THE ERHIC INTERACTION REGION MAGNETS *

B. Parker†, R. B. Palmer and H. Witte, Brookhaven National Laboratory, Upton, New York, USA

Abstract

Balancing conflicting experimental physics and machine accelerator physics demands with realistic Interaction Region (IR) magnet designs for the proposed eRHIC electron hadron collider at BNL requires new magnet concepts and careful attention to detail. Here we review work to develop conceptual IR magnet designs appropriate for the eRHIC Ring-Ring accelerator configuration.

ERHIC IR DESIGN REQUIREMENTS

eRHIC should have electron-proton and electron-ion collisions over the center of mass range 30 to 140 GeV with luminosities ranging from 10^{32} to 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. Previously we reported on a Sweet Spot IR magnet design appropriate for the 10-14 mrad crossing angle of a Linac-Ring based eRHIC accelerator configuration [1] but the present Ring-Ring layout, with 22 mrad crossing angle, requires new magnetic solutions. It is still true that we should avoid generation of strong synchrotron radiation in the vicinity of the experimental detector to avoid deleterious experimental backgrounds. So for Ring-Ring we still use Crab Crossing to rapidly separate the electron and hadron beams into independent magnetic channels. Experimental physics goals still dictate using large magnet apertures to meet acceptance requirements for charged and neutral particles about the forward direction of the hadron beam exiting from the interaction point (IP).

From an IR design viewpoint the Ring-Ring option brings a different mix of challenges. Unlike Linac-Ring, the Ring-Ring electron beam size aspect ratio is naturally flat with larger horizontal emittance than vertical. Also rather than disposing of the electrons after the IP, we must take care to have the electron focusing close to the IP to reduce the e-ring chromaticity. The magnets must have extra aperture for beam halo (i.e halo. populated in the circulating e-beam by the beam-beam interaction). The above means that we must provide large e-beam magnet apertures and a minimum crossing angle of 22 mrad.

Just within ±20 m of the IR collision point the eRHIC IR design has twelve different dual-aperture superconducting magnets with large magnetic fields in one aperture while providing either zero or low field in the other aperture. The most extreme eRHIC magnet requirements exist on the forward side of the IR (defined as the side of the exiting hadron beam) where forward charged particles and neutrons must be allowed to exit as shown in Fig.1.

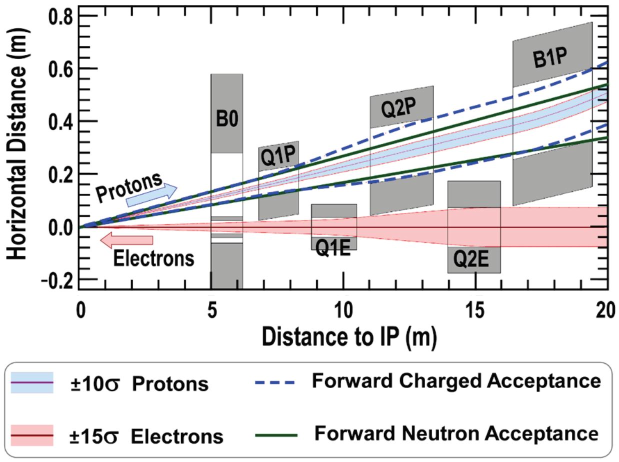

Figure 1: eRHIC IR forward magnet layout schematic.

One important takeaway from Fig.1 is to note that the forward side proton/ion magnet apertures are completely dominated by experimental acceptance requirements and the 10 sigma outline shown for the circulating beam only uses the small central regions of the magnet apertures. But our 275 GeV proton beam energy requires strong muti-tesla focusing and guide fields. The nearby electron beam must be protected against magnetic external fields to avoid e-beam optics aberrations and the generation of synchrotron radiation (Synrad) that could cause undesirable experimental backgrounds. A second takeaway for Fig.1 is to note the B0 spectrometer dipole which is a new feature of the present Ring-Ring IR design.

