2004 LAPAC Review

IR Quad Design Studies

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Introduction

There are two fundamental inner triplet design approaches (both need large-aperture quadrupoles):

a) Single-bore magnets. Quadrupoles with the largest possible aperture are required, to provide the largest beam separation and accommodate the large β-max.

b) Double-bore magnets for the dipole-first design. There are two contradictory requirements for IR quads:

- **Large β-max requires largest possible aperture;**
- **Twin-bore configuration limits the coil size and aperture.**

At present time the IRQ R&D program is focused on the large-aperture Nb_3Sn quadrupoles for the single-bore inner triplet and double-bore inner triplet with parallel axes.

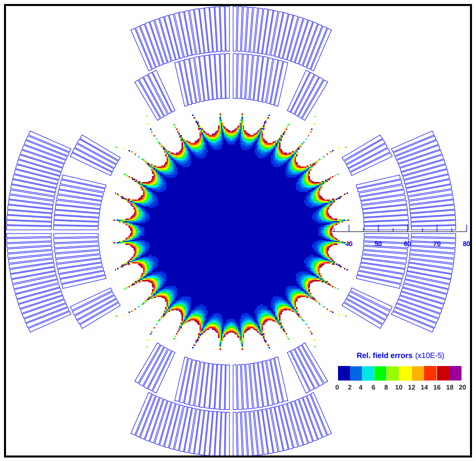
R&D questions

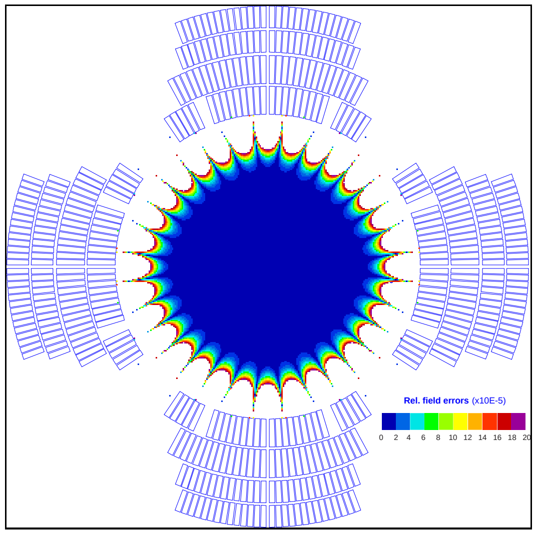
We studied Nb_3Sn quadrupoles with 90-110 mm apertures to address the following questions:

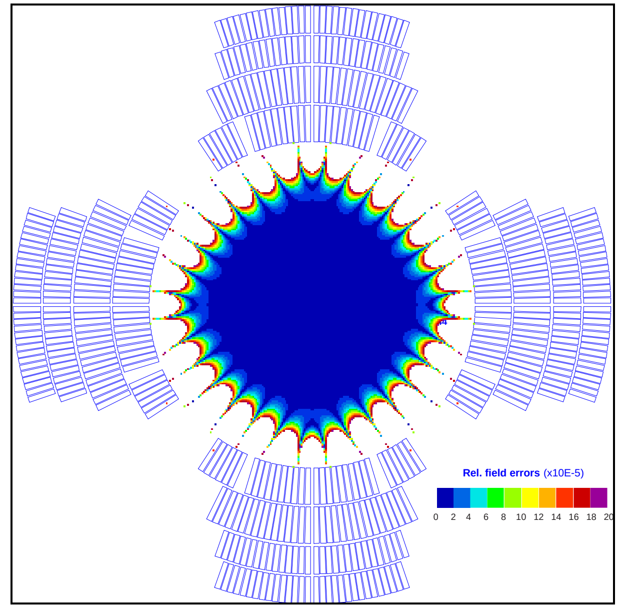
- **What are the aperture limitations for the single and double bore configurations?**
- **What are the limiting factors?**
- **What field quality can be achieved?**
- **What are the possible coil/yoke designs?**
- **What are the operation margins?**
- **What are the conductor requirements?**

