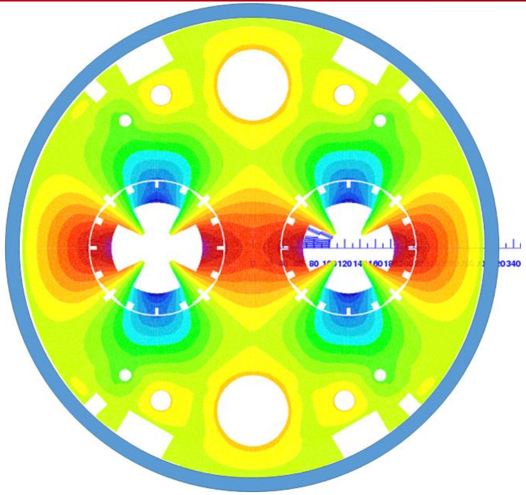


FCC quad

(v12)

Clément Lorin

with inputs from:

Tiina Salmi for the magnet protection (TUT), Jerome Fleiter for the cable sizing (CERN)

EuroCirCol Annual Meeting, 17 oct 2018, Karlsruhe Institut of Technology

Since FCC week

- FCC week:
  - 353 T/m; magnet protection not properly checked; cable dimension not heat-treated
  - cable: 40 x 0.7 mm
- First set of iterations after FCC week:
  - cable heat-treatment (w+1%; t+3%); protection check performed by Tiina (TUT); >360 T/m (Optics baseline: 360 T/m, 2592 T integrated)
  - 42/43 x 0.7 mm
  - Some iterations about cable dimensions (Jerome Fleiter (CERN) and Ian Pong (LBNL))
- Second set of iterations after FCC week:
  - cable heat-treated; 35 x 0.85 mm, G > 360 T/m

Cable parameters

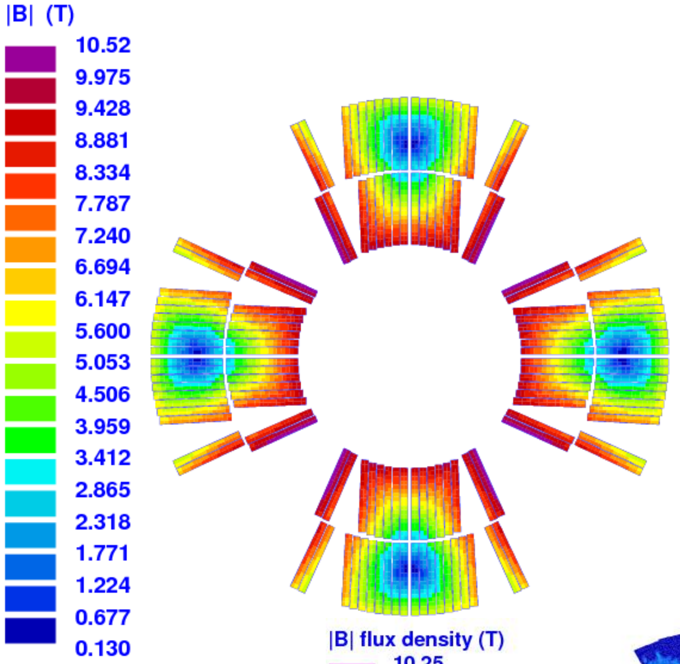
Cable parameter	Units	MQXF	v12
Strand diameter	mm	0.85	**0.85**
Cu/NonCu	-	1.2 ± 0.1	**1.65**
Nb of strands	-	40	**35**
Cable bare width (before/after HT)	mm	18.15/18.363	**15.956/16.120**
Cable bare mid-thick.(before/after HT)	mm	1.525/1.594	**1.493/1.538****
Cable bare thinness (before/after HT)	mm	1.462/1.530	**1.438/1.481****
Cable bare thickness (before/after HT)	mm	1.588/1.658	**1.549/1.585****
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**

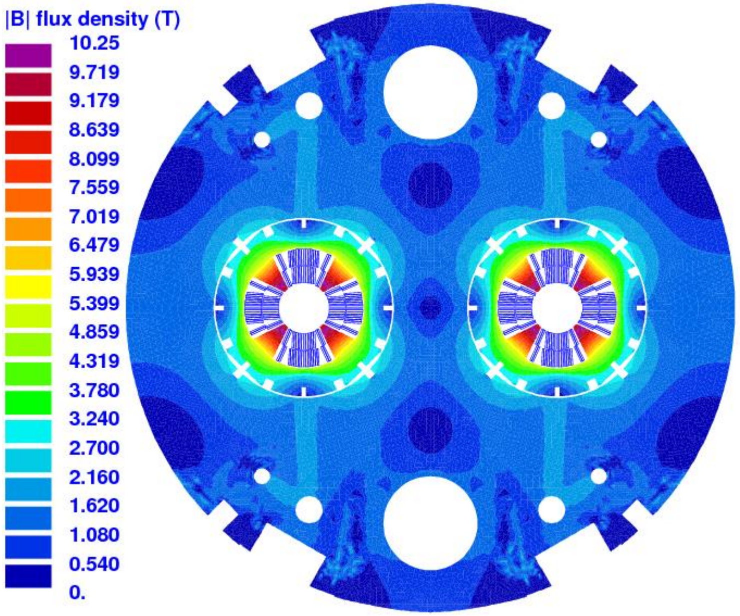
*Compaction based on MQXF RRP 0.55° keystone extra slide 15
**EuroCirCol guesstimation
J_c see extra slide 12 (EuroCirCol)

Magnet design

*Lorin C. et al, *Design of a Nb_3Sn 400 T/m quadrupole for the future circular collider*, IEEE TAS, 4004905, (2018)

