Electromagnetic Design of the 120 mm Quadrupole Aperture for the LHC Inner Triplet Phase One Upgrade

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Acknowledgements
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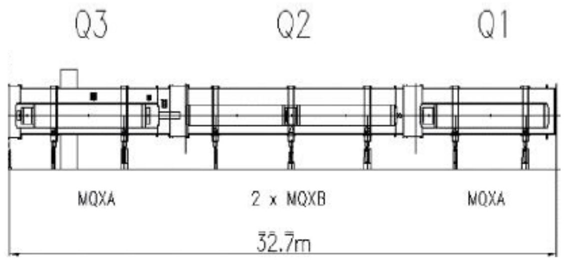
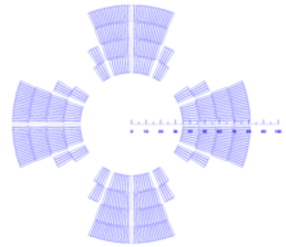
- Framework
- Electromagnetic design of the magnet cross-section
  - Cables features
  - Choice of the number of coil layers
  - Choice of the blocks angles an position based on a pure sector coil model
  - Cross-section with Rutherford cables
  - Iron yoke cross-section
- Layer jump
- NCS coil end
- Field quality
  - Random error
  - Systematic error
  - Tuning of the multipoles through mid-plane shims
- Conclusion

Framework

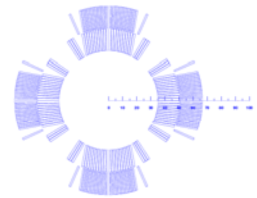
- Increases of the luminosity in the CMS and ATLAS experiments.

- Actual inner triplet quadrupoles:
  - Temperature: 1.9 K
  - Nominal gradient: 205 T/m
  - Aperture diameter : 70 mm
  - Quadrupole length: 5.5/6.37 m



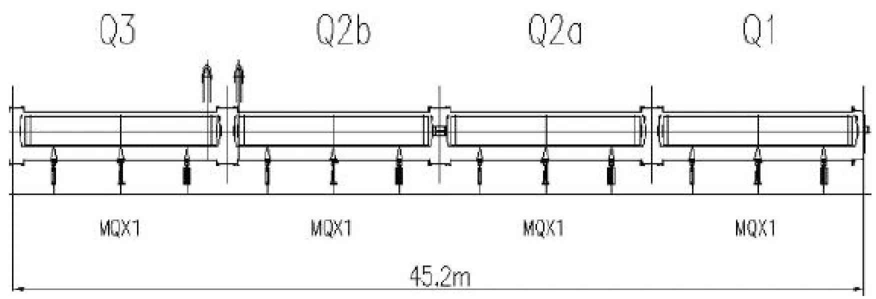


MQXA



MQXB

- New inner triplet quadrupole (MQXC) requirements:
  - Temperature: 1.9 K
  - Nominal gradient: 120 T/m
  - Aperture diameter : 120 mm
  - Quadrupole length: ~10 m



Content

Cables features

- The MQXC coil will be wound using the spare Nb-Ti cables of the LHC main dipoles (cables 01 and 02)
- Cables 01 and 02 are available in unit length of 460 m and 780 m respectively.
- The cross-sectional area of the cable 01 (insulation included) is 1.23 times larger than the cable 02.
- The cable insulation is based on a new concept allowing to increase the heat transfer [1].
- Critical currents of the cables are taken as the more pessimistic values derived from the latest measurements performed at 1.9 K.

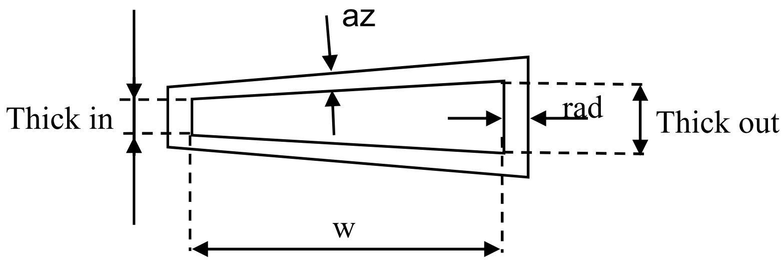


Table 1: Cables parameters

	unit	cable 01	cable 02
w	mm	15.100	15.100
thick in	mm	1.736	1.362
thick out	mm	2.064	1.598
rad. insulation	mm	0.160	0.160
az. insulation	mm	0.135	0.145
n. strand		28	36
strand diameter	mm	1.065	0.825
Cu/Sc ratio		1.65	1.95
I_{ss}	A	14800 (10T)	14650 (9T)
$\Delta I_{ss}/\Delta B$	A/T	4680 (10T)	4050 (9T)

[1] M. La China and D. Tommasini, "Comparative Study of Heat Transfer from Nb-Ti and Nb3Sn coils to HeII", Phys. Rev. Spec. Top. Accel. Beams 11 (2008) 082401

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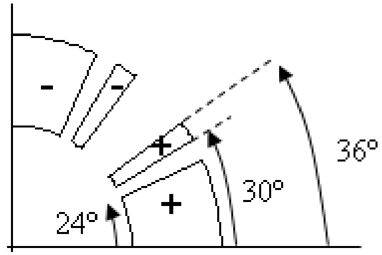
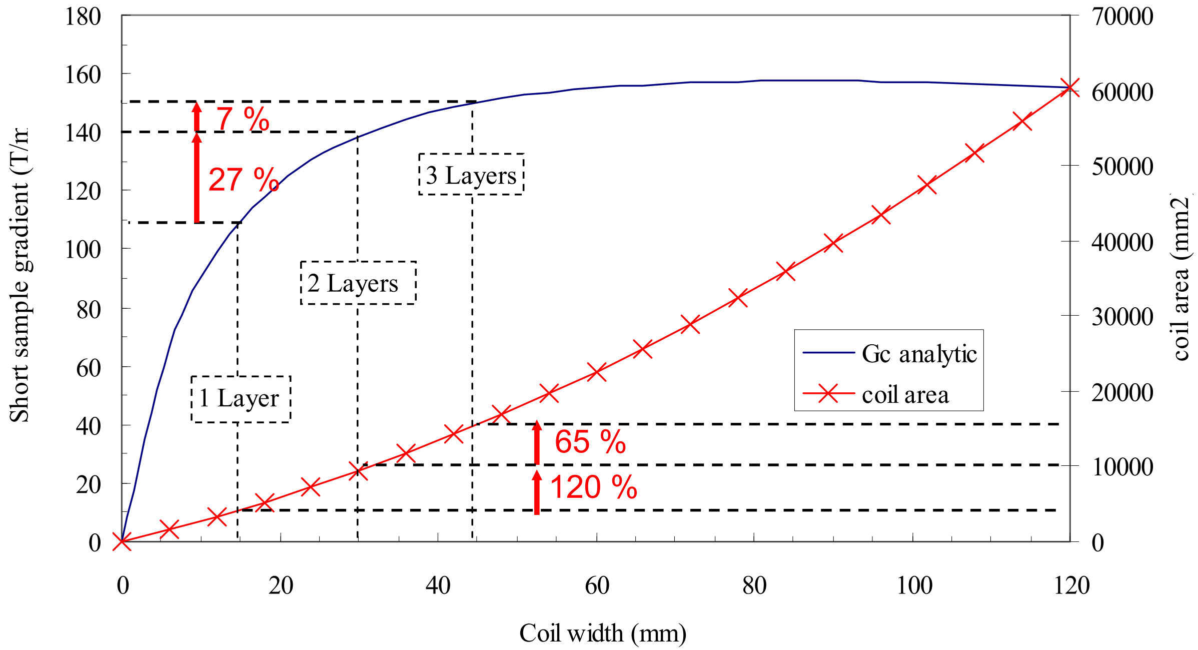
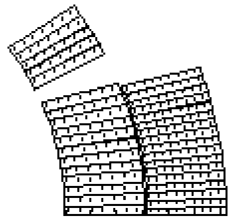
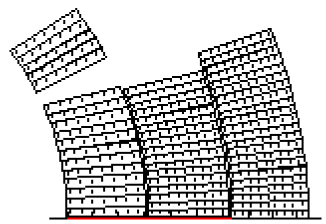
Choice of the number of coil layers

- The choice of the number of layers is made by means of a scaling law [2] assuming:
  - [0-24; 30-36°] pure sector coil of 120 mm aperture diameter
  - No current grading and no iron yoke
  - Superconducting cable performance similar to the LHC main dipole









