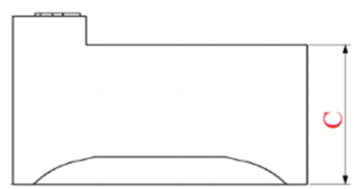
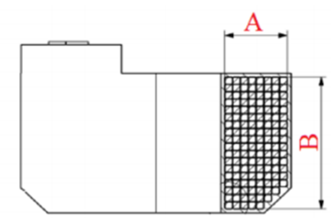
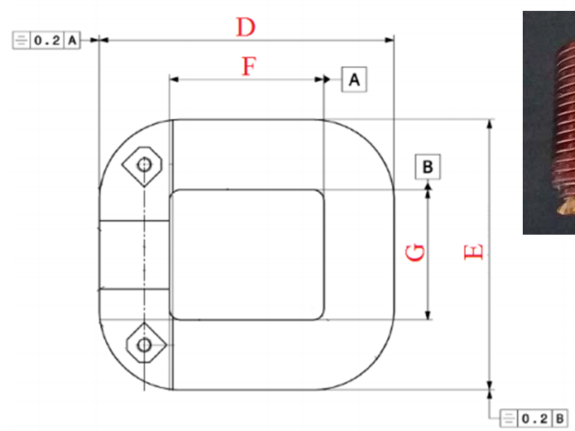
Production follow-up
Quality Control Record (Coils)

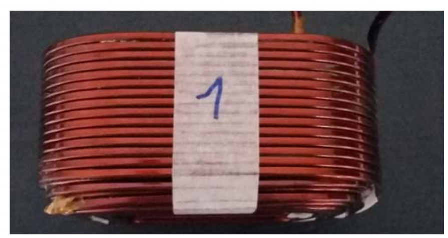
No	Test	Approval criteria	Passed / Result	Comment
TESTS BEFORE IMPREGNATION				
1	No of turns	137 turns	☑ Yes ☐ No	
2	Coil dimensional control, see page 2	Dimensions within tolerances	☑ Yes ☐ No	
3	Electrical resistance	Measured value at 20 ºC Corrected value at 20 ºC	92.8 mΩ 92.8 mΩ	
4	Resistance at 20ºC compared to 1st coil	Resistance is within ±1% of the 1st coil (93.0 mΩ)	☑ Yes ☐ No	
5	Coil inductance at Hz		1.419 mH	
6	Inter turn insulation test 1250 V peak	No signs of short circuit between turns	☑ Yes ☐ No	
TESTS AFTER IMPREGNATION				
No	**Test**	**Approval criteria**	**Passed / Result**	**Comment**
	Coil serial No	SPMQAWANC01-SD- 07		
7	Coil identification label	Correct serial number Readable Label beneath epoxy	☑ Yes ☐ No ☑ Yes ☐ No ☑ Yes ☐ No	
8	Coil dimensional control, see page 2	Dimensions within tolerances	☑ Yes ☐ No	
9	Visual inspection	**Coil free from:** Voids Cracks Dry spots Other defects	 ☑ Yes ☐ No ☑ Yes ☐ No ☑ Yes ☐ No ☑ Yes ☐ No	
10	Electrical resistance	Measured value at 20 ºC Corrected value at 20 ºC	92.6 mΩ 92.6 mΩ	
11	Resistance at 20ºC compared to 1st coil	Resistance is within ±1% of the 1st coil (93.0 mΩ)	☑ Yes ☐ No	
12	Thermal cycling test	The coil shows no degradation after thermal cycling (10 repetitions of 70 ºC to ambient temperature)	☐ Yes ☑ No	On 1st coil only
13	Ground insulation test, coil immersed in tap water	5 kV DC, I< 5 µA After 0 hours After 8 hour	☑ Yes ☐ No 0.0203 µA 0.0084 µA	
14	Dielectric test, coil immersed in tap water	5k VAC , one minute 5kV DC, I< 5 µA After 8 hours	☑ Yes ☐ No ☑ Yes ☐ No 0.0035 µA	
15	Inter turn insulation test: Capacitor discharge method, 1250 V peak	No signs of short circuit between turns	☑ Yes ☐ No	

No	Test	Approval criteria	Passed / Result	Comment
COIL DIMESIONAL CONTROL BEFORE IMPREGNATION				
1	Dimension A		25.5	
2	Dimension B		55	
COIL DIMESIONAL CONTROL AFTER IMPREGNATION				
No	**Test**	**Approval criteria**	**Passed / Result**	**Comment**
3	Dimension C	≤ 57 mm	56.85	
4	Dimension D	≤ 120.4 mm	120.3	
5	Dimension E	≤ 110.4 mm	110.3	
6	Dimension F	63.2 ± 0.1 mm	63.2	
7	Dimension G	53.2 ± 0.1 mm	53.2	
8	Symmetry to A	⌯ 0.2 A	OK	
9	Symmetry to B	⌯ 0.2 B	OK	

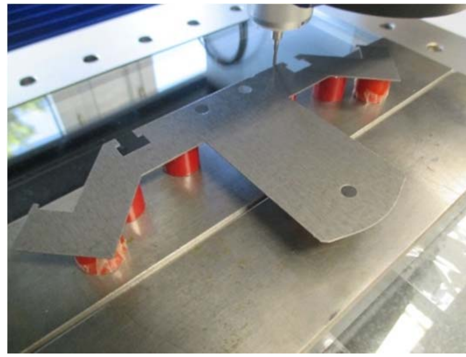


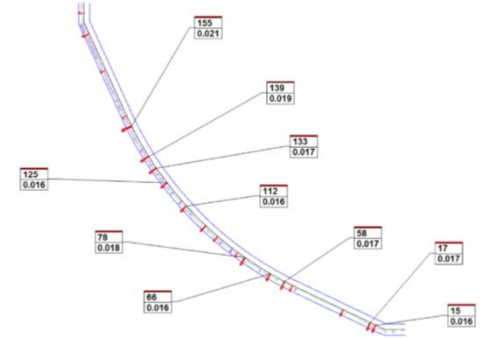






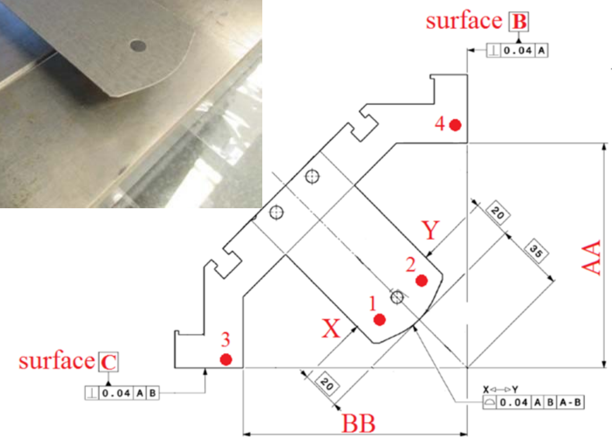
Production follow-up
Quality Control Record (YOKE)

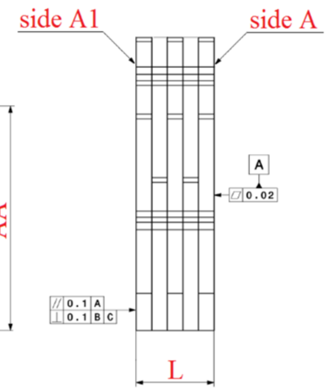


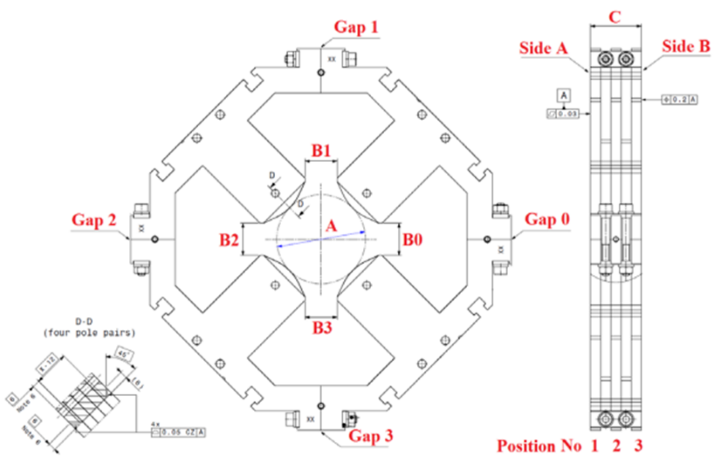


No	Test	Approval criteria	Passed / Result: Position No 1	2	3	Comment
TESTS ON PRE-ASSEMBLED YOKE						
1	Inscribed diameter A	70 ± 0.05 mm	70.022	70.033	70.028	
2	Pole distance B0	25.46 ± 0.05 mm	25.457	25.459	25.450	
3	Pole distance B1	25.46 ± 0.05 mm	25.482	25.477	25.469	
4	Pole distance B2	25.46 ± 0.05 mm	25.445	25.450	25.447	
5	Pole distance B3	25.46 ± 0.05 mm	25.460	25.482	25.467	
6	Yoke length C	$40^{+0.5}_{-0}$ mm	40.106			
7	Side A	⏥ 0.03	0.027			
8	Side B	⌖ 0.2 A	0.198			
9	Gap between the matting surfaces of the quadrants	< 0.02 mm	Gap No 0: <0.02; 1: <002; 2: <0.02; 3: <0.02			

No	Test	Approval criteria	Result: Yoke quadrant No 1-1	1-2	1-3	1-4	Comment
TESTS AFTER END CHAMFERS MACHINING							
1	End chamfer dimension Side A	6×6 ± 0.025 mm	5.977	5.978	5.987	6.004	
2	End chamfer dimension Side B	⌓ 0.05 CZ A	0.001	0	0.011	0.003	
3	End chamfers offset Side A	± 0.025 mm	0.016				
4	End chamfers offset Side B	± 0.025 mm	0.015				







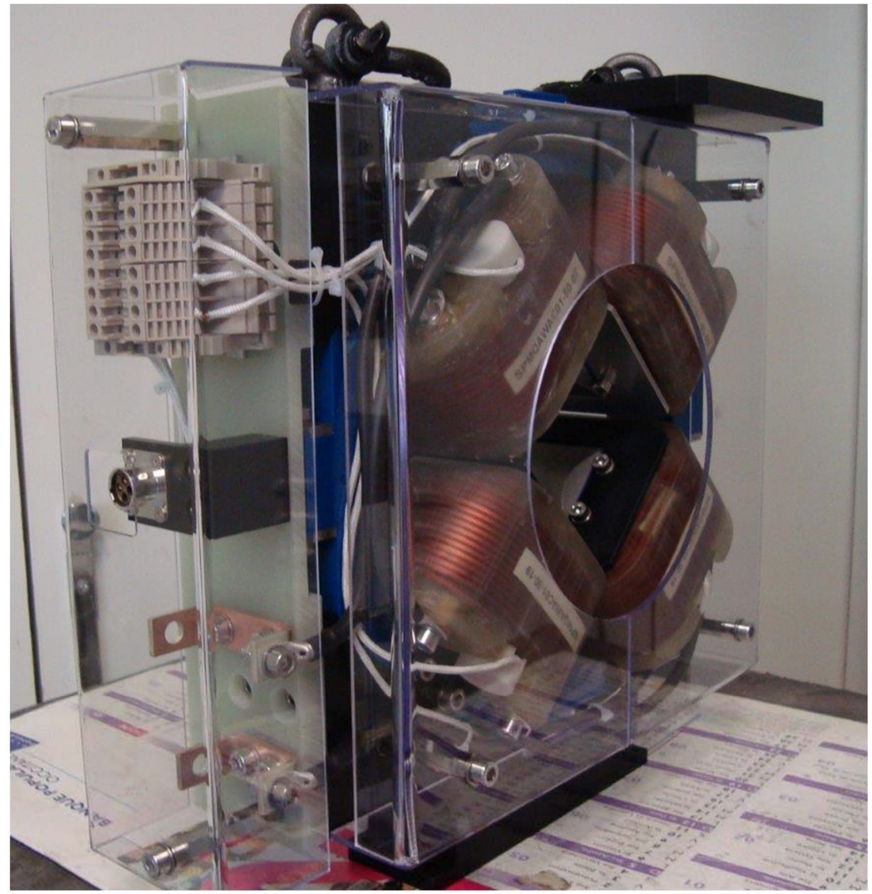
No	TEST	Approval criteria/ value	Passed / Result: Quadrant No: 1-1	Quadrant No: 1-2	Quadrant No: 1-3	Quadrant No: 1-4	Comment
1	Dimension AA	115 mm	115	115	115	115	
2	Dimension BB	115 mm	115	115	115	115	
3	Surface (Side A)	⏥ 0.02	0.01	0.01	0.01	0.01	
4	Surface (Side A1)	// 0.1 A	0.01	0.01	0.01	0.01	
5		⊥ 0.1 B C	0.01	0	0.02	0.01	
6	Surface B	⊥ 0.04 A	0	0.02	0.03	0.03	
7	Surface C	⊥ 0.04 A B	0.01	0.01	0.01	0.01	
8	Pole surface from X to Y	⌓ 0.04 A B A-B	0	0	0.01	0	
9	Packing Factor	> 97%	95.5%	95.5%	95.5%	95.5%	
10	Packing Factor with respect to the nominal value:(PF of the 1st stack)	95.5 % ± 0.2%	☐ Yes ☐ No	☑ Yes ☐ No	☑ Yes ☐ No	☑ Yes ☐ No	
11	Yoke length L	$40^{+0.5}_{-0}$ mm	POINT No 1: 40.103; 2: 40.102; 3: 40.095; 4: 40.107	POINT No 1: 40.100; 2: 40.106; 3: 40.100; 4: 40.106	POINT No 1: 40.099; 2: 40.092; 3: 40.107; 4: 40.096	POINT No 1: 40.091; 2: 40.088; 3: 40.097; 4: 40.097	
12	Yoke length with respect to the length of the 1st yoke quadrant	± 0.1 mm	☐ Yes ☐ No	☑ Yes ☐ No	☑ Yes ☐ No	☑ Yes ☐ No	

Production follow-up
Quality Control Record (MAGNET)

Description:	Specification Drawing:	Quadrupole serial No: **SPMQAWANAP-SD-0000 1**			
AWAKE quadrupole	**SPSMQAAWA0001**	Yoke quadrants serial No:			
		1-1	**1-2**	**1-3**	**1-4**
		Coils serial No:			
		SPMQAWANC01-SD- 07	SPMQAWANC01-SD- 09	SPMQAWANC01-SD- 18	SPMQAWANC01-SD- 19

Document prepared by:	Date:	Document approved by:	Date:	Revision No
MR GINESTET	12/12/2016			

