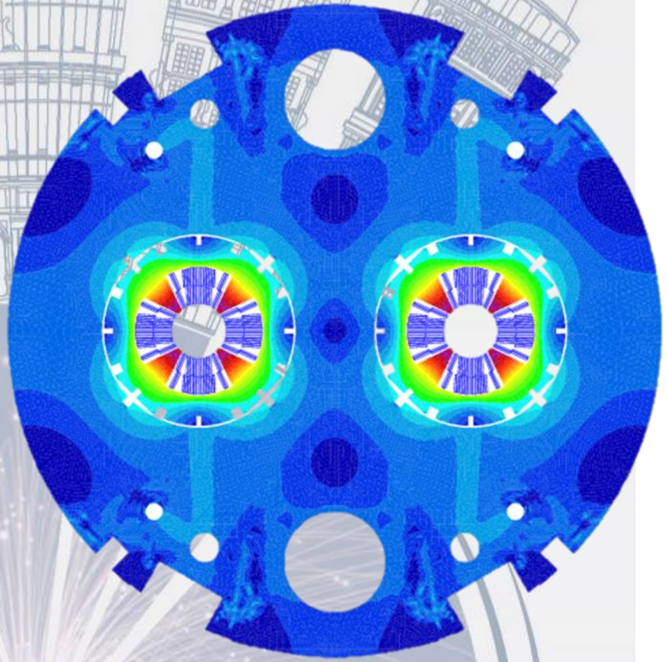
27 june 2019

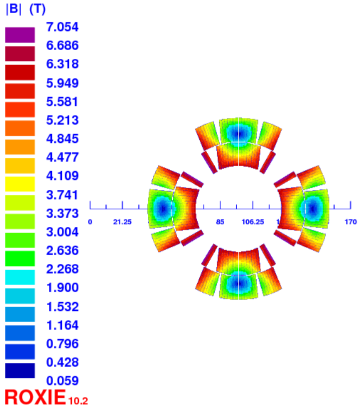


FCC Main Quad

Clément GENOT, Clément LORIN, Gilles MINIER, Tiina SALMI, Davide TOMMASINI

Inputs from: D. Schoerling, E. Rochepault, H. Felice, I. Pong, J. Fleiter, M. Segreti, M. Prioli

“History”



LHC

- MQ: 223 T/m x 3.2 m
- 2 layers design (Nb-Ti)

1st FCC week

- Baseline: 450 T/m × 6.0 m
- 4 layers graded design (2×Nb_3Sn + 2×Nb-Ti) 407 T/m with 20% LL margin, no protection check

2nd FCC week

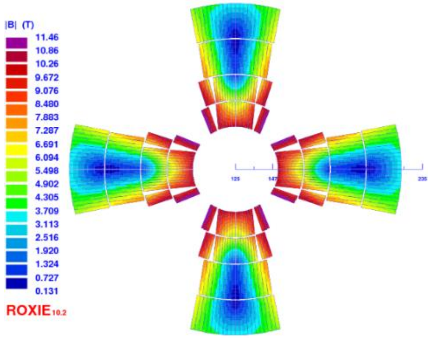
- Baseline: 420 T/m × 6.5 m
- 3 layers design (3×Nb_3Sn) 413 T/m with 20% LL margin [*E. Todesco*], 40 ms protection delay

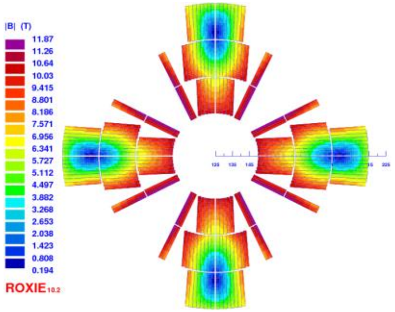
3rd FCC week

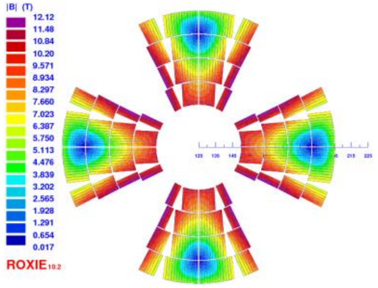
- Baseline: 381.2 T/m × 6.0 m
- 4 layers design (4 × Nb_3Sn) 400 T/m with **14%** LL margin, 40 ms protection delay

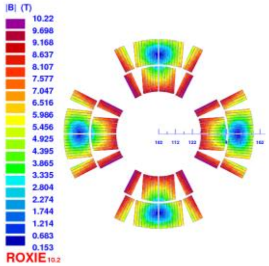
4th FCC week

- Baseline: 360 T/m x 7.2 m
- 2 layers design (2×Nb_3Sn) 353 T/m with 20% LL margin, **30 ms** protection delay

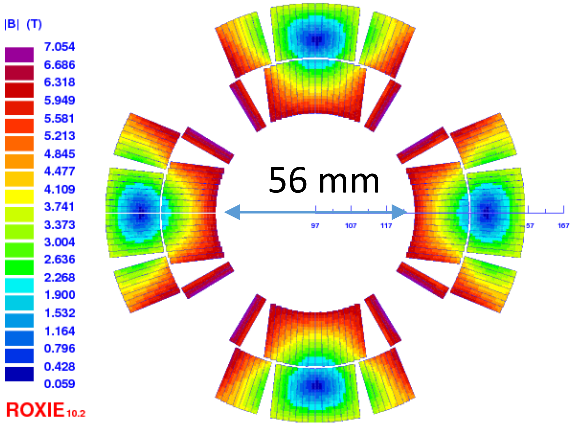






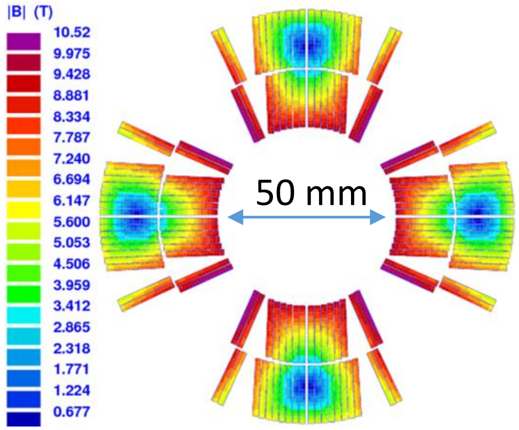


Last FCC-hh MQ version

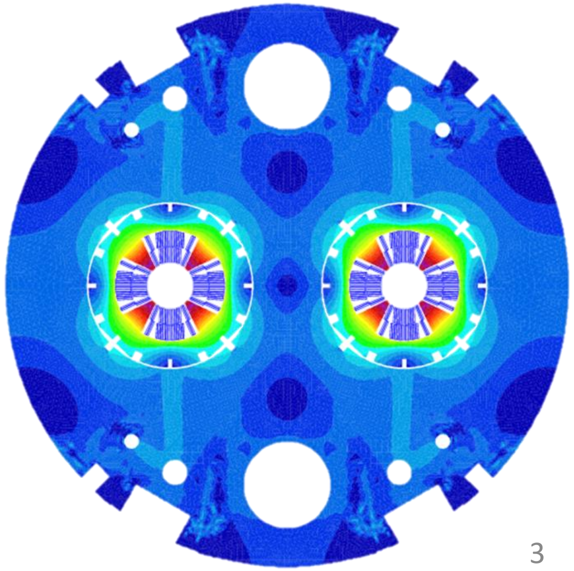


LHC MQ

Magnet parameter	Units	LHC MQ	FCC-hh MQ
Gradient	T/m	**223**	**367.4**
Nominal current	A	**11870**	**22500**
Peak field	T	**7.0**	**10.52**
Peak field / (Radius x Gradient)	-	**1.12**	**1.15**
Loadline margin	%	**20.0**	**20.0**
Temp magin	K	**2.0**	**4.6**
Inductance (2 ap.)	mH	**11**	**14.4**
Stored energy (2 ap.)	kJ	**800**	**3670**
Azimuthal force (per ½ coil) (1^{st} + 2^{nd} layers)	MN	**2.6**	**12.3**
Radial force (per ½ coil)	MN	**0.9**	**5.5**
Fx (per ½ coil)	MN	**1.5**	**7.8**
Fy (per ½ coil)	MN	**2.4**	**11.4**
Midplane shim	µm	**137**	**330**
Hotspot (total delay)	K	**-**	**350 (30 ms)**
Nb of turns per layer	-	**10 + 14 = 24**	**8 + 10 = 18**
Total weight of conductor	tonnes	**-**	**272**
Magnetic length	m	**3.15**	**7.06**

