Cosθ Superconducting Magnets

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LBNL Proposal

Work scope

We propose to perform a scoping study focused on recent and historical experience with Cos(θ) superconducting magnets, in particular magnets designed for applications requiring fast ramping, with the purpose of evaluating a) their applicability to the project, b) known cost estimates for such magnets, and c) technical effort and project risks associated with the use of the Cos(θ) magnet technology for the JLEIC.

The study includes the following elements:

1. Working with JLAB personnel, identify the primary magnets for consideration, and clarify the target magnet parameters and their level of certainty.
2. Review technical specifications of Cos(θ) superconducting magnets with operational parameters relevant to JLEIC:
   a. Summarize conductor specifications and performance data, magnet specifications and fabrication and test data.
   b. For each case identify the major technical modifications that would be required to yield a design meeting JLEIC requirements.
   c. Develop a technical risk registry associated with these modifications.
3. Review cost data (if available) for each relevant Cos(θ) magnet identified above.
   a. Identify the magnet scope associated with the cost data and the source and assumptions behind the data.
   b. Estimate the uncertainty in the cost estimates and identify other cost-elements that would need to be considered if the specific magnet were to be pursued by the JLEIC.

Milestone	Focus
1	Requirements & targets
2	**Review of Cos(θ) superconducting magnets with operational parameters relevant to JLEIC:**
3	**Cost analysis of relevant Cos(θ) magnets**
4	**Applicability of Cos(θ) magnets to JLEIC**
5	Summary of investigation

Magnet Requirements (V. Morozov)

Field & count:

- Dipoles: 133
  - Regular: 127 super-ferric, B < 3.06 T
  - Special: 2 for IR (discussed later) + 4 cos(θ) super-conducting, B < 4.7 T
- Quadrupoles: 205
  - Regular: 155 with integrated field < 48 T (60 T/m)
  - Regular*: 44 with integrated field < 72 T (90 T/m, these may require separate design, e.g. increased length)
  - Special: 6 final-focusing quadrupoles (discussed later)
- Sextupoles: 125
  - Maximum pole-tip field ~1.5 T

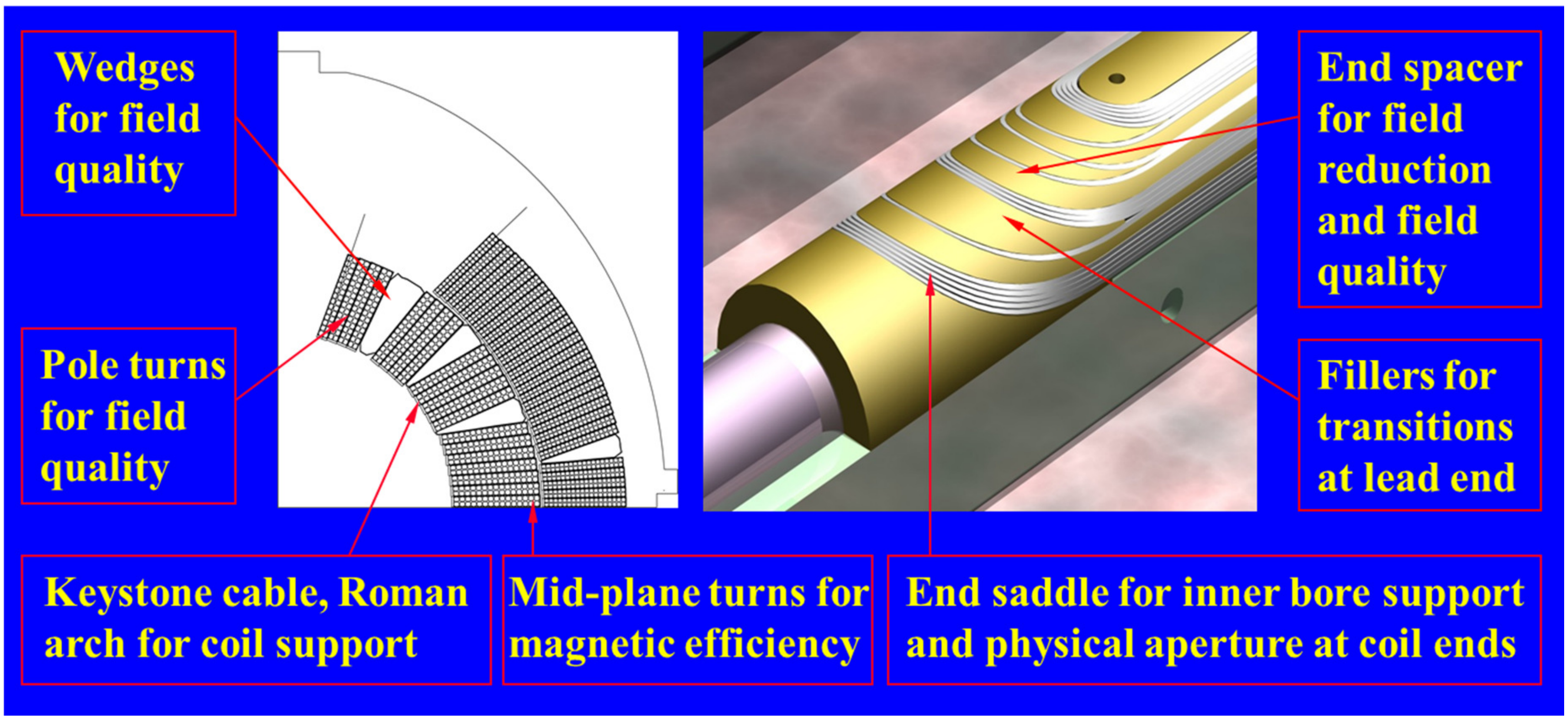
Aperture:

- Regular dipoles
  - Closed orbit allowance, COA = $\pm$1 cm
  - Sagitta of 4 m section, SG $\approx \pm$1 cm
  - Horizontal rms beam size at injection, $\sigma_{x\ inj} = (\beta_x \varepsilon_{x\ inj} + (D_x \Delta p/p_{inj})^2)^{1/2} \approx \pm 3$ mm
  - Vertical rms beam size at injection, $\sigma_{y\ inj} = (\beta_y \varepsilon_{y\ inj})^{1/2} \approx \pm 2$ mm
  - Horizontal aperture, HA = 10 $\sigma_{x\ inj}$ + SG + COA = $\pm$5 cm
  - Vertical aperture, VA = 10 $\sigma_{y\ inj}$ + COA = $\pm$3 cm
- Regular quadrupoles
  - HA = VA = 10 $\sigma_{x\ inj}$ + COA = $\pm$4 cm

Ramp rate: Approx. 0.1 T/s

Cosθ Coils with Rutherford Cables

- Achieves very good magnetic efficiency, essential to push the operating field toward the intrinsic limit of the superconductor
  - High current density in close proximity to the beam pipe
  - Self-supporting against pre-load, no need for internal support
  - Current distribution for high field quality

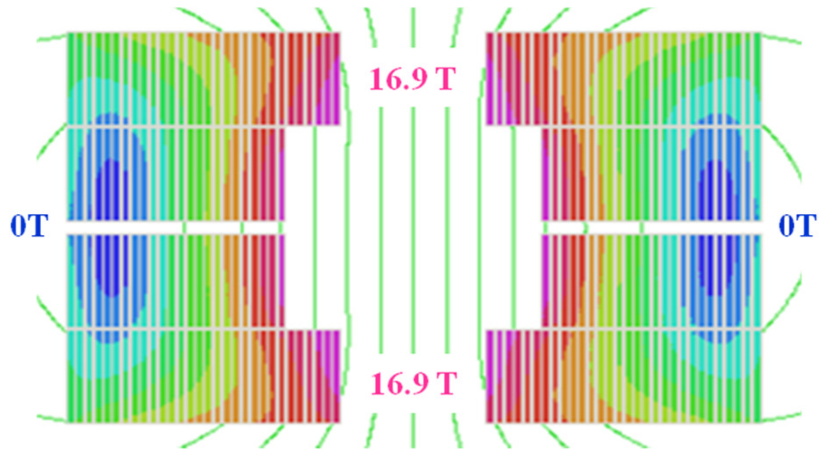


Block Coils with Rutherford Cables

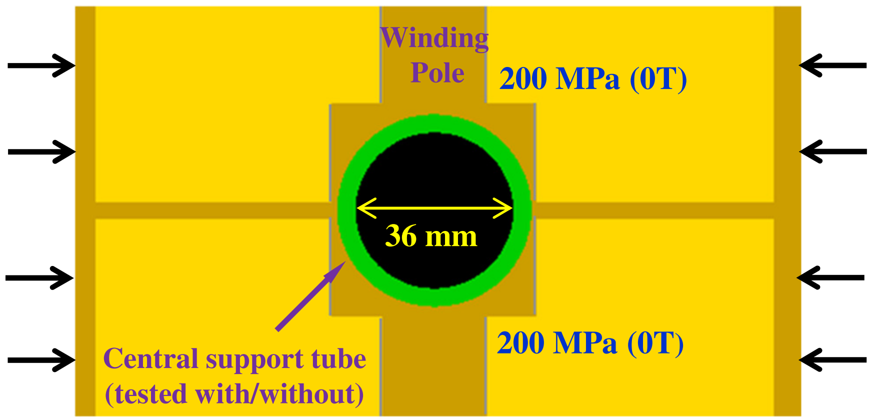
<u>Design Features</u>:

- ✓ High Je (no spacers/structure in coil)
  - Efficient design for small aperture
- ✓ Only two co-wound layers/pole
  - Optimize performance and cost
- ✓ Concentrates stress in low-field region
- ? Internal bore support (vs. Roman arch)
- ? Flared ends (vs. saddle ends)