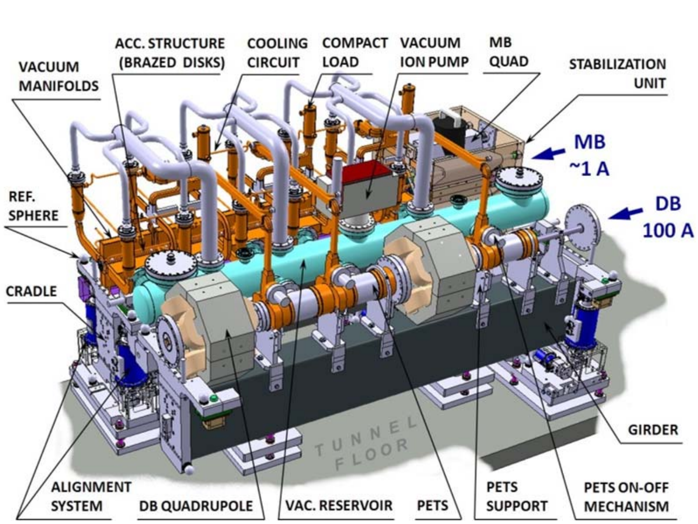
No	Test	Approval criteria	Passed / Result	Comment
1	Visual inspection	No faults or damage on any part of the magnet	☑ Yes ☐ No	
2	Magnet data plate	Plate present	☐ Yes ☑ No	Attente proposition CERN
3	Dimensional control according to **Quadrupole Yoke Dimensional Control** template	Dimensions within tolerances	☐ Yes ☑ No	[illegible]
4	Magnet resistance	Measured value at 14 °C Corrected value at 20 °C	363.344 mΩ 371.9 mΩ	
5	Magnet resistance at 20°C compared to the sum of the resistances of the coils No: 07, 09, 18, 19	Magnet resistance is within 2% of the sum of coil resistances Sum of coil resistances at 20°C Magnet resistance at 20°C	☑ Yes ☐ No 370.8 mΩ 371.9 mΩ	
6	Magnet inductance at 50 Hz		40.192 mH	
7	Magnet inductance compared to the **nominal value** (inductance of the pre-series magnet)	Inductance is within ±2% of the nominal value	☐ Yes ☑ No	aimant prototype
8	Coils-to-yoke insulation test	5 kV DC for two minutes, I< 5 µA measured value of leakage current	☑ Yes ☐ No 0.089 µA	
9	Temperature rise measurement on the coil surface	At I_{nom}=9.3 A, until a stable temperature is reached (~ 1 hour)	$T_{Ambient}$= 20 °C $T_{Coil\ Surface}$= 37.6 °C Time = 3 hour	10A
10	Thermo switch test	After temperature rise measurement increase current slowly until thermal switches switch off	T_{TS1}= 61 °C T_{TS2}= 61 °C T_{TS3}= 61 °C T_{TS4}= 61 °C	±1°

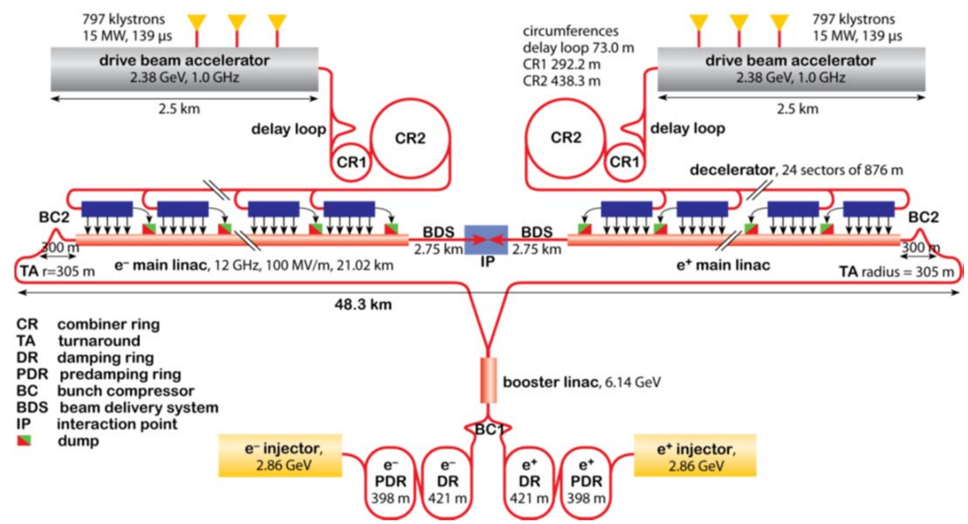


Compact Linear Collider (CLIC)

Compact Linear Collider (CLIC) -electron-positron linear collider project.
Max. energy - 3 TeV. Accelerating gradient of 100 MV/m.
Two-beam acceleration concept: the 12 GHz RF power is generated by (Drive Beam).
Drive Beam is decelerated in special Power Extraction and Transfer Structures (PETS), generated RF power is transferred to the Main Beam.

More than 60’000 “warm” magnets of 100 different types
The biggest families :
MBQ – 4’000 units
DBQ - 40’000 units





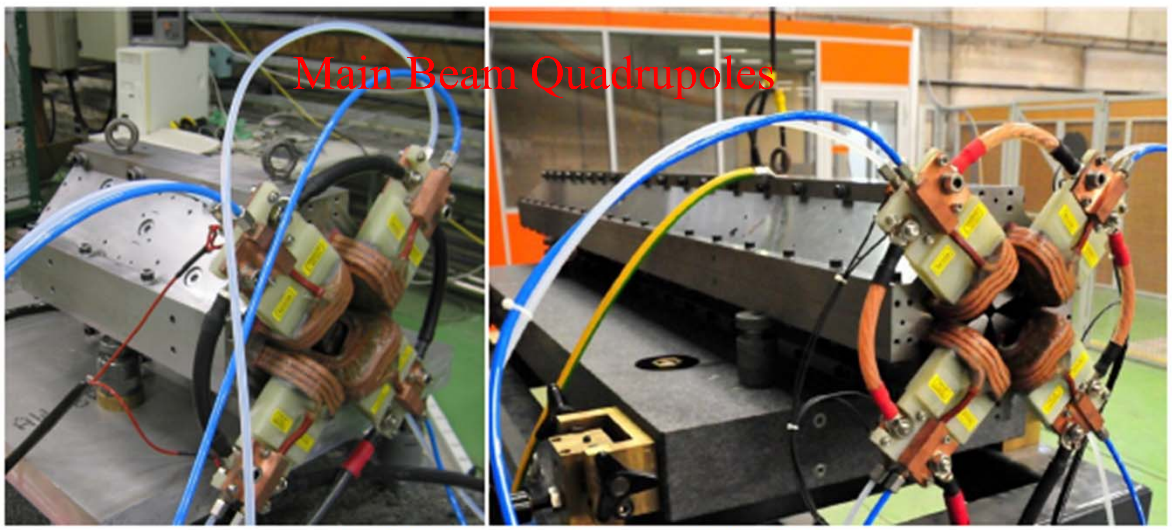
Compact Linear Collider (CLIC)

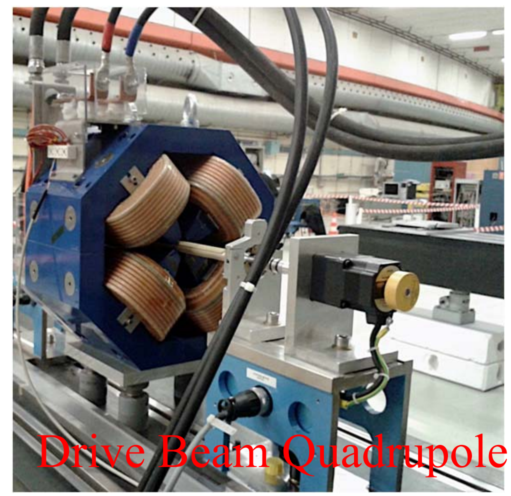
Design/Production of the following magnet prototypes

- Main Beam Quadrupole(Electromagnet)
- Drive Beam Quadrupole(Electromagnet)
- Final Focusing Quadrupole (Hybrid)

Preliminary design / cost estimate of all warm magnets “Magnets Catalogue”

- Main Beam Quadrupole (200 T/m, ø=10 mm, GL= 70/170/270/370 T, Max. yoke length 2 m)
- Drive beam Quadrupole (Gmax=81.2 T/m, ø=26 mm, GL=1.2 T - 12 T)



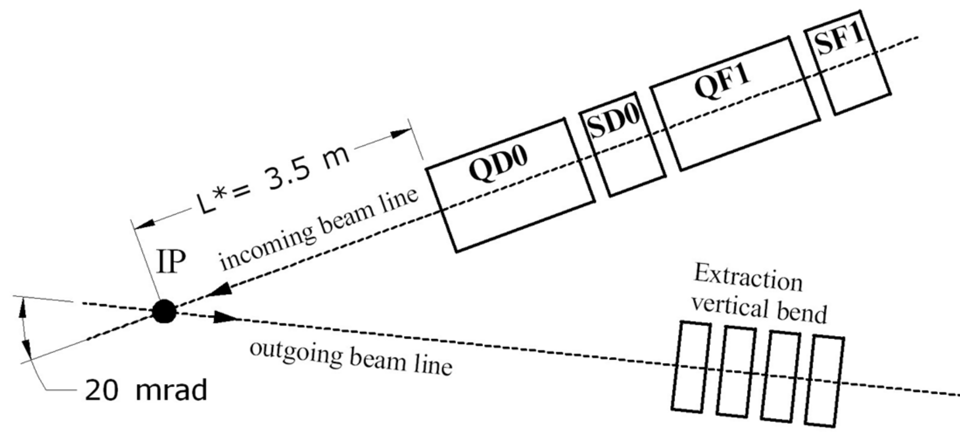


CLIC Final Focusing Quadrupole QD0

In order to produce a useful interaction rate with the maximum centre-of-mass energy, extremely small transverse beam dimensions at the collision point are required. This can be achieved with a final focus optics based on very strong magnetic quadrupoles. The most important focusing element is the last quadrupole (QD0) before the interaction point. This quadrupole shall be capable of producing a very strong field gradient to provide the required vertical beam size in the interaction point.

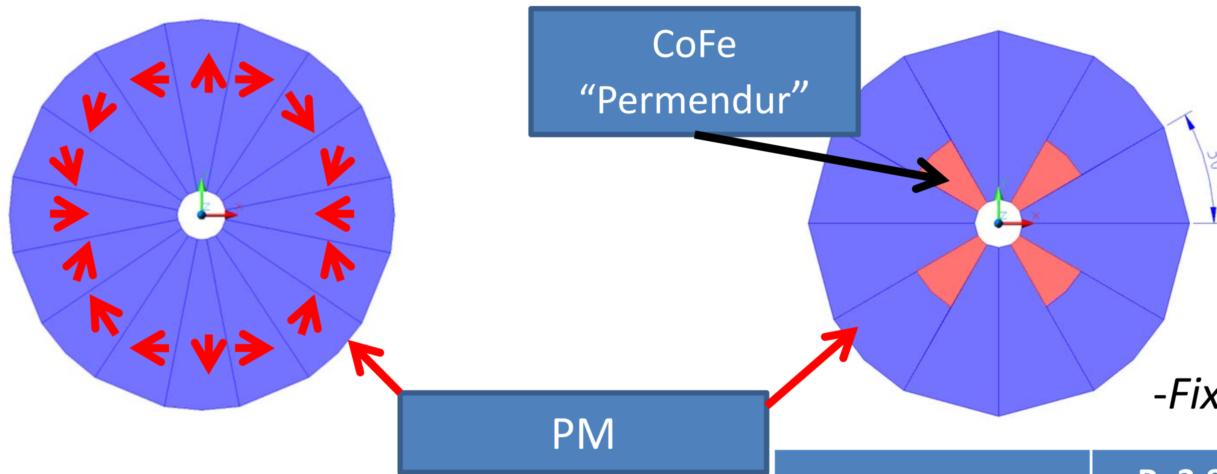
TABLE I REQUIREMENTS FOR THE FINAL FOCUS QUADRUPOLE

Parameter	Value
Nominal field gradient	575 T/m
Nominal integrated field gradient	1570 T
Magnetic length	2.73 m
Magnet bore diameter	8.25 mm
Good field region(GFR) radius	1 mm
Integrated field gradient error inside GFR	< 0.1%
Adjustment	+0 to -20%



CLIC Final Focusing Quadrupole QD0

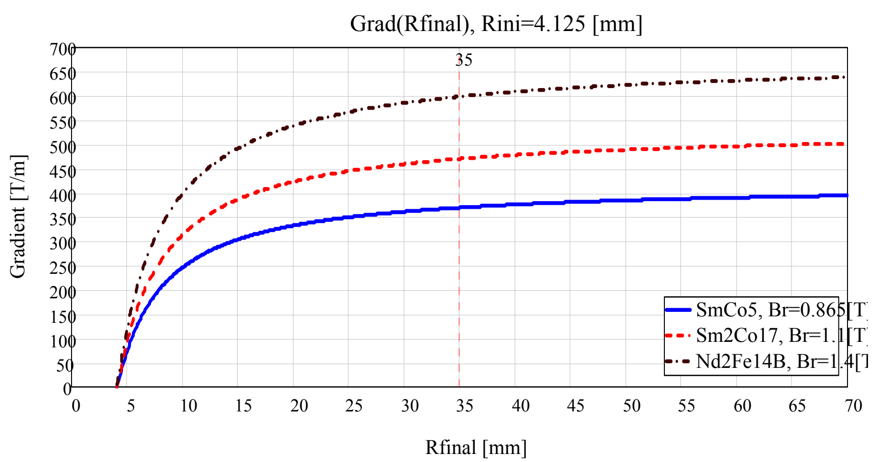
“Halbach” type | **Super Strong “Halbach” type + CoFe poles**



-Fixed grad. value only

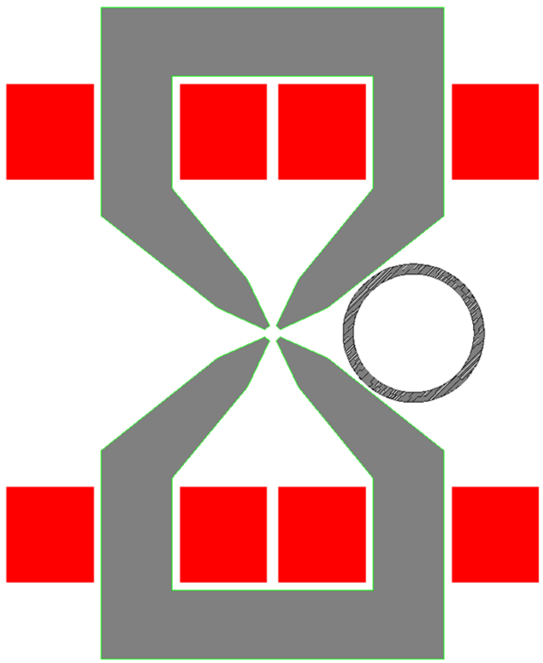
	R=3.8 [mm] (no chamber)		R=4.125 [mm]	
Material	Sm_2Co_{17}	$Nd_2Fe_{14}B$	Sm_2Co_{17}	$Nd_2Fe_{14}B$
Grad [T/m] “Halbach”	450	593	409	540
Grad [T/m] “Super Strong”	564	678	512	615

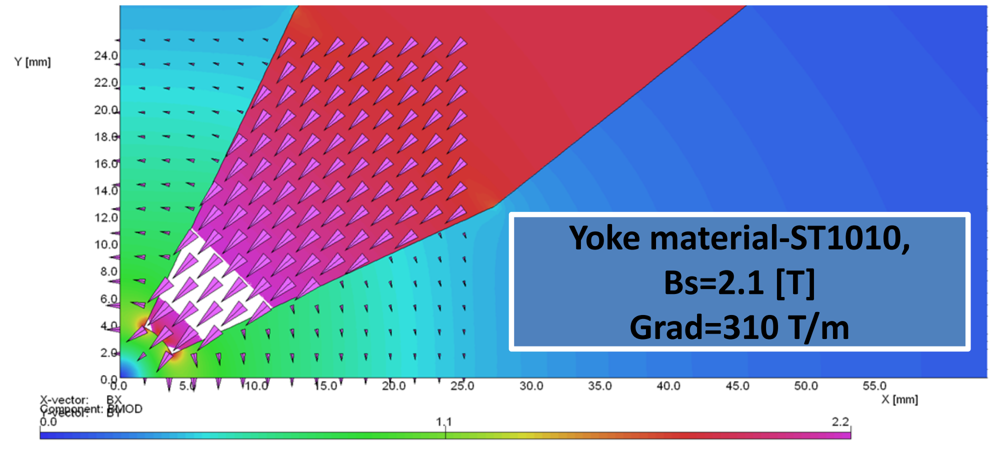
Grad=2*Br*(1/Ri-1/Rf), *(Ri= 4.125mm)*

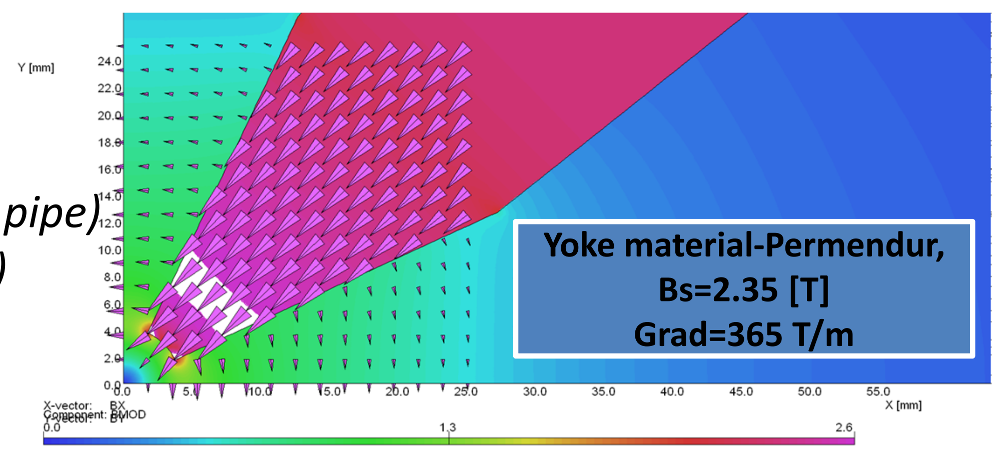


CLIC Final Focusing Quadrupole QD0

<u>Electromagnet</u>







-"8 shape" Quad design:

