CORRECTOR MAGNETS FOR THE CBETA AND eRHIC PROJECTS AND OTHER HADRON FACILITIES*

N. Tsoupas[†], S. Brooks, A. Jain, F. Meôt, V. Ptitsyn, and D. Trbojevic

Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

The CBETA project [1] is a prototype electron accelerator for the proposed eRHIC project [2]. The electron accelerator is based on the Energy Recovery Linac (ERL) and the Fixed Field Alternating Gradient (FFAG) principles. The FFAG arcs of the accelerator are comprised of one focusing and one defocusing quadrupoles which are designed as either, iron dominated or Halbach-type permanent magnet quadrupoles [3]. We present results from 2D and 3D electromagnetic calculations on corrector electromagnets for both the iron dominated, and Halbach type quadrupoles.

INTRODUCTION

The proposed eRHIC accelerator [2] will collide 20 GeV polarized electrons with 250 GeV polarized protons or 100 GeV/n polarized $^3He^{+2}$ ions or other non-polarized heavy ions. The electron accelerator of the eRHIC will be based on a 1.665 GeV Energy Recovery Linac (ERL) placed in the RHIC tunnel with two recirculating rings placed also in the RHIC tunnel alongside the hadron RHIC accelerator. Fig. 1 is a schematic diagram of the eRHIC accelerator showing the hadron accelerator (blue ring), and the electron accelerator (red ring).
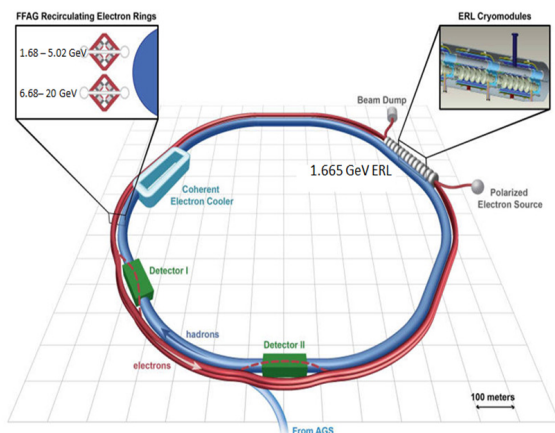

Figure 1: Schematic diagram of the eRHIC accelerator. The blue and red rings are the hadron and the electron accelerators respectively. The right insert is the ERL and the left insert is a cross section of the two FFAG rings of the electron accelerator. The green rectangles are the experimental areas for the electron-hadron collisions.

The 1.655 GeV ERL is shown as insert in the top right corner and the cross section of the two recirculating electron rings shows in the insert on the top left corner. The experimental areas of the electron-hadron collisions are the green rectangles. Two important concepts are involved in the electron accelerator, namely, the ERL and the FFAG concepts. The ERL concept provides 1.665 GeV of energy to the electron bunches each time they pass through the ERL for the electrons to achieve the top energy of the 20 GeV before the collision with the hadrons. Following the collision the electrons deliver back to the ERL the 20 GeV of energy by recirculating 12 times through the ERL, each time delivering to the ERL 1.665 GeV of energy. Since it takes 12 passes for the electrons to achieve the 20 GeV of energy, and also 12 passes to give back the energy to the ERL, the electron bunches circulating in the accelerator have 12 different energies, ranging from 1.685 to 20 GeV. The three electron bunches with the energies 1.685, 3.350 and 5.015 GeV are circulating in one FFAF arc and the rest of the bunches with energy range from 6.68 GeV to 12.0 GeV in the second FFAG arc. Thus this FFAG places electron bunches with large energy range in a small transverse distance of ~22 mm in each of the FFAG arcs. The CBETA which is the prototype of the eRHIC accelerator will employ both, the ERL and FFAG concepts and is under construction in Cornell University. Fig.2 is a layout of the accelerator showing the ERL (LA) the FFAG sections (FA, ZA, ZB, and FB) and the splitter/merger sections (TX, SX).
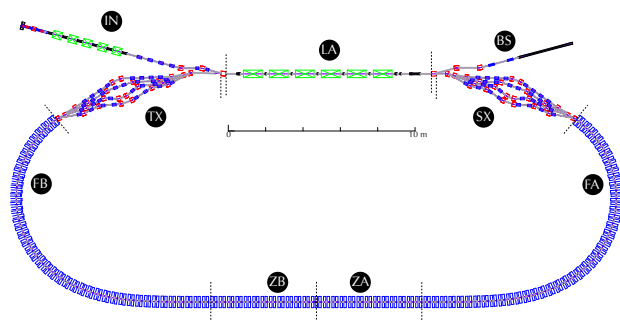

Figure 2: Layout of the CBETA accelerator. The section labeled (LA) is the ERL, The sections labeled (FA), (ZA), (ZB), and (FB) are the FFAG which will accommodate 4 energies of the recirculating electron bunches.