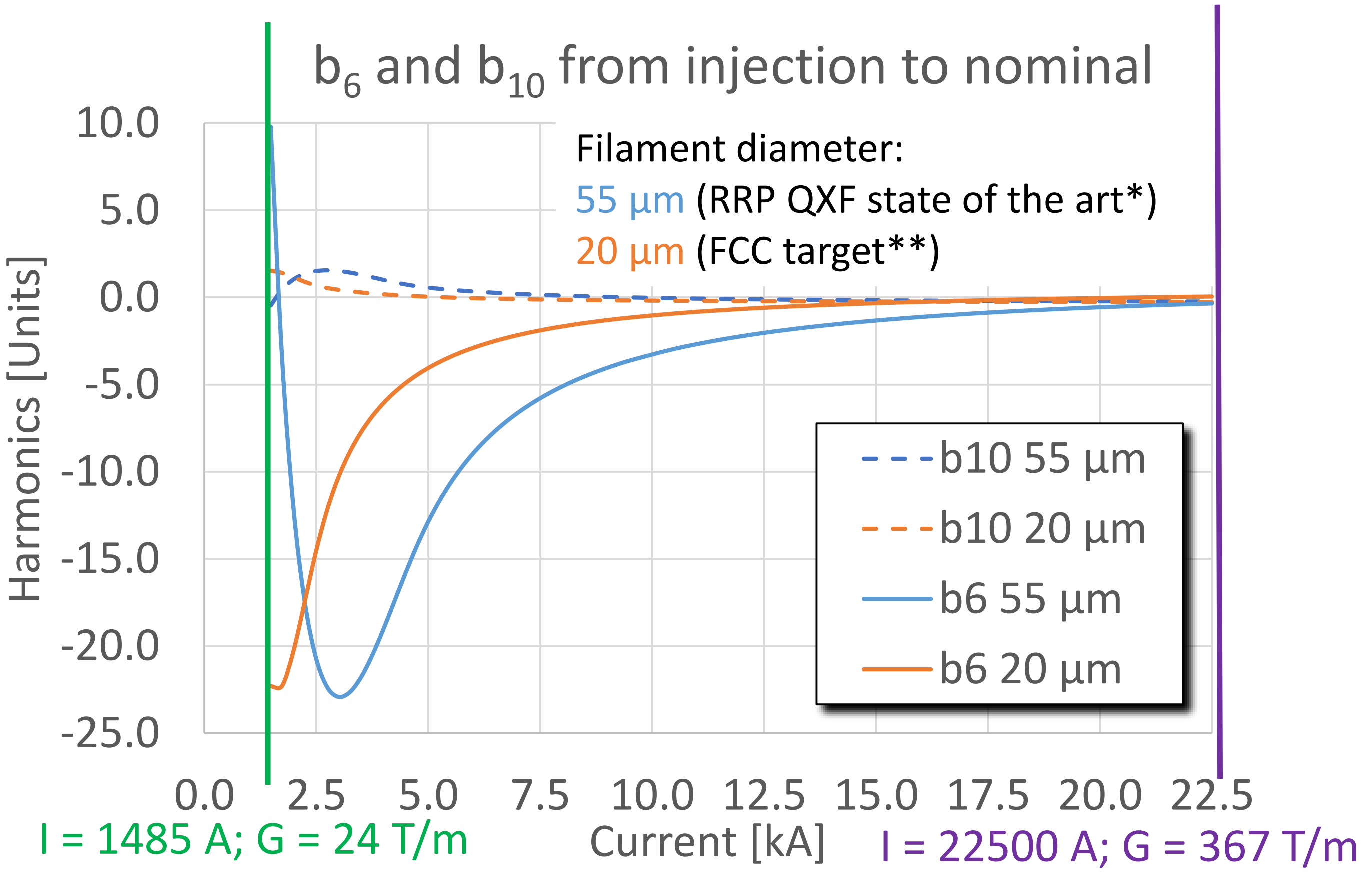


FCC-hh MQ



Harmonics contents 2D analysis

- Current ramp-up after preparation cycle from injection (3.3 TeV/beam) to nominal (50 TeV/beam)



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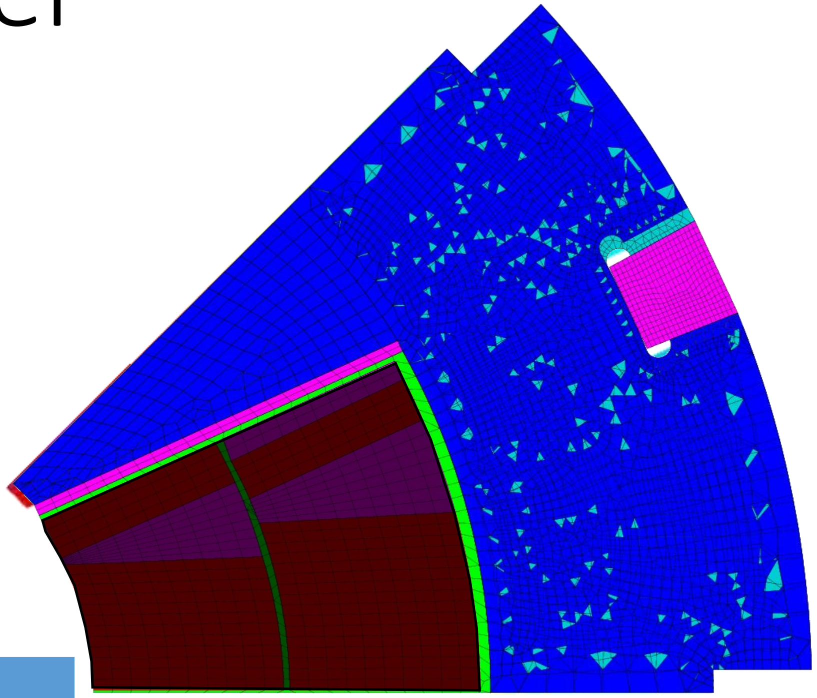
*QXF cable is made with a strand of 0.85 mm in diameter, too - Simon Hopkins et al., *The FCC conductor development programme*, 4th FCC week, Amsterdam 9th-13th April 2018

**Ballarino A., Bottura L., *Targets for R&D on Nb3Sn conductor for High Energy Physics*, IEEE TAS, 6000906, (2015)

Mechanical model



Double pancake glued (dark area)

Sliding contact elsewhere (without separation)

Mechanical properties:

Material	E [GPA] / 293 K	E [GPA] / 4.2 K	Pr	(L4.3K – L293K)/L293K
Nb_3Sn	30	33	0.3	3.4e-3*
Epoxy	5	8	0.34	6.0e-3
13RM19 (steel)	200**	210*	0.28*	2.7e-3**
DISCUP (copper)	96***	96	0.3	3.3e-3

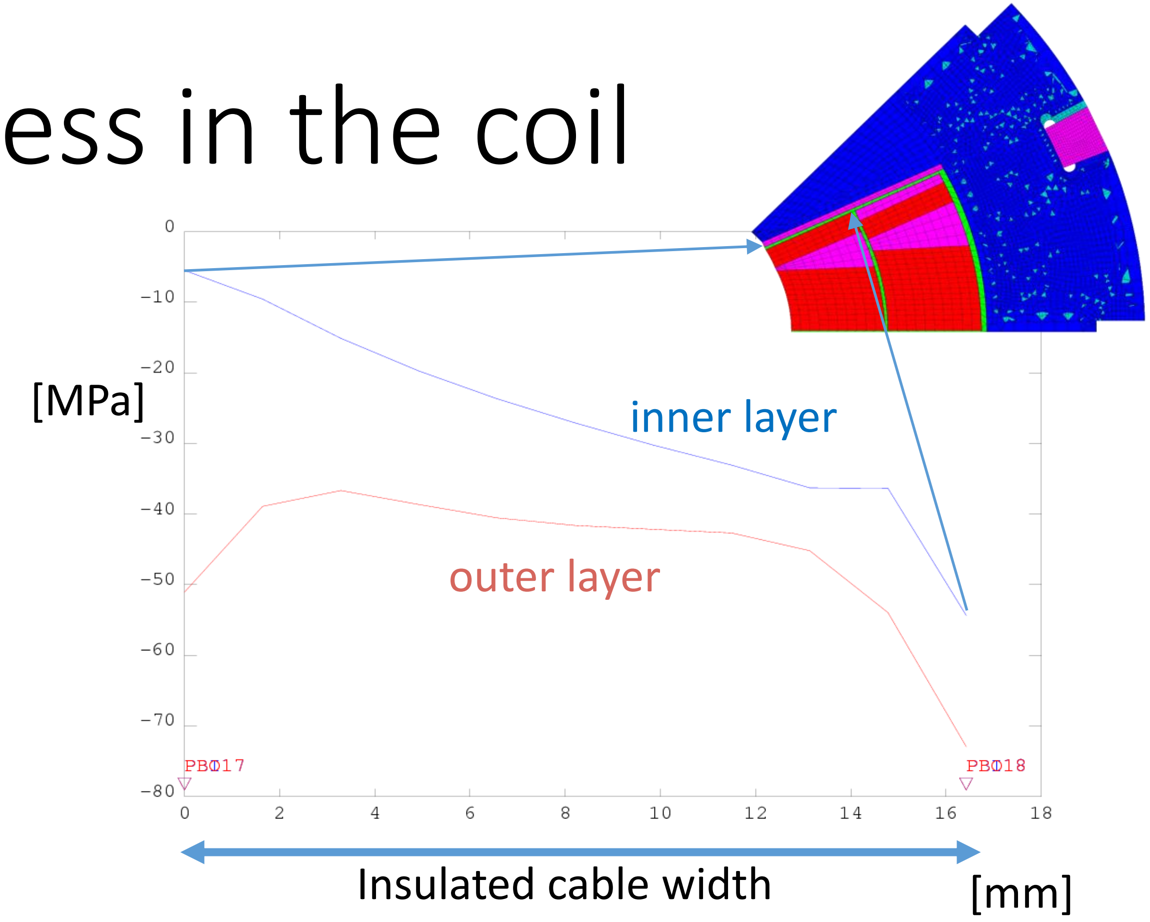
*Tommasini D. et al. https://indico.cern.ch/event/556692/contributions/2591664/ 3rd FCC week Berlin, 2017 + EuroCirCol meeting

**Lanza C., Perini D., Characteristics of the austenitic steels used in the LHC main dipoles, MT17, 24-28 September 2001, Geneva

***Scheuerlein et al, *Mechanical properties of the HL-LHC 11 T Nb3Sn magnet constituent materials*, IEEE TAS, 4003007, (2017)

Peak stress in the coil

Goal:
good coil-pole contact at nominal (< -5 MPa)



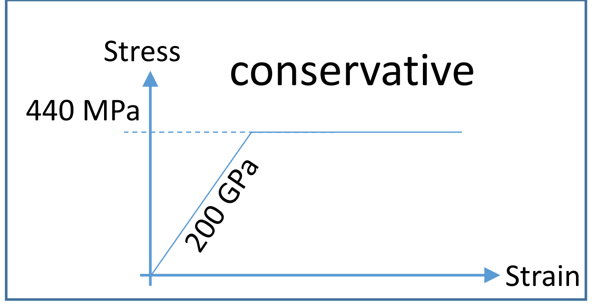
Azimuthal stress in the Nb_3Sn blocks of the coil

Collaring	Collaring - 10% creep*	Cold	Powering
peak / average	peak / average	peak / average	peak / average
-101.5 / -85.5	-91.4 / -76.9	-88.5 / -73.2	-111.1 / -69.7

