Limits of SC Final Doublet Magnets

Workshop on Design Challenges of Small-angle IR

LAL-Orsay, October 19, 2006

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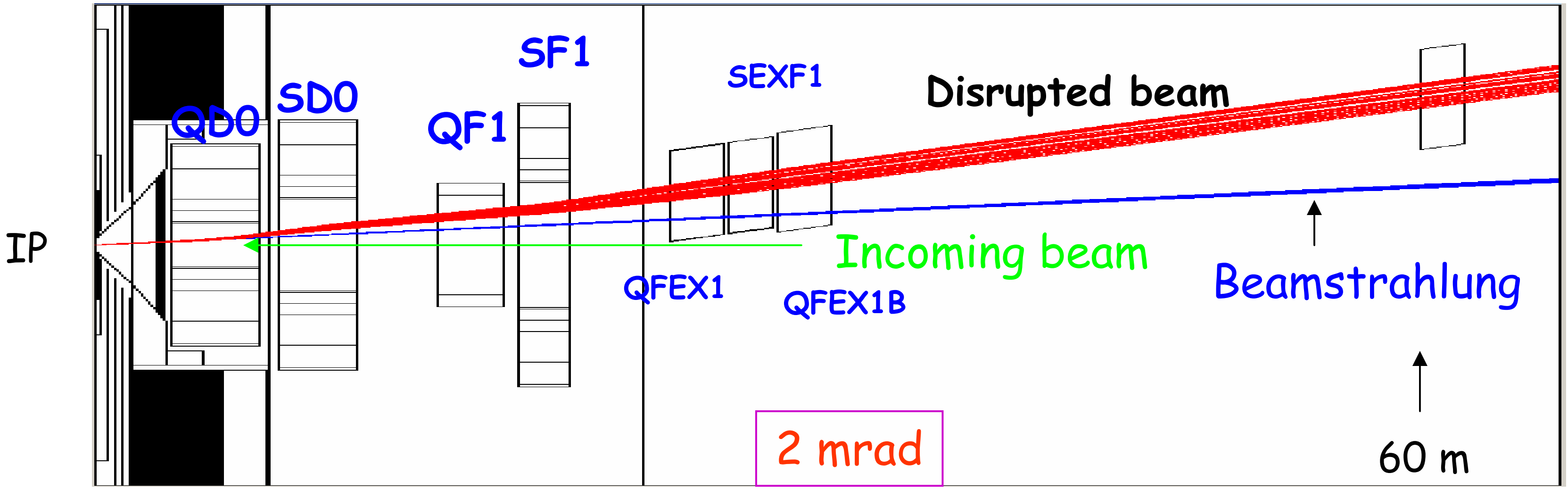
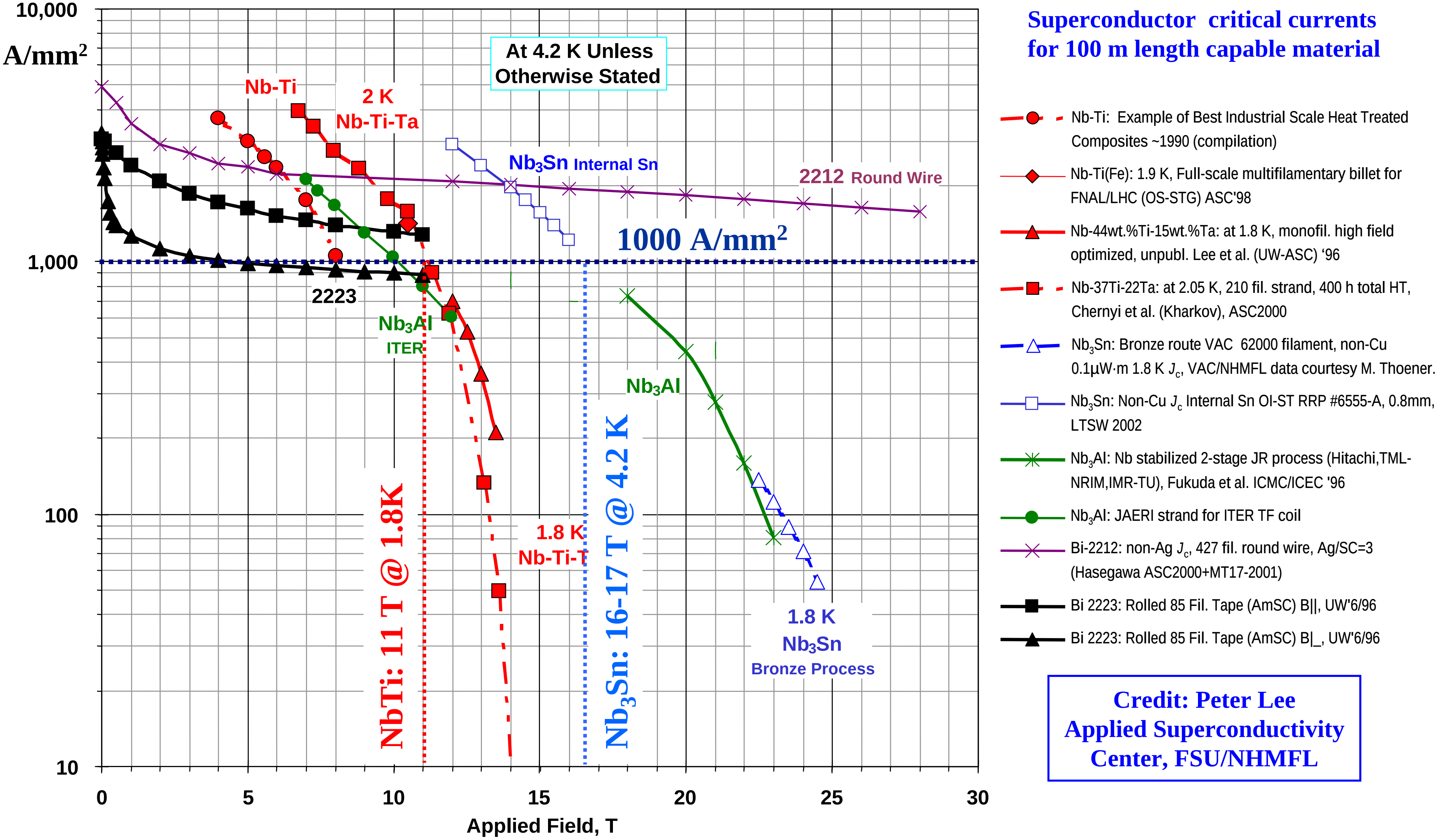
2 mrad Magnets



Magnet type	Bore radius, mm	Field at radius, T	Eff. length, m	Qty
Quad QD0	35	5.6	2.5	2
Sextupole SD0	88	4.0	3.8	2
Quad QF1	10	0.68	2.0	2
Sextupole SF1	112	2.12	3.8	2
SeptumQEX1A	113	1.33	3.0	2

Conductor Options



Superconductor critical currents for 100 m length capable material

Credit: Peter Lee
Applied Superconductivity Center, FSU/NHMFL

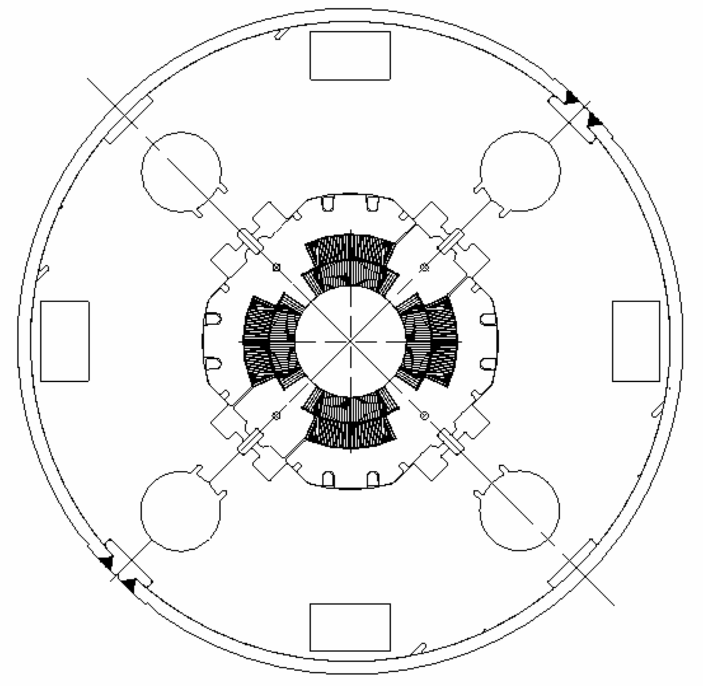
RDR approach (Vancouver)