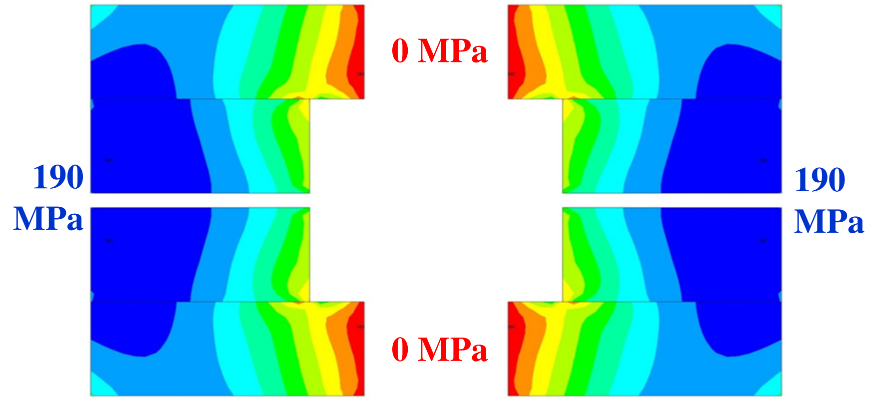
Magnetic Field (B_0 = 16 T)



Bore structural support



Coil Stress (B_0 = 16 T)



Intermediate Field Cosθ Dipoles

RHIC parameters directly relevant to JLEIC:

- Coil aperture: 80 mm
- Operating field:3.45 T
- Ramp rate: 0.042 T/s
- Magnetic Length: 9.45 m
- Sagitta: 48.5 mm
- Number of dipoles: 373

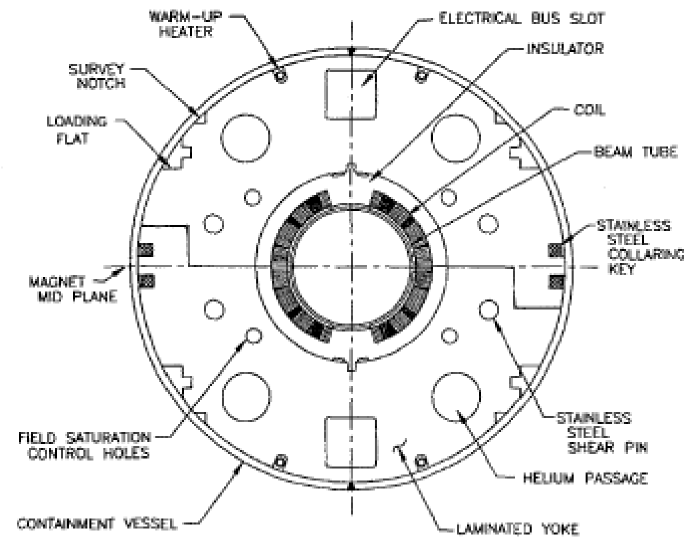


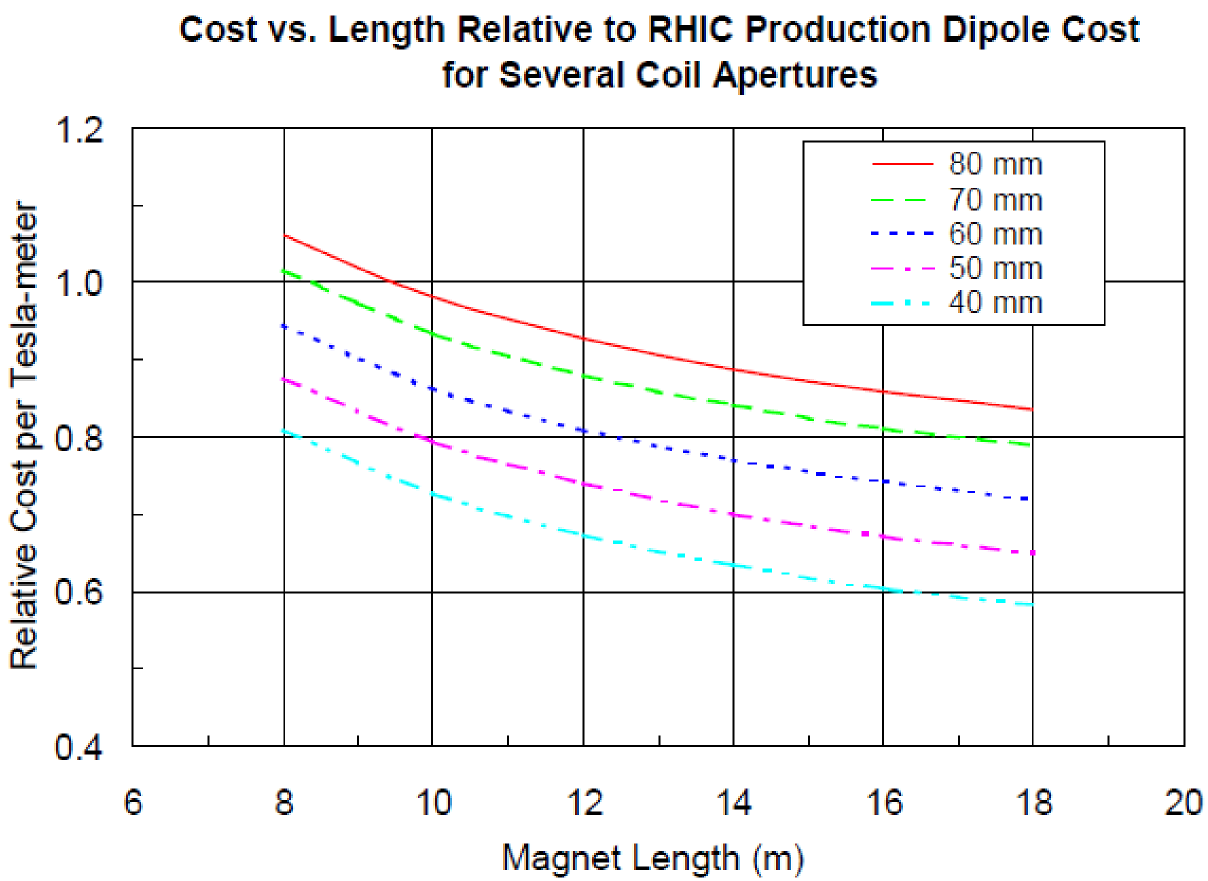
Fig. 4 A cross section of the central portion of the RHIC arc dipole magnet. For the RHIC machine, 373 of these magnets were built by the Northrop-Grumman Corporation in various lengths.