Magnet parameter	Units	400 T/m*	v12
Gradient	T/m	400	**367.4**
Nominal current	A	12285	**22500**
Peak field	T	12.12	**10.52**
Peak field / (Radius x Gradient)	-	1.212	**1.146**
Loadline margin	%	14	**20.0**
Temp magin	K	-	4.6
Inductance (2 ap.)	mH/m	17.9	2.04
Stored energy (2 ap.)	kJ/m	1397	520
Azimuthal force (per ½ coil) (1^{st} + 2^{nd} layers)	MN/m	3.53	1.74 (0.81+0.93)
Radial force (per ½ coil)	MN/m	1.58	0.78
Fx (per ½ coil)	MN/m	-	1.100
Fy (per ½ coil)	MN/m	-	1.620
Midplane shim	µm	300	325
Hotspot (total delay) I_{nom}	K	307 (40 ms)	300 (30 ms)
Nb of turns per layer	-	9+12+16+19 = 56	8 + 10 = 18
Area of conductor	cm²	124.2	57.2
Total weight (same integrated gradient 2592 T)	tonnes	541	272
Magnetic length	m	6.48	**7.06**

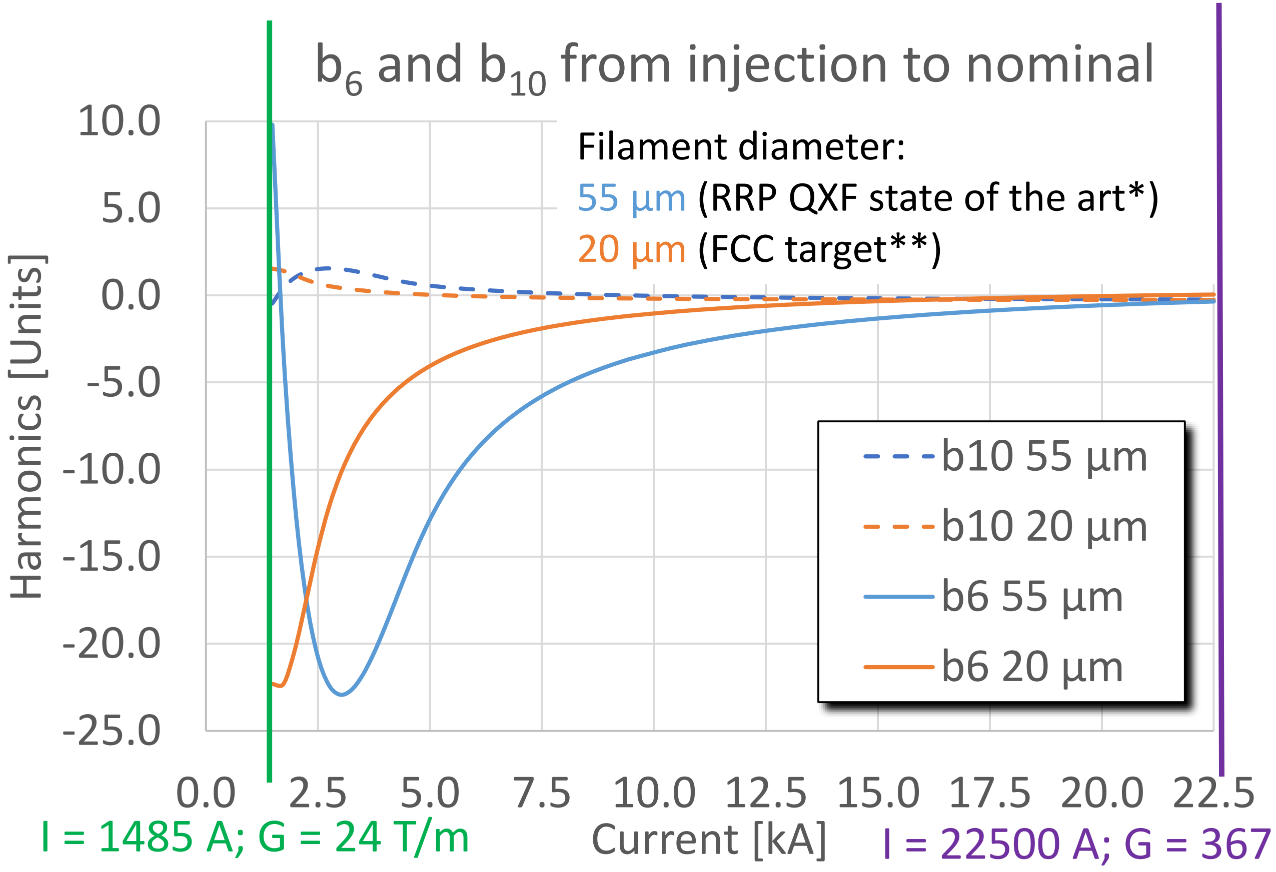




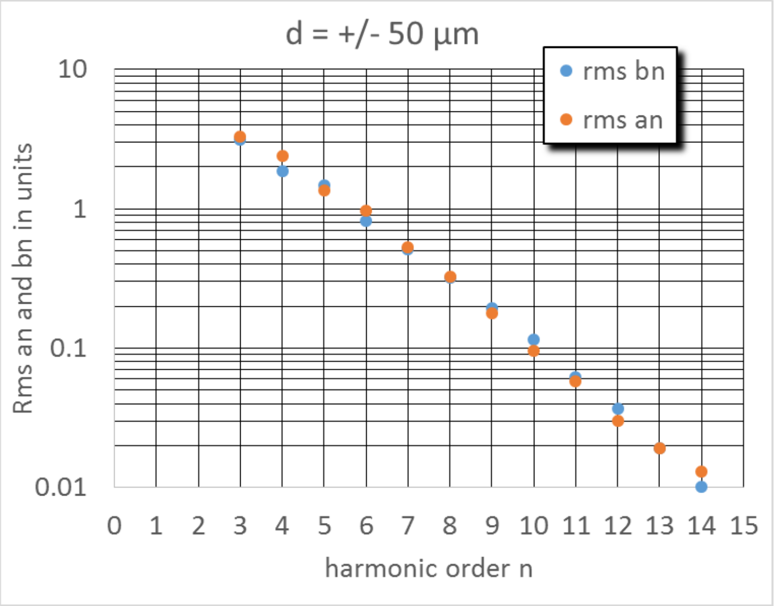
Harmonics contents

Current ramp-up after preparation cycle

from injection (3.3 TeV/beam) to nominal (50 TeV/beam)



