State-of-the-Art Magnet Technology to Obliterate Boundaries in Science and Medicine

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Abstract
Two examples will be introduced to demonstrate the permanent magnet technology and its feasibility in the medical and scientific applications, where in general electromagnets have been used. First, the quadrupole focusing magnets with an innovative field-adjustable feature and temperature compensator were designed and produced for future ion collider and proton therapy. And second, the dipole magnets were designed and developed for commercial mass spectrometers. The comprehensive design studies including magnetic and mechanical design using finite element analysis and iterative optimization are completed. Permanent magnet prototypes have been successfully built using rare earth magnets and the magnetic field measurement was conducted and compared with the numerical estimates.

Keywords: Rare earth permanent magnet, quadrupole, dipole, proton therapy, mass spectrometer

1. Introduction

Permanent magnets (PMs) have been used for a variety of applications including military, aerospace, oil exploration, telecommunications, automobile, electronics, power generation, and medical devices [1][2]. Some other applications, especially for particle and nuclear physics experiments in science, technology and medicine, prefer electromagnets (EMs) rather than PMs, because of finer field controllability and higher accuracy requirements. However, the fabrication, operation and maintenance costs of EMs used to produce the desired magnetic field for particle accelerators are considerable. High energy costs are associated with supplying the EM coils with the current to produce the desired field and with the active cooling system. Significant costs are encountered also with high temperature superconducting magnets, which are expensive and require cryogenic operation temperatures. Another disadvantage is EM's large volumes, which inherently can bring maintenance problems.

The recent research trend is to switch EM to PM since the magnet production technology is advanced and economically cost effective. For instance, US National Institute of Standards and Technology (NIST)'s watt balance is a precision electromechanical weight measuring instrument which requires to provide the magnetic field of >0.5T over 3cm wide, 8cm long air gap of interest with field uniformity ≤±0.01%. In 2014, Electron Energy Corporation (EEC), with the forefront of technological advances for innovative and creative applications, has replaced NIST's EMs with EEC Sm_2Co_{17}-27 materials and achieved the average field of 0.5516T and the uniformity of ±0.0063% [3]. The dimensions of magnet system are 60cm in diameter, 45cm in height, and its weight is ~850kg. The cost savings for liquid helium alone is $75,000 per year. Another example is Halbach oriented quadrupole focusing magnets for application to proton radiosurgery, which Loma Linda University Medical Center and EEC have successfully developed in 2016 [4]. Using EEC Sm_2Co_{17}-27 materials, more than a dozen of 24-segmented quadrupole magnets have been built to demonstrate the required field gradient ranging from 100 to 260T/m with the field gradient error $\leq 10^{-3}$ within the bore. Testing with high energy protons produced beams with highly symmetric cross sections suggesting that the PM assemblies can be practically manufactured to produce high quality quadrupole fields suitable for proton radiosurgery.

In this paper, the design and development of PM assembly for the medical and scientific applications will be addressed in details with two case studies. First, the quadrupole focusing magnets with an adjustable strength feature were designed and produced for future ion collider and proton therapy. And second, the dipole magnets were developed for aerospace and commercial mass spectrometers. This paper introduces some design considerations and guidelines for the new state-of-the-art technology solution. Using finite element analysis (FEA), iterative optimization of the magnetic and mechanical design was completed. PM prototypes were built using rare earth magnets. The efforts were focused on magnetic alignment, physical alignment, and field gradient error. The magnetic field measurement was conducted and compared with FEA data.

2. Quadrupole Magnets for Future Ion Collider

Accelerator science is not only associated with large-scale national or international facilities dedicated to fundamental particle and nuclear physics experiments, but also widely accepted for electron, proton and ion beam accelerators in all aspects of science, technology and medicine. In a typical Fixed Field Alternating Gradient (FFAG) accelerator, a beam of charged particles is guided and focused using an electromagnetic field with a gradient. The PM quadrupole focusing magnets have in particular the potential to bring a paradigm change in accelerator technology since the field does not vary with time. A smaller, lighter accelerator system such as an FFAG-based design would facilitate an exponential reduction in initial construction costs. This dramatic price reduction could enable building more proton centers to treat cancer patients, non-invasive cargo scanning, practical accelerator driven sub-critical nuclear reactors and waste transmutation facilities [5][6][7][8]. In this study, we have constructed and tested a PM quadrupole prototype for non-scaling FFAG accelerators.