Ref: E. Willen, BNL Report 64183

Development and production approach:

- Designed to minimize cost
  - Single layer coil
  - Mechanical support from iron yoke (no collar)
- Built-to-print in industry
  - Most parts and tooling designed and procured by industry
  - Fast rate (~1 magnet/day at peak)

Cost Scaling: Aperture and Length



Ref: E. Willen, presented at the workshop on Magnets for a Very Large Hadron Collider, Port Jefferson, November 1998 (http://vlhc.org/vlhc/mtworkshop.html) ; and BNL report 64183

JLEIC: Aperture, Length and Sagitta

Sagitta:

- Current approach is to add 20 mm in aperture and cut length in half
- This would not appear to be the optimal approach for a RHIC-type magnet
  - RHIC dipole includes ~50 mm sagitta over ~10 m (600 m radius)
  - Test performed on a UNK magnet for GSI show no significant performance degradation after bending to 50 mm radius a magnet initially built straight
    - However, not clear that all requirements can be met with this approach
  - Alternative approach to build dipole directly from bent coil was recently demonstrated by INFN (also in the context of the GSI project)
  - E. Willen scaling indicates cost increase (in $/Tm) going from 8 to 4 m length is comparable to cost of going from 80 to 120 mm aperture (+30%)

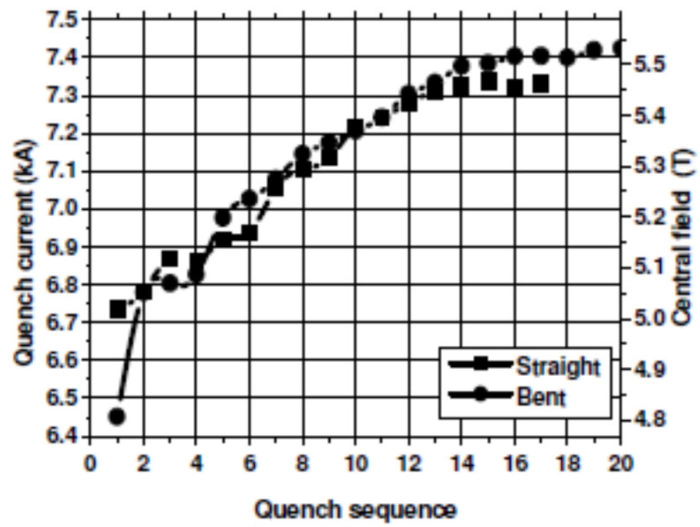
Cost:

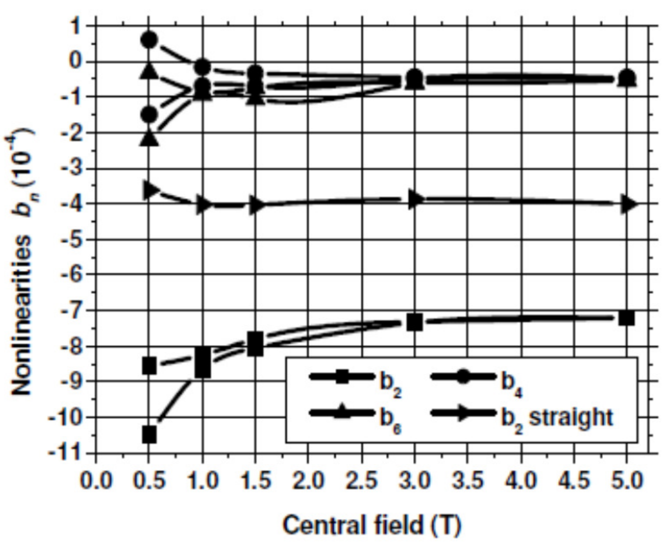
- Simple escalation of RHIC production cost (1993 to 2016) gives 230k$/magnet

