Interaction Region Magnets

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Forewords & Talk Outline

- Caveat: my experience comes from Super*B* (i.e. 4 GeV on 7 GeV) which is a quite different regime w.r.t. a Higgs factory (shorter magnets, ~ smaller gradients, softer and weaker synchrotron radiation, etc.)
- I will present some general consideration about scaling laws worked out by L. Todesco, P.Ferracin and others.
- I will present some of the peculiar features of the SuperKEKB I.R. and of the Super*B* I.R. that are of main interest for a two rings collider.

Why I.R. Quadrupoles Are Not Easy Pieces

- Usually:
  - they are the strongest quadrupoles of the lattice
  - the β_y (β_x)function reaches her maxima at the QD0 (QF1): the mechanical aperture is large
  - their field quality must be excellent to preserve dynamic aperture
  - their thickness is limited by the detector acceptance (single ring), nearby beam line (two rings): they are thin

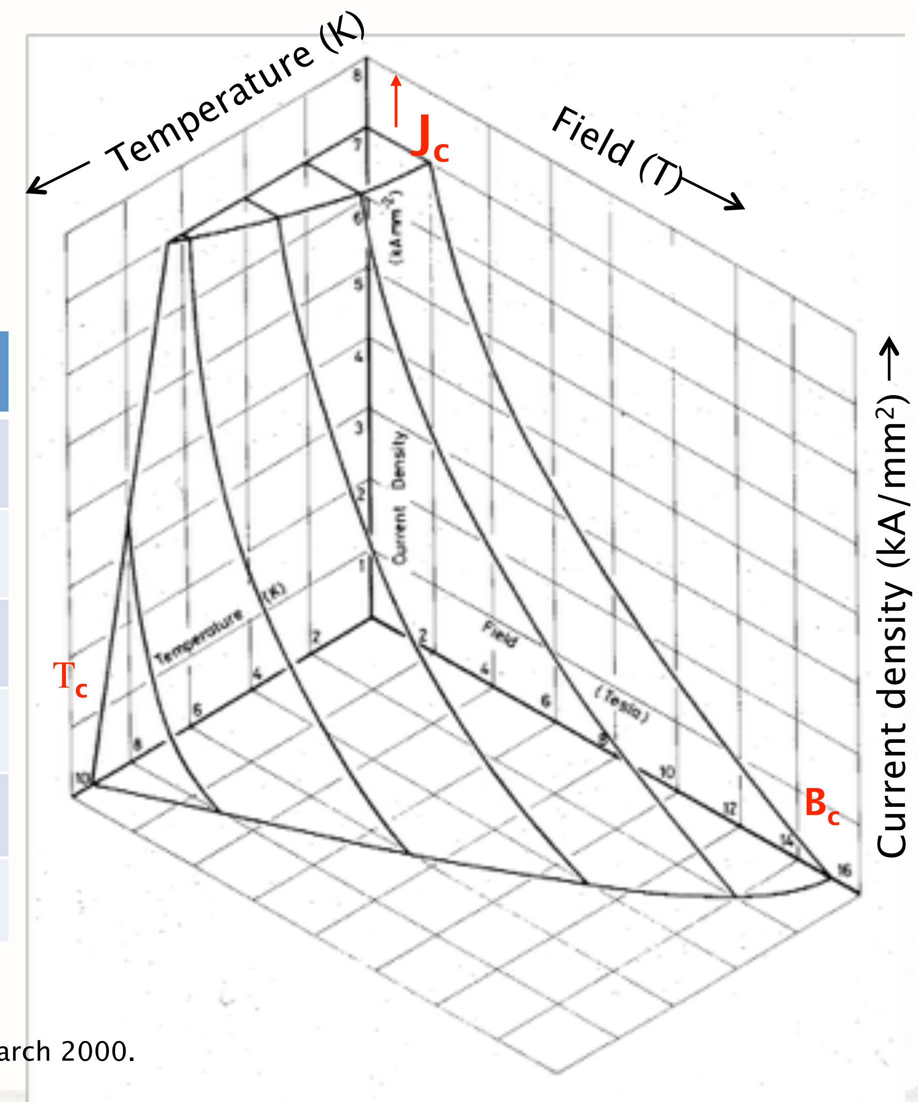
Super Conductors Limit: $B \propto J$

- The superconductor current density must be below the critical surface.
- The highest the gradient and the larger the aperture ⇒ the larger the field on the superconductor and the lower the current ⇒ thicker coil pancake
- e.g.: Niobium Titanium critical surface approximate expression

$$J \leq J_c \approx \frac{C_0}{B} \times b^{\alpha} \times (1-b)^{\beta} \times (1-t^{1.7})^{\gamma}$$

$$\begin{cases} b & \equiv \frac{B}{B_{c2}} \\ t & \equiv \frac{T}{T_{c20}} \\ B_{c2} & \equiv B_{c20} \times (1-t^{1.7})^{\gamma} \end{cases}$$

NbTi Parameters	
B_{c20}	14.5
T_{C0}	9.2
C_0	23.8
α	0.57
β	0.9
γ	1.9



*L. Bottura, A practical fit for the critical surface of NbTi, IEEE Transactions on Applied Superconductivity, Vol. 10, no. 1, March 2000.

S.C. Quadrupole Thickness Scaling Law

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM, No. 19, January 2012
Preprint of MT22 Invited paper submitted to *IEEE Trans. Appl. Supercond.* (should be cited accordingly).

Limits to high field magnets for particle accelerators

E. Todesco, P. Ferracin

w is ~ coil width

$$G = \kappa_q j_o \log\left(1 + \frac{w}{r}\right) \qquad (2)$$

where r is the aperture radius and κ_q=0.69 in the horrible but very practical units (T/m)/ (A/mm^2) [11]. These equations can

j_0 = 600 A/mm^2

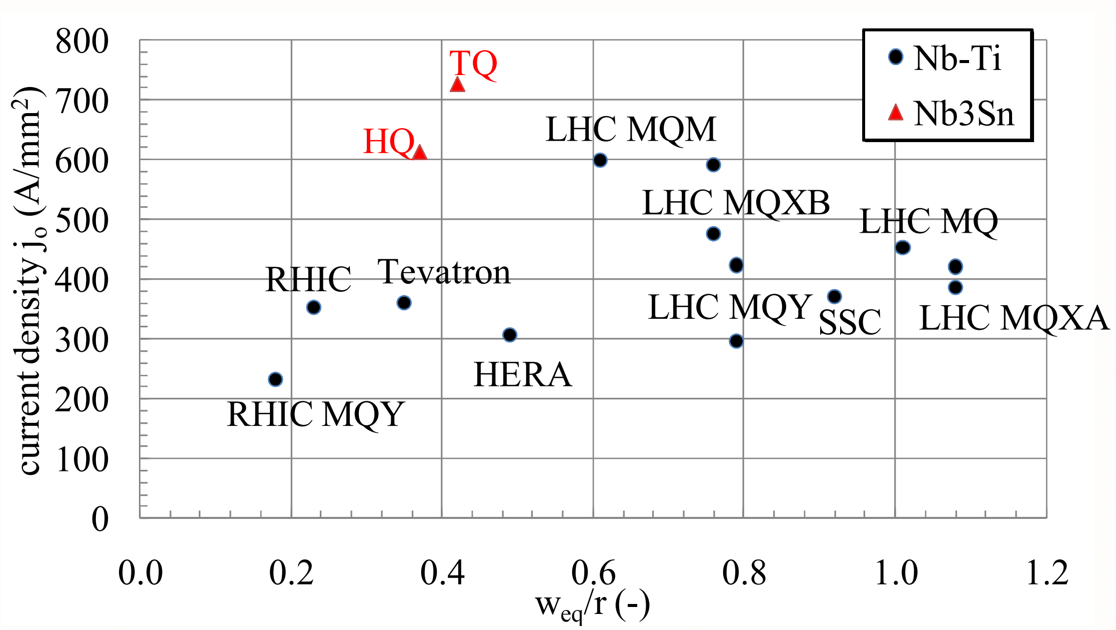


Fig. 7: Overall current density versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb_3Sn models).