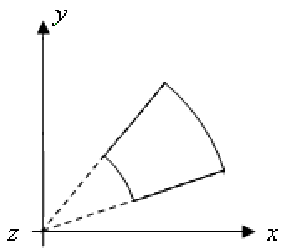
➡ The more reasonable choice is a 2 layers coil

[2] L. Rossi and E. Todesco, "Electromagnetic design of superconducting quadrupoles", Phys. Rev. ST Accel. Beams 9 (2006)

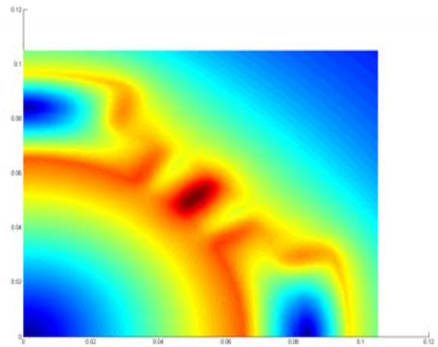
Content

Pure sector coil blocks model

- To help in the choice of the MQXC quadrupole coil cross-section we propose to first work with basic quadrupole coils made of pure sector blocks.
- Advantage in working with pure sector blocks model:
  - Magnetic field expressed everywhere by means of simple equations derived from Fourier transform.
  - Equations are easy to implement in a code and fast to compute.
  - We can compute the gradient, the field quality, the peak field, the magnetic forces…
  - An unsaturated iron yoke can be taken into account.



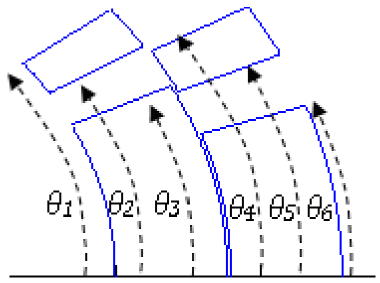
Pure sector block


Example of magnetic flux density obtained with our model

- Goal :
  - To carry out a parametric study in order to have an overview of all the possible quadrupole cross-sections providing a good field quality (3 first allowed harmonics below 1 unit).
  - To spot the cross-sections providing a high gradient.

Pure sector coil blocks model

- The three first allowed multipoles b_6, b_{10} and b_{14} have to be minimized.
- The free parameters to play with to minimize the multipoles are the blocks angles.
- A coil made up of 4 blocks is chosen so as to have 6 free parameters.
- An unsaturated iron yoke is set at 37 mm from the coil



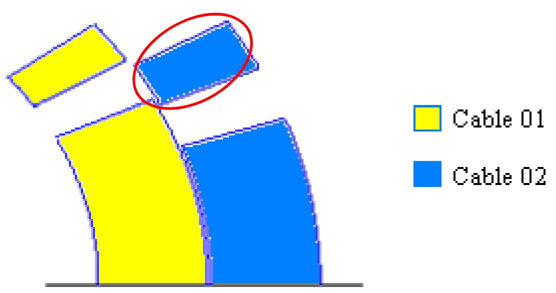
Half of a quadrupole coil made up of 4 pure sector blocks

- Parametric study procedure:
  - A scan is done through all possible angles combinations
  - The sets of angles giving b_6, b_{10} and b_{14} < 1 unit are kept (R_{ref} = 2/3 of the aperture diameter)
  - Computation of the short sample gradient, the short sample current, the magnetic forces acting on the coil, and the amount of cables used to wind a coil.

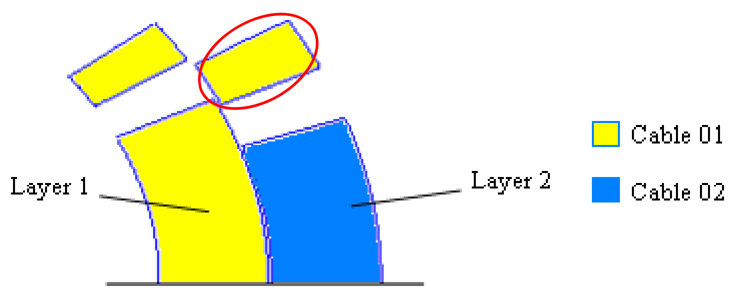
Study of the special and normal grading schemes

- Special grading scheme (like LHC MQY and MQXA) :
  - Enhances the current margin in the upper block of the outer layer.
  - In some cases it can lead to an enhancement of the short sample gradient.