Random positioning



Random harmonics:

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

d = 50 or 100 in µm

$\beta = 0.58$

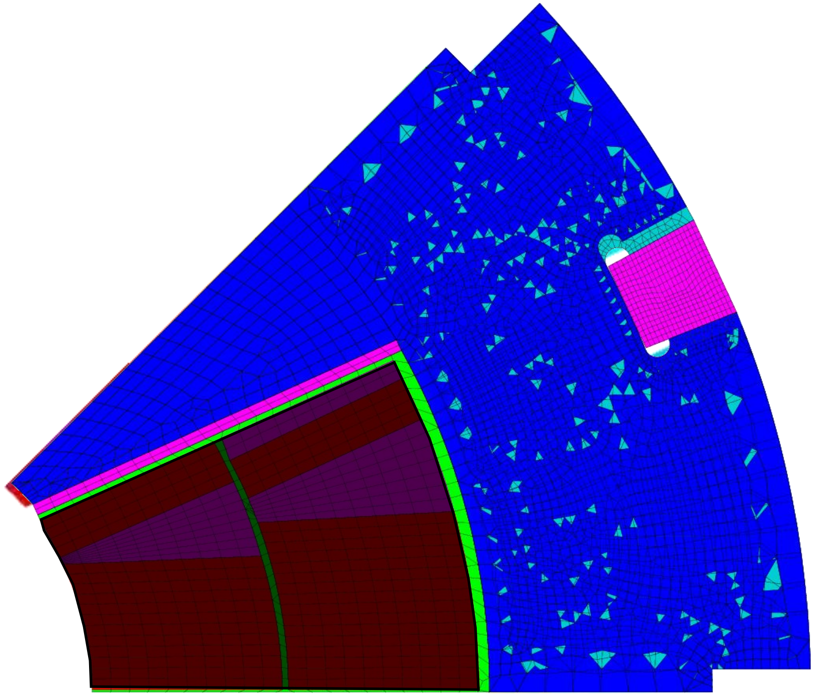
$\alpha = 0.4$

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

*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)

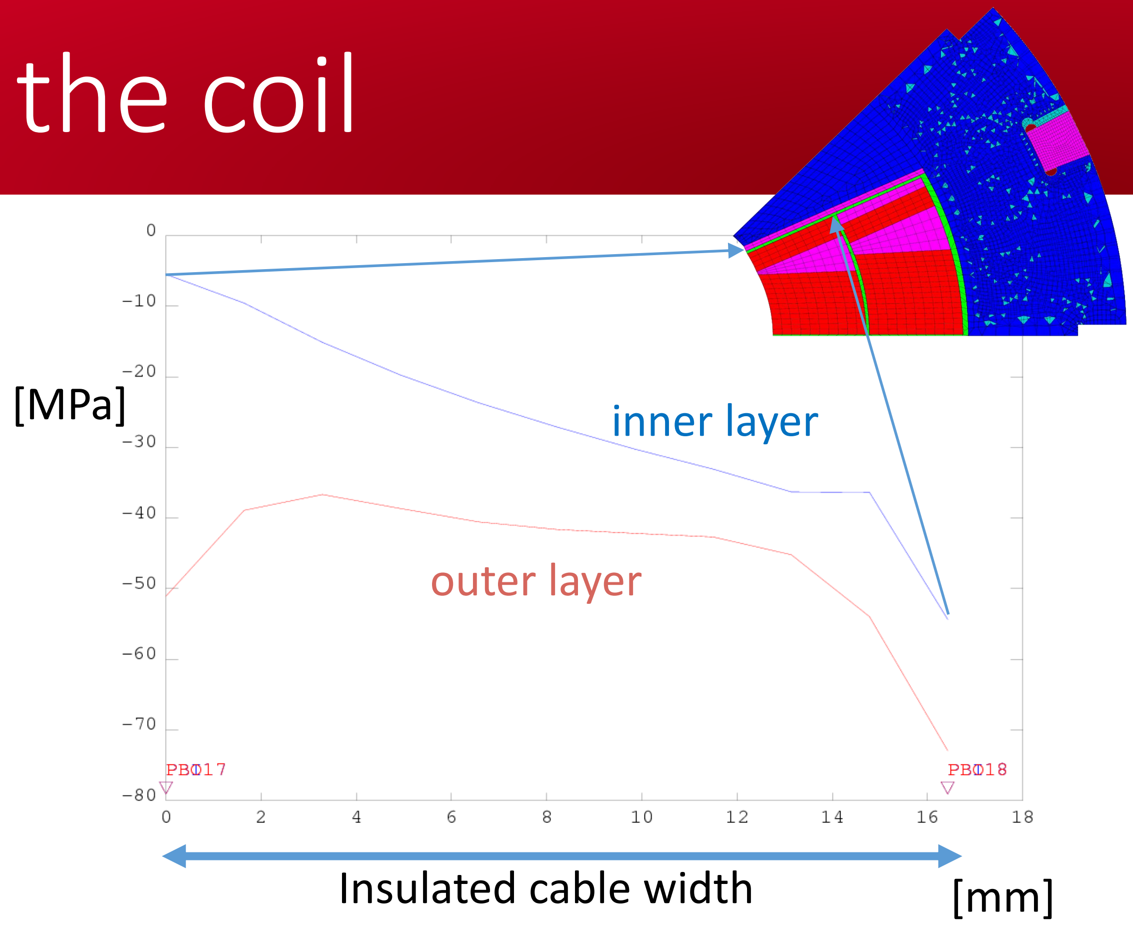
Mechanical properties:

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)



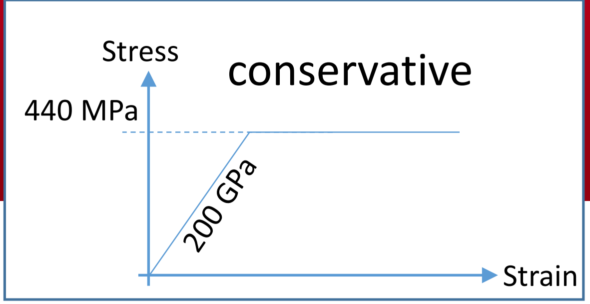
Azimuthal stress in the Nb_3Sn blocks of the coil

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

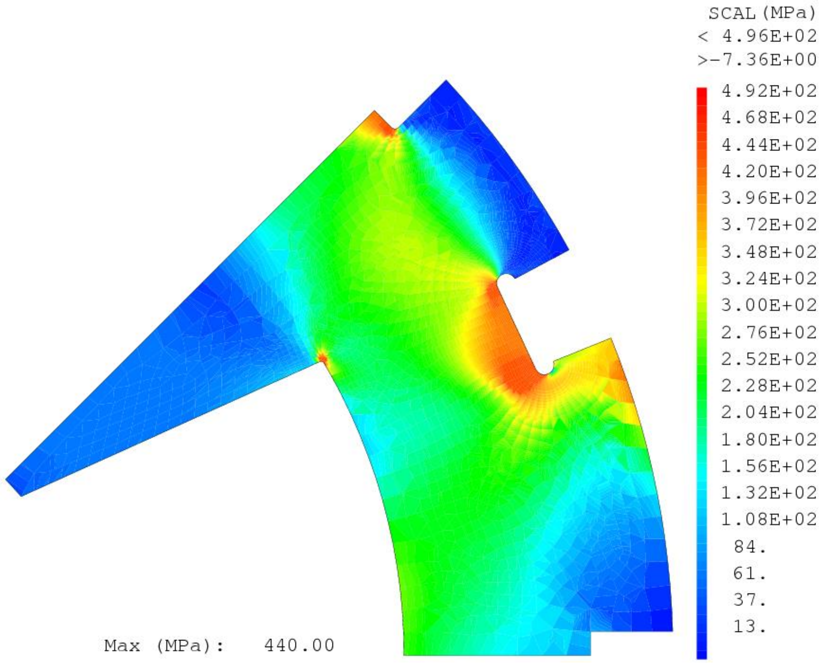
Elasto-plastic model for collar

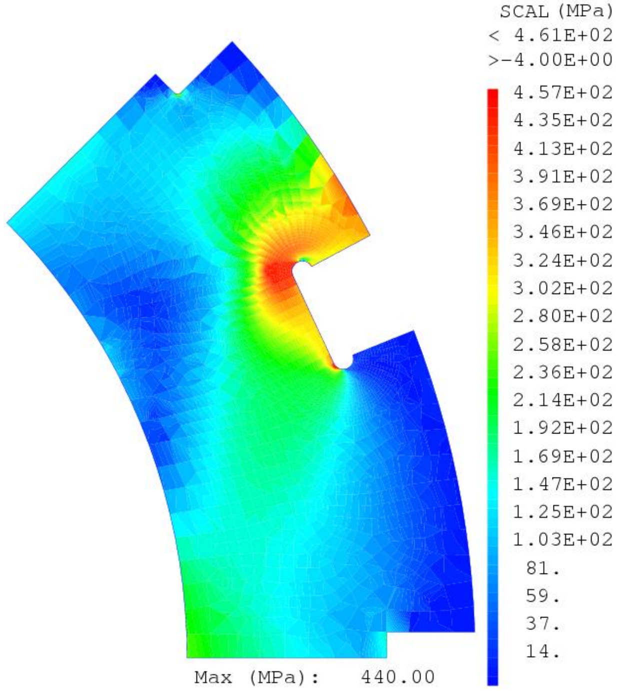


- Collar steel: 13RM19 (LHC quad steel)
- Yield strength of the collars $\sigma_{0.2}$ = 440 MPa*

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**)

Preliminary protection study via CLIQ

- Work under progress at TUT* (Tiina Salmi)
- Assuming a 21 ms delay (detection+validation+triggering)
- A single CLIQ unit (500 V, 50 mF)
- Preliminary hotspot temperature at nominal ~300 K and a peak voltage of 500 V
- More in Tiina’s talk, and more to come in the coming weeks

