The Superconducting Interaction Region Magnet System for the CESR Phase III Upgrade *

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Introduction

In 1998 CESR and the CLEO detector will commence another major upgrade to bring their performance up to B factory levels. New interaction region (IR) insertion magnets were designed to allow the highest possible luminosity from an equal energy, crossing angle, bunch train configuration of CESR [1][2]. With the new magnets the IR limited luminosity is expected to be at least 3×10^{34} $cm^{-2}s^{-1}$ — well above the phase III luminosity goals of $1-3\times 10^{33}$ $cm^{-2}s^{-1}$. The new magnets will have the focussing capability of running with smaller β_y^*, crossing angles large enough to accommodate beams from two separate rings, or even round beams — ideas which conceivably could take CESR into the 10^{34} range [3][4].

Compared with previous IR magnets for CESR, the new superconducting magnets will have higher gradients, larger apertures and shorter focal lengths. The high gradients and short focal lengths allow the magnets to be placed closer to the interaction point (IP) at near optimal locations, largely mitigating the effects of long-range beam-beam interactions. The close-in location also improves the optical quality of the lattice which could improve the tune shift limit. Increased physical aperture provides more room for larger crossing angles which allows for better beam separation and higher long range beam-beam current limits. More aperture also makes room for carefully chosen orbit offsets which can reduce detector backgrounds thereby improving the quality of the data, lengthening the lifetime of the detector and increasing the data taking time by making tuning faster.

The new magnets will have some unusual capabilities such as nested skew and dipole coils for coupling and orbit correction, and a cryostat positioning system which can adjust the position of the magnets during operation. So we expect to see increases to the data taking time due to the higher functionality: energy changes, coupling correction, magnet alignment and positioning, and beam steering will be far easier and faster. However, the intimate magnetic and mechanical coupling with CLEO solenoid has caused design complications as well.

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IR Luminosity Optimization

Generally luminosity can be increased by raising the stored beam current and the most straightforward way to do this is to increase the number of bunches in each beam. However as more and more bunches are stored the long range beam-beam interaction (LRBBI) eventually reduces the beam lifetime and effectively limits the current. In a crossing angle configuration, the crossing angle at the IP generates orbit separation at the nearby crossing points where the beams pass by each other but do not actually collide. The bigger the angle the larger the separation and the higher the long range beam-beam current limit. Phenomenological models based on a series of measurements on CESR [6] indicate that beta functions and beam separations at the nearby crossing points ought to be kept to values similar to those in the arcs, otherwise they become the dominant source of LRBBI and limit the current in the machine. The minimum feasible bunch spacing, (14 ns, set by the relative frequencies of the synchrotron injector and the CESR storage ring [5]), determines the first crossing point to be only 2.1 m from the IP. Thus the optimum IR optics design should have an overall focal length in both planes of about 2.1 m or less, so the magnet design was driven toward very short high gradient magnets, with large aperture, located as close to the IP as possible.

The long range beam-beam interaction, together with countless magnet engineering, detector mechanical and background constraints, were simultaneously optimized for maximum luminosity [7]. The optimization program indicated that for our application superconducting magnets (SC) have a large advantage over permanent magnets (PM) in that they have the best combination of high gradient and large aperture.

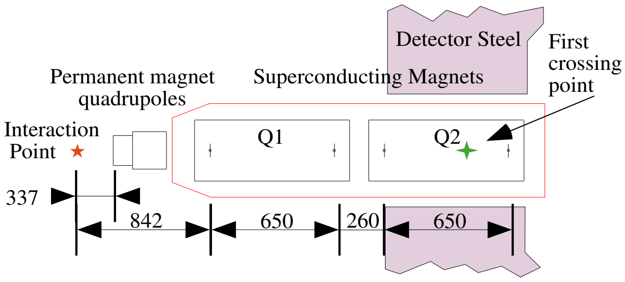

Figure 1: Schematic showing outlines of superconducting IR magnets and their proximity to the IP.

Nevertheless, because PM's can be placed closer to the IP than SC magnets (SC magnets need radial and axial space for thermal insulation) it was advantageous to also use short, 24 cm long, vertically focussing PM's starting 337 mm from the IP [8].