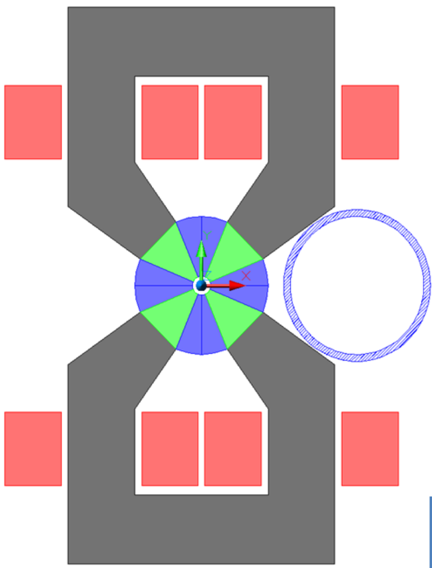
-(it permits to arrange the spent beam pipe)

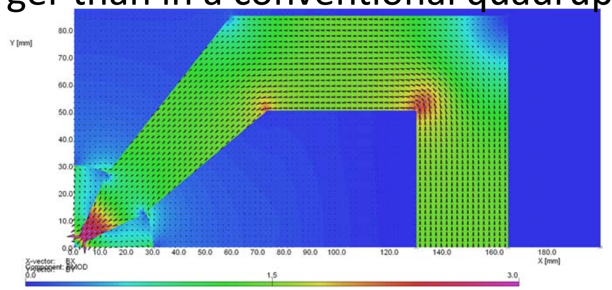
- Saturation appears (in both solutions)

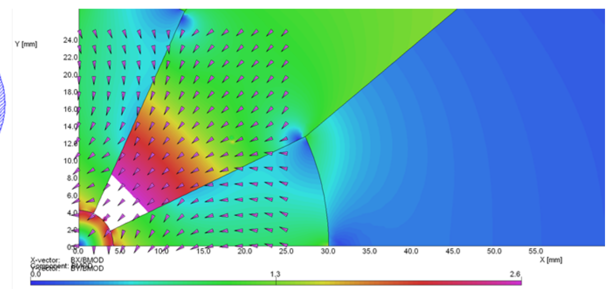
CLIC Final Focusing Quadrupole QD0

Hybrid magnet

- 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.



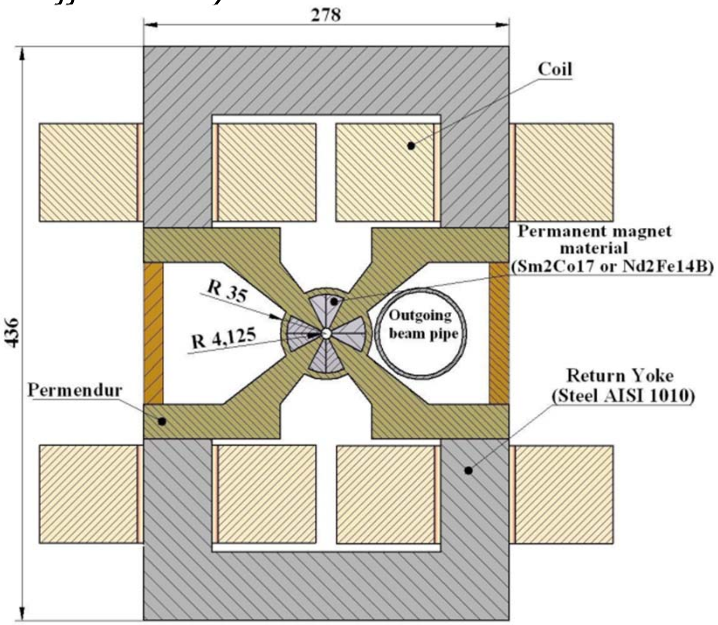


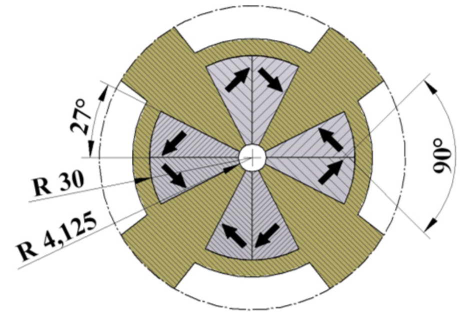


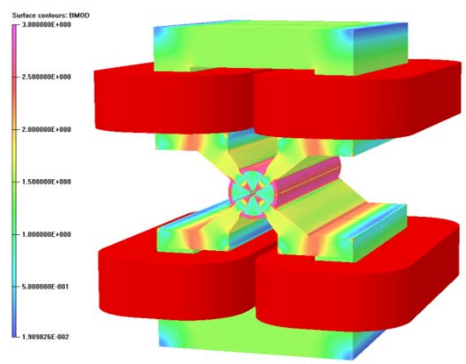
	Iw=5000 [A]
Grad [T/m] Sm_2Co_{17}	550
Grad [T/m] $Nd_2Fe_{14}B$	615

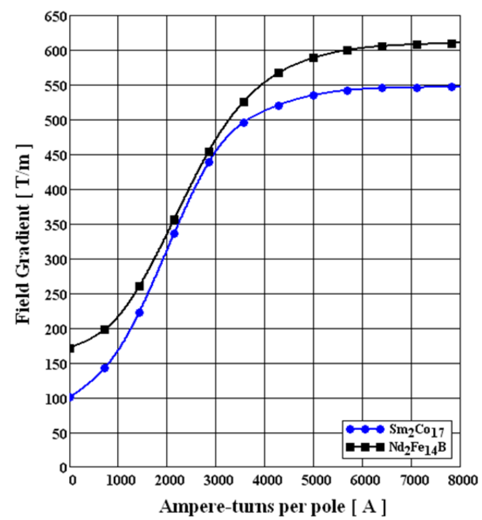
Hybrid QD0 Final version

The presence of the "ring" decrease slightly the Grad (by 15-20 T/m) but will assure a more precise and stiff assembly



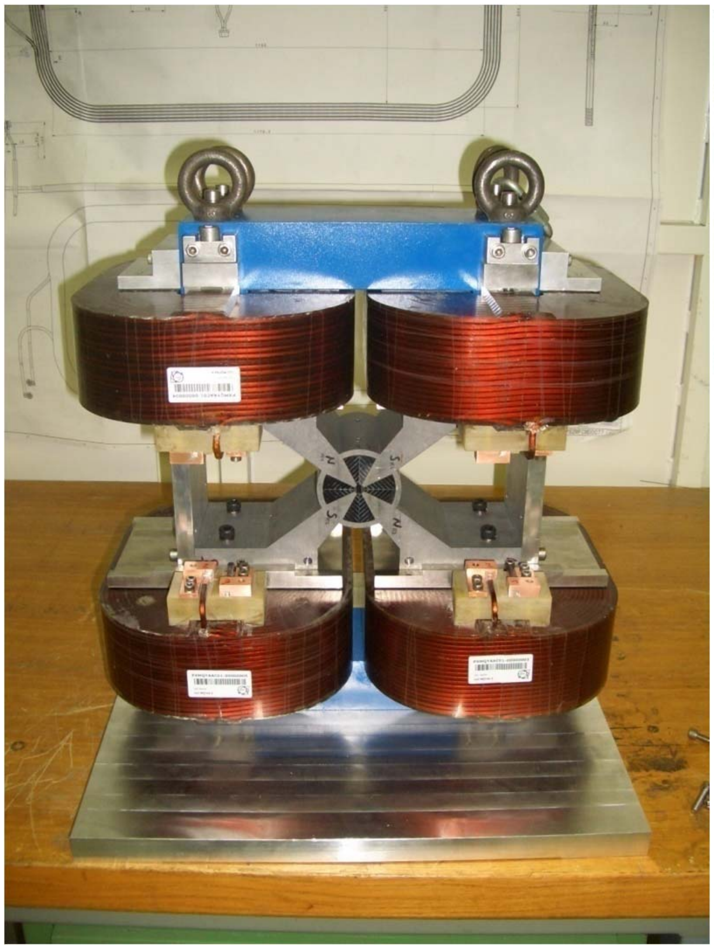


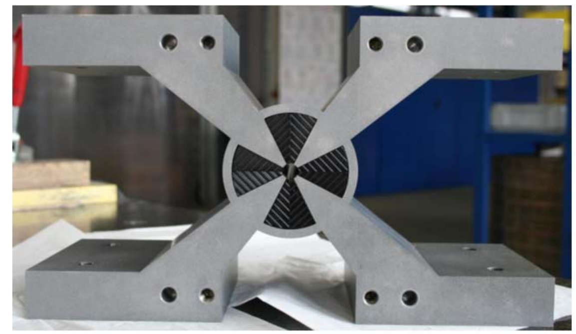


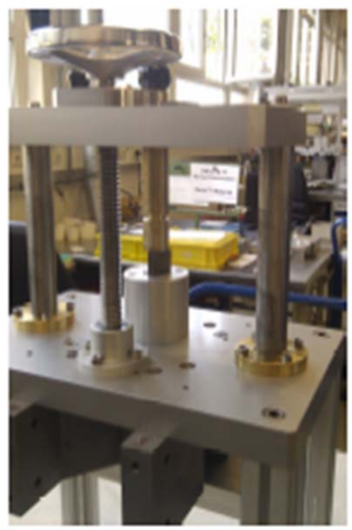


100 mm Prototype QD0

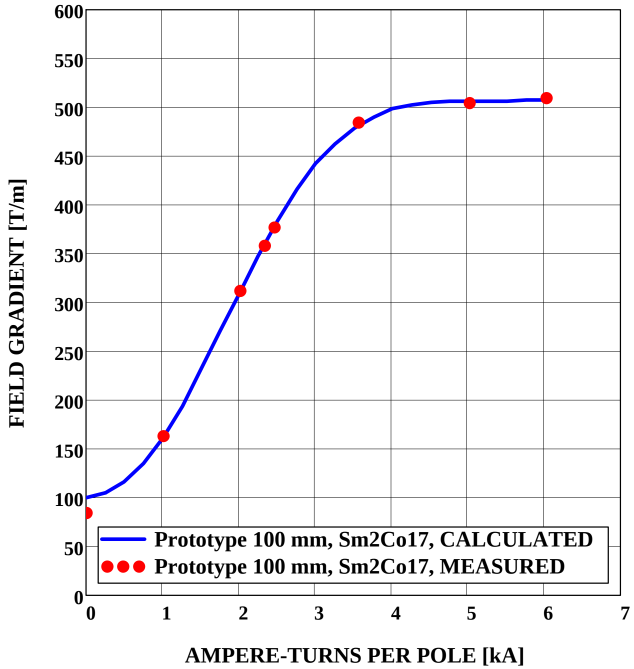
In order to verify the conceptual design, tolerances on integrated field strength and to study the assembling procedure, a prototype model with full-scale cross-section, working at nominal conditions, but with much shorter yoke length of 100 mm has been built. The hybrid quadrupole prototype needs four permanent magnet assemblies of 100 mm length; each consists of four permanent blocks of 50 mm length glued together. The permanent magnets blocks made of VACOMAX 225HR (Sm_2Co_{17}) and VACODYM 655HR ($Nd_2Fe_{14}B$) were supplied by Vacuumschmelze, Germany. The permendur part of the quadrupole structure was machined by wire EDM to a tolerance of ± 25 μm. The selected material for this part was VACOFLUX 50 by Vacuumschmelze.