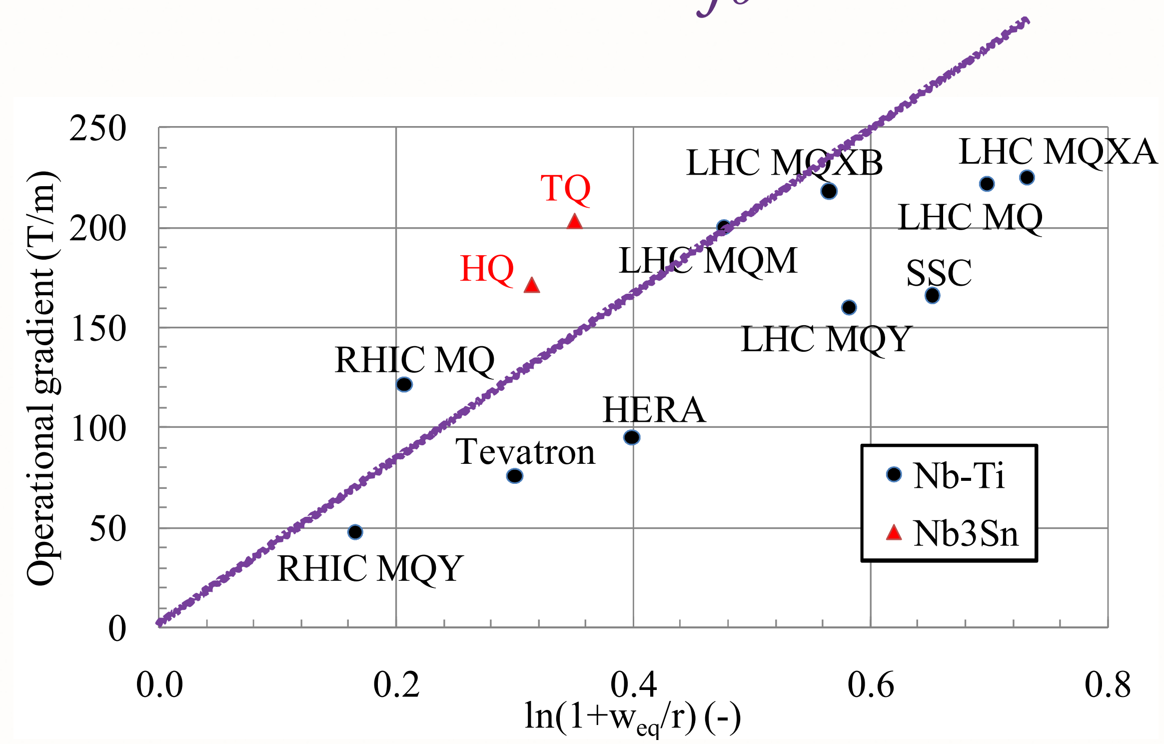


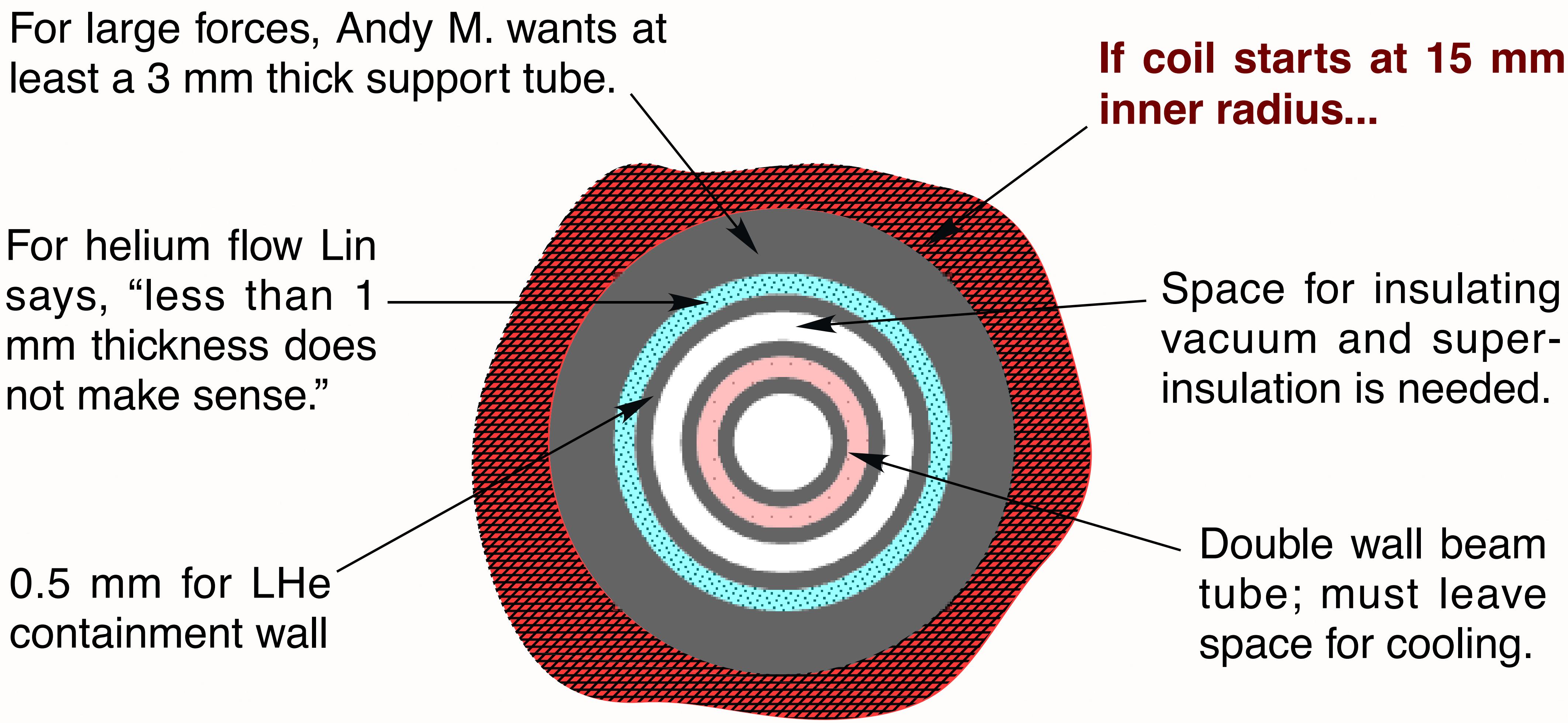
Fig. 6: Operational gradient versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb_3Sn models).

Warm Bore: Cold To Warm Transition

- r is larger than the bare beam stay clear. A first order assumption can be: r = b.s.c.+ 10mm for a cold bore magnet

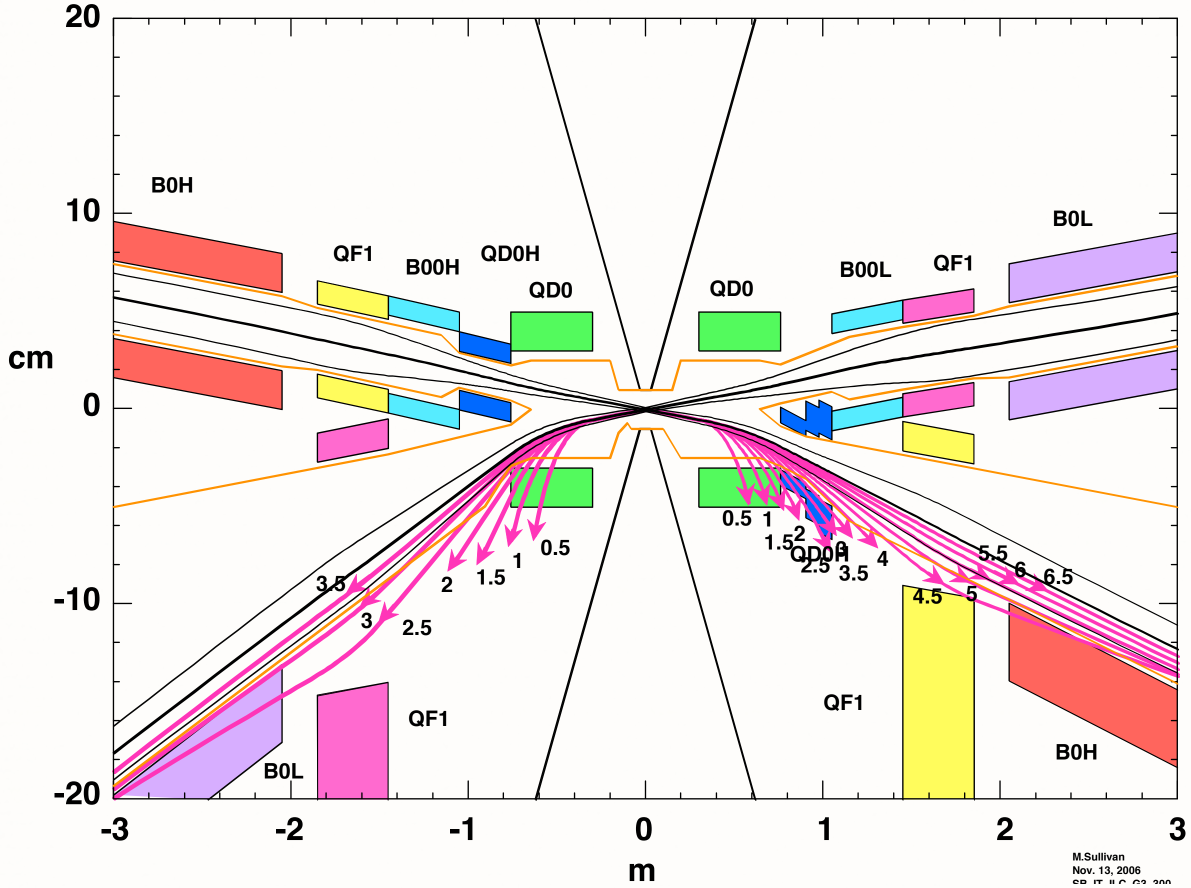
Superconducting Magnets for the NLC: A Design Odyssey

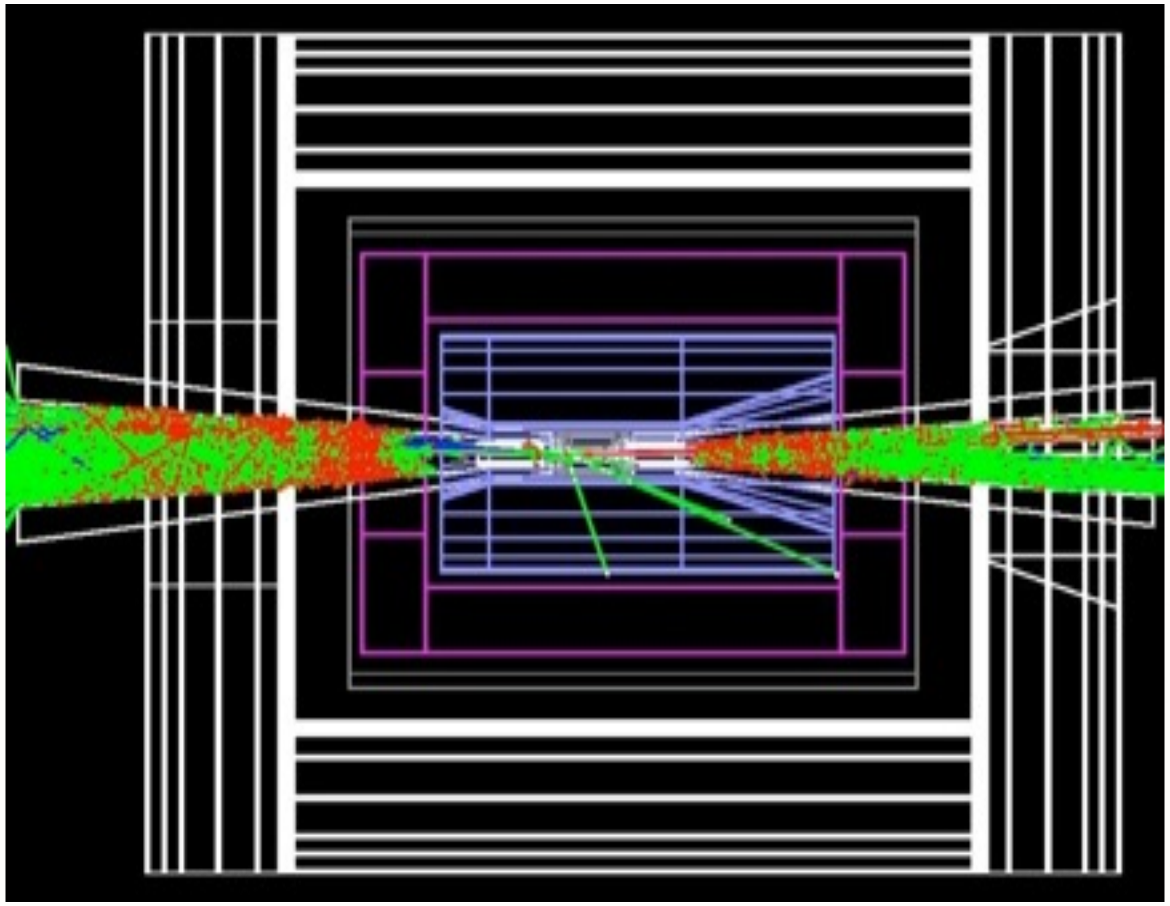
Brett Parker will be your guide today...



