FCC main quadrupole magnets: preliminary study at CEA

Clément LORIN

Acknowledgment
Franck BORGNOLUTTI, Jean-Michel RIFFLET, Pierre VEDRINE (CEA)
Luca BOTTURA, Mikko KARPPINEN, Ezio TODESCO (CERN)

Target

	G (T/m)	B_{peak} (T)	Bore (mm)	Length (units x m)
MQ FCC	450	13	50	800 x 6
MQ LHC	223	6.5	56	392 x 3.2

Number of apertures	(-)	2	
Inter-aperture spacing	(mm)	250	194
Operating temperature	(K)	1.9	
Margin along the loadline	(%)	20	
Yoke ID max	(mm)	250	
Yoke OD max	(mm)	700	

Nb_3Sn Jc fit

$$B_{c2}(T) = B_{c20}\left(1-\left(\frac{T}{T_{c0}}\right)^2\right)\left(1-0.31\left(\frac{T}{T_{c0}}\right)^2\left(1-1.77\ln\left(\frac{T}{T_{c0}}\right)\right)\right),$$

$$J_c(B,T) = \frac{C}{\sqrt{B}}\left(1-\frac{B}{B_{c2}(T)}\right)^2\left(1-\left(\frac{T}{T_{c0}}\right)^2\right)^2.$$

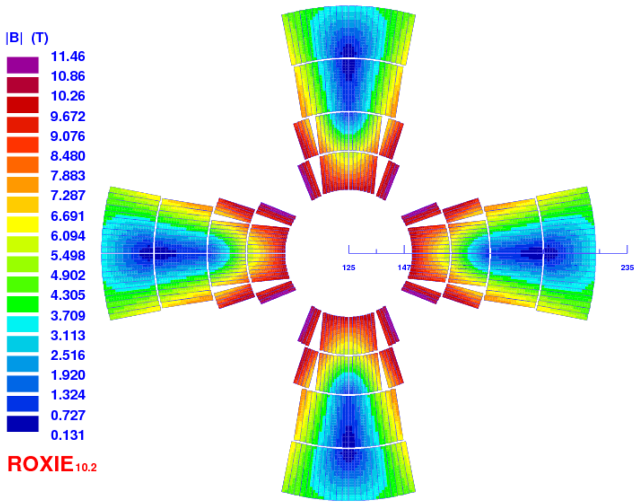
C	= 4.4559e10	[A $T^{0.5}$ m^{-2}]
Bc20	= 29.08	[T]
Tc0	= 17.81	[K]

We all need to have the same data for fair and easy comparison of the designs.
Fit parameters by M. Karppinen (CERN) based on target Jc values from L. Bottura (CERN)

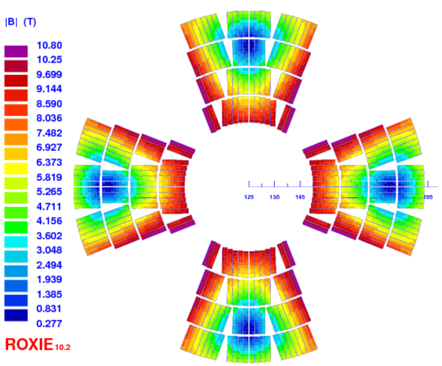
Summers L.T. A model for the prediction of Nb3Sn critical current as a function of field, temperature,strain, and radiation damage, IEEEE trans. on mag. 27,2,1991

Sweep of possibilities

- 407 T/m
- 20%
- 2 Nb_3Sn x 15 mm
- 2 Nb-Ti x 20 mm



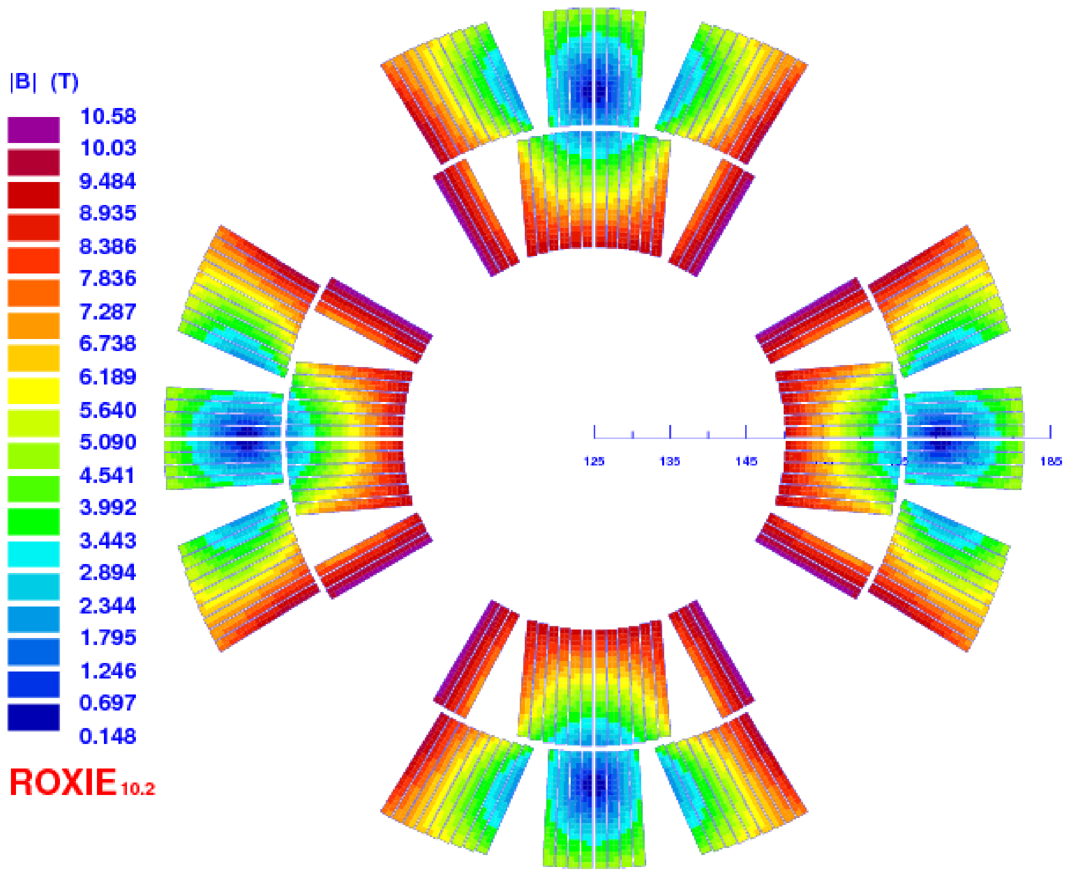
- 386 T/m
- 20%
- 4 Nb_3Sn x 10 mm
- No grading