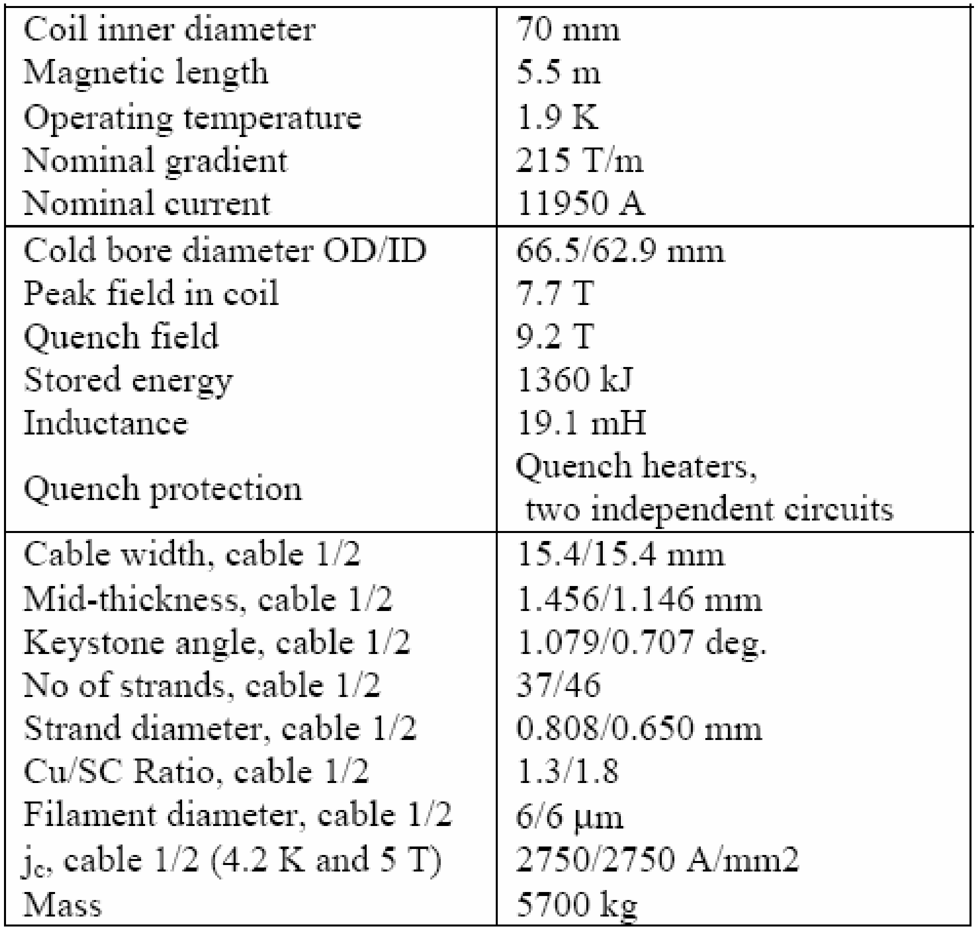
- IR magnets designs are based on 1.9K NbTi technology developed for first-generation LHC IR
- *Preliminary* analysis (Vl. Kashikhin & A. Zlobin) indicates that LHC-IR type 70-mm NbTi quadrupole magnet design (MQXB) is adequate to meet QD0 requirements
- Sextupole *preliminary* design (Vl. Kashikhin) is also derived from MQXB experience and parameters (strand/cable, mechanical support concept etc) and meets specs

Reference Quad Design: LHC MQXB

Features/Parameters

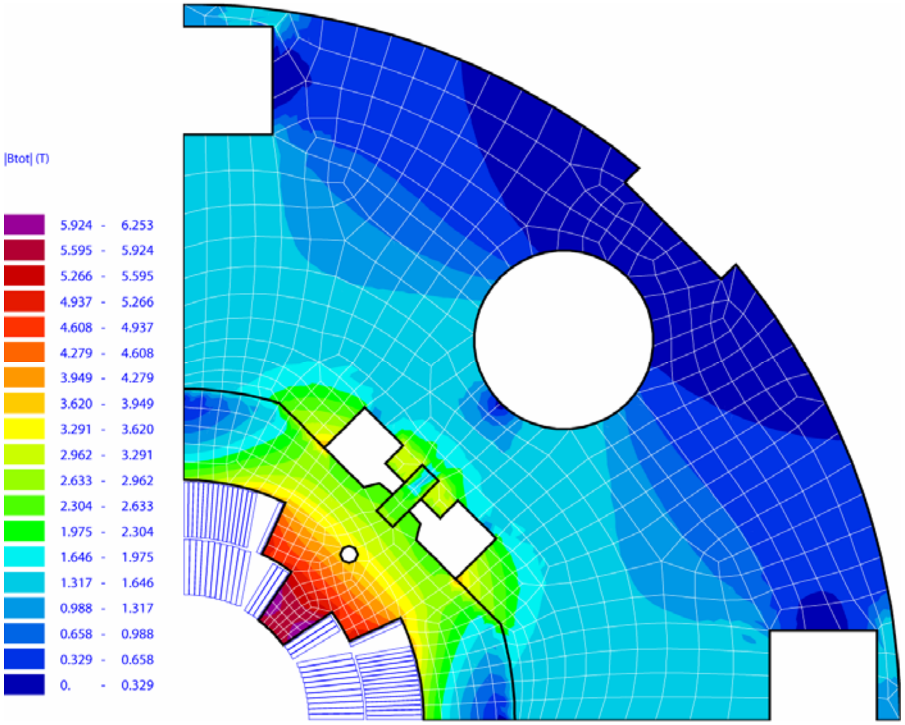
- Aperture 70 mm
- NbTi @ 1.9K
- Self-supporting collar





Coil inner diameter	70 mm
Magnetic length	5.5 m
Operating temperature	1.9 K
Nominal gradient	215 T/m
Nominal current	11950 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	7.7 T
Quench field	9.2 T
Stored energy	1360 kJ
Inductance	19.1 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	15.4/15.4 mm
Mid-thickness, cable 1/2	1.456/1.146 mm
Keystone angle, cable 1/2	1.079/0.707 deg.
No of strands, cable 1/2	37/46
Strand diameter, cable 1/2	0.808/0.650 mm
Cu/SC Ratio, cable 1/2	1.3/1.8
Filament diameter, cable 1/2	6/6 µm
j_c, cable 1/2 (4.2 K and 5 T)	2750/2750 A/mm2
Mass	5700 kg

QD0 Design (Vl. Kashikhin)



Parameter	Unit	Value
G_{nom}	T/m	160.0
I_{nom}	kA	8.8
B_{p_nom}	T	6.3
$B_{p\_q}(I_{nom})$	T	9.9
Field margin	T	3.6