Normal grading

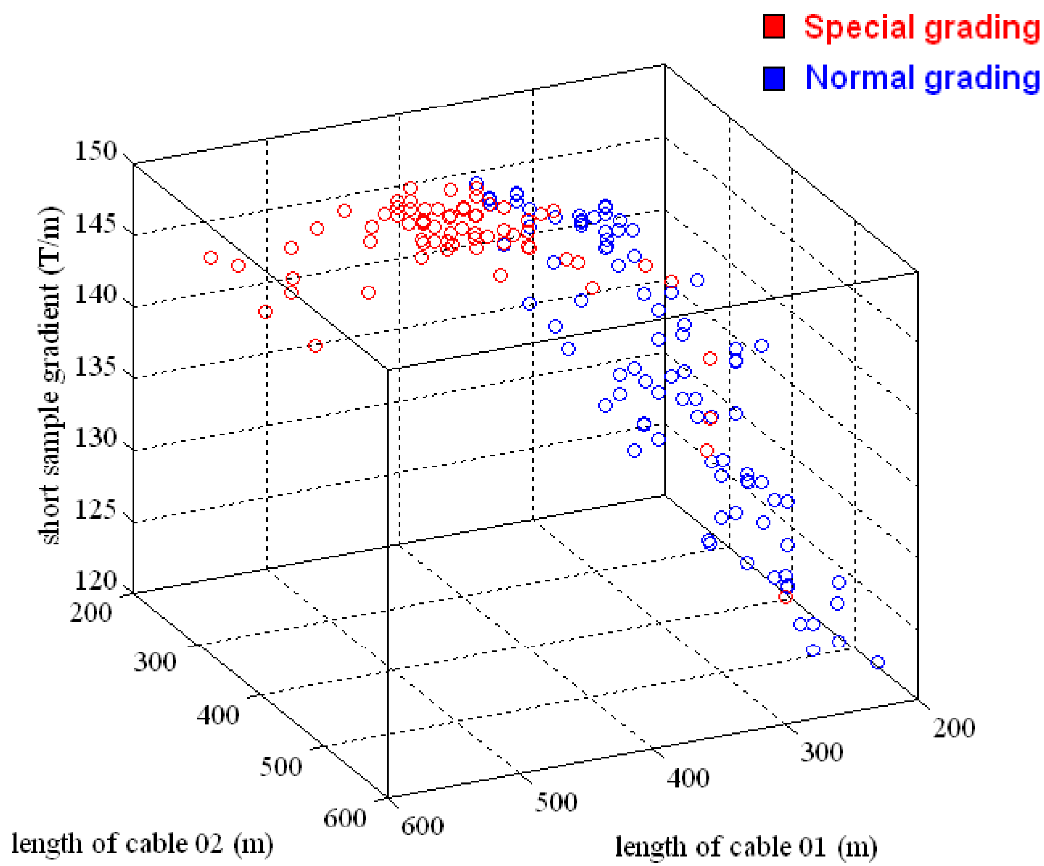


Special grading

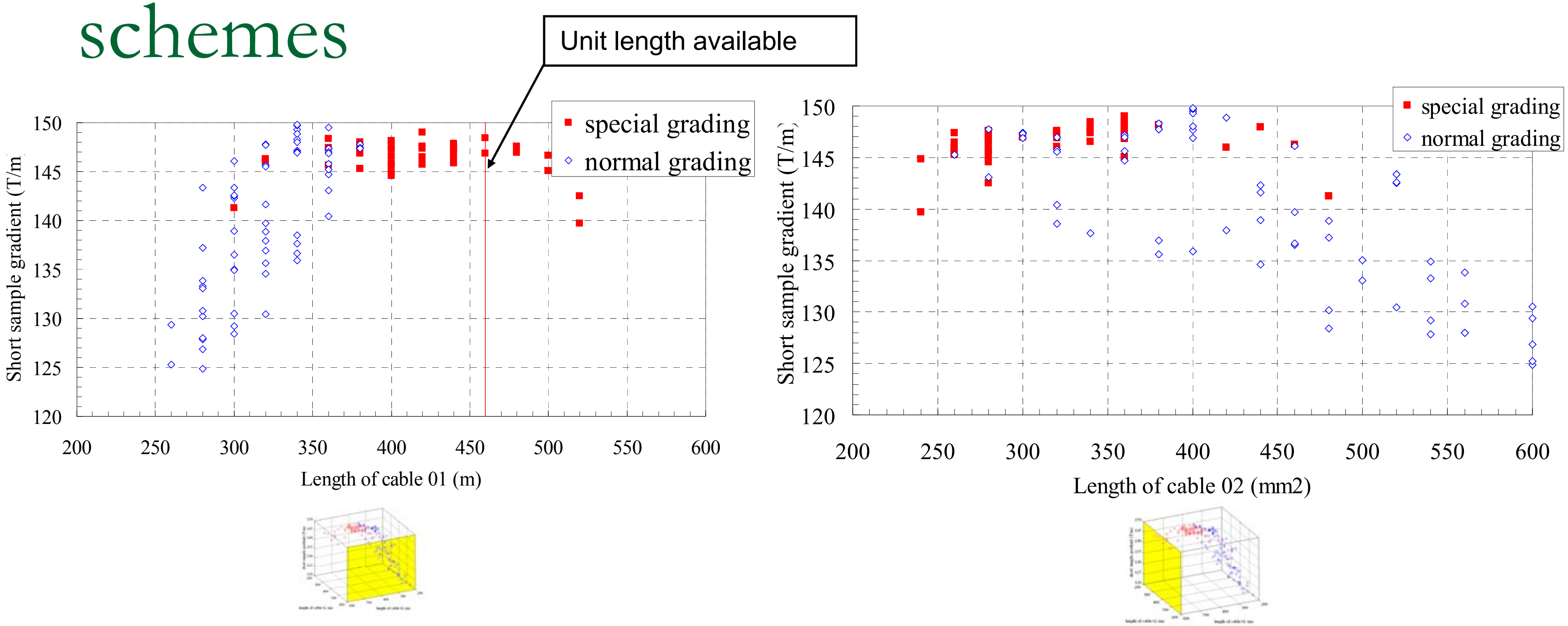


Study of the special and normal grading schemes

- A scan through all block angles combination has been done.
- Each marker is a cross-section providing a good field quality.



Study of the special and normal grading schemes

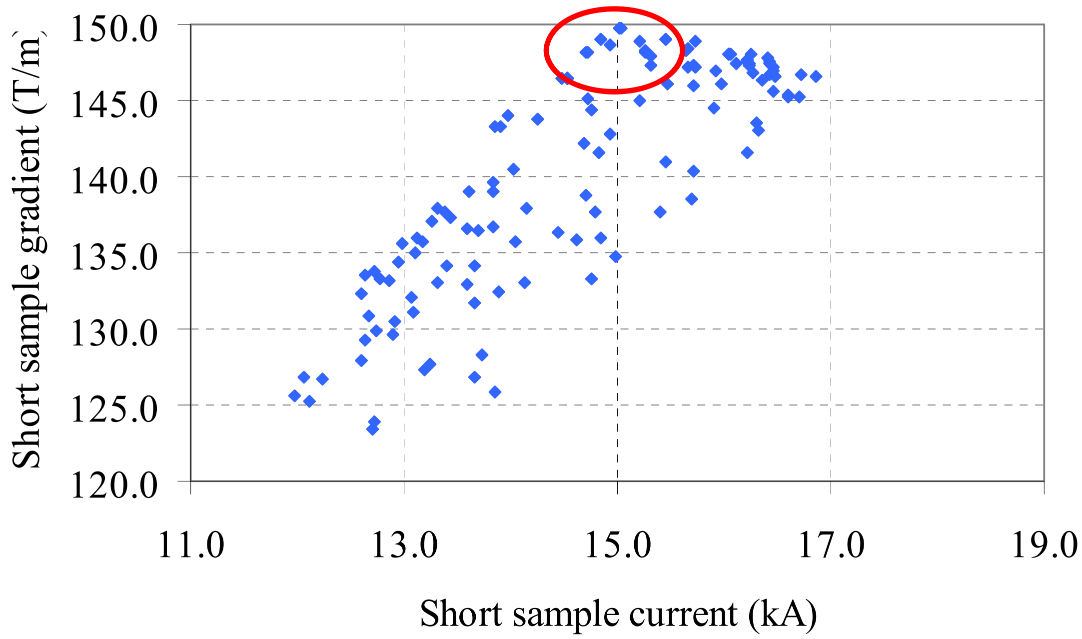


- The special grading scheme provides a larger set of magnet with a maximal gradient in between 145T/m and 150 T/m.
- But in both the special and normal grading cases the maximal gradient is ~150 T/m.
- The special grading scheme uses more cable 01 which has the smallest unit length (460 m) (780 m for the cable 02).

→ The normal grading scheme better fits the constrains

Deeper study of the normal grading case

- 150 cross-sections provide a good field quality



- Highest short sample gradient of 150 T/m for a short sample current ~15 kA

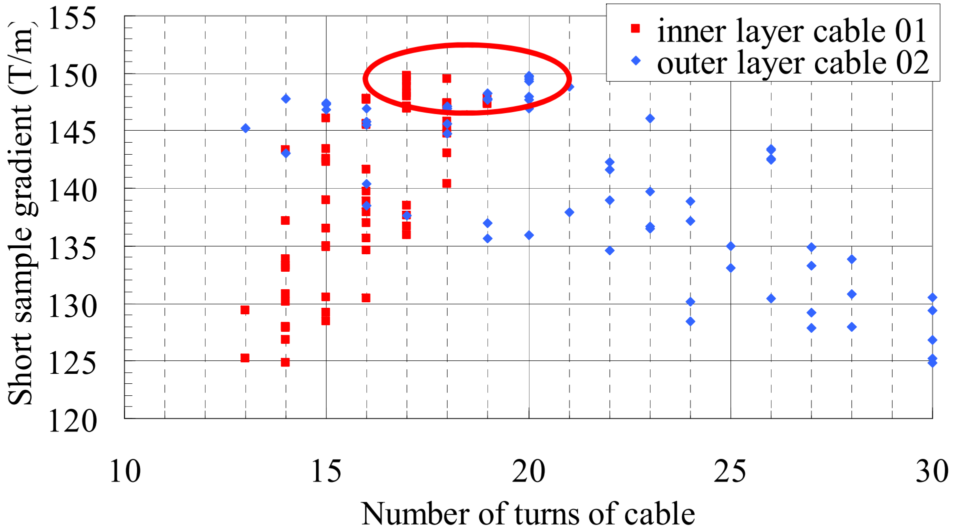
↓

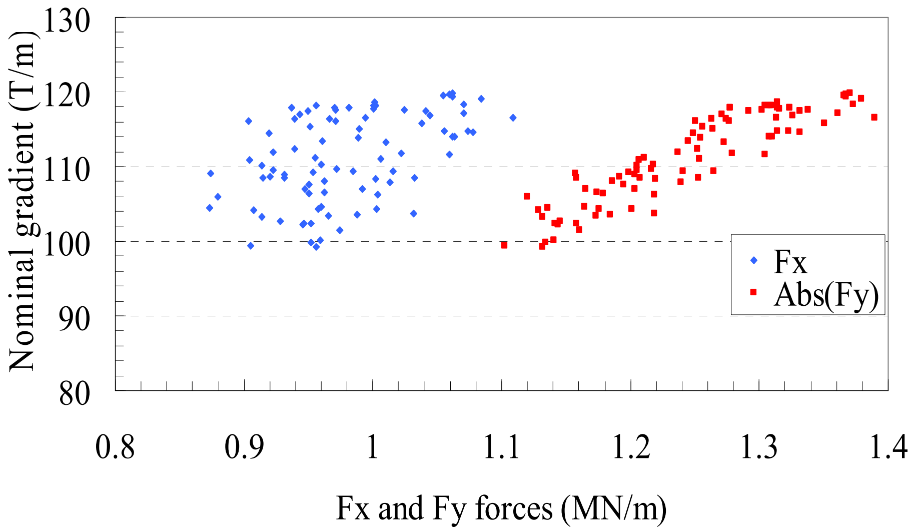
20% margin on the short sample current

↓

Nominal gradient of 120 T/m and nominal current ~12 kA

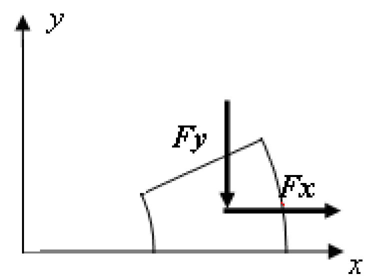
Deeper study of the normal grading case





- To reach the highest gradient the number of turns of cables 01 and 02 tends toward the same values of 15-20 turns i.e.300 - 400m / pole for a 10-m-long magnet (head excluded)

