LACED PERMANENT MAGNET QUADRUPOLE DRIFT TUBE MAGNETS*

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Abstract

A laced permanent magnet quadrupole drift tube magnet has been constructed for a proof-of-principle test. The magnet is a conventional tape-wound quadrupole electromagnet, using iron pole-pieces, with the addition of permanent magnet material (neodymium iron) between the poles to reduce the effects of saturation.[1] The iron is preloaded with magnetic flux generated by the permanent magnet material, resulting in an asymmetrical saturation curve. Since the polarity of the quadrupole magnets in a drift tube linac is not reversed we can take advantage of this asymmetrical saturation to provide greater focusing strength. The magnet configuration has been optimized and the vanadium permendur poles needed in a conventional quadrupole have been replaced with iron poles. The use of permanent magnet material has allowed us to increase the focusing strength of the magnet by about 20% over that of a conventional tape-wound quadrupole. Comparisons will be made between this magnet and the conventional tape-wound quadrupole.

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 where many different ions must be accelerated, the focusing field strength must be variable and the maximum field gradient as high as possible. A laced permanent magnet quadrupole furnishes one solution to the problems of providing an adjustable high field strength magnet in a small volume.

The conceptual design of this type of magnet has been described previously.[1] In this paper we present a short review of the principles of the magnet and discuss its design and performance.

Magnet Principles

The basic features of the magnet are shown in Fig. 1. A conventional iron dominated magnet forms the basis for the laced quadrupole. The major change in the magnet is the addition of permanent magnet material between the pole-pieces.

Iron pole-pieces determine the shape of the quadrupole field. A conventional tape-wound copper coil energizes the magnet, however the coil starts at a larger radius than in a conventional quadrupole. The small radius region between the pole-pieces is filled with the rare earth permanent magnet material. This material is oriented to inject magnetic flux into or subtract flux from each pole-piece, as the arrows show in Fig. 1, where the arrows refer to the magnetization axis of the permanent magnet material. Note that the entire path for the magnetic flux due to the permanent magnets is contained in the iron. For infinitely permeable iron the magnets therefore do not add to the field in the aperture. They do add flux to the iron, however, and this flux is directed to cancel flux produced by the coil. The field in the iron is therefore reduced, allowing higher quadrupole gradients in the magnet before reaching saturation of the iron.