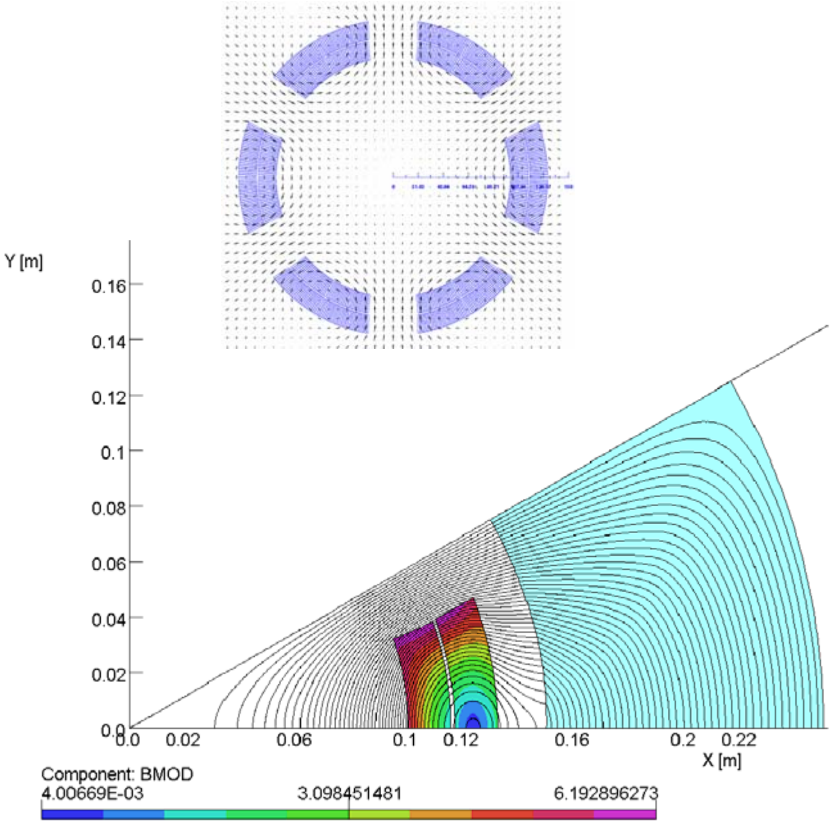
There is 0.9 T field margin assuming 2.7 T detector’s background field

Large aperture sextupole (Vl. Kashikhin)

Shell type coil sextupole with cold iron

Design close to LHC IR Quadrupoles

Coil ampere-turns	**343 kA**
Current	**7 kA**
Calculated strength	**519.2 T/m^2**
Coil maximum field	**6.2 T**
Iron core field (max)	**3.8 T**
Field energy	**376 kJ/m**
Lorentz force, Fx	**56.5 t/m**
Lorentz force, Fy	**-83.2 t/m**
Number of turns	**22(inner) + 27(outer)**
NbTi Superconducting cable	**LHC IR inner**
Jc at B=5 T, 4.2	**2750 A/mm^2**
Strand diameter	**0.808 mm**



Open Issues for NbTi approach

- Required aperture has increased in later versions of the optics
- Additional bore space may be needed for corrector coils
- Peak coil fields will increase when detailed 3D effects, interaction with solenoid and anti-solenoid are considered

⇒ It appears that NbTi design margins are sufficient to take these effects into account, but detailed analysis is needed

- More detailed calculations of magnetic center motion (SC magnetization, Lorentz forces, mechanics, iron saturation and hysteresis, etc)

⇒ present estimate is 1-5 μm magnetic center stability

⇒ need to develop correctors, optimize magnet movers for larger magnet weight/size

Alternative approach using Nb_3Sn

- LARP R&D status: first Technology Quad (TQ) achieved ~200 T/m in 90 mm aperture; second TQ ready for test; third TQ under fabrication
- After optimization, Technology Quads should provide up to 250 T/m
- LARP R&D Goal: 300 T/m in 90 mm aperture for High-Gradient Quad (HQ) by 2009
- Nb_3Sn quad development also underway at CEA, with ILC-relevant features

Potential advantages: gradient/bore/length; thermal margin; 4.2K operation
Note: specify/evaluate SC quads based on aperture & gradient, not pole field
Typical gradients for Nb_3Sn should be 200-250 T/m in 90 mm bore
(without taking into account solenoidal field)

Issues:

- Support structure designs for high-performance, brittle conductor presently require large transverse size
- Effect of persistent currents on magnetic center stability
- Uncertainties in performance limits and cost

LARP

High Gradient Quads for LARP

Goal: investigate viability of Nb_3Sn quads for the LHC luminosity upgrade

1. Capability to deliver predictable and reproducible performance:

TQ (Technology Quads, 2005-07) D = 90 mm, L = 1 m, G_{nom} > 200 T/m

2. Capability to scale-up the magnet length:

LQ (Long Quadrupoles, 2008-09) D = 90 mm, L = 4 m, G_{nom} > 200 T/m

3. Capability to reach high gradients in large apertures:

HQ (High Gradient Quads, 2008-09) D = 90 mm, L = 1 m, G_{nom} > 250 T/m

Oct 25, 2005	**Type**	**Length** [m]	**Gradient** [T/m]	**Aperture** [mm]	**FY05**	**FY06**	**FY07**	**FY08**	**FY09**
MODEL MAGNETS									
Technology Quad (TQ)	cos(2θ)	1	> 200	90		3N+1R	2N+1R		
Long Quad (LQ)	cos(2θ)	4	> 200	90				1N	1N
High Gradient Quad (HQ)	cos(2θ)	1	> 250	90					2N
SUPPORTING R&D			**Peak Field** [T]						
Sub-scale Quad (SQ)	block	0.3	10-11	110	1N+1R	1N+1R	1N+1R	1N	
Short Racetrack (SR)	block	0.3	10-12	N/A		1N	1N	1N	
Long Racetrack (LR)	block	4	10-12	N/A			2N+1R		

HQ Design Issues

Conductor:
- strand (optimal design, critical current at high field)
- cable (limits on maximum width & keystone angle)

Magnetic:
- number of layers (cable design, winding issues)
- use of wedges, conductor grading, end field optimization

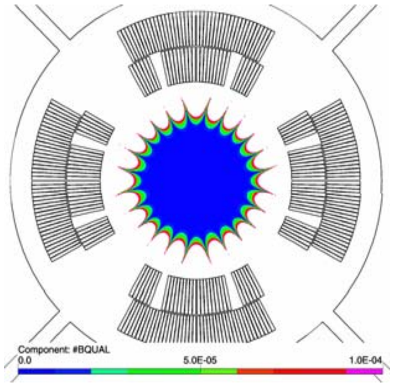
Mechanical:
- collar-based vs. shell-based structure
- structure and coil alignment
- end axial support

Integration:
- coordination with model magnet, supporting R&D
- coordination with IR magnets study
- fabrication, cost and schedule considerations
- target parameters, design features, R&D plan

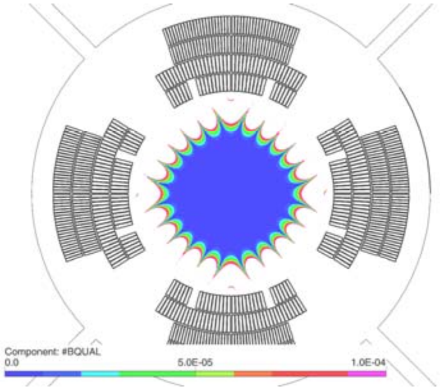
Coil Geometries

Parameter	Cos2θ (2L)	Cos2θ (4L)	Block (2L)	Racetrack (4L)
G_{ss} (T/m) (*)	245	265	230	234
$b_{6, 10, 14, 18}$ @ 22 mm	< 0.05	< 0.05	< 0.05	< 0.07
Inductance (mH/m)	4.9	23.7	4.8	14.2
$J_{cu}^{(ss)}$ (A/mm^2)	1.5	1.4	1.5	1.5
SC area (cm^2)	46.5	48.5	47.8	51.4