- Magnetic forces at nominal current (80% of the short sample):
  - F_x is around 1 MN/m
  - F_y increases continuously with the gradient. At G_n = 120 T/m, F_y~ 1.4 MN/m



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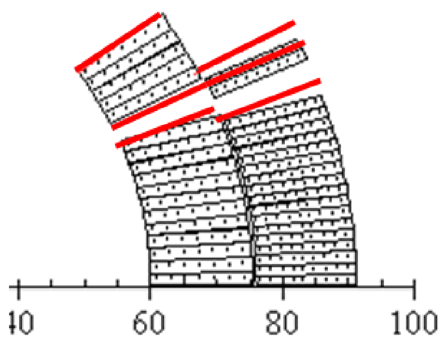
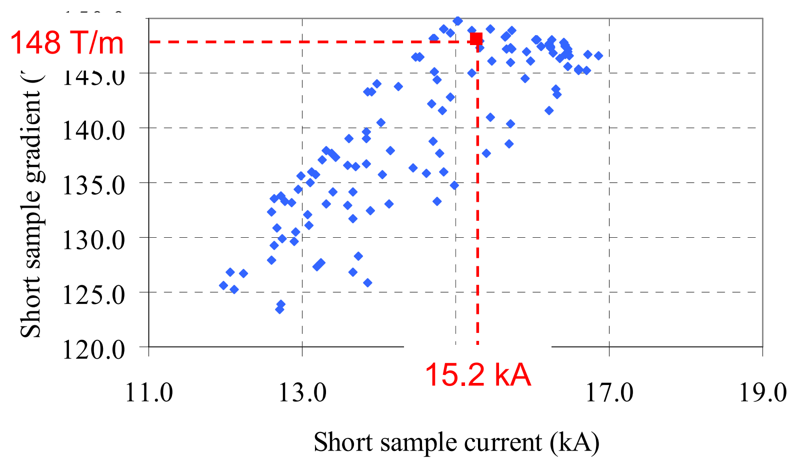
Cross-section with Rutherford cables

- We dispose of several set of angles all providing good field quality, low current and high gradient
- For each block we compute the number of turns of cables which best fits with the sector coil angles
- The field harmonic distortion due to the discrete cable size and the slight variation from a purely radial sector block are compensated by tuning the block position and allowing small block tilts.
- The Choice of the MQXC coil cross-section has been done according the amount of cables used and the mechanical feasibility.

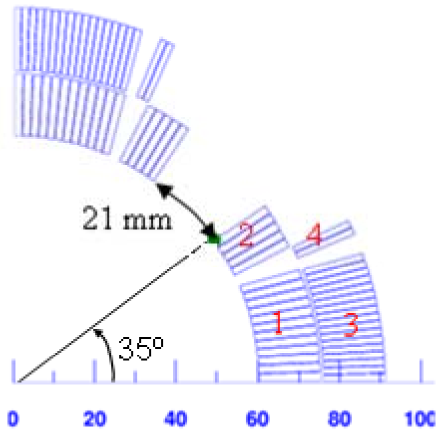


Cross-section chosen for the MQXC
And analytical solution (red lines)

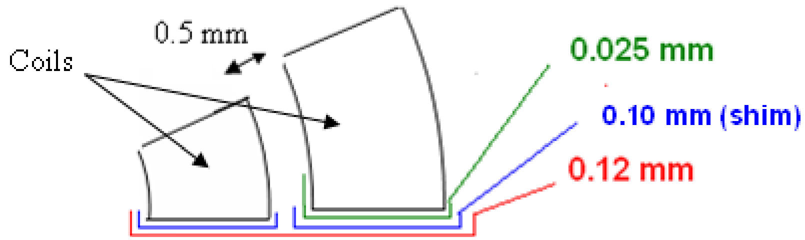


Coil cross-section

- Number of turns of cables:
  - Cable 01 (inner layer): 17 turns or 340 m of cable for a 10-m-long magnet (head excluded)
  - Cable 02 (outer layer): 19 turns or 380 m of cable for a 10-m-long magnet (head excluded)

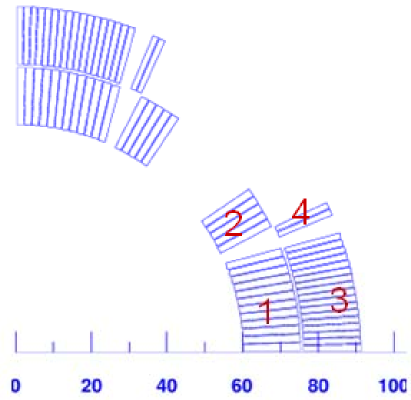


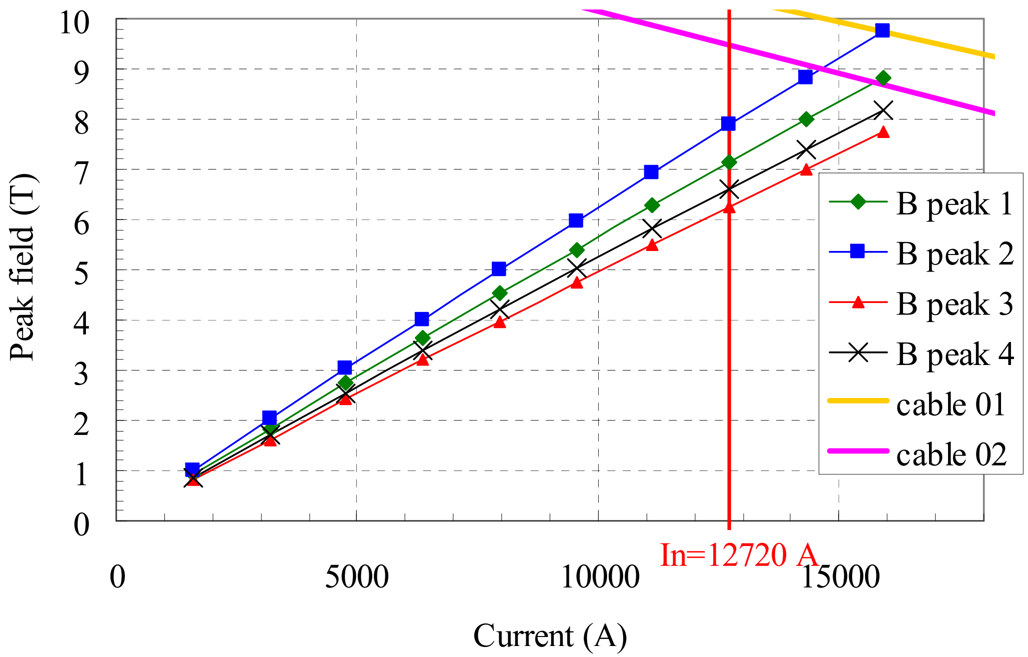
- Nose length of 21 mm (16 mm for the LHC main dipole).
- 0.5 mm inter-layers insulation.
- Mid-plane componnents:
  - 0.12 mm common insulation sheet.
  - Individual 0.10 mm kapton shim to fine tune the multipoles.
  - A 0.025 mm shim in the outer layer mid-plane.