Possible room for improvement by internal grading as in MQY

→ Only double Nb_3Sn layer designs are shown hereafter

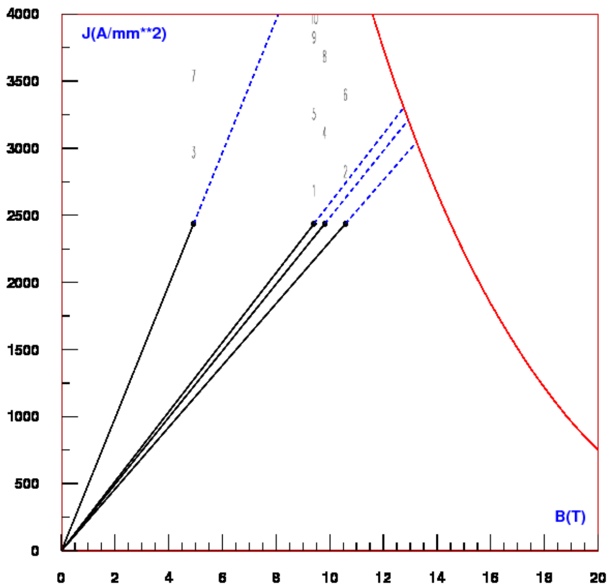
2 layers – angle: V1

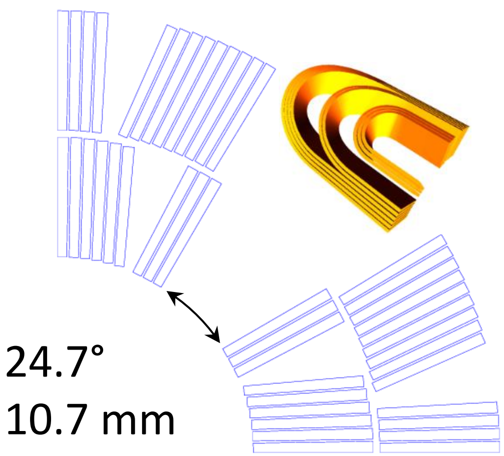


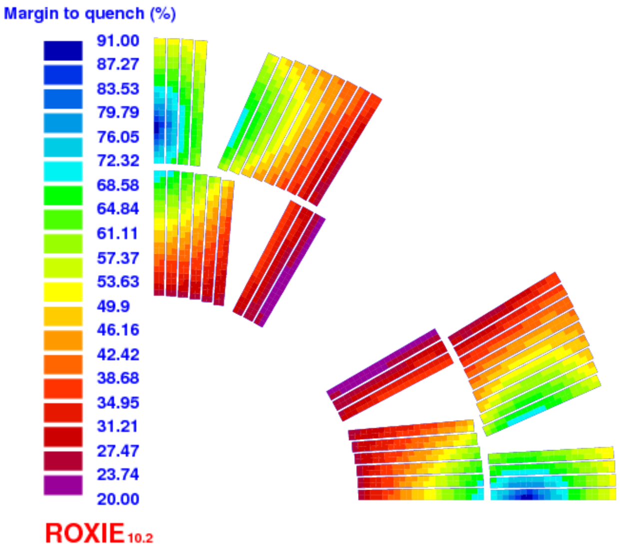
Cable parameter*	value	unit
strand diameter	0.7	mm
nb of strands	42	N/A
width	15.20	mm
thin edge	1.182	mm
THICK edge	1.400	mm
average thickness	1.291	mm
keystone angle	0.82	°
pitch length	120	mm
Packing Factor	84.9	%
thin edge compaction	84.4	%
THICK edge compaction	100.0	%
I_c degradation	10	%