*Study based on the STEAM-SIGMA software

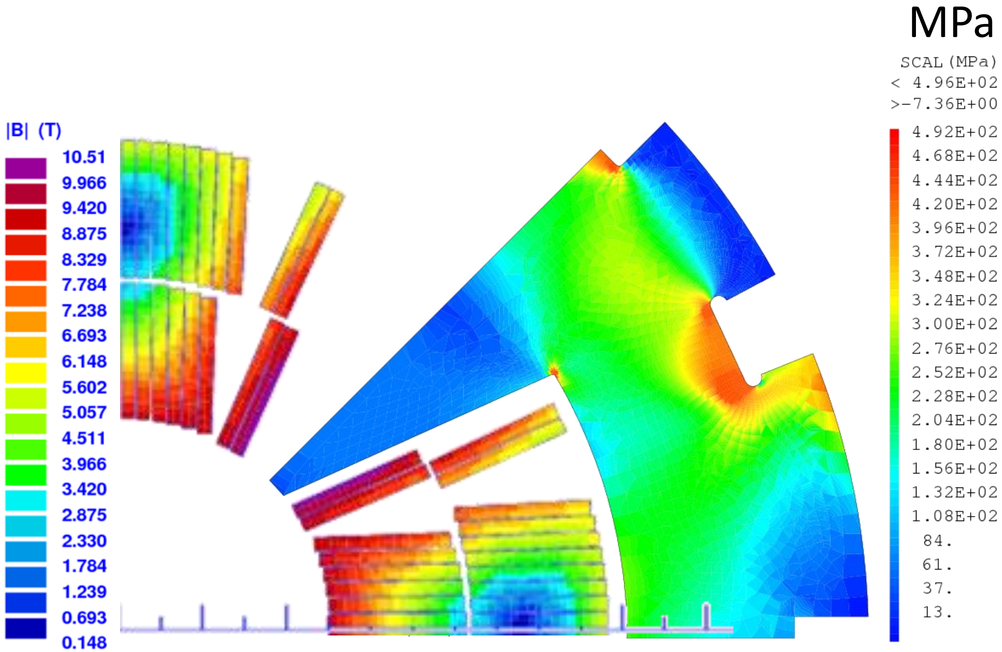
Conclusion

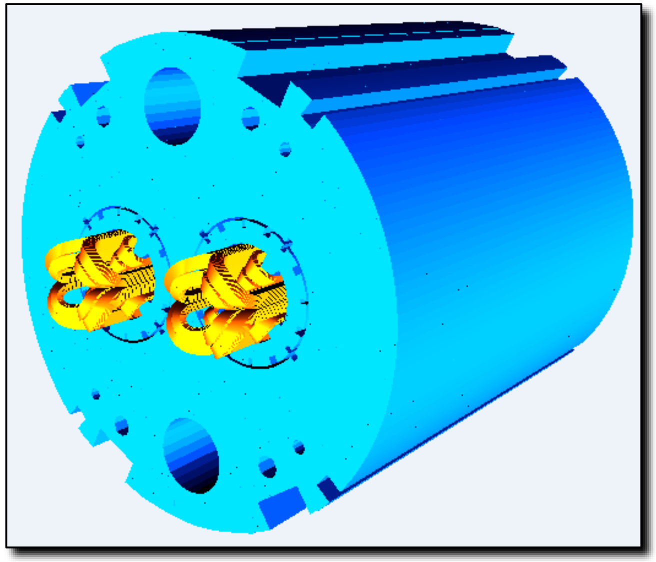
- Emag
  - 2D model
  - 35 MQXF-like strands cable (geometry)
    - 20-55 µm filament – FCC J_c target:
  - 367 T/m gradient at nominal

- Protection (preliminary)
  - protection ~300 K with 21 ms delay before CLIQ firing
  - 500 V to ground (CLIQ unit voltage)

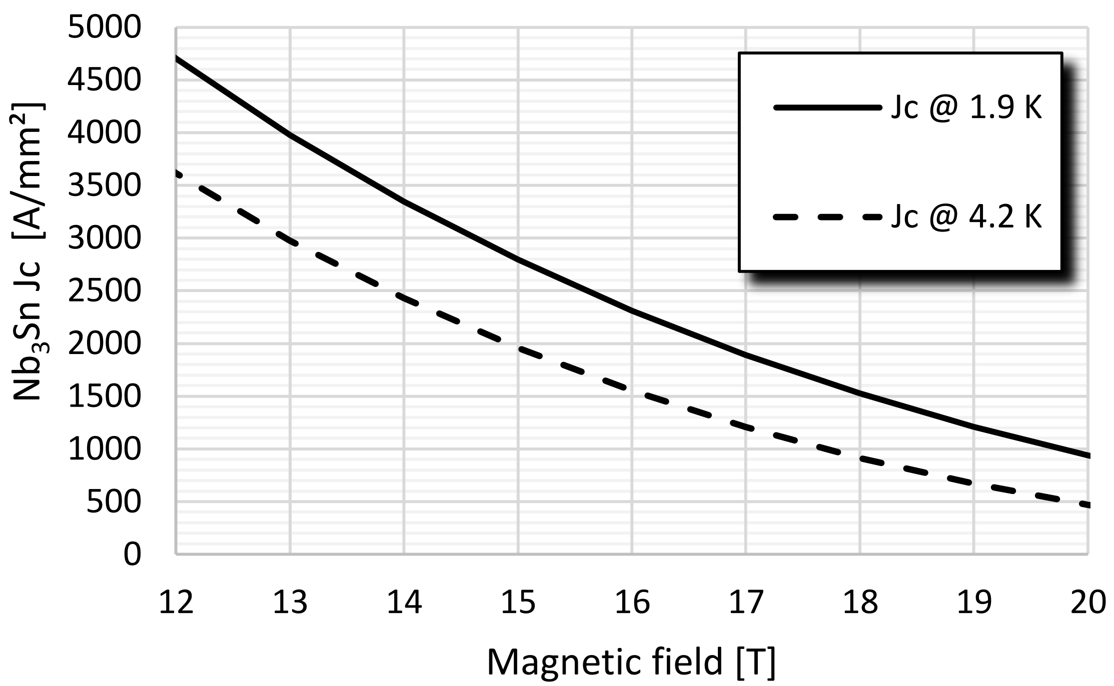
- Mechanics
  - 2D model
    - Collar structure
    - Creep of 10 % after collaring
    - Yield strength of collar 440 MPa
    - Peak stress at room temperature 115 MPa max

- Next steps
  - working out end spacer geometry (3D roxie)
  - Extrapolated the geometry to the wider MQXF cable (40 strands instead of 35 strands) to test the windability…since no 35 strand cable available.
  - 3D model with OPERA





Extra: Jc curve



$$
\begin{cases}
J_c = \dfrac{C(t)}{B} b^{0.5}(1-b)^2 \\
B_{c2}(T) = B_{c20}(1-t^{1.52}) \\
C(t) = C_0(1-t^{1.52})^{\alpha}(1-t^2)^{\alpha}
\end{cases}
$$

where $t = T/T_{c0}$ and $b = B/B_{c2}(t)$ with B the magnetic flux density on the conductors. T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, C_0 = 275880 AT/mm² are fitting parameters computed from the analysis of measurements on the conductor. The cabling degradation is assumed to be 3%.