Coil cross-section

- Short sample current : 15.9 kA.
- Short sample gradient: 147.1 T/m.
- The quench field of 9.8 T is located in the block 2.





	unit	MQXC quad
Aperture dia.	mm	120
Inner iron dia	mm	260
Outer iron dia.	mm	550
Critical Gradient	T/m	147.1
Critical current	kA	15.9
Op. gradient	T/m	118.5
Op current	kA	12.72
Inductance	mH/m	5.06
Ref radius	mm	40
b_6 (I = In)	unit	-0.006
b_{10} (I = In)	unit	-0.036
b_{14} (I = In)	unit	-0.076
F_x (I = In)	MN/m	0.93
F_y (I = In)	MN/m	-1.35

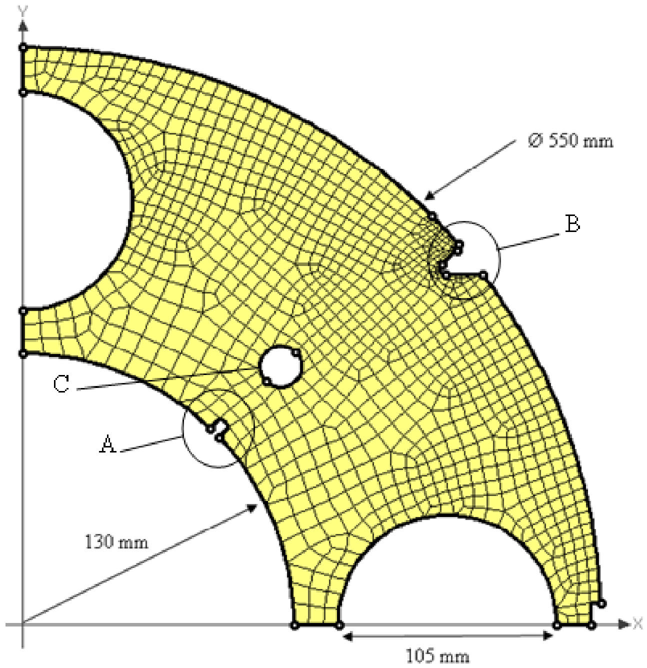
Content

Iron yoke cross-section

- Collars have to support all the E.M. forces. Their thickness has been set to 37 mm.
- Yoke inner diameter of 260 mm.
- Yoke outer diameter limited at 550 mm for tooling and tunnel limited space reasons.
- The yoke is a stack of 5.8 mm thick iron sheet with a package coefficient of 0.985.

- Heat exchanger: 4 holes of 105-mm-diameter in line with the mid-plane. It is the best option from the integration point of view and it is acceptable from the magnetic point of view.

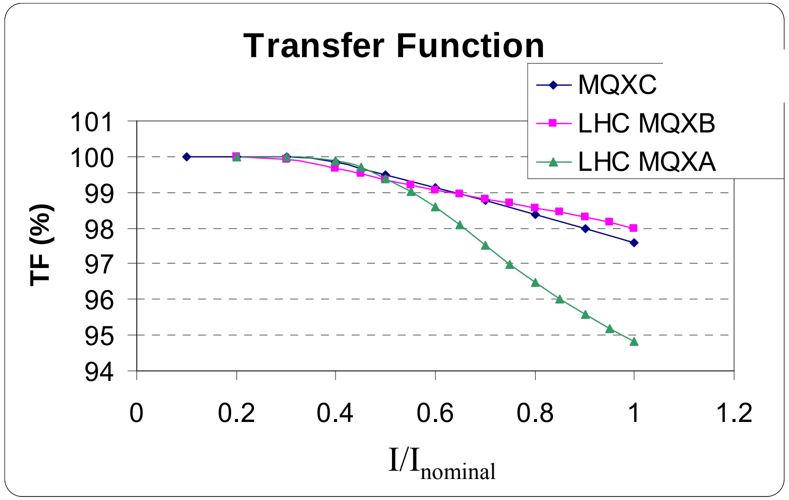
- 105-mm-holes are centered in order to leave 20 mm of matter on each side.
- Yoke features:
  - A: slot for the key
  - B: notch to handle the magnet
  - C: cavity of 20.5 mm diameter for the axial iron rod

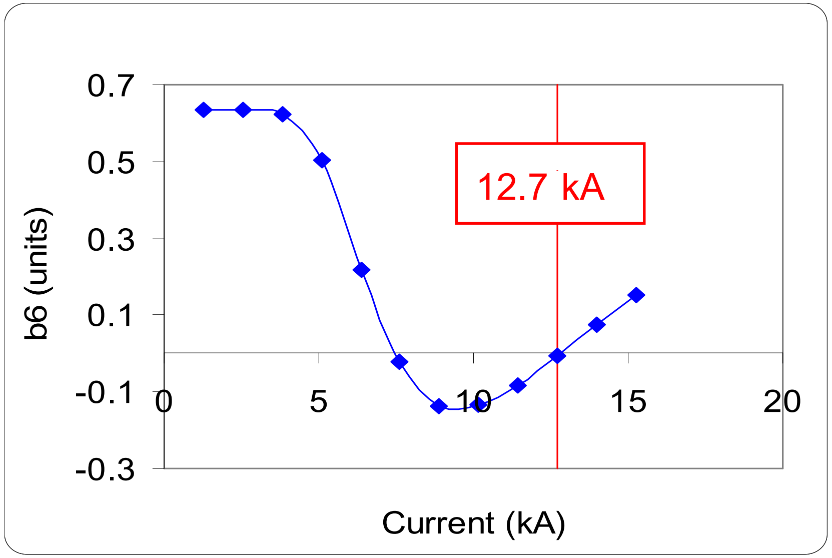


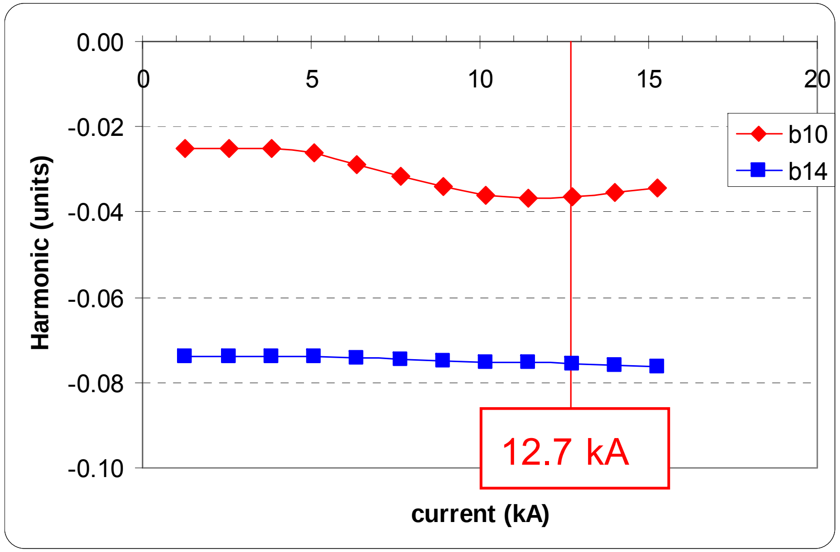
Iron yoke cross-section

- The reduction of the transfer function (~2.4%) is in between what we have for the LHC MQXA (6%) and the LHC MQXB (2%)

- Multipoles variation (R_{ref}=2/3 ap. diameter):
  - Δb_6 ~ 0.8 units
  - Δb_{10} ~ 0.1 units
  - Δb_{14} ~ 0.01 units