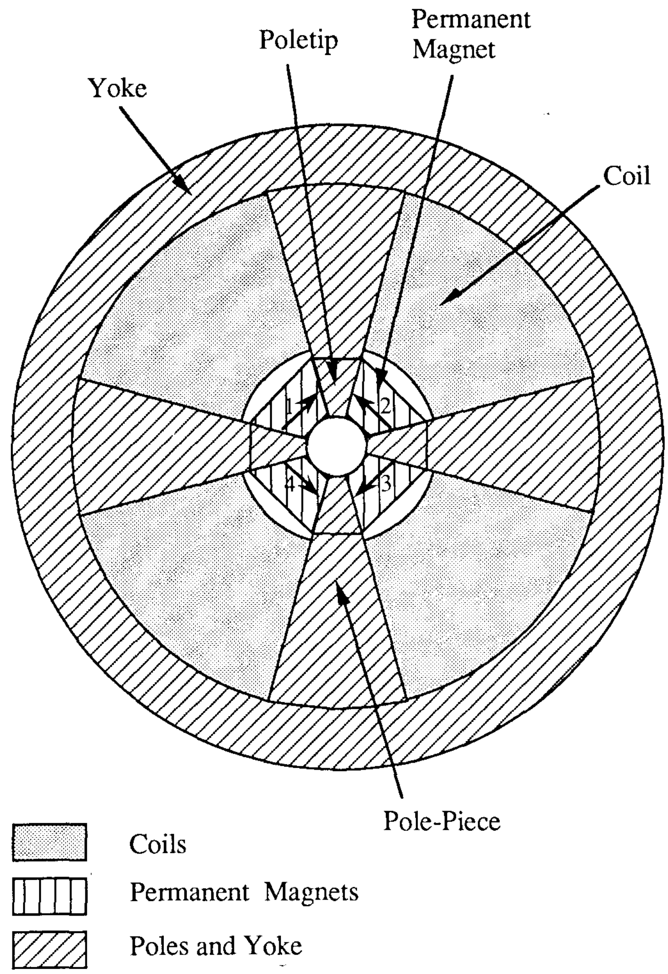

Fig. 1 - Schematic of the laced permanent magnet quadrupole. The poles are smaller and the coil starts at a larger radius than in a conventional quadrupole, leaving room for the permanent magnets between the poles.

Another way to view the effects of the permanent magnet material becomes evident when looking at the curve of focusing strength (B'L) versus current (I), shown in Fig. 2. The permanent magnet material preloads the iron so that the curve becomes asymmetrical with respect to the origin. The saturation point is pushed further from the origin for positive current, and closer to the origin for negative current. We can take advantage of this asymmetry in a drift tube linac where the polarity of the quadrupole magnets is never reversed.

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Design Considerations

The configuration of the laced quadrupole is optimized for maximum focusing strength, or B'L. Fundamental to the design of drift tube quadrupoles is the severe constraint on the size of the magnets due to insertion of the magnets into drift tubes. For the laced quadrupole, the length and outside diameter of the magnet cannot be increased over those of the conventional magnet since either type of magnet must fit into the same size drift tube. Given this constraint, we increase the focusing strength by increasing the current in the coil and by increasing the poletip length. The design changes that allow this are detailed below.

One major change is in the size of the polepieces. Reducing the flux in the iron allows the use of less iron in the polepieces, which allows one to use more copper per turn. The additional copper in each turn is critical to avoid overheating of the magnet. Since the permanent magnets reduce the saturation effects in the iron but do not directly increase the field gradient, an increase in the product of the current and number of turns (NI) is needed to achieve

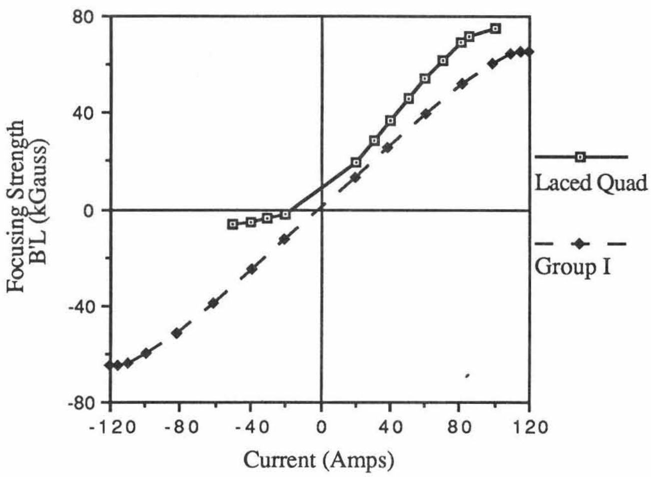

Fig. 2 - Focusing strength (B'L) as a function of current. The solid curve is for the laced quadrupole, and the dotted curve is for an equivalent conventional quadrupole.

higher strength quadrupoles. As the number of turns are actually reduced to make room for the permanent magnets, the current needs to be increased. The smaller polepieces allow more current per turn without increasing the current density in the copper.

Removing copper from the inner radius of the coil provides another significant advantage for the laced quadrupole. In the conventional magnet the coil comes as close to the aperture as possible, to allow for the maximum number of turns. Since the coil must completely surround the pole, the length of the polepiece is limited to the length of the window in the coil. As there is no coil in the central region of the laced quadrupole, the poletip can be lengthened, as shown in Fig. 3. This has the advantage of greatly increasing the focusing strength, which is the product of the field gradient and the effective length of the magnet, by increasing the effective length. Without the reduction in flux due to the permanent magnets, however, the polepiece could not be made in this shape because the short section located in the coil window would become saturated. Figure 4 shows the magnet assembled in the yoke. The permanent magnet pieces (not shown) fit between the poletips, almost completely filling the available trapezoidal space. They are the same length as as the poletips.