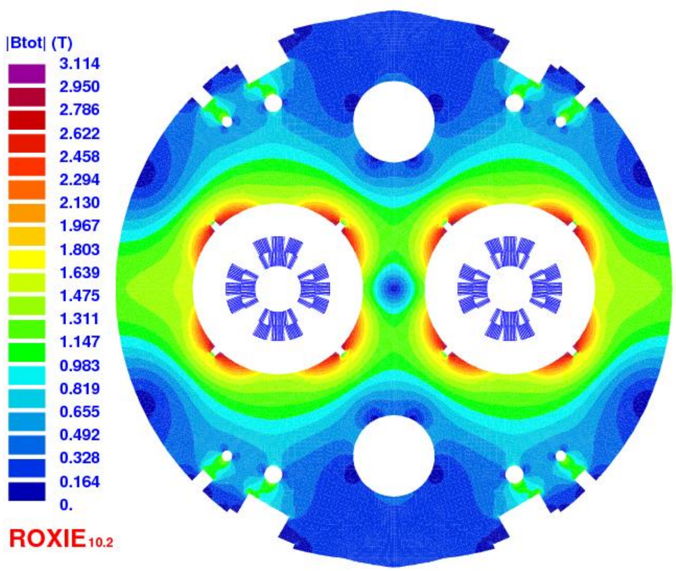
*CEA, C. Lorin

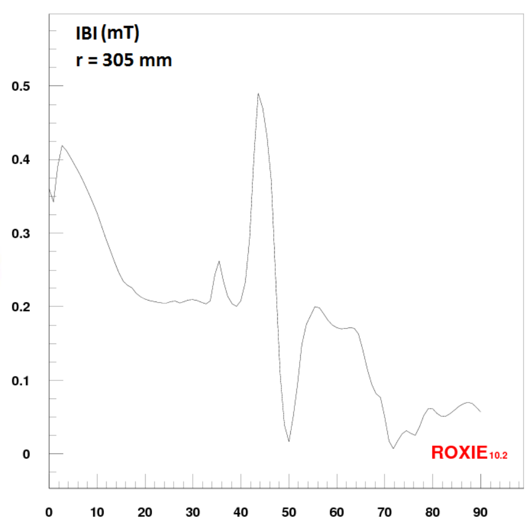
Loadline – Temp. margins : V1

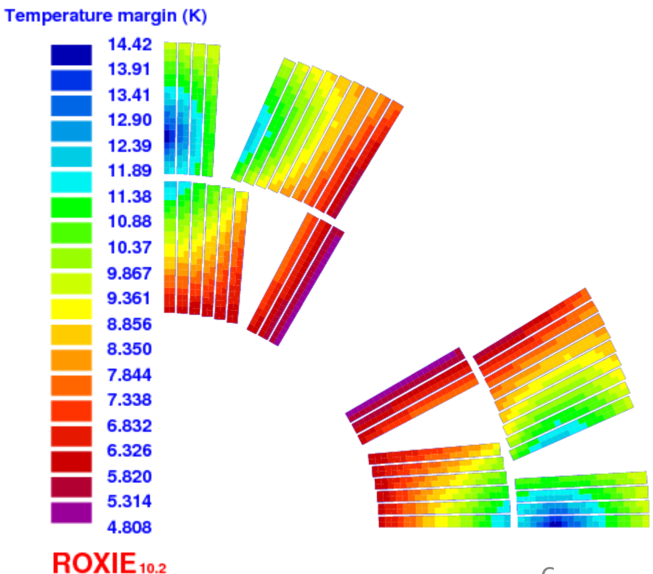










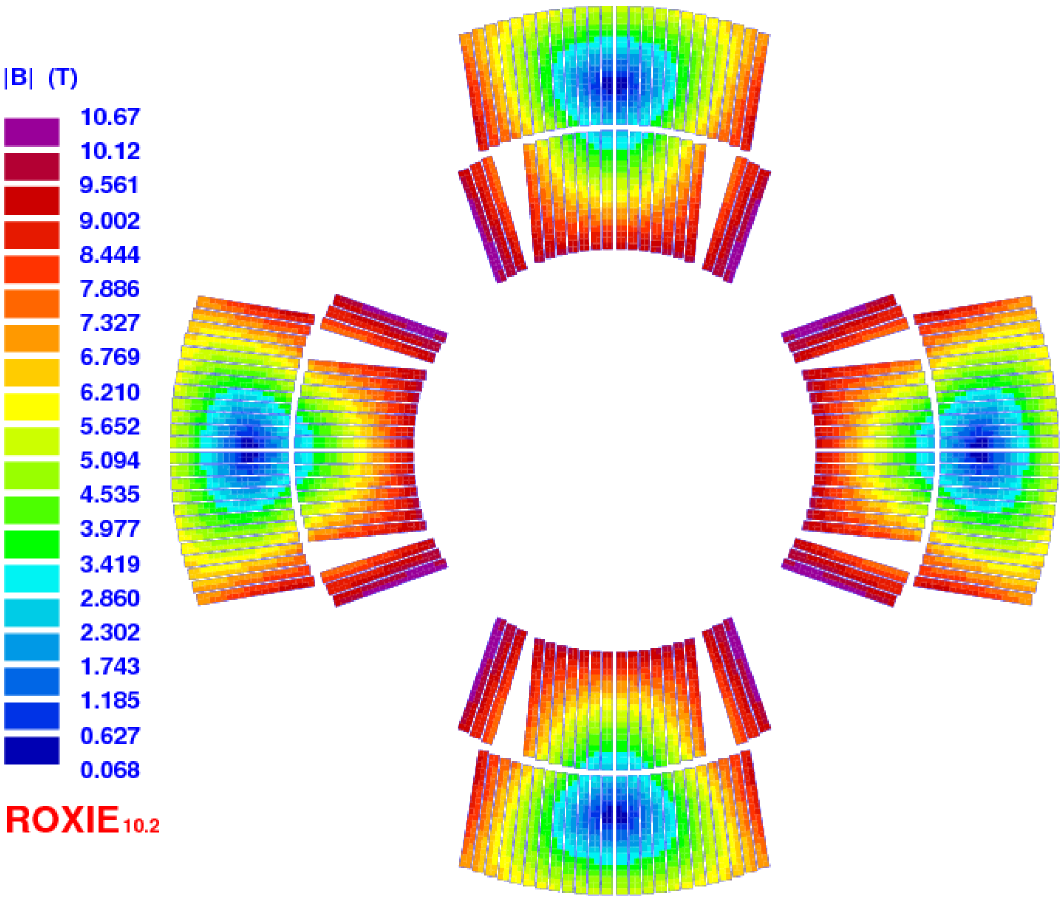


Main quantities : V1

Quantity	Value	Unit
$G_{I_{nom}}$	377	T/m
I_{nom}	19,420	A
Margin loadline	20.0	%
Margin temp.	4.8	K
B_{peak}	10.58	T
Inductance diff.	2.78	mH/m
Stored energy	528	kJ/m
Nb turns	22	N/A
inner layer	9	N/A
outer layer	13	N/A
Yoke ID	184	mm
Yoke OD	600	mm
Fx (per ½-coil)	1160	kN/m
Fy (per ½-coil)	-1646	kN/m
Opening angle insulated	24.7	°

Quantity	Value	Unit
b6 @ 2/3 aperture	0.05	10^{-4}
b10 @ 2/3 aperture	-0.42	10^{-4}
b14 @ 2/3 aperture	1.03	10^{-4}
b6 @ r = 10 mm	0.006	10^{-4}
b10 @ r = 10 mm	0.007	10^{-4}
b14 @ r = 10 mm	0.002	10^{-4}
T	1.9	K
F _I_ inner layer	-800	kN/m
F _I_ outer layer	-1019	kN/m

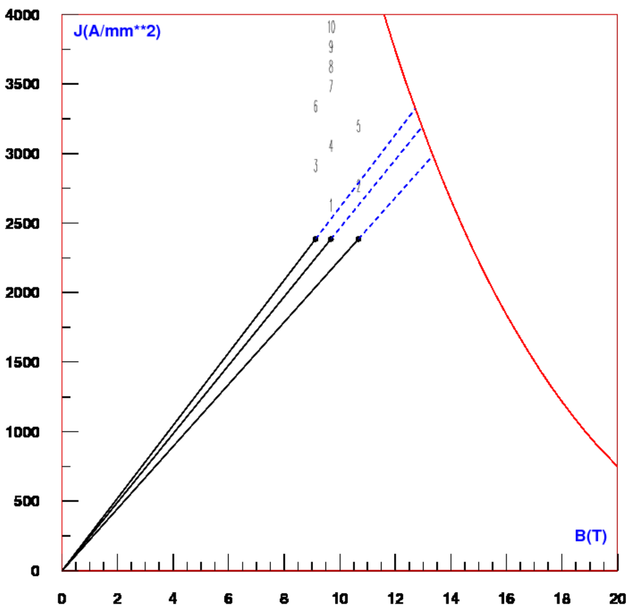
2 layers – 3 blocks: V2

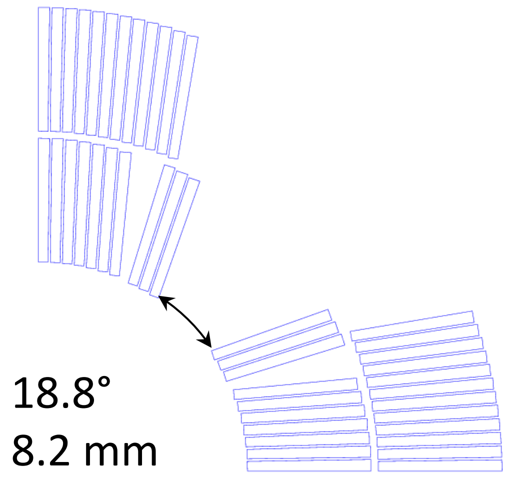


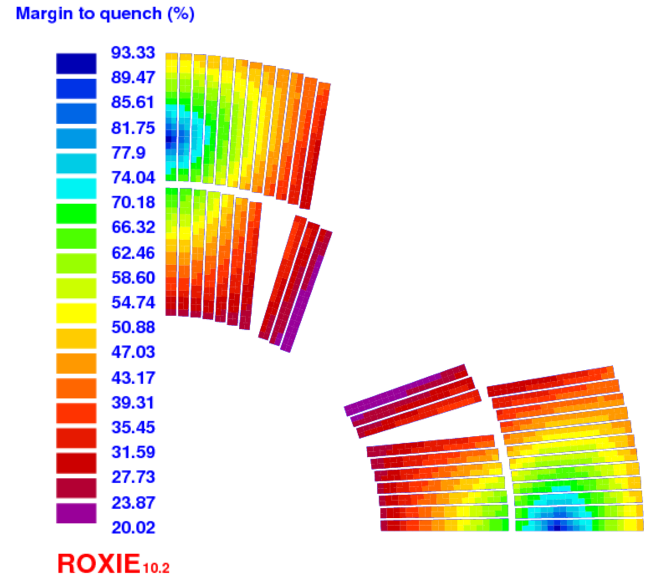
Cable parameter*	value	unit
strand diameter	0.7	mm
nb of strands	40	N/A
width	14.71	mm
thin edge	1.150	mm
THICK edge	1.353	mm
average thickness	1.251	mm
keystone angle	0.79	°
pitch length	110	mm
Packing Factor	86.6	%
thin edge compaction	82.2	%
THICK edge compaction	96.6	%
I_c degradation	10	%