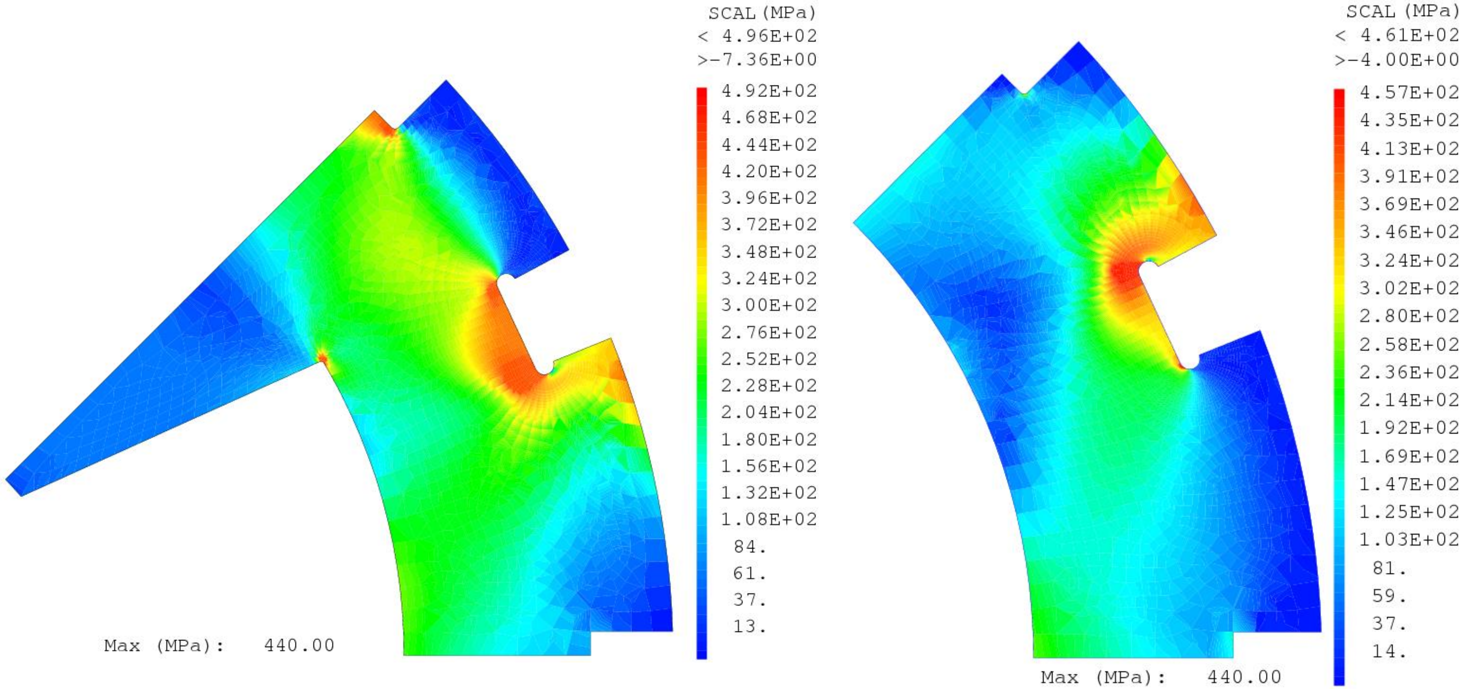
The pole could be even more loaded

*Felix Wolf : "Strong creep behavior starting at 125 MPa" in Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb3Sn Rutherford cable stacks, https://indico.cern.ch/event/743626/contributions/3154023

Elasto-plastic model for collar



- Collar steel: 13RM19 (LHC quad steel)
- Yield strength of the collars $\sigma_{0.2}$ = 440 MPa*



MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Grade	$\sigma_{0.2}$ [MPa]	σ_R [MPa]	A_5	E [GPa]	HBS 5/750
13RM19	440	800	52%	200	260
20-7 MN	460	795	50%	183	234
YUS 130 S	445	795	53%	194	250
Hyform 200 mod.	390	763	54%	188	277
KHMN	320	630	67%	186	220

Azimuthal stress in the Nb_3Sn blocks of the coil

Collaring Elasto Plastic model
peak / average
-111.6 / -86.5

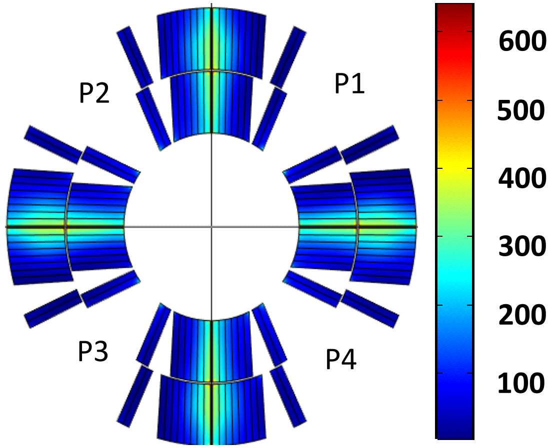
Collaring Elastic model
peak / average
-101.5 / -85.5

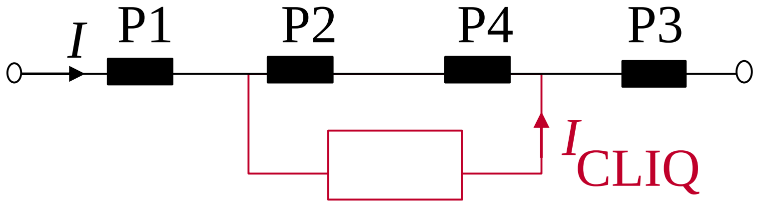
*Lanza C., Perini D., Characteristics of the austenitic steels used in the LHC main dipoles, MT17, 24-28 September 2001, Geneva
**Bertinelli F., et al., Production of austenitic steel for the LHC superconducting dipole magnets, IEEE TAS, vol 16, no 2, (2006)
(for information YUS130 S for LHC dipoles**)

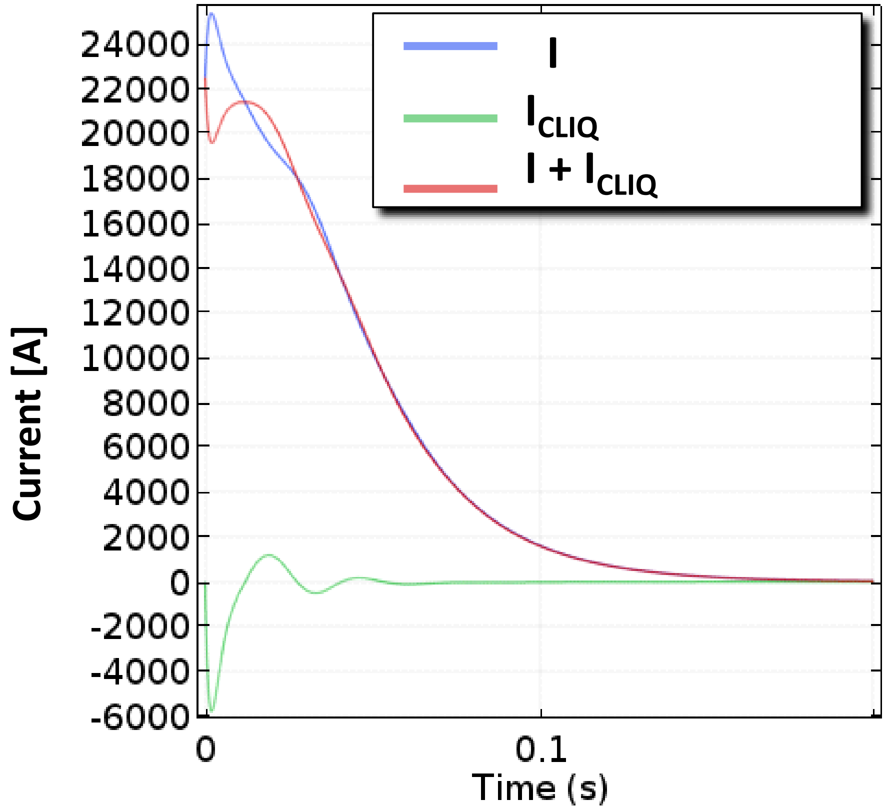
CLIQ Protection

[T. Salmi, M. Prioli, E. Ravaioli]

Energy deposition after 10 ms **[mJ/cm³]**

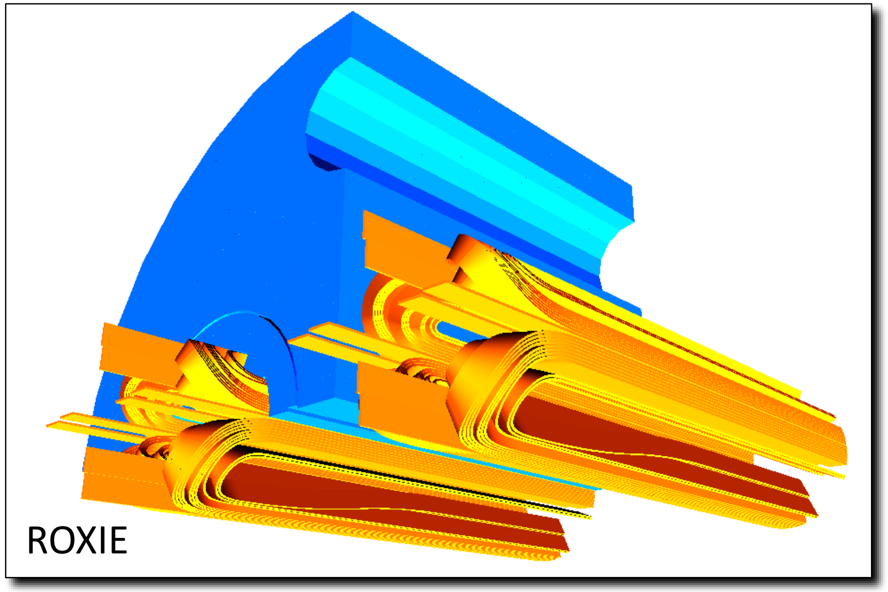


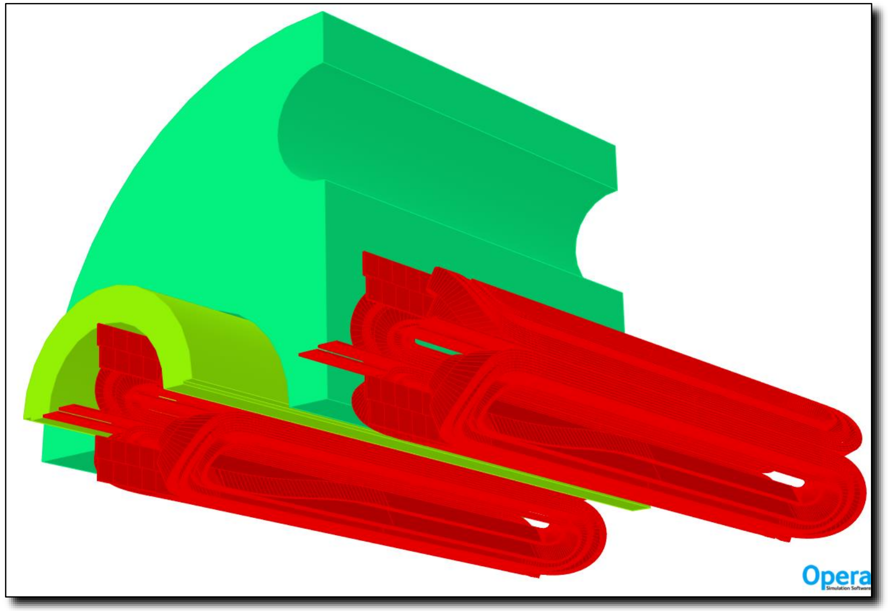




QUANTITIES	Values	Unit
Capacitance CLIQ unit	50	mF
Voltage CLIQ unit	500	V
Detect. + val. + trig. times	10+10+1	ms
Hotspot temp. 100% I_{nom}	300	K
Hotspot temp. 105% I_{nom} (< 350 K)	325	K
Voltage to ground (<1.2 kV)	250	V