Double Ring Extra Complication

Early design of Super*B* IR (Courtesy Mike Sullivan)



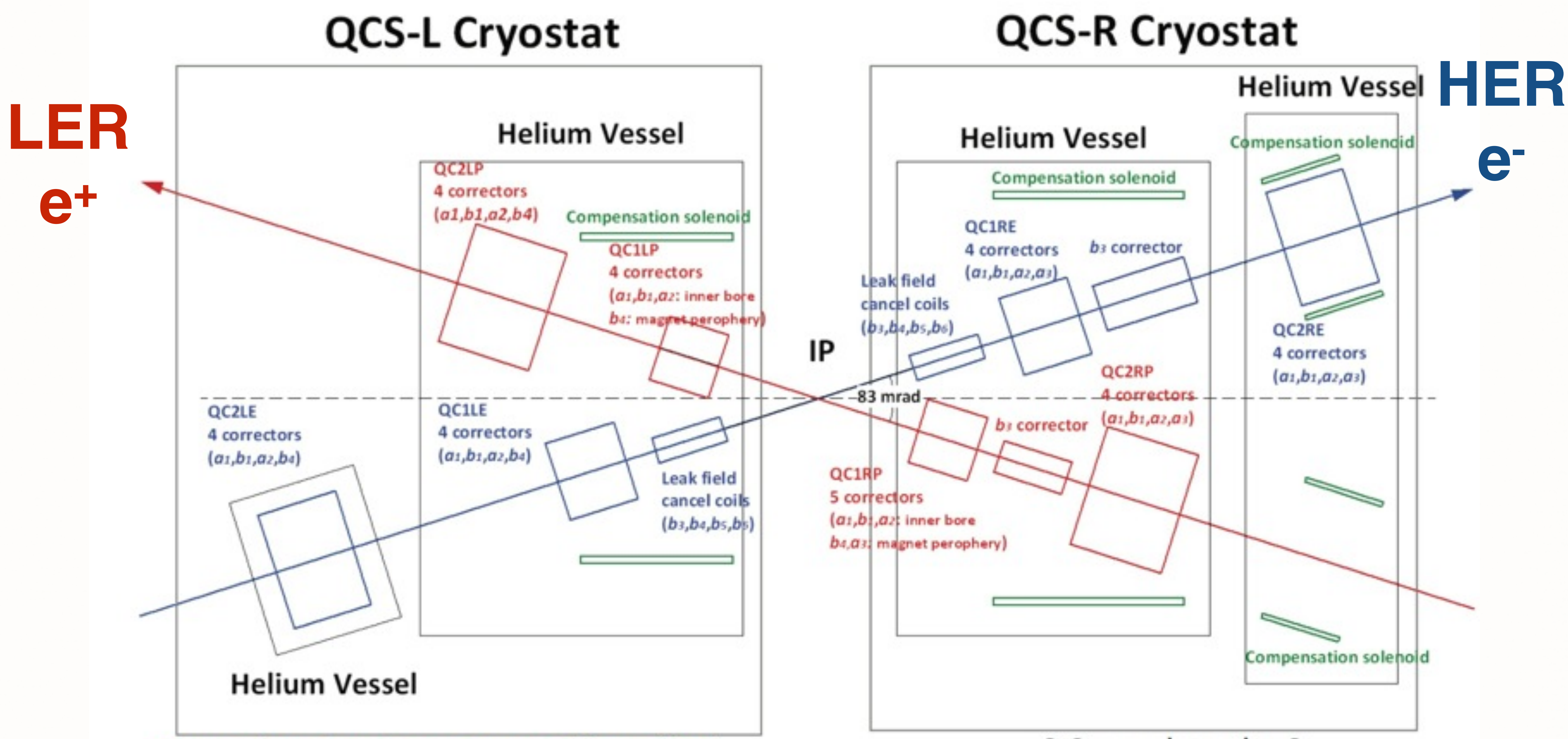


Geant 4 simulation

- High luminosity $e^+ e^-$ collider suffers from beamstrahlung backgrounds. A QD0 shared by both beams behaves like an obnoxious spectrometer.

E.g.: SuperKEKB (Ohuchi-san talk NA-PAC13)

S.C. Magnet System



Target luminosity = 8 $\times 10^{35}$ cm^{-2} s^{-1}

Beam size at IP: e- = 62 nm, e+= 46nm

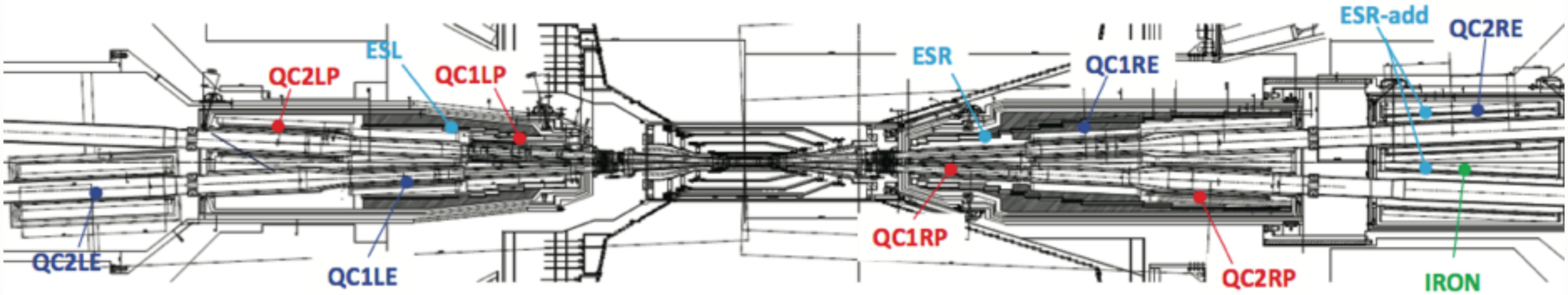
S.C. quadrupole: 8

S.C. solenoid: 4

S.C. corrector: 43

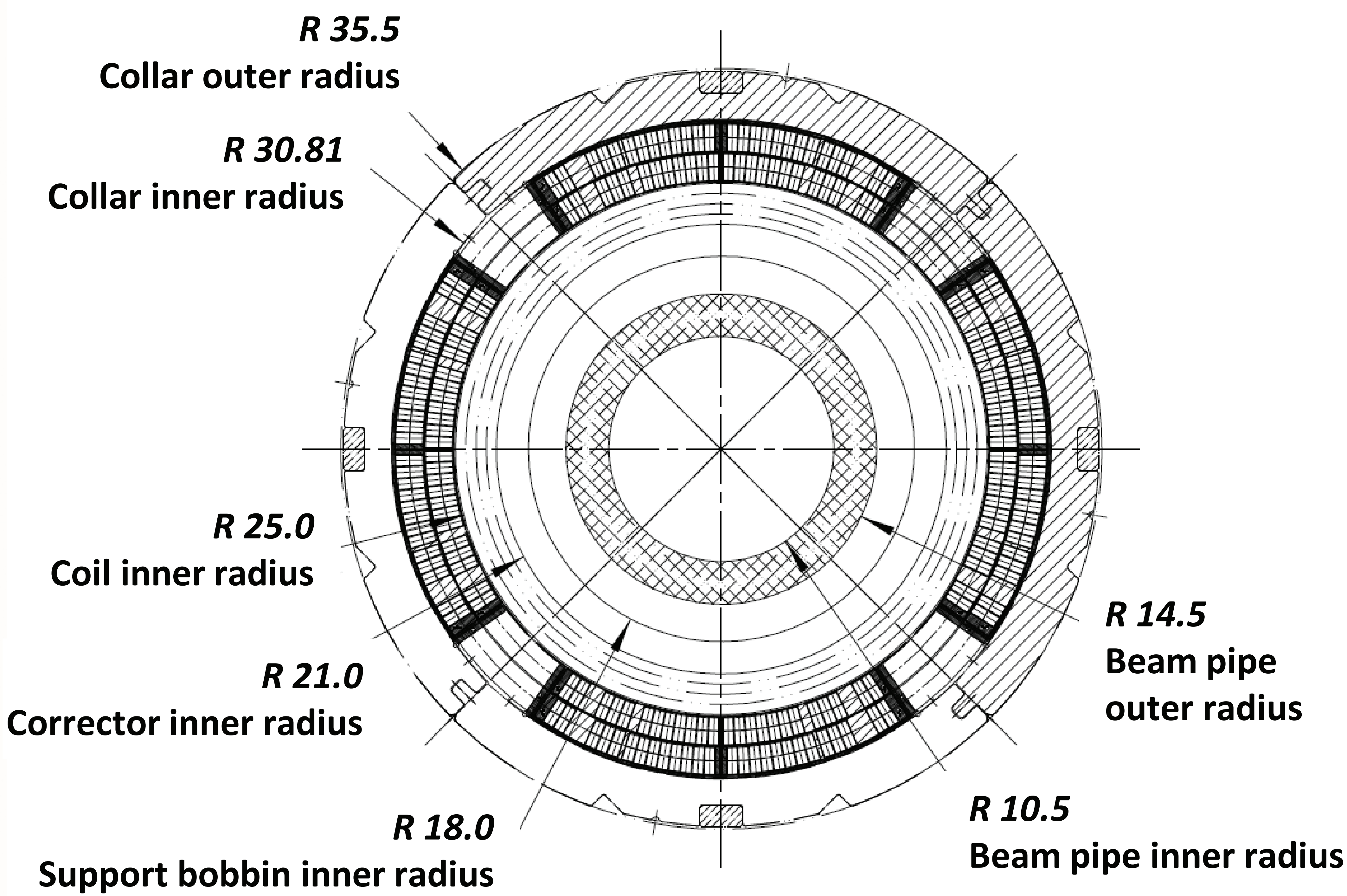
2013/9/29-10/4 NA-PAC 2013 4

S.C. magnets in SuperKEKB IR (Ohuchi-san)



	Integral field gradient, (T/m)·m Solenoid field, T	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	Iron Yoke	2925	0	-0.7	0
QC2RP	11.56 [26.28 × 0.410]	Permendur Yoke	1925	-2.114	0	-1.0
QC1RE	26.45 [70.89×0.373]	Permendur Yoke	1410	0	-0.7	0
QC1RP	22.98 [68.89×0.334]	No Yoke	935	7.204	0	-1.0
QC1LP	22.97 [68.94×0.334]	No Yoke	-935	-13.65	0	-1.5
QC1LE	26.94 [72.21×0.373]	Permendur Yoke	-1410	0	+0.7	0
QC2LP	11.50 [28.05 × 0.410]	Permendur Yoke	-1925	-3.725	0	-1.5
QC2LE	15.27 [28.44×0.537]	Iron Yoke	-2700	0	+0.7	0