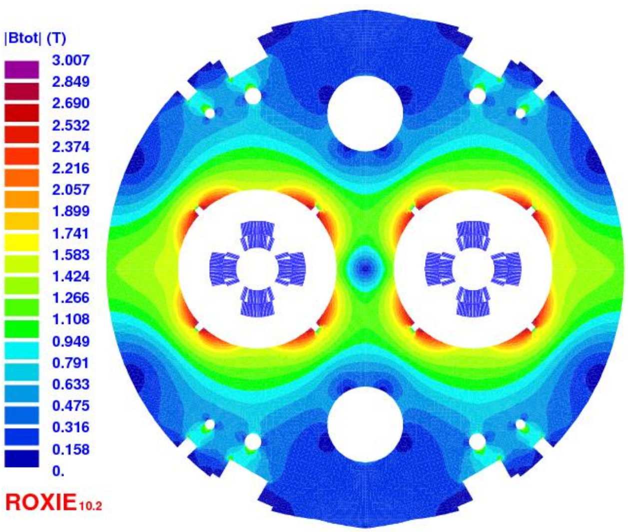
***FNAL: Barzi E.** et al., Superconducting strand and cable development for the LHC upgrades and beyond, IEEE Trans. on Appl. Supercond. 23 3 2013.

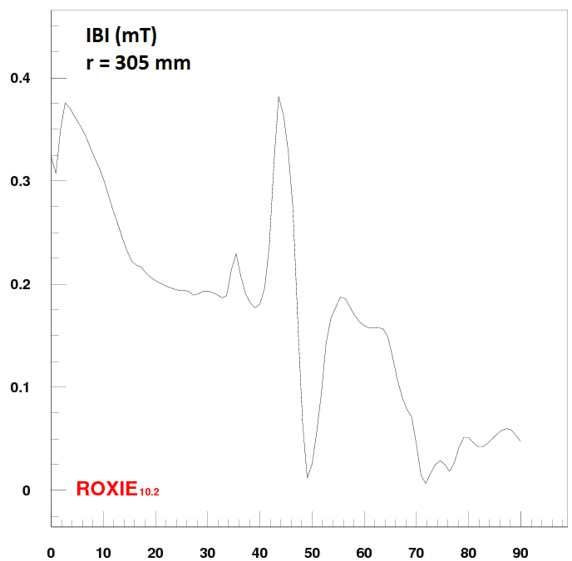
Loadline – Temp. margins : V2

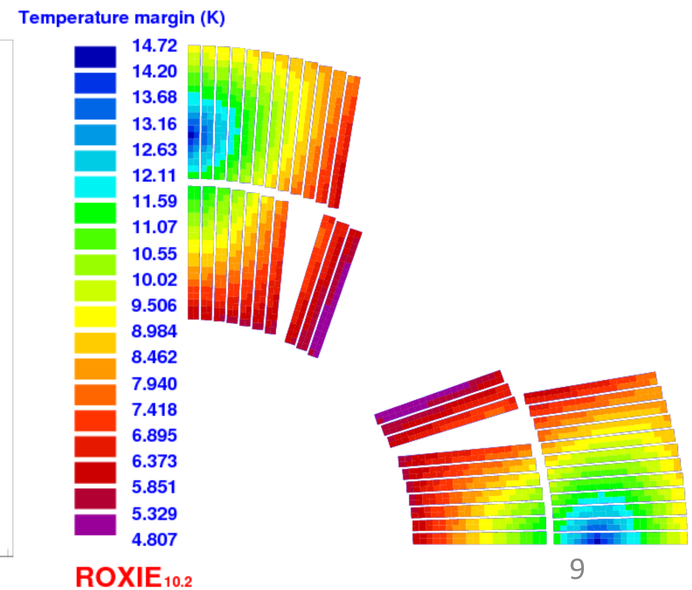










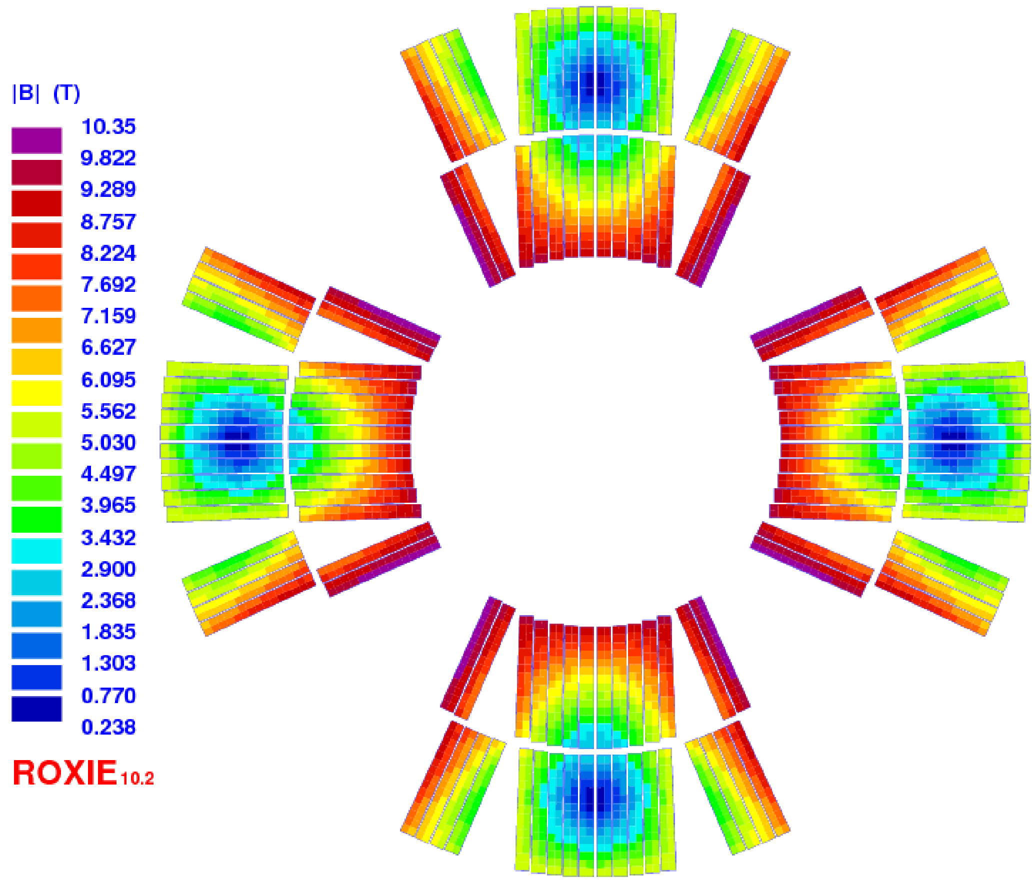


Main quantities : V2

Quantity	Value	Unit
$G_{I_{nom}}$	385	T/m
I_{nom}	18,110	A
Margin loadline	20.02	%
Margin temp.	4.81	K
B_{peak}	10.67	T
Inductance diff.	3.2	mH/m
Stored energy	522	kJ/m
Nb turns	22	N/A
inner layer	10	N/A
outer layer	12	N/A
Yoke ID	184	mm
Yoke OD	600	mm
Fx (per ½-coil)	1024	kN/m
Fy (per ½-coil)	-1575	kN/m
Opening angle insulated	18.8	°

