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CONCEPTUAL DESIGN OF A QUADRUPOLE MAGNET FOR eRHIC*

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Abstract

eRHIC is a proposed upgrade to the existing Relativistic Heavy Ion Collider (RHIC) hadron facility at Brookhaven National Laboratory, which would allow collisions of up to 21 GeV polarized electrons with a variety of species from the existing RHIC accelerator.

eRHIC employs an Energy Recovery Linac (ERL) and an FFAG lattice for the arcs. The arcs require open-midplane quadrupole magnets of up to 30 T/m gradient of good field quality.

In this paper we explore initial quadrupole magnet design concepts based on permanent magnetic material which allow to modify the gradient during operation.

INTRODUCTION

To discover and understand the emergent phenomena of Quantum Chromodynamics the eRHIC facility is presently being designed. eRHIC adds an electron accelerator to the existing proton accelerator called RHIC (Relativistic Heavy Ion Collider). eRHIC would be an unprecedented facility for Nuclear Physics to study QCD; it is planned to collide unpolarized and 80% polarized electrons (6.6–15.9 GeV) with up to 70% polarized protons (25-250 GeV). The center of mass energy range is 30–145 GeV.

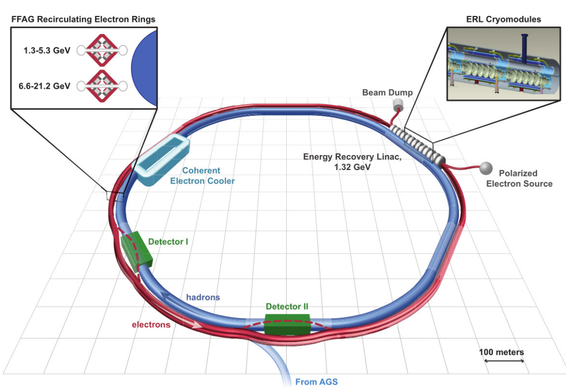

Figure 1: The layout of the eRHIC accelerator.

It was decided to employ the fixed-field alternating gradient (FFAG) accelerator concept for eRHIC. It is planned to add two FFAG rings to the RHIC tunnel for up to 16 beams. The targeted luminosity is $> 10^{33}$ cm^{-2} s^{-1}; plans exist to increase the hadron beam intensity, which would increase the luminosity to $> 10^{34}$ cm^{-2} s^{-1}. Collisions with Au and He are also planned. Figure 1 shows an overview of the facility.

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MAGNET REQUIREMENTS AND CONCEPT

The FFAG lattice requires quadrupole magnets with a gradient strength of up to 28 T/m in a good field region of ±17 mm. The required gradient quality is 1×10^{-3}. In addition to this the poles are not allowed to penetrate the area around the midplane. The open-midplane (±7 mm) is required because of synchrotron radiation.

One design choice is to use permanent magnets. This is possible as the magnets are not required to sweep. The use of permanent magnets allows to dispense with expensive power supplies in the RHIC tunnel, which also greatly simplifies cabling.

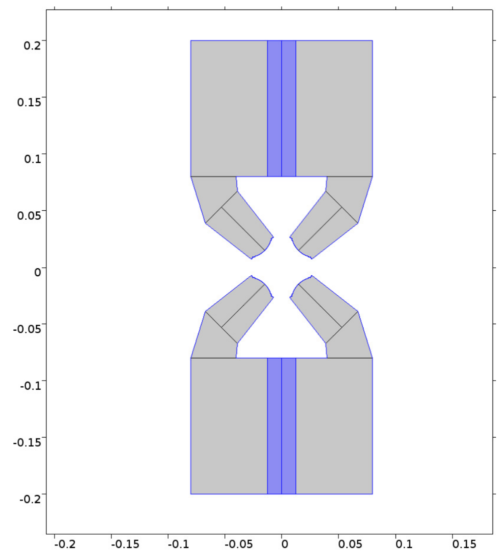

Figure 2: Magnet geometry. The permanent magnetic material is shown in blue.

We envisage NdFeB permanent magnetic material with a remanent magnetic field of about 1.1 T for this design. NdFeB is sufficiently radiation hard provided the grade chosen is relatively low. Studies are underway to demonstrate this.

The geometry of the permanent magnetic material is chosen so that the operating point of the permanent magnet is close to the energetic maximum. Figure 2 shows the general geometry of the quadrupole; the permanent magnets are shown in blue. The total cross-sectional area of the permanent magnets is 60 cm^2 and the height of each block about 12 cm.

