Susana Izquierdo Bermudez for the QXF team

# Magnetic design

Acknowledgements: G. Ambrosio, P. Ferracin, P. Hagen, M. Juchno,
G. L. Sabbi, E. Todesco, X. Wang

# Contents



LARP

# Introduction

## Magnetic design and field quality targets

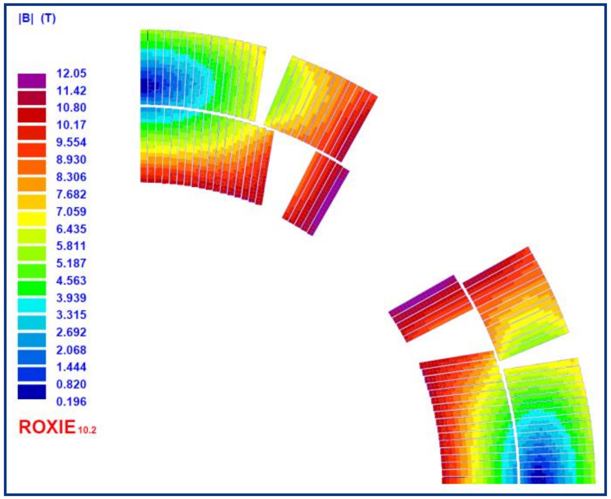
(from E. Todesco talk):

- Large difference between injection and top energy
  - At injection the triplet is nearly transparent to the beam → loose requirements of ~ 10 units
  - At top energy the LHC becomes the triplet → tight requirements of ~ 1 units

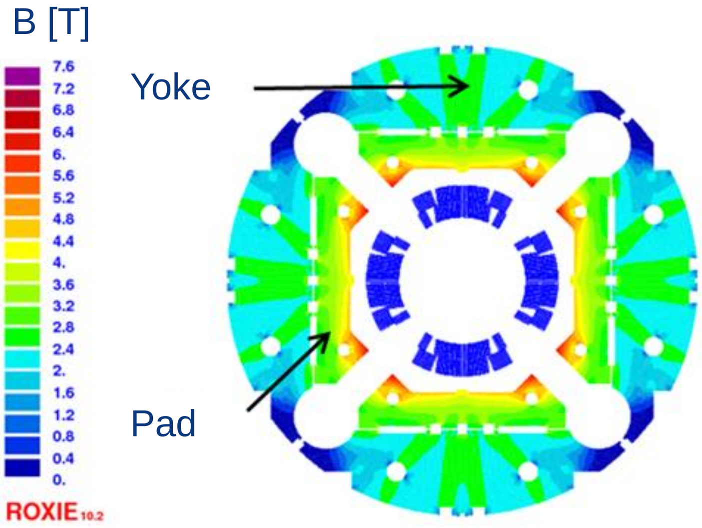
- Consequences on magnet design
  - Large tolerance on persistent currents (~20 units)
  - Tight control of saturation
  - The most critical components are random ($b_3$, $a_3$, $b_4$, $a_4$) associated to the coil asymmetry

# Magnet parameters

| Parameters | | Units |
|---|---|---|
| Operational temperature | 1.9 | K |
| Clear aperture diameter | 150 | mm |
| Nominal gradient | 140 | T/m |
| Nominal current | 17.46 | kA |
| Nominal peak field on the coil | 12.1 | T |
| Stored energy at $I_{nom}$ | 1.32 | MJ/m |
| Temperature margin | 4.5 | K |
| Differential inductance at $I_{nom}$ | 8.22 | mH/m |
| Superconductor current density ($j_{sc}$) | 1635 | A/mm$^2$ |
| Engineering current density ($j_{eng}$) | 770 | A/mm$^2$ |
| Overall current density at ($j_{overall}$) | 490 | A/mm$^2$ |
| Forces x | 2.64 | MN/m |
| Forces y | -3.88 | MN/m |

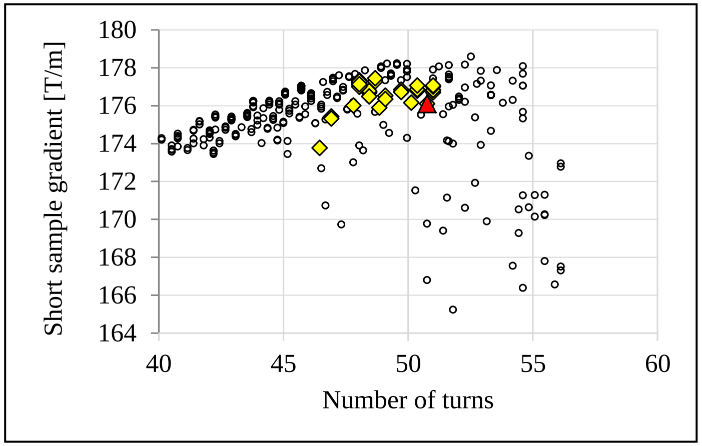


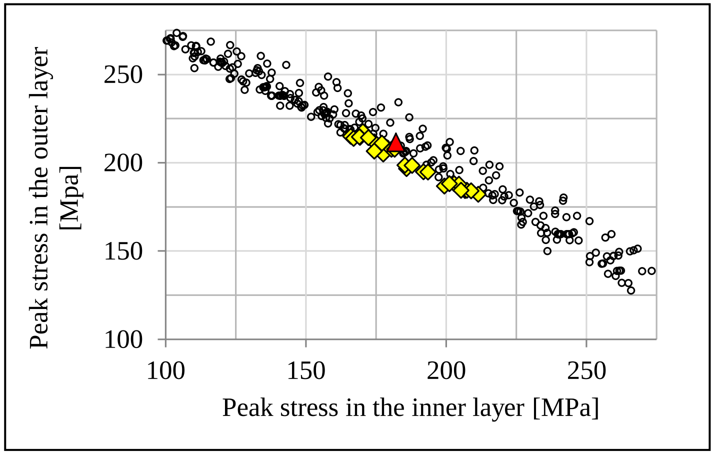

The magnetic structure is made out of two parts, the “pad” and the “yoke”. Details will be addressed [M. Juchno].



# Coil Cross Section

- Criteria for the selection
  - Maximize gradient and # of turns (protection)
  - Distribute e.m. forces and minimize stress




[F. Borgnolutti]
*Magnetic design optimization of a 150 mm aperture Nb3Sn low-beta quadrupole for the HiLumi LHC.*
*IEEE Trans. Appl. Sup.*, vol. 24, no. 3, 2014.

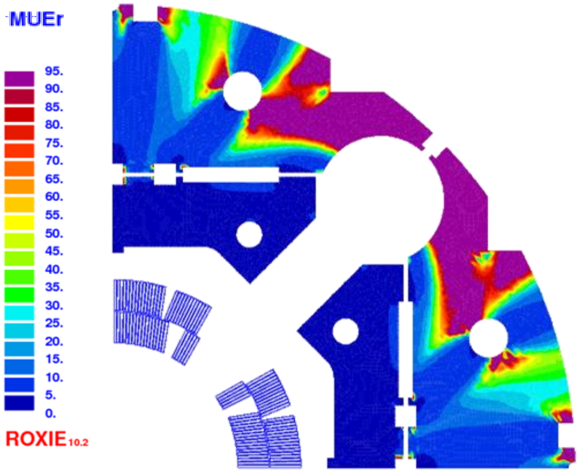
- All harmonics below 1 units at $R_{ref}$ = 50 mm
- Field harmonics computed assuming the conductor is aligned in the outer diameter.

| Units at $R_{ref}$ = 50 mm | *Conductors aligned in the winding mandrel* | *Conductors aligned in the outer diameter* |
|---|---|---|
| **b6** | -1.13 | 0.32 |
| **b10** | -0.98 | -0.40 |
| **b14** | -0.65 | -0.67 |
| **b18** | -0.26 | -0.28 |

