

SWEET SPOT DESIGNS FOR INTERACTION REGION SEPTUM MAGNETS *

B. Parker[†], Brookhaven National Laboratory, Upton, New York, USA

Abstract

In order to manage the particular Interaction Region (IR) magnet challenges of an electron-hadron collider such as eRHIC, we create superconducting coil configurations with a region of low magnetic field going through an otherwise high field coil structure. These low field regions, denoted sweet spots, allow the electron beam to pass close by the hadron beam aperture without generating synchrotron radiation-related background. In this paper we heuristically introduce principles of sweet spot coil design, show some sweet spot coil design examples, and discuss sweet spot advantages and limitations.

INTRODUCTION

For the eRHIC IR design we should avoid generation of strong synchrotron radiation in the vicinity of the experimental detector that could lead to deleterious experimental backgrounds, as experienced during the HERA-II commissioning [1]. We do this by using Crab Crossing to separate the electron and hadron colliding beams into independent magnetic channels [2]. eRHIC experimental physics requires large acceptance for charged and neutral particles about the forward direction of the hadron beam exiting from the interaction point [3] and this in turn implies using large hadron magnet channel apertures to pass these particles without loss on to detector stations remote from the interaction point. But the hadron IR optics requires strong focusing gradients and substantial dipole fields are needed to cleanly separate the forward going charged and neutral particles. These forward side hadron IR magnets produce potent external fields through which we must somehow pass the electron beam.

We have considered using dedicated coils to explicitly cancel these external fields, as is done for SuperKEKB [4], active coil shielding as proposed for the ILC TDR baseline [5], and cutout regions in magnetic yokes as was done for HERA-II [1]; however, the option we found that keeps the crossing angle as small as possible, while satisfying reasonable magnet design limitations, is to send the electron beam through a sweet spot hole in the hadron magnet superconducting coil structure.

SWEET SPOT PRINCIPLES

In order to appreciate how it is possible to create a low field region in a high field coil structure, first consider an isolated, infinitely long conductor with constant current density as shown in Fig. 1. For Fig. 1 we overlay the conductor and its field lines with a plot of the normalized vertical field strength about the conductor's mid-plane.

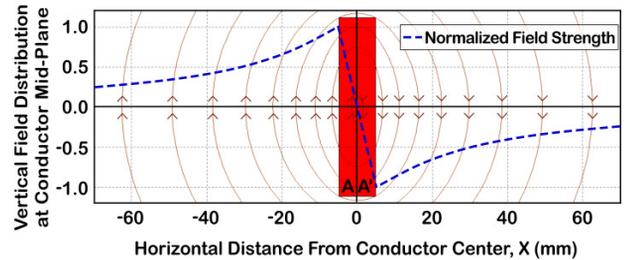


Figure 1: Normalized Mid-Plane Vertical Field Near an Isolated Conductor.

The current direction is away (into the paper) and by the right hand rule the field must reverse sign on opposite sides of the conductor. A general principle is that somewhere inside an isolated conductor the field crosses zero.

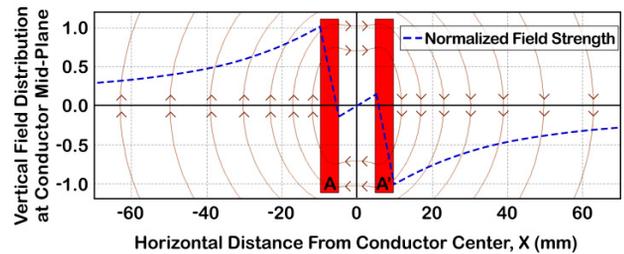


Figure 2: Normalized Mid-Plane Vertical Field Near an Isolated Split Conductor.

Now consider separating the conductor into two equal parts A and A' as shown in Fig. 2. In the gap between A and A' the vertical field component at the coil mid-plane is small due to partial cancellation between the two coil sections. The field zero crossing point we identify as the sweet spot and in a sufficiently small region about the sweet spot we can use passive magnetic shielding without the shield material saturating and losing its effectiveness.

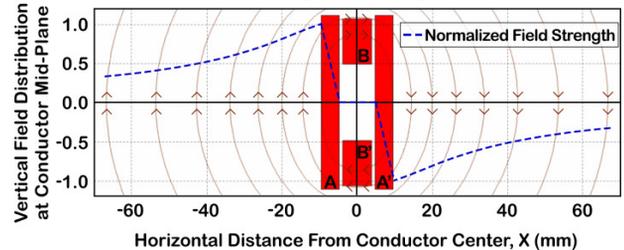


Figure 3: Normalized Mid-Plane Vertical Field Near an Isolated Conductor with an Extended Size Sweet Spot.

But suppose that the residual field in the gap is larger than we can reasonably shield in the space left after accounting for the electron beam aperture; in this case we can place equal conductor currents B and B' symmetrically above and below the region we want to shield as shown in Fig. 3. With the proper current in B and B' we can diminish the residual vertical field between A and A' near the AA' mid-plane. Note that in practice the horizontal field component also remains small near the mid-plane

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[†] email address : parker@bnl.gov

since the vertical and horizontal components are related by Laplace's equation in the source free interior space.

