

# INTERACTION REGION MAGNETS

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## Abstract

The magnets of the very final focus are among the most challenging devices of a collider. They must be very compact to leave large acceptance for the surrounding detectors still providing strong focusing power together with excellent field quality not to degrade the collider dynamic aperture. Being all placed very close one respect each other and well inside the detector (which is usually a magnetic spectrometer) several strategies to compensate the cross talk of the leaking field and the coupling introduced by the detector field had been recently proposed and some are now in the construction phase. In this paper I will shortly review these novel compensation techniques, the present status of the interaction region magnets now under construction and the main concepts of their design together with a summary of some of the research and development project in the field.

## MAIN ISSUES OF THE INTERACTION REGION MAGNETS IN $e^+e^-$ HIGH INTENSITY COLLIDERS.

The main strategy followed by the  $e^+e^-$  collider community in the last decade to increase the luminosity is to decrease the beam size at the Interaction Point (IP). The recipe seems deceptively simple and straightforward but in reality it implies major advances in almost each aspect of the collider. The prototypical example of the last generation high luminosity  $e^+e^-$  colliders based on this approach are SuperKEKB [1] which is now in an advanced construction phase and which is expected to start the first phase of commissioning by 2015, together with its main competitor SuperB [2] whose fate was doomed by the economical crisis in Italy and the shortcoming of the promised funding. Both machines are based on the large Piwinski angle collision scheme [3] in which very low emittance beams are demagnified down to a vertical size of roughly 30 nm and brought in collision with a large crossing angle. The main requirements from the machine designers that are hard to met from the perspective of the magnet builders are the quadrupoles of the final doublet. These magnets must be very short and strong to ease the problem of chromaticity correction, they must provide excellent field quality over a large aperture since the horizontal and vertical beta functions are usually reaching their maxima in the final doublet and any spurious sextupolar component will be detrimental for the dynamic aperture of the ring. Additional complications arise from the requirements of the users (i.e. the detector community). The final doublet must be as compact as possible to leave space for the detector surrounding the IR, moreover the losses near the IP must be kept at a minimum to reduce the detrimental effects of machine backgrounds on the performances and life span of the detector. The most worrisome source of back-

ground that must be carefully considered in the design of the magnets of the IR are radiative Bhabha (i.e. beam-strahlung) and Touschek that, at least for SuperKEKB and SuperB, are the driving terms of the loss rate near the IP. It turns out that a conventional design with the two quadrupoles closest to the IP shared among the electron and positron rings in the final doublet is not viable since it is not possible to meet at same time the requirement to have the incoming beam on the magnetic axis to reduce the synchrotron radiation fan impinging on the detector and the requirement to have the outgoing beam on the magnetic axis to reduce the radiative Bhabha losses. In essence each beam line must be equipped with its own set of focusing quadrupoles. The main challenge is the limited amount of space available in between the two beam lines that require a very thin magnet design.

## THE SUPERKEKB IR MAGNETS.

The SuperKEKB collider is a major upgrade of the KEKB Bfactory. It will collide 4 GeV positrons on 7 GeV electrons aiming for a final luminosity of  $8 \cdot 10^{35}$  Hz/cm<sup>2</sup>, that is a 40-fold increase with respect to its ancestor. The final doublet [4] (see Fig. 1) consists of several superconducting magnets: 8 main quadrupoles, 4 compensation solenoids, 35 corrector coils and 8 coils to cancel the leaking field of quadrupoles facing the IP on the Low Energy Ring (LER) that perturbs the High Energy Ring (HER) (see Table 1).

Table 1: SuperKEKB IR magnets name and main parameters. GL is the integrated gradient, Z is the distance of the pole face from the IP,  $r_{in}$  is the inner radius of the coil,  $r_{out}$  is the outer radius of the collar.