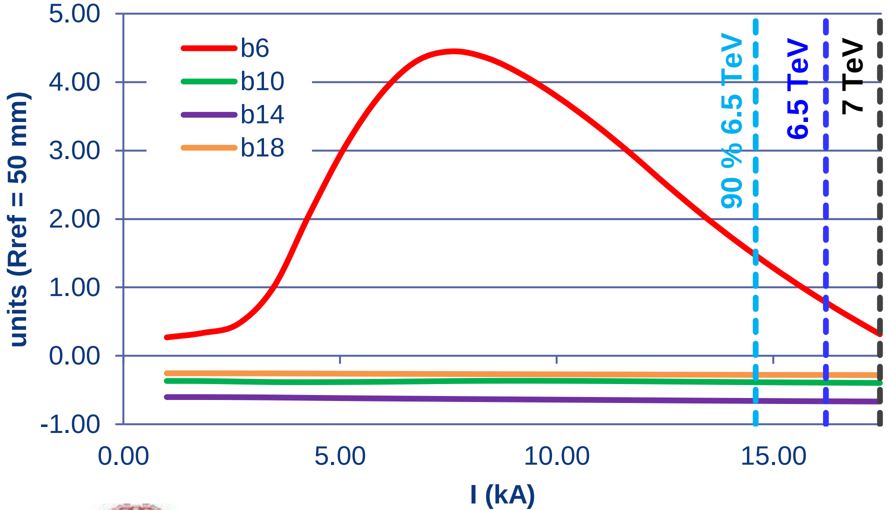
CERN LARP

# Iron saturation

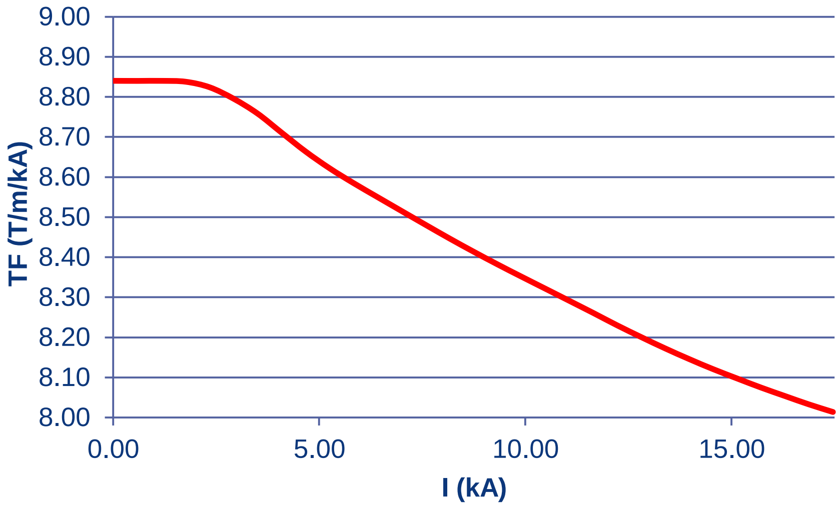
- Important impact of the iron saturation in the transfer function and $b_6$
- All field quality optimized at top field (7 TeV)
- Going to 6.5 TeV we add a fraction of unit of b6
- Having 10% less on the top of this (ABP request) would give a 1 systematic unit of b6
- Optimization at 6.5 TeV instead of 7 TeV new guideline (November 14)




Allowed harmonics
(Only geometric + Iron saturation effects)



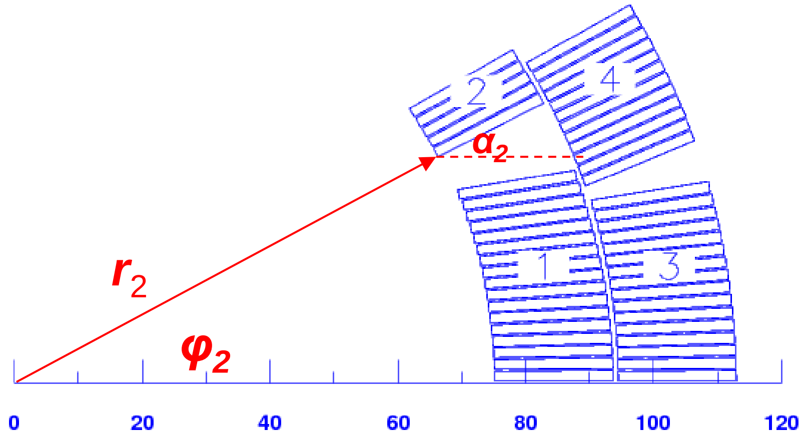

Transfer function
(Only geometric + Iron saturation effects)

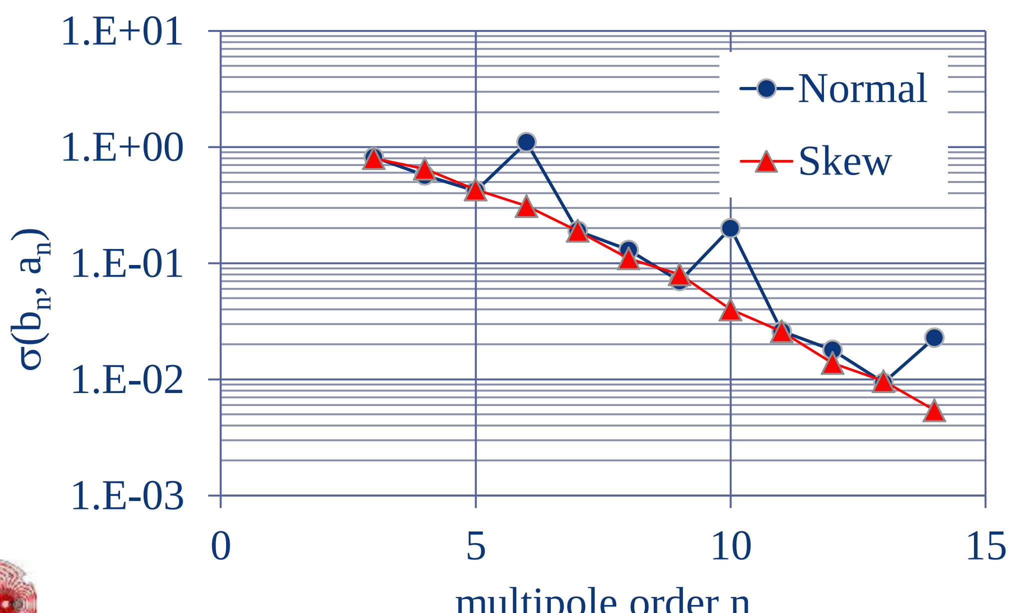



CERN LARP

# Manufacturing tolerances

- 30 µm tolerances on blocks position
- The amplitude of the allowed multipoles have been increased based on the experience from LHC.




| RANDOM COMPONET | | |
|---|---|---|
| Order | Normal | Skew |
| 3 | 0.82 | 0.80 |
| 4 | 0.57 | 0.65 |
| 5 | 0.42 | 0.43 |
| 6 | 1.10 | 0.31 |
| 7 | 0.19 | 0.19 |
| 8 | 0.13 | 0.11 |
| 9 | 0.07 | 0.08 |

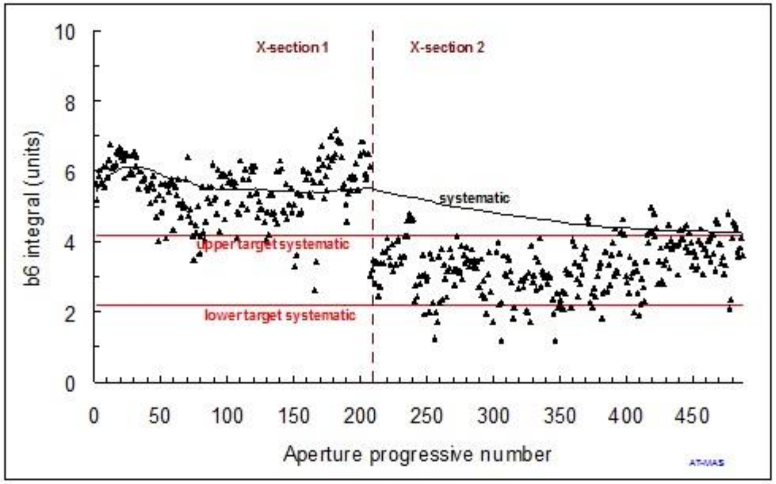
CERN LARP

# Magnetic shimming

**Two main aspects to worry about:**

- Having a 1 units tolerance on $b_6$, one could need one fine tuning after the construction of the first models - possibility of changing $b_6$ by 3 units is requested - this can be done through **coil shimming.**

  **But**, we have a small production, so the change should be made at a very early stage, and once only.



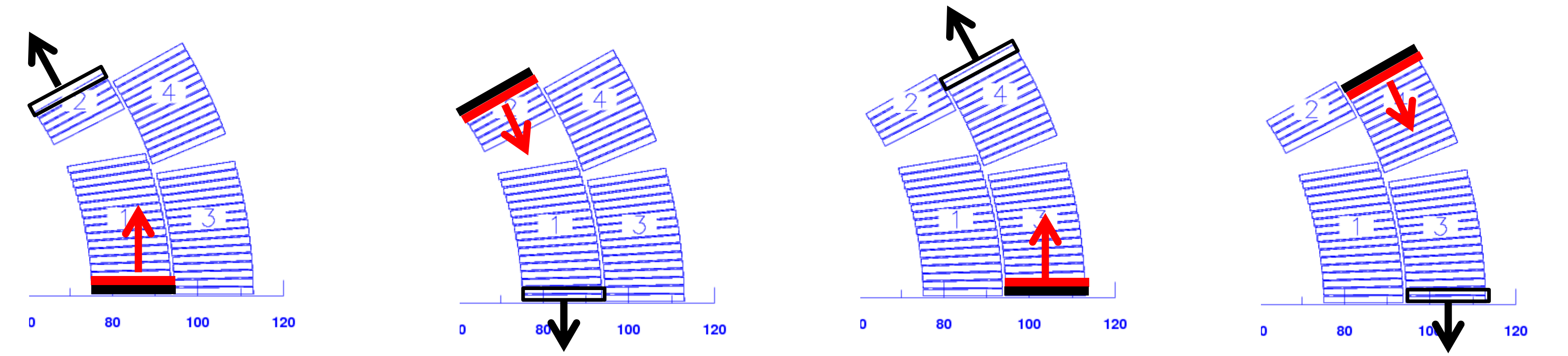

*Intervention on the Main Quadrupoles cross section during LHC production*

- The size of non allowed multipoles ($a_3$, $b_3$, $a_4$, $b_4$)
  - This parameter is difficult to estimate. (you need an homogeneous set of few magnets)
  - First data HQ shows we are a factor two-three off
    - Similar results on the first MQXC Nb-Ti magnet (no it is not specific to Nb3Sn technology)
    - Good result considering we are on a short model, first iteration
  - **Plan B: passive shimming with ferromagnetic material**