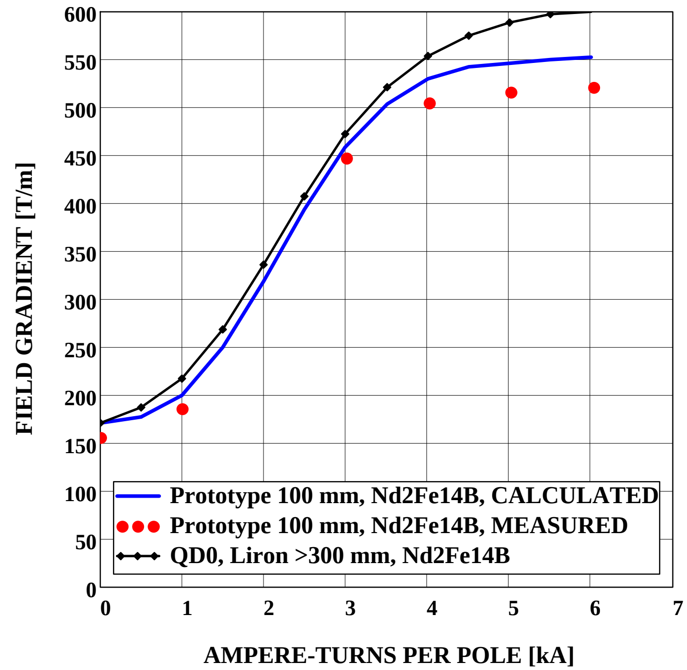


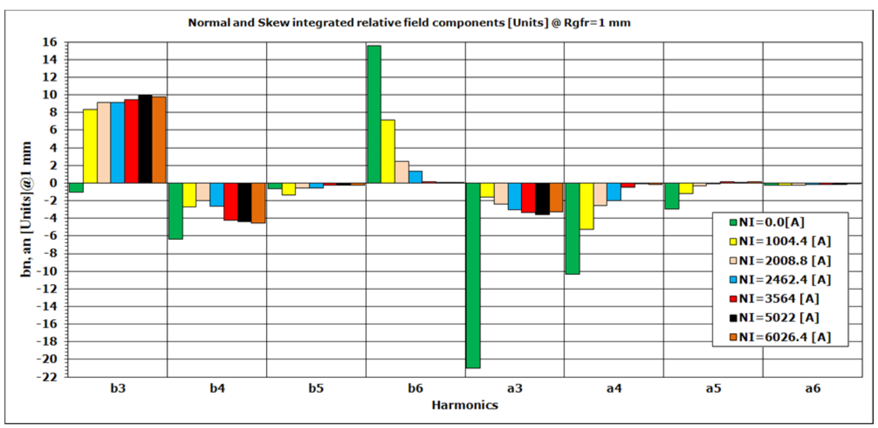


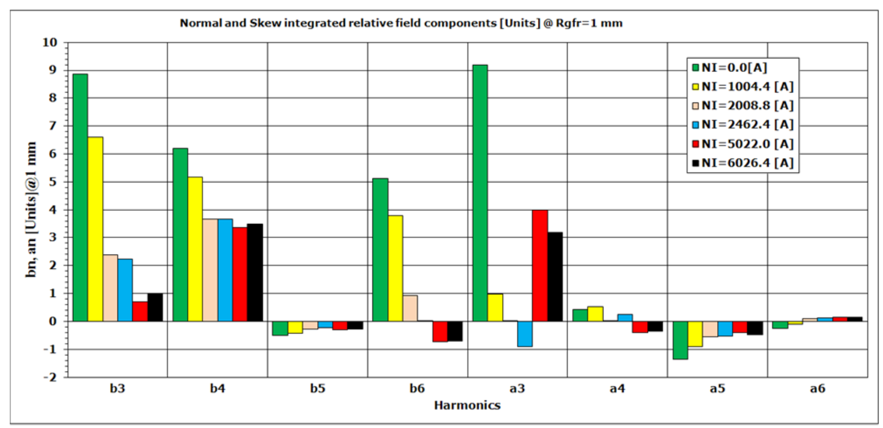


Results of the magnetic measurements on QD0 proto





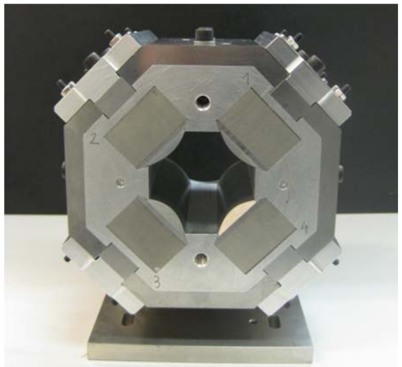


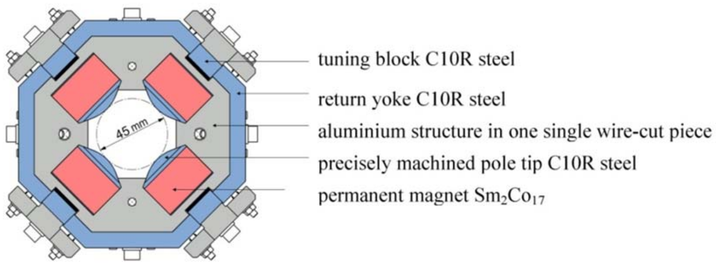


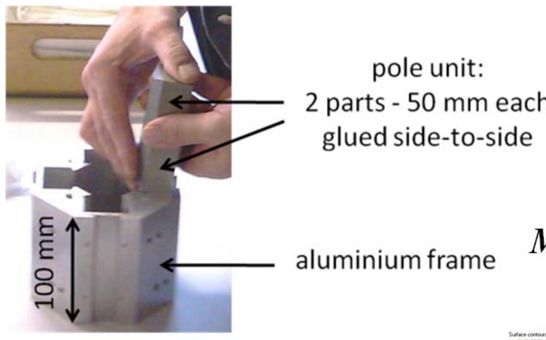
LINAC 4

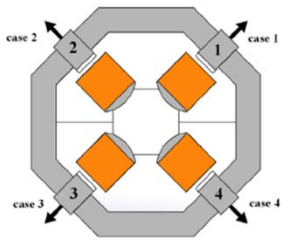
As the first step of a long-term programme aiming at an increase in the LHC luminosity, CERN is building a new 160 MeV H^- linear accelerator, Linac4, to replace the ageing Linac2 as injector to the PS Booster.

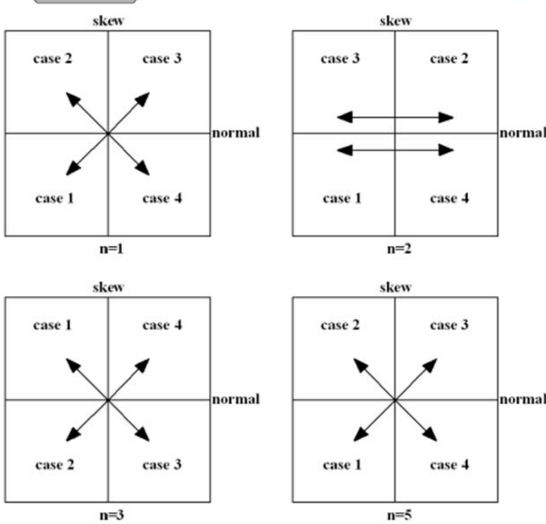
10% Tunable permanent magnet



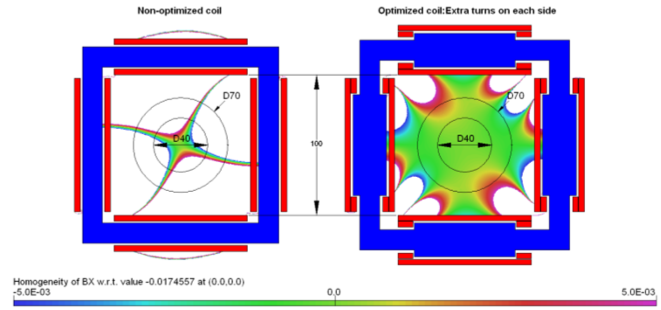




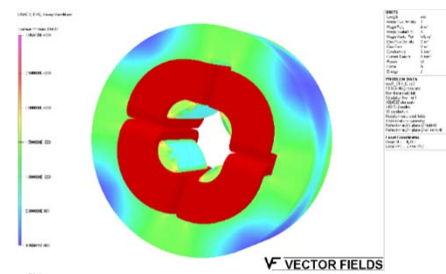




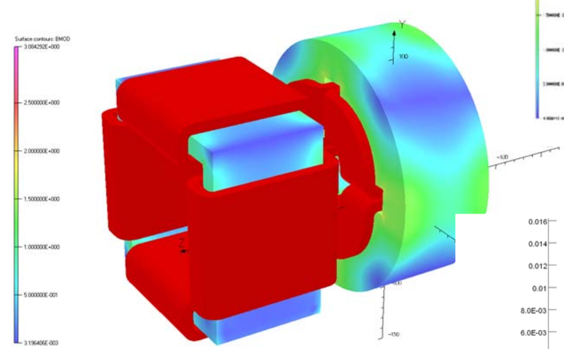
H/V corrector field quality optimization by extra turns at the coil sides

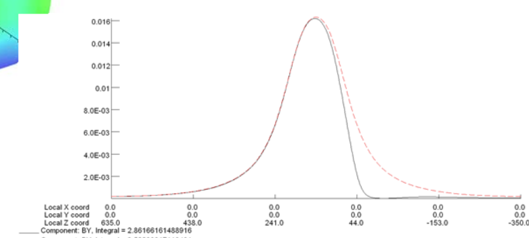


Inter-tank quadrupole



Magnetic coupling simulations

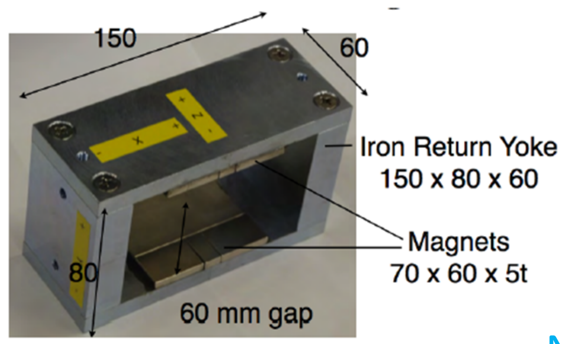


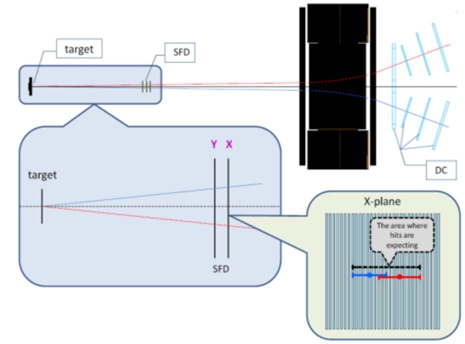


High resolution spectrometer for DIRAC

THE one of the aim of the DIRAC experiment is the observation of the long-lived $\pi^+\pi^-$ atoms, using the proton beam of the CERN Proton Synchrotron. The dipole magnet will be used to identify the long-lived atoms on the high level background of $\pi^+\pi^-$ pairs produced simultaneously with π+π- atoms.

1st version of PM DIPOLE(BL=10 mTm) based on NdFeB material, 50% of flux lost after 1st year of operation due to irradiation

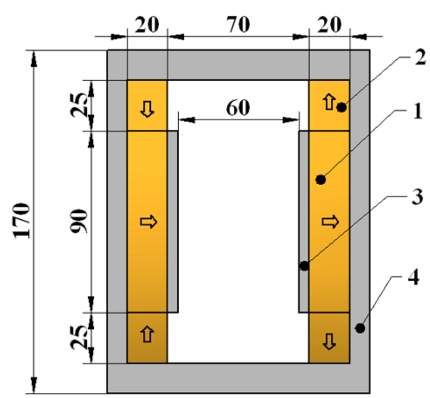




New PM Dipole BL=2 mTm based on Sm2Co17

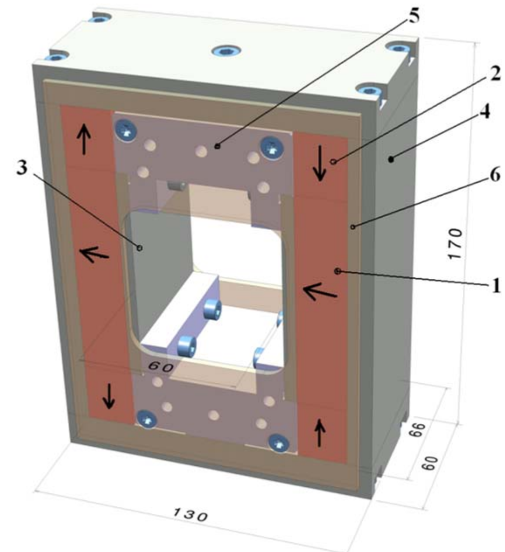
Table 1: Requirements for the dipole magnet

Parameter	Units	
Overall length	mm	< 66
Overall width × height	mm × mm	170 × 130
Yoke length	mm	< 60
Horizontal full aperture	mm	60
Integrated field strength $\int B_{x(0,0,z)}dz$	T×m	0.02
Good Field Region(GFR) X × Y	mm × mm	20 × 30
Integrated field quality $\Delta\int B_x dz/\int B_{x(0,0,z)}dz$ inside GFR	%	< ± 2



Reference:
Design, manufacture and measurements of permanent dipole magnets for DIRAC, DIRAC-NOTE-2013-04 https://cds.cern.ch/record/1622178?ln=sv.
Vorozhtsov, A (Dubna, JINR) ; Buzio, M (CERN) ; Kasaei, S (Inst. Stud. Theor. Phys. Math, Iran) ; Solodko, E (Dubna, JINR) ; Thonet, P A (CERN) ; Tommasini, D (CERN)

PM Dipole Sm2Co17



1) Permanent block Type 1 (Sm2Co17)

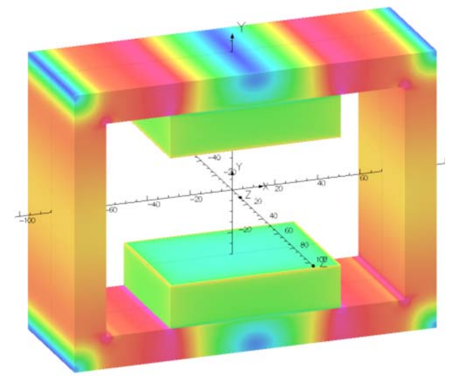
2) Permanent block Type 2 (Sm2Co17)

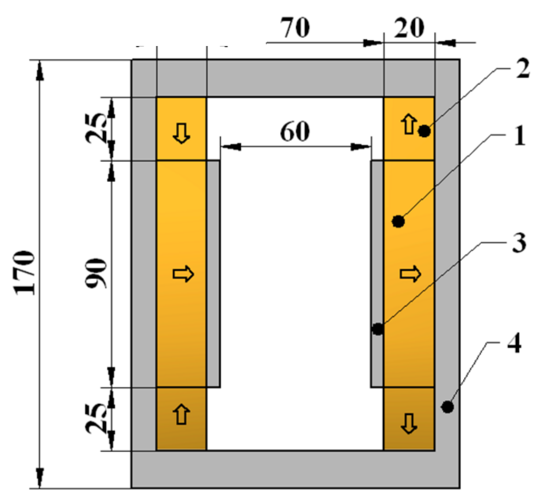
3) Pole (AISI 1010)

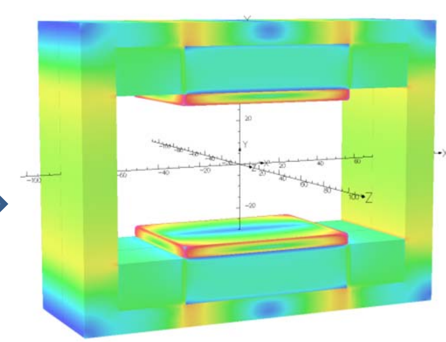
4) Return yoke (AISI 1010)

5) Central insert (stainless steel)

6) Cover plates (aluminum)





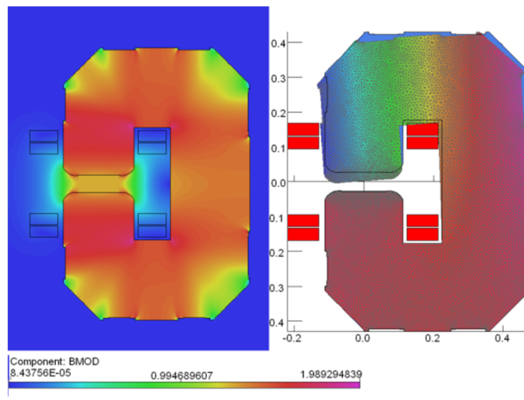


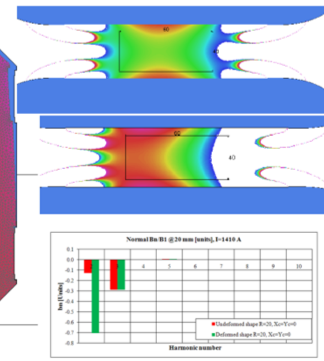
MedAustron - centre for ion-therapy and research

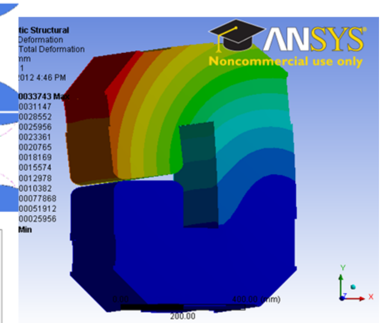
The centre comprises an accelerator facility based on a synchrotron, for the delivery of protons and light ions to irradiation stations, for cancer treatment and for clinical and non-clinical research. The accelerator complex consists of the injector with ion sources and an ion linac that will accelerate particles up to the synchrotron injection energy of 7 MeV/u. This is followed by a synchrotron capable of accelerating particles to the planned extraction energy, ranging from 60 MeV to 250 MeV for protons and 120 MeV/u to 400 MeV/u for carbon ions, suitable for the medical application.

