PERMANENT MAGNET BEAM TRANSPORT

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Abstract

Permanent Magnet (PM) quadrupoles, dipoles and other multipoles have been developed and used in an increasing number of accelerator applications for transporting and manipulating charged particle beams. Research applications include Drift Tube Linear Accelerators, Storage Rings, and Recirculators. Industrial applications include various accelerators for Isotope Production and Neutron Generation Accelerators. The inherent advantages and disadvantages of permanent magnet technology as well as practical implementation will be discussed. The possibility of new innovative applications for both research and industrial accelerators will also be discussed.

I. INTRODUCTION

Approximately 15 years ago the first iron-free ring type rare earth PM Quadrupoles (PMQ's) were constructed and installed in linear accelerators [1], [2]. Since that time, this technology has been implemented in an increasing number of beam transport applications. The fundamental theory for ring type PM multipoles was described by K. Halbach [3], based on anisotropic samarium-cobalt PM materials that were developed in the early 1970's. These new materials and design ideas led to several important developments of PM devices for beam transport and manipulation.

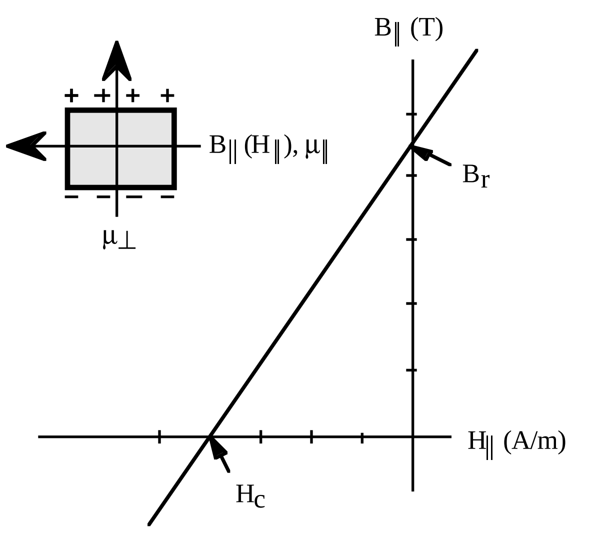

Figure 1: Anisotropic Rare Earth PM Materials

II. RARE EARTH PM MATERIALS

Subsequently, other important rare earth based materials have been developed, e.g. Neodymium-Boron-Iron. Figure 1 shows the idealized B(H) characteristics for these types of materials.

In these materials:

$$\mathbf{M} = \mathbf{B}/\mu_o - \mathbf{H}$$

If we make the assumption that:

$B_r/\mu_o = H_c$, then $|\mathbf{M}|$ = constant,

and for B_r = 1.0 Tesla, $|\mathbf{M}| \approx$ 8,000 Amp/cm.

Thus, the equivalent surface current flowing around the surface of blocks of these materials, as illustrated in Figure 1, is sizable, and it is no surprise that such blocks are difficult to position near each other or near other permeable materials.

Three different anisotropic PM materials may be considered for multipole design: Samarium-Cobalt, Neodymium-Boron-Iron, and Ceramic (Hard Ferrite). Table 1 below shows the range of magnetic properties which are available with these materials.

PM Material	B_r (kGuass)	H_c (kOe)	H_{ci} (kOe)	E_{max} MGOe
Sm_1Co_5	8.8 - 10.0	8.7 - 9.5	19.0 - 20.0	19 - 25
Sm_2Co_{17}	10.2 - 10.7	9.6 - 10.3	18.0 - 21.0	24 - 28
Nd-B-Fe	10.4 - 13.5	18.0 - 21.0	12.0 - 24.0	26 - 44
Sr-Fe-O	2.05 - 4.35	1.70 - 3.50	2.35 - 4.20	0.9-4.3

Table 1: PM Material Magnetic Properties

Several temperature characteristics of PM materials need to be considered in the design of PM devices. PM materials will undergo long term decay of their field strength, the decay amount and time constant being dependent on the specific material. This can be considered aging and may be avoided by "temperature stabilization" of the material. This consists of heating the magnetized PM material to a temperature greater than its highest operating temperature for several hours, which essentially pre-ages the material. Other important temperature characteristics of these PM materials are the reversible temperature coefficients of B_r and H_c which are different from each other and vary depending on the material. The reversible temperature coefficients of B_r and H_c in units of (% Change / °C) are shown in Figure 2. The coefficient of H_c for ceramic is positive, which uniquely creates concern for low temperature environments.