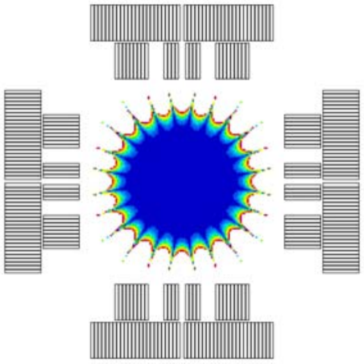
(*) J_c (12T, 4.2K) = 2.4 kA/mm^2 and T_{op} = 1.9 K; actual yoke geometry; 90 mm aperture at the main quadrupole axes



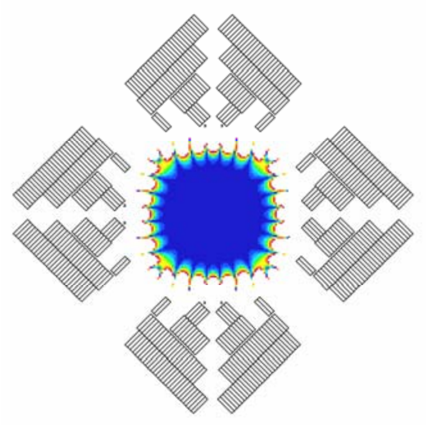
Cos2θ (2L)



Cos2θ (4L)



Block (2L)

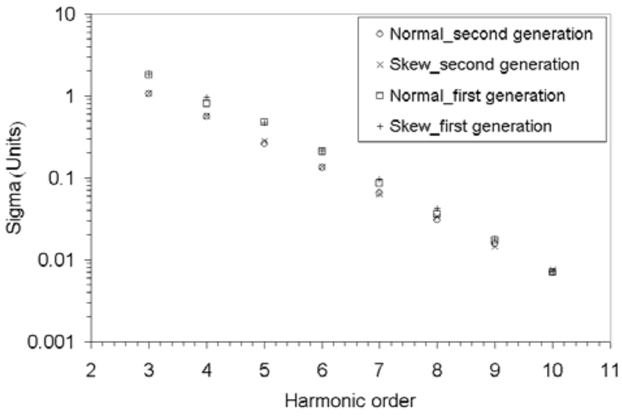


Racetrack (4L)

Field Quality

- All designs have same coil aperture on the magnetic mid-planes (x & y axis)
- Resulting design harmonics are within 0.07 units (22 mm reference radius)
- Fabrication tolerances will dominate with respect to design harmonics:

Random error simulation (±50 μm)

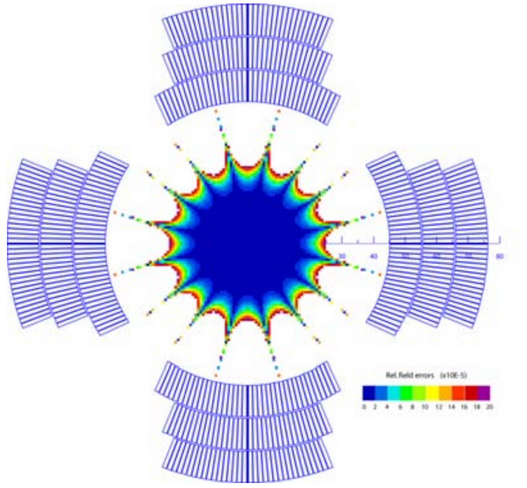


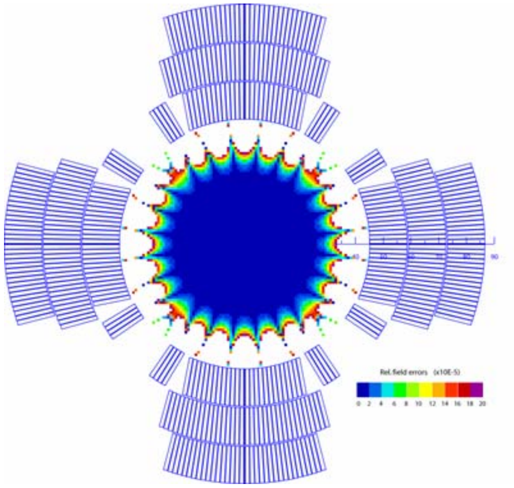
MQXB vers. 3.2 (17 mm)

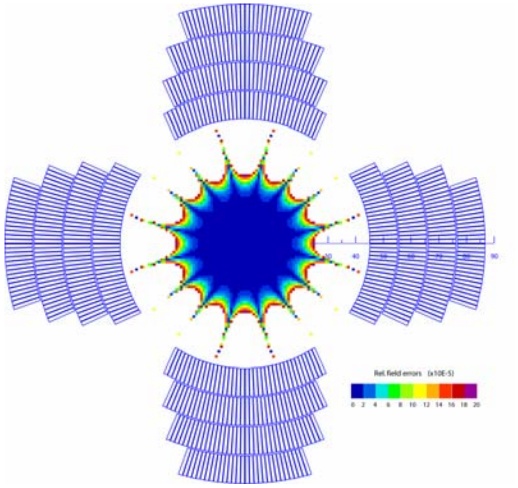
n	$\langle b_n \rangle \pm \delta b_n$	$\langle a_n \rangle \pm \delta a_n$
3	0.00 ± 1.66	0.00 ± 1.34
4	0.00 ± 1.25	0.00 ± 1.29
5	0.00 ± 0.65	0.00 ± 0.65
6	0.21 ± 0.97	-0.03 ± 0.19
7	0.00 ± 0.12	0.00 ± 0.10
8	0.00 ± 0.08	0.00 ± 0.05
9	0.00 ± 0.04	0.00 ± 0.04
10	-0.01 ± 0.04	0.00 ± 0.04

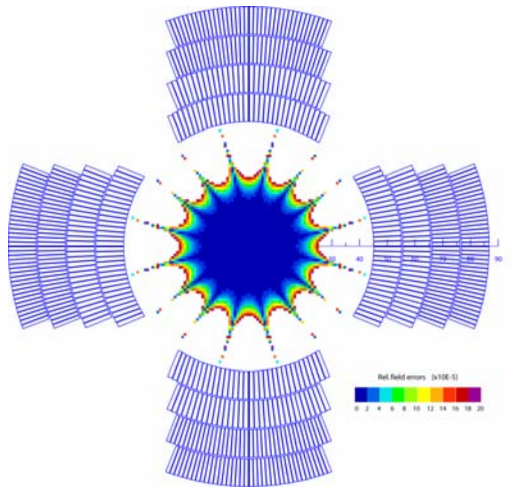
- Field quality and bore components (absorbers etc.) determine useful aperture
- Using same coil aperture on the magnetic mid-planes is ok for comparison