The starting point for the initial design of the quadrupole are Tanabe's equations for quadrupoles [1]. The equations below are used to obtain approximate coordinates for the

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pole corner (x_c/y_c):

$$x_{\text{opt}} = -0.14 \log \left(\frac{\Delta B}{B} \right) - 0.25$$

$$x_c = h \sqrt{0.5 \left(\sqrt{\rho_0^2 + x_{\text{opt}}^2 + 1} + \rho_0^2 + x_{\text{opt}} \right)}$$

$$y_c = h \sqrt{0.5 \left(\sqrt{\rho_0^2 + x_{\text{opt}}^2 + 1} - \rho_0^2 - x_{\text{opt}} \right)}$$

with

$$\rho_0 = r_0/h.$$

In these equations h is chosen to 21 mm and r_0 is the required good field region. The pole is then optimized as outlined in the next section.

POLE OPTIMIZATION

To optimize the pole we use the commercial finite element code COMSOL[1]. We employ a 2D planar magnetostatic simulation. As the required magnets are long (meter scale) this is a reasonable approach. For the material properties of the iron for the yoke we employ a non-linear BH-curve of low carbon steel.

The pole is optimized using the Nelder-Mead algorithm. In the optimization ten points spread evenly over 5 mm at the pole end are allowed to change their position perpendicular to the pole face. The target function is the gradient quality $((G_{\max} - G_{\min})/G_{\text{av}})$.

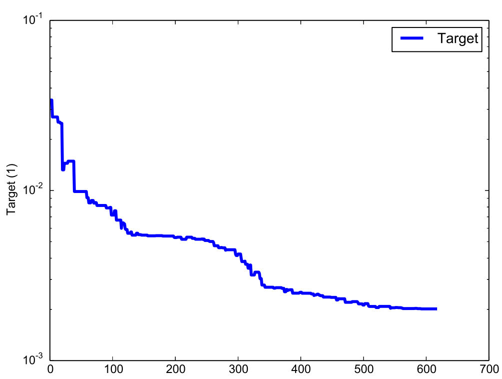

Figure 3: Target function.

In about 600 iterations the simulation converges to the pole shape shown in Fig. 4. The convergence of the simulation is shown in Fig. 3. Figure 5 shows the obtained gradient quality, about 0.5×10^{-3}, referenced to the gradient at the origin.

The normalized harmonics at the reference radius of 17 mm is shown in Table 1. The table shows that apart from a small duodecapole component the higher order harmonics are well behaved.

[1] COMSOL AB, Tegnergatan 23, SE-111 40 Stockholm, Sweden

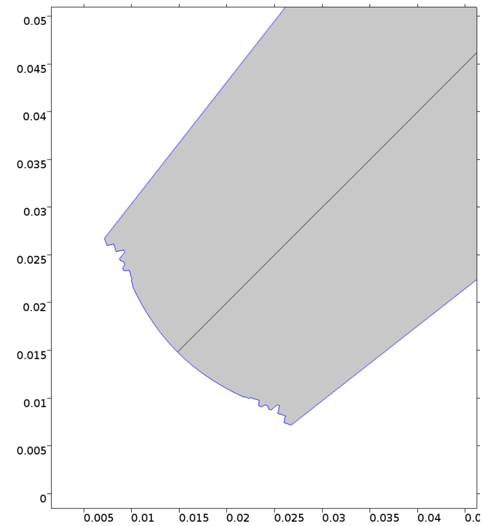

Figure 4: Optimized pole.

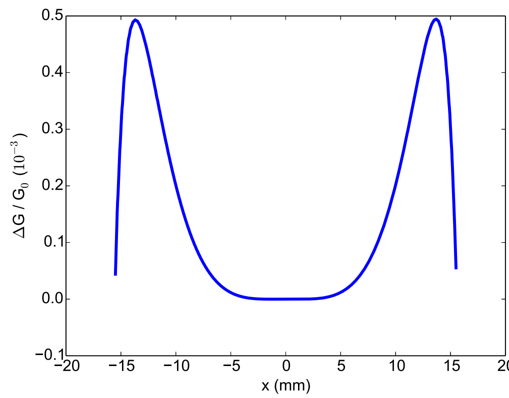

Figure 5: Gradient quality on the centre plane.

GRADIENT CORRECTION

It is unlikely that in a real magnet all obtained permanent magnets will be exactly identical. It is therefore desirable to identify a correction scheme to compensate little differences. Furthermore, it might also be desirable to be able to change the quadrupole field, either while being operated in the accelerator or for some other reason.