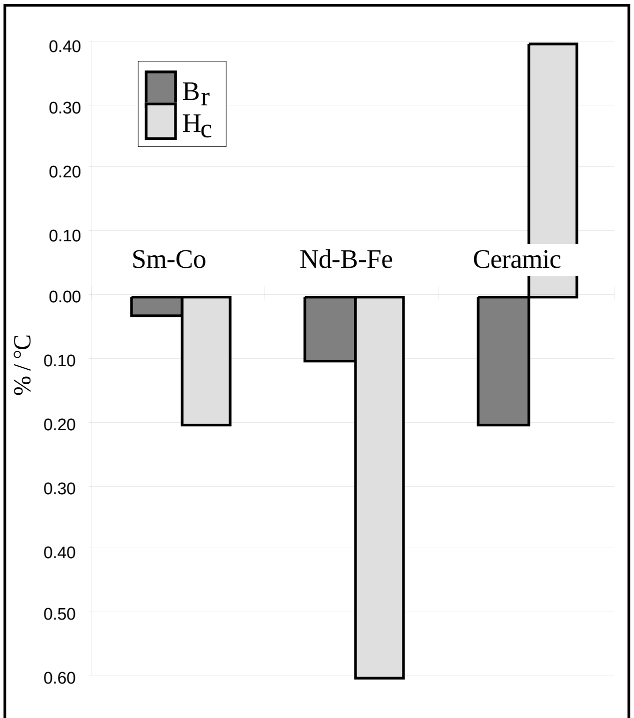

Figure 2: Reversable Temperature Coeffcients

The radiation damage resistance of PM materials has been investigated by several researchers, e.g. [4], [5]. For Ba-Fe-O ceramic PM materials, no damaging effects on magnetic properties are observed up to a integrated flux of 10^{18} neutrons / cm^2 (fast Epicadium neutrons, E > 0.5 eV). Samarium Cobalt PM materials show a similar resistance to damage, with Sm_2Co_{17} generally showing more resistance to damage than Sm_1Co_5 materials. Nd-B-Fe materials however show significantly less resistance to damage with noticeable effects observed at integrated flux levels of $10^?$ neutrons / cm^2. Results for rare earth based materials are, however, somewhat equivocal with the same alloy from different manufacturers showing quite different damage results.

The cost of PM materials varies greatly, depending on the specific material, the accuracy and amount of machining, and the quantity. The maximum energy product $(BxH)_{max}$ is a reasonable measure of effectiveness of the PM material in magnetic circuit design. Based on actual quotations that the author has received in the last year, Figure 3 shows the cost per unit volume ($ /cm^3) and the cost per unit volume-E_{max} ($ / cm^3-E_{max}). It can be observed from the figure that Ceramic and Nd-B-Fe overlap in their ($ / cm^3-E_{max}) values.