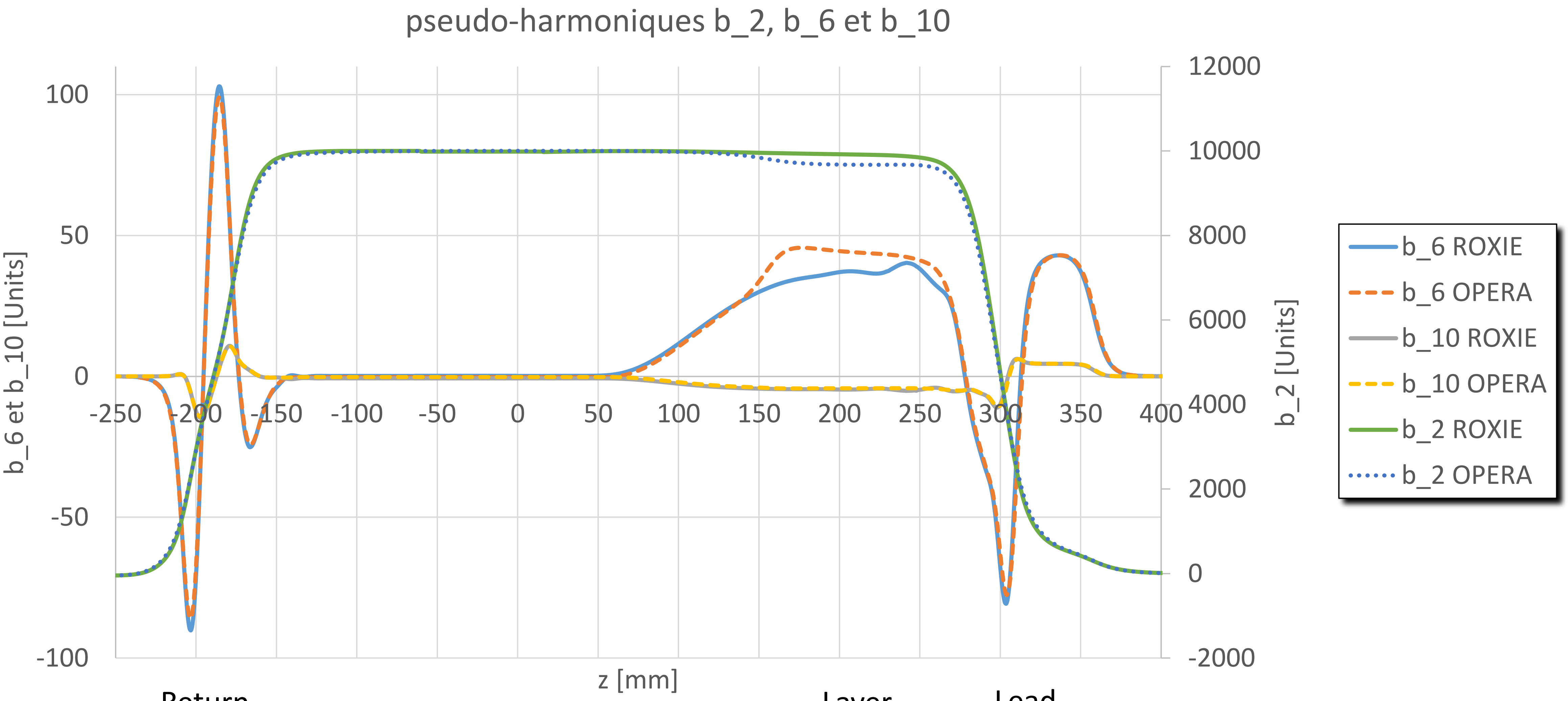
3D emag analysis – OPERA/ROXIE





- Coil end design via ROXIE
  - Cable windability
  - Harmonic optimization
- Geometry ROXIE -> OPERA
  - End collar via OPERA
  - Peak field calculation (*ongoing investigation*)
- Lead extra length = 5 cm

3D emag analysis – OPERA/ROXIE



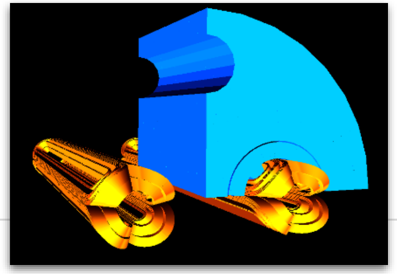
Return end

Layer jump

Lead end

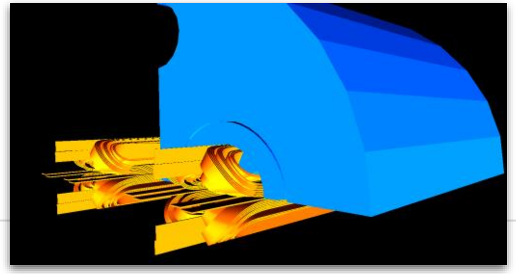
3D integrated harmonics (L_{mag} = 7,06 m)

Return end



Straight section

Lead end



$$L_{mag_{RE}} = 77{,}42\ mm$$

$$L_{mag}^{SS} = 6700\ mm$$

$$L_{mag_{LE}} = 282{,}64\ mm$$

$$\overline{b_{6_{RE}}} = -2{,}14$$

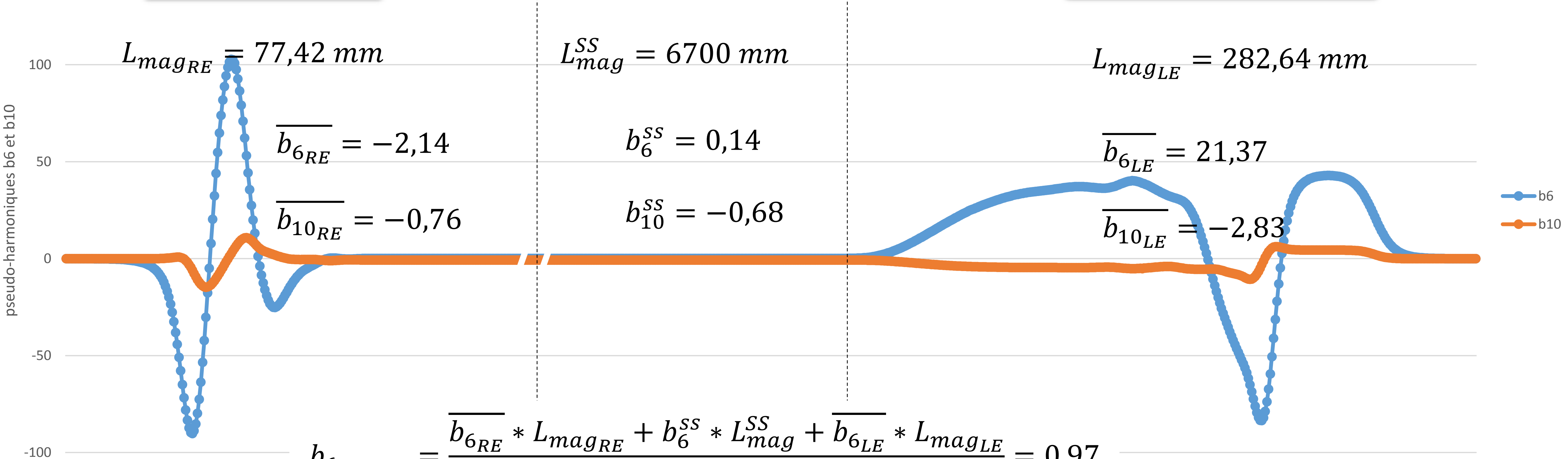
$$b_6^{SS} = 0{,}14$$

$$\overline{b_{6_{LE}}} = 21{,}37$$

$$\overline{b_{10_{RE}}} = -0{,}76$$

$$b_{10}^{SS} = -0{,}68$$

$$\overline{b_{10_{LE}}} = -2{,}83$$

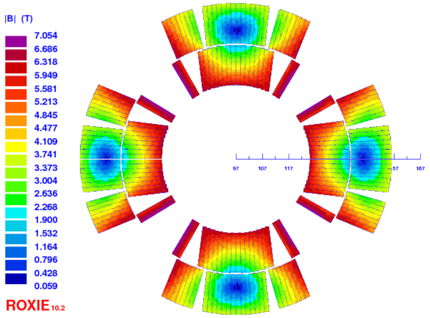


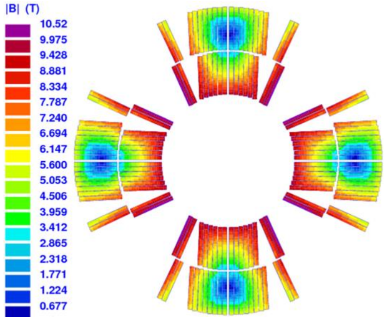
$$b_{6_{aimant}} = \frac{\overline{b_{6_{RE}}} * L_{mag_{RE}} + b_6^{SS} * L_{mag}^{SS} + \overline{b_{6_{LE}}} * L_{mag_{LE}}}{L_{mag}} = 0{,}97$$

$$b_{10_{aimant}} = -0{,}77$$

Cable windability

- Nb_3Sn cable less compact than Nb-Ti: stability ⇲
- Nb_3Sn interstrand resistance less control (steel core): stability ⇲