Shell type quadrupole coils

90-mm	100-mm	110-mm



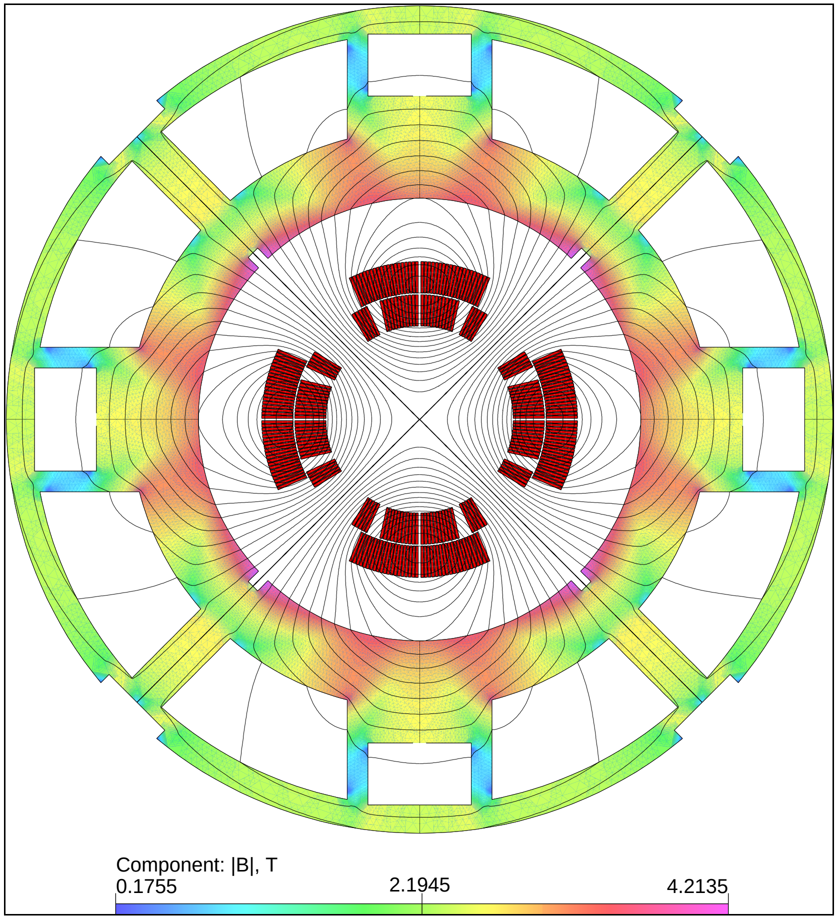




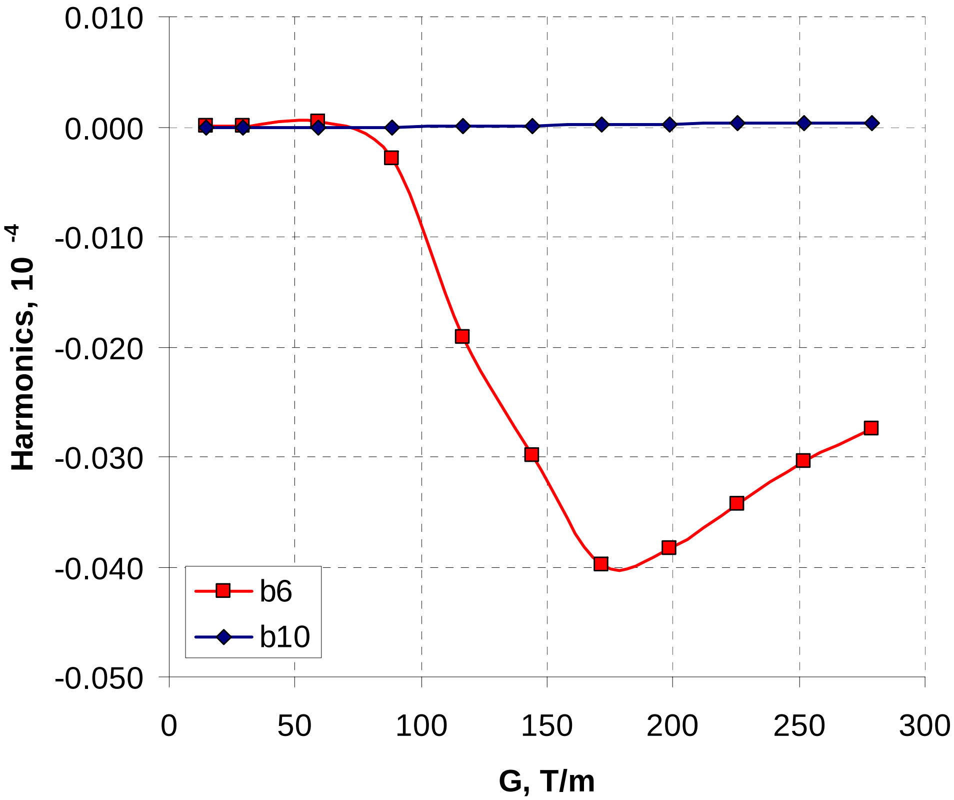
n	b_n @ 17 mm			b_n @ $R_{bore}/2$			b_n @ 17 mm
	110 mm	100 mm	90 mm	110 mm	100 mm	90 mm	70 mm*
6	0.00003	0.00011	0.00018	0.00022	0.00053	0.00056	-0.013
10	0.00007	0.00013	0.00048	0.00333	0.00286	0.00451	-0.001
14	0.00004	0.00004	0.00024	0.01179	0.00456	0.00691	-0.0011

2 or 4 layer coils provide necessary gradient and field quality

90-mm magnet yoke with cooling holes



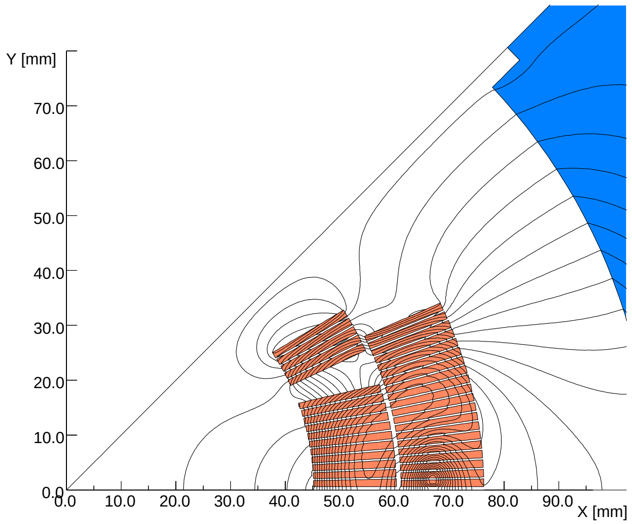
$R_{ref} = R_{bore}/2$

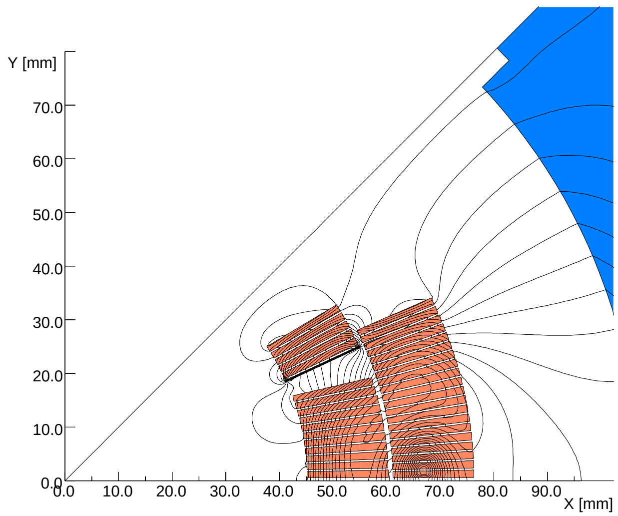


The cold-mass can fit into the existing LHC cryostat.

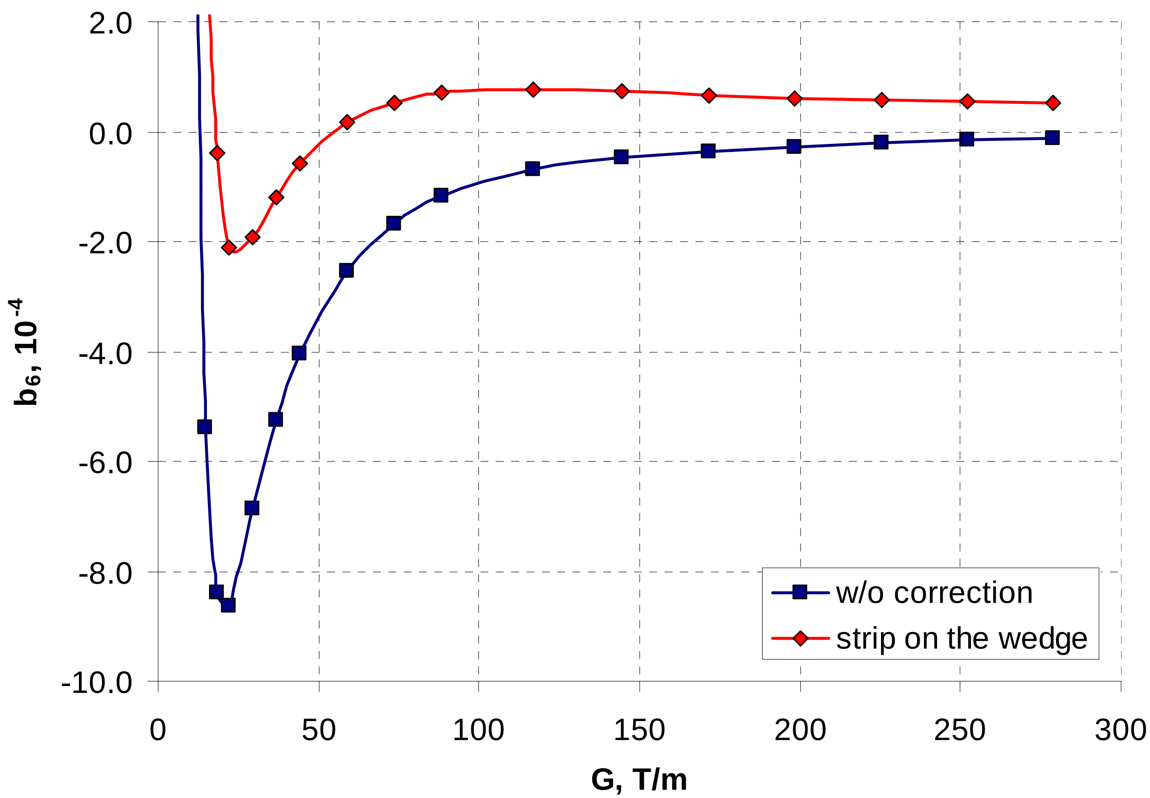
Large cooling holes to remove heat depositions.