LARP

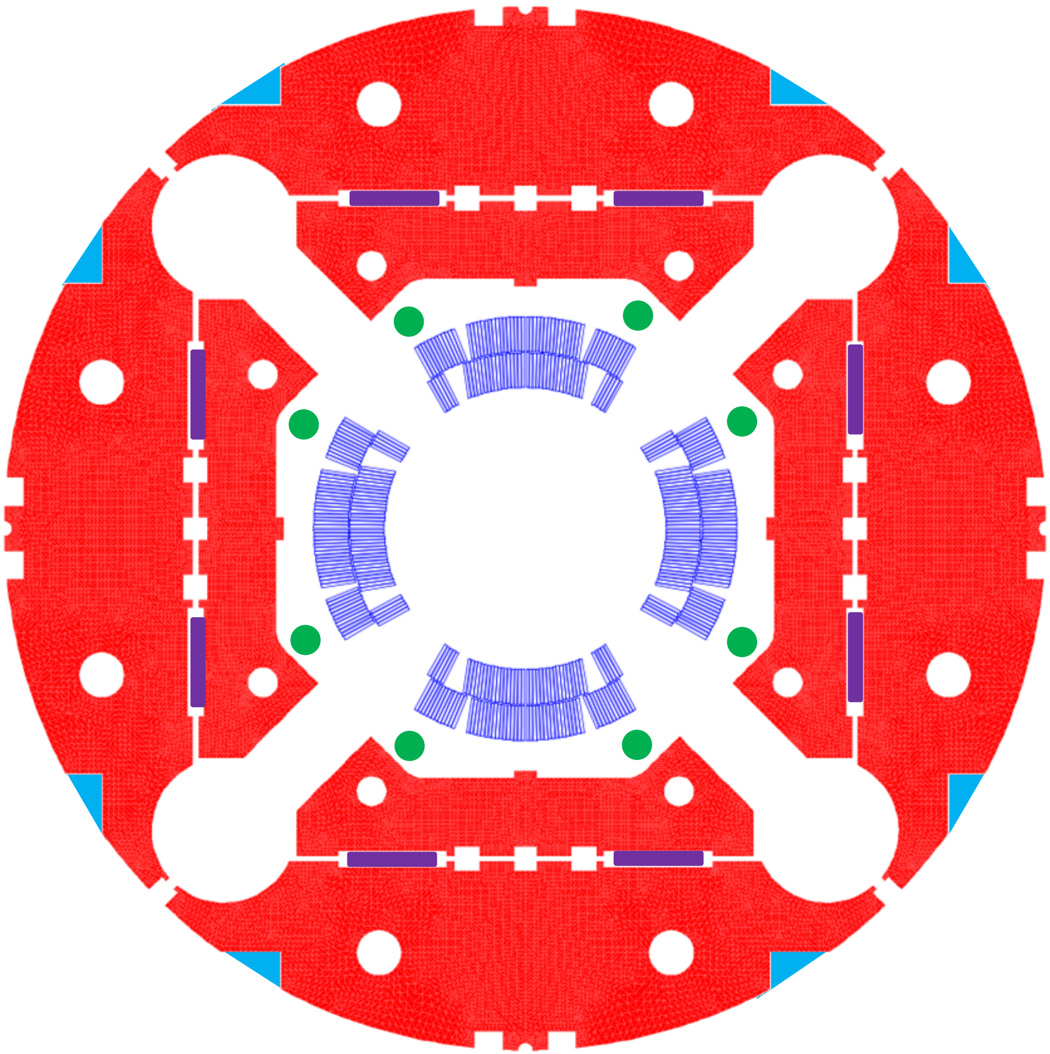
# Coil shimming

- Possibility of changing $b_6$ by 3 units is requested.
- Using a 100 µm shim, we can correct up to 4 units without impact on the coil compaction.
- The impact on $b_{10}$ is less than 1 unit.




| +100 µm Mid plane IL<br>-100 µm Pole IL | +100 µm Pole IL<br>-100 µm Mid plane IL | +100 µm Mid plane OL<br>-100 µm Pole OL | +100 µm Pole OL<br>-100 µm Mid plane OL |
| --- | --- | --- | --- |
| $\Delta b_6 = -3.4$ | $\Delta b_6 = 3.1$ | $\Delta b_6 = -1.0$ | $\Delta b_6 = 1.1$ |

# Ferromagnetic shims



In order to correct the non allowed multipoles ($a_3$, $b_3$, $a_4$, $b_4$) three families of shims have been explored:

- **Rods in the collars**. Not interesting because the iron strongly saturates, they are transparent.
- **Shims in the bladder slots**, very interesting.
- **Shims in the yoke slots.** They are too far from the coil to act.

[P. Hagen]

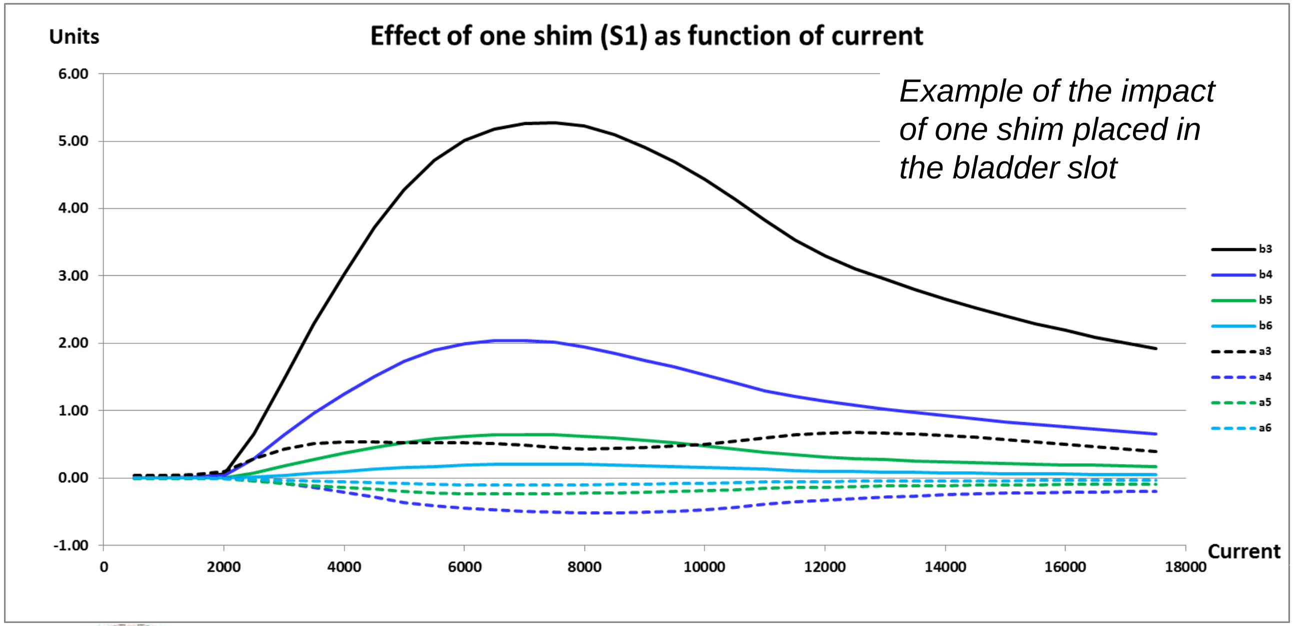
# Ferromagnetic shims

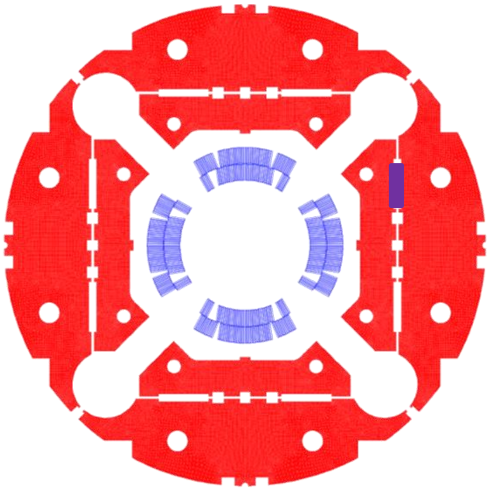
Different shim configuration in the bladders slots allow us to correct up to

- ±5 units of $b_3$ and $a_3$
- ±3 units of $b_4$
- ±1 units of $a_4$

Fine tuning is possible:

- Changing the size of the shim
- Varying the permeability of the shims along the Z-axis



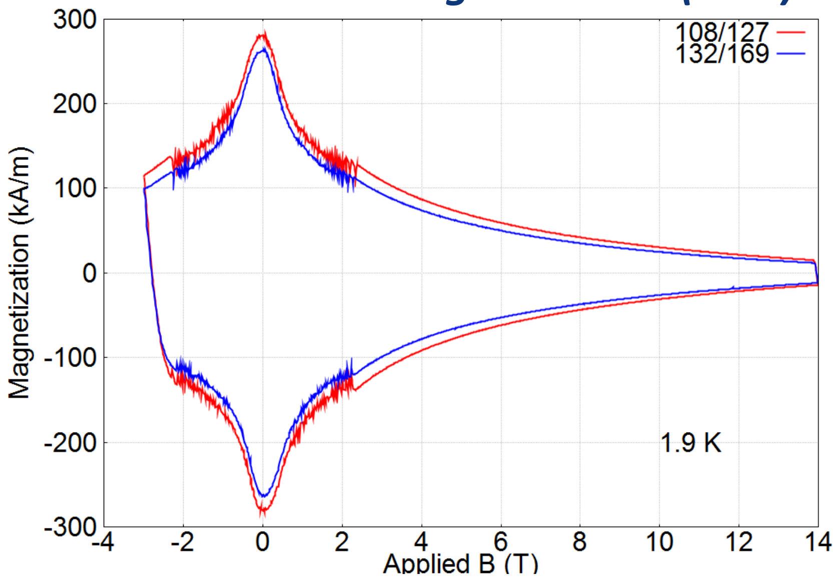



[P. Hagen]