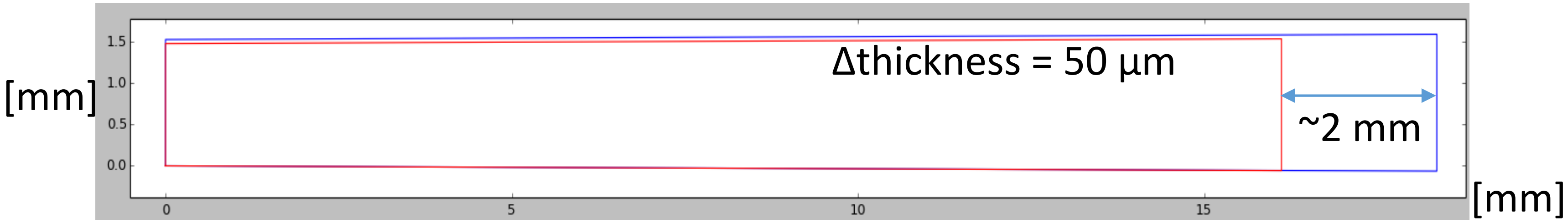


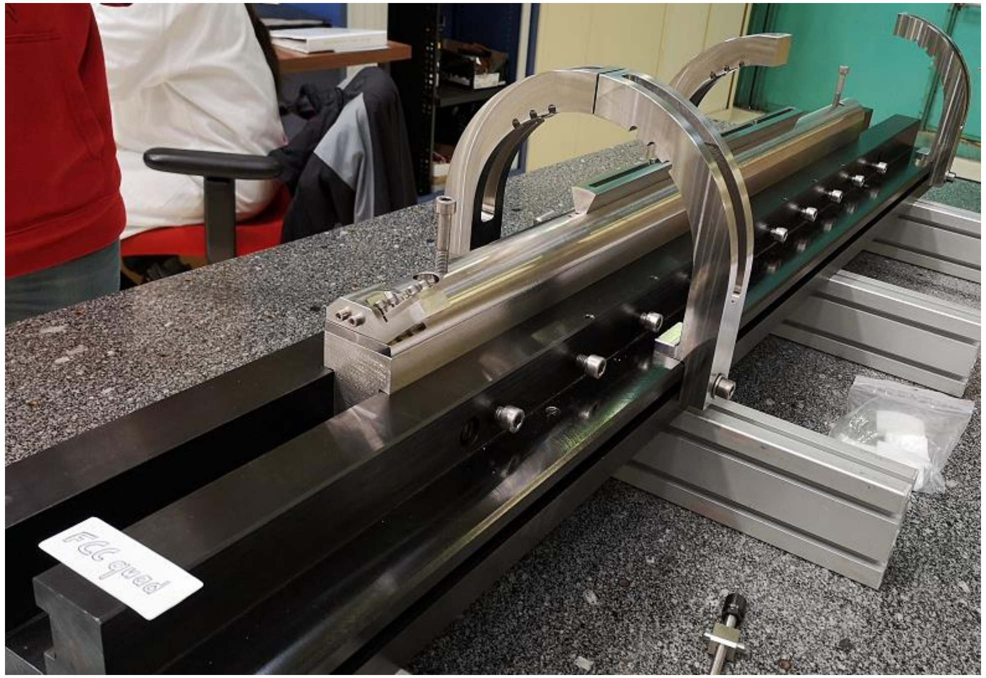


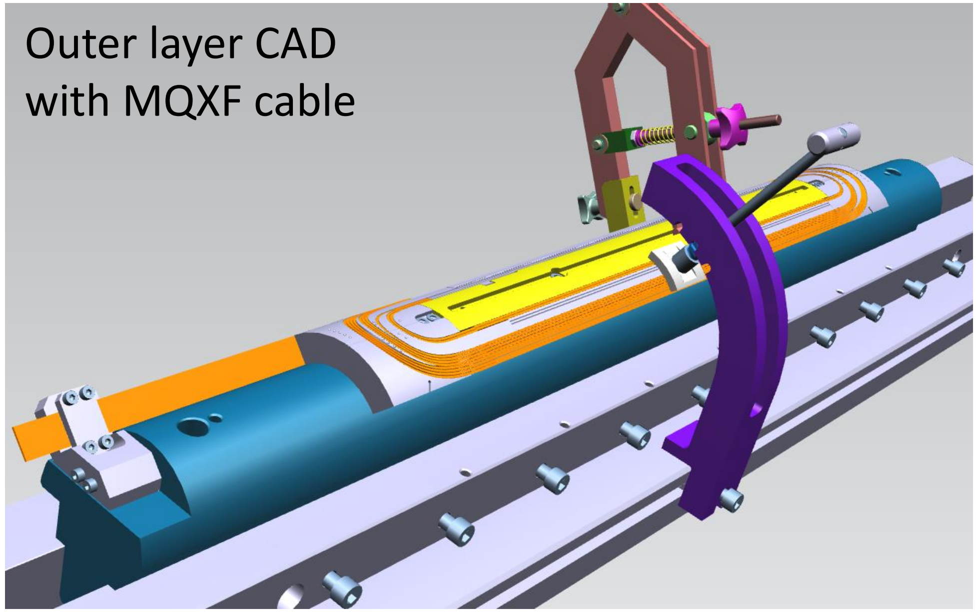
Machine	LHC (Nb-Ti)	FCC-hh (Nb_3Sn)
Aperture (mm)	56	50
Strand size (mm)	0.825	0.85
Cu/non-Cu	1.95	1.65
Number of strand (-)	36	35
Bare cable width (mm)	15.1	15.956
Mid-thickness (mm)	1.48	1.493
Keystone (°)	0.9	0.4
Inuslation (µm)	130	150

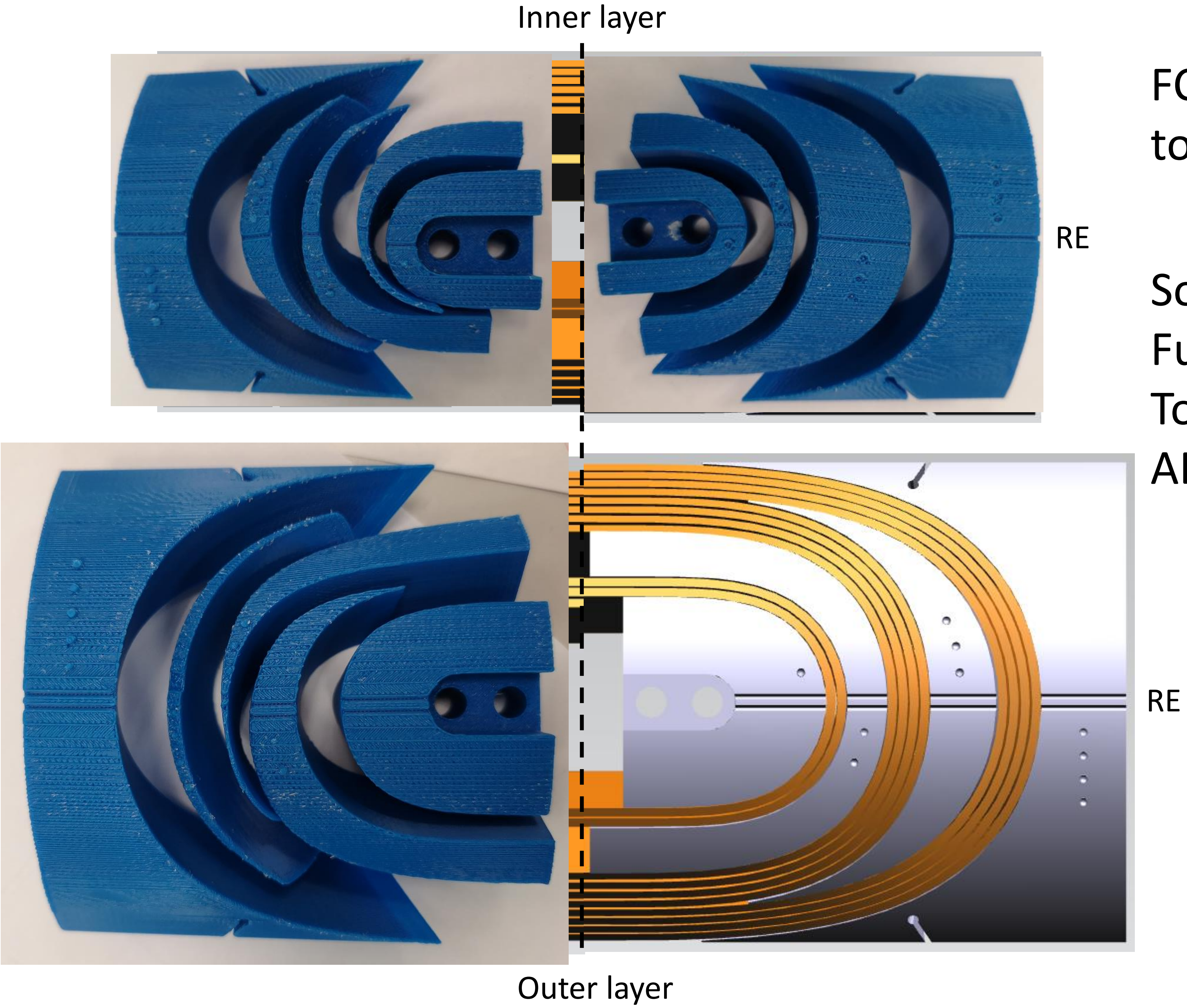
Windings trials

- Closest cable geometry available is MQXF one: 40 strands instead of 35






Outer layer CAD
with MQXF cable



FCC quad end spacers extruded to the MQXF cable width

Some of the spacers 3D printed
Fused Deposition Modelling
Tolerance~ 0.2 mm
ABSpluS-P430

Conclusion

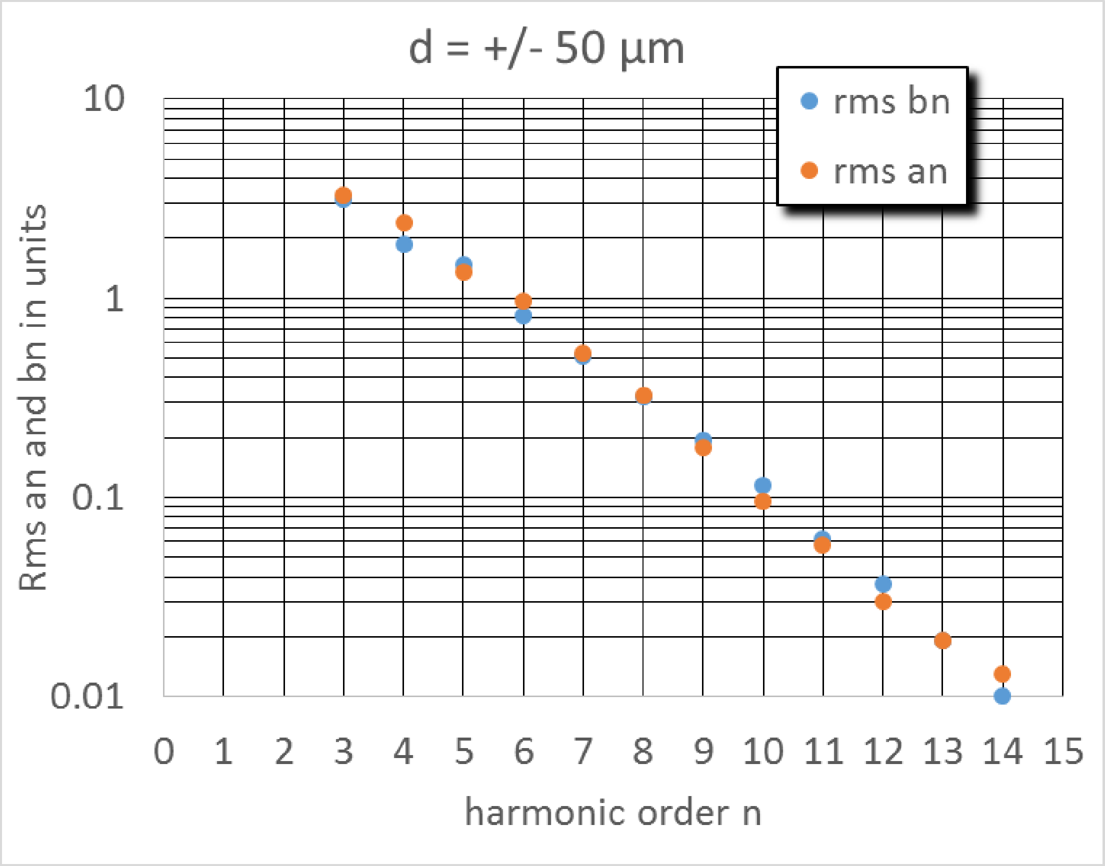
- Several designs investigated over the past 5 years
- Gradient in the 360 T/m range looks feasible
- Mechanic : < 150 MPa
- Protection : < 350 K
- NEVERTHELESS, to me:
  - very challenging in terms of windability of two layers magnet to reach 360 T/m
    - 0.85 mm x 35 strands (or 0.7 mm x 43 strands) -> too unstable?
    - Validation on going with winding trials