Coil magnetization effect and its correction



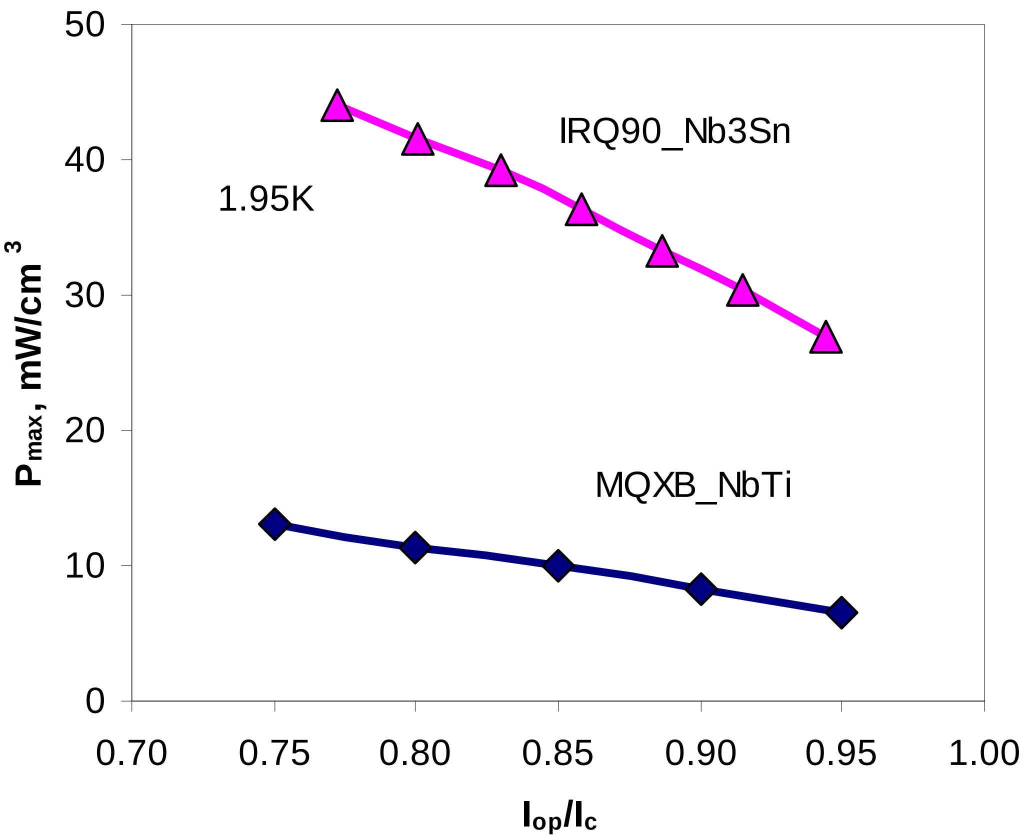


$R_{ref} = R_{bore}/2$



300-μm iron strip improves the field quality by a factor of 4.

Thermal analysis



The Nb_3Sn magnet designed with 20 % quench margin can withstand 40 mW/cm^3 of peak power dissipation in the midplane turns at T_{op}=1.95K.

Quench protection

The inductance and stored energy the 110-90 mm quads and calculated T_{hs} and T_{blk} are reported below for F_{qh} of 50% and 25%.

The acceptable T_{max} for accelerator magnets is 300-400 K and F_{qh}<50%.

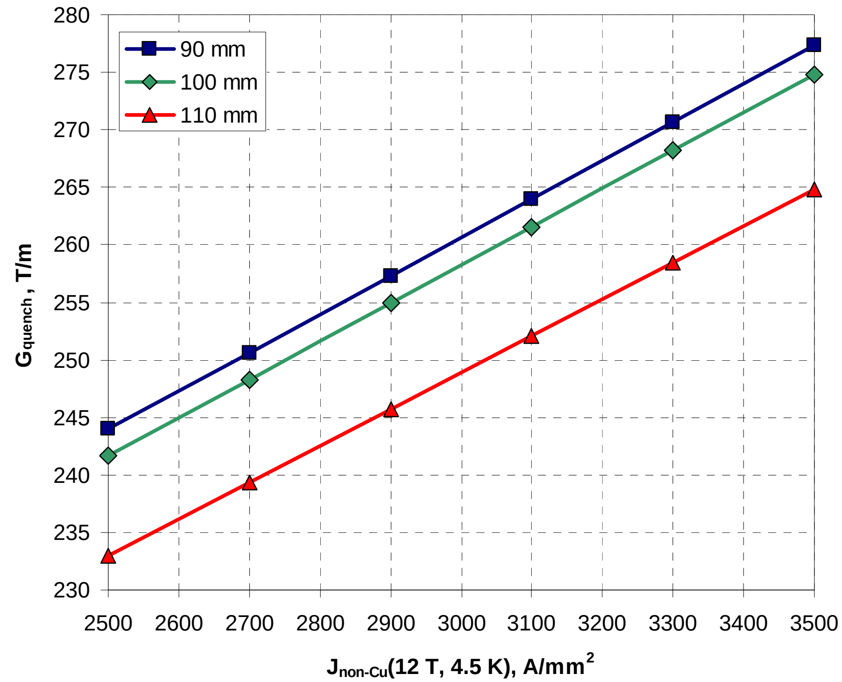
Even for F_{qh}=25% T_{max} is within 315-335 K. With F_{qh}=50% T_{max} does not exceed 250 K.

Parameter		Aperture		
		110 mm	100 mm	90 mm
L, mH/m		17.46	14.71	4.86
W(205 T/m), kJ/m		1181	703	468
T_{hs}, K	F_{qh}=50%	230	225	230
	F_{qh}=25%	335	320	315
T_{blk}, K	F_{qh}=50%	150	140	127
	F_{qh}=25%	220	200	180

Magnet parameters

Parameter		Unit	Aperture size		
			110 mm	100 mm	90 mm
N of layers			4	4	2
N of turns			248	228	144
Coil area (Cu + nonCu)		cm^2	84.88	59.31	48.09
NonCu Jc at 12 T, 4.5 K		A/mm^2	3000	3000	3000
Quench gradient		T/m	248.9	258.2	260.6
Quench current		kA	14.13	12.31	17.64
Peak field in the coil at quench		T	15.28	14.51	13.50
Inductance		mH/m	17.46	14.71	4.86
Stored energy at 205 T/m		kJ/m	1181.4	702.9	468.2
Lorentz forces in the first octant at Gnom=205 T/m	Fx	MN/m	3.44	2.38	1.50
	Fy	MN/m	-3.42	-2.39	-1.92
Maximum coil stress		MPa	99	90	73