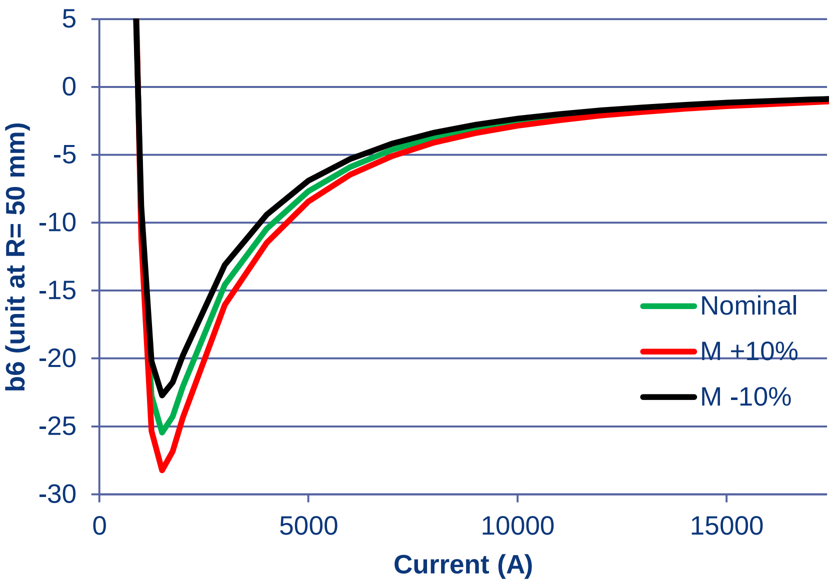
# Persistent Currents

- Estimates using magnetization measurements of actual QXF 169 wires performed at Ohio State University
- Harmonics are provided for second up-ramp following a pre-cycle corresponding to the one used for strand measurements

***Measured magnetization (OSU)***




***Calculated $b_6$ (after pre-cycle)***




[X. Wang]

# Persistent Currents

| Persistent current harmonics | $b_6$ | | $b_{10}$ | |
|---|---|---|---|---|
| | **Nominal** | **D(+20%M)** | **Nominal** | **D(+20%M)** |
| **1.0 kA (injection)** | **-10.0** | **-2.4** | **3.4** | **+0.8** |
| **17.5 kA (high field)** | **-0.97** | **-0.12** | **-0.1** | **0.0** |

- Effect of ±20% magnetization on $b_6$, $b_{10}$ included
  - Nominal $b_6$ value of -10 units can be adjusted using current reset level during pre-cycle
  - Dynamic aperture simulations accept $b_6$ up to 20 units at injection

- **Present value of magnetization average and spread are compatible with field quality requirements**

- For future study: assessment of the variability in wire magnetization and resulting uncertainty

[X. Wang]

LARP

# Eddy Currents

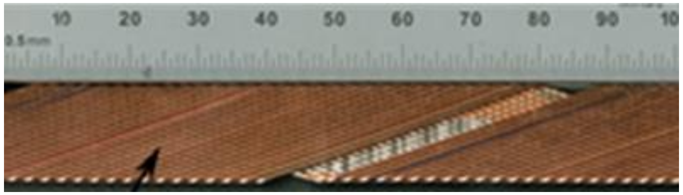
**Stainless Steel Core to control the cross-over resistance $R_c$**

**Pros:**
- Suppression of ramp-rate dependence of field quality
- Increased reproducibility

**Cons:**
- Less quench back for protection
- Stability (current sharing among layers)

Two options to choose initial value for SQXF01:
- scaling from HQ (~60% coverage, giving ~10 mm width) or
- scaling from 11 T (~80% coverage, giving ~14 mm width)

**Choice:** 12 mm x 0.025 mm **(~70 % coverage)**



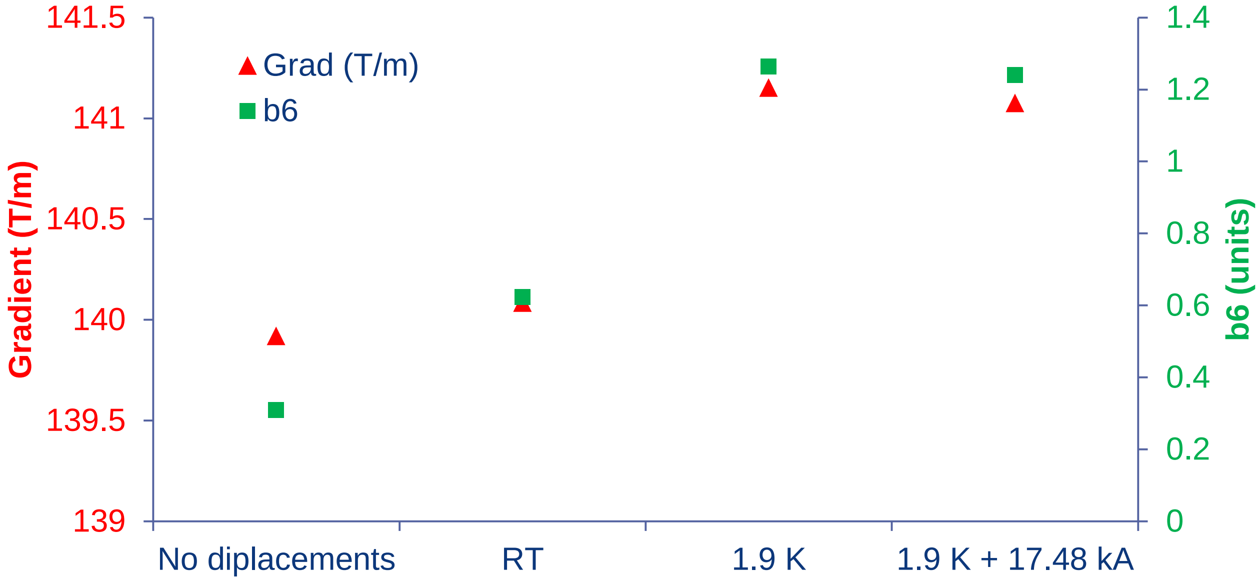
*HQ experience*
*(HQ01e: no core/HQ02a: 60 % cov.)*

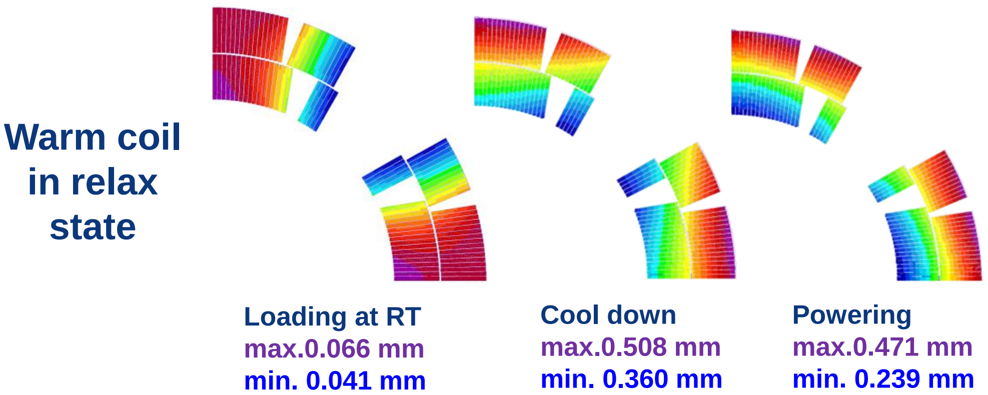
| Harmonics | HQ01e | HQ02a | Reduction (%) |
|---|---|---|---|
| $b_2$ | 14.60 | 0.85 | 94 |
| $b_3$ | 1.56 | -0.12 | 92 |
| $b_4$ | 0.43 | 0.04 | 90 |
| $b_5$ | 0.21 | 0.00 | 98 |
| $b_6$ | 2.09 | 0.10 | 95 |
| $a_3$ | 4.73 | 0.44 | 91 |
| $a_4$ | 0.18 | -0.14 | 25 |
| $a_5$ | 0.52 | 0.12 | 77 |
| $a_6$ | -0.26 | -0.04 | 84 |

[G. L. Sabbi]

# Coil deformation during powering

- Cross section is optimized for the warm coil in relax state, assuming the conductors are aligned in the outer diameter.
- In operation conditions, we expect 0.7 % more gradient and +0.93 units of $b_6$.
- Most of the contribution is coming from cool down: **the variation of the field quality during powering due to electromagnetic forces is negligible.**