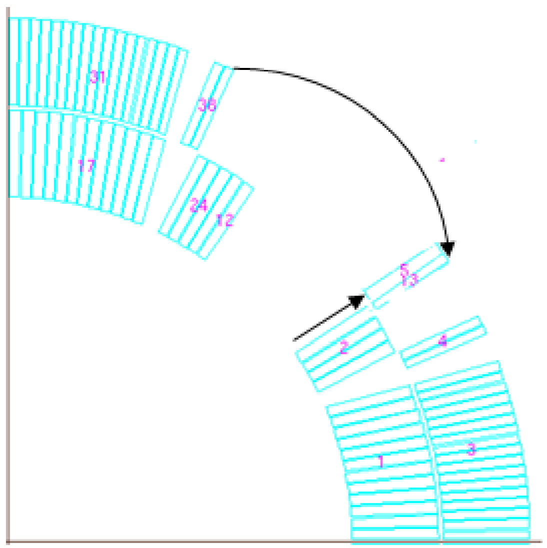


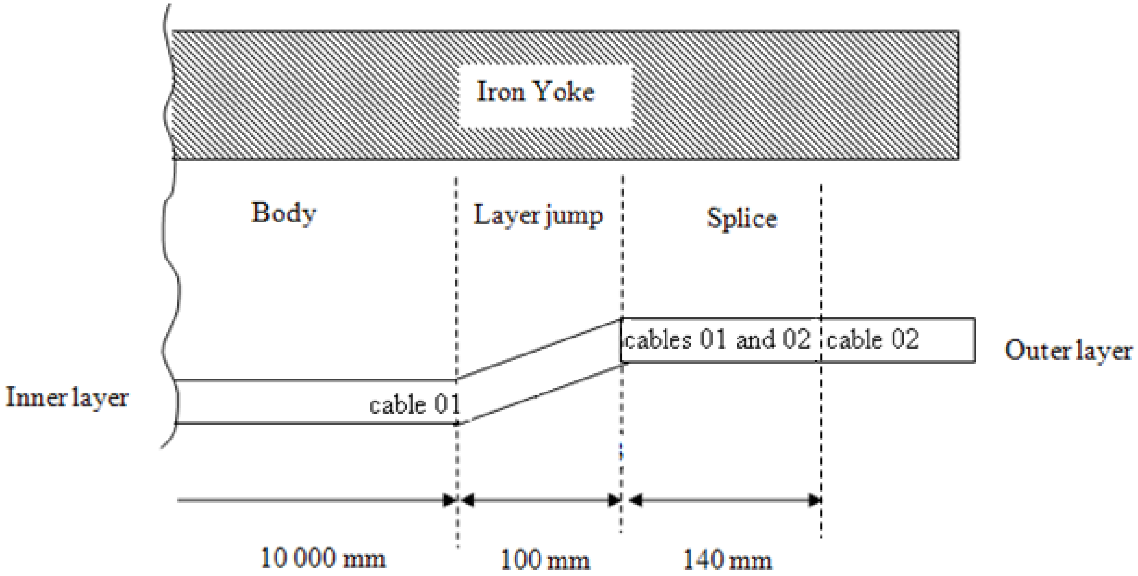


Content

Layer jump and splice

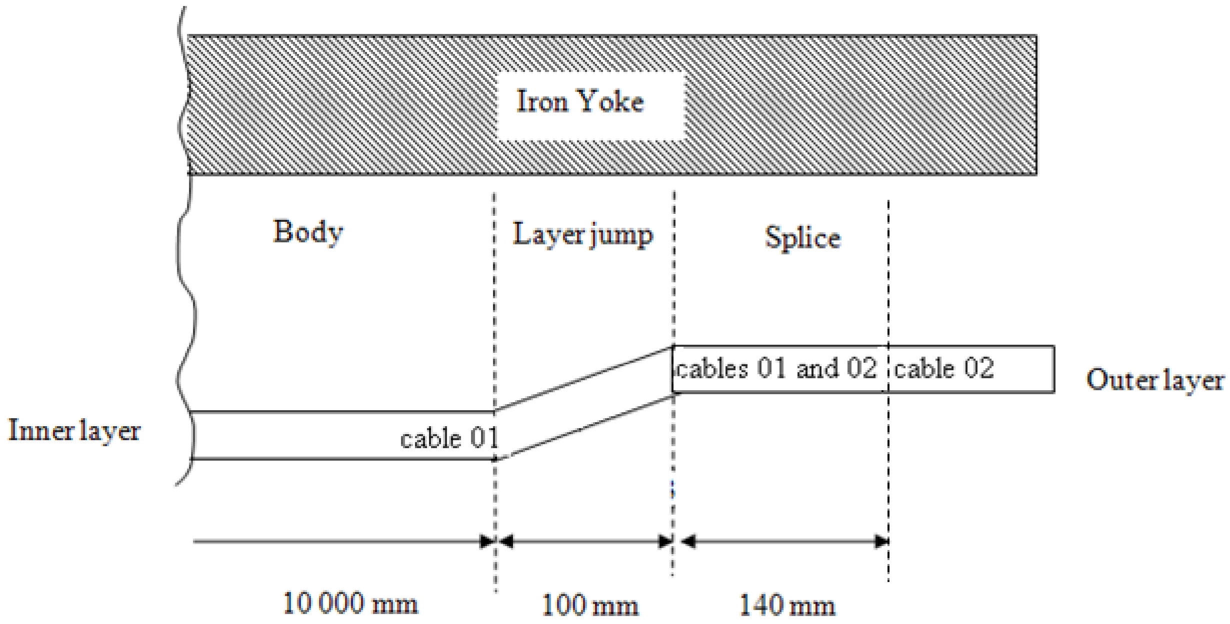
- The layer jump is used to connect electrically the inner layer to the outer layer.
- The splice is the section where the inner and outer layer cables are overlapped.
- The length of the layer jump and of the splice are similar to what we have for the main dipoles.
- The peak field leading to a quench is always located in the straight part.





Layer jump and splice

- The magnetic length of the splice is of 240 mm
- Magnet straight part of 7.25 m is considered for the computation of the integral
- Multipoles are given at 2/3 of the aperture radius



multipole	integral
b_4	**-0.02**
b_6	**0.43**
b_{10}	**-0.08**
b_{14}	**0.00**
a_2	**1.61**
a_6	**-0.22**
a_{10}	**-0.02**
a_{14}	**0.01**
G (T/m)	**118.49**

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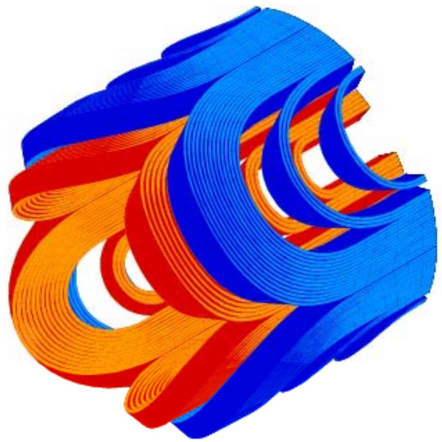
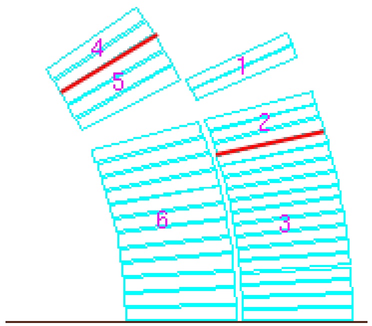
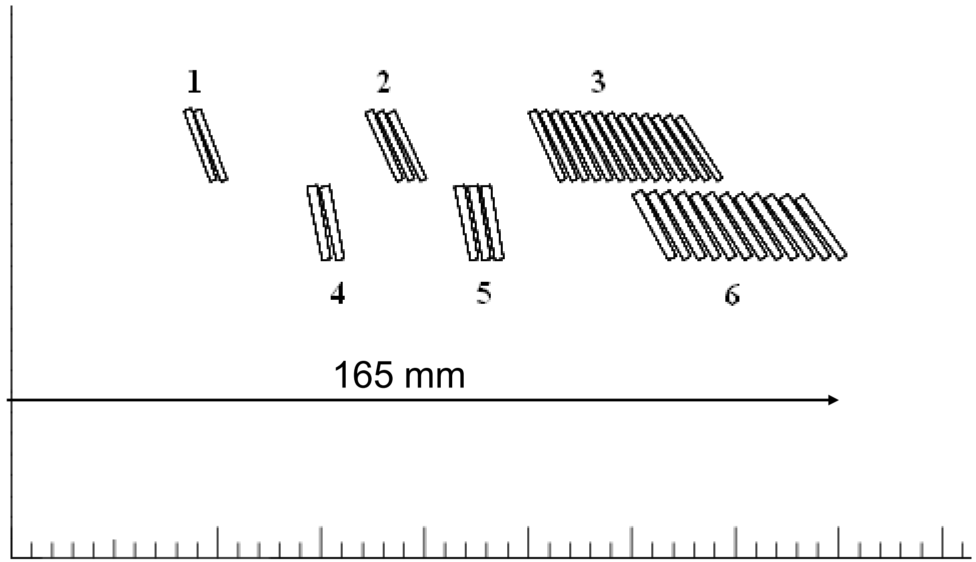
NCS Coil head



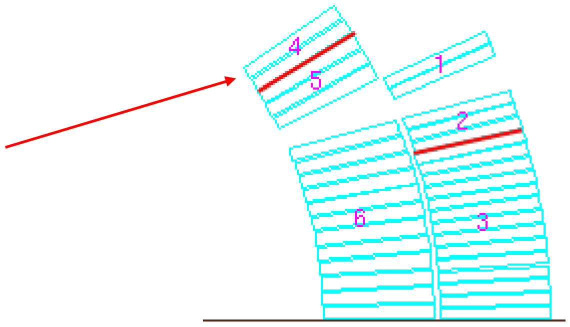
- Head design done with Roxie:
  - Cables on mandrel
  - Elliptical shape of the head
  - Cable edges of equal perimeter
- The 4 blocks are split up into 6 blocks and their position has been optimized to reduce the peak field in the head and the allowed multipoles b_6, b_{10} and b_{14}.
- The length of the head is of 165 mm.