Magnet	GL, T(T/m × m)	Type	Z, mm	$r_{in}/r_{out}$ , mm
QC2RE	13.04 (31.12×0.419)	Yoke	2925	59.3/115
QC2RP	11.54 (28.15×0.410)	Yoke	1925	53.8/93
QC1RE	25.39 (68.07×0.373)	Yoke	1410	33.0/70
QC1RP	22.96 (68.74×0.334)	no Yoke	935	25.0/35.5
QC1LP	22.96 (68.74×0.334)	no Yoke	-935	25.0/35.5
QC1LE	26.94 (72.23×0.373)	Yoke	-1410	33.0/70
QC2LP	11.48 (28.00×0.410)	Yoke	-1925	53.8/93
QC2LE	15.27 (28.44×0.537)	Yoke	-2700	59.3/115

The quadrupoles closer to the IP are the QC1RP and QC1LP, two vertical focusing magnets acting on the LER. They are quite strong (68.74 T/m) and very thin (the coil thickness is less than 6 mm). The small crossing angle ( 83 mrad ) together with the small  $l^*$  (935 mm) does not allow to shield the magnet with a return yoke surrounding it

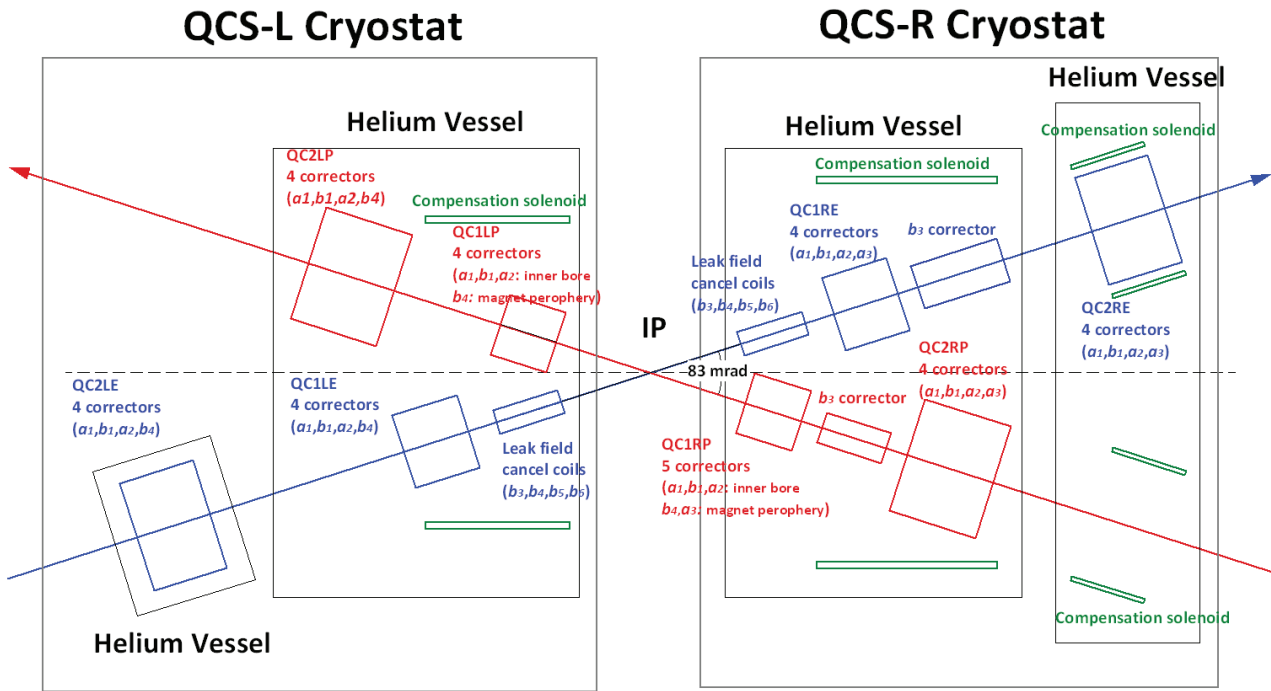


Figure 1: Layout of the Super Conducting magnets of the SuperKEKB IR.

hence a different strategy had been developed to overcome the detrimental effects of the non linear components of the QC1RP and QC1LP on the near running HER.

vessel surrounding the HER beam pipe using the serpentine coil design concept [6].

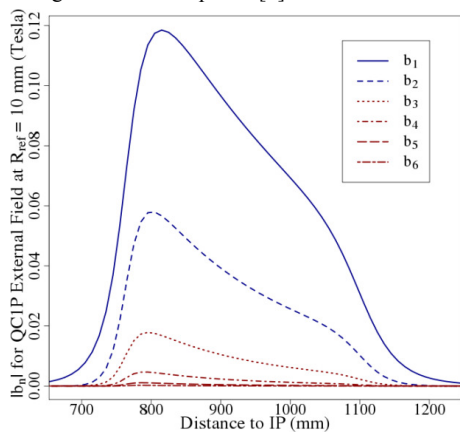


Figure 2: Decomposition into magnetic multipoles for QC1P external field as a function of distance with respect to the IP on the HER beam line. Reference radius 10 mm.