-> Back-up plan : to go back to 4 layer designs to reach 360 T/m

EXTRA SLIDES

Cable position versus harmonic content

Random positioning



Random harmonics:

$$\sigma_n(d) = d\alpha\beta^n \text{ in units}$$

$$d = 50 \text{ or } 100 \text{ in } \mu m$$

$$\beta = 0.58$$

$$\alpha = 0.4$$

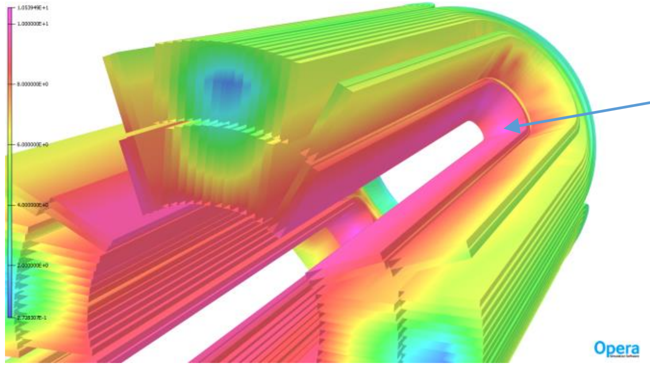
(for allowed harmonics $\alpha = 0.8$, Ezio/Susana’s comment, nevertheless no statistics reported on quadrupole, only for dipoles)

OPERA (no iron) : $B_{p_{head}} = \boxed{10{,}29\ T}$

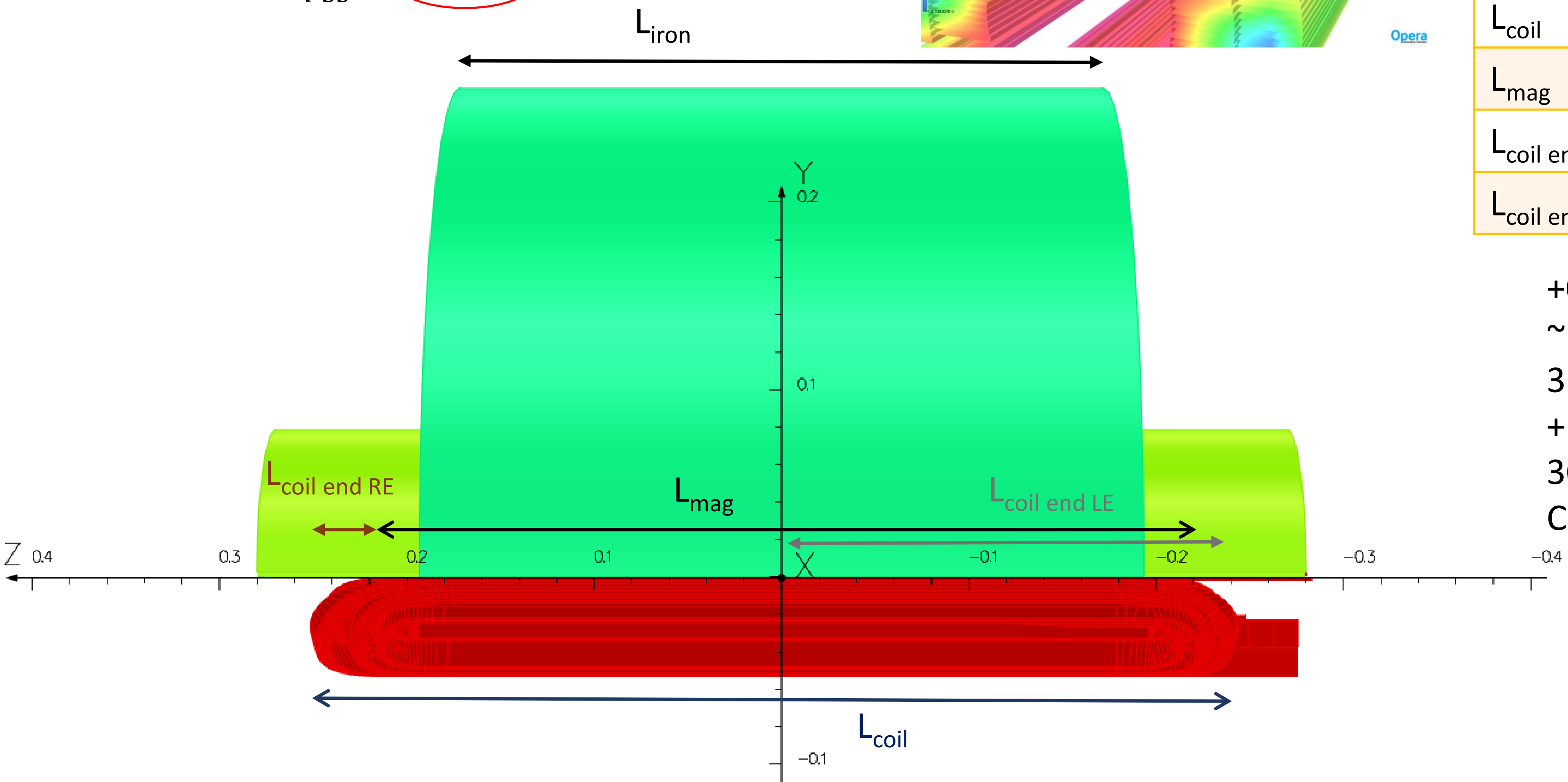
OPERA (no iron) : $B_{p_{SS}} = 9{,}91\ T$

OPERA (with iron) : $B_{p_{head}} = 10{,}54\ T$

OPERA (with iron) : $B_{p_{SS}} = \boxed{10{,}04\ T}$



B_{peak}	10,54	T
$L_{straight\ section}$	180	mm
L_{iron}	392	mm
L_{coil}	539	mm
L_{mag}	484	mm
$L_{coil\ end\ RE}$	27,5	mm
$L_{coil\ end\ RE}$	269,5	mm



+0.3 T in the RE head
~17% margin
367 T/m -> 360 T/m ->
+19% margin
300 K@ Inom -> 350 K
Could recover the margin

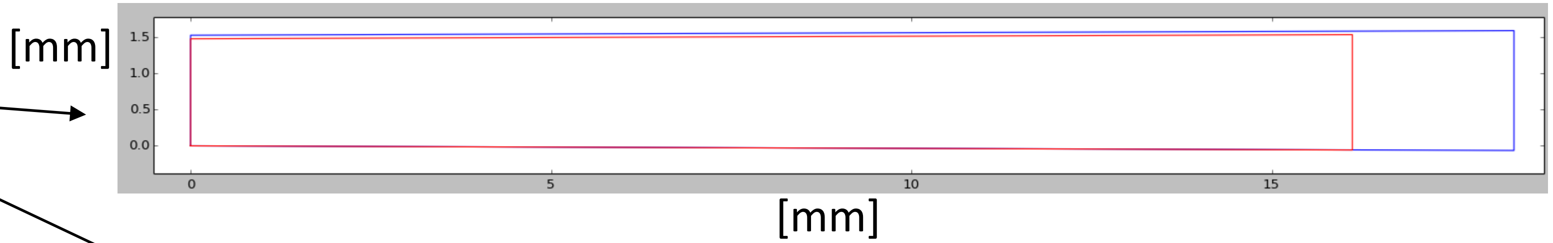
Actually, Bp_{head} could be reduced by 0.3 T by inserting a spacer between the first two turns of the inner layer / return side. Under investigation.

MQXF vs FCC MQ cables

CABLE PARAMETER	Units	MQXF	FCC quad (v12)
Strand diameter	mm	0.85	**0.85**
Cu/NonCu	-	1.2 ± 0.1	**1.65**
Nb of strands	-	40	**35**
Cable bare width (before/after HT)	mm	18.15/18.363	**15.956/16.120**
Cable bare mid-thick.(before/after HT)	mm	1.525/1.594	**1.493/1.538***
Cable bare thinness (before/after HT)	mm	1.462/1.530	**1.438/1.481* (15.4%)**
Cable bare thickness (before/after HT)	mm	1.588/1.658	**1.549/1.596* (8.9%)**
Cable width expansion	%	1.2	**1.0****
Cable thickness expansion	%	4.5	**3.0****
Keystone	°	0.40	**0.40**
Transposition pitch length	mm	109	**96**
Insulation thickness per side (5 MPa)	µm	145 ± 5	**150**

Winding trials:
Reconcile FCC quad geom. and QXF cable

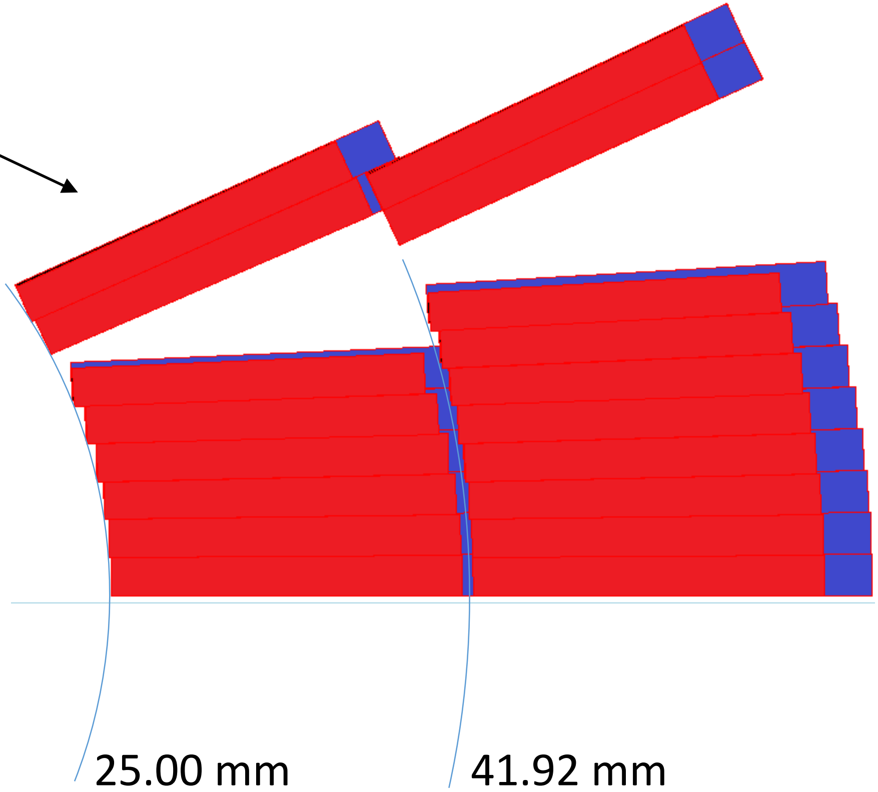
- Red reacted FCC cable (0.4°)
- Blue reacted MQXF cable (0.4°)
  - -> Δthickness = 50 µm