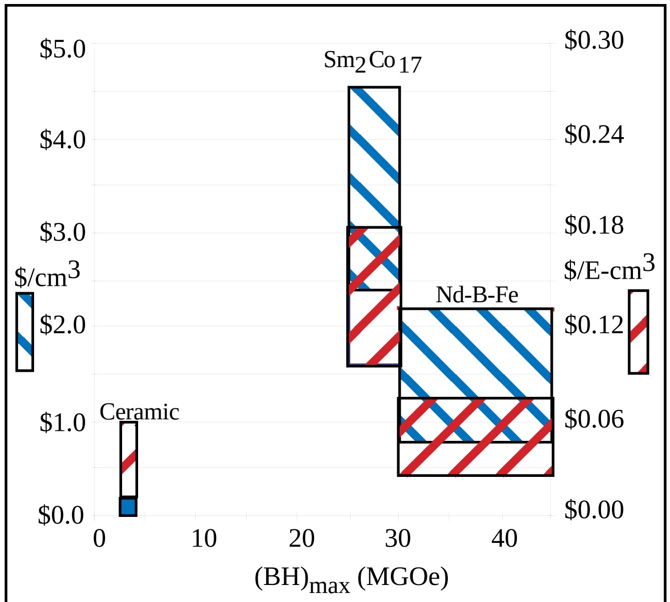

Figure 3: PM Material Cost

III. PM Multipole Applications

Although many applications of PM multipoles have been implemented, conventional electromagnetic multipole are still more widely used. The primary reason is the requirement for adjustable field strength. Although adjustability can be implemented in PM multipoles, in many other cases the reason that they are not used is unfamiliarity with and unavailability of the technology. The descriptions below show several easily and economically implemented examples of PM multipoles for beam transport.

The most widely adopted example of PM quadrupole (PMQ) technology is for beam focusing in the drift tubes of ion linear accelerators. Figure 4 shows the design of the 156 identical PMQ's which were produced for the SSC drift tube linac (DTL). These PMQ's have a gradient of 133 T/m and integrated strength of 4.64 T. Their cost was relatively high due to their high strength requirement and low allowable error harmonics, coupled with the compact design. The PM blocks are positioned in a "zero clearance" assembly and the outer housing is a press fit aluminum ring. This design requires PM blocks with 5 different orientations manufactured with very high mechanical and magnetic precision. Tuning is

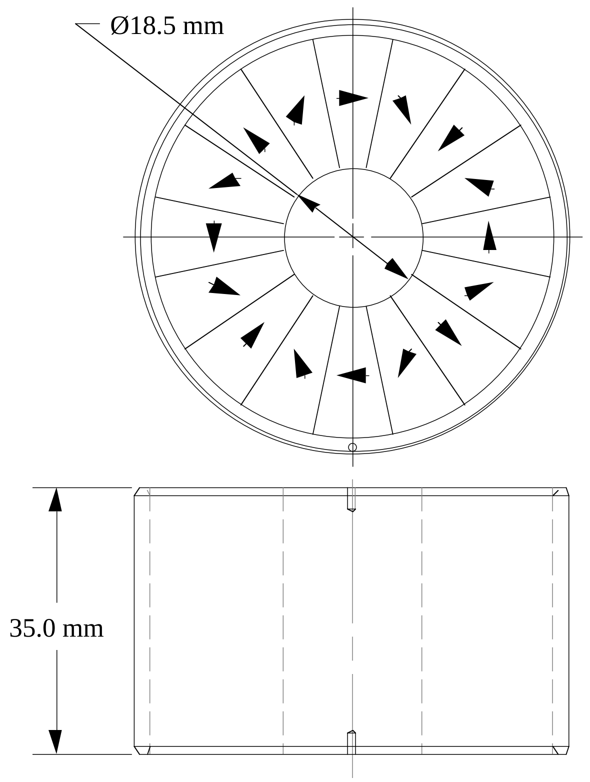

Figure 4: SSC DTL PM Quadrupole

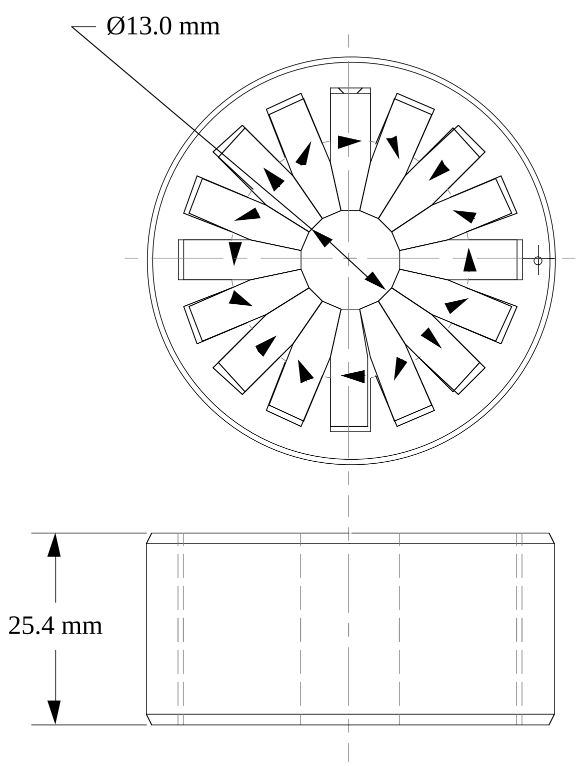

Figure 5: Low Cost PM Quadrupole for DTL

accomplished by machining the bore to reduce the error harmonics to the required values.

