PERMANENT MAGNETS FOR HIGH ENERGY NUCLEAR PHYSICS ACCELERATORS*

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Abstract

The proposed eRHIC accelerator[1] will collide 20 GeV polarized electrons with 250 GeV polarized protons or 100 GeV/n polarized 3He ions or other unpolarized 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 and two Fixed Field Alternating Gradient (FFAG) recirculating rings placed alongside the RHIC accelerator. The electron bunches reach the 20 GeV energy after passing 12 times through the ERL by recirculation in the FFAG rings. After the interaction with the hadron bunches the electron bunches will give back their energy to the ERL in the form of electomagnetic radiation after passing 12 times through the ERL. The FFAG rings consist of FODO cells comprised of one focusing and one defocusing quadrupoles made of permanent magnet material. Similarly other sections of the electron accelerator will utilize permanent magnets. In this presentation we will discuss details on the design of these magnets and their advantages over the current-excited magnets.

INTRODUCTION

The proposed eRHIC accelerator [1] shown schematically in Fig. 1 consist of the hadron accelerator (blue ring in Fig. 1) and the electron accelerator comprised of a 1.665 GeV Energy Recovery Linac (ERL) and two rings (red arcs) based on the FFAG principle. The accelerator will collide 20 GeV polarized electrons with 250 GeV polarized protons or 100 GeV/n polarized ${}^{3}He^{+2}$ ions or other non-polarized heavy ions.The electron bunches reach the 20 GeV energy by passing 12 times through the ERL and by recirculating in the FFAG rings. After the interaction with the hadron bunches the ERL will retrieve the energy from the electron bunches in the form of electomagnetic radiation after the bunches pass 12 times through the ERL. One of the two modes of operation of the eRHIC accelerator is the 15.0 GeV where the low energy FFAG arc accomodates the energy range of the electron bunches from 1.685 GeV to 5.016 GeV (see inserts in Fig. 1) with the high energy arc from 6.680 GeV to 15.0 GeV and the other mode is the 20 GeV with the corresponding energy range of the electron bunches shown on Fig. 1). The experimental areas of the electron-hadron collisions are shown by the yellow 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

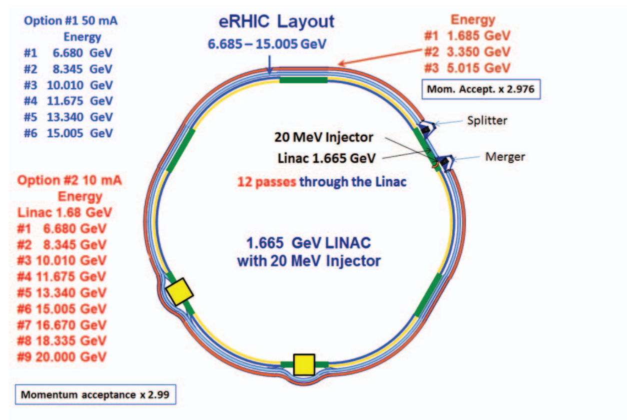

Figure 1: Schematic diagram of the eRHIC accelerator. The blue and red rings are the hadron and the electron accelerators respectively. The yellow rectangles are the experimental areas for the electron-hadron collisions.

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 20.0 GeV in the second FFAG arc. Thus this particular design of the FFAG places electron bunches with large energy range in a small transverse distance of ~22 mm in each of the FFAG arcs. 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.

THE FFAG CELL

The FFAG arcs of the eRHIC consists of FODO cells which can be made of a pair of quadrupoles which are displaced in the transverse direction or a pair of magnets each having a dipole and a quadrupole component. Figure 2 shows the parameters of one particular design of an eRHIC cell which is made of a pair of displaced quadrupoles. The traces on the figure are the trajectories of the central particle of the three recirculating electron bunches.

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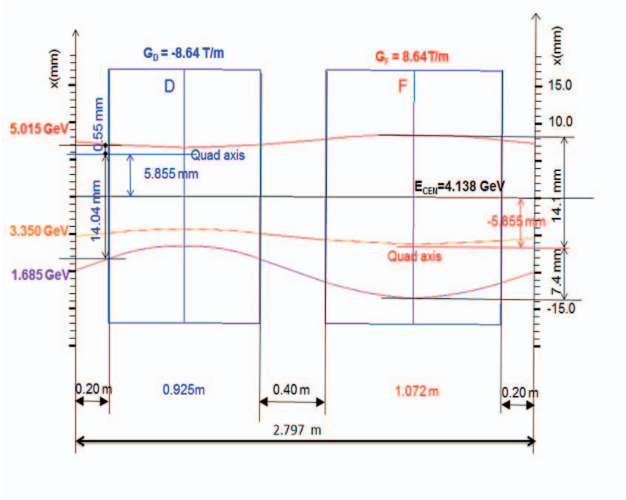

Figure 2: Schematic diagram of an eRHIC cell comprised of displaced defocusing and focusing quadrupoles. The traces on the figure are the trajectories of the central particle of the three recirculating electron bunches.