Quantity	Value	Unit
b6 @ 2/3 aperture	-0.02	10^{-4}
b10 @ 2/3 aperture	-0.83	10^{-4}
b14 @ 2/3 aperture	0.39	10^{-4}
b6 @ r = 10 mm	-0.003	10^{-4}
b10 @ r = 10 mm	-0.01	10^{-4}
b14 @ r = 10 mm	0.001	10^{-4}
T	1.9	K
F _I_ inner layer	-837	kN/m
F_I_ outer layer	-861	kN/m

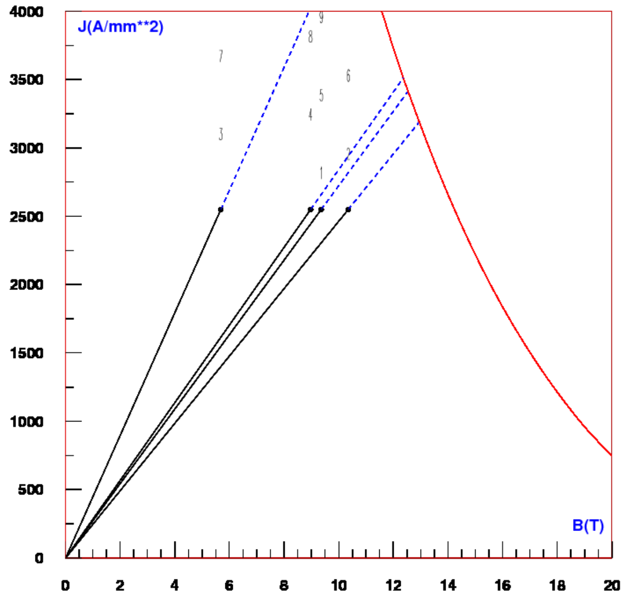
2 layers – low inductance: V3

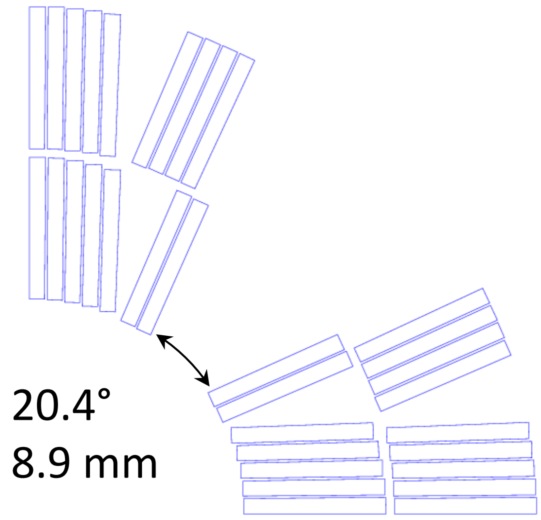


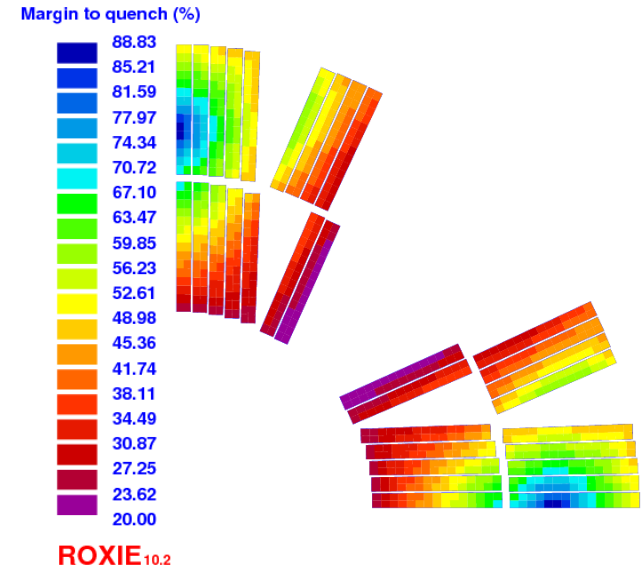
Cable parameter*	value	unit
strand diameter	1.0	mm
nb of strands	30	N/A
width	14.423	mm
thin edge	1.772	mm
THICK edge	1.895	mm
average thickness	1.833	mm
keystone angle	0.43	°
pitch length	111	mm
Packing Factor	81.6	%
thin edge compaction	88.6	%
THICK edge compaction	94.8	%
I_c degradation	10	%

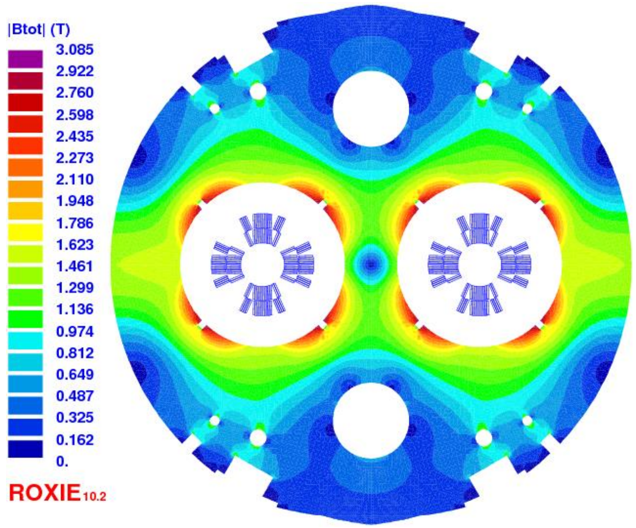
*CERN, from Mikko Karppinen/Luca Bottura