- Same insulation: 150 µm/side

- Inner radius: 25.00 mm
- Outer radius: 41.92 mm

- 2 mandrels (no layer jump)
- FCC quad 2D optimization:
  - Central post -> extrapolated to MQXF cable width
  - Copper wedges -> extrapolated to MQXF cable width
- FCC quad 3D optimization:
  - End spacers ->extrapolated to MQXF cable width
- MQXF cable
  - Bearing in mind that the components are based on the reacted cable -> bare cable 70 µm thinner



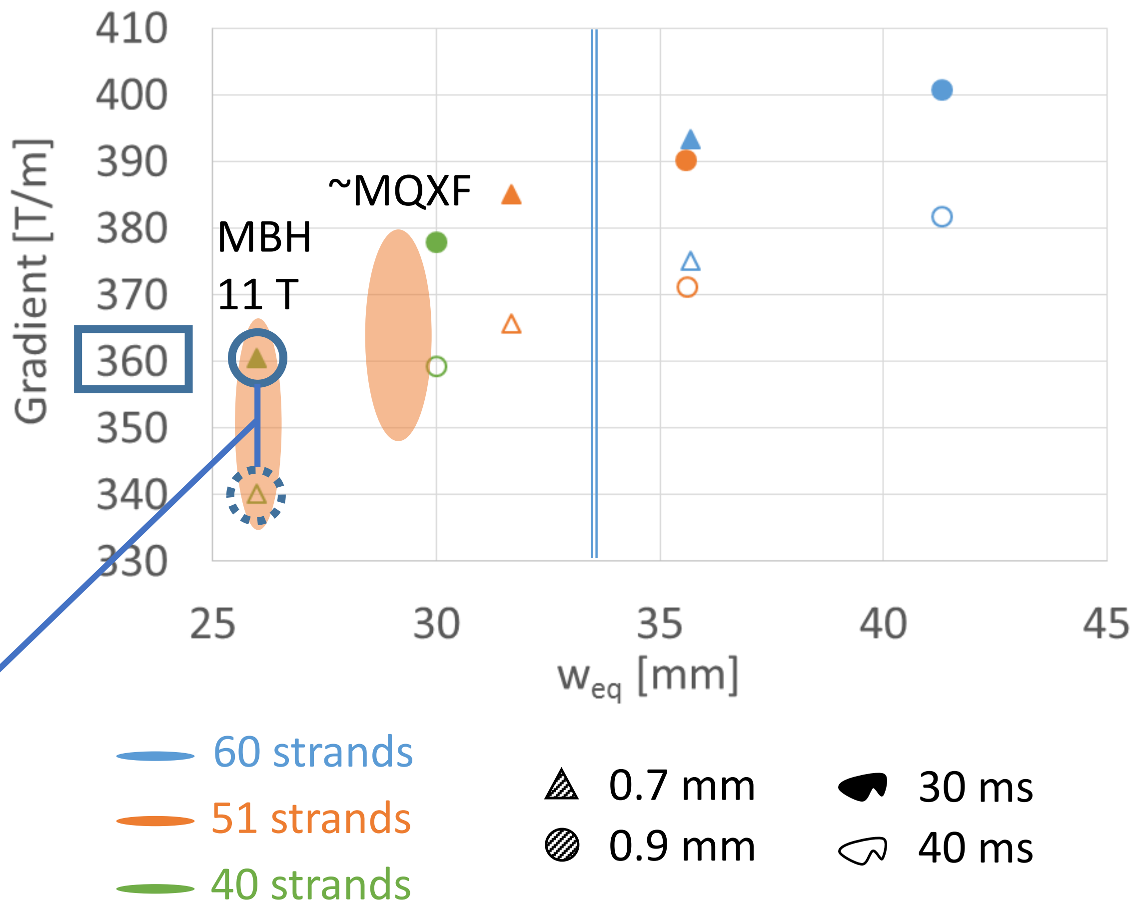
2D exploration of the parameter space

- Strand diameter: 0.7 mm or 0.9 mm
- Nb of strands: 40-51-60
- Protection delay: 30 ms or 40 ms

Protection: 40 to 30 ms (Hotspot = 350 K)

  - + 20 T/m on the gradient (~5%)

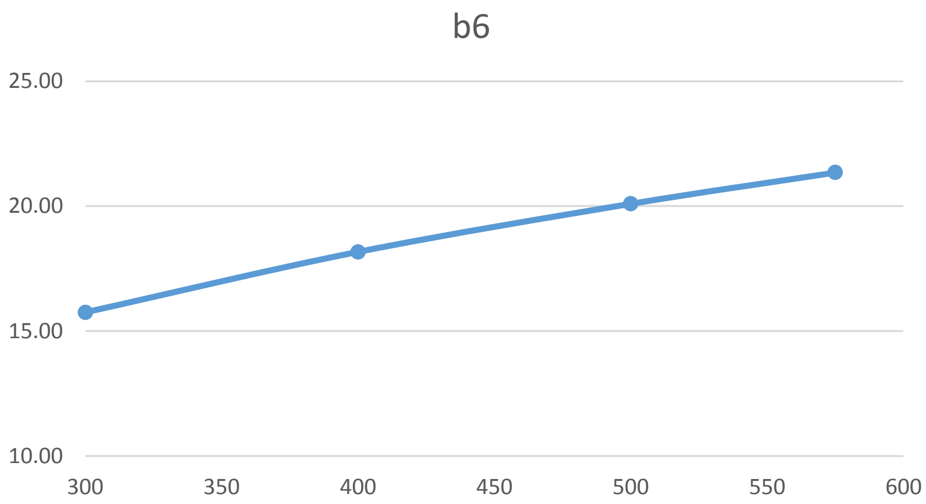
- 2 layers efficiency:
  - Lower than ~51 strands
- Worry about windability (50 mm aperture)
  - Windability test with MBH 11 T cable or MQXF cable would be welcome



Design selected for this study:

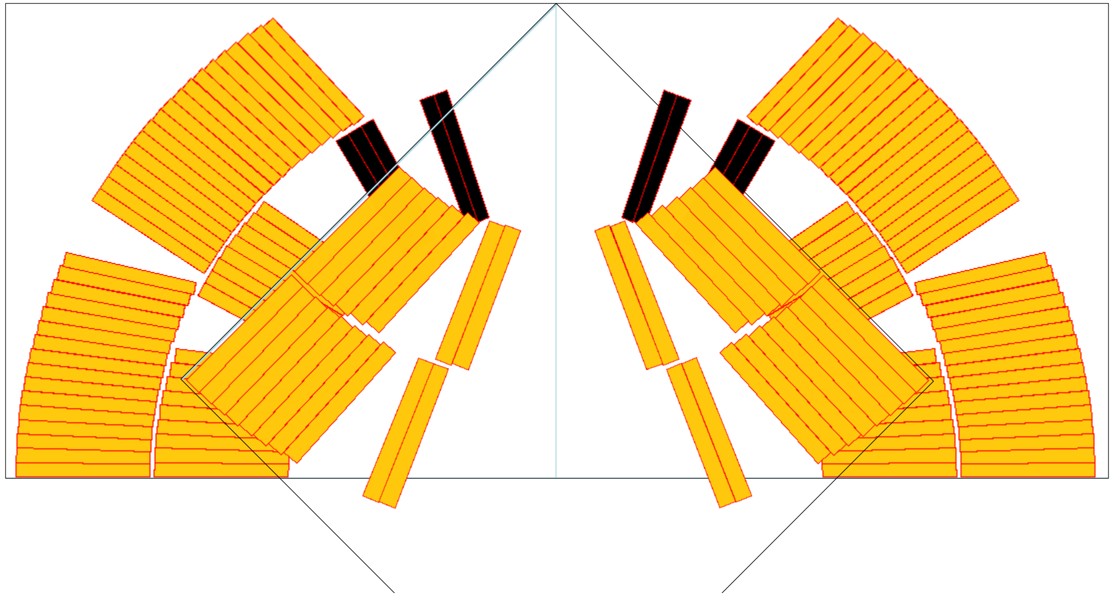
Most simple design in-line with the optics baseline of 360 T/m

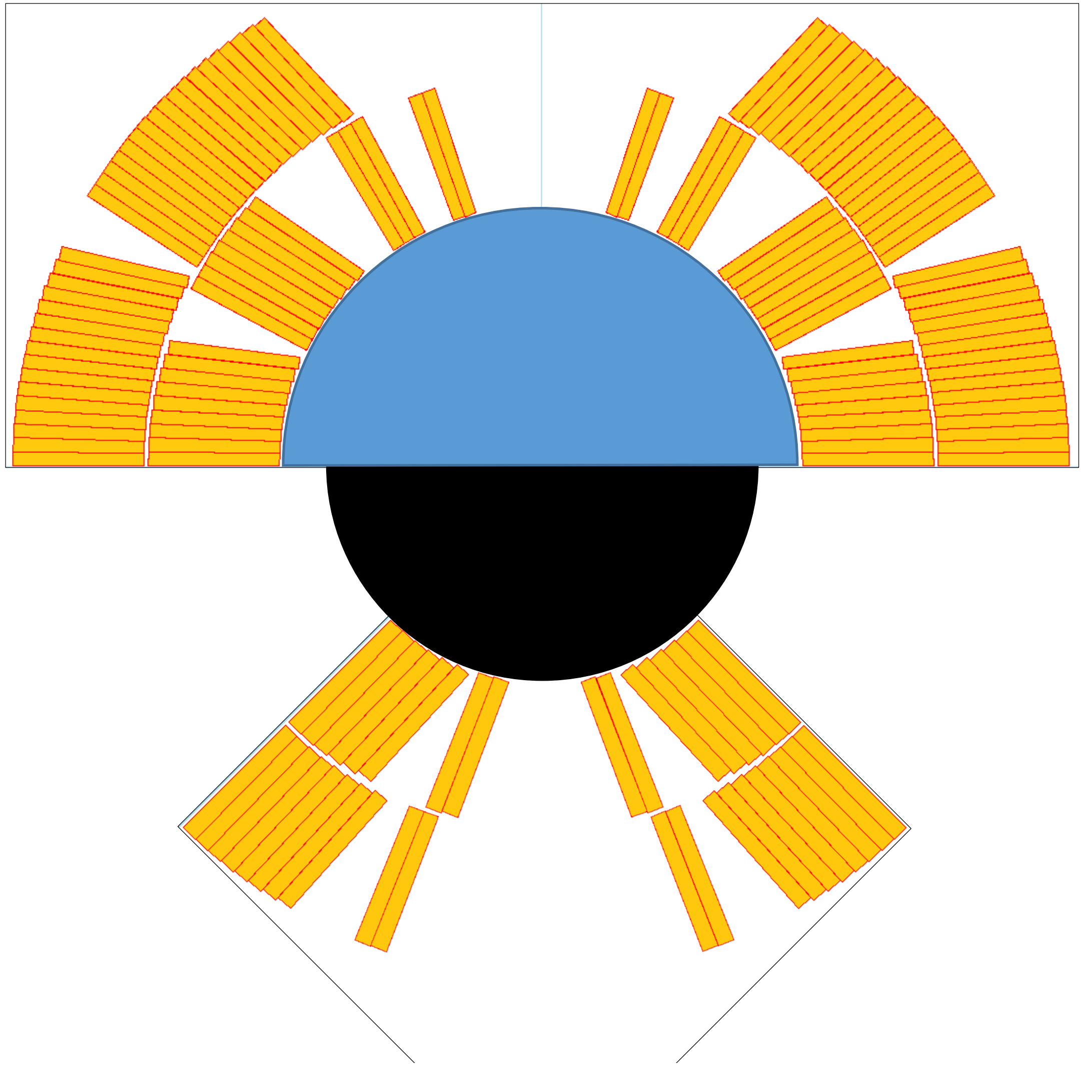
Layer jump impact on b6



calcul b6 le long de l'aimant :		
R [mm]=	b6=	L_saut
300	0,75	141
400	0,84	163
500	0,92	183
575	0,97	196