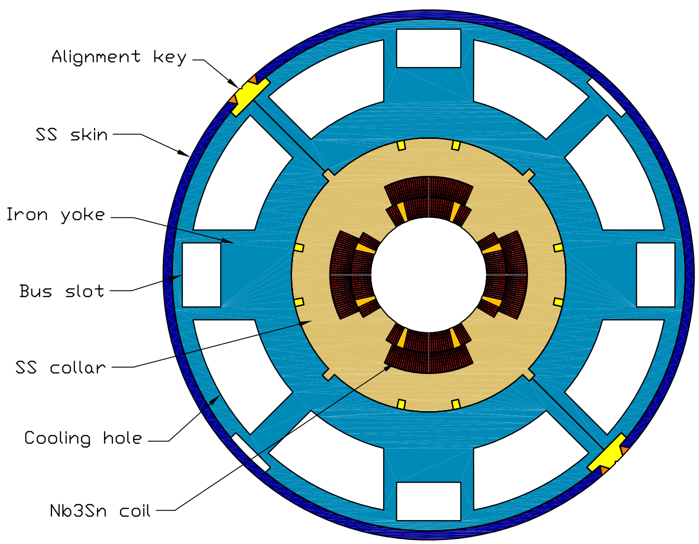
Coil area and forces grow as aperture square.



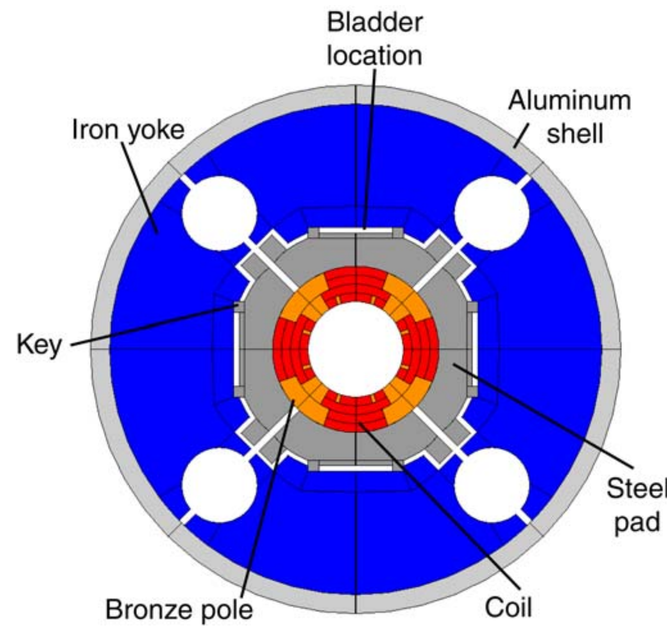
100-110-mm aperture seems to be the upper limit for the nominal gradient of 205 T/m and conductor J_c(12T,4.2K) = 3 kA/mm^2.

90-mm magnet mechanical structures

Collared design



Bladder and key design



Two types of mechanical structures and coil designs are under investigation. The 90-mm magnet can use 2 or 4-layer coils supported by free-standing collars within the "perforated" yoke or by Al shell in the bladder and key design.

Summary

Shell type Nb_3Sn magnets with 90-110 mm apertures based on advanced superconductors satisfy gradient and field quality requirements and have sufficient thermal margins.

The 100-110-mm aperture is the upper limit for a magnet with the nominal gradient of 205 T/m.

While the 90-mm design can employ 2 or 4 layer coils, the 100 mm and 110 mm designs require 4 layer coils to limit the maximum current by 14 kA and simplify coil windings.

Different coil cross-sections and yoke structures are to be investigated during the model magnet R&D.

Study of racetrack type magnets

Aperture and gradient limits in the racetrack configuration?

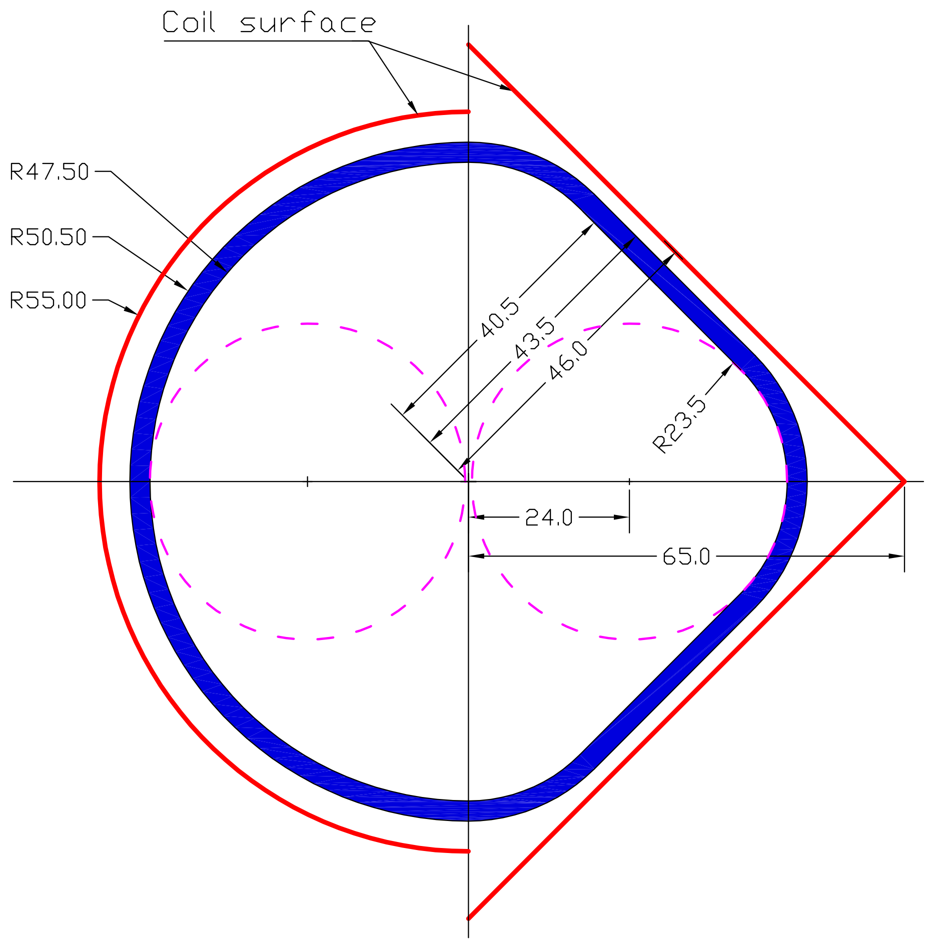
Field quality?

Efficiency with respect to the shell type designs?

The racetrack quadrupole magnets were optimized with the following basic constrains, used also during the shell type magnet optimization:

- **$J_{non\text{-}Cu}$(12T,4.2K) = 3000 A/mm^2;**
- **Cu/nonCu = 1.3;**
- **Round iron yoke, μ = 1000;**
- **Coil-yoke space in the midplane = 15 mm;**
- **One spacer/octant for the field quality correction.**

Equivalent aperture of racetrack quadrupole



Equivalence criterion – the same space for beams as in 110-mm shell type magnet.