QC1RP main dimensions



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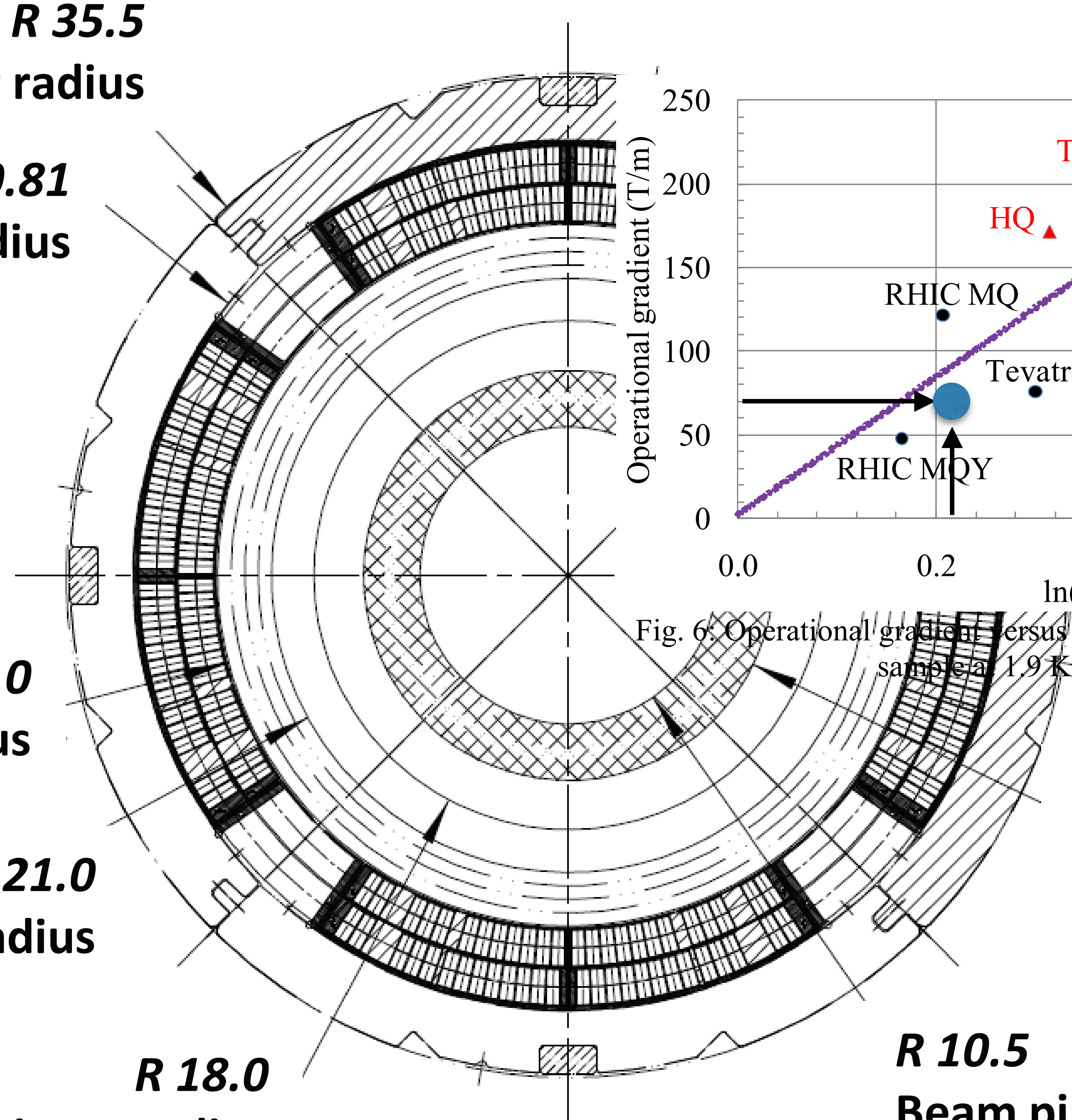


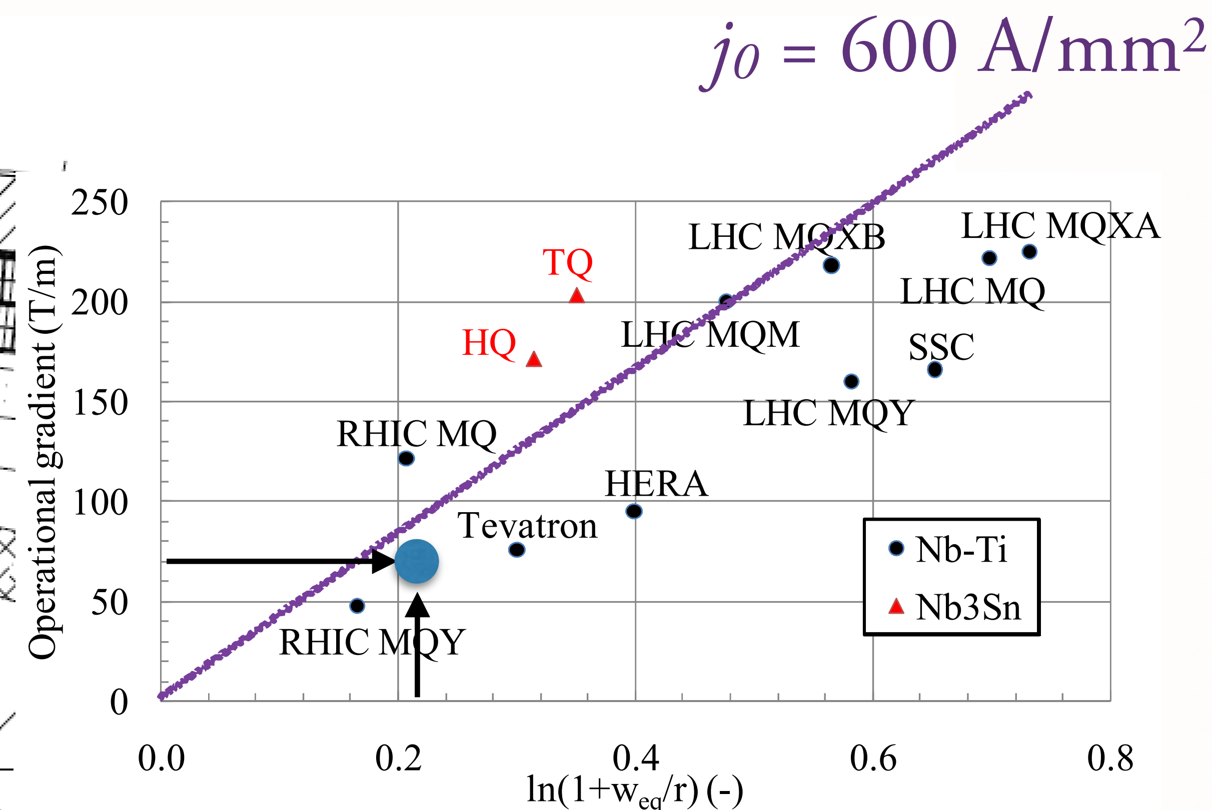
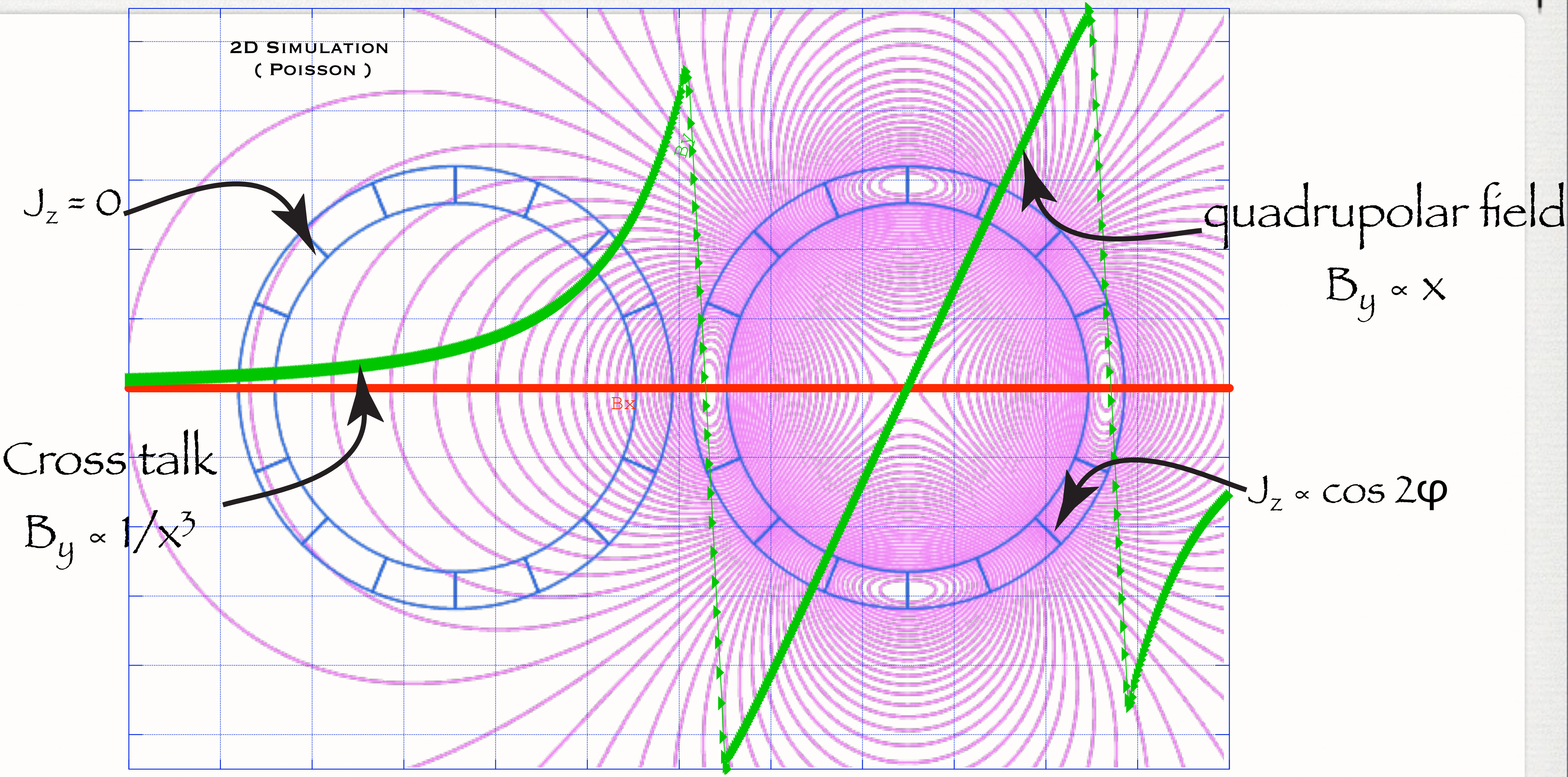


Fig. 6: Operational gradient versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb_3Sn models).