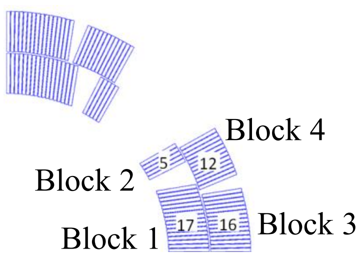

**Displacements relative to coil in relax (warm) state**

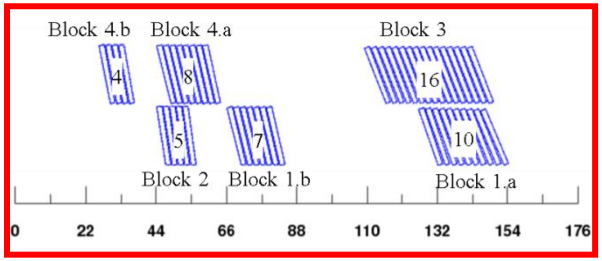
[M. Juchno]

# 3D: Field in the coil

**3D magnetic optimization to reduce the peak field enhancement at the ends:**

1. Conductors placing at the ends

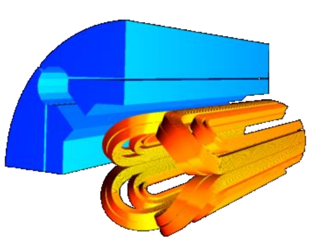



**Design solution**: 6 blocks in the ends

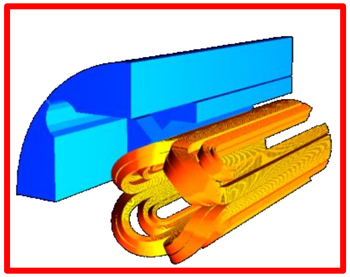
- Peak field enhancement in the outer layer is reduced by 0.3 T by splitting block 4 in 2
- Block 1 is divided to minimize the integrated harmonics

2. Reduction of the magnetic extension of the yoke



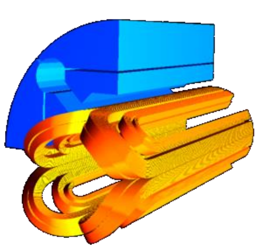
$\Delta B_p$ = 0.3 T

$\Delta l_{mag}$ = 0 mm



$\Delta B_p$ = -0.1 T

$\Delta l_{mag}$ = -18 mm



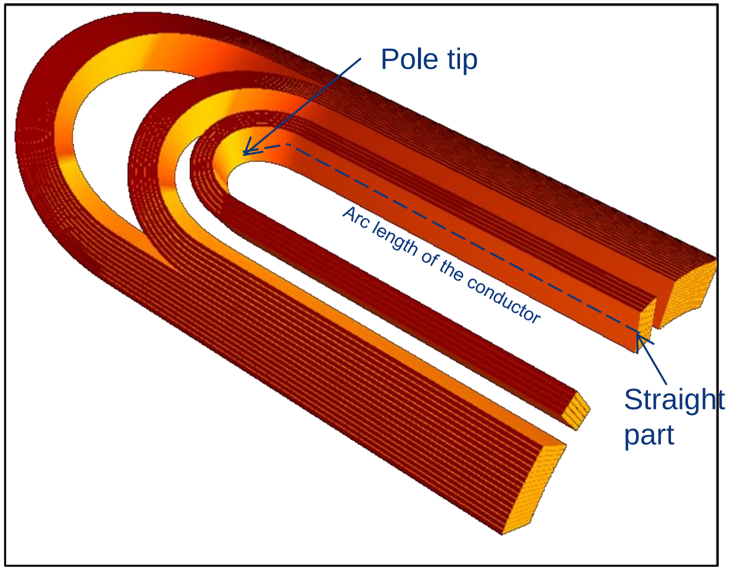
$\Delta B_p$ = -0.3 T

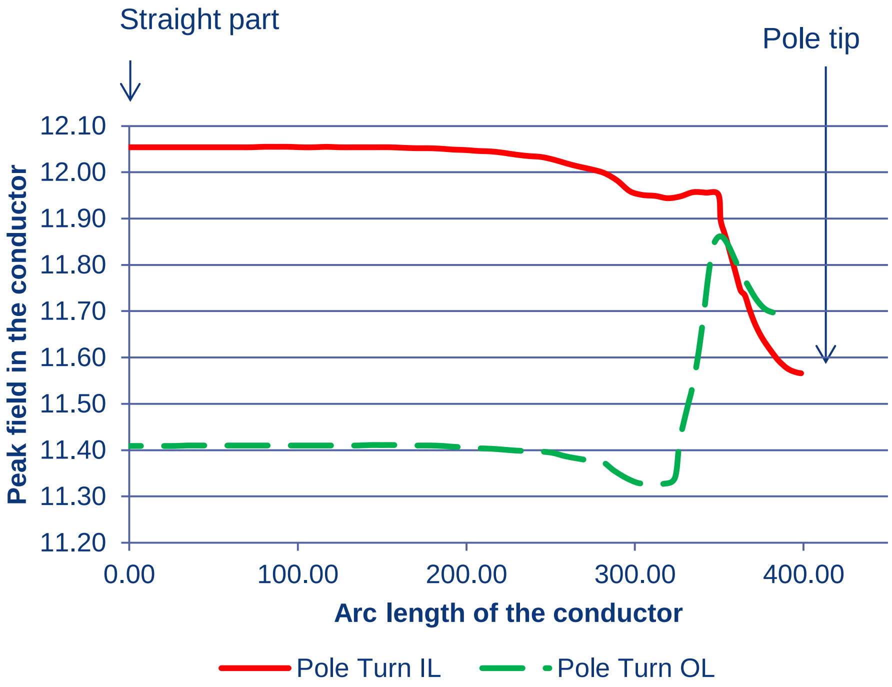
$\Delta l_{mag}$ = -23 mm

**Design solution**: Only magnetic pad is shortened

- Peak field in the ends is lower than in the straight section
- Compared to the solution with yoke and pad shortened :
  - More uniform stress distribution in the coil
  - Lower reduction on the magnetic length
- HQ design

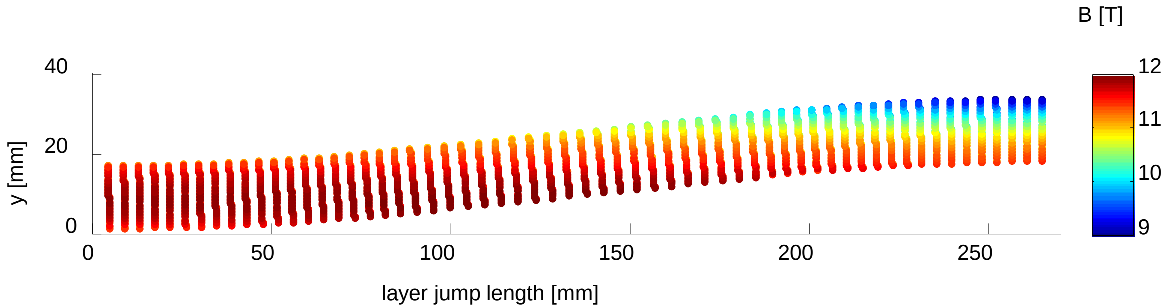
# 3D: Field in the coil



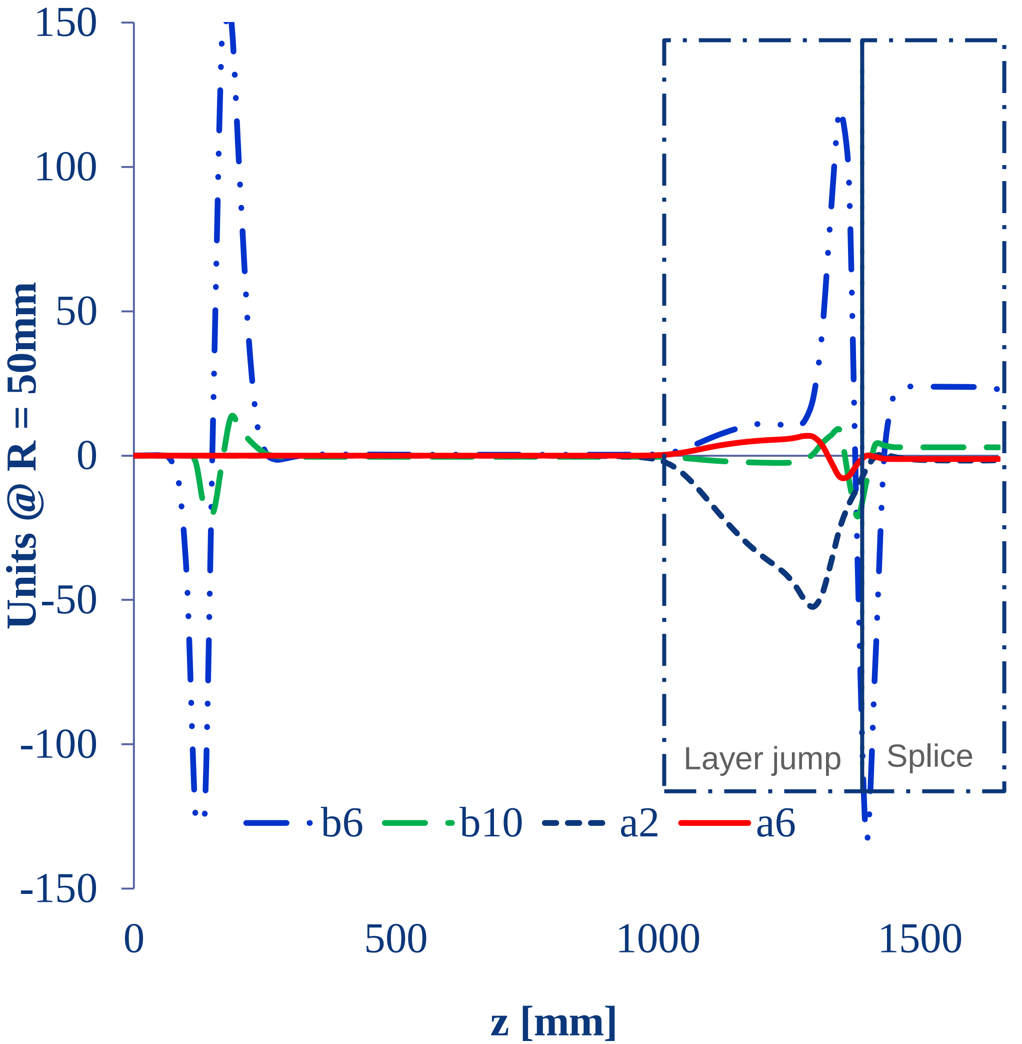

**Layer jump**

- Dimensions defined by scaling the hard way bending radius in HQ with the cable width.
- The field in the layer jump is lower than in the straight section