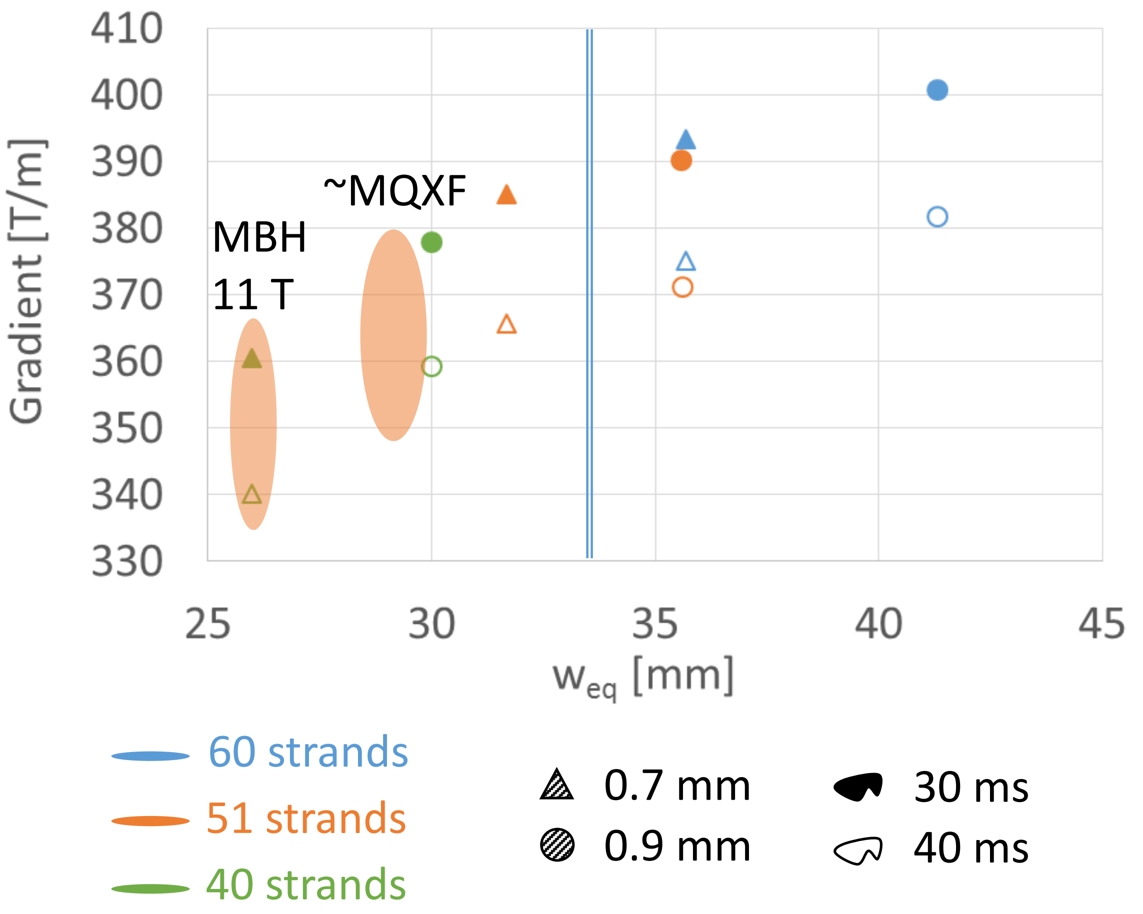
2D exploration of the parameter space

- 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



Various 35 strands cable versions are proposed, they match the thin edge compaction of HL-LHC RRP cables. The cable is based on 0.85 mm MQXF strand, as 0.7 mm 11T strands are extruded from the same billets as MQXF strands, 11T cables can be used as reference, too.

based on MQXF 0.4°

	MQXF 0.4°		v11			
width	18.15 mm		15.956 mm			
mid	1.525 mm	10.3%	1.518 mm	10.7%		
thin	1.462 mm	14.0%	1.462 mm	14%		
THICK	1.588 mm	6.6%	1.574 mm	7.4%		
keystone	0.4°		0.4°			