If the requirements for the DTL PMQ's are less stringent in terms of aperture, error harmonics and allowable physical size, a low cost design is possible. This approach is applicable for example in linear accelerators used for PET isotope production and neutron generation. Typical requirements for such PMQ's are a gradient of 157 T/m and integrated strength of 4.0 T. The design for such a PMQ is shown in Figure 5. The PM blocks are positioned in an aluminum spline and if tuning is required, adjustment may be accomplished by either machining or mechanical displacement of the PM blocks.

The "Small Recirculator" experiment presently underway at the Lawrence Livermore Laboratory [6], is designed incorporating PM quadrupoles. The requirements for these PMQ's leads to a design which is perhaps the lowest cost possible. The required integrated strength is 0.93 Tesla and the design utilizes 8 PM blocks with only

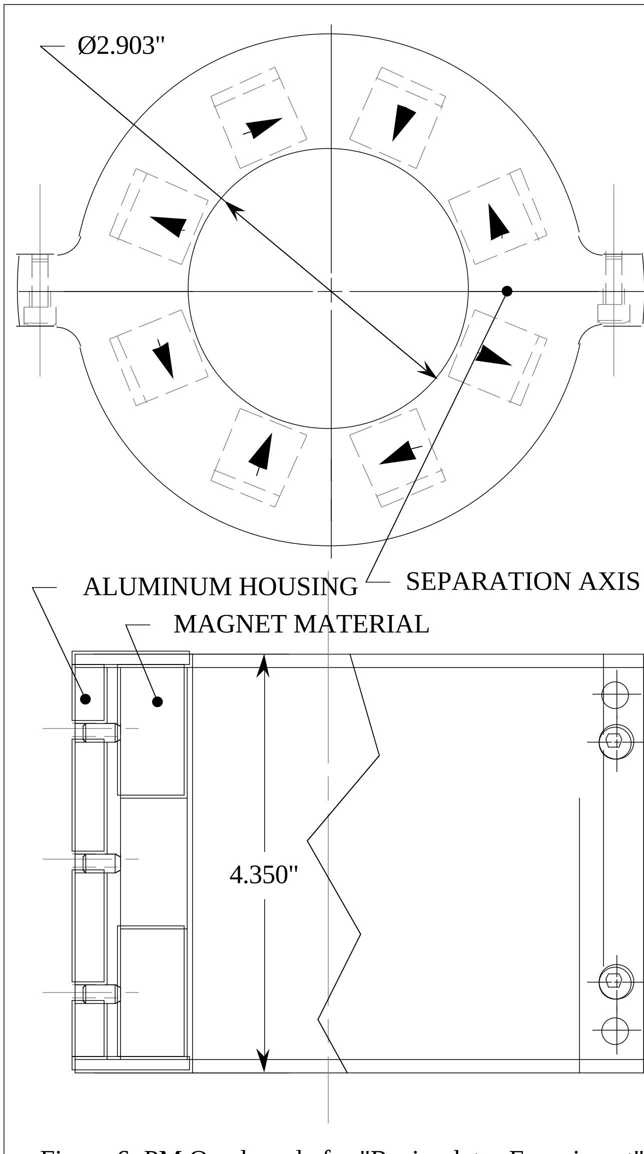

Figure 6: PM Quadrupole for "Recirculator Experiment"

one orientation. The design for these PMQ's is shown in Figure 6. This design allows the quadrupole magnets to be split so that they may be easily be installed over the vacuum chamber.

The examples above describe iron-free ring quadrupole designs. A different approach is usually appropriate for the design of dipole magnets for charged particle beam bending. Figure 7 shows a bending magnet that was designed for the SRL Tandem Cascade Electrostatic Accelerator for target switching at the output of the accelerator. This magnet has a field strength of B_o = 3.6 kGauss and an effective length of 100 mm. The design incorporates a resistive coil for adjusting the B_o value by approximately ±25%. The disadvantage of such a hybrid PM / elecrto-magnet design is that the coil sees an effective air gap which includes the thickness of the PM layer, thus requiring considerably more power to excite a given ΔB_o than an electromagnet alone.