In Fig. 2, from [5], is represented the harmonic decomposition of the external field of the QC1P on a reference radius 10 mm with respect to the HER beam line as a function of distance with respect to the IP. The  $b_1$  (dipole) and  $b_2$  (quadrupole) components can be accounted for in the model of the HER lattice and can be properly managed. The higher components (see Fig. 3 from [5]) are too large not to impact the HER dynamic aperture hence a set of canceling superconducting coils had been wound around the helium

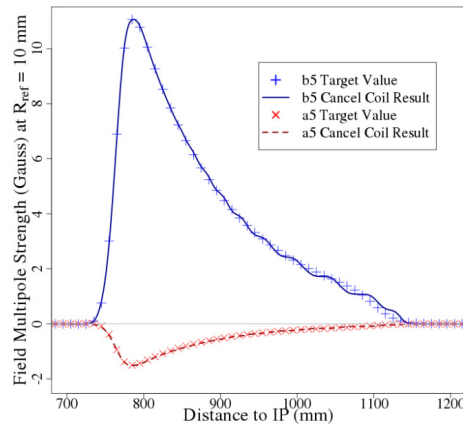


Figure 3: The  $b_5$  (decapole) and  $a_5$  (skew decapole) field components as a function of distance from the IP. In crosses the target value needed for perfect cancellation of the QC1 leaking field, with continuous and dashed line the field generated by the canceling coils.

### THE SUPERB IR MAGNETS.

The SuperB collider had been approved by the Italian Research Minister as part of the Italian National Research Plan with a 5 years construction budget and then shut down as a consequence of the economical crisis. It was conceived as an  $e^+e^-$  collider composed by an electron LER (4.18 GeV) and a positron HER (6.7 GeV) with a design peak luminosity of  $10^{36}$  Hz/cm<sup>2</sup>.

The SuperB collision scheme required a short focus final doublet to reduce the vertical beta function down to  $\beta_y^* = 0.2$  mm at the IP. The final doublet (see Fig. 4) was designed as a set of permanent samarium cobalt magnets (PM) and superconducting (SC) quadrupoles. The HER (LER in parentheses) PM quadrupoles provided an integrated gradient of 23.1 T (11.2 T) over a magnetic length of 11 cm (7cm). The front pole face had been placed at 38 cm (30 cm) from the IP. The remaining vertical focusing strength would be provided by two (one) SC quadrupoles having an integrated gradient of 39.2 T (28.7 T) over a total magnetic length of 45 cm (30 cm).

The requested horizontal beam stay clear fixed both the warm bore diameter to 24 mm and the maximum thickness allowed for the cryostat and the SC cold mass to 22 mm. The limited amount of available space together with the requested field purity and gradient strength posed very demanding constraints on the SC magnets design.

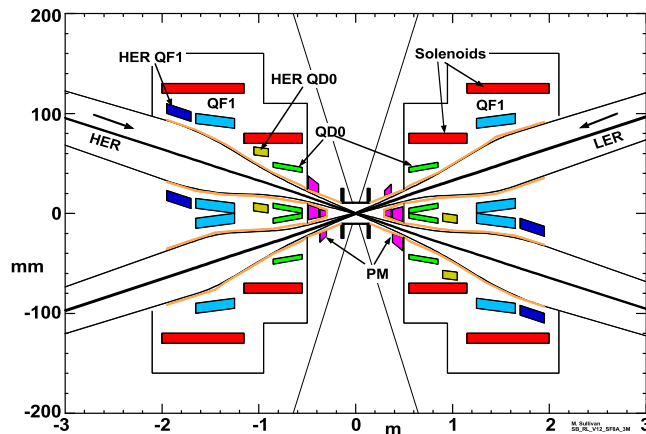


Figure 4: Top view of the IR layout. The PM and the cold masses of the SC magnets are represented together with the horizontal LER and HER beam stay clear.