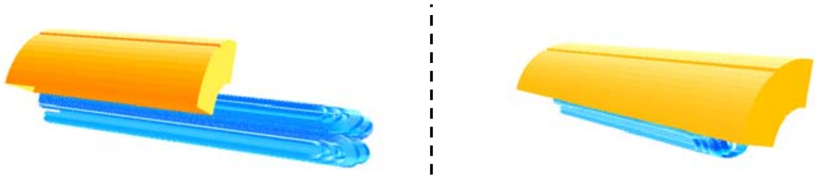


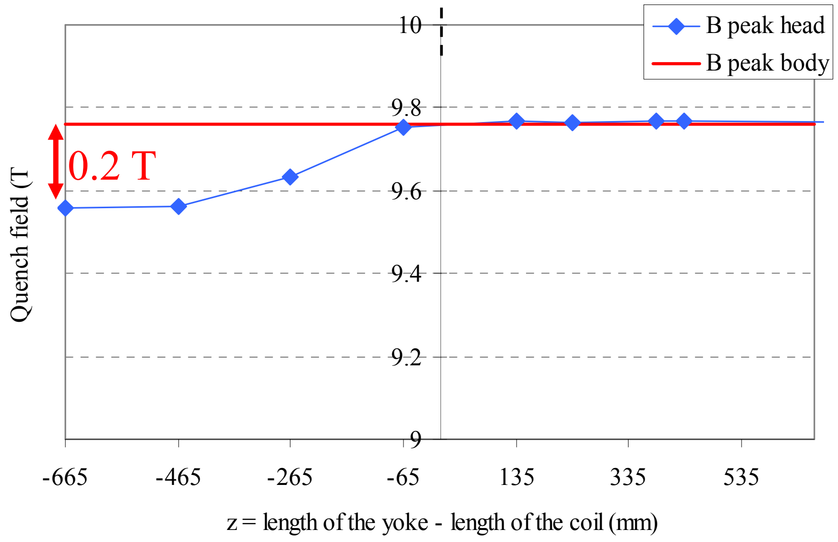


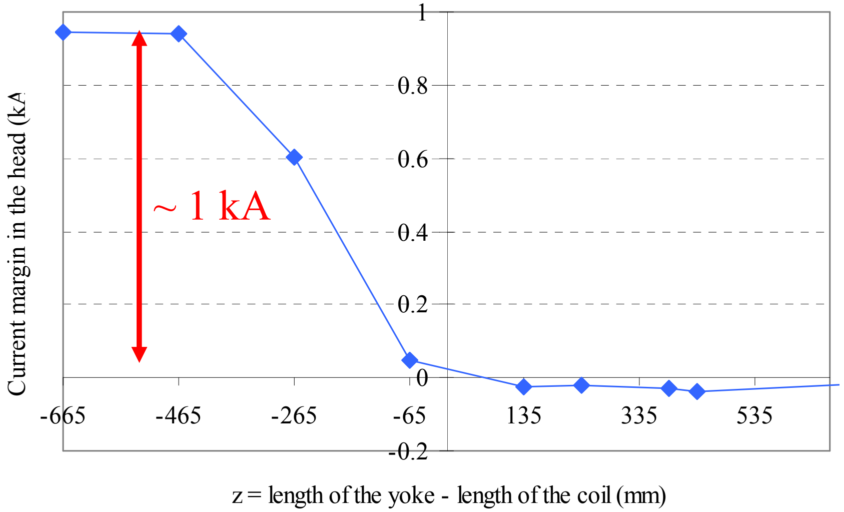
NCS Coil head

- Impact of the length of the iron yoke on the peak field:
  - The quench limit is always in the upper block of the inner layer
  - Shortening the iron yoke can give a field margin on the head of 0.2 T i.e. ~2%.



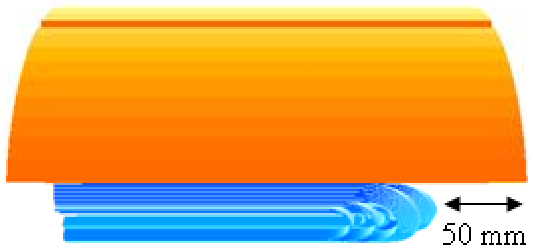






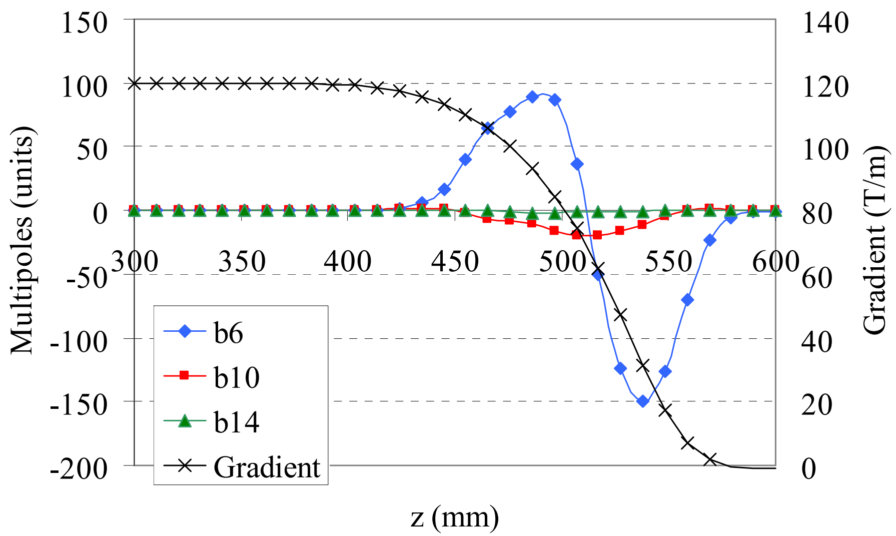
NCS Coil head

- Choice of the length of the yoke: 50 mm longer than the head edge to shield the magnet from external magnetic perturbations.



L_{mag}	113
b_6	-6.5
b_{10}	-5.5
b_{14}	-0.4

contribution to the integral
-0.10
-0.08
-0.01



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  - Uncertainty error
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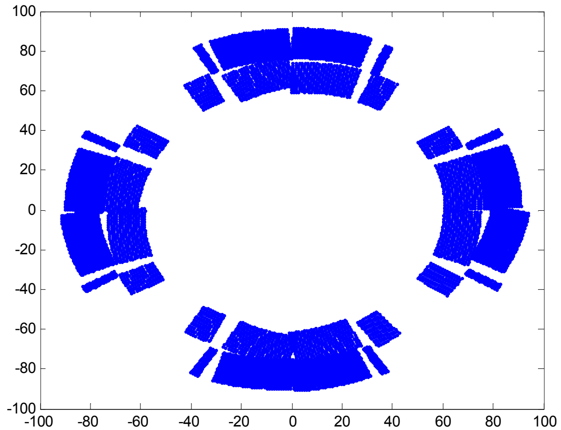
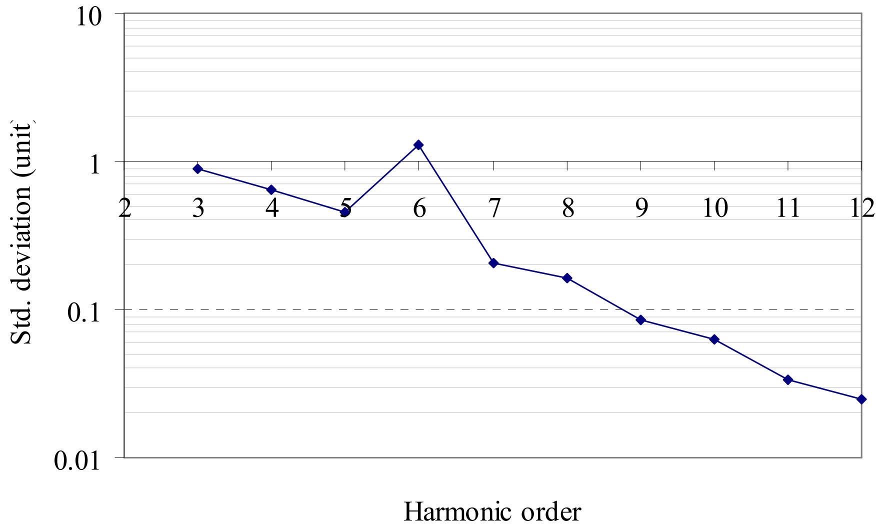
Field quality: Random error

- Origin: The random error of the field harmonic is due to the non-reproducibility of the industrial process of the coil manufacturing and assembly.
- To estimate the field error we used a Mont-Carlos analysis considering the largest rms coil block displacement found in the LHC magnets i.e. 0.030 mm.
- We assume that the precision in coil positionning does not depend on the aperture diameter [3].



