A PERMANENT MAGNET QUADRUPOLE MAGNET FOR CBETA*

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Abstract

Recently a collaboration between Brookhaven National Laboratory and Cornell University was established, aiming to build the CBETA accelerator.

CBETA is a 150 MeV electron test accelerator, which prototypes essential technologies of eRHIC, which is a proposed upgrade to the existing Relativistic Heavy Ion Collider (RHIC) hadron facility at Brookhaven National Laboratory.

Similar to eRHIC, CBETA employs an FFAG lattice for the arcs. The arcs require short, large aperture quadrupole magnets, which are located close together. BNL has been working on a design employing permanent magnets; we show the concept and the engineering design of these magnets.

Prototype magnets have been constructed recently; we report on magnetic field quality measurements and their agreement with computer simulations.

INTRODUCTION

eRHIC is a proposed upgrade to the existing RHIC facility at Brookhaven National Laboratory, which would allow to collide spin-polarized protons with up to 18 GeV electrons. Part of eRHIC could be FFAG (fixed field alternating gradient) arcs, which could lower the cost of the facility.

Recently the CBETA collaboration was established between Cornell University and Brookhaven National Lab to prototype essential technology to reduce the risk for eRHIC. CBETA will accelerate electrons up to 150 MeV using a recirculating LINAC and FFAG arcs. CBETA is described in more detail in [1].

Due to the fixed magnetic field in the arcs it is attractive to utilize permanent magnets instead of a more conventional approach. One way to realize this is a so-called hybrid magnet approach, where permanent magnets in combination with conventional iron poles are used to generate the required field. This paper describes the design, assembly and first measurement results.

The arc lattice of CBETA is shown schematically in Fig. 1. As shown in the figure, CBETA requires two types of quadrupole magnets, which are offset to generate a combined function field (dipole and quadrupole component). The required magnet parameters are summarized in Table 1.

It is worth noting that the Qd and Qf magnets have an identical cross-section; they only differ in their length. This was a design choice at the time the lattice was studied, which minimized the design effort. The lattice was designed using 3D field maps; the exact design procedure will be described elsewhere.

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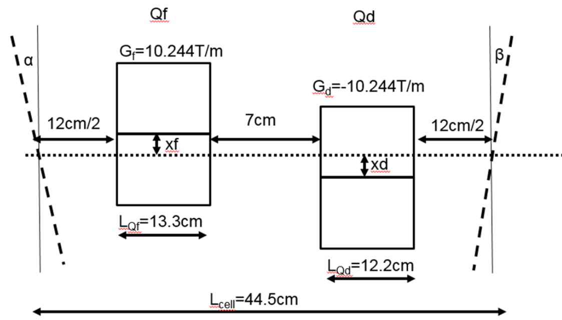

Figure 1: Schematic of the CBETA lattice. $xf = 7.462$ mm, $xd = 20.802$ mm. Qf is rotated by 1.104° and Qd by −1.0787°. $\alpha = 2.562°$ and $\beta = -2.43822°$.

Table 1: CBETA Magnet Specification

Length Qf	133	mm
Length Qd	122	mm
Gradient Qf/Qd	10.244	T/m
Good field region dia.	36	mm
Operating temperature	15-30	°C
Gradient variation	4	%

Challenging in terms of field quality is the magnet to magnet variation, which should be of the 10^{-4} level. The required gradient quality is of the percent level (provided the magnet to magnet variation is small).

CONCEPT

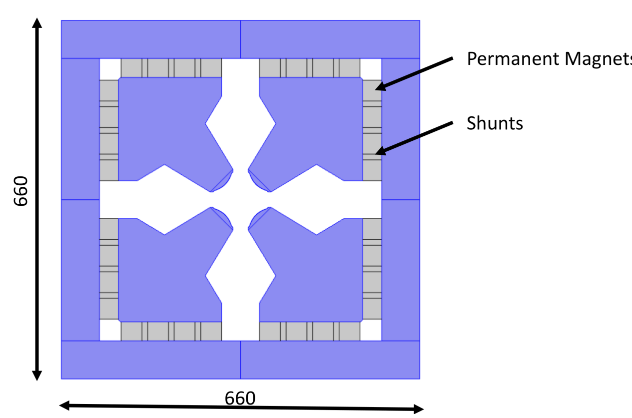

Figure 2: Cross-section of the CBETA quadrupole magnets. The iron part of the magnet is shown in blue. Dimensions in mm.

The concept presented in this paper is an iron dominated hybrid approach, where the necessary flux is generated by permanent magnets. Figure 2 shows a cross-section of the magnet geometry. The permanent magnets are located vertically and horizontally next to the poles; the magnetic field is generated by conventional iron poles.