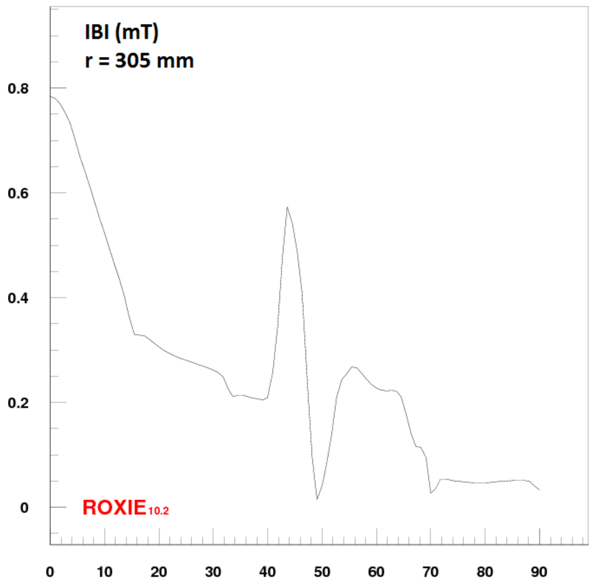
Loadline – Temp. margins : V3

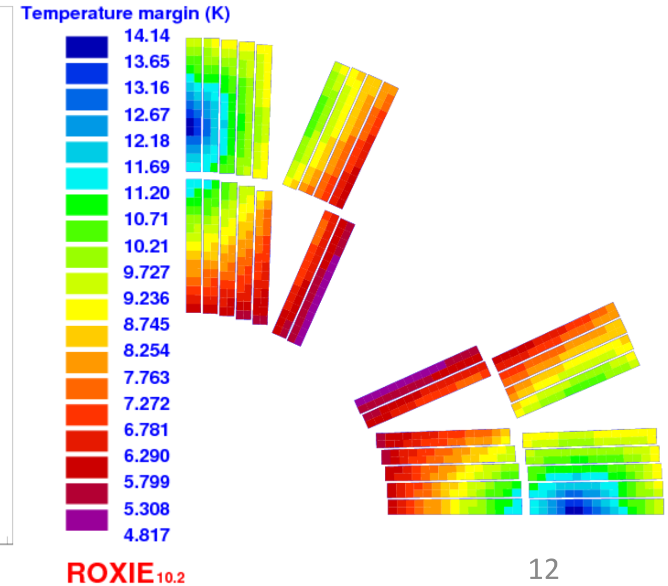










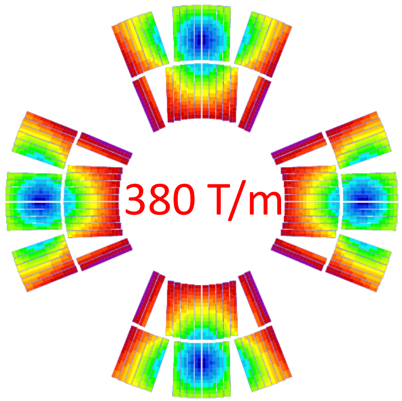


Main quantities : V3

Quantity	Value	Unit
$G_{I_{nom}}$	375	T/m
I_{nom}	26710	A
Margin loadline	20.00	%
Margin temp.	4.78	K
B_{peak}	10.35	T
Inductance diff.	1.54	mH/m
Stored energy	551	kJ/m
Nb turns	16	N/A
inner layer	7	N/A
outer layer	9	N/A
Yoke ID	190	mm
Yoke OD	600	mm
Fx (per ½-coil)	1126	kN/m
Fy (per ½-coil)	-1648	kN/m
Opening angle insulated	20.4	°

Quantity	Value	Unit
b6 @ 2/3 aperture	-0.01	10^{-4}
b10 @ 2/3 aperture	0.004	10^{-4}
b14 @ 2/3 aperture	0.52	10^{-4}
b6 @ r = 10 mm	0.004	10^{-4}
b10 @ r = 10 mm	-	10^{-4}
b14 @ r = 10 mm	0.001	10^{-4}
T	1.9	K
F_I_ inner layer	-824	kN/m
F_I_ outer layer	-956	kN/m

Consideration 1 (based on 800 x 6 m x 450 T/m)

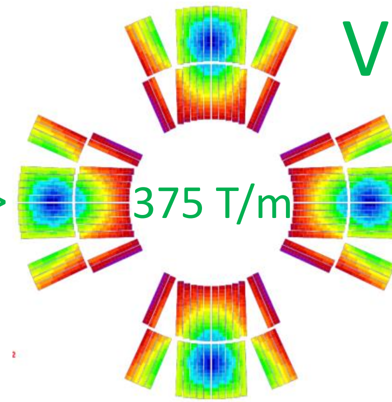


- 17 turns - >
- 7.1 m
- 'saved':

  10 cm x 16 turns x 8 half-coils

  = 12.8 m

V3



- 16 turns - >
- 7.2 m
- 'saved':

  7.1 m x 1 turn x 8 half-coils

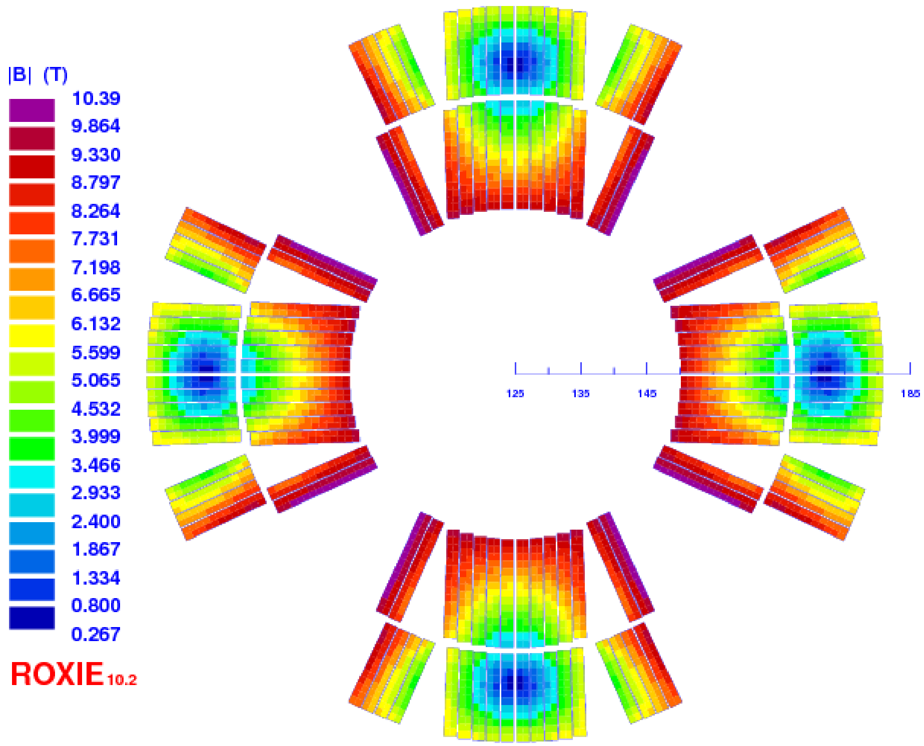
  = 56.8 m

- Real cable saving: (56.8 m -12.8 m) x 800 mag. = 35.2 km*
- Cable length for 1 magnet = 16 turns x 8 half-coils x 8 m ≈ 1 km

→ Savings = the cable length for the spare quads

*80 m of magnet material like:
Al shell
Fe pad/Bronze pole or StSt collar
Fe yoke