	Std. dev. (unit) (1σ)	
n	bn	an
3	0.89	0.89
4	0.64	0.64
5	0.46	0.46
6	1.28	0.33
7	0.21	0.21
8	0.16	0.16
9	0.08	0.08
10	0.06	0.06
11	0.03	0.03
12	0.02	0.02
13	0.01	0.01
14	0.01	0.01



[3] E. Todesco, et al., "Estimating field quality in low-beta superconducting quadrupoles and its impact on beam stability", LHC project report 1061

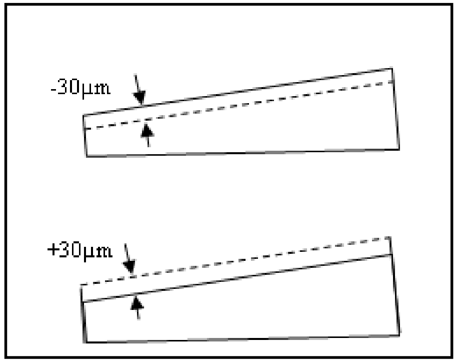
Content

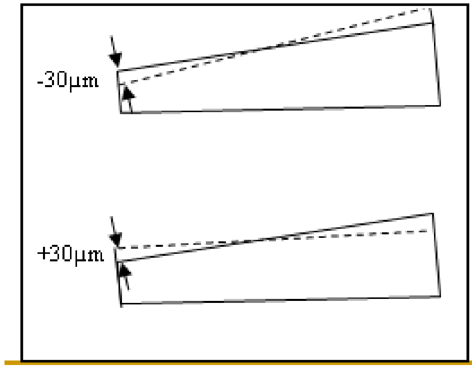
- Framework
- Electromagnetic design of the magnet cross-section
  - Cables features
  - Choice of the number of coil layers
  - Choice of the blocks angles an position based on a pure sector coil model
  - Cross-section with Rutherford cables
  - Iron yoke cross-section
- Layer jump
- NCS coil end
- Field quality
  - Random error
  - **Uncertainty error**
  - Tuning of the multipoles through mid-plane shims
- Conclusion

Field quality: Uncertainty

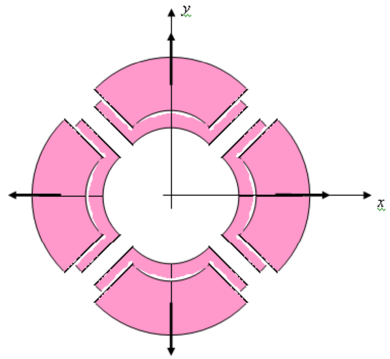
- Origin: The uncertainty in the mean is due to systematic errors meet in the magnets components.
- Estimation method: Quadratic sum of the min/max multipole values of each defect

Error on the copper wedges

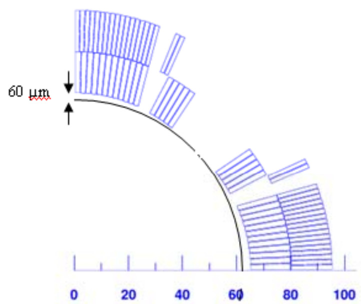




Error on the collar

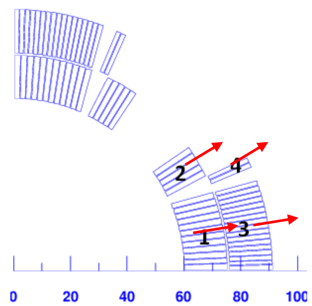


Collar lamination: +/- 0.05 mm



Collar lamination: + 0.06 mm

Imperfection in curing mould



Polymerisation defect:+0.05mm

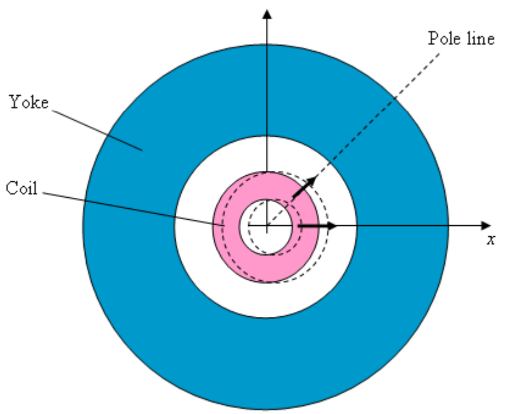
Radial offset of the splice:

+/-0.1mm

Negligible

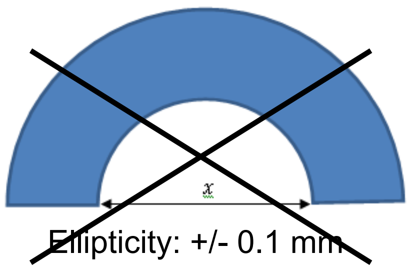
Field quality: Uncertainty

Error on the yoke



Shift of the coil inside the yoke

+/- 0.1 mm



Ellipticity: +/- 0.1 mm

Negligible

Collar permeability

μr = 1 ⟶ 1.003

Negligible

Longitudinal shift of one layer

Negligible

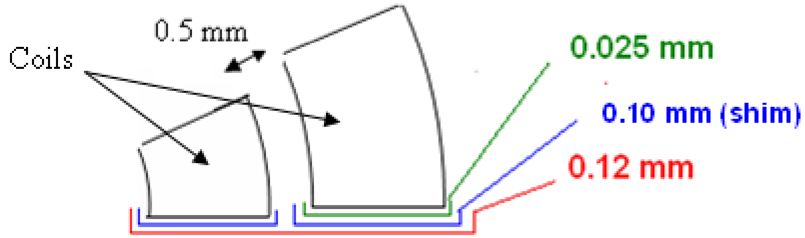
Field quality Table

- The total magnetic length considered is:
  - 7722 mm =7250(body)+240 (L jump & splice)+ 116 (NCS head) +116 (CS head)

	geometric	*uncertainity*		*random 1 sigma*
		min	*max*	
b3		-0.46	0.46	0.89
b4	0.00	-0.05	0.06	0.64
b5				0.46
b6	0.42	-1.01	0.97	1.28
b7				0.21
b8				0.16
b9				0.08
b10	-0.23	-0.16	0.17	0.06
b11				0.03
b12				0.02
b13				0.01
b14	-0.07	-0.03	0.03	0.01
a3				0.89
a4				0.64
a5				0.46
a6	-0.26	-1.27	0.03	0.33
a7				0.21
a8				0.16
a9				0.08
a10	-0.03	-0.06	0.10	0.06
a11				0.03
a12				0.02
a13				0.01
a14	0.01	-0.05	0.00	0.01

Content

Tuning of the multipoles through mid-plane shims



- Each layer has a individual 0.1 mm thick shim to tune the multipoles.
- Adding shims produce negative multipoles
- Removing shims produce positive multipoles

	geometric	uncertainty	random	tunning range
b6	0.42	+/-1.01	1.28	+/- 5.2
b10	-0.23	+/-0.16	0.06	+/- 0.65
b14	-0.07	+/-0.03	0.01	+/- 0.15

- Multipoles largest expected values are in the compensation range

Summary

- We performed a scan of all possible cross-section providing a good field quality by means of pure sector coil blocks based model allowing fast computation.
- We found out a set of cross-sections providing both high gradient and low current and we studied them considering real cables.
- The MQXC cross-section has been chosen according the amount of cables used and the mechanical feasibility of the coil.
- We studied the saturation effect of the yoke.
- We studied the layer jump and the splice effect on the field quality.
- We optimized the NCS coil head so as to reduce the peak field in the head and to minimize the multipoles.
- We studied the uncertainty and random field errors.
- We showed that the expected b_6, b_{10} and b_{14} field errors can be compensated by means of 0.1 mm shims.

- **Future works**: Design of the coil end connection side and study of coil cross-sections with the top pole angle of the inner and outer layer of the same order.