MAGNETS FOR THE FFAG CELL

Two of the possible designs for the magnets of the FFAG cell are shown in Fig. 3 with the isometric view of the iron dominated permanent magnet quadrupole on the left and the Halbach type permanent magnet [2]on the right.

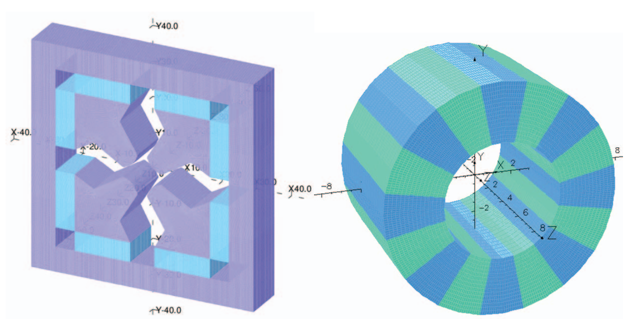

Figure 3: (Left) Isometric view of iron dominated permanent magnet quadrupole. (Right) Halbach type permanent magnet quadrupole.

In this paper we only consider the Halbach type of magnets as magnets for an FFAG cell and we will discuss some the advantages over the iron dominated permanent magnet.

HALBACH PERMANENT MAGNETS

The multipolarity of a Halbach magnet is determined by the direction of the easy axis of the permanent magnet wedges as shown in Fig. 4. The value of the symbol n in Fig. 4 determines the multipole generated when the easy axis of each of the wedges is derived by the equation $\alpha = (n+1)\theta + \pi$, where θ is the azimuthal location of the easy axis.

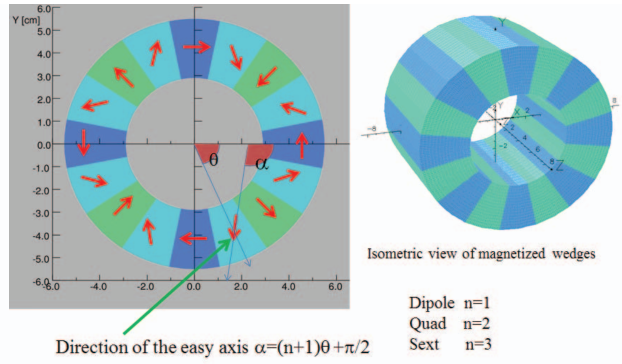

Figure 4: (Left) Cross section of a Halbach magnet made with 16 permanent magnet wedges. The direction of the wedge's easy axis which is designated by the symbol α in the figure determines the multipolarity of the Halbach magnet. (Right) the isometric view of the Halbach magnet.

ADVANTAGES OF THE HALBACH TYPE OF MAGNETS

In the subsections below we will discuss some of the advantages of the Halbach type permanent magnets which makes the desirable magnets for the FFAG cell.

Modified Halbach Magnets

The high energy bunches moving on off-axis trajectories in an FFAG quadrupole are emitting synchrotron radiation which may damage the permanent magnet material of the Halbach magnet. To eliminate this effect we remove the permanent magnet wedges which are on the horizontal plane of the magnet as shown on the left picture of Fig. 5. The wedges along the vertical are also removed to keep the four fold symmetry required for a quadrupole. The modified Halbach quadrupole can generate zero 12pole component, by varying the direction of the easy axes of the wedges adjacent to the 45^o and 135^o wedges. The picture on the right in Fig. 5 is an isometric view of the modified quadrupole.

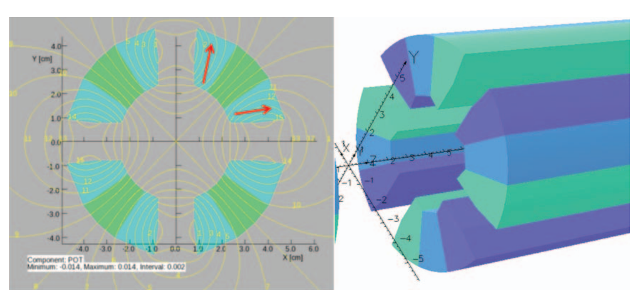

Figure 5: (Left) Modified Halbach Quadrupole: The cross section of the modified Halbach quadrupole with the permanent magnet wedges along the horizontal plane removed to eliminate the radiation damage of the wedges from the synchrotron radiation. (Right) Isometric view of the modified quadrupole.

One Remarkable Property of Permanent Magnets

The B vs H curve of the NdFeBo-N35 permanent magnet material is shown in Fig. 6. This curve shows that the permeability of this material is approximately equal to 1 ($\mu \sim 1.0$) which provides this material with the remarkable property of "field superposition".