This concept possesses several advantages: the approach is largely conventional, so it poses a low risk. The field quality ultimately is defined by the pole shape and pole alignment, which is established technology. This approach allows us to achieve very tight magnet to magnet variation.

NdFeB was chosen as the material for the permanent magnets, due to cost and radiation considerations. NdFeB permanent magnets usually have relatively large magnetic tolerances, e.g. the magnetization angle can vary up to several degrees. Several vendors guarantee a standard tolerance for the magnetization of ±3%; it is possible to obtain permanent magnets with tighter tolerances, but this drives the cost.

Each magnet pole has to receive the same amount of flux, as otherwise unwanted higher order harmonics are generated. This magnet concept facilitates a multi-stage approach to ensure this.

Part of the concept is to use multiple individual permanent magnet blocks per pole. In total per quadrupole 72/96 (Qf/Qd) permanent magnet blocks are required. Each block is 37.3 mm wide and 35 mm tall (=c-direction, direction of magnetization). The required length of the blocks for Qd is 31.2 mm and for Qf 28.5 mm. Each permanent magnet is magnetized in the c-direction; a minimum B_r of 1.37 T is required to achieve the required gradient.

One advantage of this design is that the way the permanent magnets are used only the magnetic properties in the c-direction play a role. Any transverse magnetic field due to a tolerance of the magnetic axis is short-circuited in the nearby yoke. The large number of permanent magnets per magnet helps to reduce the statistical error; a further improvement could be accomplished by measuring each block and matching suitable magnets.

Small differences in magnetic flux can also be corrected by adding magnetic shunts next to the permanent magnets. This can be facilitated by adding thin strips of soft-iron in gaps next to the permanent magnets; for example, a single 1 mm wide strip of 3%SiFe will change the magnetic flux through one pole by about 1%; using thinner strips and shorter lengths a very fine-grained control can be accomplished.

The pole shape of the CBETA magnets is largely hyperbolic, with minor shimming at the ends to improve the good field region. The CBETA magnets are large aperture magnets and the beam is relatively far away from the poles, so the pole tolerance is not that challenging to achieve. Finite element studies show that a mechanical tolerance of 100 µm has a negligible effect on the field quality. Low carbon steel is used for the yoke and pole (C content ≤ 0.010%).

TEMPERATURE COMPENSATION

It is well known that NdFeB possesses a negative temperature coefficient ($\alpha = -1.1 \times 10^{-3}\ 1/K$). A temperature change of 1 K could therefore introduce an unacceptable error. For CBETA we adopt a concept which for accelerator magnets has been shown to work at Fermilab and CERN [2, 3]. Thin strips of NiFe (30-32% Ni) are placed next to the permanent magnets, which act as temperature dependent shunts. NiFe possesses a low Curie temperature, e.g. the saturation magnetization changes from 0.3T to 0.1T from 20-45°C.

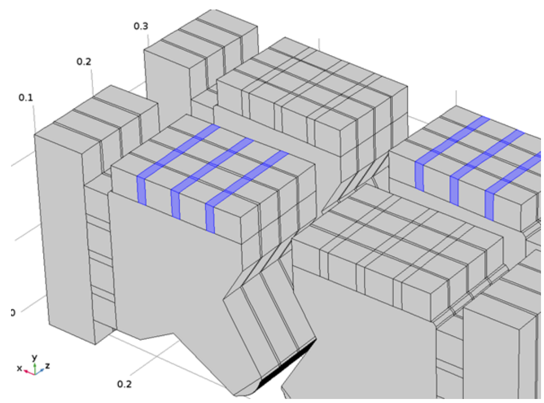

Figure 3: Strips of NiFe can be added to the quadrupole magnets in the space between permanent magnets (shown in blue).

By adding the correct amount of NiFe the negative temperature coefficient can be completely canceled out, which was demonstrated in bench tests at BNL. The NiFe strips (similar to magnetic shunts used for balancing the poles) can be added after assembly in between permanent magnet rows as indicated in Fig. 3.

ASSEMBLY

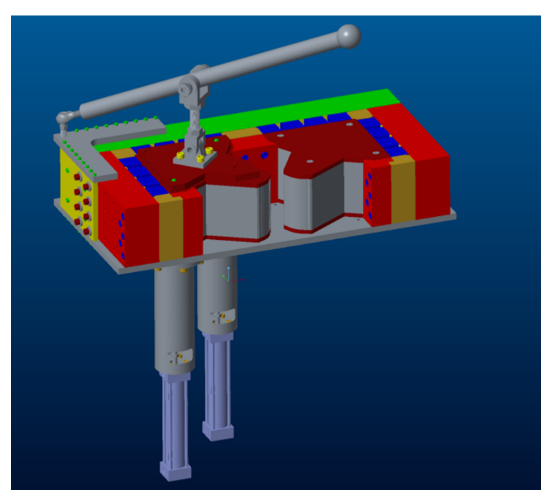

Figure 4: Assembly fixture.