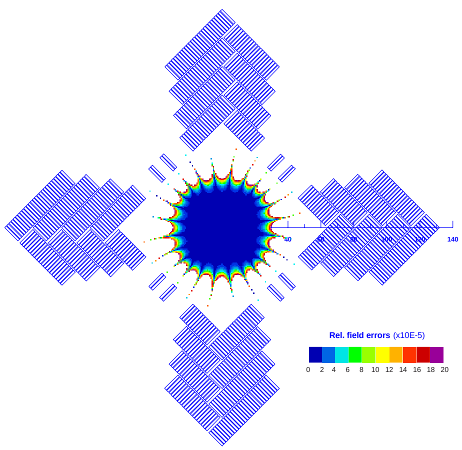
Constrains:

- **the same thickness of beam tubes;**
- **the same areas of the cooling channels.**

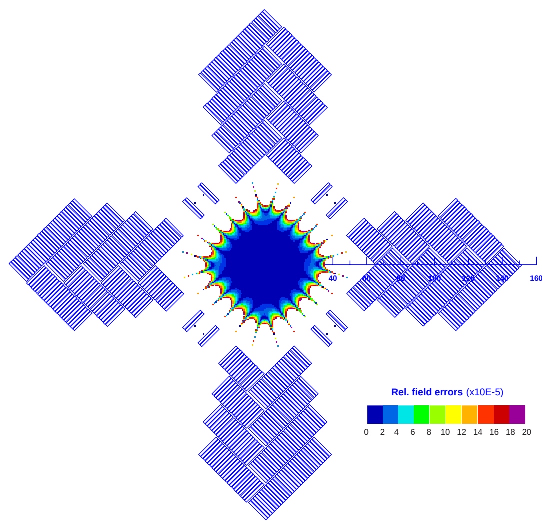
110-mm shell ⇔ 92-mm racetrack (in the pole plane).

90-100 mm (in the pole plane) coil designs

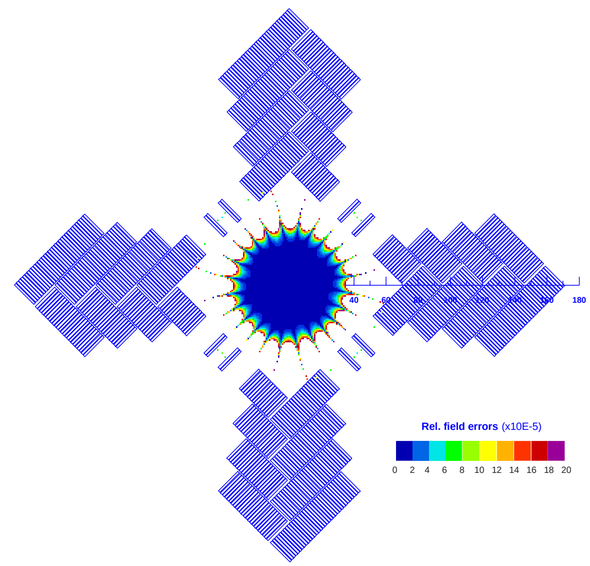
90-mm



92-mm



100-mm



The 90-100 mm racetrack magnets can employ interleaving coil design to maximize efficiency.

Field quality I

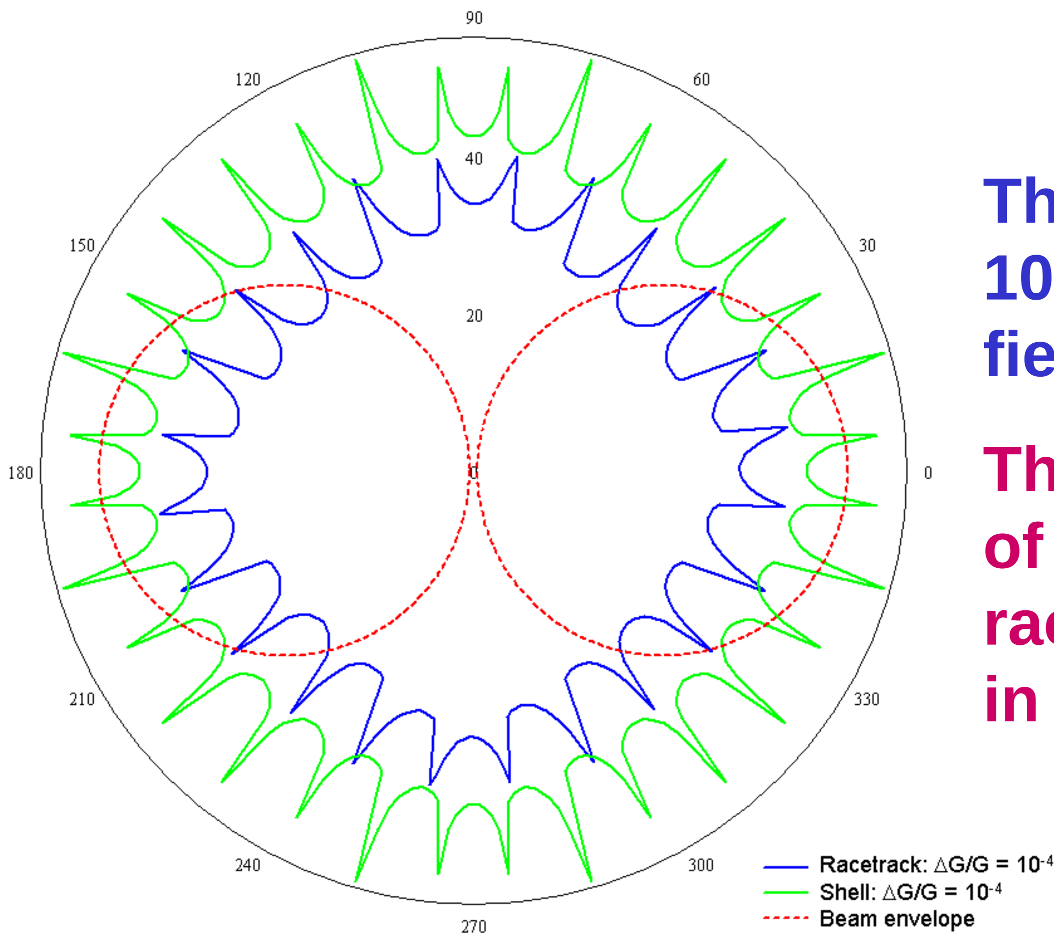
$R_{ref} = R_{bore}/2$

Harmonic	Racetrack			Shell		
	90 mm	**92 mm**	100 mm	90 mm	100 mm	**110 mm**
b_6	-0.0008	**0.0004**	-0.0001	0.0006	0.0005	**0.0002**
b_{10}	-0.0797	**0.1484**	0.0055	0.0045	0.0029	**0.0033**
b_{14}	-0.0529	**-0.0490**	-0.0447	0.0069	0.0046	**0.0118**
b_{18}	0.0025	**0.0016**	0.0017	-0.0047	-0.0036	**-0.0032**
a_4	0.0035	**-0.0041**	0.0039	-	-	-
a_8	0.0051	**0.0245**	0.0508	-	-	-
a_{12}	0.0040	**0.0015**	0.0027	-	-	-
a_{16}	0.0000	**0.0000**	0.0000	-	-	-

The limiting harmonic is b_{14}: a factor of 5 larger in the racetrack than in shell type magnets.