*The overall layer jump length is 270 mm and the bending radius is 800 mm.*

# 3D: effects on field quality




## Integrated field harmonics

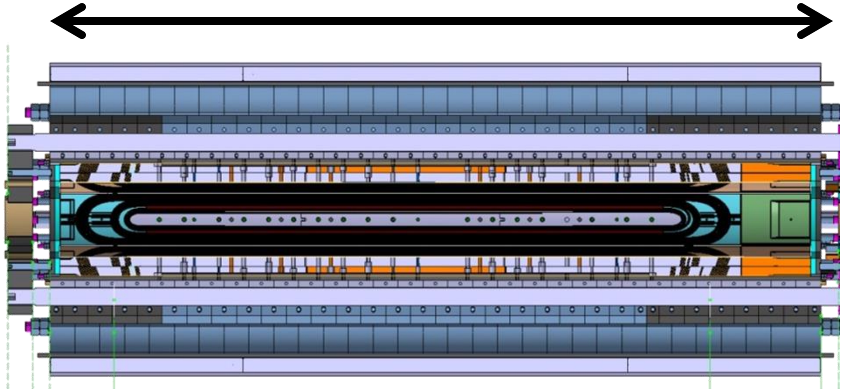
$$\overline{b_n} = \frac{\int B_n(I,z)dz}{B_2^{\infty} l_{mag}(I)}$$

main field in the straight section

**Integral over the magnet yoke extension:**

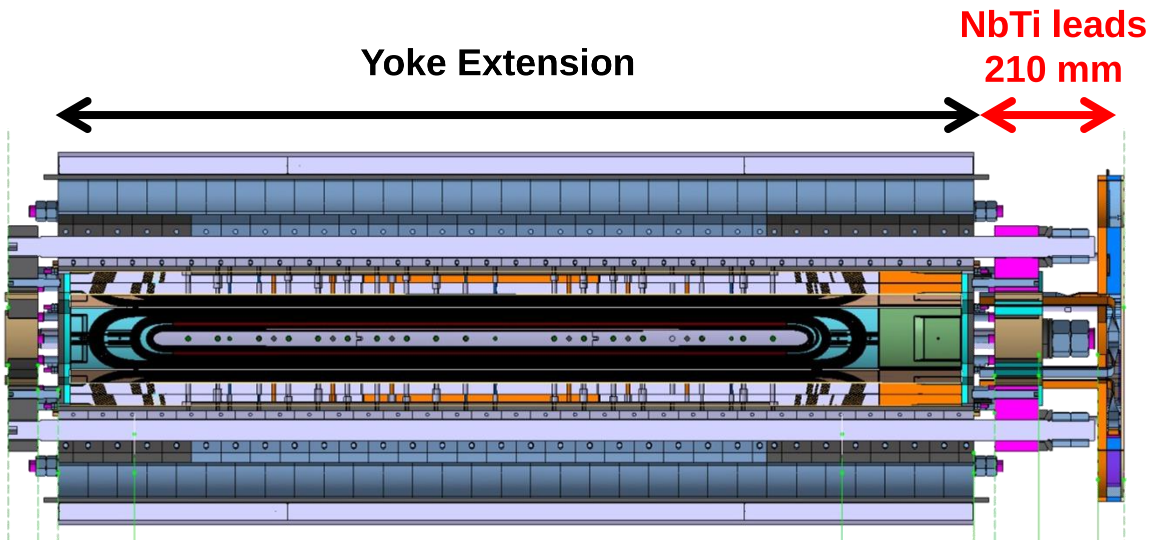
| | b6 | b10 | b14 | a2 | a6 |
|---|---|---|---|---|---|
| 2D | 0.32 | -0.40 | -0.66 | 0.00 | 0.00 |
| 3D-SQXF | 8.06 | -0.54 | -0.70 | -8.90 | 0.60 |
| 3D-LQXF – 4 m | 2.65 | -0.44 | -0.67 | -2.67 | 0.18 |
| 3D-LQXF – 6.8 m | 1.69 | -0.42 | -0.67 | -1.57 | 0.10 |

**Yoke Extension**



# 3D: effects on field quality

**The contribution of the NbTi leads should be also taken into account:**



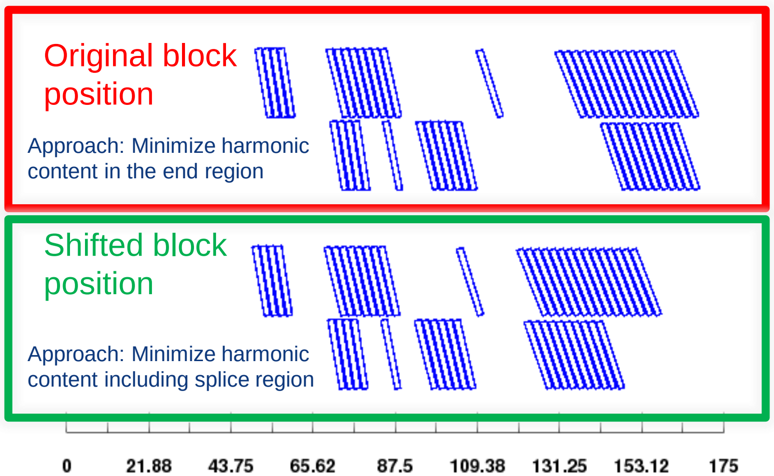

**NbTi leads contribution:**

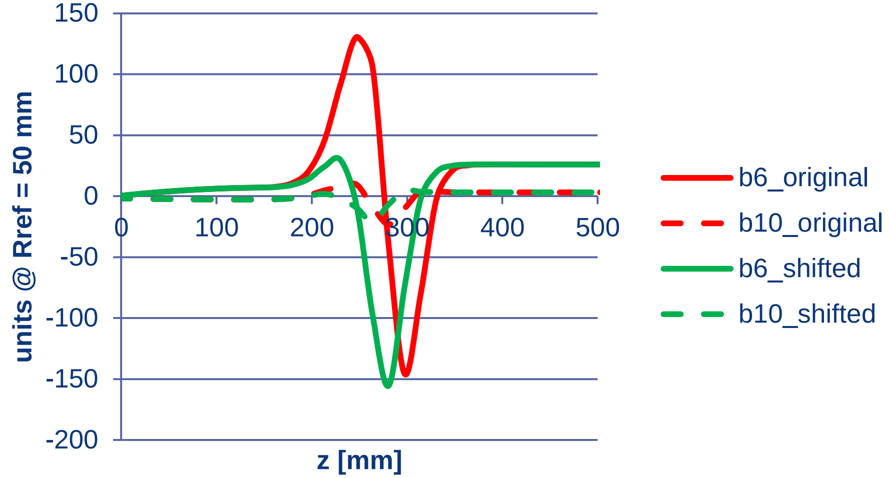
| | Δb6 |
|---|---|
| 3D-SQXF | 4.13 |
| 3D-LQXF – 4 m | 1.23 |
| 3D-LQXF – 6.8 m | 0.73 |

- Plans for the next iteration:
  - Minimize the length of the splice region and NbTi leads extension
    - Nuts on the axial tie rods will be shifted from lead end to the return end
  - Partial compensation optimizing the block position in the lead end
  - Partial compensation in the straight section

# 3D: effects on field quality

- Partial compensation of the splice and leads contribution by optimizing the block position in the lead end:



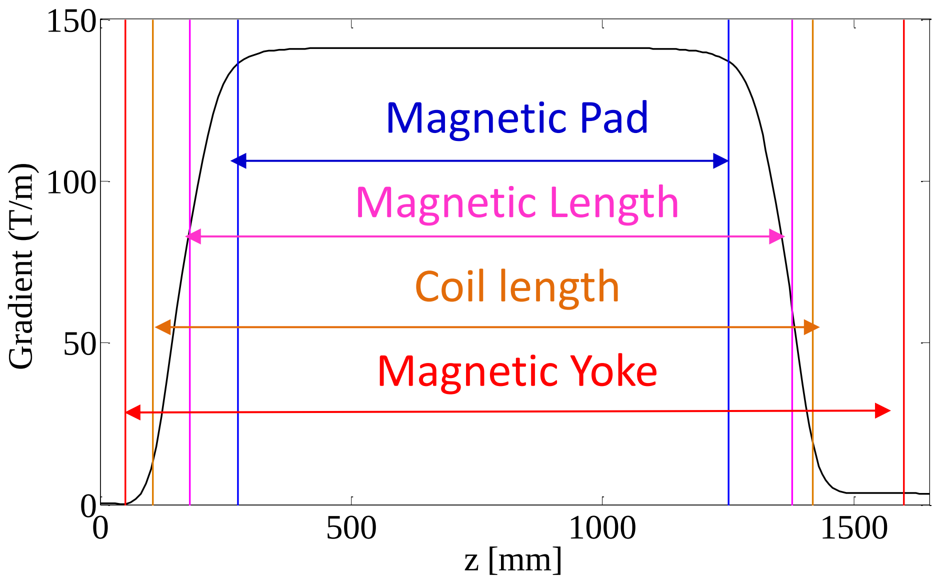



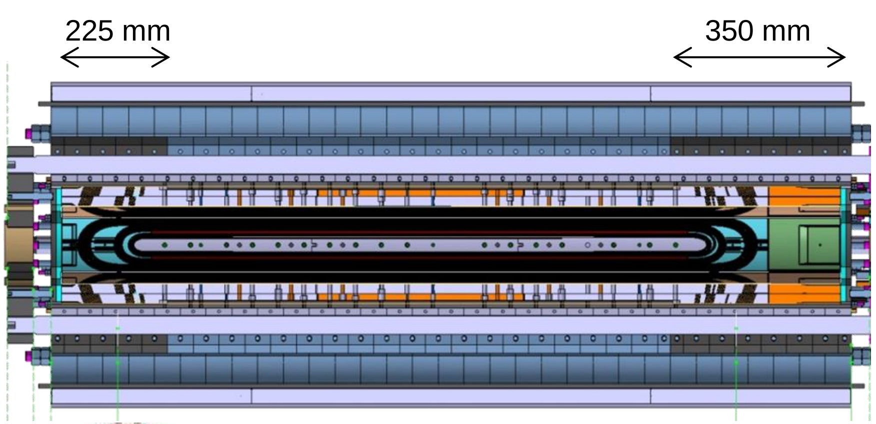

| | b6 original | b6 shifted |
|---|---|---|
| 2D | 0.32 | |
| 3D-LQXF – 4 m | 3.9 | 2.3 |
| 3D-LQXF – 6.8 m | 2.4 | 1.5 |

***Remark: One half of the integrated $b_6$ is coming from the 210 mm NbTi leads***

- The rest, will be compensated with the magnet cross section

# Magnetic and Physical Lengths




- Gradient = 140 T/m at RT
- Magnetic Length at 1.9K :

*(assuming longitudinal thermal contraction = 3 mm/m )*

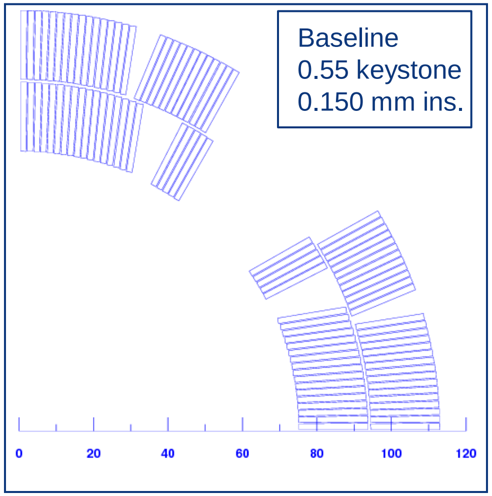
  - LQXF CERN = 6.8 m
  - LQXF LARP = 4.0 m

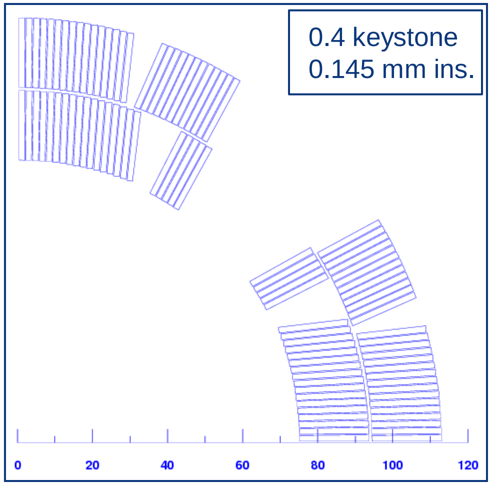
| Parameters | Units | SQXF | LQXF LARP | LQXF CERN |
|---|---|---|---|---|
| Magnetic length at RT | mm | 1198 | 4012 | 6820.5 |
| Magnetic length at 1.9 K | mm | 1194.4 | 4000 | 6800 |
| Coil length at RT (from conductor to conductor) | mm | 1313 | 4127 | 6935.5 |
| Overall coil length at RT (including splice extension) | mm | 1510 | 4324 | 7132.5 |
| Magnetic yoke extension at RT | mm | 1550 | 4364 | 7172.5 |
| Magnetic pad extension at RT | mm | 975 | 3789 | 6597.5 |

CERN LARP

# Possible "New" Coil Cross Section

- For PIT, reduction of keystone angle from 0.55 to 0.4 deg., with same cable mid-thickness, under consideration
  - Thin/thick edge 0.025 mm thicker/thinner
  - Cross-section as close as possible to baseline
    - Still, new wedges, poles and spacers
      - 8-9 months from cable geometry definition to beginning of winding



# Summary

- Magnet parameters have been selected taking into account many years of magnet R&D in the US and at CERN.
- Coil cross section is a scale up of HQ, keeping the same coil lay out (4-blocks, 2-layer with same angle) and similar cable width/aperture.
- Present value of magnetization average and spread are compatible with field quality requirements.
- Based on HQ experience, stainless steel core covering ~ 70 % of the cable width will reduce the eddy current effects to acceptable limits.
- 100 μm provide the flexibility to correct up to +- 4 units of $b_6$ without an impact on the coil compaction. This is enough to account for 3D effects and impact of coil deformation during powering.
- Ferromagnetic shims to be placed in the bladder slots provide enough flexibility to correct the low order non allowed multipoles.
- The option of reducing the keystone angle from 0.55 to 0.4 deg., with same cable mid-thickness has been explored. The resulting cross section is close to the present design but still, new wedges, poles and spacers are needed.

CERN LARP

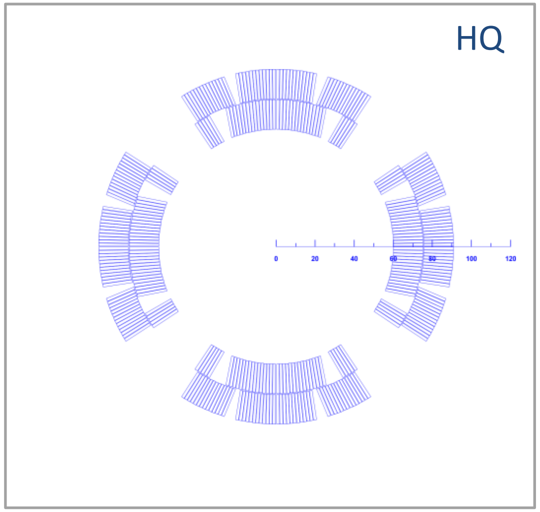
# Additional slides

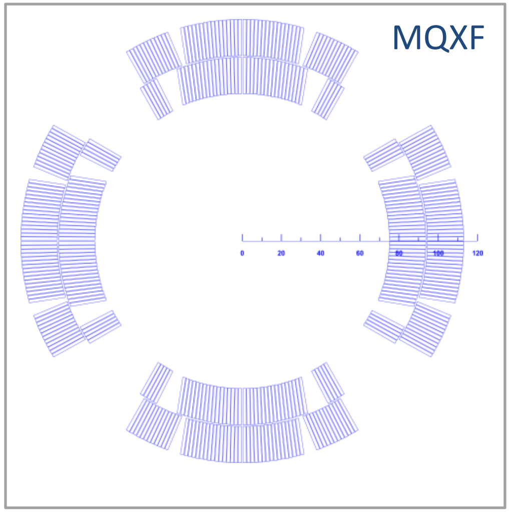
# Coil Cross Section

- The cable width/aperture (w/r) is approximately maintained
  - Aperture from 120 mm to 150 mm
  - Cable from 15 to 18 mm width
  - Similar stress with +30% forces
- Same coil lay-out: 4-blocks, 2-layer with same angle
  - Optimized stress distribution
- Similar peak field → Lower $J_{overall}$

$$B_p = r \cdot G = r \cdot j \cdot \log(1 + w/r)$$

  - Positive side effect for quench protection (from **580 to 490 A/mm²**)



# Mechanical Optimization of the ends

WP3 meeting
Review End Parts Design

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | | | | | | | | | | | 2014 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| October | | | November | | | | December | | | | January | | | | | February | | | | March | | | | April | | | | | May | | | | June | | | | | July | | | | Aug | |
| 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |
| | SPC1 | | | | | | | | | | | | | SPC2 | | | | | Preparation | | | | SQXF1IL | | | | | OL | | | | | SQXF2 | | | | | | | | | SQXF3 | |

**V1**
**SPC1 IL**
Cu
Oct-2014

**V2**
**SPC1 OL**
Cu
Oct-2014

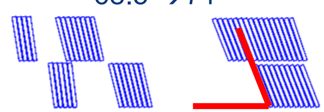
**V3**
**SPC2** and SQXF1
Cu
Jan 2014 April 2014