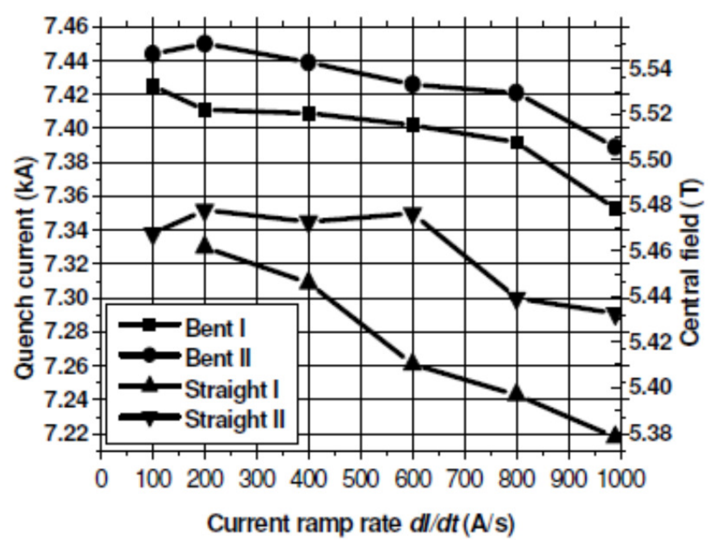
UNK Dipole Bending Experiment

CHARACTERISTICS OF DXB 24 SUPERCONDUCTING DIPOLE

Superconducting alloy	NbTi
Titanium percentage, %	50±4
Matrix material	copper
Wire diameter, mm	0.85
Filament diameter, µm	6
Filling factor	0.42±0.02
Copper to non-copper area ratio	(1.39±0.1)/1
Twist pitch, mm	10±2
Residual Resistance Ratio (RRR) of matrix	≥ 70
Critical current at B = 5 T, T = 4.23 K, A	600±50
Critical current density at B = 5 T, T = 4.23 K, kA/mm^2	2.5±0.2
Wire coating	oxide
Cable strand number	19
Transfer function with iron yoke, T/kA	0.984







Ref: Bogdanov et al., 2005

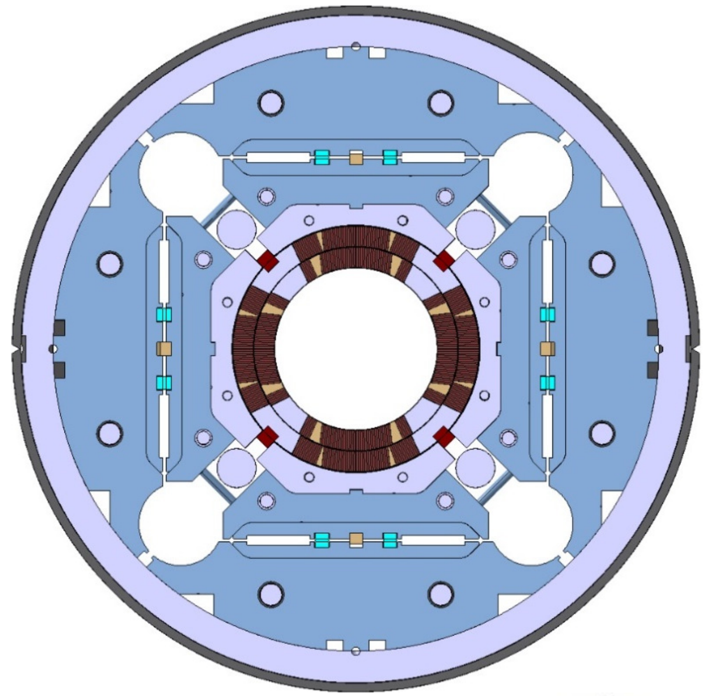
IR Magnet Requirements(V. Morozov)

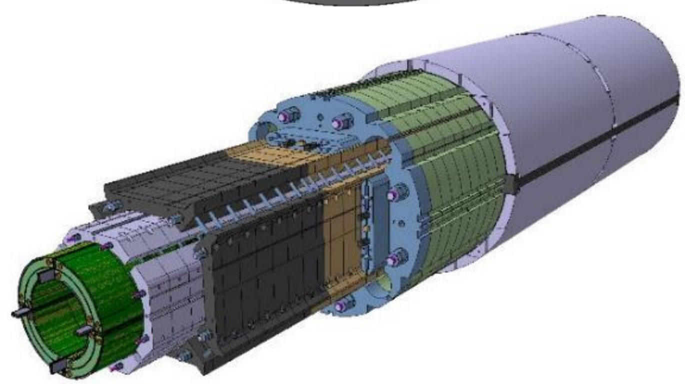
Name	Type	Length [m]	Good-field radius [cm]	Inner radius [cm]	Outer radius [cm]	Min. beam separation [cm]	Strength [T or T/m]	Pole-tip field [T]
QFFB3_US	Quad [T/m]	1	3	4	12	36.0	-116	-4.6
QFFB2_US	Quad [T/m]	1.5	3	4	12	26.5	149	6
QFFB1_US	Quad [T/m]	1.2	2	3	10	18.0	-141	-4.2
SB1	Dipole [T]	1	4	17	24	25.0	-2	-2
QFFB1	Quad [T/m]	1.2	4	9	17.1	35.9	-88	-8
QFFB2	Quad [T/m]	2.4	4	15.7	24.7	48.2	51	8
QFFB3	Quad [T/m]	1.2	4	17	26.7	67.2	-35	-6
SB2	Dipole [T]	4	4	40	90	102	4.7	4.7