2.1.Magnetic design

There are 3 design goals in the magnetic design. The first goal is the field gradient (α) of 34.42T/m in the region of interest, at a radius 16.0mm, relative to the quadrupole axis (z-axis). The field quality of the PM for the beam optics of the cell is pure quadrupole. Therefore, the magnetic field at the median plane of the quadrupole is

$$B_x(x,0) = 0 \qquad (1)$$

$$B_y(x,0) = \alpha x \qquad (2)$$

where x is less than 15.2mm.

The second design goal is the field gradient error ≤ 10^3 within radius of 16.0mm. If there are non-zero magnetic multipoles, the field on the median plane can be expressed as

$$B_y(x,0) = \alpha x+\beta x^2+\delta x^3 \,..... \qquad (3)$$

The magnetic field gradient error can be caused mainly by the magnetic field alignment, mechanical alignment, magnetic material uniformity and magnetization direction. For instance, if the highest value of αx is 0.48T, the error field is calculated as

$$|B_{actual} - B_{goal}| \leq 0.48\text{T}/10^3 \qquad (4)$$

Finally, the last design goal is to minimize the alignment and gradient error during the magnet material production and assembly. Although field deviation may exist due to several reasons, such as magnetic and mechanical misalignment, active/passive shimming and/or mechanical tuning magnets are taken into consideration in the early stages of magnetic and mechanical design.

FEA tool (Opera®) was used for the magnetic design and optimization of the quadrupole magnet. The PM choice was EEC-N44SH grade with the minimum coercivity of 987kA/m (12.4kOe), which has enhanced resistance to demagnetization due to the radiation. The coercivity margin of individual magnet was also calculated by permeance coefficient. Fig. 1 shows the magnetic contour plot on the cross-section of 3D model to verify the magnetic field gradient and field harmonics. The harmonic coefficients are related to the azimuthal variation of the field components and it is ideal that the rest of harmonic coefficient is less than $1\text{x}10^{-4}$ of quadrupole coefficient for the accelerator applications.

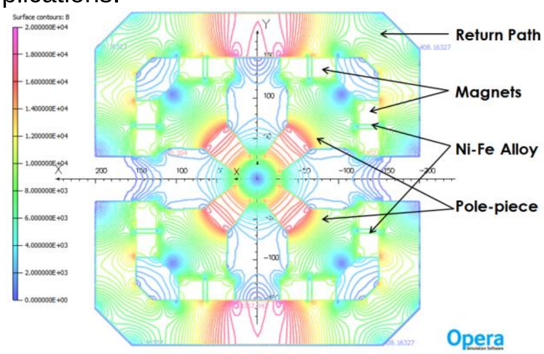

Fig. 1. FEA magnetic field contour plots on the symmetric cross-section of 300-mm long quadrupole magnet in the range of 0~2T.

2.2.Mechanical design

The magnetic field performance depends mainly on the symmetry of each quadrupole in terms of magnet strength, orientation, pole position and pole tip shape. Thus the mechanical design efforts were focused on the field harmonics. The innovation is 1) modular design for cost saving, and 2) adjusting mechanism of each modular magnet for field tuning. The modular magnet consists of PMs, Ni-Fe alloy, and pole-piece and its length is 100-mm. The dimension of module is determined based on the manufacturability and cost. The magnetic field tuning can be implemented by two ways: first, adjusting mechanically the pole tip position for a majority of field tuning, and second, applying the passive shims for a fine field tuning. There are two major advantages of the mechanical tuning method; 1) since the adjusting screws are connected to individual modular magnet, the housing design is capable of independent field-adjustment on each modular quadrupole. This helps to improve the magnetic field quality under manufacturing uncertainties. 2) The important functions of the housing are not only to retain the magnet assembly, but also to stack and align a number of modular sub-magnet assemblies. With alignment pins (not shown in Fig. 2), the single quadrupole magnet can be stacked using a fixture.

Fig. 2 describes the 3D computer-aided design (CAD) of quadrupole magnet assembly. The overall dimensions are 514x500x300mm and its weight is ~470kg (1,050lbs). According to the magnetic design results, the attractive force between top and bottom magnet assemblies is estimated as 5,500N (1,236lbs), which was taken into consideration to design the mechanical fixture through the mechanical stress analysis using Solidworks® simulation. The gravitational effect was also considered for calculation. The weight and volume were minimized through the optimization.