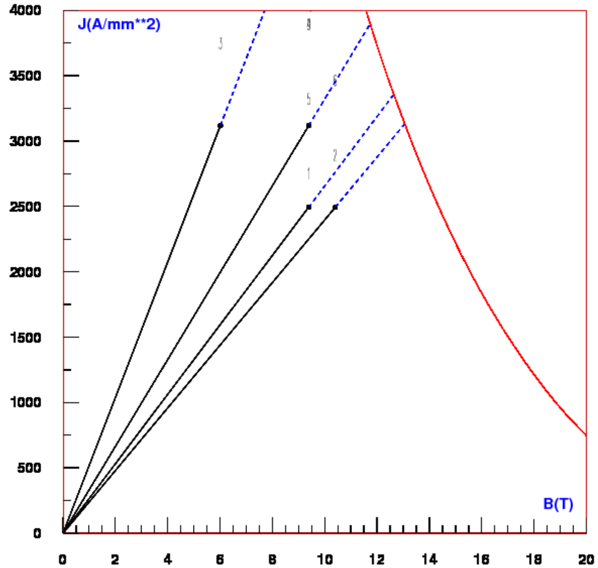
2 layers – cable graded: V4

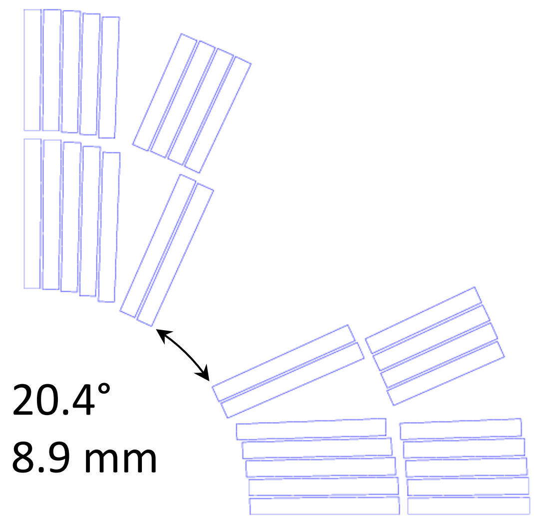


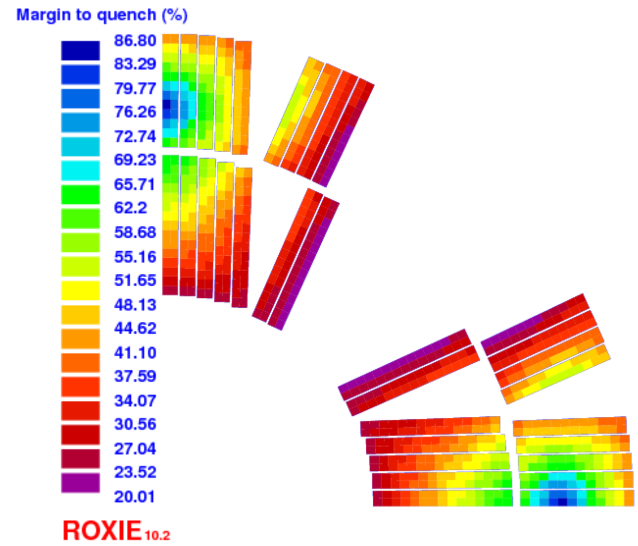
Cable parameter*	Nb_3Sn	Nb_3Sn	unit
strand diameter	1.0	1.0	mm
nb of strands	30	24	N/A
width	16.423	13.314	mm
thin edge	1.772	1.780	mm
THICK edge	1.896	1.880	mm
average thickness	1.834	1.830	mm
keystone angle	0.43	0.43	°
pitch length	111	90	mm
Packing Factor	81.6	80.7	%
thin edge compaction	88.6	89.0	%
THICK edge compaction	94.8	94.0	%
I_c degradation	10	10	%

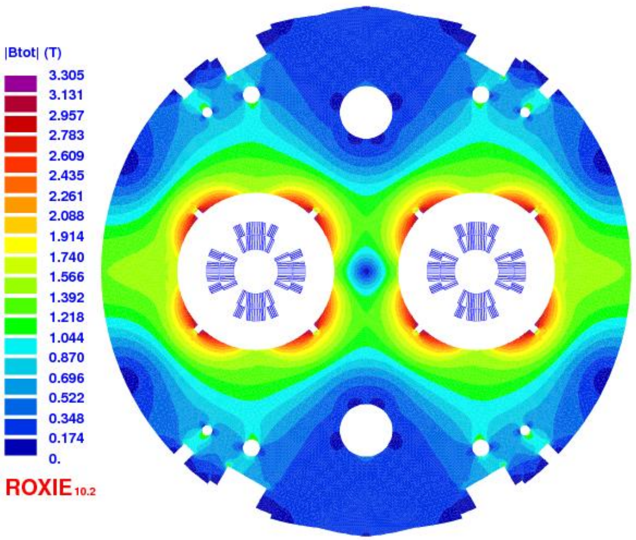
*CERN-CEA, from Mikko Karppinen/Luca Bottura/Clement Lorin