The entire magnet is designed so that it can be rotated about the beam axis, allowing beam switching between four different targets for the production of PET isotopes.

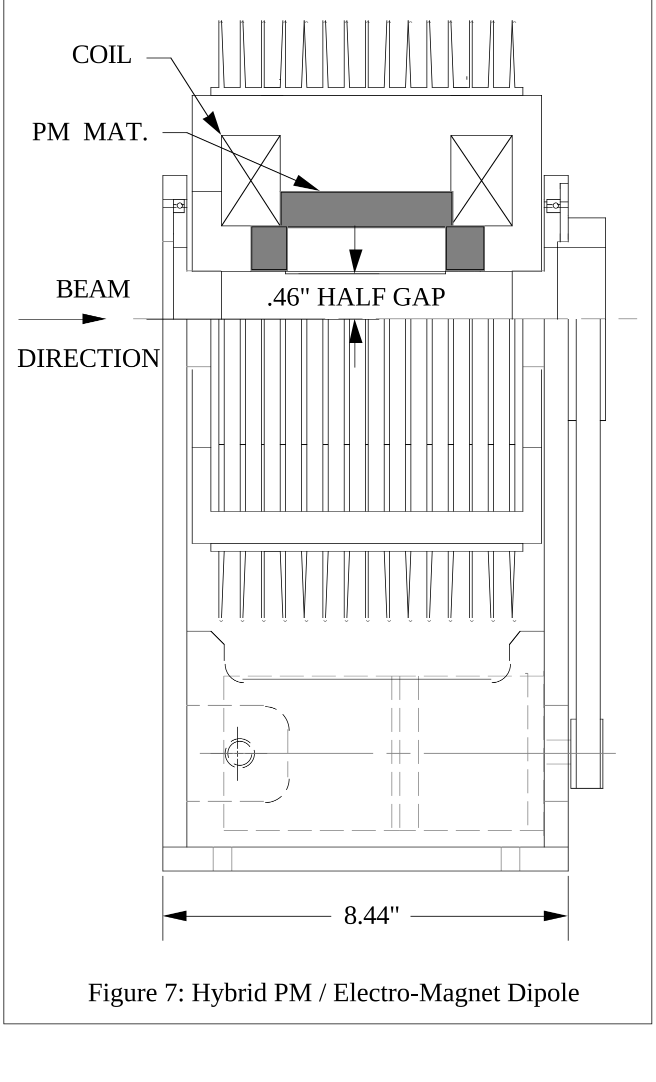

Figure 7: Hybrid PM / Electro-Magnet Dipole

IV. Planned PM Multipole Applications

Dr. S. Martin at the KFA, Jülich, Germany has designed a "Proton Pipe" which would be a low cost and efficient means of transporting a proton beam over a wide range of energies from 30 MeV to 200 MeV, [7]. The only adjustment required would be at the end for matching, and this could be accomplished with two triplets which could also be PMQ's, with the variables being the distance between elements. Figure 8 shows the beam radius and Beta X functions for a matched 70 MeV proton beam.