The bulk of the focussing starts at 842 mm with a 650 mm long vertically focussing SC quadrupole labeled Q1 (See Figure 1). This magnet lies completely within the 1.5 T solenoid field of CLEO detector. Very close to Q1 is Q2, a horizontally focussing quadrupole mechanically identical to Q1 and situated in the fringe field of CLEO solenoid. The resulting beam optics has beta functions that never get larger than 80 m, even for β_y^* of 1 cm. (See Figure 2). The worst crossing point is the first, at 2.1 m from the IP, where we have $\beta_y = 24$ m and $\beta_x = 34$ m — comparable with typical arc values. At other IR crossing points the beta functions are less. Thus the LRBBI in the IR is largely mitigated.

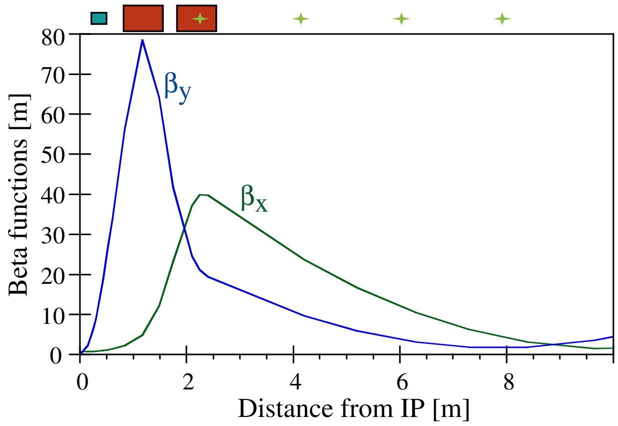

Figure 2: Beta functions for IR limited luminosity. Crossing points and magnet positions are shown at the top. β_y^* is 1 cm.

Cryostat		
ID Warm Bore	[mm]	145
OD Cryostat	[mm]	500
Main Quadrupoles		
Gradient Maximum	[T/m]	48.4
Gradient Operating Q1/Q2	[T/m]	44.0/27.6
Skew Quadrupoles		
Gradient Maximum	[T/m]	±4.8
Correction Dipoles		
Field Maximum	[T]	±0.13

Table 1: General specifications for the various magnet coils at nominal rotation (not 4.5 degree, see text).

Magnet Design and Specifications

To a great extent the design and specifications of the quadrupole coils were based on the LEP interaction region quadrupoles recently installed as part of the energy upgrade to LEP 200 [11]. Considerable effort was made to avoid taxing any engineering requirements, such as conductor position tolerance, peak field, or current margin; so that relatively little R&D would be needed. Likewise, Q1 and Q2 were specified to be identical to reduce the design and tooling time, although a smaller aperture would have sufficed for Q1. General magnet parameters are given in Table 1.

We required a field quality of $< 5 \times 10^{-4}$, for all harmonics, at 50 mm radius. This was based on dynamic aperture considerations. Since the beams are on separated orbits through the quadrupoles, and the lattice functions change significantly along the magnet's length, the magnet has been designed to satisfy the field quality requirement in both the ends and body separately; that is, there is no end-body cancellation of unwanted harmonics. The specified level of field homogeneity provides a dynamic aperture greater than the physical aperture (with the pretzel on) in collision optics, with $\beta_y^* = 1$ cm.

The quadrupole's design current margin (along the load line) has been specified to be at least 30% above short-sample, under worst-case conditions as described above (peak field 6.3 T). Since there is neither the time nor resources available for a great deal of development effort in prototyping this magnet, a relatively generous design margin has been required. The magnets are required to reach the design field gradient, possibly with some training: they are required not to need retraining after thermal cycling.

The maximum vertical correction dipole field of 0.13 T is specified to allow some tolerance for vertical quadrupole alignment errors. Such a field can correct for up to 3 mm of vertical positioning error. Horizontal positioning error is less critical and can be handled by warm correction dipoles outside the interaction region as well as by the magnet positioning system.