Name	Type	Length [m]	Good-field radius [cm]	Inner radius [cm]	Outer radius [cm]	Min. beam separation [cm]	Strength [T/m]	Pole-tip field [T]
QFFB4e	Quad	0.5	4	5	11	21	-3.1	-0.16
QFFB3e	Quad	0.58	4	5	11	15	47.9	2.39
QFFB2e	Quad	0.7	2	3	8	10.5	-57.7	-1.73
QFFB1e	Quad	0.4	1.2	2	6	8	24.4	0.49
QFFB1e_US	Quad	0.7	2	3	7	12	-43.9	-1.32
QFFB2e_US	Quad	0.7	4	5	10	16	45.5	2.28
QFFB3e_US	Quad	0.5	4	5	10	22	-16.4	-0.82

MQXF (Nb_3Sn) IR Quadrupole (LHC)

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. turns Inner-Outer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at Inom	T	11.4
Stored energy at Inom	MJ/m	1.2
Diff. inductance	mH/m	8.2
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4





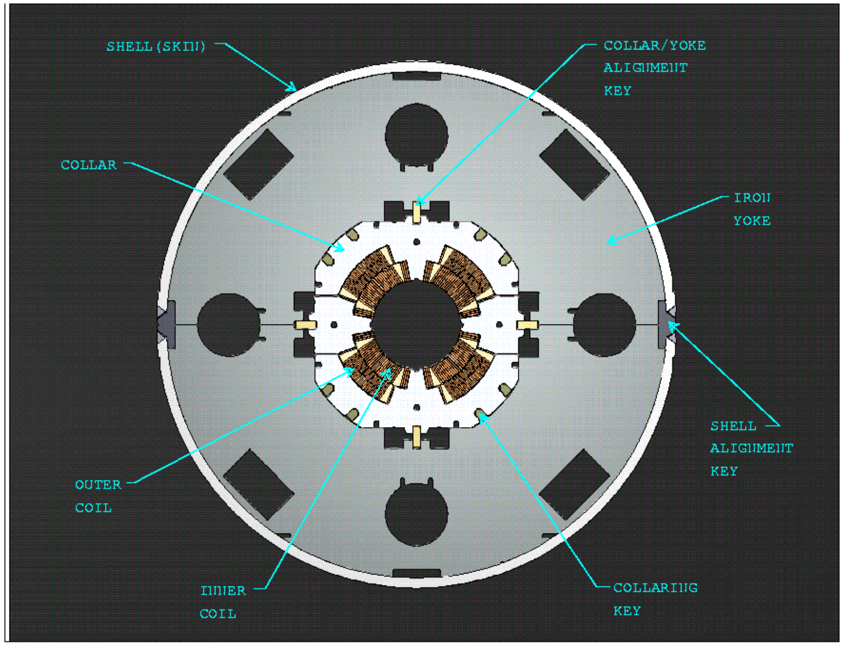
MQXB (NbTi) IR Quadrupole (LHC)

Operating Gradient (IP1/5)	205 T/m
Operating Gradient (IP2/8)	215 T/m
Coil Inner Diameter	70mm
Magnetic Length	5.5 m

Mechanical support entirely provided by stainless steel collar, 25 mm thick

Strand and Cable Parameters

Parameter	Inner cable	Outer cable
Strand diameter [mm]	0.808	0.65
Radial width [mm]	15.40	15.40
Minor edge [mm]	1.326/1.320	1.054/1.051
Major edge [mm]	1.587/1.610	1.238/1.241
Keystone angle [deg]	0.990/1.079	0.690/0.707
Mean thickness [mm]	1.456	1.146
Packing factor	0.89/0.91	0.91
Number of strands	37/38	46
Cable Lay	right/left	left