The FFAG arcs for either eRHIC or CBETA accelerators consists of FODO cells, each cell comprised of one focusing and one defocusing quadrupole. The top plot in Fig. 3 shows the orbits, the middle plot the $\beta_{x,y}$ functions, and the bottom the $\eta_{x,y}$ dispersion functions of the electron bunches with

the four different energies in one of the CBETA cells. The remarkable property of the FFAG is the accommodation of bunches with large energy range into a relatively small transverse space of the FODO cell.
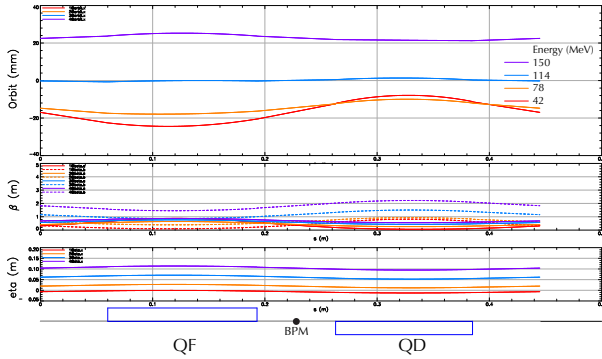

Figure 3: The orbits, the $\beta_{x,y}$ functions, and the $\eta_{x,y}$ dispersion functions of the electron bunches with the four different energies in one of the CBETA cells.

THE MAGNETS OF THE FFAG CELL

There are two possible designs for the magnets of the FODO cell. The iron dominated permanent magnets shown in the left picture of Fig. 4 and the Halbach type magnets shown in the right picture of the figure.
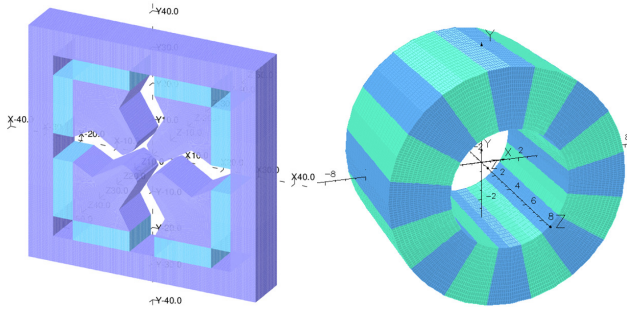

Figure 4: (Left) Isometric view of iron dominated magnet. (Right) Halbach type quadrupole.

The material shown as dark blue in the left picture of Fig. 4 is soft iron and the permanent magnet material is shown as the cyan color. The Halbach type of magnet shown in the right picture of Fig. 4 is made of permanent magnet wedges which are magnetized along a specified direction. Details on the design and measurements of these magnets are in Ref. [1].

THE CORRECTOR MAGNETS

In the following subsections we describe the corrector magnets for the iron dominated quadrupole and the Halbach quadrupole, and we provide results from the 2D and 3D electromagnetic design of the corrector magnets. The specifications of the corrector magnets call for electromagnets with air cooled conductors and an effective strength in the

range of ±50 Gauss for the normal and skew dipole and ±0.4 T/m for the normal quadrupole. The field uniformity of the corrector should be $\sim \pm 10^{-2}$ in the range of ±3 cm. In all calculations the material of the permanent magnet was not included since it does not affect the field of the corrector due to the high saturation ($\mu \approx 1.0$) of the permanent magnet material. The insignificant effect of the permanent magnet on the corrector's field has been proven experimentally [4].

Correctors for the Iron Dominated Magnets

For the iron dominated magnets we have found three type of corrector magnets that comply with the specifications, the normal quadrupole and the normal and skew dipole.

The normal quadrupole corrector Figure 5 shows the isometric views of two different but equivalent coil arrangements which can generate a quadrupole field. The left picture in Fig. 5 shows the coils of the corrector wound on the poles of the magnet, and the right picture shows the coils on the return yoke. The field uniformity of the quadrupole corrector is $\sim \pm 10^{-4}$ and exceeds the specifications
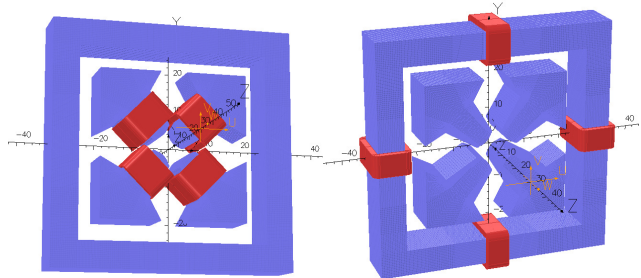

Figure 5: (Left) Isometric view of the magnet with the corrector coils on the poles . (Right) Isometric view of the magnet with the corrector coils on the return yoke.

The normal dipole corrector Figure 6 (Left) is an isometric view of the magnet with the coil of the normal dipole corrector. (Right) An expanded view of the cross section midway the length of the magnet. The corrector can provide a dipole field of 50 Gauss with current density of 1 A/mm². The conductor of the coil are arranged to provide an approximate $\cos(\theta)$ current distribution.