Field quality II

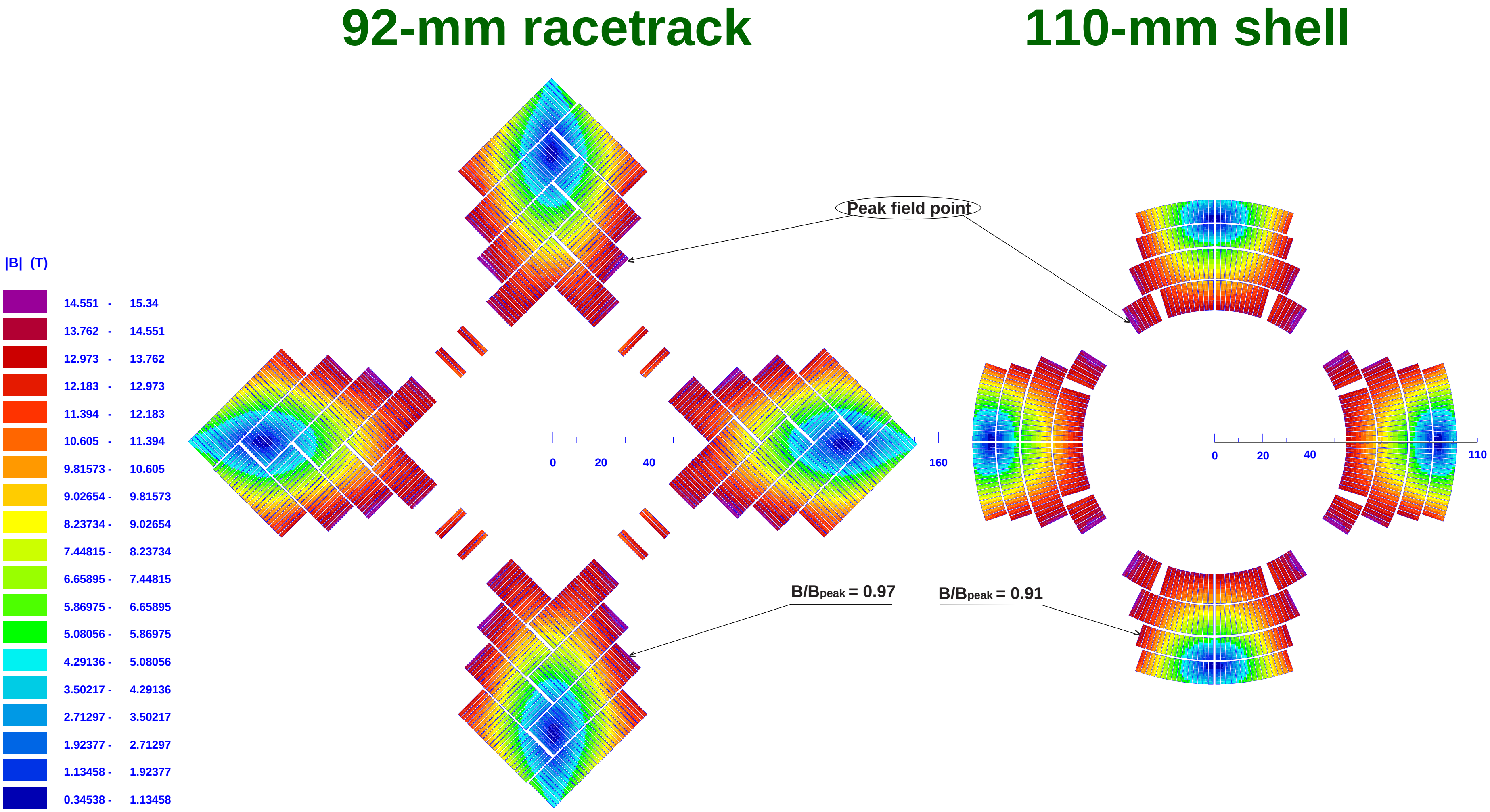
Good field region in 92-mm racetrack and 110-mm shell type magnets



The plot shows contours of 10^{-4} field uniformity (good field region).

The good field region is 70% of the beam envelope in the racetrack magnet, and 90% in the shell type magnet.

Peak field



Cable grading in the racetrack magnet is ineffective.

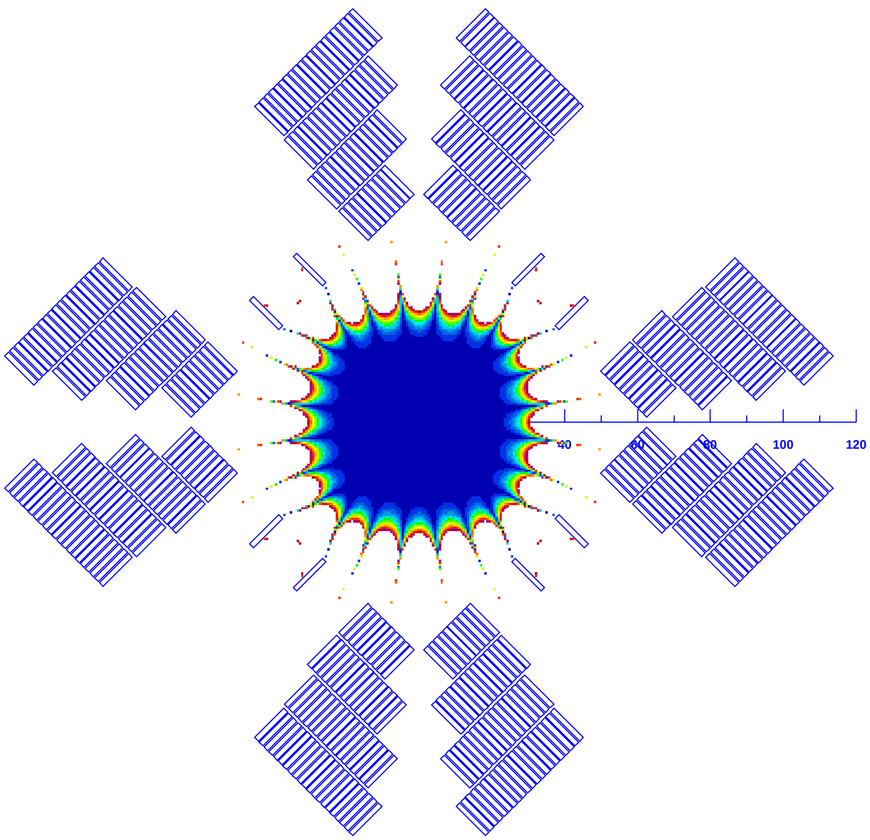
Magnet parameters

Parameter		Unit	Racetrack			Shell		
			90mm	**92mm**	100mm	90mm	100mm	**110mm**
N of layers			4	**4**	4	2	4	**4**
N of turns			332	**368**	388	144	228	**248**
Coil area (Cu + nonCu)		cm^2	96.53	**133.08**	169.22	48.09	59.31	**84.88**
NonCu Jc at 12 T, 4.5 K		A/mm^2	3000	**3000**	3000	3000	3000	**3000**
Quench gradient		T/m	240.8	**240.4**	226.4	260.6	258.2	**248.9**
Quench current		kA	11.87	**13.70**	14.52	17.64	12.31	**14.13**
Peak field in the coil		T	14.9	**15.3**	15.7	13.5	14.5	**15.3**
Inductance		mH/m	30.86	**33.44**	39.94	4.86	14.71	**17.46**
Stored energy @ 205 T/m		kJ/m	1575.6	**2282.0**	3452.0	468.2	702.9	**1181.4**
Forces/octant at 205 T/m	Fx	MN/m	3.67	**4.42**	6.10	1.50	2.38	**3.44**
	Fy	MN/m	-3.78	**-4.83**	-6.37	-1.92	-2.39	**-3.42**

92-mm racetrack quadrupole has lower efficiency than 110-mm shell type magnet: coil area is larger by 57%, stored energy – by 93% and forces – by 41%. It may require an inner support tube.