The B0 spectrometer magnet shown in Fig.2 is used to cover an intermediate experimental acceptance region between what can be detected in the main solenoid detector and that corresponding to particles that will exit through the IR magnets. The B0's C-magnet configuration allows access for experimental detectors to be placed inside its large main aperture with 1.7 T dipole field. The electron beam passes through a zero field region created by a canceling dipole and passive shield combination.

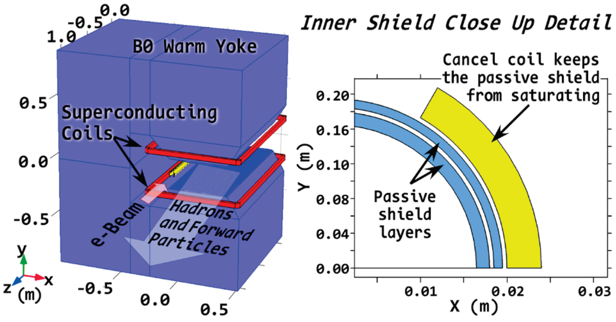

Figure 2: The B0 spectrometer superferric magnet design.

EXTERNAL FIELD CANCELLATION

The most critical and challenging magnet in the Ring-Ring IR layout is the first forward side hadron quadrupole shown in Fig.1, Q1P. Introduction of the B0 spectrometer pushes Q1P further from the IP and increases the IR Twiss beta functions. In order to limit the hadron ring chromaticity impact, Q1P needs to have as large a gradi-

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† email address : parker@bnl.gov

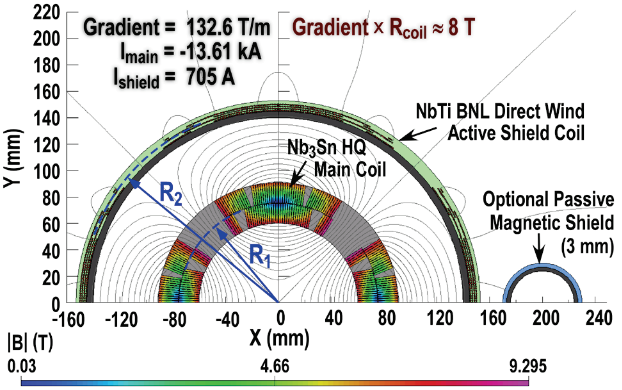

Figure 3: High field R&D quadrupole with a Direct Wind active quadrupole shield coil. Color contour map shows the field magnitude on the main inner coil.

ent as practical. Q1P must also have a large clear 96 mm full bore, shown in Fig.1, to pass the ±5 mrad neutron cone along with forward off-momentum charged particles; but Q1P's external field cannot be allowed to impact the incoming electron beam only 150 mm away from the circulating hadron beam. The only reasonable way we have found to accomplish this is to use an active shield coil configuration similar to that shown in Fig.3.

Active shielding works by nesting two coil structures of common field multipolarity, $\boldsymbol{m}$, ($\boldsymbol{m}$=2 for the Fig.3 quadrupole) and different average coil radii, $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$. If the two coils have opposite field polarities, then, in the absence of intervening magnetic material, their long range external fields will cancel if their gradient ratio is $(\boldsymbol{R}_1/\boldsymbol{R}_2)^{2\boldsymbol{m}}$. Even though physical coils have a mix of multipolarities and the $2\boldsymbol{m}$ power scaling is derived for a thin coil approximation, we find in general this design procedure works very well to give good initial parameters.

Since the two coils cancel each other in their common external region, they also work against one another in the common region inside both coils. For the coils of Fig.3 this results in a 7% gradient reduction with respect to the bare inner coil alone. Note that the flux which would have shown up outside both coils is now shunted to the region between the two coils. Thus if not enough space is provided between the coils, it is possible for the peak field to shift outward to the outer surface of the main coil.

The shield coil from Fig.3 is shown in greater detail in Fig.4. To be able to make fine coil pattern adjustments in both the body and coil ends, as demonstrated for the ILC QD0 actively shielded prototype, we want to make use of BNL Direct Wind technology to fabricate the shield coil [2-3]. With the passive shield shown in Fig.4, the field seen by the e-beam is less than 1 Gauss.