For a pure $\cos(m\phi)$ current coil with multipole, m , (Dipole=1, Quad=2 etc.):

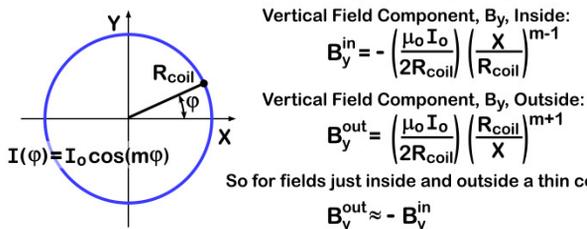


Figure 4: Mid-Plane Internal and External Vertical Field Dependence Due to a $\cos(m\phi)$ Current Distribution.

In order to generalize the above from an isolated 2d conductor to a magnetic field multipole distribution of normal field multipole, m , let us compare the field just inside and outside a $\cos(m\phi)$ current distribution as shown in Fig. 4. As before the field reverses itself on opposite sides of the conductor boundary. So it should be possible with nested current distributions, of the same sign, that yield a zero crossing sweet spot in the space between the nested coils. Note that with currents of the same polarity in both the inner and outer coils, their fields will add constructively inside the main inner coil aperture.

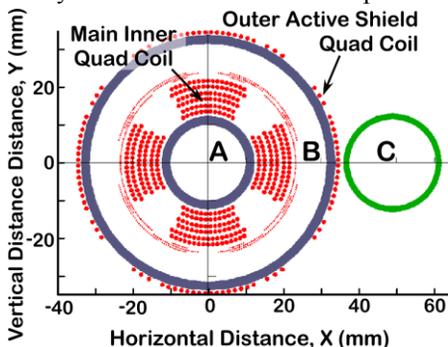


Figure 5: ILC QD0 Quadrupole Active Shield Configuration. Current flows in opposite directions in inner and outer quadrupoles such that by design their combined external field vanishes outside in region C.

This behavior is in marked contrast with that of active shielding coils as exemplified by the ILC QD0 coil configuration shown in Fig. 5 [4]. For active shielding the field cancellation takes place in the external field region outside both coils and in order to cancel the external field the current in the inner and outer coil structures must be opposite; thus not only do the fields cancel in the external region, C, but some degree of cancelation is unavoidable in the inner main field region, A.

But if we could instead use currents running in the same direction, we could look to create a sweet spot in region B that would be closer to the beam in the main aperture A. This change would also increase the gradient inside aperture A. The sweet spot advantage is apparent here in that we can simultaneously decrease the beam separation and increase the magnetic efficiency of a given coil configuration. The disadvantage with a sweet spot is that the field is reduced only in the immediate sweet spot

vicinity in contrast to the active shielding configuration where the field is cancelled everywhere outside the coils.

SWEET SPOTS IN PRACTICE

For the dipoles and quadrupoles of the eRHIC IR there are differences in the way the coil structures should be optimized. This can be understood by again considering the ideal $\cos(m\phi)$ current distribution of Fig. 4 where we find that an ideal quadrupole external field falls off more rapidly, $1/x^3$ compared to a dipole, $1/x^2$. This different behavior manifests itself as the magnitude of the residual field near the sweet spot rising more rapidly with distance from the zero crossing in a quadrupole than in a dipole.

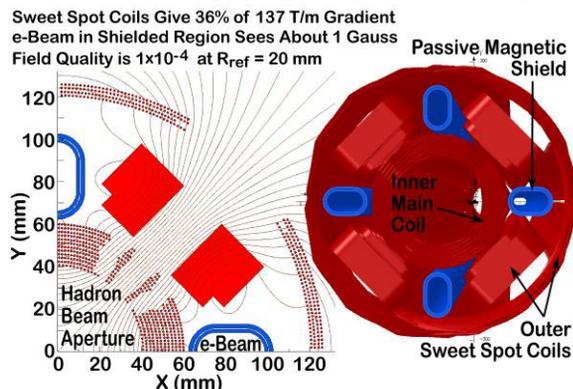


Figure 6: eRHIC Q1 IR Quadrupole Design.

With a dipole we find it possible to create a well shielded sweet spot region using only simple inner and outer coil structures, while for quadrupoles, such as the eRHIC Q1 shown in Fig. 6, we sometimes need to place conductor above and below the sweet spot region. The left side of Fig. 6 shows a 2d quadrupole-symmetric section cut from the eRHIC Q1 magnet body and a full 3d view from outside the coil structure on the right side.

For the eRHIC Q1 design shown, the main inner coil structure and the outermost sweet spot coil are planned to be $\cos(2\phi)$ NbTi superconducting coils produced using the BNL Direct Wind technique [5] while the intermediate sweet spot coil uses racetrack style coils. Racetrack coils are used in the middle region in order that the conductors in that part of the coil do not have to cross the magnet's mid-plane where we want to pass the electron beam. We also have designs for sweet spot magnets where all the sweet spot coils are made with racetrack geometry as this might be advantageous for magnet assembly.