Open midplane design

90-mm coil



There was an attempt to optimize racetrack coil with midplane spacer in order to reduce the heat depositions in the coil.

A satisfactory field quality can be achieved, however the maximum gradient is only 215-225 T/m that does not provide sufficient quench margin.

Summary

- **The equivalent of 110-mm round aperture is 92 mm in the pole plane of square racetrack aperture.**
- **Racetrack quadrupole with 92-mm aperture is less effective than the shell type design with 110-mm aperture by all the major parameters.**
- **Due to the coil size limitations, the racetrack design is not appropriate for the 2-in-1 configuration.**

Study of double aperture magnets

The required relatively small beam separation distance leads to:

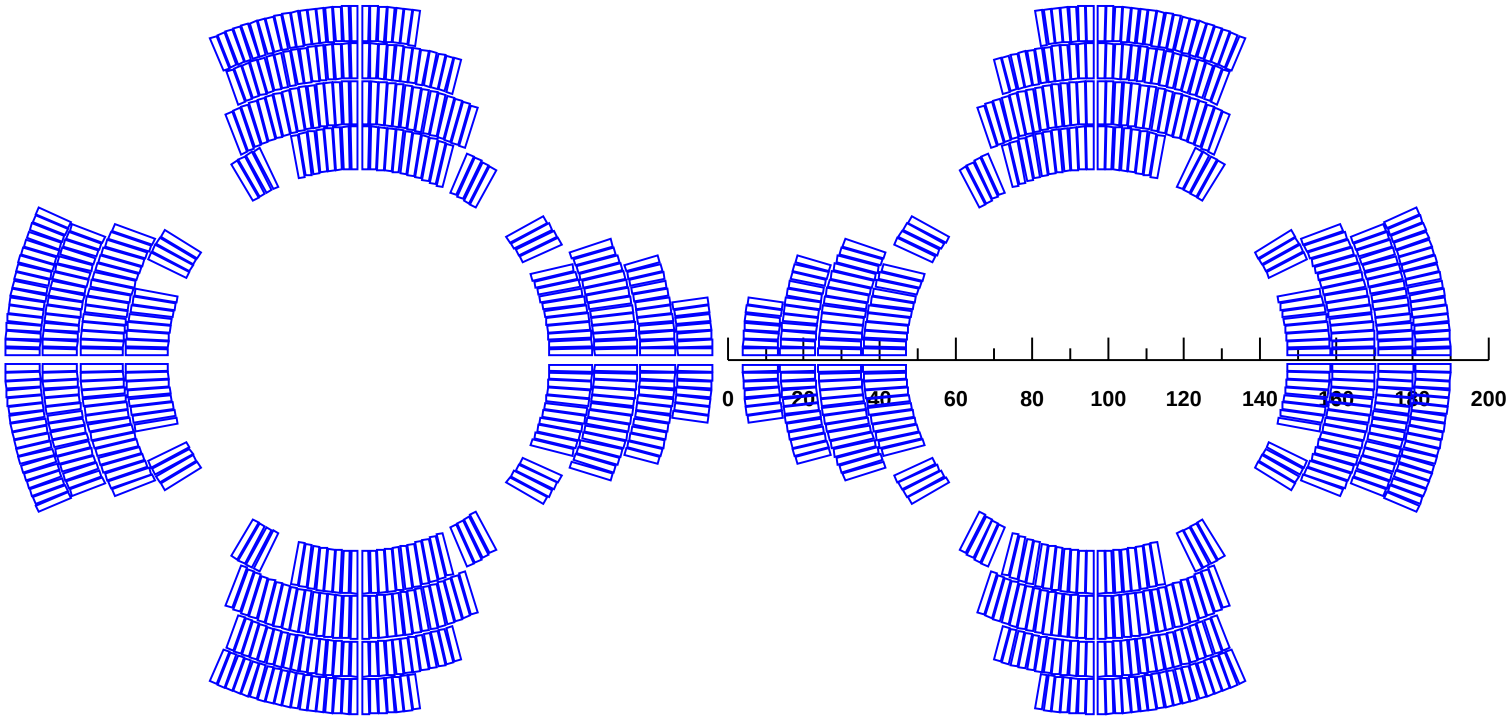
- **Large coupling between coils**
- **Large yoke saturation effect.**

Solution ⇒ warm iron yoke and asymmetric coils.

Aperture was fixed at 100 mm, beam separation - at 194 mm.

100-mm asymmetric coil design

G_{max}= 247.6 T/m, I_{max}= 15.34 kA for J_c(12T,4.2K) = 3000 A/mm^2



Two types of quadrant coils address the field coupling issue.