Table 1: Normalized Harmonics

	Real	Imaginary
1	-0.0523	-0.3001
2	10000	0.0374
3	-0.0154	0.8457
4	-0.1104	0.0817
5	0.0925	0.5419
6	3.045	-0.0188
7	0.0718	0.3048
8	-0.0642	-0.1004
9	-0.0268	0.822
10	-0.8	-0.0746

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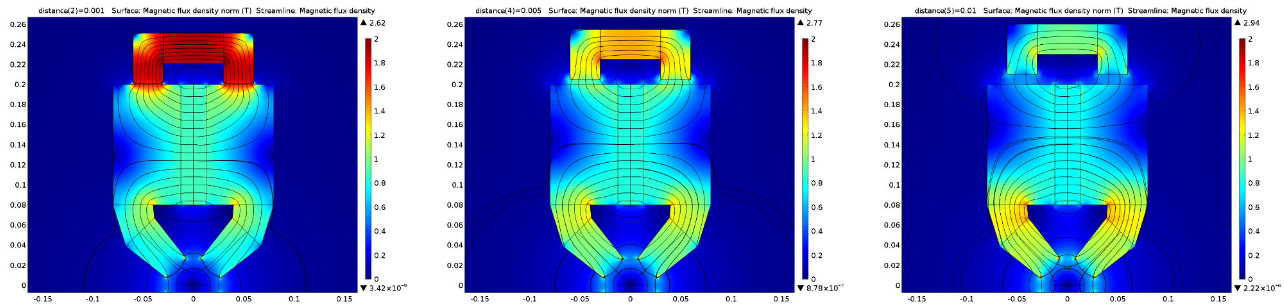

Figure 6: Effect of adding a clamp with varying distance from the yoke. Left figure: 1 mm distance, middle figure: 5 mm, right figure: 10 mm.

In principle it is possible to move the permanent magnets themselves in and out of the magnetic circuit as demonstrated in [2]. Here we adopt another approach, mostly as it is desirable to not move the permanent magnets after they have been attached to the quadrupole yoke.

We employ external clamps as shown in Fig. 6, which act as magnetic shunts. The clamps divert the magnetic flux away from the poles, thus lowering the gradient. This effect can be seen in Fig. 6, which shows the magnetic field equivalent to the magnetization if clamps at varying distances from the yoke are added.

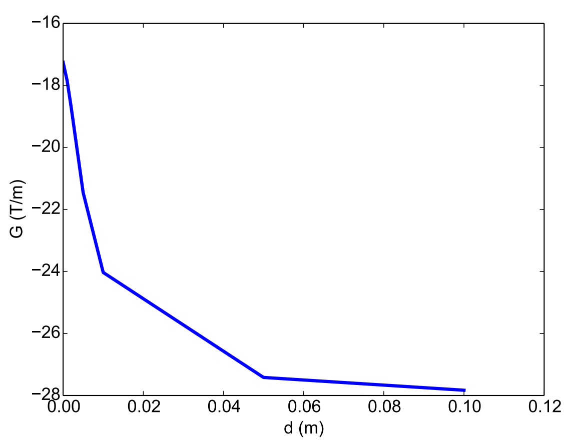

Figure 7: Change of the gradient with varying distance.

Figure 7 shows the gradient variation as function of distance. Depending on the desired variability of the gradient the size of the clamp can be adjusted, so the effect demonstrated here is only to show the principle. With the clamp employed here the gradient can be varied from about 17.5 T/m to 28 T/m.

Variations of the permanent magnets can be compensated in a similar fashion. Thin strips of soft-iron can be placed across the permanent magnets to artificially degrade a permanent magnet at a specific longitudinal position. The field quality then only depends on the pole shape and their alignment with respect to each other.

CONCLUSION

This paper shows the conceptual design of a quadrupole suitable for an FFAG ring for the eRHIC accelerator. The field quality in this design is only determined by the iron poles, which were optimized using the Nelder-Mead algorithm. The gradient quality of 0.5×10^{-3} is better than required.

External clamps can be used to change the gradient strength after assembly; this is advantageous as the quadrupole itself does not require any moving parts. A similar system can be employed to balance small differences in the permanent magnetic material: small magnetic shunts placed across each permanent magnet allow to fine-tune the strength of each individual permanent magnet.

Future work should optimize the field quality for the varying gradient strengths to ensure that the gradient quality is similar for each gradient.

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