Leaking Field Compensation

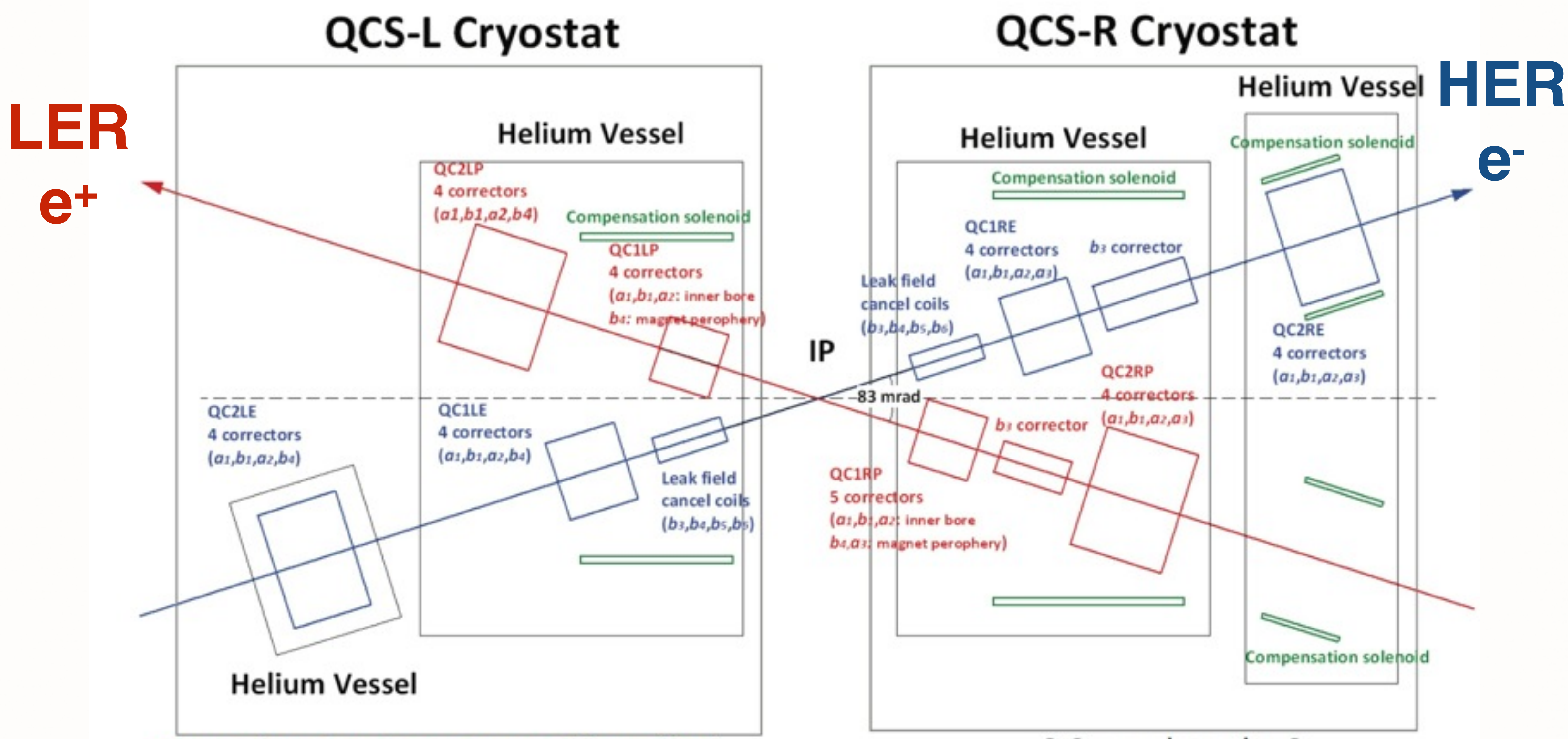


- Idea: exploit the superposition principle to design the coil shape in such a way that the integrated beam kick is a linear function of the displacement from the reference orbit

E.g.: SuperKEKB (Ohuchi-san talk NA-PAC13)

Super KEKB

S.C. Magnet System



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SuperKEKB approach

- Canceling coils to null the terms B_3,B_4,B_5 and B_6 of the field leaking from the QC1RP: B_1 and B_2 are retained.

SUPERCONDUCTING CORRECTOR IR MAGNET PRODUCTION FOR SUPERKEKB*

B. Parker[#], M. Anerella, J. Escallier, A. Ghosh, H. Hocker, A. Jain, A. Marone, P. Wanderer, BNL, Upton, NY 11973, USA
Y. Arimoto, M. Iwasaki, N. Ohuchi, M. Tawada, K. Tsuchiya, H. Yamaoka, Z. Zong, KEK, Tsukuba, Ibaraki 305-0801 Japan

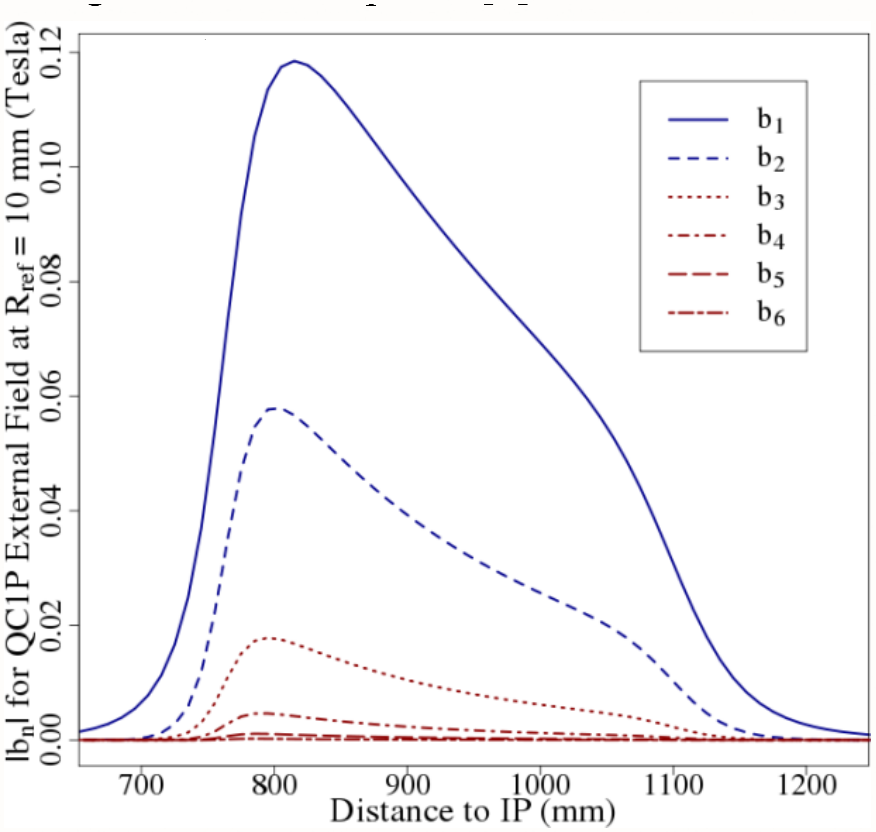


Figure 3: Decomposition into magnetic multipoles for QC1P external field plotted as a function of distance to the IP, for 10 mm reference radius, at the HER beam line.