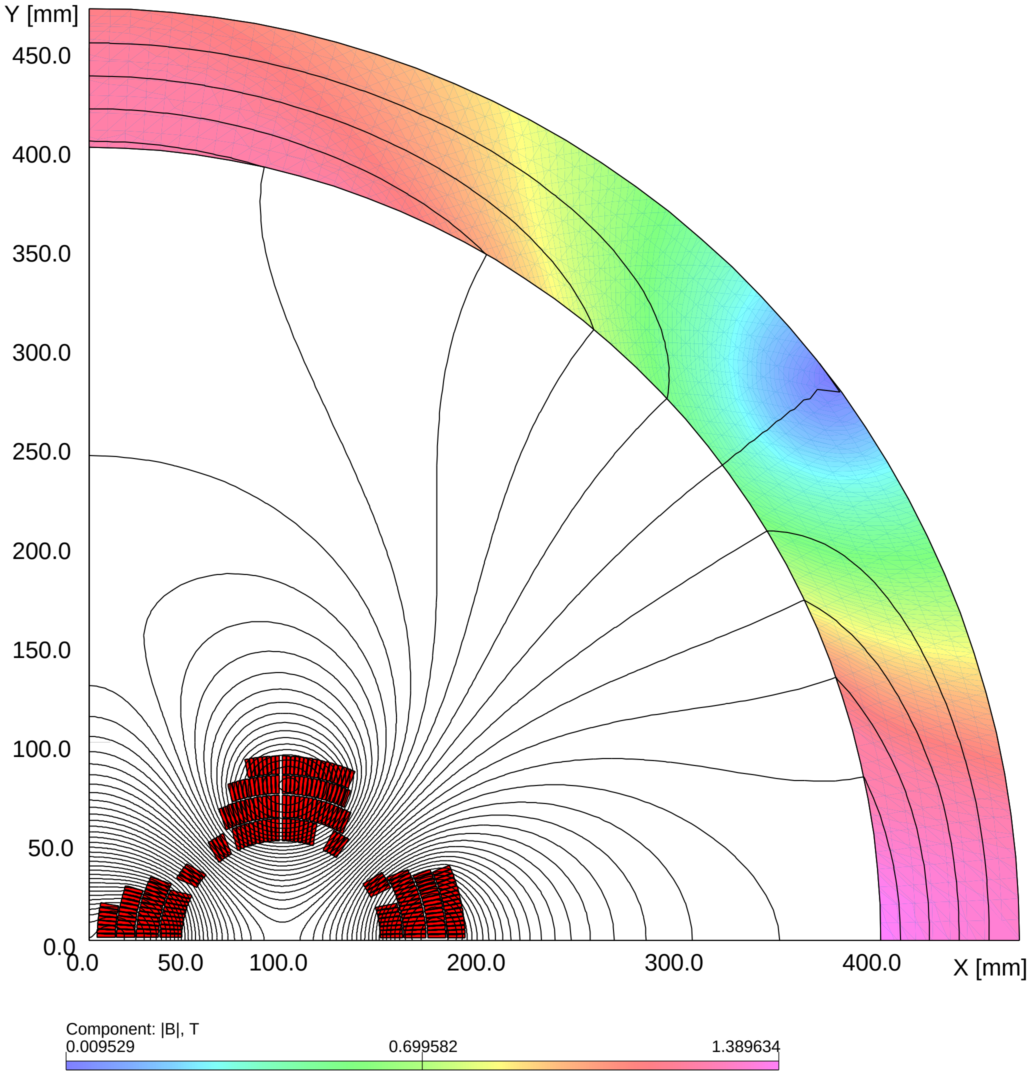
Field quality

$$R_{ref} = R_{bore}/2$$

```
MAIN FIELD:     6.45440 NORMAL REL. MULTIPOLES (1.D-4):
b 1:       0.00528  b 2:  10000.00000  b 3:      -0.01577
b 4:      -0.00610  b 5:      0.00261  b 6:       0.00324
b 7:       0.03312  b 8:     -0.00252  b 9:      -0.17381
b10:       0.13609  b11:      0.08060  b12:      -0.05976
b13:       0.02184  b14:     -0.02200  b15:       0.01077
b16:      -0.00120  b17:     -0.00406  b18:      -0.00261
```

Geometrical field quality is comparable with that in the existing MQXB magnets

Warm iron yoke design



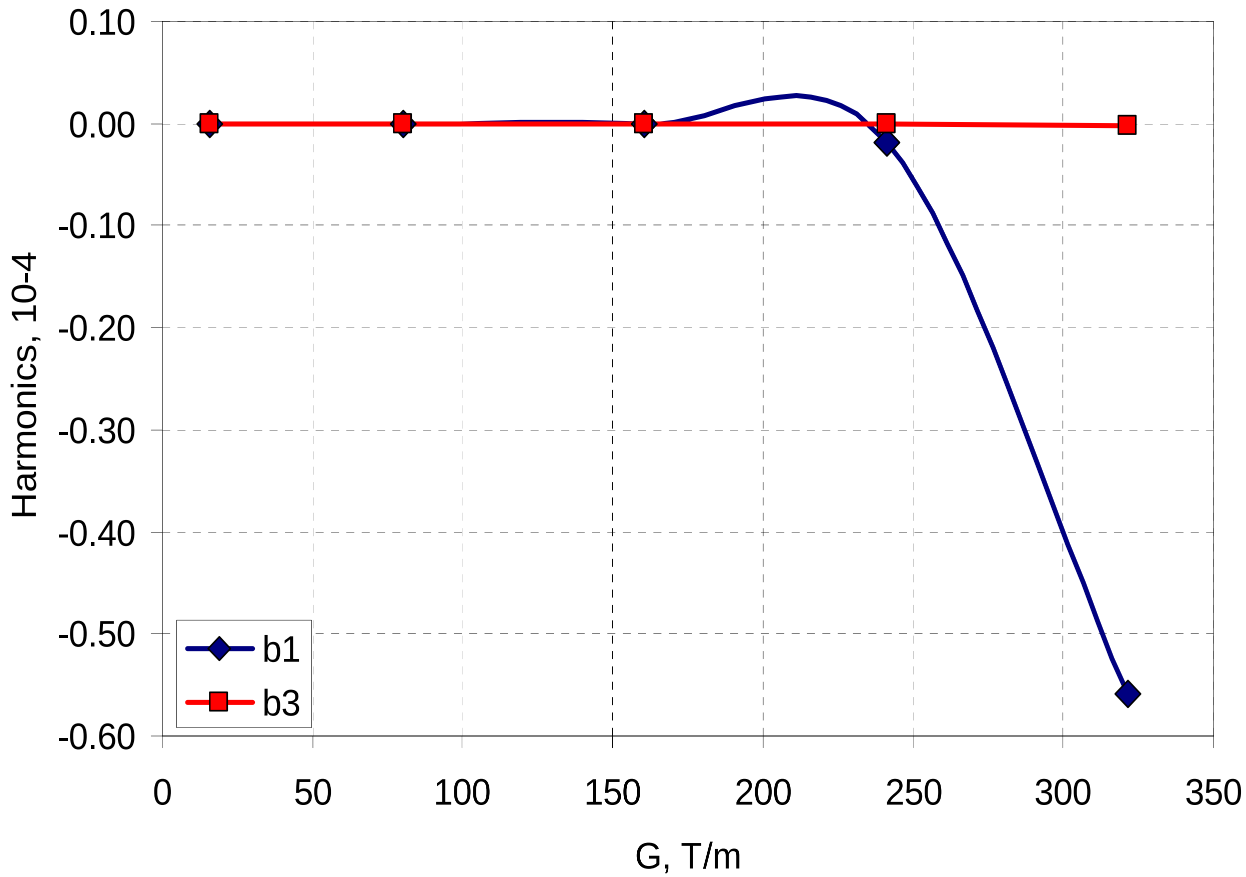
Yoke IR = 400 mm.

Yoke OR = 470 mm.

Yoke dimensions are to be optimized (reduced).

The coil support structure should be studied.

Yoke saturation effect



There is virtually no effect of the yoke saturation up to 250 T/m

Summary

- **The 2-in-1 quadrupole can accommodate a maximum bore size of ~100 mm for the beam separation distance of 194 mm.**
- **Asymmetric coils and a warm iron yoke allow to control geometrical field quality and the yoke saturation effect.**
- **Analysis of field and force sensitivity to tolerances of coil positioning inside the warm yoke will be performed later.**
- **The possible mechanical structures can involve collar and/or key and bladder designs that is subject to study and optimization.**

Conclusion

- Large aperture IR quadrupoles based on Nb_3Sn satisfy major requirements necessary for the LHC luminosity upgrade, including: field gradient and field quality, operating margins and quench protection.
- Shell type-coil is the most effective approach that allow 100 mm aperture in both single-bore and double bore IRQs.
- The most important limiting factors are the critical current of Nb_3Sn strands and magnet mechanics.
- Final quadrupole parameters will be determined based on the results of model magnet R&D.