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# HYBRID RARE EARTH QUADRUPOLE DRIFT TUBE MAGNETS\*

K. Halbach, B. Feinberg, M. I. Green, R. MacGill, J. Milburn, and J. Tanabe University of California Lawrence Berkeley Lab 1 Cyclotron Road Berkeley, California 94720

#### Abstract

A prototype quadrupole permanent magnet with adjustable field strength has been constructed and tested. The magnet consists of iron pole pieces to provide the required field shape along with rare earth permanent magnet material (samarium cobalt) to energize the magnet. A unique feature of the configuration is the adjustability of the field by rotating the outer rings consisting of permanent magnets and iron. Magnetic tests show small field errors coming from well understood assembly details. Mechanical tests show the design needs further consideration to ensure reliability. It is planned to use this type of magnet in the SuperHILAC prestripper drift tubes.

## Introduction

Quadrupole electromagnets for a heavy ion linac provide a demanding application of magnet technology. The available space is severely limited by the size of the drift tubes and the magnets must be cooled not only to dissipate the heat generated by the energizing current, but also because of the strong radio-frequency heating. In addition, for a heavy ion linac such as the SuperHILAC where many different tors with masses up to uranium must be accelerated, the focusing field gradient must be variable with the maximum field gradient as strong as possible.

As the volume of a magnet becomes limited, a point is reached where permanent magnets can provide than higher field strength conventional а electromagnets. When the size of conventional magnets is reduced the current density in the coils must increase for the fields to remain constant, while for permanent magnets the magnetic fields do not change as the dimensions are scaled. If the magnet is small enough the crossover point will be reached, and permanent magnets will be stronger. Quadrupole magnets for Alvarez linac drift tubes have already crossed this threshold, and recent quadrupole electromagnet designs have required pulsed operation at low duty cycle to avoid the resistive heating problems due to the high current density operation.

An adjustable hybrid iron/permanent magnet quadrupole was constructed and tested to determine whether such a device would behave as predicted. The conceptual design has been described previously<sup>1</sup> and a brief summary follows.

## Magnet Principles

Conventional iron pole pieces are used to determine the shape of the quadrupole field. The region between the pole pieces is filled with the rare earth permanent magnet material. This material behaves as if it were injecting magnetic flux into or subtracting flux from each pole piece, as the arrows show in Figure 1, where the arrows refer to the easy axis of the permanent magnet material. A ring of iron

\*This work was supported by the Director, Office of Energy Research, Office of High energy and Nuclear Physics, Nuclear Science Division, U. S. Department of Energy under Contract No. DE-ACO3-76SF00098. surrounds the pole pieces, with permanent magnet material attached to the inner circumference of the ring. The ring pieces will either add to the flux in each pole piece as the figure shows, or by rotating the ring 90°, subtract from the flux in each pole piece. Two axially separated rings were used for the prototype magnet, with the two rings rotating in opposite directions to ensure that no net torque is introduced during rotation.



Fig. 1 Schematic of the hybrid REB quadrupole. Note that the outer ring represents two rotatable rings.

Figure 2 shows a photograph of some of the magnet pieces, including the polepieces and the rings. The field quality was measured for this magnet, and the error fields (in the form of multipole errors) are presented below. There are three sources of field errors for hybrid iron/permanent magnet quadrupoles. The fundamental ( $n\approx 2$ ) and the harmonics allowed by the 90° rotational symmetry (n=6, 10, 14, ...) are determined by the iron polepiece shape. Pole assembly errors form the second source of field errors, and contribute to errors in all of the multipole indices. These two sources of error are not unique to the hybrid iron/permanent magnet quadrupole, and are well understood from the standpoint of conventional magnet design.<sup>2</sup> Thus, the same principles used to design the quadrupole pole shapes and to determine the fabrication and assembly tolerances for conventional electromagnets can be applied to the hybrid magnets.



Fig. 2 Photograph of the prototype magnet assembly.

The only errors unique to the permanent magnet technology are those due to unequal excitation of the poles. These errors only introduce odd harmonics. In a conventional magnet pole excitation errors are avoided by wrapping equal numbers of turns around each pole and connecting these turns in series. For the hybrid Rare Earth Quadrupole (REQ) magnet identical pole excitation is achieved by precisely matching the strength of the permanent magnet material surrounding each pole tip. See reference 2 for a detailed study of errors in multipole magnets.

Errors due to unequal excitation of adjacent poles, such that opposite pairs of poles are equally excited, do not affect the field quality. This error configuration will only shift the value of the magnetic equipotential on the symmetry axis between the adjacent poles, and thus not affect the magnet quality. However, unequal excitation of opposite poles violates the 90° rotational symmetry and will therefore contribute odd harmonics to the field.