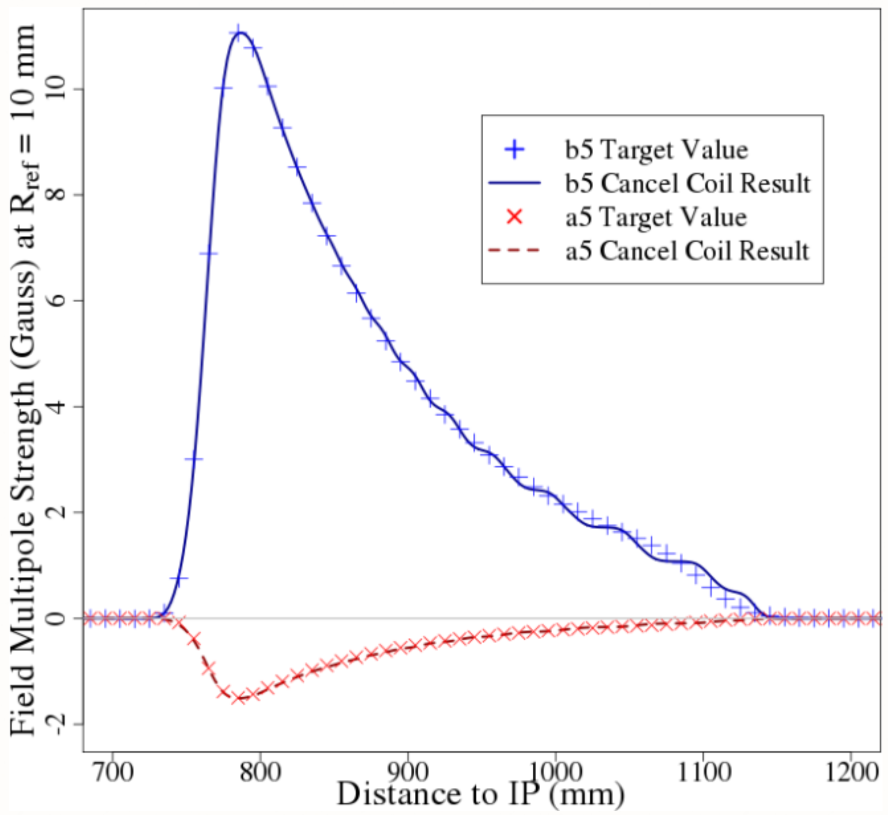
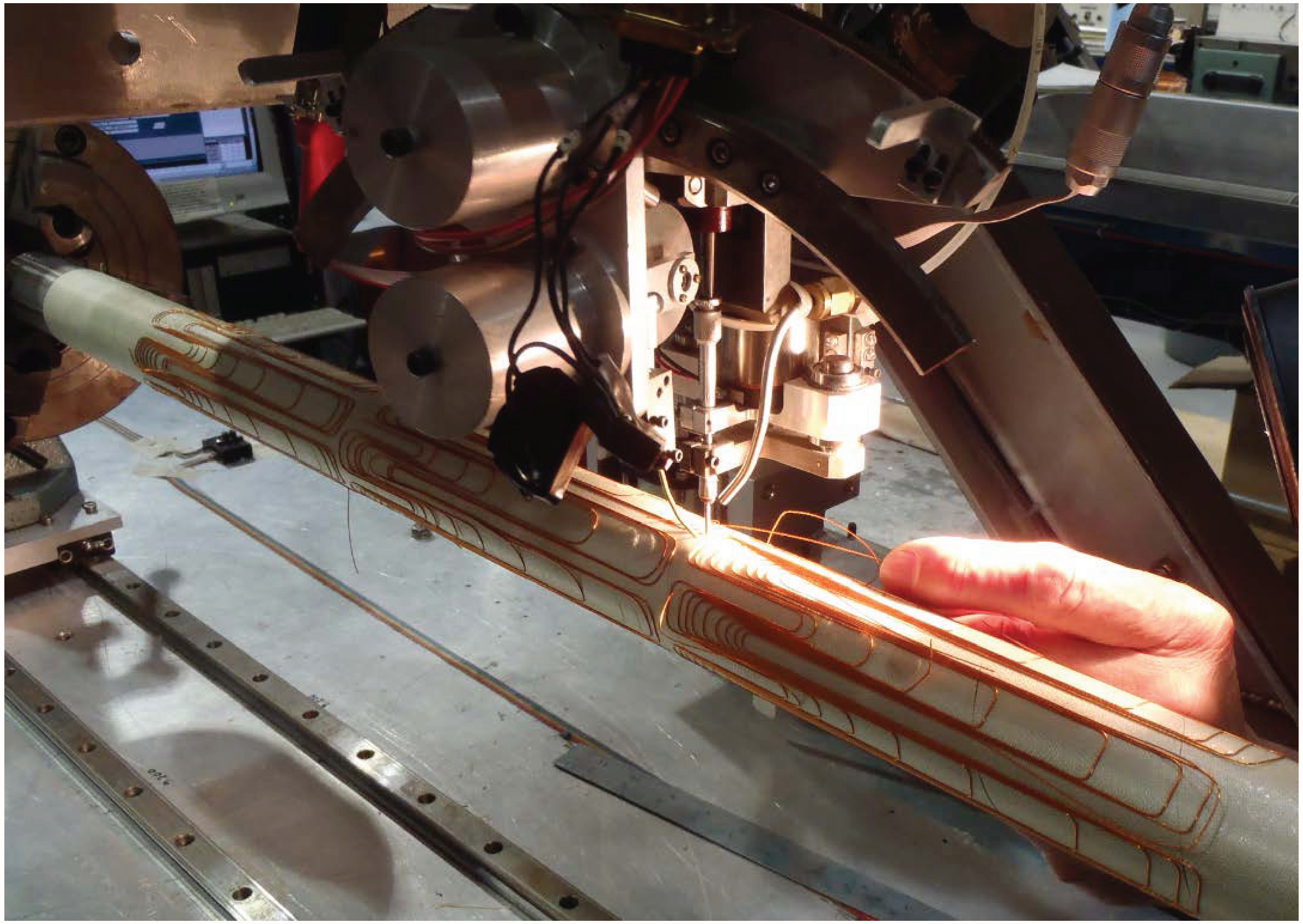


Figure 6: The b5 and a5 field multipole distributions generated by the b5 cancel coil with an applied twist transformation are compared here to the target goals set for perfect QC1P external field cancellation.

How To Produce Such A Field?

- Direct winding technique + Biot Savart + F.E.M. simulation + inspiration (and lot of perspiration)

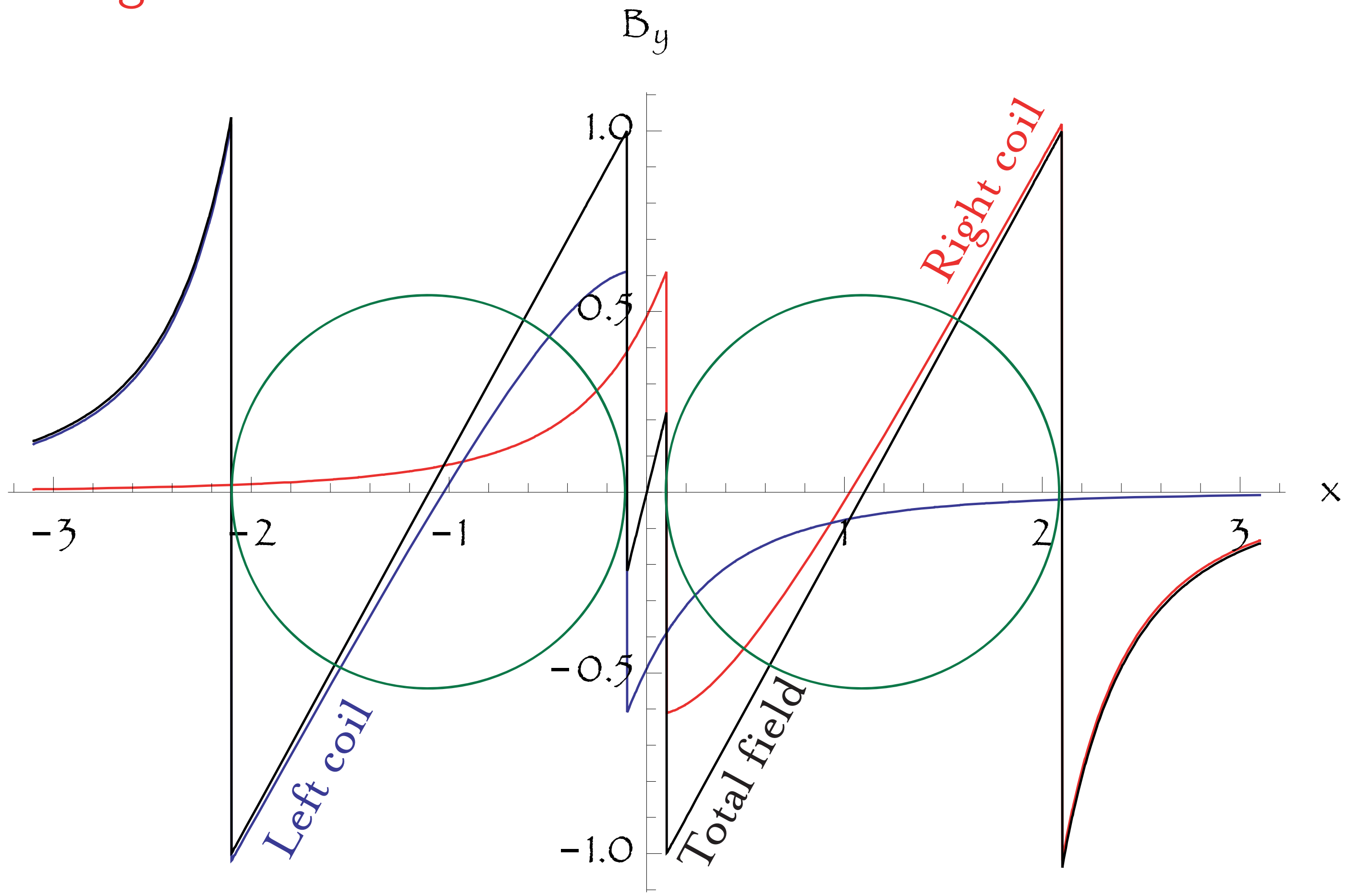


BNL Direct Winding Machine at work

SuperB Approach

- In SuperB we tried to reduce l* at the very minimum to ease the chromatic correction
- We designed a pair of combined function magnets able at same time to null the leaking field of the nearby quad and to generate a pure quadrupolar field.

$B_y(x)$ generated by:
the right coil, the left coil, their sum



How We Did It? Double Helix Coils

MOPAS055 Proceedings of PAC07, Albuquerque, New Mexico, USA

COMBINED FUNCTION MAGNETS USING DOUBLE-HELIX COILS *

C. Goodzeit, R. Meinke, M. Ball, Advanced Magnet Lab, Inc., Melbourne, FL 32901, U.S.A.

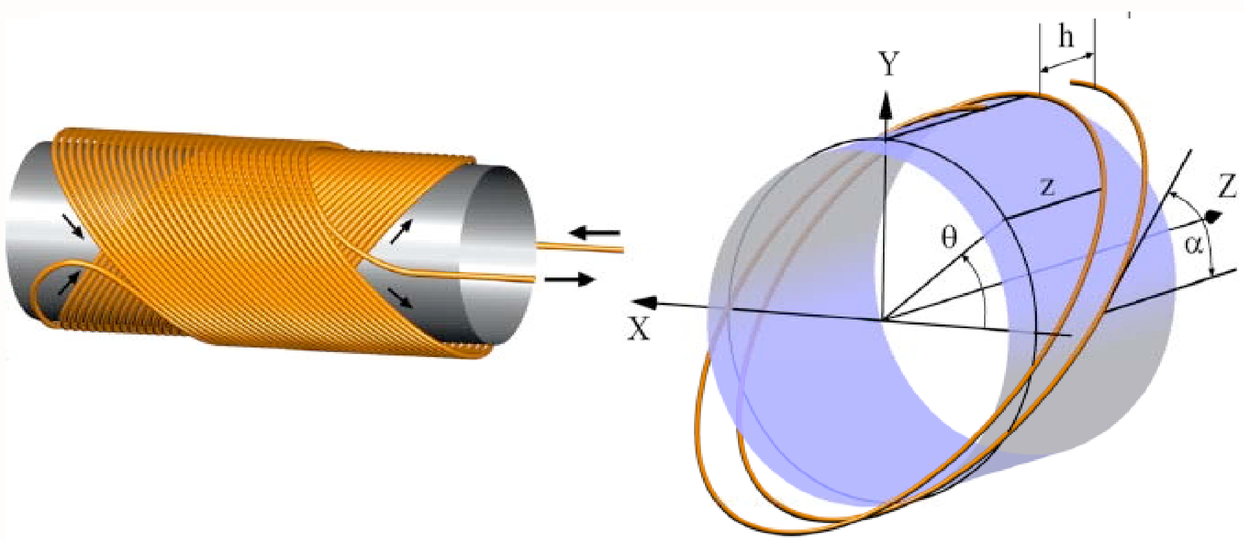


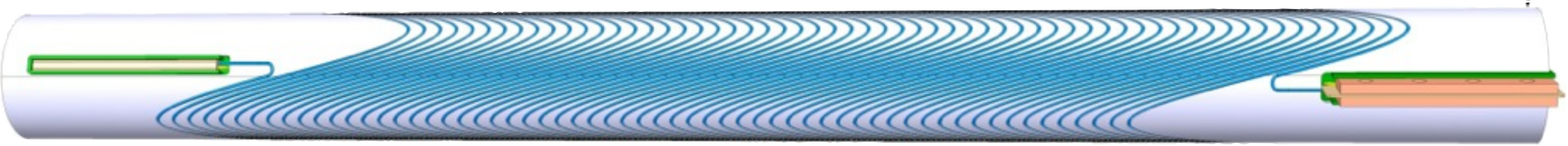
Figure 1. (Left) Layout of double helix winding. The axial field components of the 2 layers cancel each other and the total transverse field is enhanced. (Right) For the case of a dipole, the z coordinate of the conductor path is given