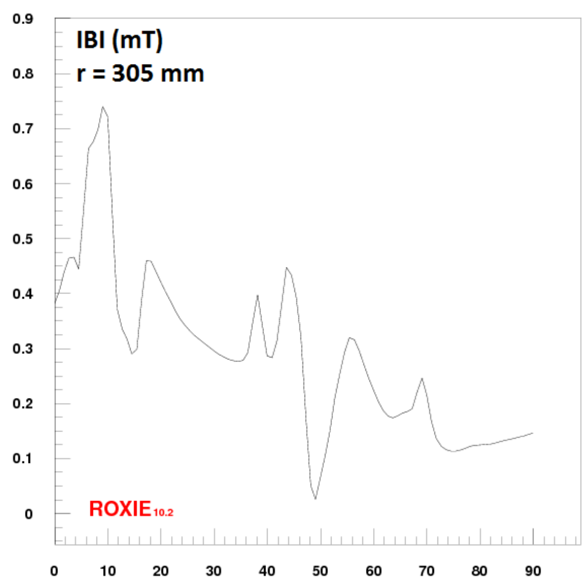
Loadline – Temp. margins : V4

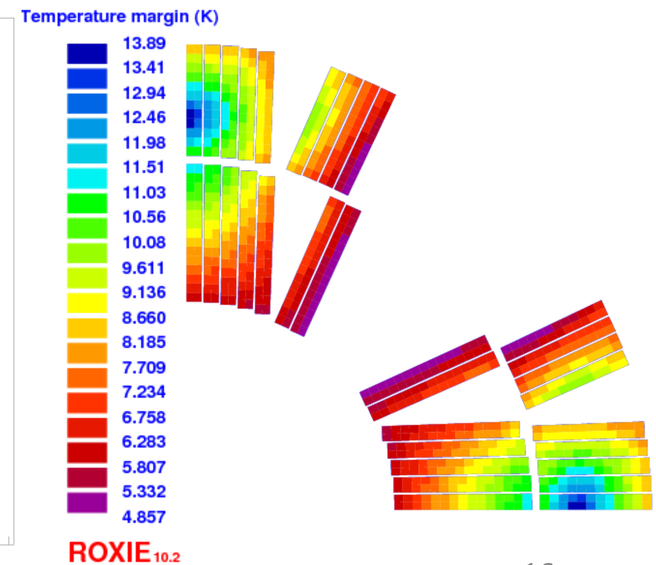












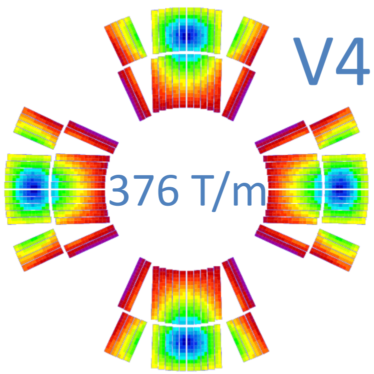
Main quantities : V4

Quantity	Value	Unit
$G_{I_{nom}}$	376	T/m
I_{nom}	26115	A
Margin loadline	20.01	%
Margin temp.	4.85	K
B_{peak}	10.39	T
Inductance diff.	1.58	mH/m
Stored energy	544	kJ/m
Nb turns	16	N/A
inner layer	7	N/A
outer layer	9	N/A
Yoke ID	178	mm
Yoke OD	600	mm
Fx (per ½-coil)	1139	kN/m
Fy (per ½-coil)	-1660	kN/m
Opening angle insulated	20.4	°

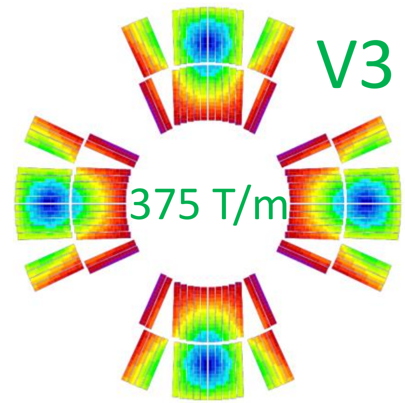
Quantity	Value	Unit
b6 @ 2/3 aperture	0.07	10^{-4}
b10 @ 2/3 aperture	0.07	10^{-4}
b14 @ 2/3 aperture	0.51	10^{-4}
b6 @ r = 10 mm	0.009	10^{-4}
b10 @ r = 10 mm	0.001	10^{-4}
b14 @ r = 10 mm	0.001	10^{-4}
T	1.9	K
F_I_ inner layer	-811	kN/m
F_I_ outer layer	-985	kN/m

Consideration 2 (based on 800 x 6 m x 450 T/m)

- 16 turns - >
- 7.2 m



- 16 turns - >
- 7.2 m



- 'saved':

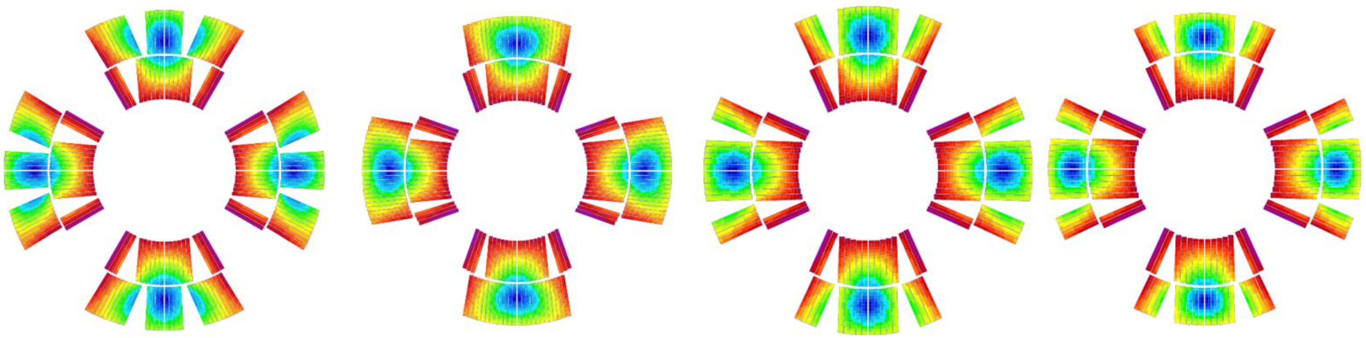
  6 strands x 9 outer turns x 8 half-coils x 710 mag. = 306720 str. total
- 1 magnet = (7 inn. turns x 30 str. + 9 out. turns x 24 str.) x 8 half-coils = 3408 str./magnet

- Savings = conductors for the 90 remaining magnets

Conclusion

- 2 layers design: 375 T/m -> grading needed to go to higher gradient
- Layer jump alignment (no easy way bending?)
- Graded - > Splice ?
- Opening angle as wide as possible (end design)
- Optimization: integrated gradient (T.m/m) vs quantity of conductors

Summary - Thank you



Quantity	V1	V2	V3	V4	Unit
$G_{I_{nom}}$	377	385	375	376	T/m
I_{nom}	19 420	18 110	26 710	26 115	A
Inductance diff.	2.78	3.2	1.54	1.58	mH/m
Stored energy	528	522	551	544	kJ/m
Nb of turns	22	22	16	16 graded	N/A
Angle (insulated)	24.7	18.8	20.4	20.4	°
Fx (per ½-coil)	1160	1024	1126	1139	kN/m
Fy (per ½-coil)	-1646	-1575	-1648	-1660	kN/m
F _I_ inner layer	-800	-837	-824	-811	kN/m
F _I_ outer layer	-1019	-861	-956	-985	kN/m
ϕ x Nb of strands	0.7 x 42	0.7 x 40	1.0 x 30	1.0 x 30 1.0 x 24	mm x N/A

V2 @ 385 T/m vs. 375 T/m

Quantity	Value	Value	Unit
$G_{I_{nom}}$	**385**	**375**	T/m
I_{nom}	**18,110**	**17 630**	A
Margin loadline	**20.02**	**22.1**	%
Margin temp.	**4.81**	**5.18**	K
B_{peak}	**10.67**	**10.39**	T
Inductance diff.	**3.2**	**3.17**	mH/m
Stored energy	**522**	**495**	kJ/m
Nb turns	**22**	**22**	N/A
inner layer	**10**	**10**	N/A
outer layer	**12**	**12**	N/A
F_I_ inner layer	**-837**	**-793**	kN/m
F_I_ outer layer	**-861**	**-816**	kN/m
Fx (per ½-coil)	**1024**	**971**	kN/m
Fy (per ½-coil)	**-1575**	**-1492**	kN/m
Opening angle insulated	**18.8**	**18.8**	°

FROM RESEARCH TO INDUSTRY

Main Quadrupoles

« In order to save money and complexity over the whole project, the coil is not graded, and the same cable, identical to the one used for the outer layer of the MBs, is employed to wind both layers of the quadrupoles. This means that the magnetic design is not fully optimized but allows the use of real double pancake techniques, avoiding the splice between layers in the high field region »

Lucio Rossi in ***THE LHC SUPERCONDUCTING MAGNETS,*** 2003 Particle accelerator conference, 12-16 may 2003, Portland , USA