Coupling Compensation

The CLEO detector solenoid couples the horizontal and vertical beam trajectories. To produce a flat beam at the IP, and to avoid a family of coupling resonances, the coupling must be compensated before the beams collide. This is done by a combination of variable skew quadrupole coils concentrically wound around the main quadrupoles, a fixed rotation angle of 4.5 degrees of all magnetic elements including the main quadrupole, and warm sqew quadrupoles located just outside the IR. This scheme has sufficient flexibility to allow decoupling even with round beam optics [1].

Round Beam Limitations

As designed the IR magnets will accommodate round beam optics with β^* of 3 cm. An additional electromagnet would be located just outside the CLEO yoke, and the relative sign of the focussing of the permanent magnet versus the SC magnets would change. The round beam apertures are actually less restrictive than than for flat because they do not include a crossing angle.

CLEO Interaction

The stray fields from the quadrupoles and other coils significantly add to the CLEO detector solenoid field and create regions of reduced uniformity which must be taken into account when tracking. [9]

The CLEO solenoid field causes large forces and torques on the various coils. It tends to crush the ends of the quadrupoles (effectively with 26,000 lbs of clamping force) and put large torques on the dipole coils (nearly 10,000 ft-lbs). Because one end of one dipole is shielded from the solenoid, it experiences a net horizontal force of over 4000 lbs. A 3 mm misalignment of the quadrupole within the steel yoke causes a 1100 lbs force of attraction toward the steel [10]. These forces are larger than the weight of the magnets and cryostat. The torques and net forces must be borne by the cryostat, rails, and support pylon with very little overall distortion.

Support and Positioning System

Because of the high gradients, small misalignments of the quadrupoles can cause very large and uncorrectable closed orbit distortions. To be able to adequately correct the orbit using warm corrector magnets outside the IR we will need to have the quadrupole magnetic centers within about 0.1 mm vertically and 0.5 mm horizontally of the design axis. The tolerance on run-to-run stability needs to be an order of magnitude tighter. Vibration amplitudes should be less than $\sim 1\ \mu$m. For this reason a beam-based positioning system was designed which can precisely realign the quadrupoles while beam is stored. This system is somewhat redundant with the set of dipole coils. However, the dipole coils only provide correction for vertical offsets, and are thought to be somewhat risky at this time because of the large torques and forces they cause through their interaction with the CLEO solenoid. The dipole coils can be used to effec-

[1] For round beam optics, the beams are decoupled at the IP but the eigen-planes are not exactly horizontal and vertical.

tively align the magnetic and mechanical centers if needed. Also the dipoles have more effective range than the positioning system.

The cryostat will be kinematically mounted on a set of eccentric cams. Stepper motors control the angle of the cams and allow smooth ($\sim 5\ \mu m$ resolution) independent positioning of the center of eac magnet over a range of roughly 1 mm in all directions. The cams are held by bimetallic rails attached to a thick steel pylon which is suspended from CLEO detector steel. The rails are made of 316L stainless welded to magnet iron so as not to perturb the detector solenoid field. The CLEO pole-end has a cutout corresponding to the pylon giving it a keyhole shape. In this manner good access to the detector electronics can be provided by pulling back the pole-end without having to disassemble the superconducting magnets.

Cryogenic Design

A rigidly attached current leads box will be located right above the main part of the cryostat just outside the CLEO detector. The warm to cold transition will be vertical which considerably simplifies a bath cooled cryogenic design. It is expected that the dominant liquification load will be from the 12 power leads for each cryostat. The overall specified cooling limit is a linear combination of 60 W for gas returned cold and 0.66 g/s liquification; was set primarily by the available refrigeration power at Cornell. Roughly 1200 W of refrigeration will be available for the superconducting RF systems, the CLEO solenoid, and the IR quadrupoles; the quadrupoles are allotted 10% of this capacity.

Quench onset of the magnet is expected to be determined by the peak field in the quadrupole coil. The peak field due to the quadrupole current (alone) occurs in the coils ends. In addition to the quadrupole's field, the skew quadrupole, correction dipole, and especially the CLEO solenoid fields must also be considered. Quench protection will be passive as large peak quench temperatures are not anticipated.

Acknowledgments

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