The double helix winding concept can be readily extended to produce pure higher order multipole magnets, and as we shall show, combinations of superimposed multipole fields. This can be seen from the general expression for the conductor path of a double-helix coil given by:

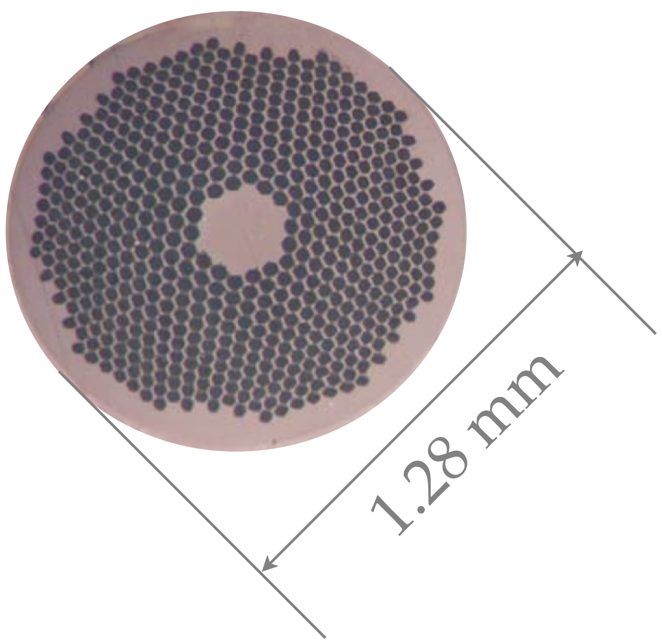
$$z(\theta) = \frac{h\theta}{2\pi} + A_0\left(\sin\theta + \sum_{n=2}^{N} \varepsilon_n \sin(n\theta + \phi_n)\right) \quad (1)$$

where the geometric variables are described in Figure 1.

First Prototype of the SuperB QD0



- Magnetic length 510 mm, inner bore diameter 50 mm
- With 60 turns/layer the quadrupole gradient is 50 T/m at 2600 A
- The stored energy is 1.1 kJ (twice the QD0 one)
- The current density in the wire is the same of the QD0

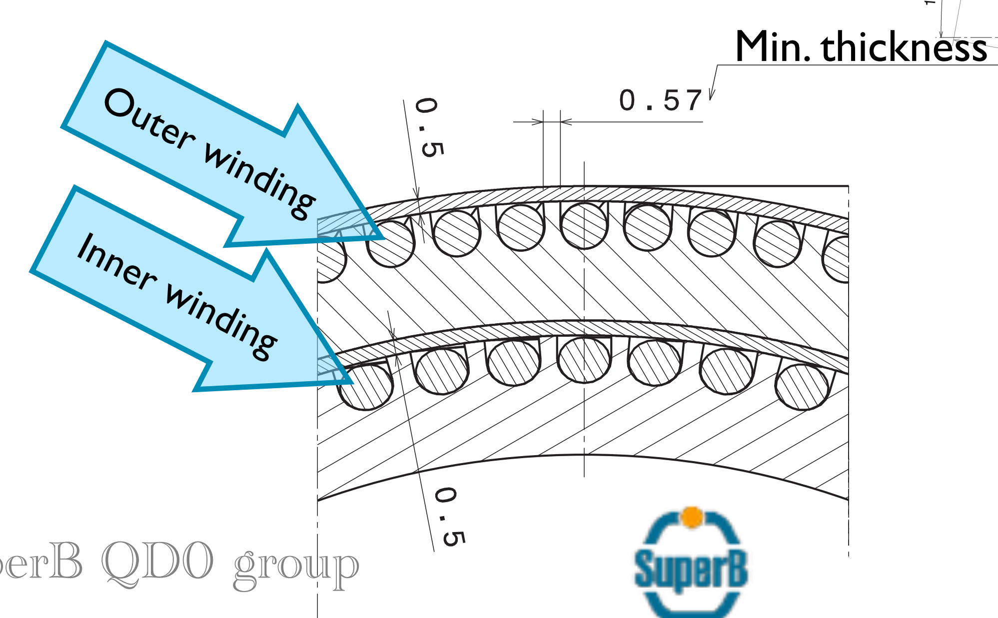


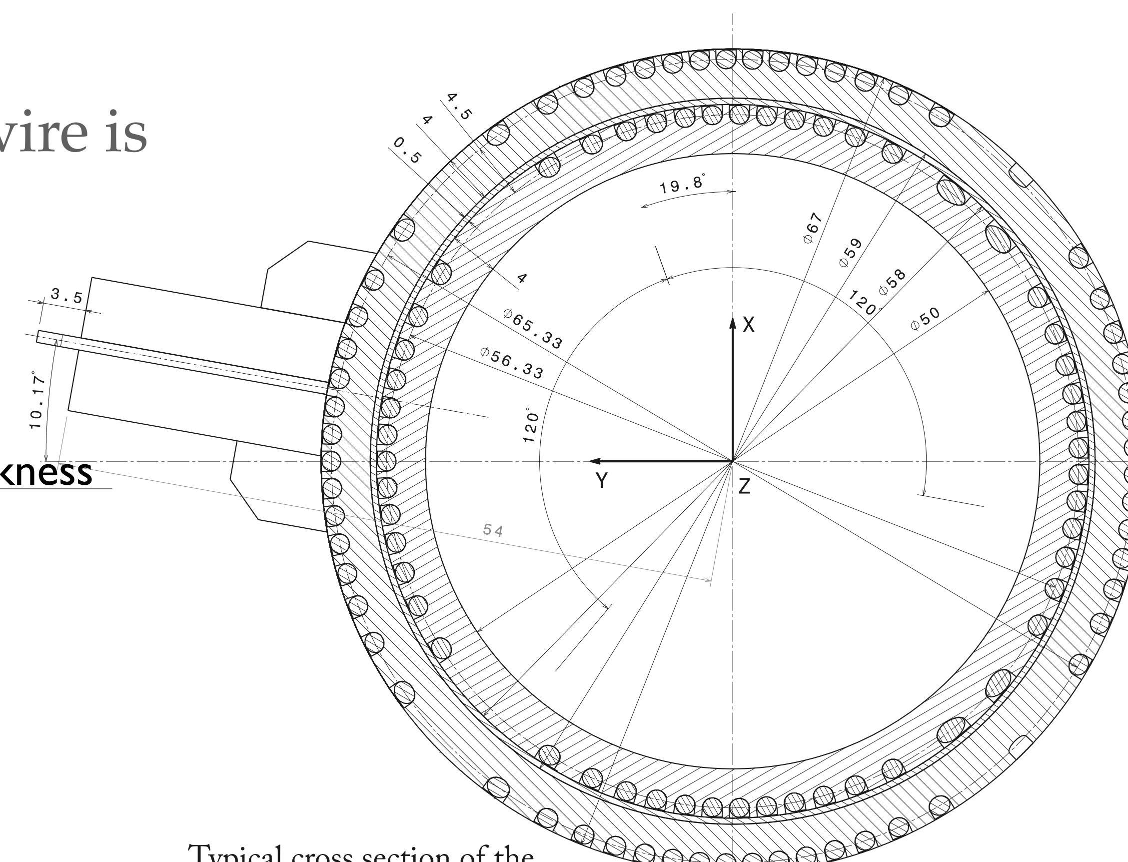
CMS strand kindly gifted by Luvata

B(T)	T(K)	I_c(A)
4	4.25	2475
5	4.25	2039
6	4.25	1608
7	4.25	1205

$\phi = 1.28$ mm

Cu/SC = 1.1





Typical cross section of the Quadrupole prototype

SuperB I.R.

	QD0	QD0H	QF1	QF1H	Large Solenoid	Small solenoid	
Magnetic lenght (m)	0.30	0.15	0.40	0.25			
Gradient (T/m) or Field(T)	95.60	70.60	40.80	38.10	1.5	1.5	Nominal parameters
Aperture (mm)	35.00	50.00	73.00	78.00	240	140	
Inner radius of inner layer	18.90	26.40	37.90	40.40	120	70	
Outer radius of inner layer	20.43	27.93	39.43	41.93			
Inner radius of outer layer layer	22.40	29.90	41.40	43.90			Dimensions
Outer radius of outer layer	23.93	31.43	42.93	45.43	130	80	
Outer radius including insul.	24.43	31.93	43.43	45.93			
Num. of turns	96	48	124	80	960	680	
Pitch (mm)	6.4	6.4	6.4	6.4	-	-	
Calculated mag. lenght (m)	0.3072	0.1536	0.3968	0.256			
Current (A)	2626	2615	2129	2101	1050	950	Other parameters
Axial.lenght inner layer (m)	0.3792	0.25504	0.54338	0.41239	0.84	0.595	
Axial.lenght outer layer (m)	0.39294	0.26877	0.55711	0.42613			
Axial length (m)	0.40294	0.27877	0.56711	0.43613	0.85	0.6	
Total wire lenght (m)	38	25	87	60	754	320	
Stored Energy (J)	574	561	1970	1374	31972.5	6768.75	
Peak field (T)	2.16	2.32	1.92	1.91			
Inductance (mH)	0.17	0.16	0.87	0.62	58.00	15.00	
E/m (J/g)	1.32	1.96	1.98	2.00			

SuperB I.R.