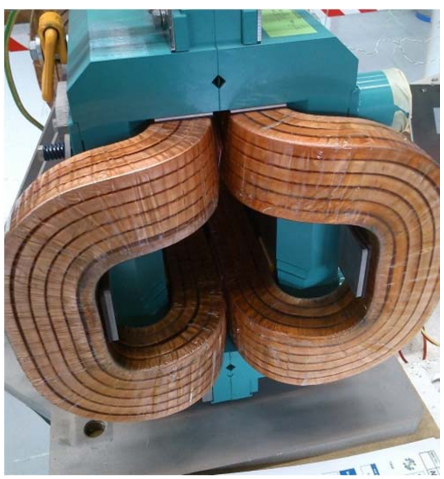
EM design / Production follow up / 2D and 3D modelling, Coupled EM / Stress analysis

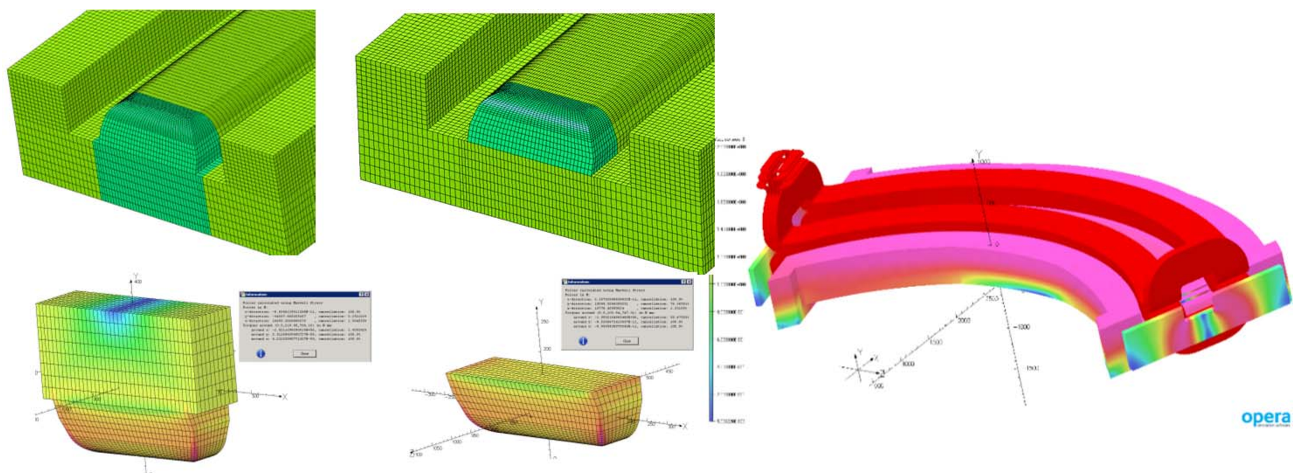
- H/V corrector MCX-B
- Scanning magnets MSH/V-E
- Main Synchrotron Dipole MBH-C (final design)
- High Energy Beam Transfer Line (MBH-E)
- 90° dipole MBV-F
- Betatron Core
- Gantry magnets (quadrupoles, 58° dipole)







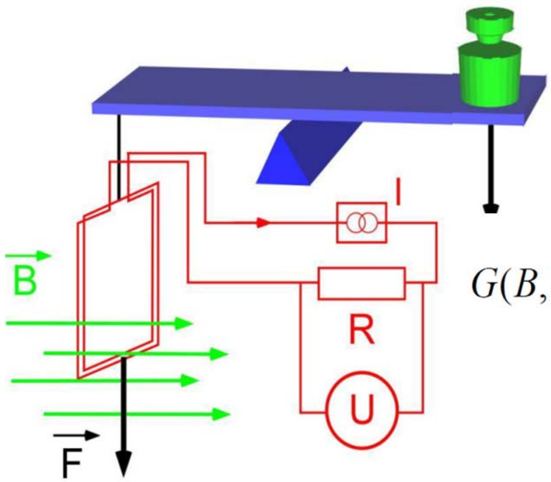




Watt balance Mark II Experiment

Watt balance: establish a link between electrical and mechanical quantities via power equivalence

static phase / weighing mode



$$I\cdot\int d\ell\times B = mg$$

mg

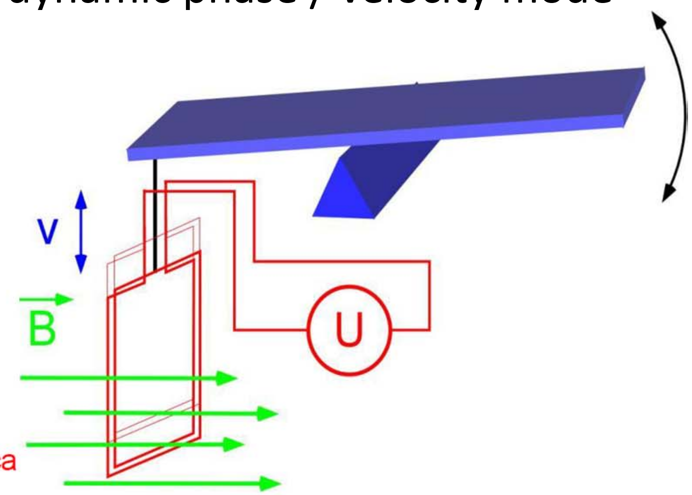
$$G(B,\ell) = \underbrace{\frac{mg}{I}}_{\text{static}} = \underbrace{\frac{U}{v}}_{\text{dynamic}} \Rightarrow \boxed{UI = mgv}$$

electrical power

mechanica power

Only if magnetic field is stable and does not depend on the current

dynamic phase / velocity mode



$$U_{ind} = v\cdot\int d\ell\times B$$

Using the expressions from quantum physics (QHE & JVS)

$$U = C_J\cdot U_J = C_J\, n_J\,\frac{h}{2e} f_J$$

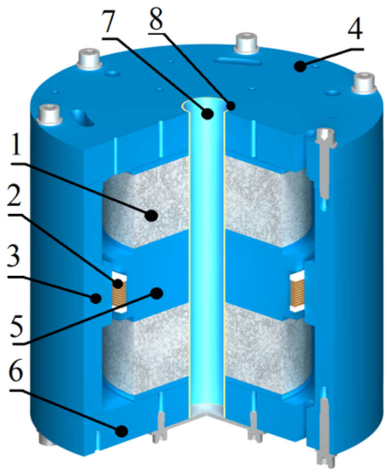
$$R = C_H\cdot R_H = C_H\,\frac{h}{n_H\, e^2}$$

$$\boxed{m = C\,\frac{f_{J1} f_{J2}}{g\,v}\,h}$$

$$C = \frac{C_{J1}\, n_{J1}\, C_{J2}\, n_{J2}\, n_H}{4C_H}$$

courtesy of Blaise Jeanneret (METAS)

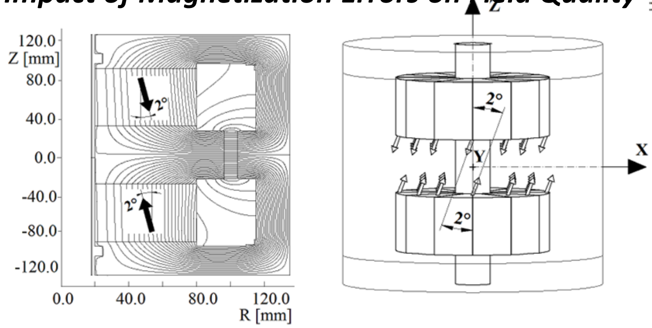
Watt balance Mark II Experiment

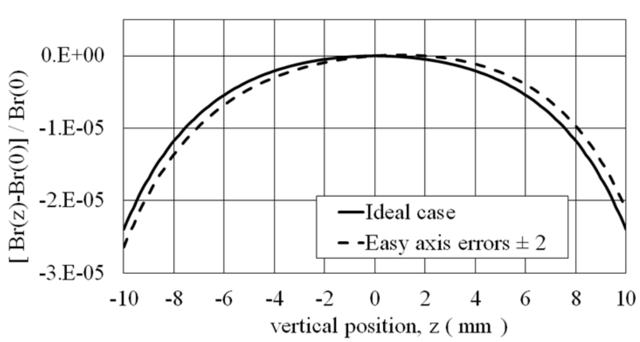


1. Permanent magnet (SmCoGd)
2. Coil (Cu)
3. External cylinder (Fe)
4. Top cover (Fe)
5. Pole (Fe)
6. Bottom cover (Fe)
7. Centering cylinder (Brass)
8. Saturable shunt (Fe-Ni)

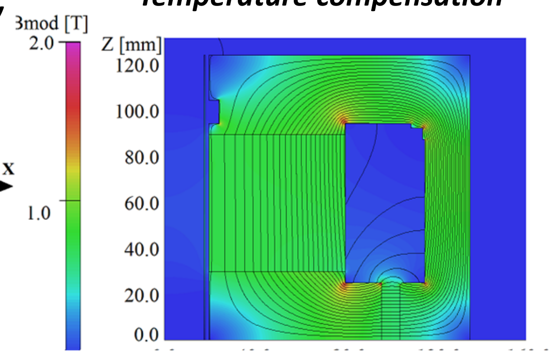
- Sm2Co17Gd
  Br=0.83 T, HcB=622 kA/m temperature coefficient α ≈ -0.001% / °C
- The yoke - low carbon steel AISI 1010
- saturable shunt Ni30%Fe alloy, Curie temperature of 55 °C.

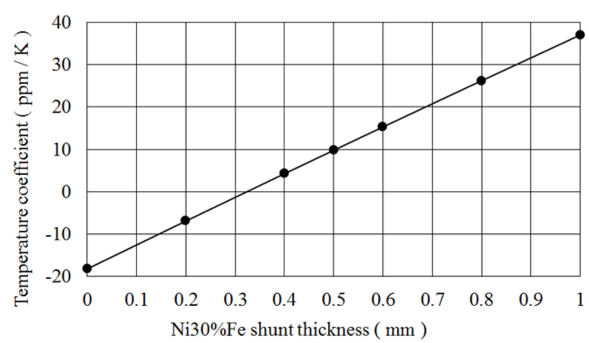
Impact of Magnetization Errors on Field Quality



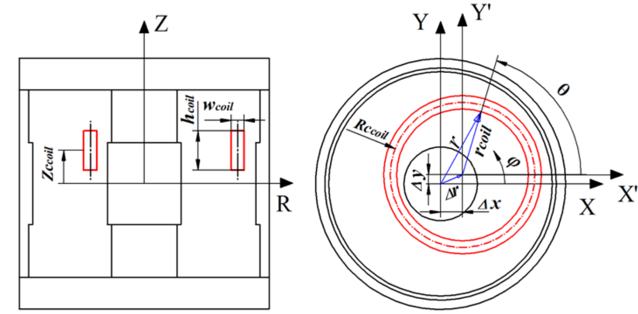


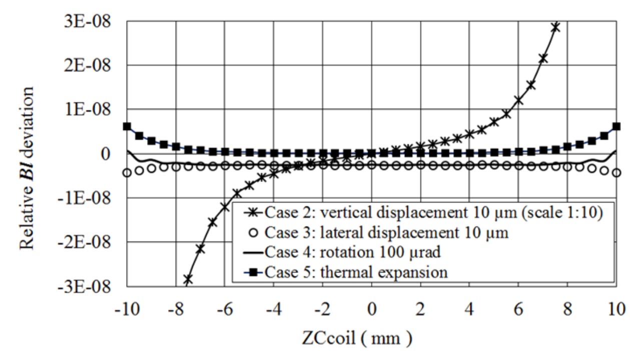
Temperature compensation





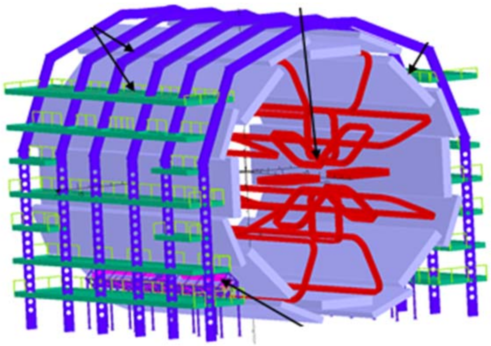
Coil Signal

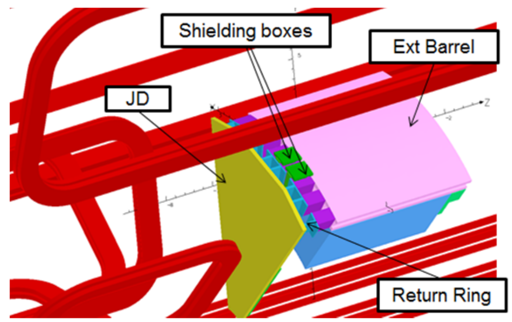


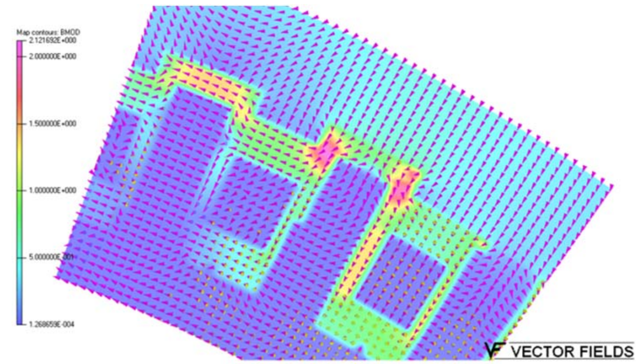


ATLAS detector

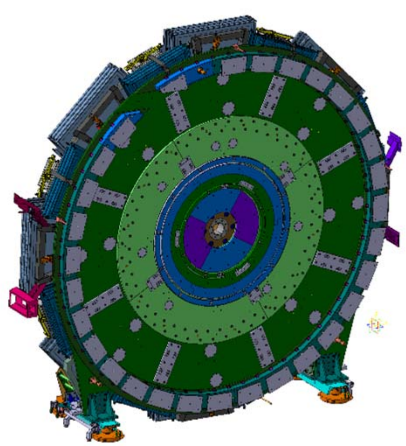
- Calculation of the field perturbation due to the magnetic materials => Field reconstruction
- Protection(shielding) of the equipment, sensitive to the magnetic field



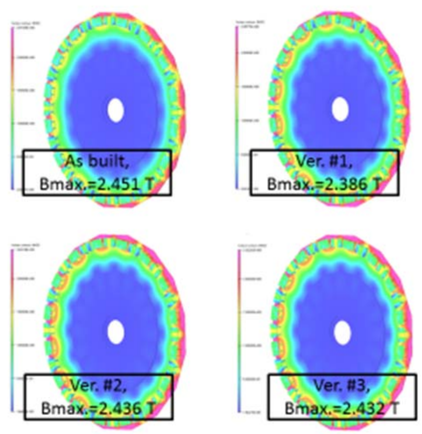




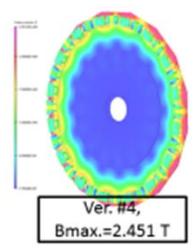
- Prepare the LS2 (2019), JD disc / Small Wheel upgrade /New HUB

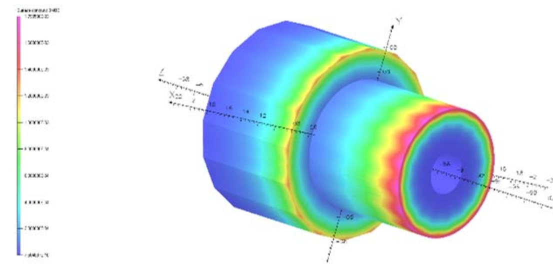


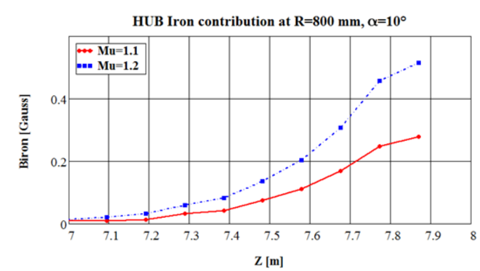
Total field on JD surface & JD forces



Toroid field (BT+ECT)	JD force [Tons]
"as built"	-9.34
Ver. #1	-9.57
Ver. #2	-9.75
Ver. #3	-9.92