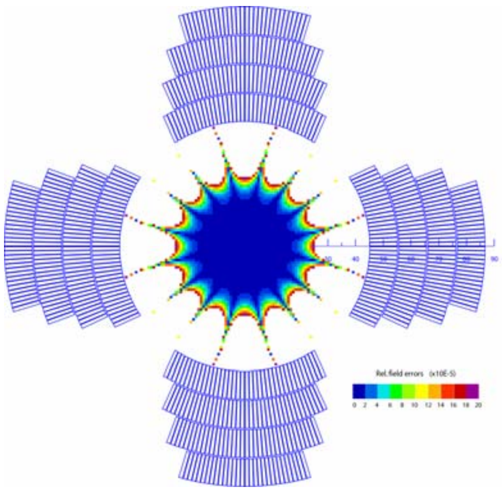
Cross-section Comparisons

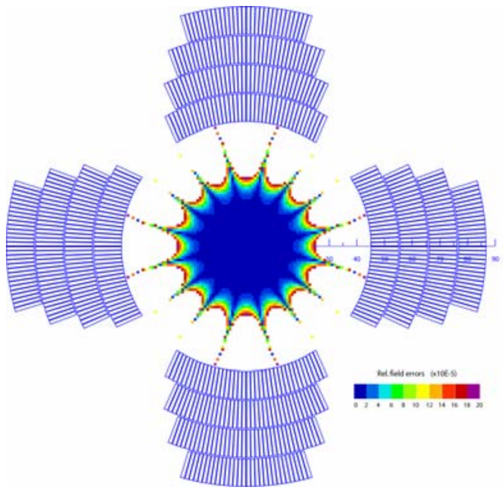












Cross-Section Analysis and Selection

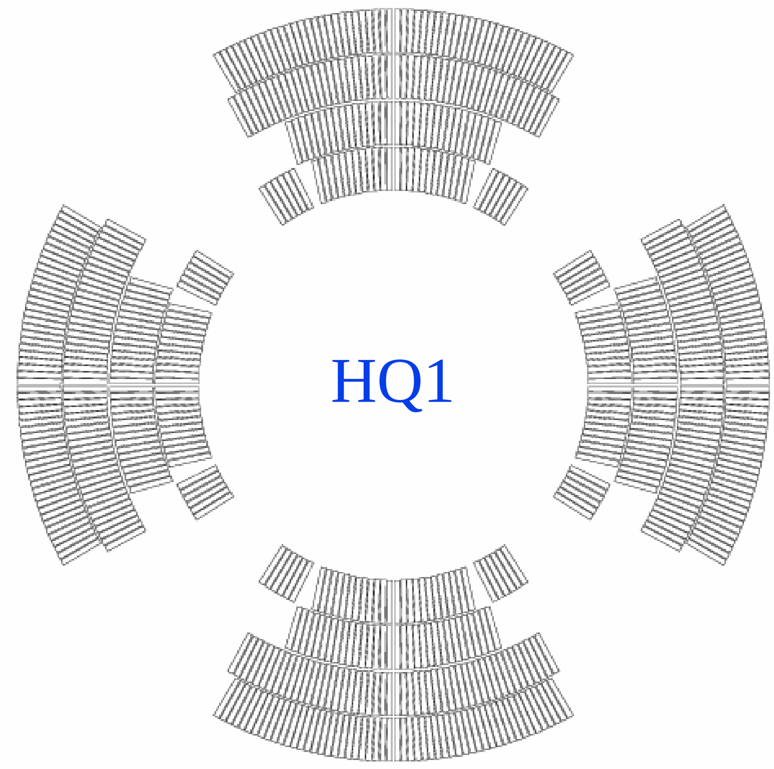
Pre-conditions for comparison:

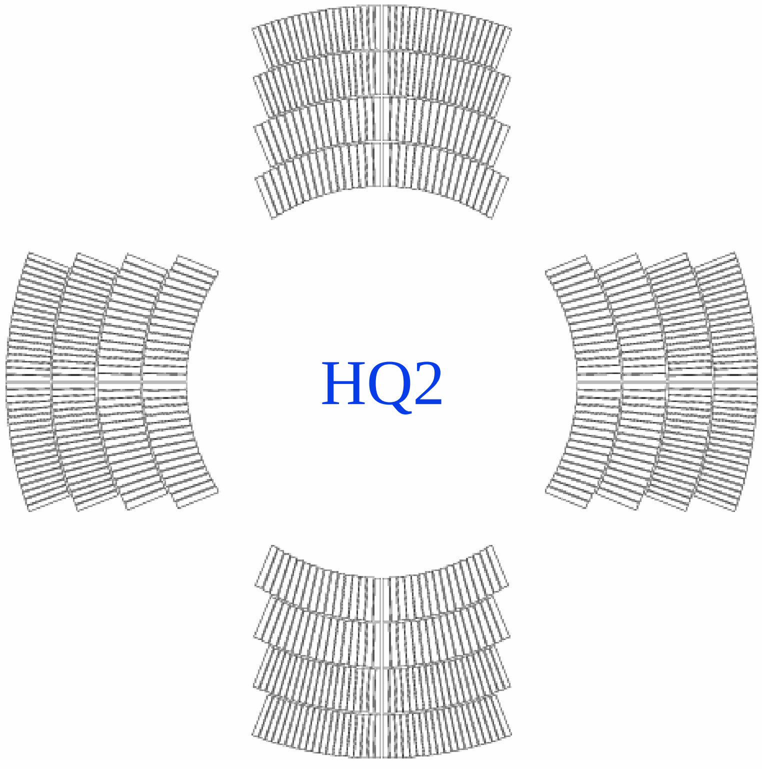
- Same current density. How to account for cabling/stress degradation
- Strand parameters (diameter, cu/sc): consistent (same) and practical
- Cable parameters (no. str., angle, compact.): consistent (same) & approved
- Iron yoke: same distance from coil and magnetic properties

Criteria for comparison:

- Maximum gradient
- Coil stress distributions
- Practicality, cost and schedule: strand procurement, use of TQ tooling (coils)
- Winding/Fabrication issues: minimum radii, spacer design, radial placement
- Complications vs. R&D interest/features
- Coil volume, Quench protection, Field quality, ...

Reference cross-sections





LARP

Conductor and Cable Parameters

Parameter	Unit	HQ1		HQ2	
		Inner	Outer	Inner	Outer
Strand diameter	mm	0.7	0.7	0.85	0.7
Cu/non-Cu ratio		0.87	0.87	0.87	0.87
No. strands		27	27	23	27
Cable width (bare)	mm	10.05	10.05	10.05	10.05
Mid-thickness (bare)	mm	1.26	1.26	1.54	1.26
Keystone angle	deg	1.0	1.13	1.40	1.13
Insulation thickness	mm	0.125	0.125	0.125	0.125
No. turns/octant		34	52	32	38
Conductor area/octant	cm^2	35.3	54.0	41.8	39.5