**V4** (delayed ~ 1 month)
**SQXF2**
Bad Nb3Sn
June 2014

**V5**
**SQXF3**
Nb3Sn
End July 2014

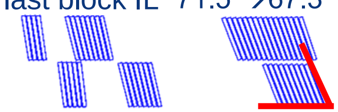
- Increase de Harmonic Order of the baseline ellipse (more roundish)
- Pole converged to BEND design

- Change angle last block IL 68.5°→71°



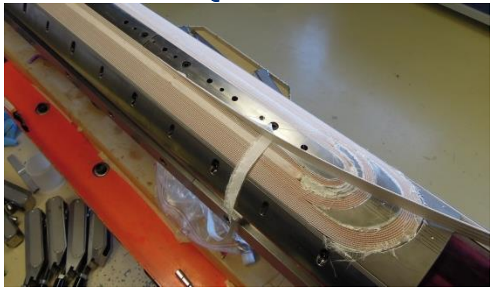
Minor changes:
- Radius on the edges
- Flexible features

- Modify spacing among cables last block IL 71.5°→67.3°



Shorter coils with plastic end spacers to optimize ends

SQXF coils



# Field quality

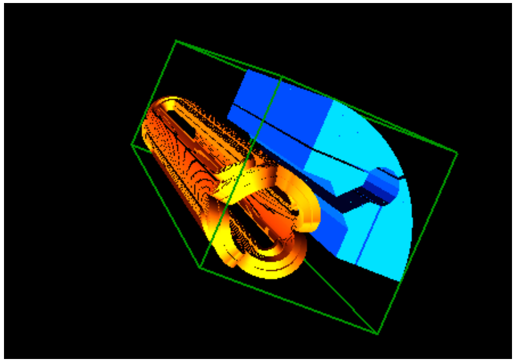
**Field quality in low- superconducting quadrupoles and impact on the beam dynamics for the Large Hadron Collider upgrade**

Boris Bellesia, Jean-Pierre Koutchouk, and Ezio Todesco

TABLE II. Standard deviation of measured multipoles in RHIC and LHC quadrupoles, reference radius taken as 2/3 of aperture.

| | Ap (mm) | T (K) | Measured | $b_3$ | $b_4$ | $b_5$ | $b_6$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RHIC MQ | 80 | 300 | 380 | 1.69 | 1.02 | 0.54 | 0.48 | 1.75 | 1.02 | 0.53 | 0.33 |
| RHIC MQ | 80 | 4.2 | 91 | 1.86 | 1.50 | 1.74 | 0.70 | 1.77 | 0.97 | 1.55 | 0.35 |
| RHIC Q1 | 130 | 4.2 | 26 | 0.52 | 0.56 | 0.34 | 0.88 | 0.66 | 0.32 | 0.40 | 0.18 |
| RHIC Q2 | 130 | 4.2 | 27 | 0.50 | 0.24 | 0.30 | 0.57 | 0.60 | 0.28 | 0.39 | 0.40 |
| RHIC Q3 | 130 | 4.2 | 13 | 0.86 | 0.65 | 0.32 | 0.19 | 0.69 | 0.42 | 0.21 | 0.10 |
| LHC MQ | 56 | 300 | 402 | 1.81 | 0.42 | 0.70 | 1.36 | 2.22 | 2.29 | 0.73 | 0.48 |
| LHC MQ | 56 | 1.9 | 39 | 1.65 | 0.38 | 0.61 | 1.82 | 2.05 | 1.80 | 0.71 | 0.45 |
| LHC MQM | 56 | 300 | 46 | 1.83 | 0.97 | 0.65 | 1.01 | 2.07 | 1.13 | 0.57 | 0.35 |
| LHC MQMC | 56 | 300 | 14 | 1.39 | 0.58 | 0.63 | 1.09 | 1.63 | 1.14 | 0.63 | 0.40 |
| LHC MQML | 56 | 300 | 38 | 1.64 | 0.57 | 0.64 | 0.88 | 1.63 | 0.99 | 0.42 | 0.29 |
| LHC MQY | 70 | 4.2 | 11 | 1.39 | 0.49 | 0.39 | 0.58 | 1.28 | 0.80 | 0.57 | 0.24 |
| LHC MQXA | 70 | 1.9 | 19 | 0.60 | 0.28 | 0.13 | 0.42 | 0.75 | 0.70 | 0.15 | 0.11 |
| LHC MQXB | 70 | 1.9 | 8 | 0.73 | 0.24 | 0.42 | 1.03 | 1.08 | 0.92 | 0.33 | 0.70 |

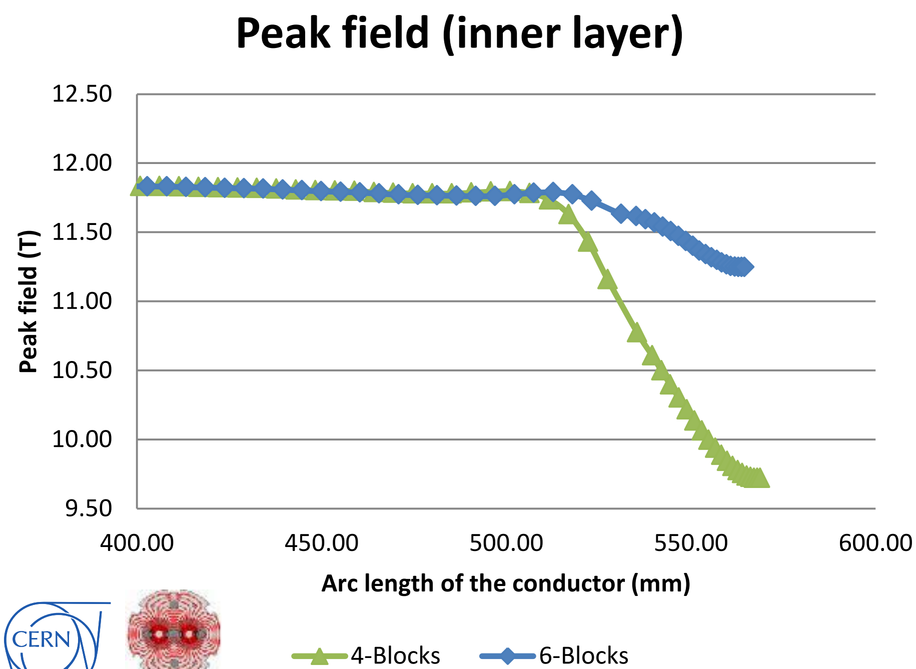
# Impact of block subdivision in peak field

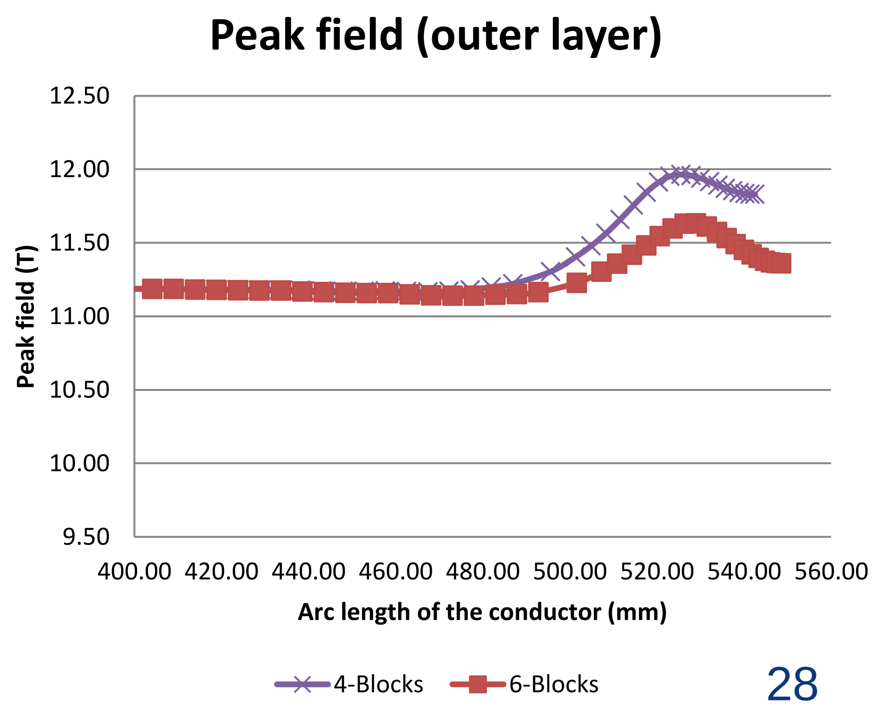


**Remark**: analysis done in MQXF_V0 cross section, strand self field not included

Configuration
- Magnetic yoke z = [0-700] mm
- Magnetic pad z = [0-500] mm
- Non-magnetic pad z = [500-700] mm

| | | INNER LAYER | | | OUTER LAYER | | |
|---|---|---|---|---|---|---|---|
| | | Block 1A | Block 1B | Block 2 | Block 3 | Block 4A | Block 4B |
| 3D peak field | 4 Blocks | 10.43 | | 11.85 | 8.53 | **11.96** | |
| | 6 Blocks | 9.70 | 10.43 | **11.85** | 7.34 | 9.98 | 11.63 |
| 2D peak field | | 10.41 | | **11.82** | 6.78 | 11.17 | |




CERN LARP

# Magnet lengths