The skew dipole corrector Figure 7 (Left) is an isometric view of the magnet with the coil of the normal dipole corrector. (Right) An expanded view of the cross section midway the length of the magnet. The corrector can provide a dipole field of 50 Gauss with current density of 1 A/mm². All the conductor of the coil above the median plane carry the same current density and those below the median plane the opposite current density.

Correctors for the Halbach Type Magnets

The Halbach magnets can accommodate almost any corrector multipole. Here we will present the normal and skew
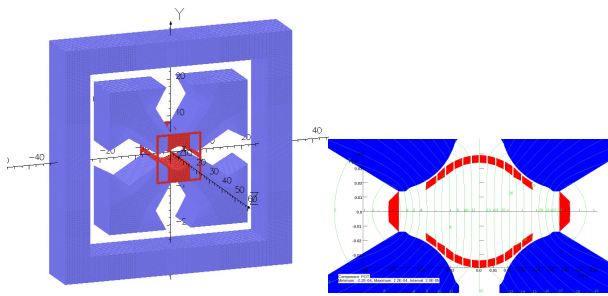
Figure 6: (Left) Isometric view of the magnet with the coil of the normal dipole corrector. (Right) Cross section of an expanded view midway of the magnet. The green lines are the equipotential magnetic lines.
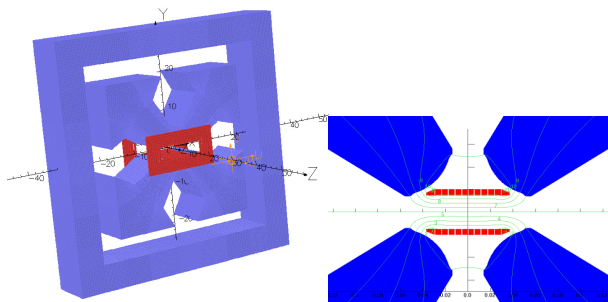

Figure 7: (Left) Isometric view of the magnet with the coil of the skew dipole corrector. (Right) Cross section of an expanded view midway of the magnet. The green lines are the equipotential magnetic lines.

dipole and quadrupole. A rectangular window frame magnet can accommodate all the correctors. For example the left picture in Fig. 8 shows a window frame magnet with a coil powered as a normal dipole is placed around a Halbach quadrupole magnet. It has been shown experimentally [4]
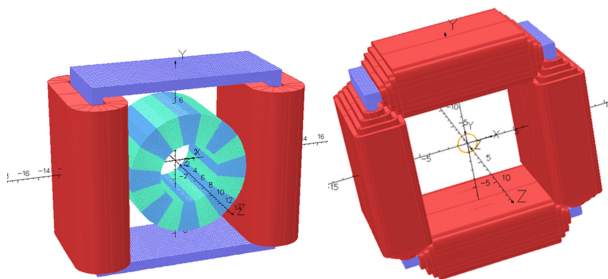

Figure 8: (Left) Isometric view of a window frame magnet as a normal dipole corrector placed around a Halbach magnet. (Right) A window frame magnet with coils in all its sides can be used as a normal dipole and quadrupole and skew dipole. By rotating the window frame magnet by 45° the corrector can provide normal and skew dipole and skew quadrupole.

that the field of the window frame dipole corrector magnet is superimposed to the that of the Halbach magnet. The superposition is independent of the corrector's field direction (isotropic). The superposition is due to the saturated nature

of the permanent magnet that makes the permeability of the permanent magnet material ($\mu \approx 1.0$). A skew dipole can be made by rotating the window frame magnet (left picture in Fig. 8) by 90° or by placing an additional coil on the horizontal sides of the window frame as shown in the right picture in Fig. 8. The side coils are powered independently of the top-bottom coils. The normal quadrupole corrector is identical to the window frame magnet shown in the left picture of Fig. 8 but the coils are powered in such a way to generate a quadrupole field. A window frame magnet powered as a quadrupole is also known as a Panofsky quadrupole. By rotating a Panofky quadrupole by 45° we generate a skew quadrupole field. In addition the four coils can also provide normal and skew dipoles simultaneously.

CONCLUSIONS

We designed dipole and quadrupole correctors for the iron dominated and the Halbach type of magnets which are two possibilities for the cells of CBETA or eRHIC projects . We found that the correctors for the Halbach magnets are easier to design and provide the required field with superior field uniformity.

REFERENCES

[1] http://arxiv.org/abs/1504.00588

[2] E.C. Aschenauer, et al., "eRHIC Design Study: An Electron-Ion Collider at BNL", arXiv:1409.1633, Chapter 3, (2014).

[3] K. Halbach, "Design of permanent multipole magnets with oriented rare earth cobalt material" , Nucl. Instrum. Meth. 169 (1980) pp. 1-10.

[4] private comunication Jain Animesh coauthor.