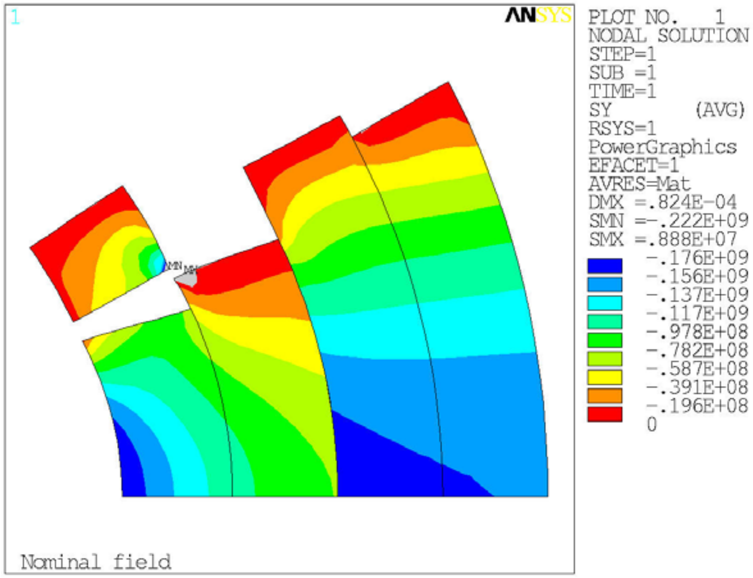
LARP

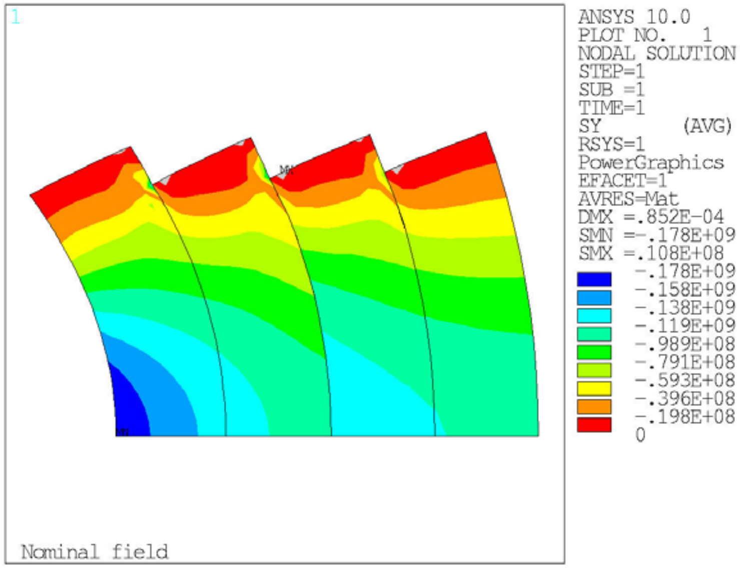
Performance Parameters

Parameter	Symbol	Unit	HQ1	HQ2
Short sample gradient*	G_{ss}	T/m	308	317
Short sample current*	I_{ss}	kA	10.7	12.6
Coil peak field	B_{pk} (I_{ss})	T	15.6	15.8
Copper current density	J_{cu} (I_{ss})	kA/mm^2	2.2/2.2	2.1/2.6
Inductance	L (I_{ss})	mH/m	24.5	18.0
Stored energy	U (I_{ss})	MJ/m	1.3	1.4
Lorentz force/octant (r)	F_r (I_{ss})	MN/m	1.7	1.7
Lorentz force/octant (θ)	F_θ (I_{ss})	MN/m	-6.0	-6.1
Average coil stress (θ)	σ_θ (I_{ss})	MPa	150	152
Dodecapole (22.5 mm)	b_6		-0.2	0.0
10-pole (22.5 mm)	b_{10}		-0.05	-0.92

(*) Assuming J_c(12 T, 4.2 K) = 3.0 kA/mm^2; operating temperature T_{op}=1.9K

Coil Stresses

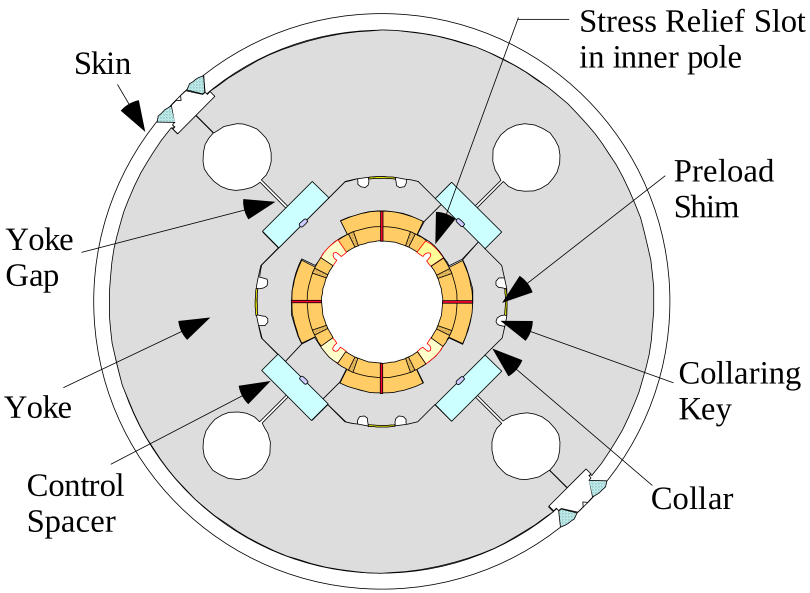


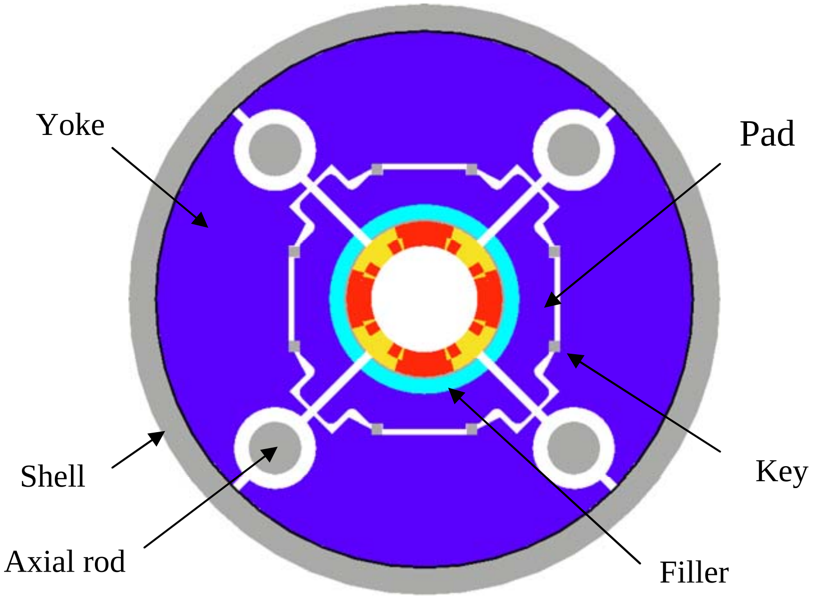


LORENTZ STRESS AT 300 TESLA/METER (MPA)

Coil	ANSYS (Fig 3)		Mid-plane stress: Σ F_θ/(layer width)			
Design	L1&2	L3&4	L1	L2	L3	L4
HQ1	176	167	139	98	179	150
HQ2	178	131	148	143	159	114

Mechanical Structures





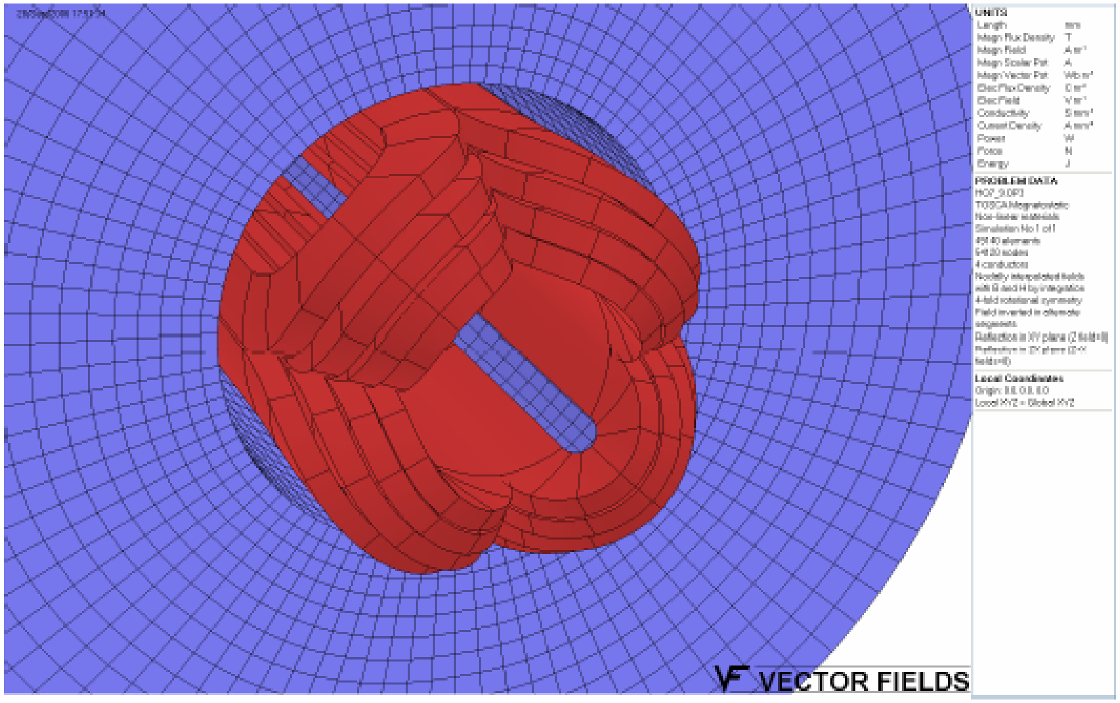
TQC

- Stainless steel collars and skin
- Control spacers to limit pre-load
- End support plates, no pre-load