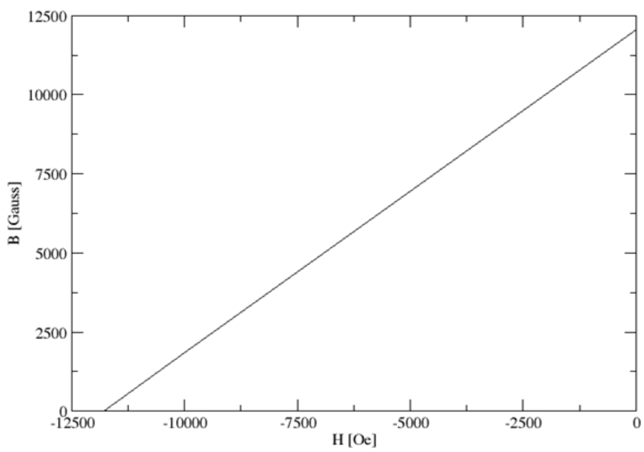

Figure 6: The B-H curve of the NdFeBo-N35 permanent magnet material.

This property of field superposition has been proven experimentally by superimposing the magnetic field of a Halbach permanent magnet quadrupole with the field of a window frame magnet. The picture on the right in Fig. 7 shows the permanent magnet quadrupole inside a window frame magnet shown on the right picture of Fig. 7.This superposition is independent of the direction of the dipole magnetic field generated by the window-frame magnet. (Isotropic property of the permanent magnet material).

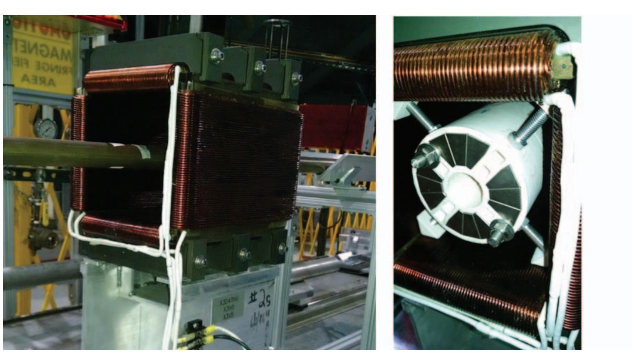

Figure 7: The picture on the right shows a Halbach-type permanent magnet quadrupole inside a window frame electromagnet which is also shown on the picture on the left.

Field Superposition of Dipole and Quadrupole

Figure 8 shows the vector potential lines from the superposition of a modified dipole and a modified quadrupole magnets. The vector potential lines have been calculated by the use OPERA computer code. Figure 9 shows an isometric view of a Halbach quadrupole magnet (left) a dipole magnet (middle) and the combination of both magnets (right). The field generated by the combination of the two magnets is the sum of the fields generated by each magnet separately.

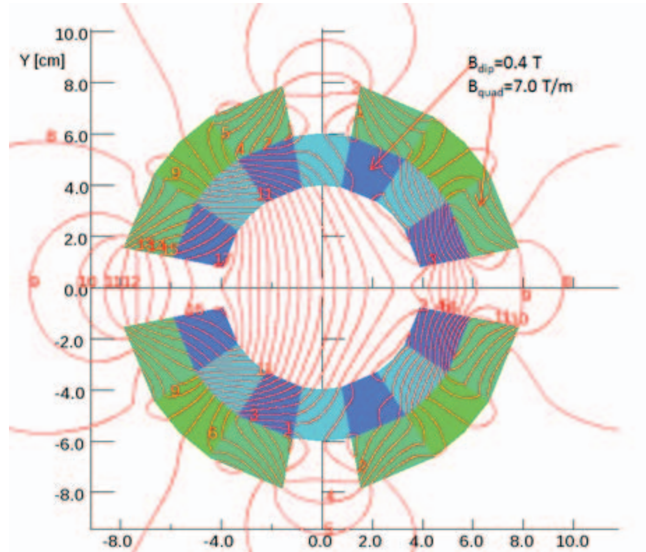

Figure 8: A two dimensional model generated by the OPERA computer code showing the superposition of a modified Halbach-type dipole with a modified Halbach-type quadrupole. The field of this magnet is the superposition of the field generated by the dipole and the quadrupole separately .

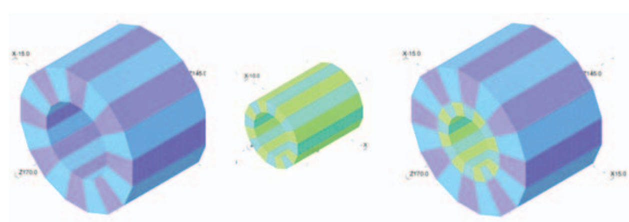

Figure 9: An isometric view of a Halbach quadrupole magnet (left) a Halbach dipole magnet (middle) and the combination of the two magnets (right).

CONCLUSIONS

The Halbach type permanent magnets posses remarkable properties of field superposition which makes them desired magnets for the FFAG cells.

REFERENCES

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

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