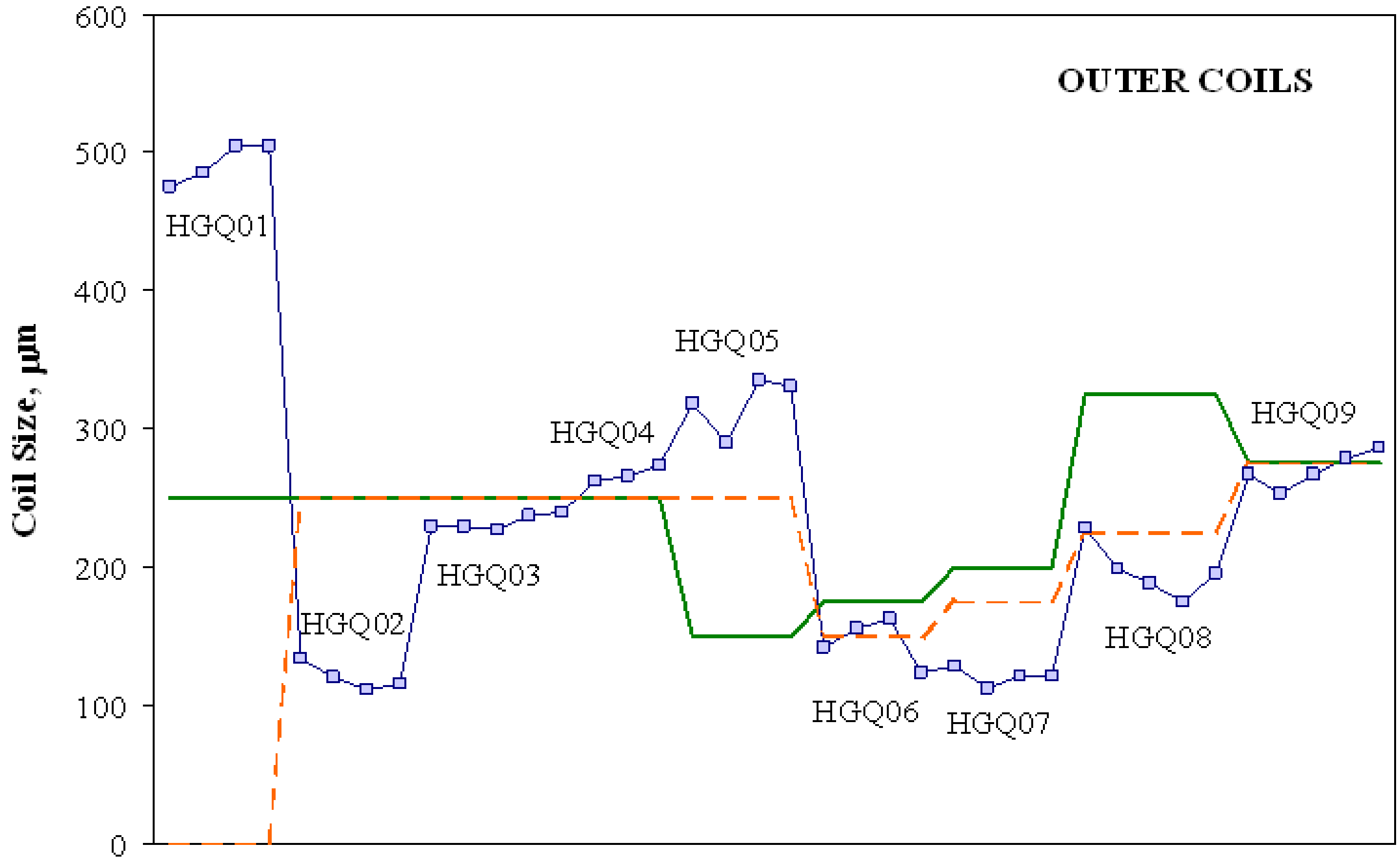
MQXB Field Quality Target

MQXB AP Reference Table 2.0 (collision)						
n	$<b_n>$	$d(b_n)$	$s(b_n)$	$<a_n>$	$d(a_n)$	$s(a_n)$
Body						
3	0	0.3	0.8	0	0.3	0.8
4	0	0.2	0.8	0	0.2	0.8
5	0	0.2	0.3	0	0.2	0.3
6	0	0.6	0.6	0	0.05	0.1
7	0	0.05	0.06	0	0.04	0.06
8	0	0.03	0.05	0	0.03	0.04
9	0	0.02	0.03	0	0.02	0.02
10	0	0.02	0.03	0	0.02	0.03
Lead end (magnetic length ~0.41m)						
2	-	-	-	40	-	-
6	2	2	0.8	0	0.5	0.2
10	-0.2	0.2	0.1	0	0.1	0.1
Return end (magnetic length ~0.33m)						
6	0	1.2	1	-	-	-
10	-0.25	0.25	0.1	-	-	-