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2. Design of Normal-Conducting Quadrupole Magnets for Linac4 at CERN
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J.S. Schmidt, J. Bauche, B. Biskup, C. Bracco, S. Doebert, B. Goddard, E. Gschwendtner, L.K. Jensen, O.R. Jones, S. Mazzoni, M. Meddahi, K. Pepitone,A. Petrenko, F.M. Velotti, A. Vorozhtsov, Nuclear Instruments and Methods in Physics Research A, Volume 829, September 2016, Pages 58-62
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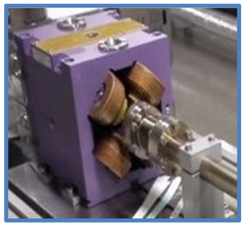
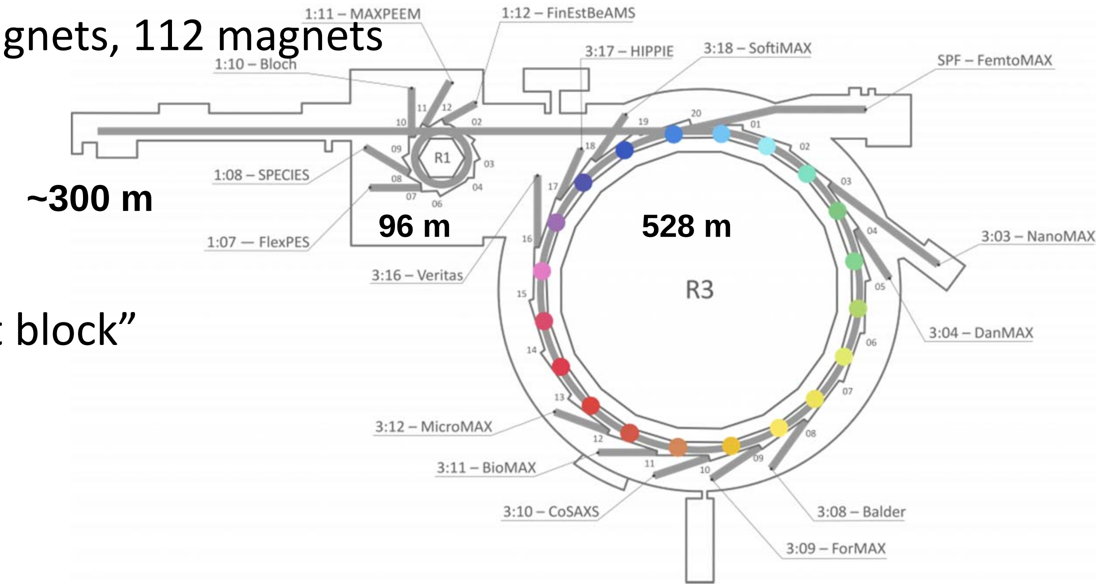
7. Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC Alexey Vorozhtsov, Michele Modena, and Davide Tommasini.
8. 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS2018), Shanghai, China, 5 - 9 March, 2018. *Design Study of the High Gradient Magnets for a Future Diffraction Limited Light Source at MAX IV,* A.S. Vorozhtsov P.F. Tavares, 2018

Extra slides

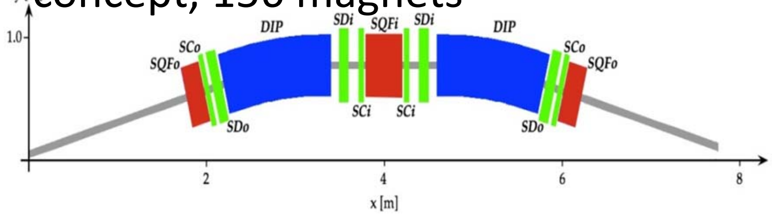
High gradient magnets for the synchrotron light source MAX IV

LINAC (3.4 GeV): various type of NC magnets, 112 magnets

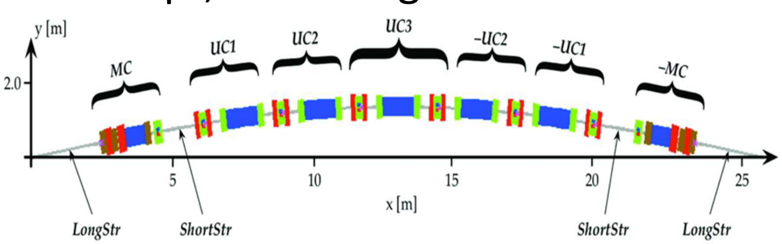


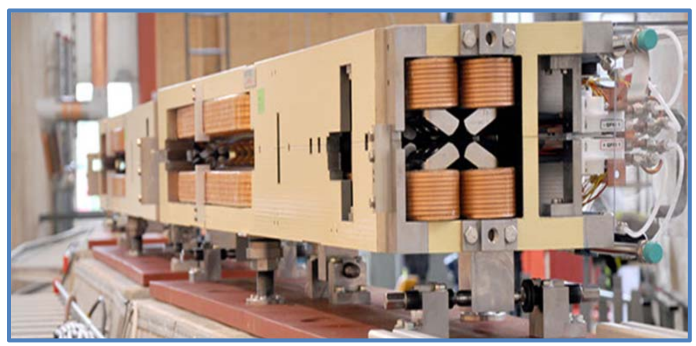


1.5 GeV lattice: 12 achromats, "magnet block" concept, 156 magnets



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

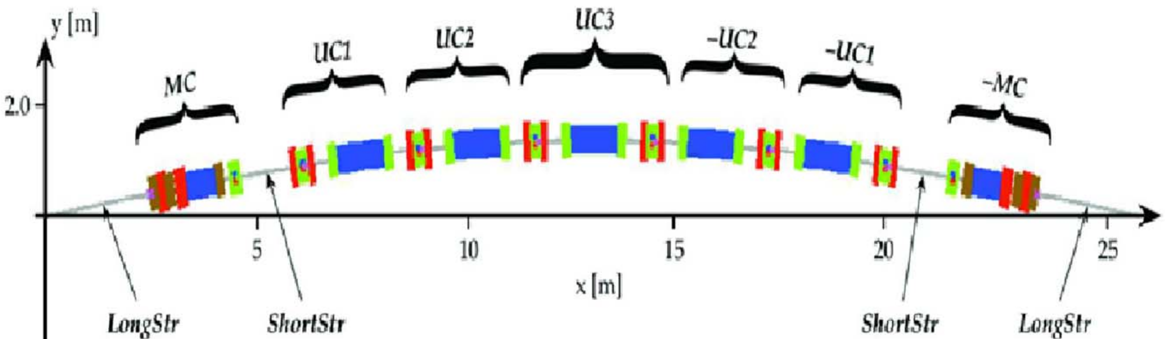




courtesy of M. Johansson

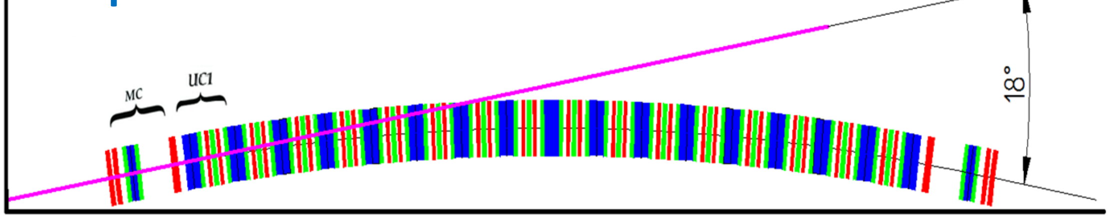
3 GeV ring upgrade

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
- Horizontal emittance 300 nm rad

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



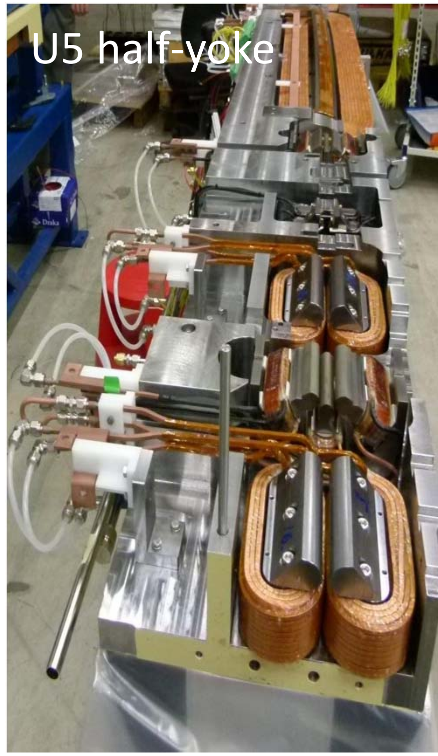
- 17 unit cells and two matching cells.
- 20 achromats x 19 cells = 380 cells total
- Min. magnet aperture Ø= 11 mm
- Horizontal emittance 20 nm rad

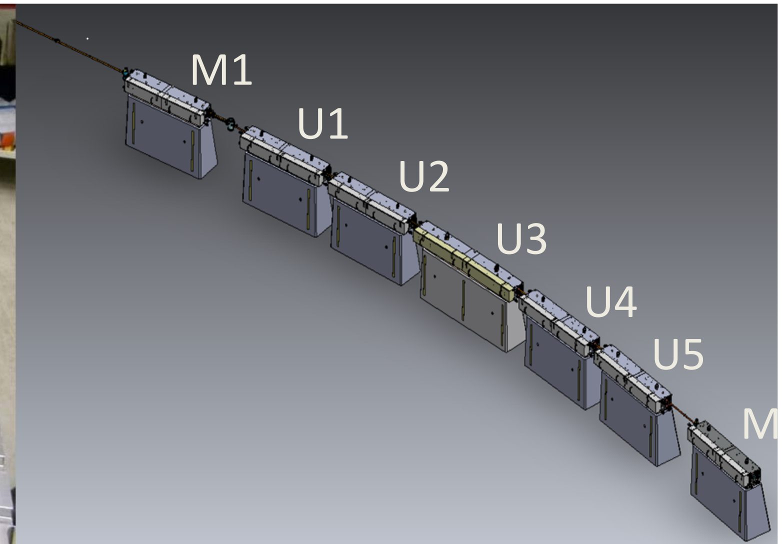
- Achromat length = 26.4 m
- Ring circumference = 26.4 x 20 = 528 m

[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

“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(half block) = ~450 kg (M1, M2), ~490 kg (U1,…), ~620kg (U3)
- Magnet aperture= Ø25 mm, total power consumption ~300 kW.

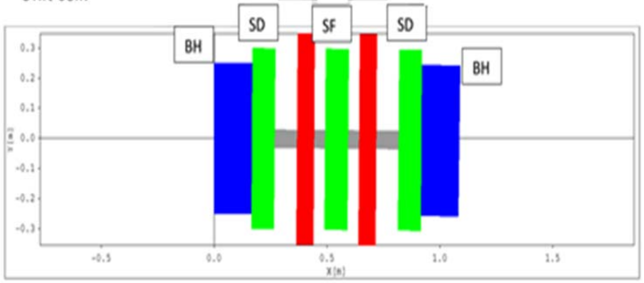




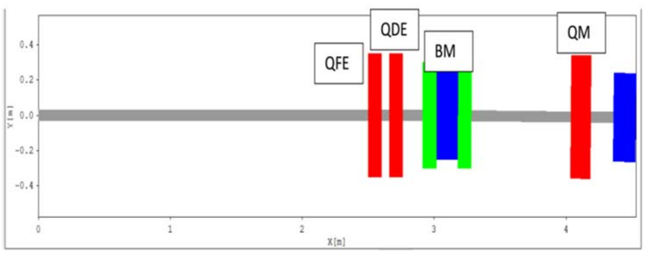
courtesy of M. Johansson

3 GeV ring magnets for the new lattice

Unit cell:



Matching cell:



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 Δ∫Gdz/∫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

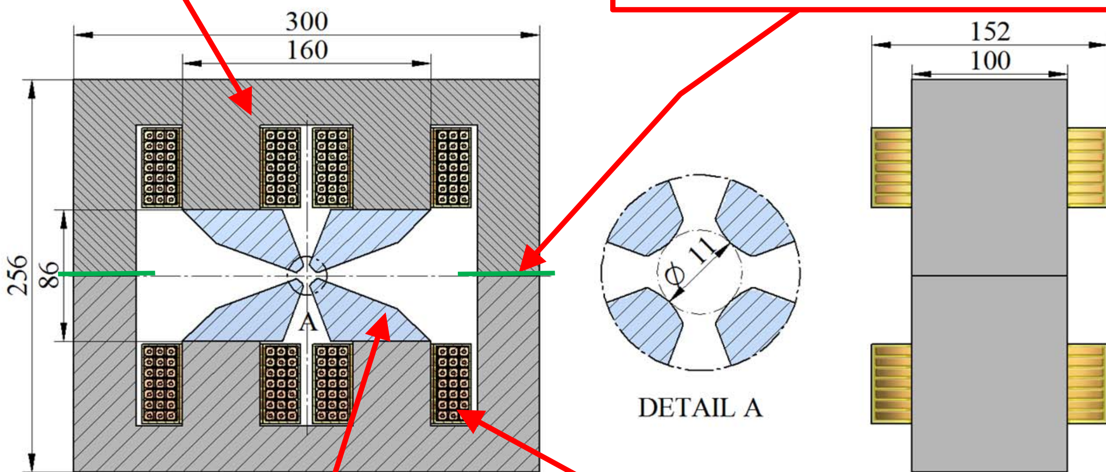
✓ **Conventional electromagnet**

✓ **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

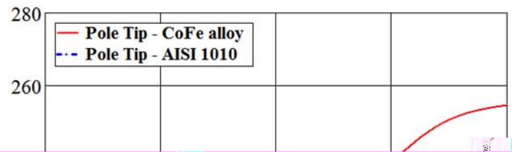


Pole Tip (separate pieces)
Material: Cobalt Iron alloy, Bs=2.35T

4 water cooled coils

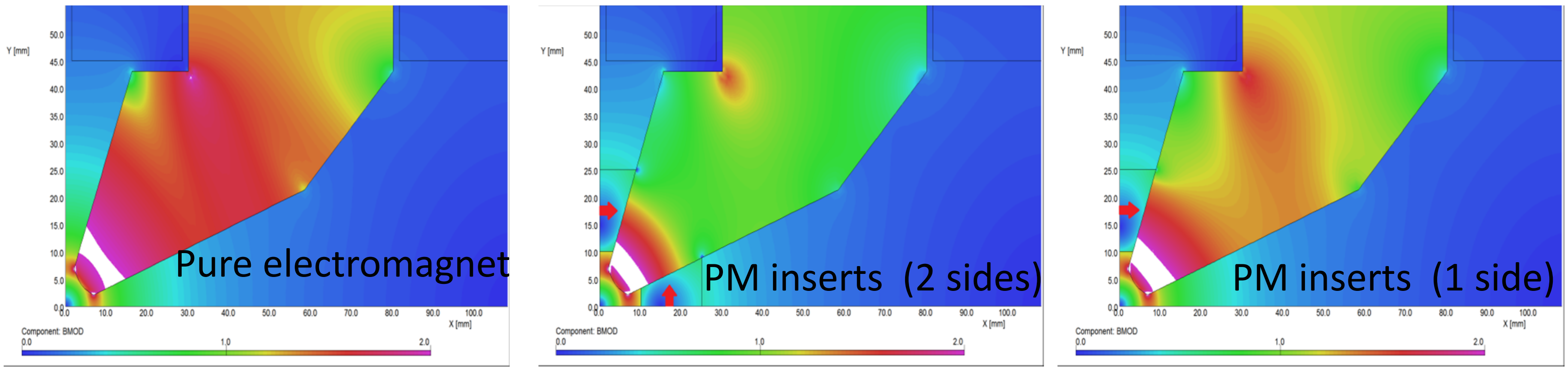
Main parameters		
Magnet		
Overall dimensions	300 x 256 x 152	mm^3
Half return yoke mass (length 100 mm)	17.8	kg
Total magnet mass	52	kg
Coil		
Number of turns / coil	21	
Conductor dimensions	6 x 6 Ø 2.5	mm
Nominal current I_{nom} @234 T/m	140	A
Current density @ I_{nom}	4.6	A/mm^2
Resistance @ 20°C	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