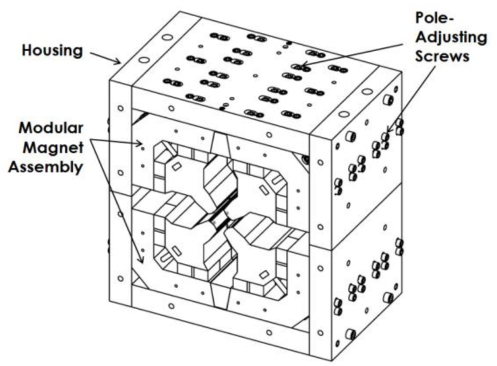

Fig. 2. Mechanical 3D CAD drawing of 300-mm long quadrupole magnet assembly.

2.3.Quadrupole magnet development

EEC's vertically integrated manufacturing capability and over 48-years magnet production experience enables us to implement a "fast prototyping" process and build 14 modules. Using wire EDM machines, the pole tip profile was precisely fabricated within ±25µm tolerance. The magnetic field data of each module were compared and 12 modules were selected for final 300-mm long quadrupole assembly.

2.4.Field harmonics test

After the quadrupole magnet assembly was complete, EEC performed the magnetic field measurement of field gradient and harmonics. The field gradient was measured using the real time data acquisition system and a 3D Hall probe mounted on the precision XYZ station with the resolution of 1µm (0.00004") as shown in Fig. 3. Fig. 4 displays the field gradient measurement of each pole and its average is 34.22T/m (vs. 34.42T/m of FEA estimate). The magnetic field harmonics were measured using a harmonic coil and its test setup is shown in Fig. 5. Faro® laser tracker helps to track the position of each quadrupole while adjusting the pole location mechanically. Table 1 summarizes the normal harmonics test data (skew harmonics is not included). The harmonics was measured up to octupole because a higher order is not meaningful. From Test 1 to Test 2, the adjusting idea was proved effective to lower the sextupole less than 10^{-4}. However the octupole didn't change due to the geometrical non-symmetry. Future work will focus to improve the symmetry by minimizing the imbalance of the poles.

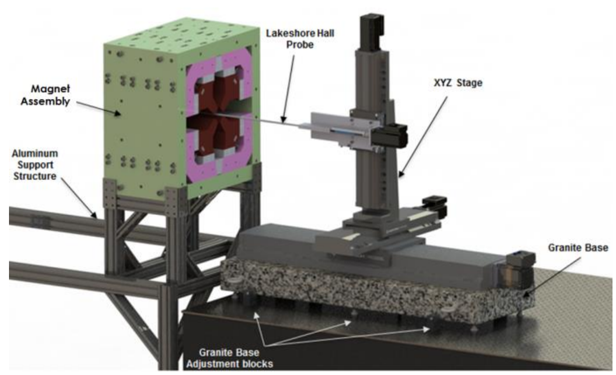

Fig. 3. Mechanical 3D schematic of quadrupole magnet test setup with a 3D Hall probe on precision XYZ station.

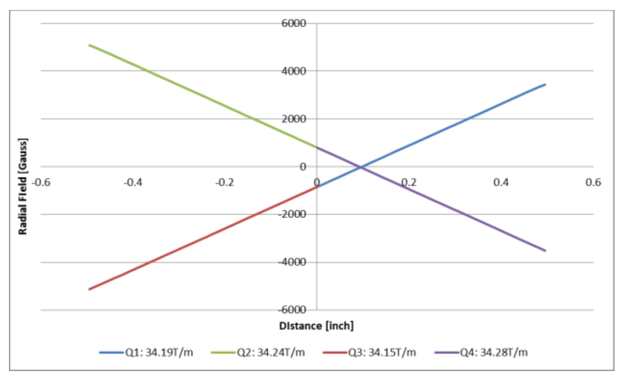

Fig. 4. Field gradient measurement of each pole from the center-axis to the pole tip proximity on the symmetric plane.