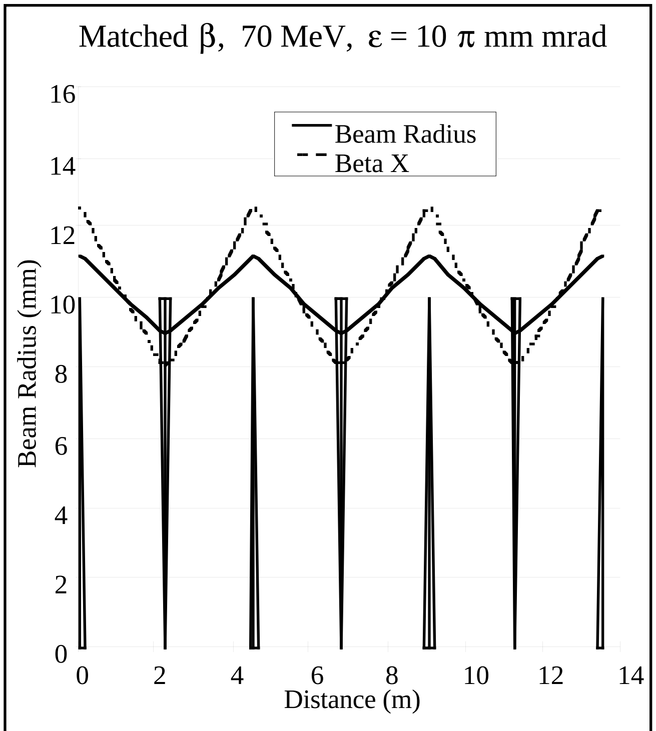

Figure 8: 70 MeV Proton Beam Pipe

The PMQ's for this Proton Pipe require a gradient of 1 Tesla/meter and a length of 25.4 mm. The distance between the F and D elements is 2 meters. A design for the PMQ's in this application is shown in Figure 9, which is based on Ceramic PM material. The cost of the quadrupoles in such a system is probably comparable with the cost of the vacuum pipe and vacuum system components.

As a another example of a planned new application, a very high frequency low current linac is being studied for proton radiation therapy. Quadrupole focusing would be provided by PMQ's located between multi-cell cavities in a 3 GHz RF structure. The problem for the PMQ design in this application is in the miniaturization of the magnet assemblies and the measuring system. Typical requirements for these PMQ's are a gradient of 200 Tesla/meter and a length of 40 mm. A diagram showing the proposed design and the scale is shown in Figure 10.

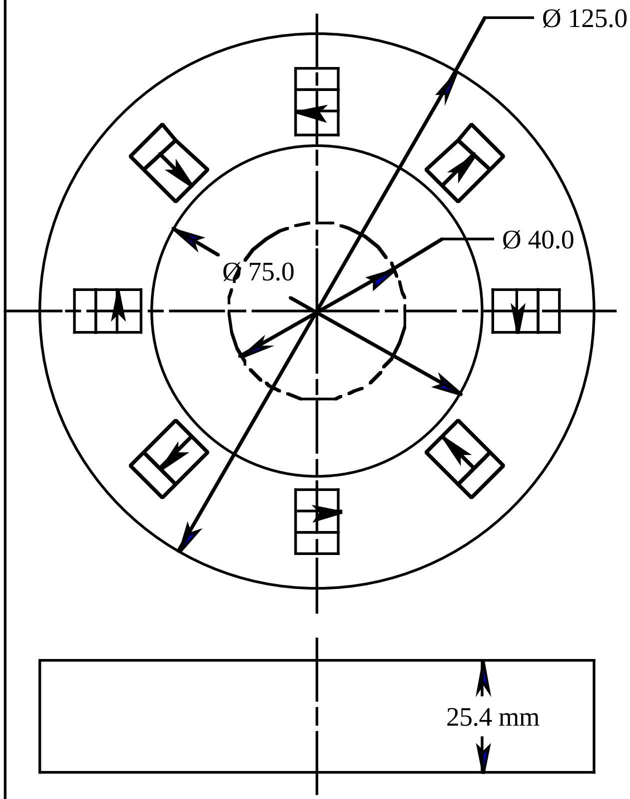

Figure 9: PM Quadrupole for Proton Pipe

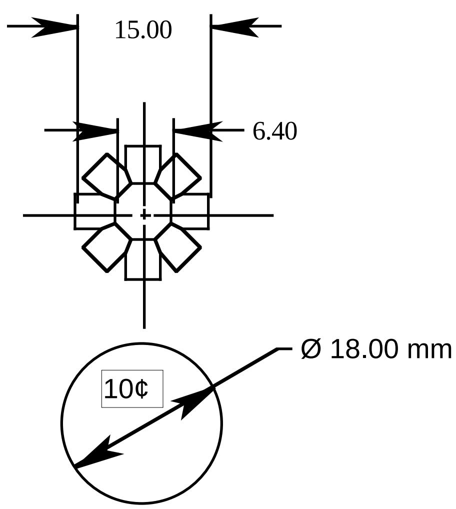

Figure 10: PM Quadrupole for 3 GHz Proton LINAC

V. REFERENCES

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