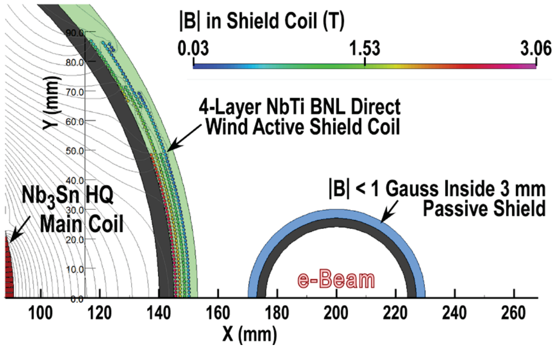

Figure 4: High field R&D quadrupole with a Direct Wind active quadrupole shield coil. Color contour map shows field magnitude at the outer active shield coil

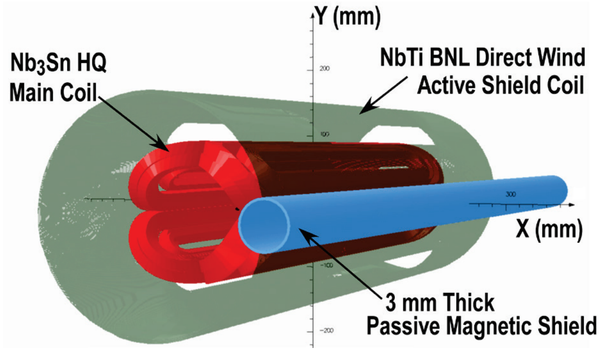

Figure 5: High field R&D quadrupole with a Direct Wind active quadrupole shield coil shown in 3D view.

A 3D model of this coil configuration is shown in Fig.5. With the 3D model we calculate the net external field over the length of the magnet as shown in Fig.6. We see that at 175 mm horizontal offset, and even without a passive shield, the external field magnitude is everywhere less than 300 Gauss, compared to the 3 T value at the shield. Only rudimentary hand adjustment of the shield coil end turn spacing was needed to achieve this result. If accelerator physics simulations show a need for even lower external field, we can reintroduce a passive shield.

The coil configuration in Figs.3-6 is under consideration for prototyping to validate performance of such high-field actively shielded magnets. For such a test we would use coils from the successful LARP HQ program for the inner main coil [4] and wind the shield coil using Direct Wind technology already developed with the ILC QD0 active shield and eRHIC Sweet Spot test coils [1-3].

Even though the HQ 120 mm inner coil diameter does not match the 96 mm aperture of Q1P, utilizing existing coils and technology for a prototype test offers immense time and capital resource advantages. We feel that a successful test of a HQ based prototype at 8 T coil field would go a long way to establish the viability of this active shield coil concept for Q1P at its 6.8 T field. Note Q1P has the highest coil field of all the proposed new

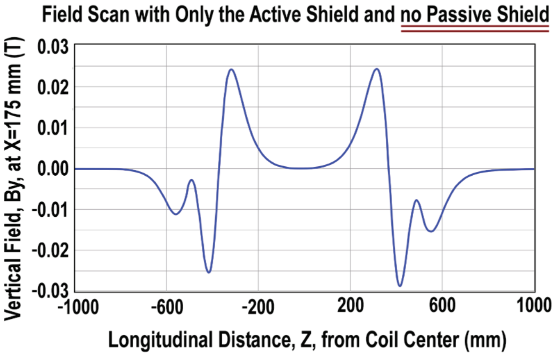

Figure 6: External field scan using full 3D coil model.

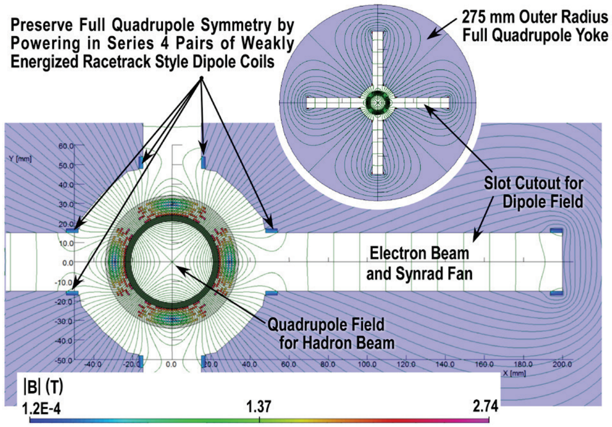

Figure 7: Multifunction magnet concept with strong hadron focusing and weak dipole field for electrons in a common quadrupole symmetric magnetic yoke.