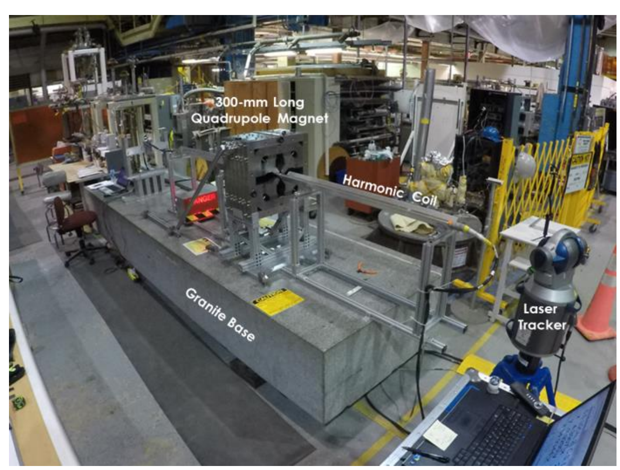

Fig. 5. Field harmonics test setup with harmonic coil and laser tracker mounted on the granite base.

Tab. 1. Normal harmonics test data comparison.

Harmonics	Test 1	Test 2
Dipole	0	0
Quadrupole	10,000	10,000
Sextupole	3.14	0.74
Octupole	5.61	5.67

3. Dipole Magnets for Mass Spectrometer

The mass spectrometer is an instrument to measure the mass, or more correctly the mass-to-charge ratio, of ionized atoms or other electrically charged particles. Mass spectrometers are now used in physics, geology, chemistry, biology and medicine to determine chemical and structural compositions, to measure isotopic ratios, for detecting leaks in vacuum systems, and in homeland security. In general, in Fig. 6, a mass spectrometer consists of an ion source, a mass-selective analyzer (including PM/EM), and an ion detector. The magnetic-sector can be dipole or quadrupole. Here dipole mass spectrometers are discussed in details with two examples.

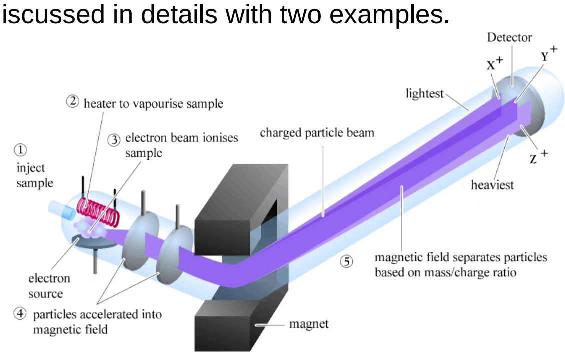

Fig. 6. Mass spectrometer schematic according to Lorentz Law [Source: http://www.chem.ucalgary.ca].

3.1. Mass spectrometer design

All commonly used mass analyzers use electric and/or magnetic fields to apply a force on charged particles (ions). The relationship between force, mass, and the applied fields can be summarized in Newton's second law and the Lorentz force law:

$$F = ma \tag{5}$$

$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{6}$$

where F, m, a, e, $\boldsymbol{E}$, $\boldsymbol{v}$, $\boldsymbol{B}$ are the force applied to the ion, mass of the ion, acceleration of the ion, ionic charge, the electric field, the ion velocity, & applied magnetic field, respectively. A charged particle moving with velocity v in a uniform, static magnetic field B follows a circular path in a plan normal to B. Equating the Lorentz force with the centripetal force, the radius R of the path of the particle's uniform circular motion is given by

$$qvB = F = ma = m\frac{v^2}{R} \rightarrow R = \frac{m}{q}\frac{v}{B} \tag{7}$$

Thus the field uniformity can determine the mass resolution and drifts in the calibration of the instrument. In practice, it is difficult to achieve very stable and spatially uniform magnetic fields, especially with PMs. The following examples describe the state-of-the-art magnet technology that was applied to overcome these challenges.

3.2.Mass spectrometer development 1

EEC and Duke University have collaborated to develop a miniaturized, low-cost mass spectrometer that can serve as an efficient and sensitive methane detector [9]. In Fig. 7-a, a novel and simple dipole magnet was designed using EEC-N50 grade magnet and its outer dimensions are 194x110x69mm. The entire assembly weight is approximately 8kg. According to FEA, the peak field is slightly larger than 0.3T and field strength varies less than 1% across a region 62x65mm in the middle of the ion travel region. To verify the simulations, the magnet assembly was fabricated and tested using a Lakeshore 460 Gaussmeter with 3-axis Hall probe mounted on the precision XYZ station (Fig. 7-b). Experimental and FEA data match closely. The design has proved promising to improve the imaging performance in a mass analyzer for a larger range of mass to charge ratios.