TQS

- Aluminum shell over iron yoke
- Assembly with bladders and keys
- Aluminum rods for axial pre-load

Coil End Optimization



UNITS

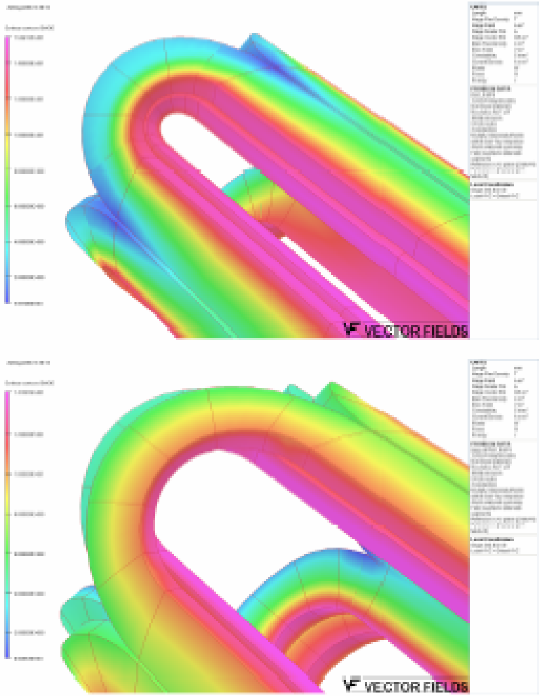
Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S m^{-1}
Current Density	A m^{-2}
Power	W
Force	N
Energy	J

PROBLEM DATA

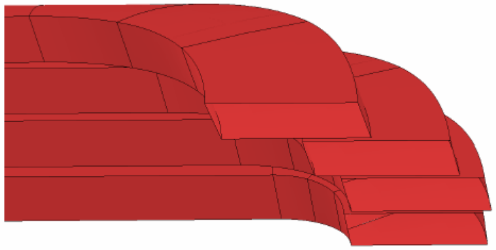
TOSCA Magnetostatic
Non-linear materials
Simulation No 1 of 1
4 conductors
Nodally interpolated fields
with B and H by integration
4-fold rotational symmetry
Field inverted in alternate segments

Local Coordinates

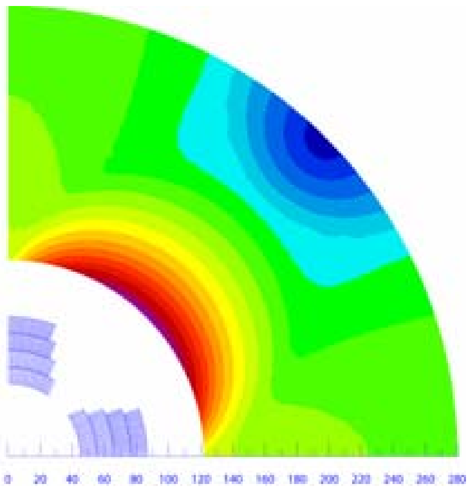
Local XYZ = Global XYZ

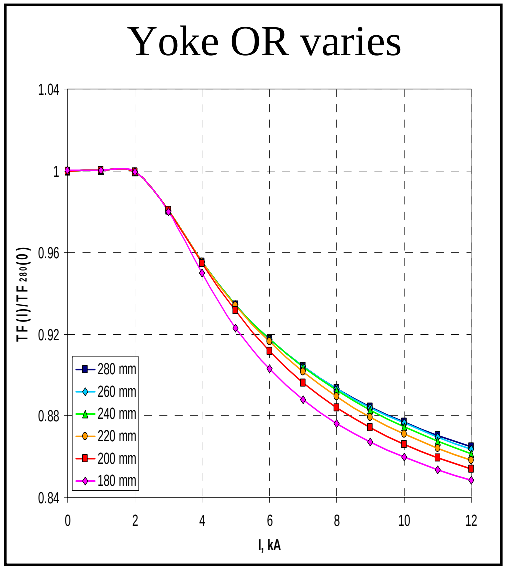


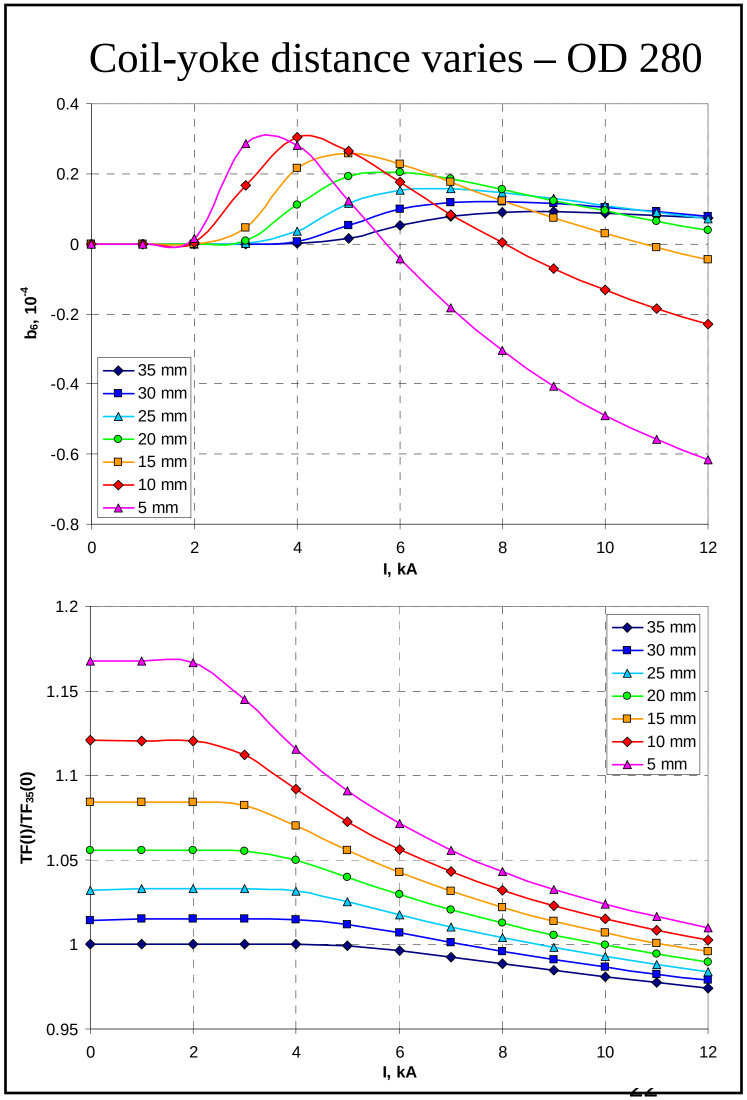
№	Offsets, mm					End length, mm	B_p^{end}, T			
	BL 1	BL 2	BL 3	BL 4	Yoke		BL 1	BL 2	BL 3	BL 4
9	380	371	355	328	328	97.4	13.96 (-1.50) [-9.7%]	13.43 (-2.03) [-13.1%]	13.47 (-0.67) [-4.7%]	13.10 (-1.04) [-7.3%]