With this eRHIC Q1 coil geometry we create a low field region very close to the main coil package that is suitable for using the two-layer passive magnetic shield shown. We plan to use Direct Wind for all of the eRHIC magnets since such coils have built in pre-stress and are self-contained. They do not have coil collars that would limit how close we can approach the main coil. Finally we can produce the wide variety of eRHIC IR magnet designs needed without having to make individual tooling for each different IR magnet coil configuration.

This eRHIC Q1 design provides 137 T/m gradient in the hadron aperture with about 36% of the total gradient coming from the outer sweet spot coils. Inside the main

coil the field is over 6 T; but inside the body of the shielded region, just 6 mm from the edge of the main coil, the field is less than 1 gauss. As for main field quality, the size of the hadron aperture is set to accommodate a 4 mrad wide neutron cone as well as 5 mrad divergent off-momentum forward charged particles from the interaction point and the circulating hadron beam only uses a small fraction of the available aperture. With the coil layout plus passive shielding shown for Q1, the field quality is fine for the eRHIC hadron optics being 1 unit (e.g. 10^{-4} of fundamental) at a reference radius of 20 mm. Because the passive shield always sits in a low field region, the field quality does not change appreciably with varying excitation current.

A caveat to note is that the low field sweet spot balance between the inner and outer coils works best in the effectively 2d “body section” of the magnet and is not as good near the magnet ends. Once current starts to return at the magnet ends we cannot maintain the same 2d coil symmetry throughout the entire end region. Fortunately the field strength near the extreme end of each of the coils drops significantly and we can take advantage of this for optimization. For the Q1 racetrack and outer sweet spot coil it is sufficient to stretch out their end turns to roughly match the external field profile of the inner main coil. For this the racetrack coil conductor returns in discreet groups with end spacers between each group and the outer sweet spot coil end turn-spacing is artificially increased. The result is that even though the cancellation cannot be perfect over the entire end region, the magnitude of the residual field is still small enough not to saturate the shield.

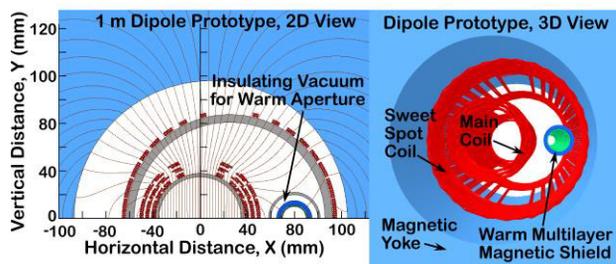


Figure 7: eRHIC Dipole Sweet Spot Prototype Design.

We are in the midst of constructing a 1 m long sweet spot dipole prototype magnet, illustrated in Fig. 7, with the dual goals of advancing Direct Wind technology and gaining experience with an actual sweet spot magnet. For this dipole we use 1.6 mm diameter superconducting cable with greater current carrying capacity than the 1 mm cable we used before. This allows winding coil structures with fewer layers, reduces the number of process steps, and slightly increases the engineering current density. After completing multiple winding machine upgrades we have successfully produced the outer sweet spot dipole prototype coil shown in Fig. 7.

The prototype dipole design has a 326 mm outer radius yoke that is not completely visible in Fig. 7 since the 2d section on the left and the 3d view on the right are enlarged to show some coil and shield detail. At a combined main dipole field of 4.2 T, the field in the shielded sweet spot region should be a few gauss. With this design we

reduced the size of the sweet spot coil by breaking left/right dipole symmetry; the 6 layer main inner dipole coil is left shifted to make room for a single sweet spot region on the right. The inner and outer coils produce comparable amounts of external magnetic flux which must return through their common yoke. We avoid saturating just one side of the yoke by offsetting the yoke center and lining it up over both coils' combined effective magnetic moment center.

When completed the plan is to test the prototype dipole in a vertical dewar with an evacuated pipe for insulating vacuum at the 80 mm sweet spot position shown in Fig. 7. In addition to conventional operation margin testing, we will use a warm magnetic probe in the sweet spot region to verify field cancellation as coil currents are varied. In subsequent testing we will insert a second pipe with a multilayer magnetic shield into the sweet spot region to try out different shielding designs and to measure the ultimate degree of field attenuation that can be achieved.

Initial optimization of the prototype dipole coil end design was done without a magnetic yoke and it became apparent that the vertical field components of the main and sweet spot coils had the same sign at the sweet spot horizontal offset in the region beyond both coils. Thus although the separate outside field contributions are small beyond the coils, there could never be complete cancellation; however, with a yoke, the magnet's virtual field boundary is sharply defined and it is not difficult to adjust the coil design lengths to ensure that the field is sufficiently reduced beyond the magnet structure so as not to saturate the shield outside the magnet.

CONCLUDING REMARKS

Sweet spot coils provide us with superconducting coil design solutions to resolving conflicting eRHIC accelerator, experimental and IR magnet design challenges. In future work we intend to evaluate using a combination of dipole and quadrupole coil windings in a sweet spot configuration to improve upon and possibly supersede the present active shielding design for the ILC QD0. A different variation on the sweet spot coil theme might also prove useful in the future for the LHeC IR design.

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