eRHIC quadrupole and dipole magnets; we have managed to keep all other coil design fields below 4.5 T and by staying below 4.5 T we are confident that we can use our Direct Wind technique to produce the wide variety of superconducting coils required for the eRHIC IR, with no new tooling, by using round NbTi cable helium cooled at 4.5K. Note a backup option for Q1P could be to use NbTi cable cooled with 1.9K He-II to gain additional field margin; however, if we can realize the desired Q1P performance using Nb_3Sn at 4.5K, and leverage LARP experience, that would be our preferred solution.

OTHER MAGNET GEOMETRIES

The forward side Q1P magnet is the only eRHIC magnet that must use active shielding; for all the other magnets the fields outside their magnetic yokes or in the cutout regions of their magnetic yokes are low enough magnitude that minor additional passive shielding suffices to protect the circulating beams. However we note that because of their very large apertures, the resulting Q2P and B1P yokes are quite massive. Since the driving requirement for these yokes is simply to be unsaturated, so as to provide good shielding, requiring a large mass seems a bit excessive; we will consider active shielding for Q2P and B1P for cost reduction and other magnet production and installation advantages. The Fig.1 electron magnets Q1E and Q2E have coil fields below 0.27 T at the top, 18 GeV, beam energy and their yoke masses are thus reasonable.

For the incoming hadron beam, i.e. the "rear side," there is no experimental particle detection required and the associated hadron apertures are much smaller than those for the forward side. With no B0 spectrometer, the rear side hadron magnets can start just beyond the detector region at 4.5 m from the IP. The rear side e-beam magnets do have experimental requirements: to permit detection of Bethe-Heitler photons coming from the IP (for luminosity measurement) and scattered electron detection (for tagging). Ideally the first electron dipole should start at the same 4.5 m distance as the first hadron quadrupole. We show in Fig.7 a dual function magnet concept developed to achieve these goals.

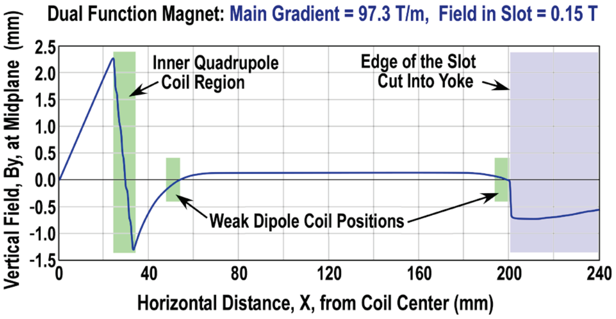

Figure 8: Field profile for multifunction magnet of Fig.7.

This first rear side magnet shown in Fig.7 has no active or passive magnetic shielding structure between the hadron and electron beams. Rather it uses the field generated by a quadrupole symmetric yoke to cancel the external field generated by a compact central superconducting coil in much the same way that a Sweet Spot coil design works [1]. By adjusting pairs of racetrack coil windings in all the slot cutout regions of the yoke we control the field strength in these slots. Inside slot regions we have locally oriented dipole field profiles as shown in Figs.7-8.

Having a wide slot cutout for the first rear side electron dipole is intentional to permit the Synrad generated in upstream electron IR quadrupoles (due to a small tail population of electron halo) to pass through this first dipole. This Synrad is absorbed away from the experiment to limit albedo backscatter and reduce detector backgrounds. With the yoke well outside the inner quadrupole coil, the yoke does not impact the central field quality. Changing the strength of the dipole field in the slots gives only a small change to the central gradient and requires only a small adjustment of the quadrupole current. Note a variation on this design, having a very strong central gradient coil, may prove useful as a quadrupole septum magnet for a future LHeC IR design [5].

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