The first step is the assembly of the back yoke frame, which is measured and adjusted until correct. Precision aluminium spacers are then mounted onto the back yoke. The purpose of the precision spacers is to define accurately the position of the poles.

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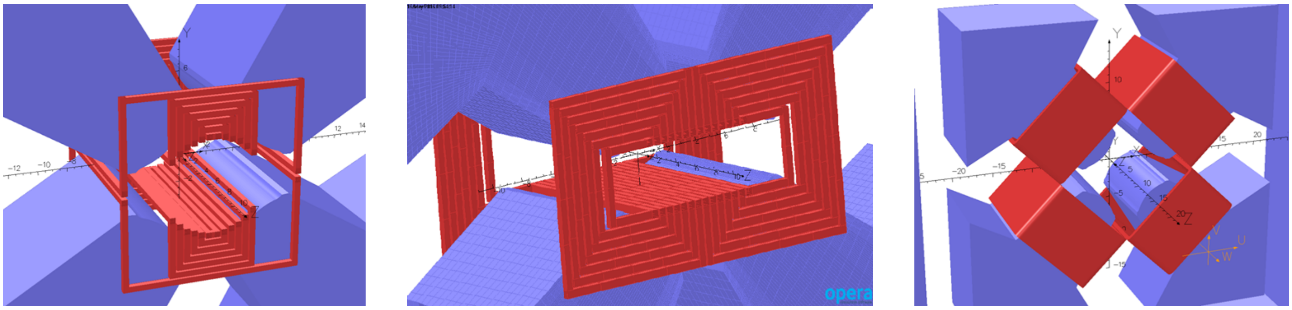

Figure 5: CBETA corrector magnets. The left figure shows the dipole corrector, the middle figure the skew dipole corrector and the right figure the quadrupole corrector.

For one pole one row of permanent magnets is then attached to the back yoke. A plastic grid helps to position the permanent magnets correctly. Pole laminations are then added up to the height of the permanent magnets. A special assembly fixture, shown in Fig. 4, was constructed to prevent the pole laminations from repelling one another during assembly. The assembly fixture consists of a pneumatically operated actuator, which possesses a ball at the end which can 'grab' laminations and hold them down during assembly. It is worth noting that at this point in the assembly there is little lateral force on the permanent magnets (in contrast to permanent magnets in air).

CORRECTORS

Each of the CBETA magnets can be equipped with a normal or skew dipole corrector. In addition, each CBETA magnet is expected to have a quadrupole corrector, which is a simple pole winding.

For the correctors a maximum current density of 1 A/mm^2 is defined to avoid water cooling. The quadrupole corrector is capable of changing the gradient by ±4% without changing the gradient quality. The normal dipole correctors deliver an integrated dipole strength of 347.26 Gcm (normal, $\Delta B/B_0 \sim 5 \times 10^{-3}$) and 590 Gcm (skew, $\Delta B/B_0 \sim 8 \times 10^{-3}$). The correctors are shown in Fig. 5.

MEASUREMENT

A prototype magnet was recently completed. Due to time constraints the prototype magnet is made of 3%-SiFe sheets instead of low-carbon steel; to avoid saturation only half of the permanent magnets were mounted. Temperature compensation was not tested at this stage. Table 2 shows the results of the measurement.

The multipoles are normalized to −10000 units of the main component. It is worth noting that the 14 units dodecapole component are the expected result. The normal and skew octupole component arise from a misalignment of the poles, which was confirmed by surveying. Even with the remaining octupole component the field quality of the quadrupole magnet is sufficient for operation in CBETA.

Table 2: Measured Normal (b_n) and Skew (a_n) Multipole Components. Reference radius: 25 mm.

	a_n	b_n
1	–	–
2	–	−10000
3	0.13	0.07
4	−0.4	−1.46
5	0.13	0.06
6	0.18	14.29
7	−0.11	0.09
8	0.04	0.03
9	0	0.01
10	−0.01	−0.65
11	0	−0.01
12	0	0
13	0	0
14	0	0.03
15	0	0

CONCLUSION

An iron dominated hybrid magnet quadrupole was developed for CBETA project, which employs NdFeB permanent magnets to provide the magnetic flux. The quadrupole can be temperature compensated using strips of NiFe. The measured gradient quality meets the requirements for the CBETA accelerator. It was noted that the measured gradient is 2% lower than expected from finite element simulations.

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