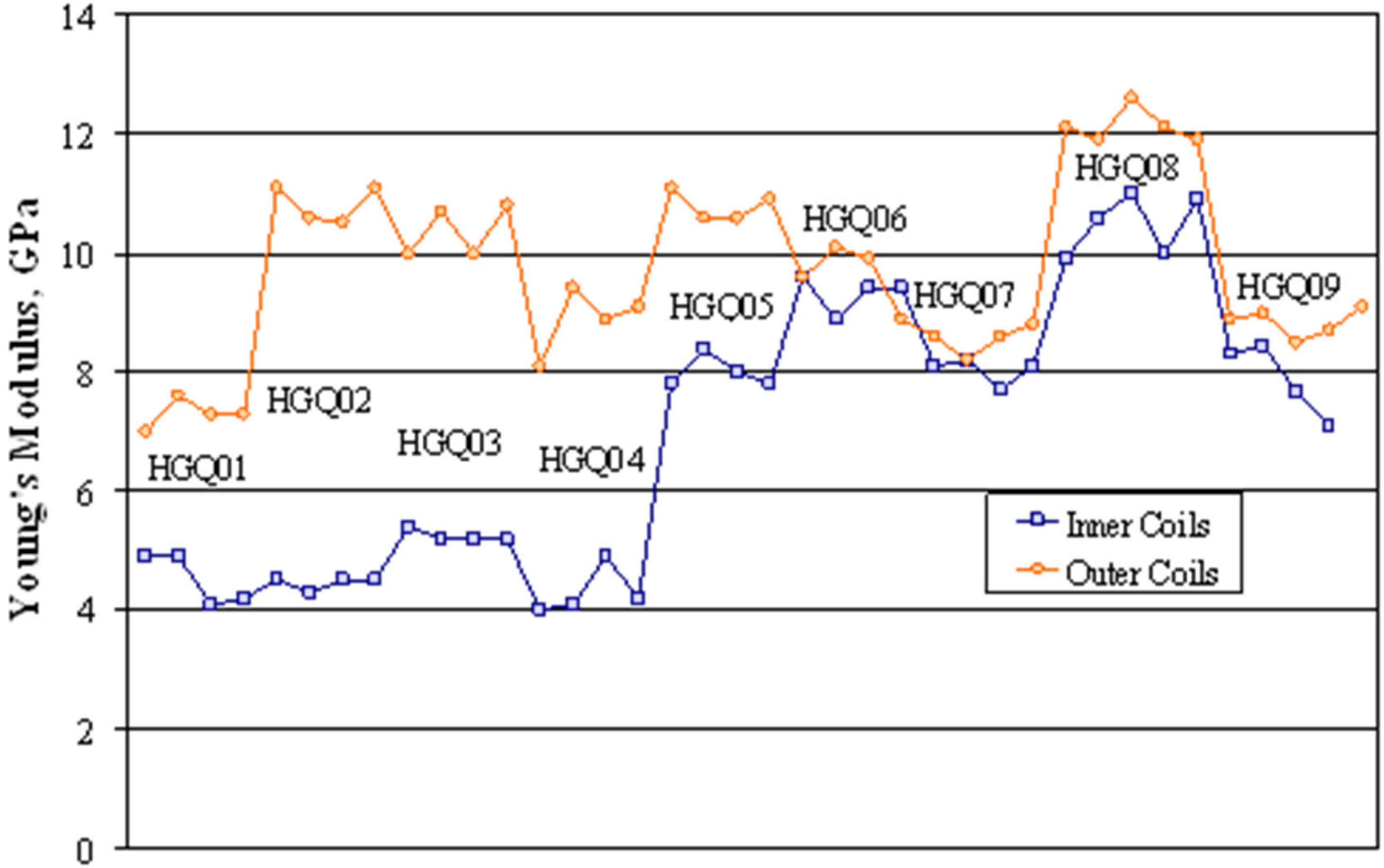
MQXB Short Model Field Quality

	HGQ01	HGQ02	HGQ03	HGQ05	HGQ06	HGQ07	HGQ08	HGQ09
b3	0.36	-0.70	1.04	0.72	0.25	0.18	0.61	0.71
a3	0.27	0.55	-0.30	0.12	-0.27	0.41	-0.01	0.35
b4	0.26	0.18	0.14	0.00	0.09	0.01	-0.12	-0.05
a4	2.00	0.53	0.32	0.19	-0.31	-0.50	-0.44	0.31
b5	-0.29	0.09	-0.34	-0.04	-0.11	-0.04	-0.01	0.08
a5	0.02	-0.17	0.26	0.05	-0.07	-0.24	0.12	-0.14
b6	-3.91	-1.54	-1.02	-0.30	-0.05	-0.45	-0.06	-0.28
a6	-0.02	0.03	0.07	-0.03	-0.05	-0.10	-0.03	0.04
b7	-0.08	-0.01	-0.06	0.01	-0.03	0.02	-0.01	0.06
a7	-0.05	0.00	-0.03	0.01	0.00	0.08	0.00	0.02
b8	0.06	0.01	0.00	0.00	0.00	0.00	0.00	-0.01
a8	0.02	0.02	0.03	0.00	0.00	0.01	-0.01	0.01
b9	0.04	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
a9	0.01	-0.01	0.01	0.00	0.00	0.01	0.01	0.00
b10	-0.10	-0.10	-0.04	0.01	0.00	-0.02	-0.01	-0.01
a10	0.02	0.00	-0.01	0.00	0.00	0.00	0.00	0.00

MQXB Coil Size Optimization



MQXB Coil Module Optimization



Field Quality Summary Comments

- MQXB (used as initial reference) represents very high field quality magnets. achieved through significant development and optimization
- Considerable improvement over a series of 9 models
- Makes sense for LHC (4 IR, 8 magnets each, 7 to 8 m long)
- JLEIC only needs one magnet of each type
- Specify field quality requirements that are adequate to ensure dynamic aperture without requiring many iterations
- If possible, incorporate magnet design features allowing field quality tuning without requiring new coils or assembly
- Specify type and strength of correctors