	QD0	QD0H	QF1	QF1H	Large Solenoid	Small solenoid	
Magnetic lenght (m)	0.30	0.15	0.40				
Gradient (T/m) or Field(T)	95.60	70.60	40.80				
Aperture (mm)	35.00	50.00	73.00				
Inner radius of inner layer	18.90	26.40	37.90				
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$j_0 = 600\ A/mm^2$

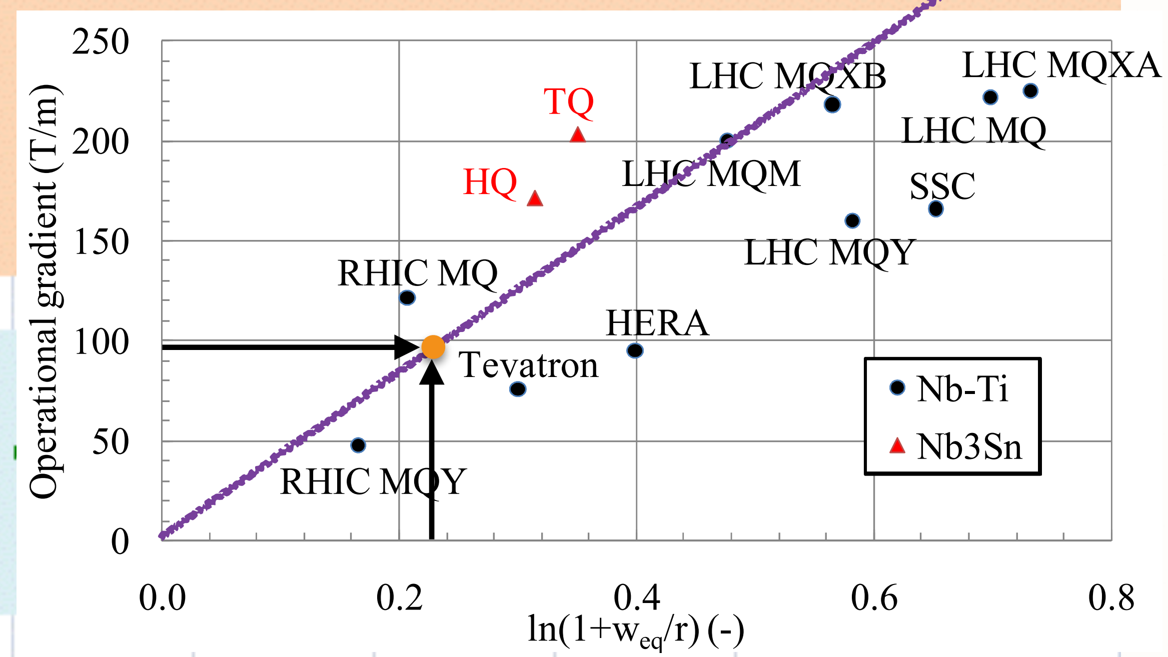
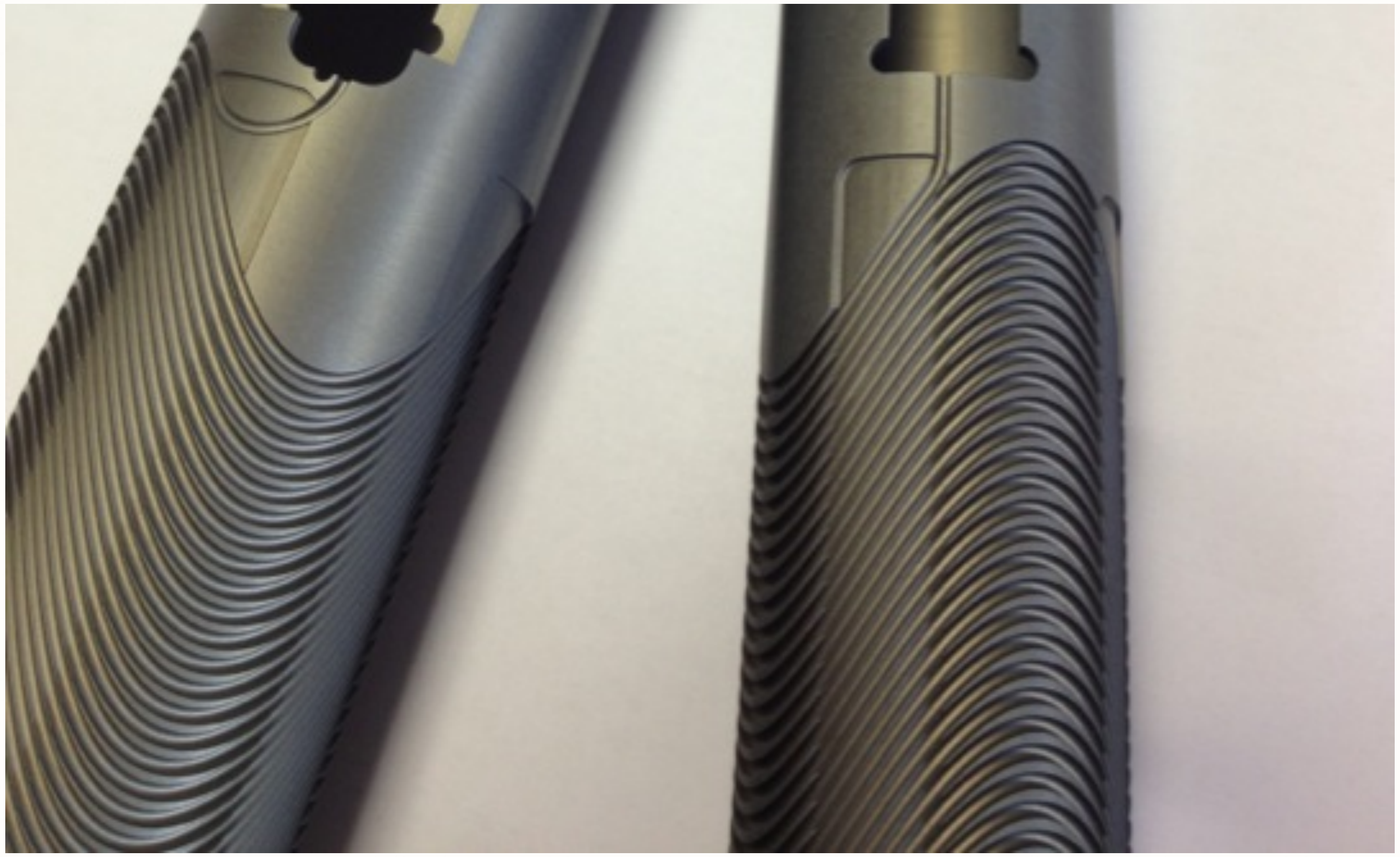
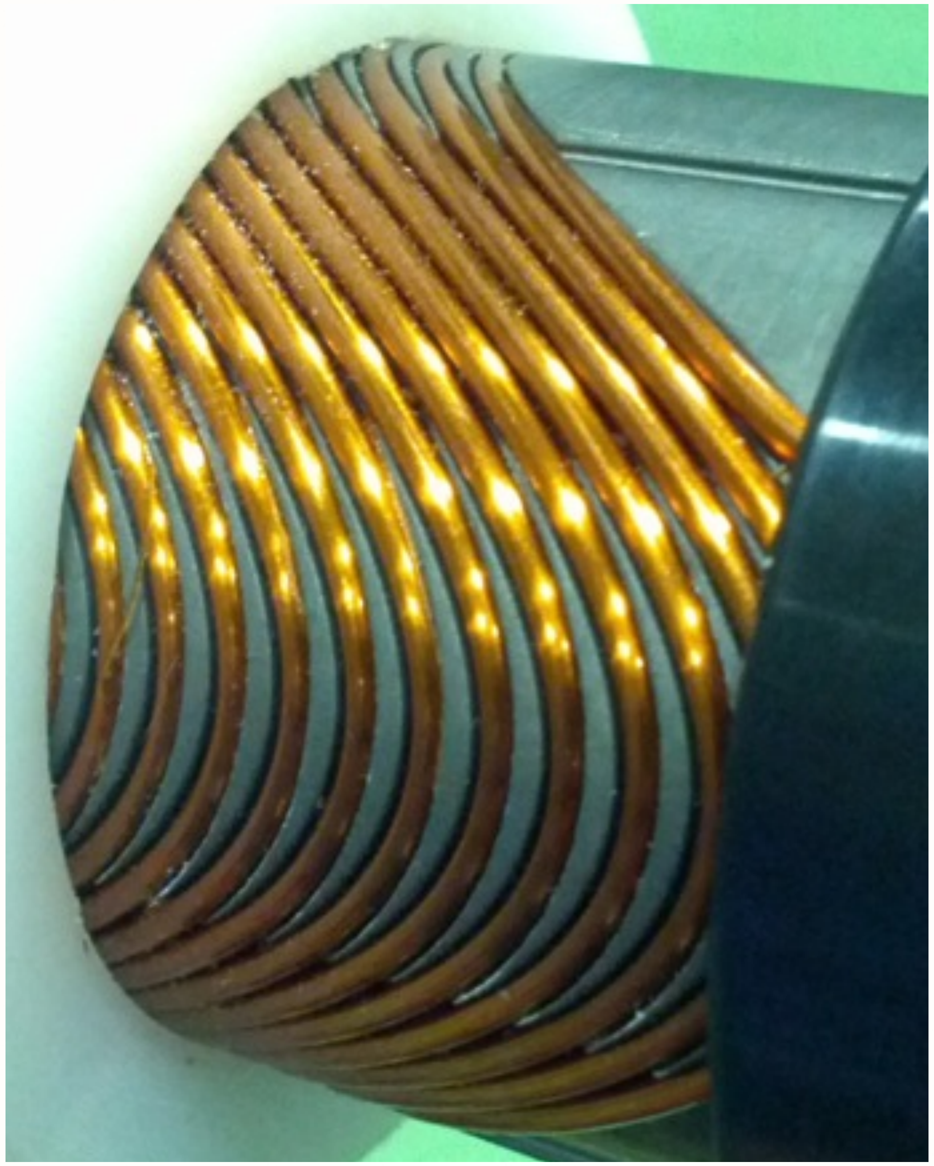


Fig. 6: Operational gradient versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb_3Sn models).

Second Prototype Of A Single QdO

- Completed in June 2014
- We are planning to cold test it by mid 2015.





Answers To Some Questions

- Is a 300 T/m quadrupole feasible?
  Yes, probably, but some R/D is needed, perhaps a baseline design should consider a 200 T/m quad.

- Is a 100T/m double bore quad feasible?
  Yes, probably, but some R/D is needed to asses the feasibility of a 7x scaled version of the Super*B* QD0.

Conclusions

- *B* factories made very fancy super conducting quads for final focus
  - Very compact and strong with leaking field compensation
- I.R. designer and magnet makers should interact from the early stage of the project not to waste time
- The R/D time needed to realize the first SuperB QD0 prototype from the I.R. designer requests was couple of years (without the test of the cross talk compensation): plan well in advance what you do need.

Thank you for your attention