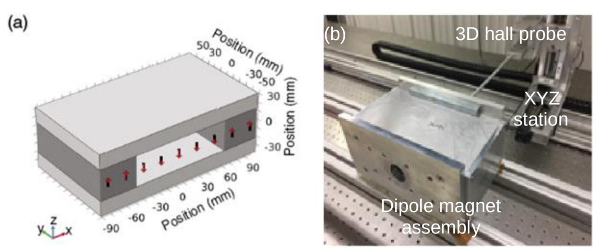

Fig. 7. (a) Dipole magnet model with arrows indicating the direction of the magnetic field, (b) magnet assembly test setup with 3D Hall probe and XYZ station.

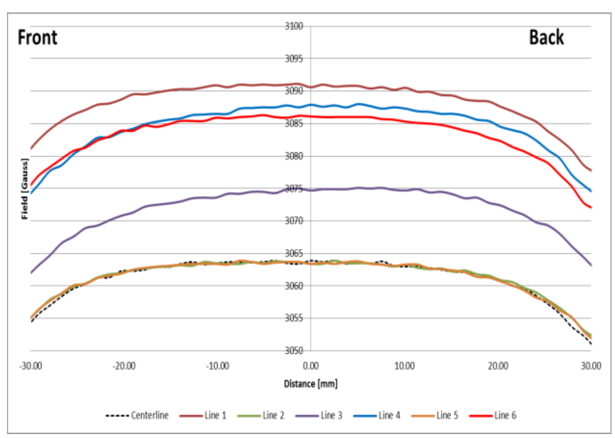

Fig. 8. Seven magnetic field data measured in the interested volume of 70x60x5mm with the average field of 0.3073T and homogeneity of 130ppm.

3.3. Mass spectrometer development 2

EEC has designed and developed another dipole magnet assembly (Fig. 9) for The National Aeronautics and Space Administration (NASA)'s Electron Spectrometer. It is used to capture the structure and dynamics of the electron precipitation causing rapidly varying auroral forms [10]. Using EEC SmCo 1:5-9 magnets and an optimized yoke profile from FEA simulations, it was feasible to achieve the linear field gradient of 0.2T/m along the symmetric plane with the maximum field of 0.0173T at a narrow gap. These results enable a large range of electron energies to be detected simultaneously from 200eV up to 30 keV as shown in Fig. 10.

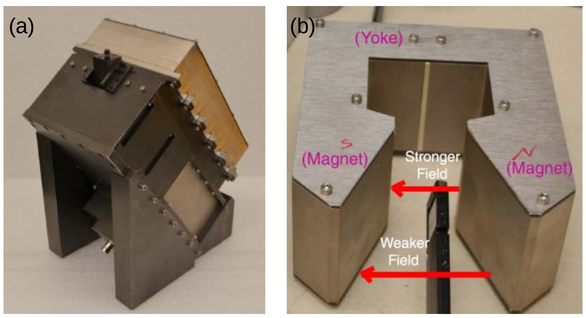

Fig. 9. (a) NASA mass spectrometer, (b) Dipole magnet assembly [10].

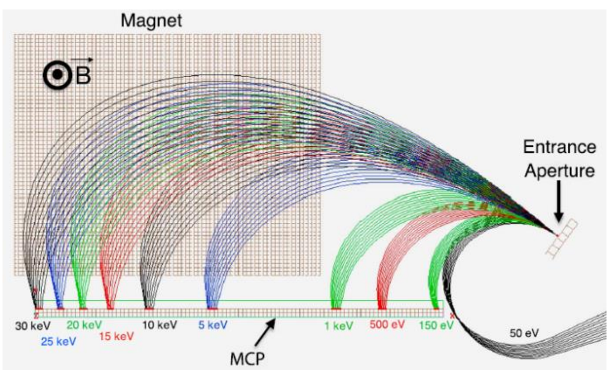

Fig. 10. Side view of the magnet assembly in a SimIon simulation, showing the electron optics for different energies through the magnetic field [10].

4. Conclusion

This paper provided the design guideline and demonstrated experimentally the state-of-the-art PM advanced technology and its feasibility in the medical and scientific applications, which has a significant potential to replace the EM requiring a high field quality and performance.

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