The main differences with respect to the SuperKEKB layout are the reduced full crossing angle (60 mrad vs 83 mrad) and the much shorter  $l^*$ , moreover the requirement on the gradient of the QD0  $\sim 1$  T/m exceeded by  $\sim 30\%$  the design gradient of the homologous QC1.

In addition to these, already very demanding, requirements from the beam dynamics team it was also requested to reduce the  $l^*$  of both the HER and the LER to roughly the same value.

It was clear that a solution like the SuperKEKB (i.e. a quadrupole acting on one beam and a set of canceling coils on the other one) was not viable since also the leaking field of the canceling coils would have been a serious problem.

Two solutions were proposed, one was based on double Panofsky quadrupoles and the other exploited the full potential of the double helix [7] concept.

A double helix magnet is composed by an even number of coaxial cylindrical solenoidal coils. The shape of each winding is modulated along the longitudinal direction. The coils are wound alternating clockwise and counter-clockwise

layers so to cancel out the longitudinal solenoidal field. It can be shown using the Biot e Savart law that in the limit of infinitely thin wire the multipolar expansion of the field inside the inner cylinder integrated along the axis of the magnet correspond to the Fourier expansion of the longitudinal displacement of the windings as a function of the azimuthal angle [7].

This idea was used to design a very thin double bore superconducting quadrupole [8] [9] with parallel magnetic axis and a few years later to design a double bore superconducting quadrupole with divergent axis suitable to meet the stringent requirements of the SuperB IR layout.

The main concept is to parametrize the shape of each spire of the coil by an Hermite polynomial controlled by  $2N$  key point. The longitudinal position of these key points can be such that the multipolar expansion of the integrated field is a pure quadrupole.

A prototype of a single core double helix quadrupole magnet had been built by the SuperB collaboration and it had been tested at 4.2 K [10]. It turned out that the magnet capability to handle the 2650 A nominal current and to survive to quenches exceeded the expectations.

## REFERENCES

- [1] T. Abe *et al.* [Belle-II Collaboration], “Belle II Technical Design Report,” arXiv:1011.0352 [physics.ins-det].
- [2] M. Bona *et al.*, *SuperB: A High-Luminosity Asymmetric  $e^+e^-$  Super Flavor Factory. Conceptual Design Report*, arXiv:0709.0451, 2007.
- [3] P. Raimondi, D. N. Shatilov and M. Zobov, “Beam-Beam Issues for Colliding Schemes with Large Piwinski Angle and Crabbed Waist,” physics/0702033 [PHYSICS].
- [4] N. Higashi, H. Koiso, Y. Ohnishi, N. Ohuchi, T. Oki, M. Tawada, K. Tsuchiya and H. Yamaoka *et al.*, “Design Study of Final Focusing Superconducting Magnets for the SuperKEKB,” Conf. Proc. C **110904**, 2457 (2011).
- [5] B. Parker, M. Anerella, J. Escallier *et al.* “Superconducting Corrector IR Magnet Production for SUPERKEKB,” THPBA07, NA-PAC 2013 (Pasadena,CA).
- [6] B. Parker, J. Escallier, “Serpentine Coil Topology for BNL Direct Wind Superconducting Magnets,” PAC05, Knoxville, TN, May, 2009, pp. 737-739. THPBA07, NA-PAC 2013 (Pasadena,CA).
- [7] R.B. Meinke, M.J. Ball, C.L. Goodzeit, Advanced Magnet Laboratory, “Combined Function Magnets Using Double-Helix Coils,” In the Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA.
- [8] E. Paoloni, S. Bettoni, M. E. Biagini and P. Raimondi, “Magnetic design studies for the final focus quadrupoles of the SuperB large crossing angle collision scheme,” Conf. Proc. C **0806233** (2008) WEPD002.
- [9] E. Paoloni, N. Carmignani, F. Pilo, S. Bettoni, P. Fabbriatore, S. Farinon, R. Musenich and F. Bosi *et al.*, “Advances in the design of the SuperB final doublet,” Conf. Proc. C **110904** (2011) 2454.
- [10] F. Bosi, P. Fabbriatore, S. Farinon, R. Musenich, U. Gambardella, R. Marabotto and E. Paoloni, “Compact superconducting high gradient quadrupole magnets for the interaction regions of high luminosity colliders,” IEEE Trans. Appl. Supercond. **23**, no. 3, 4001004 (2013).