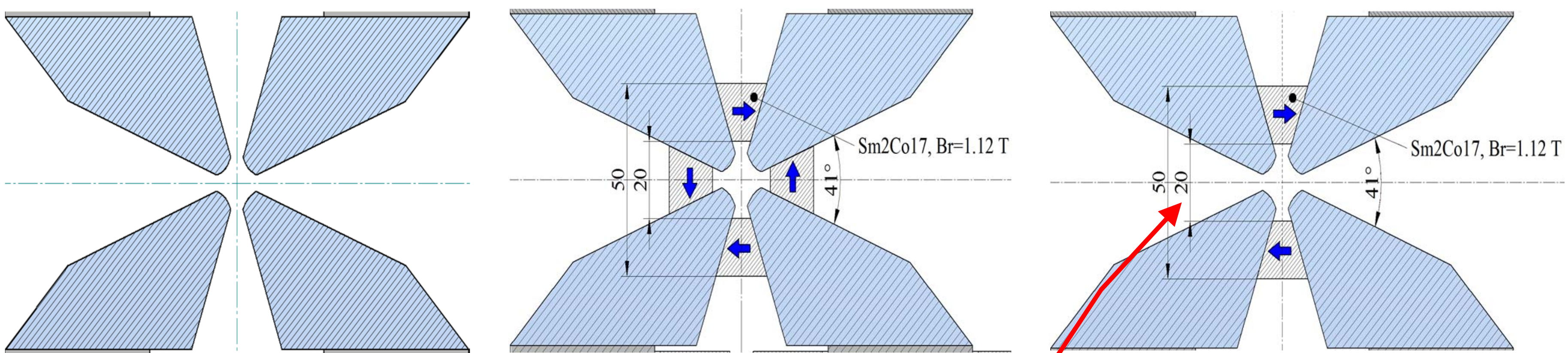
Conventional electromagnet



- Pole Tip (CoFe alloy):
  - Gnom.=234 T/m at I=139.5 A (NW=2930 A)
  - Pole field=1.2[illegible] T

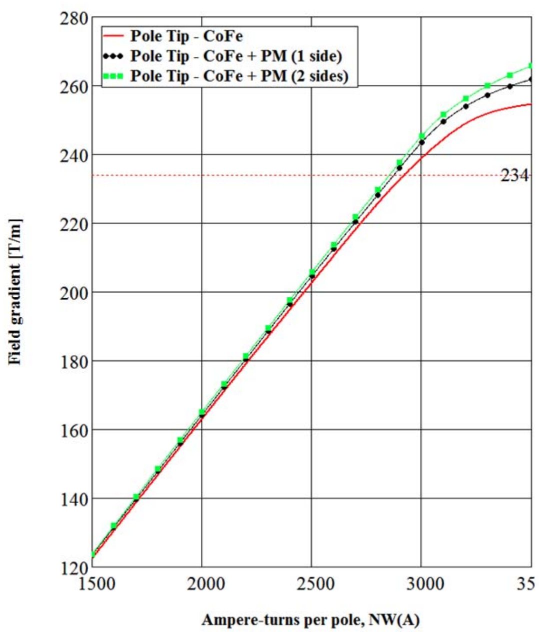
Electromagnet with Sm_2Co_{17} inserts

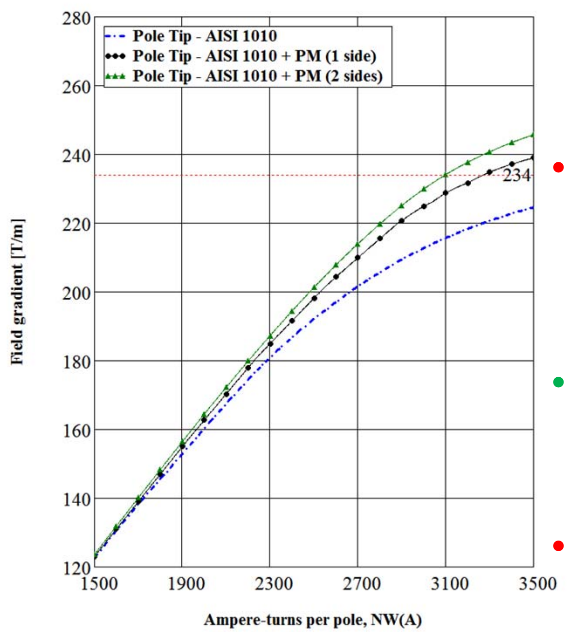




20 mm: Min. permissible value
Field quality reduction due to the field asymmetry

Electromagnet with the Sm_2Co_{17} inserts

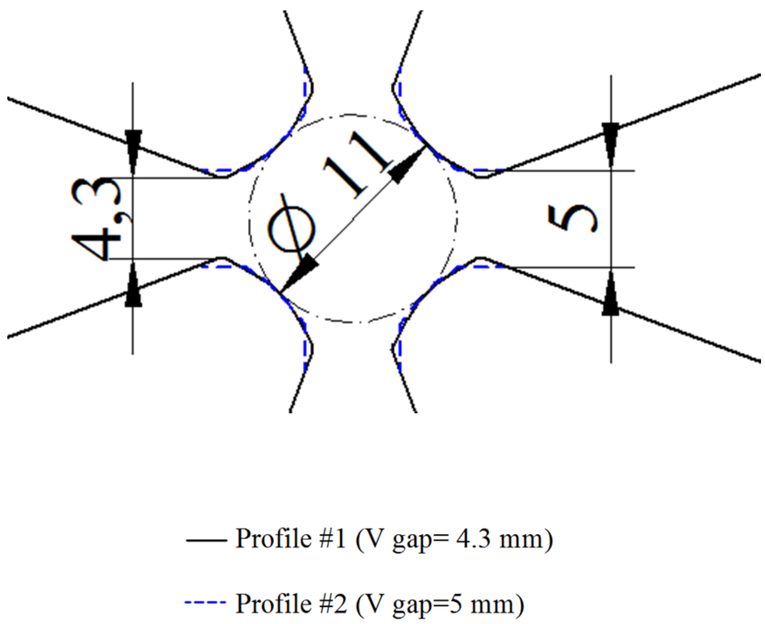




- Reduce the saturation of the Pole tip & Pole root & Return yoke: give a possibility to decrease the overall dimensions of the magnet.
- Not efficient for CoFe Pole tip @234 T/m, but extend the linear part of the excitation curve, possible to achieve the higher level of the gradient
- Significant improvement 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	%

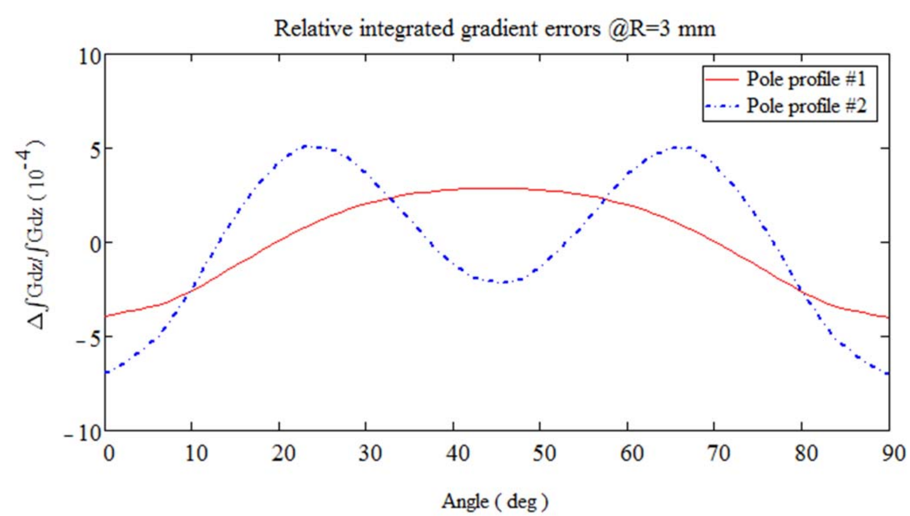
Pole profile study / Field quality



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

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

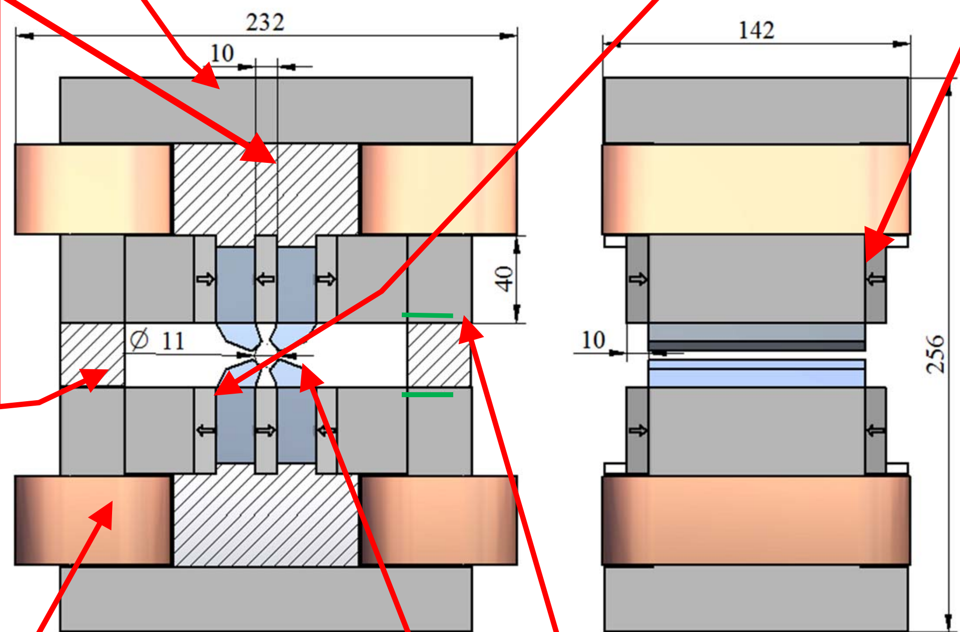


QFE magnet design (Hybrid magnet)

"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



Main parameters		
Magnet		
Nominal field gradient	234	T/m
Tuning range	-6 / + 5	%
Overall dimensions	232 x 256 x 142	mm^3
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/mm^2
Total power consumption	15	W

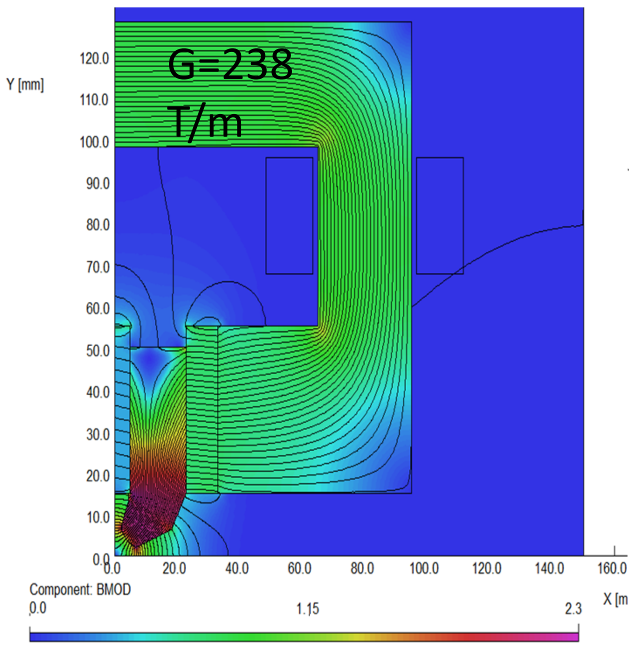
4 air cooled trim coils

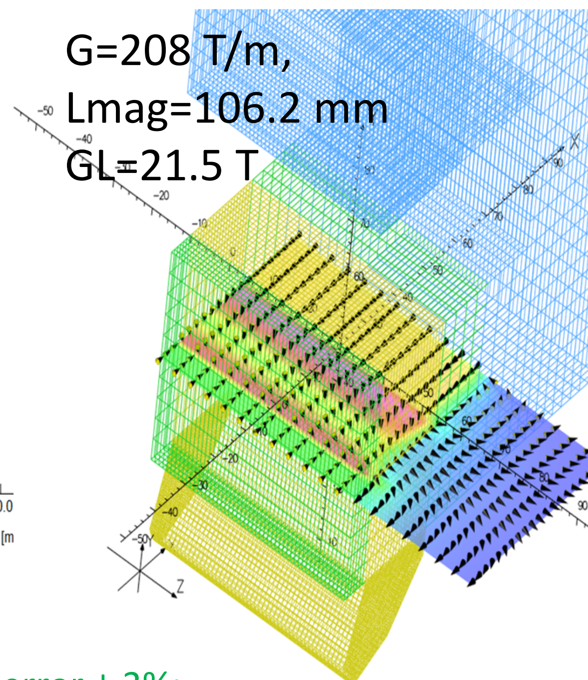
Pole Tip (separate pieces)
Material: Cobalt Iron alloy, Bs=2.35 T

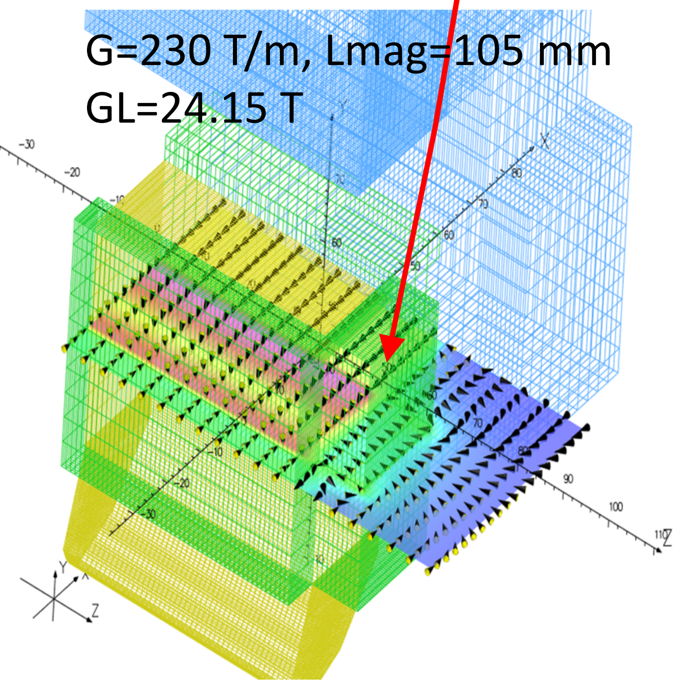
Pole profile shape and alignment:
Precise machining of the matting surface, pole profile machining in situ (1st assembly without PM)

QFE Hybrid magnet
2D & 3D modelling

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







PM imperfections:

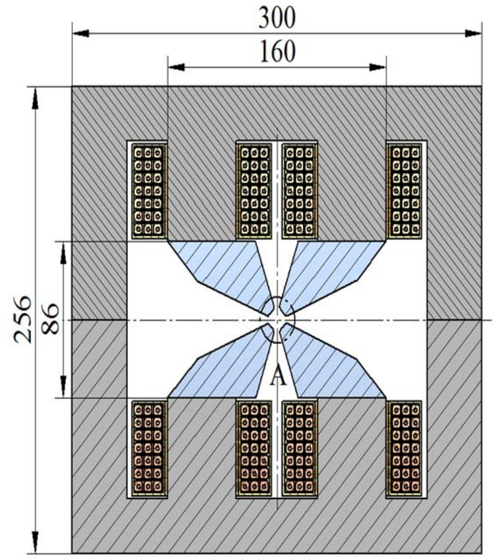
1. Direction of magnetization error ± 3%:

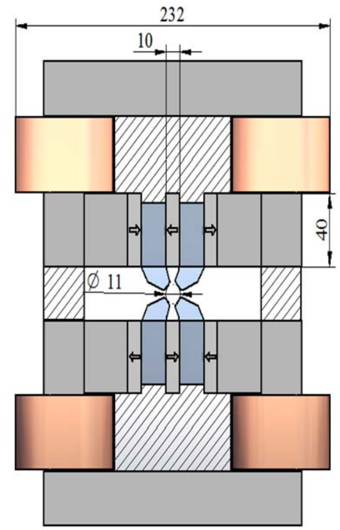
   The effect on a field quality / strength is negligible