11 T HL-LHC coil versus FCC quad coil



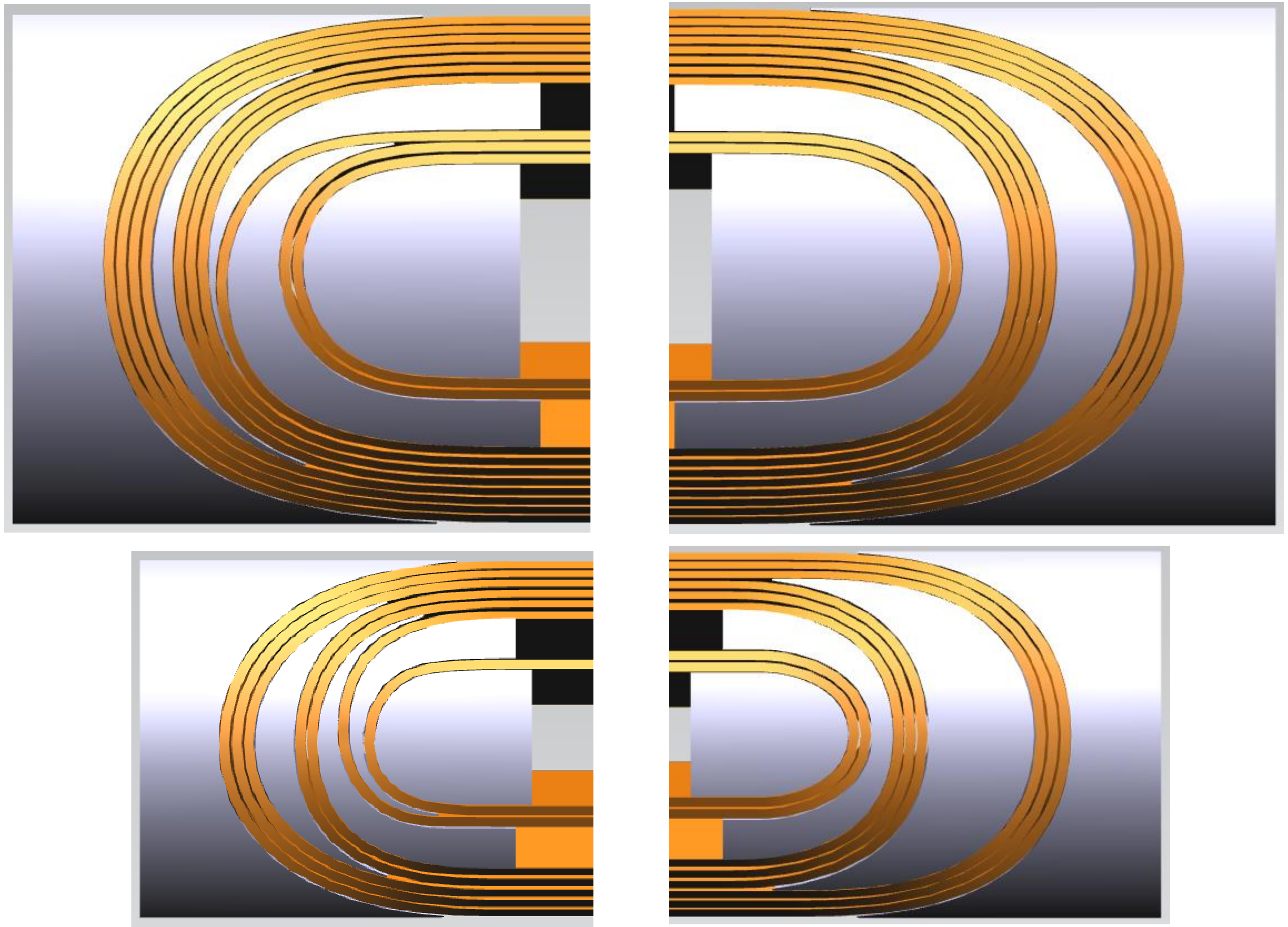


FCC quad: Rmin ≈ 4.0 mm
11T MBH: Rmin ≈ 7.5 mm

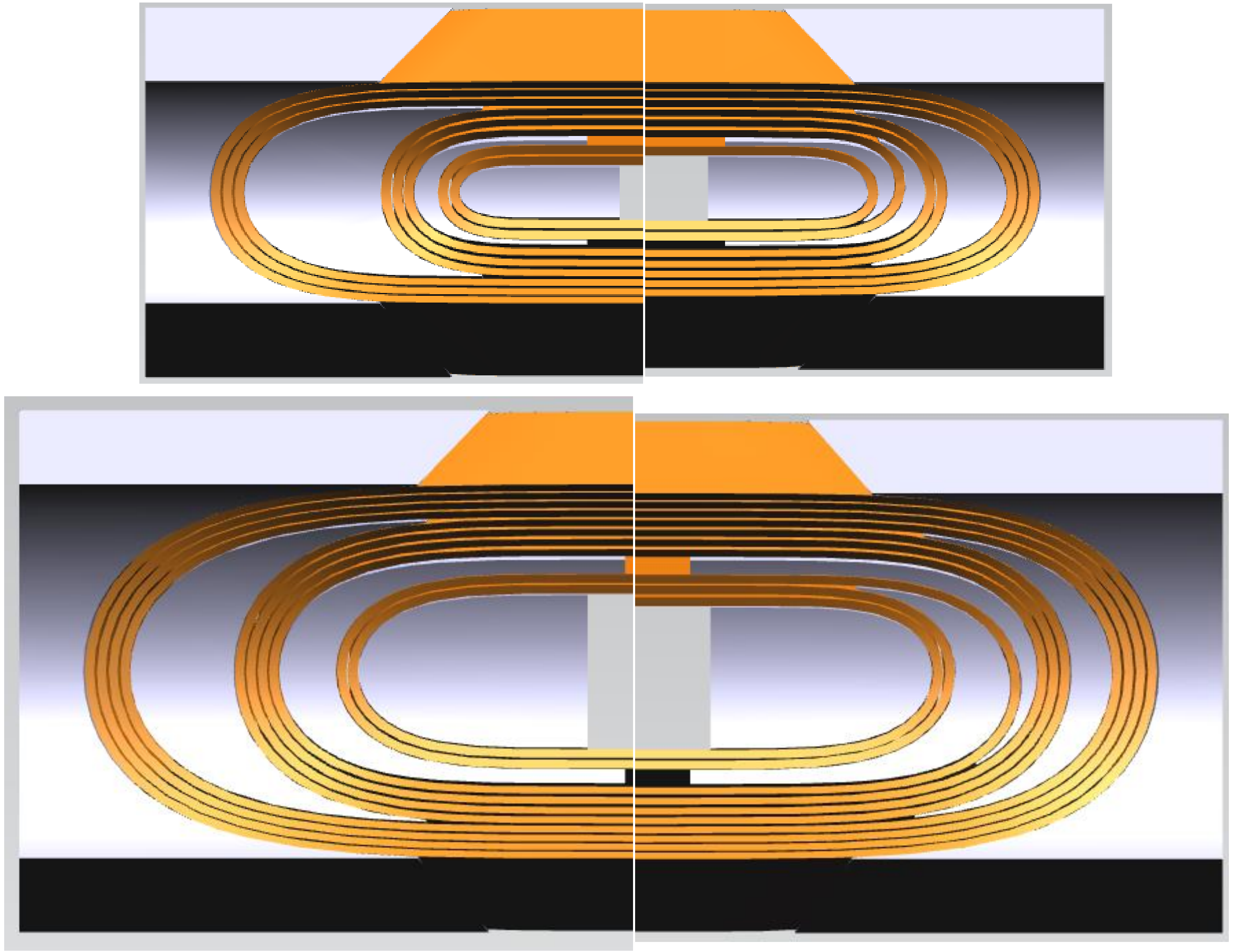
Magnet summary 1st FCC week (2015) by E. Todesco

- Problems with curvature radius in the heads [G. L. Sabbi for main dipoles, C. Lorin for main quadrupole]

FCC quad end spacers with FCC quad cable

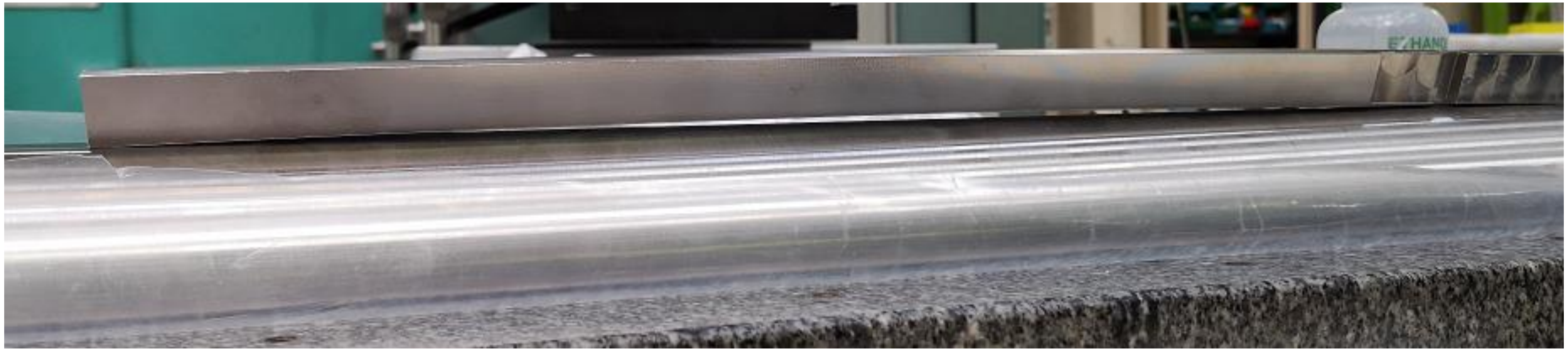


« Top » view
From outside



« Bottom » view
From the aperture

Some out-of-tolerance tooling



2 central posts and all angular wedges sent back to the manufacturer