before HT -> add +1% width; +3% thickness

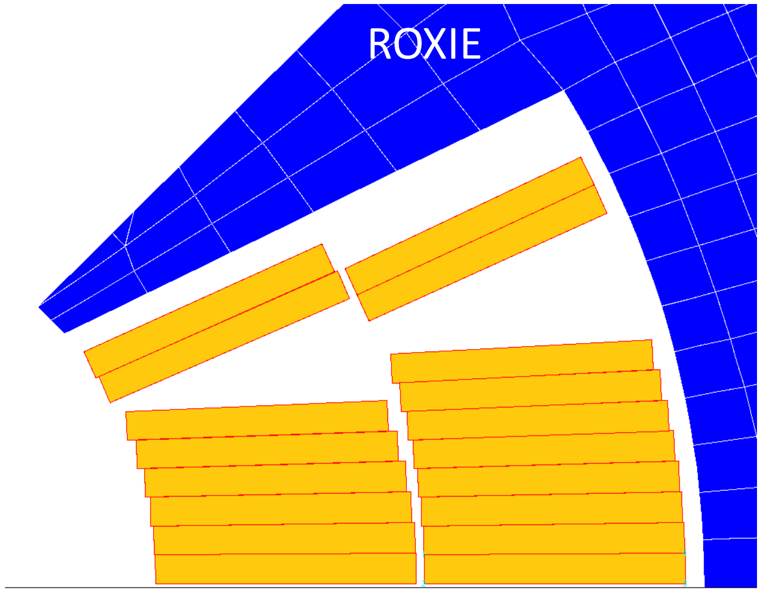
based on MQXF 0.55°

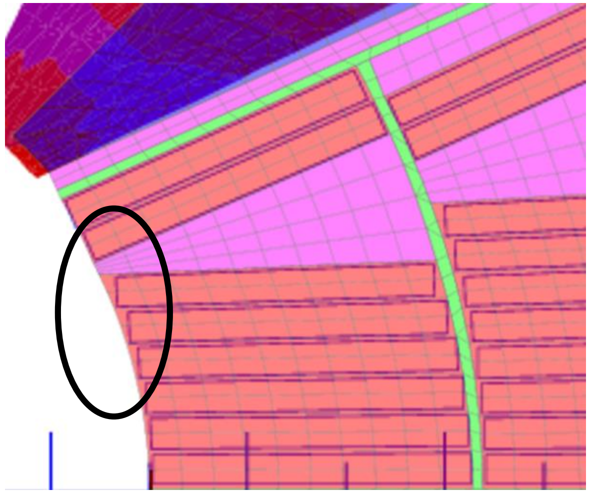
	MQXF 0.55°		v12		v12 bis	
width	18.15 mm		15.956 mm		15.956 mm	
mid	1.525 mm	10.3%	1.493 mm	12.1%	1.515 mm	10.9%
thin	1.438 mm	15.4%	1.438 mm	15.4%	1.438 mm	15.4%
THICK	1.612 mm	5.2%	1.549 mm	8.9%	1.591 mm	6.4%
keystone	0.55°		0.4°		0.55°	

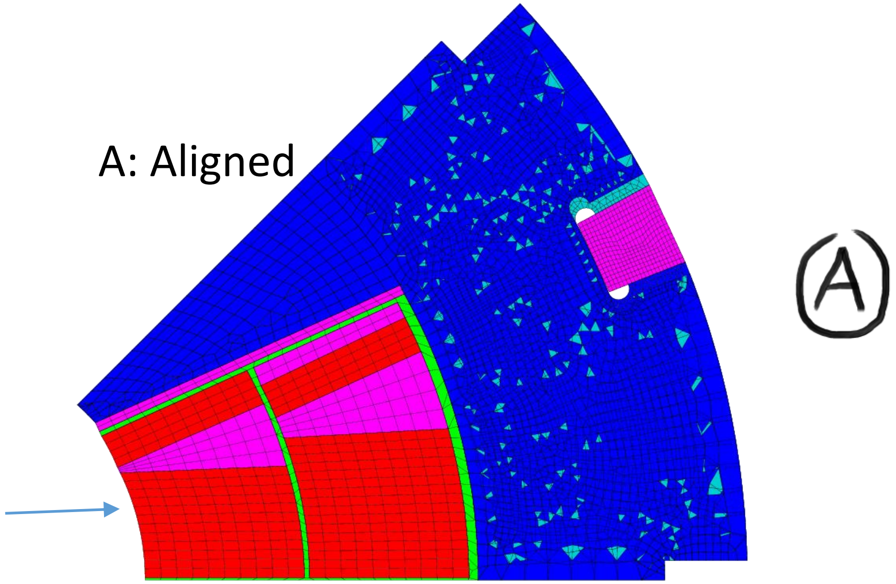
based on 11T 0.79°

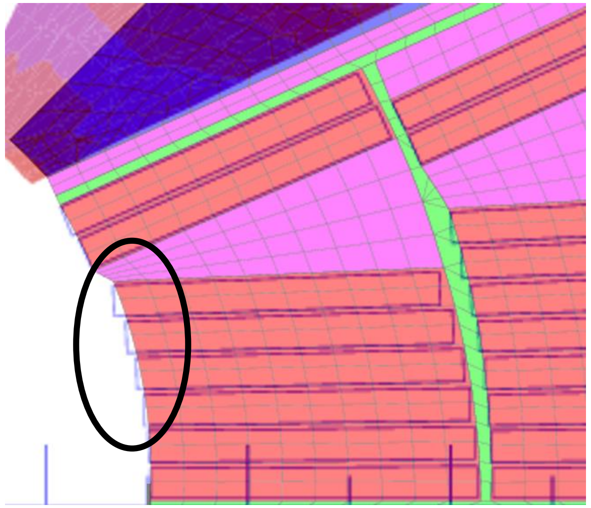
	11T 0.79°		v13		v13 bis	
width	14.70 mm		15.956 mm		15.956 mm	
mid	1.250 mm	10.7%	1.451 mm	14.6%	1.506 mm	11.4%
thin	1.150 mm	17.9%	1.395 mm	17.9%	1.395 mm	17.9%
THICK	1.352 mm	3.4%	1.507 mm	11.4%	1.618 mm	4.9%
keystone	0.79°		0.4°		0.8°	

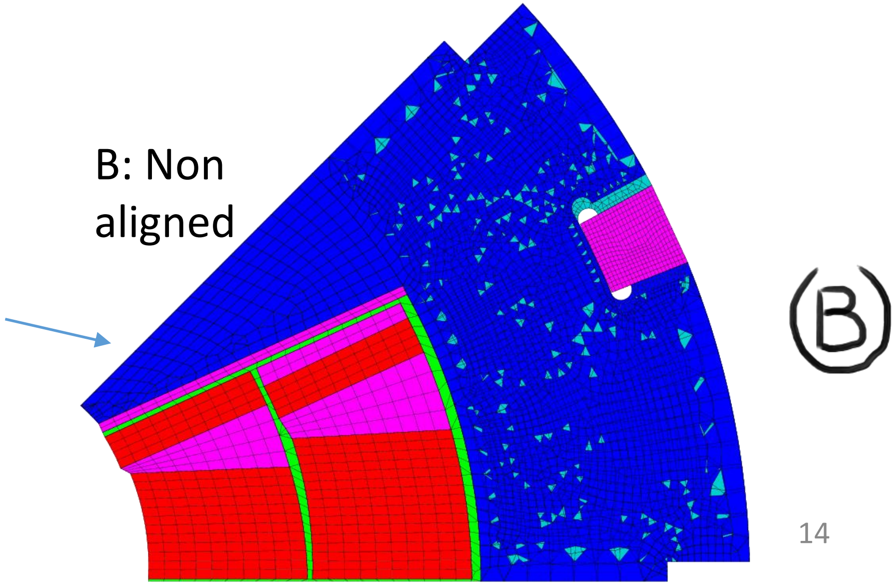
Geometry from Roxie to Cast3m: (A) and (B)