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)

PS BOOSTER TL DIPOLE

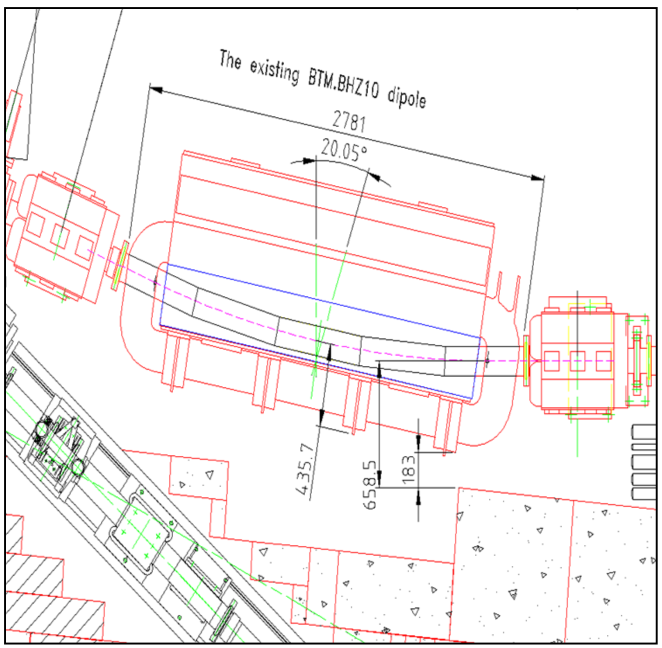
PSB-PS transfer line upgrade => proton beam to be transferred at 1.4 GeV and 2 GeV

The existing BTM.BHZ10 dipole:

- C-type, straight, bending magnet
- Total weight: 18 tonnes (Crane capacity 10 tonnes)
- Overall length: ~2760 mm
- Operates in PPM mode, energy range from 1 GeV to 1.4 GeV
- *Conclusion on existing magnet:*

  unable to provide the required field strength new coils required

  unable to provide the required field quality of ±5 units in the field range from 1.0 T to 1.5 T



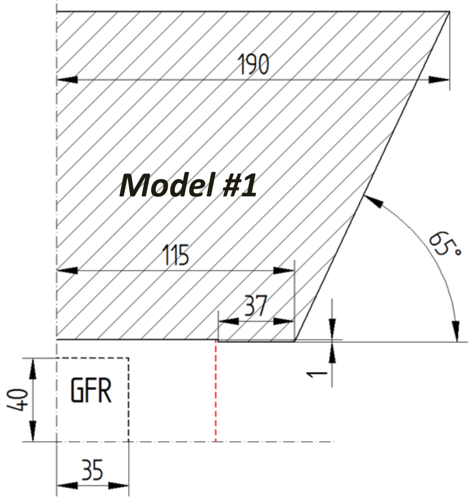
NEW magnet(Curved, H-type(2 half-yokes < 10 Tonnes each)

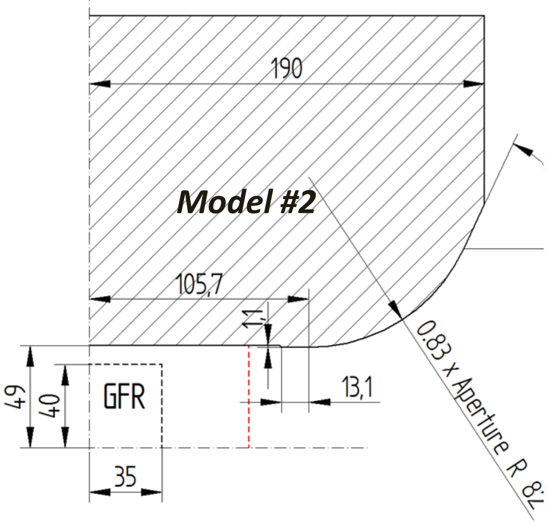
Units to be produced	1 + (2 coils)	Installed + (spare)
Bending angle A_{bend}	0.3499 (20.0478)	rad (degree)
Proton beam energy range	1.4 – 2.0	GeV
Beam rigidity B·ρ	7.144 / 9.288	T·m
Integrated magnetic field BL_{nom}	2.5[1] / 3.25[2]	T·m
Operational mode	$I_0 \leftrightarrow I_{nom}$ (ramp time=0.5 s) / DC	
Full aperture height	≥ 98	mm
Overall magnet length	≤ 2781	mm
Crane capacity	< 10’000	kg

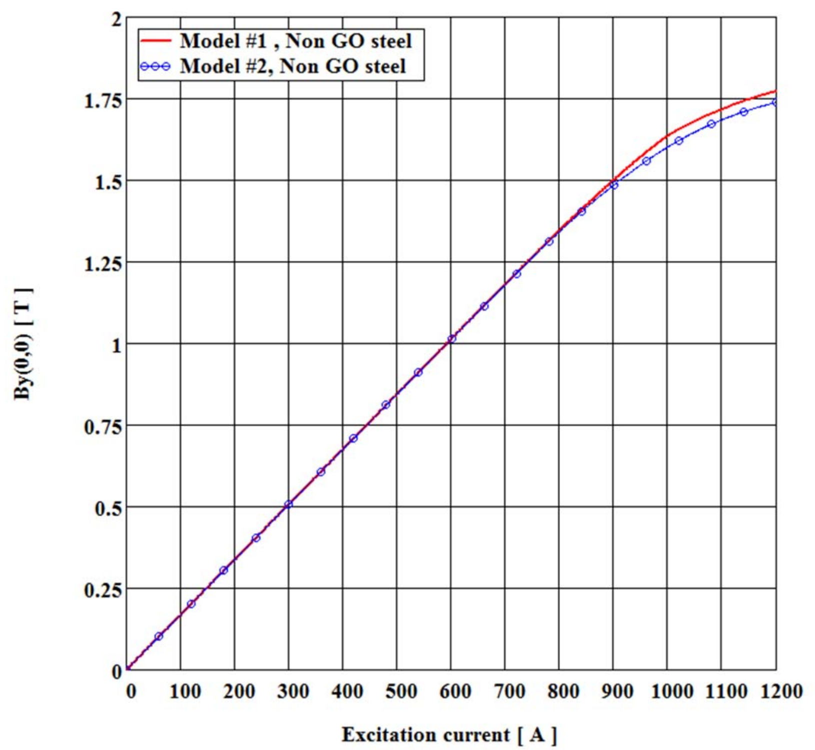
[1] Corresponds to 1.4 GeV protons
[2] Corresponds to 2.0 GeV protons

PS BOOSTER TL DIPOLE
Pole profile

	By(0,0) [T]		Errors [units]	
I [A]	Model #1	Model #2	Model #1	Model #2
640	1.0810	1.0805	± 1	± 0.75
850	1.4240	1.4174	± 6	± 0.45
900	1.5009	1.4854	± 10	± 1

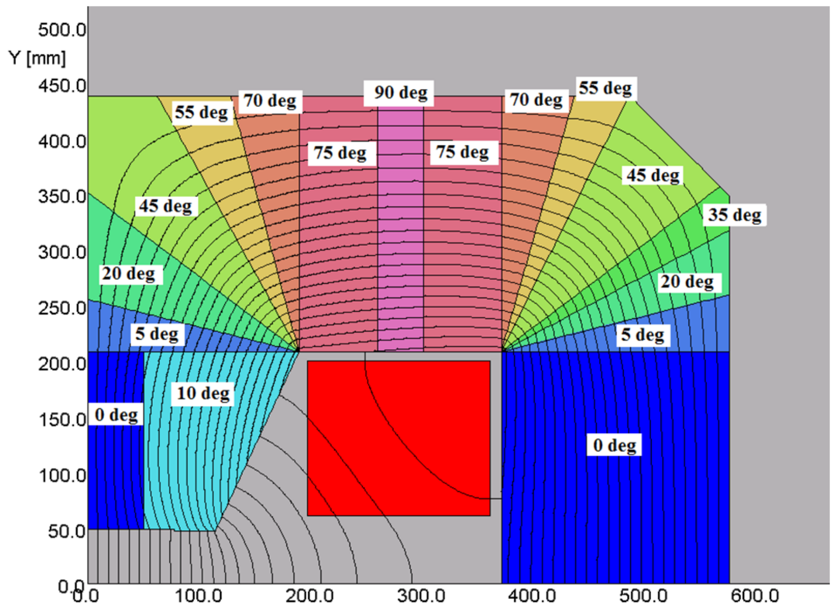




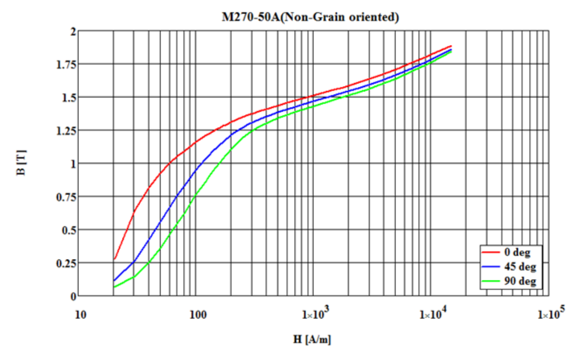


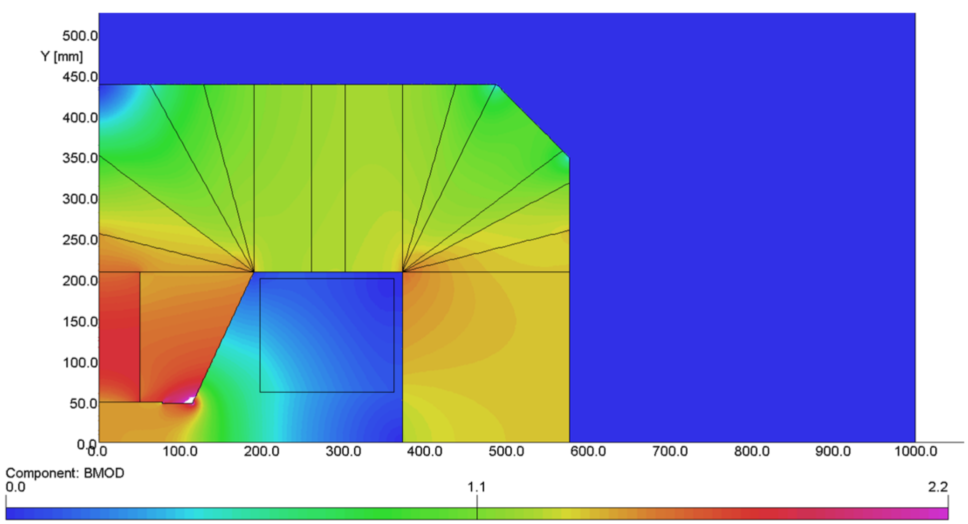
2D model (Grain oriented steel)

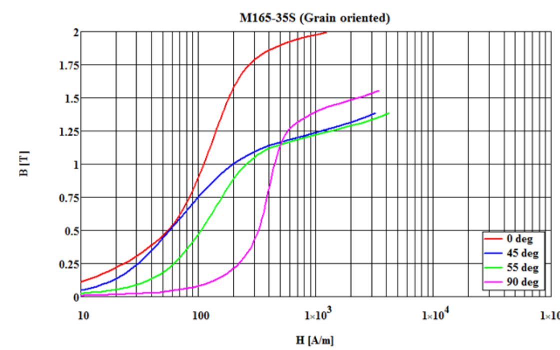
Model #1.3 : 10 regions (0, 5,10,20,35,45,55,70,75,90 deg)



	By(0,0) [T]		Errors [units]	
I [A]	Model #1 Non GO steel	Model #1.3 GO steel	Model #1 Non GO steel	Model #1.3 GO steel
640	1.0810	1.0786	± 1	± 1.25
850	1.4240	1.4300	± 6	± 2.1
900	1.5009	1.5100	± 10	± 5

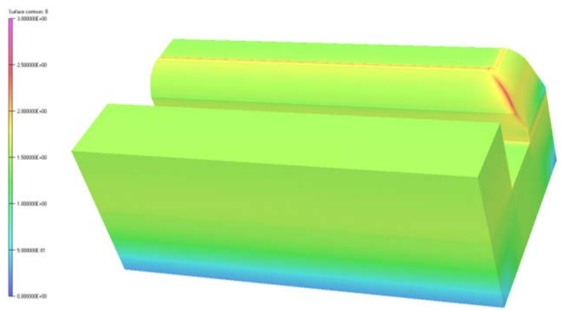




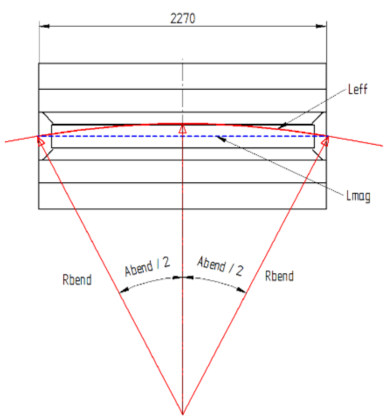


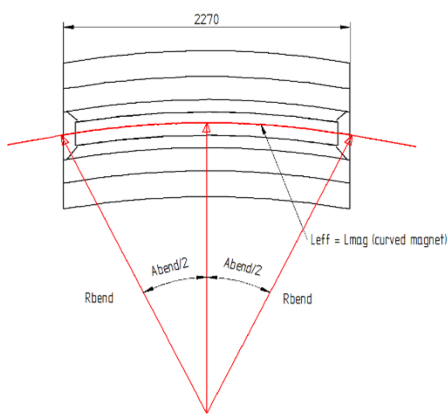
Simplified straight 3D model

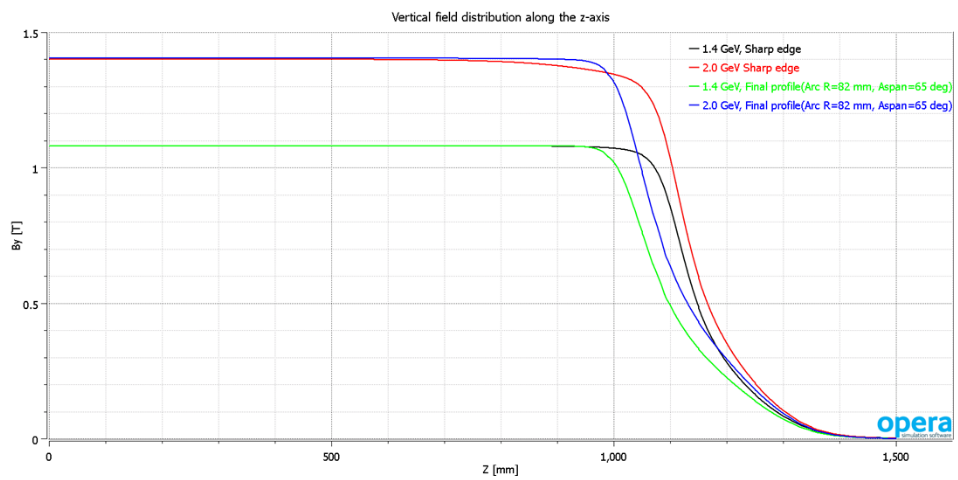
- To study and optimize the integrated field homogeneity
- To define the magnetic length and respectively the bending radius of the magnet



Axial pole profile	L_{mag} [mm] at I=640 A	L_{mag} [mm] at I=846 A	ΔL_{mag} [mm]
Sharp edge	2393.6	2363.2	30.4
Chamfer 75 mm ×45º	2315.5	2304.2	11.3
Rogowski profile	2305.6	2302.9	2.7
Arc R82, Aspan=65º	2305.3	2302.5	2.7







Curved 3D model
Field mapping & integrated field homogeneity=>Final design