To minimize the unequal excitation of opposite poles the large blocks between the polepeices should be sorted such that, referring to figure 1, the excitation strengths of blocks 1 and 3 are matched and the excitation strengths of blocks 2 and 4 are matched. This means that given four blocks a.b.c. and d in ascending order of field strength, position 1 should be filled by block a, 3 by block b, 2 by block c, and 4 by block d. A similar method of sorting can be established for the blocks attached to the rotating rings. The permanent magnet blocks should be placed such that the difference in strength for pieces located 180° apart is minimized. This can be accomplished by sorting all the ring magnet pieces in ascending order and assigning neighboring pieces to positions 180° apart.

## Magnetic Measurements

Measurements were made of the field harmonics at the poletip radius for the prototype magnet. Only the odd harmonic measurements will be presented since these form the errors unique to the permanent magnet technology. For the first set of data the ring pieces were assigned arbtrarily. Curve A in figure 3 shows the odd harmonic content of the field for the maximum strength orientation of the ring. After the ring pieces were sorted according to the rules in the last section, the relative field errors for the important lower order harmonics were decreased, as curve B shows.





Figure 4 shows the third harmonic, normalized to the fundamental, as a function of rotation angle. This shows that the error fields change as a function of the field strength, but that the magnitude is quite small for all but the smallest fields. If many identical magnets were being made, as would be the case for a linac, the field errors should be substantially smaller than for this prototype because there would be a much greater selection of permanent magnet pieces from which to choose matching pairs. Figure 4 also shows the effective focusing strength, B'L, as a function of the rotation angle of the Note that the focusing strength increases rings. quite linearly with rotation angle after the initial 15°. For this particular magnet the ratio of maximum to minimum is only a factor of 1.5, but calculations show that a field ratio of three to one can easily be obtained if desired.





#### Mechanical Considerations

This prototype was cycled repeatedly to test its

reliability. For operation in a linac it is essential that no repairs be required that involve Ropening the linac or removing the drift tubes. Repairs of this nature would cost too much in terms of down time for a machine that must operate on a 24 hour per day basis. The actuating mechanism for the rings consists of two steel airplane control cables attached to a lead screw. This type of arrangement allows the drive motor to be mounted outside of the linac for easy replacement. The prototype was operated for 15,000 cycles, representing about six months of operation based on varying the field over its full range four times per hour and operating 24 hours per day, six days per week. Galling of the bearing surface between the rings and the main body of the magnet terminated this initial test. Polishing this surface allowed operation for a further 32,000 cycles, after which the mechanical tests were terminated. The overall mechanical design must be strengthened before use in a linac can be considered.

## Future Plans

Plans have been made for using this type of magnet in the SuperHILAC prestripper. The prestripper is an Alvarez linac used to accelerate ions with a charge to mass ratio varying from a high of 0.5 to a low of 0.055. This wide variation of charge to mass, needed to accelerate beams ranging from hydrogen to uranium, means that the drift tube quadrupoles must be adjustable. Operations are now limited by the current limits of the conventional quadrupoles. Since we have had some magnet failures, these current limits have been set to avoid further damage to the magnets.

Figure 5 shows a calculation of the present prestripper transmission as a function of length along the accelerator for a uranium beam.<sup>3</sup> The calculation assumes that the acceptance of the prestripper is flooded with beam, so the scale is arbitrary. Included in the calculation are the effects due to the damaged electromagnets that are operating at less than full focusing strength. The figure also shows the improvement to be expected by replacing the conventional magnets with hybrid REQ magnets. The hybrid magnets are assumed to have a maximum focusing strength of 7.4 I, 20% higher than our conventional magnets. Calculations show that this field strength can be achieved while remaining within the constraints of our present drift tube sizes and also allowing for a three to one adjustment



Fig. 5 Calculation of the prestripper transmission as a function of length for the present conventional electromagnet drift tube quadrupoles and for the hybrid REQ magnets.

ratio. As the figure shows, the transmission should go up by about a factor of 2 if the present magnets were replaced with hybrid REQ magnets.

Prototypes of the magnets to be used in the prestripper will be constructed. These are needed to ensure the mechanical viability of the concept, especially since the prestripper magnets are considerably larger than the present magnet and must therefore operate with much higher torque to actuate the rings. It is essential that the magnets operate reliably over many cycles, since access will be difficult once mounted in the linac. For this reason the mechanical design must be thoroughly tested over a simulated 10 year lifetime before magnets are installed.

## <u>Conclusion</u>

A prototype adjustable hybrid Rare Earth Quadrupole magnet has been built and tested. This magnet behaved as expected magnetically, with small field errors coming from well understood assembly details. These field errors are expected to decrease even further if many identical magnets are constructed, as is the case for drift tube quadrupoles in a linac. The mechanical details of this magnet need further consideration to ensure reliability over the lifetime of an accelerator. Plans have been made to design and construct prototypes of the magnets needed for the SuperHILAC prestripper. It is expected that installation of this type of magnet would increase transmission of the prestripper by up to a factor of two over present operation for the heaviest beams, such as uranium.

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