Saturation Effects



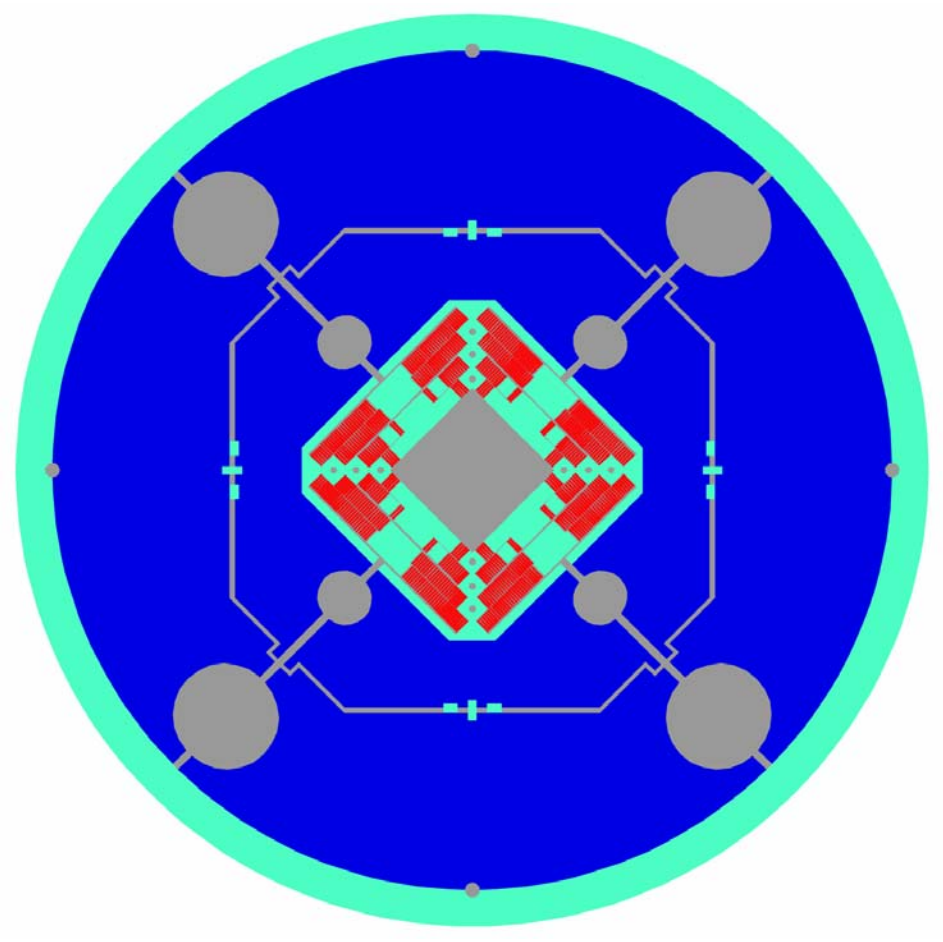

Yoke OR varies


Coil-yoke distance varies – OD 280

Assumptions for preliminary magnetic optimization:

- Yoke OD 250 mm
- Coil-yoke distance 10 mm
- Non linear B-H curve

Racetrack Quadrupoles



Main features:

- Two double-layer racetracks/quadrant
- (One) flat cable, simple coil ends
- Same structure/assembly concept
- No conductor at the midplane
- Minimum end radius 12 mm
- Separation of high field/stress points

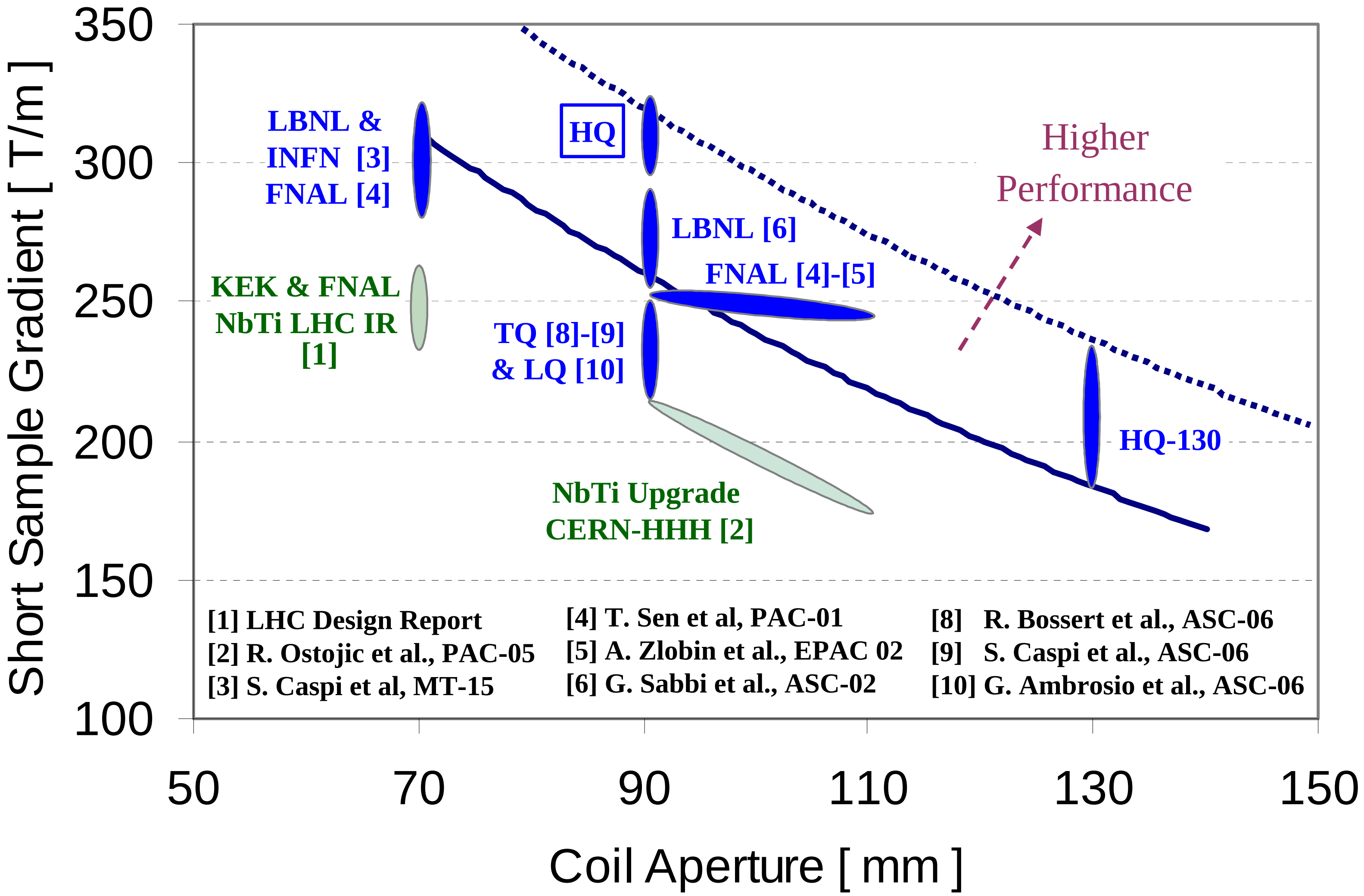
Design issues:

- Bore plate support requirements
- Design of the mid-plane wedge

Results:

- Viable alternative with good potential

Quadrupole Designs for the LHC IR



[1] LHC Design Report
[2] R. Ostojic et al., PAC-05
[3] S. Caspi et al, MT-15
[4] T. Sen et al, PAC-01
[5] A. Zlobin et al., EPAC 02
[6] G. Sabbi et al., ASC-02
[8] R. Bossert et al., ASC-06
[9] S. Caspi et al., ASC-06
[10] G. Ambrosio et al., ASC-06

Summary

- Large bore 2 mrad IR superconducting magnets appear to be feasible
- Further analysis, R&D and prototyping are needed to refine the performance expectations and cost estimation

Next steps:

- NbTi: detailed 3D magnetic and mechanical analysis (including effect of anti-solenoid, corrector package, possibly larger aperture, liner)
- Nb_3Sn: develop coil and structure designs tailored to the specific needs of ILC: focus on magnetic center positioning and small transverse size, relax requirements on higher harmonics, design for required aperture and gradient, interaction with detector solenoid
- Need to perform self consistent calculations (backgrounds, heat loads)
- Installation & maintenance procedures (combined detector/magnets)

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