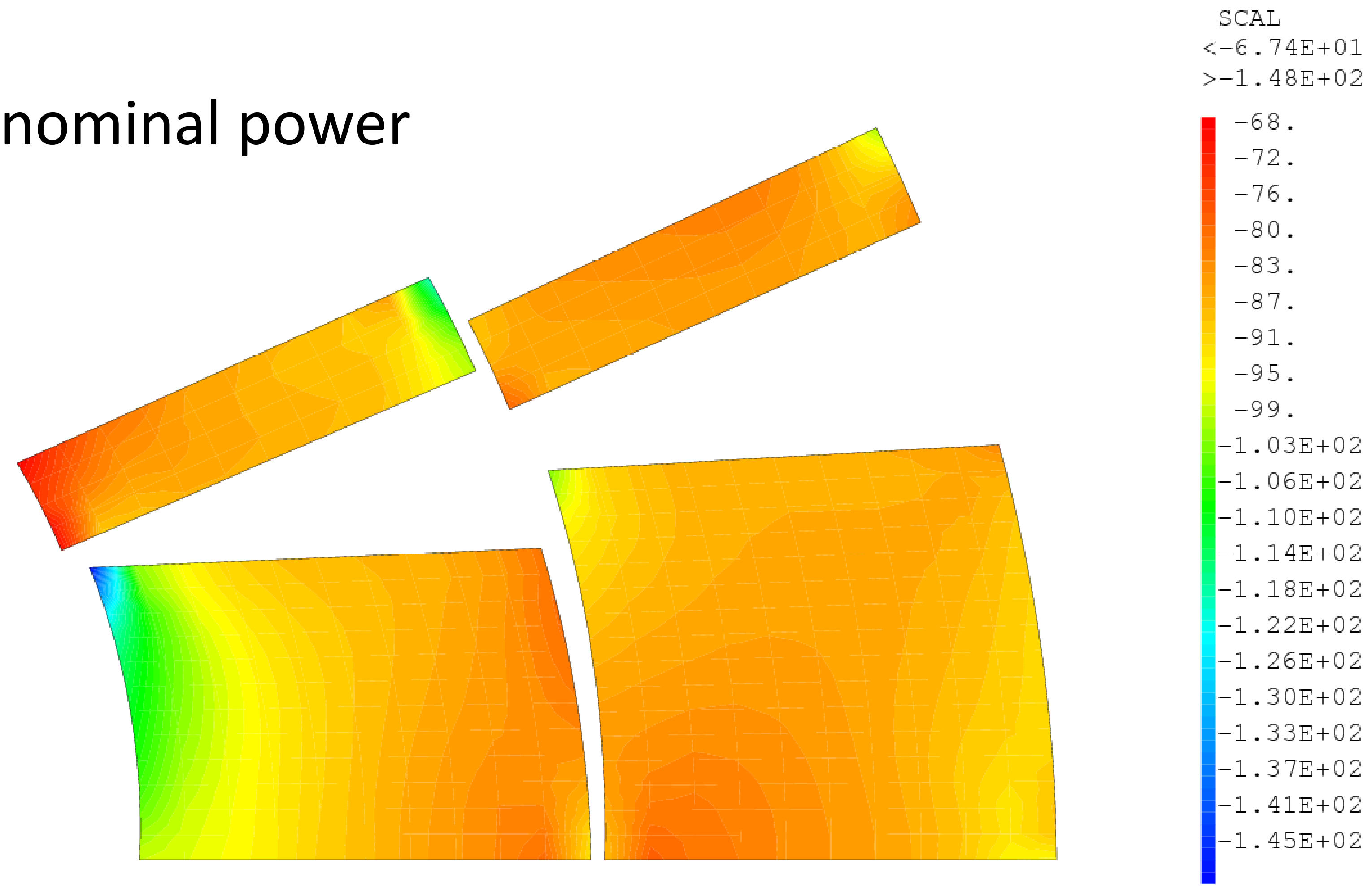




Extra: Max stress in the coil – worse case

Target : - 5 MPa contact at nominal power

- Non aligned blocks
- Elasto-plastic model
- Creep 10% after collaring



CONTRAINTE AZIMUTALE BLOCS, Moyenne et Max (MPa) : -87.671 -148.1

v12 calculation

```
MAXIMUM LOADLINE IN BLOCK   18 (%) .................      79.9305
MINIMUM TEMPERATURE MARGIN IN BLOCK    6 (T) .......       4.6287


HARMONIC ANALYSIS NUMBER ..........................            1
MAIN HARMONIC .....................................            2
REFERENCE RADIUS (mm) .............................      16.7000
X-POSITION OF THE HARMONIC COIL (mm) ..............     125.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............       0.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................   0.2251E-02
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ....................................    -6.136412
MAGNET STRENGTH (T/(m^(n-1)) ......................    -367.4498

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.64653  b 2:  10000.00000  b 3:      0.05803
b 4:      0.02041  b 5:     -0.01971  b 6:      0.27404
b 7:     -0.00836  b 8:     -0.00785  b 9:      0.01070
b10:     -0.27522  b11:      0.00194  b12:      0.00331
b13:     -0.00308  b14:     -0.17019  b15:     -0.00011
b16:     -0.00100  b17:      0.00065  b18:     -0.20609
b19:     -0.00008  b20:      0.00024  b
```