The addition of permanent magnets therefore allows the coil to run at higher currents, with reduced saturation, and with longer poletips than in a conventional magnet.

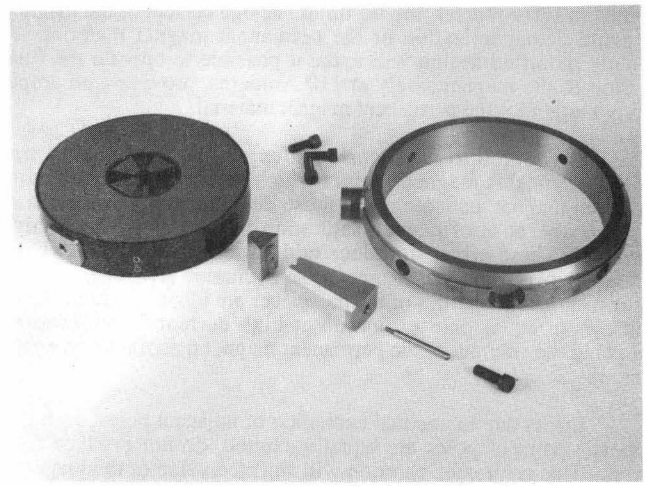

Fig. 3 - Photograph of the partially assembled laced quadrupole magnet. Note that the polepiece is composed of two sections with the poletip longer than the section surrounded by the coil. The copper coil is coated with epoxy to prevent shorts.

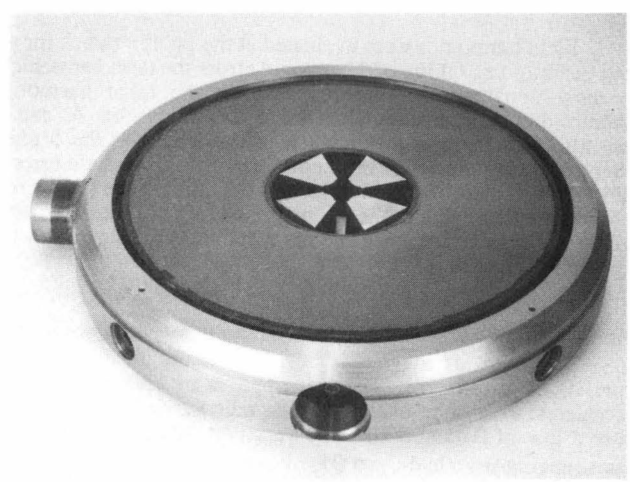

Fig. 4 - Photograph of the laced quadrupole magnet. Permanent magnets (not shown) fill the space between the poletips. The shell of the drift tube would be welded to the yoke, and a bore tube welded to the shell, in a complete assembly.

Magnetic Measurements

The primary aim of this test was to verify that high focusing strengths could be produced with the laced quadrupole. Figure 2 compares the performance of this magnet with a conventional drift tube magnet of the same size. The maximum focusing strength of the laced quadrupole is 24% higher than that of the conventional quadrupole run at the same current. Operation of the magnet was limited to 100 Amperes, the maximum design current of the magnet, to avoid demagnetization of the permanent magnet material. A slightly modified design will make it possible to operate the final version of the magnet safely at 110 Amperes, providing an ample safety margin for the permanent magnet material.

In addition to the focusing strength, the field quality was measured for this magnet. Errors which can be more severe with the laced magnet technology are those due to unequal excitation of the poles because of uneven saturation in the polepieces at high currents. These errors introduce odd harmonics in the multipole fields. In a conventional magnet, pole excitation errors are avoided if the magnetic properties of the polepieces are identical. In the laced quadrupole equal pole excitation at high current is achieved by matching the strength of the permanent magnet material between the pole tips.

Errors due to unequal excitation of adjacent poles, such that opposite pairs of poles are equally excited, do not produce field errors. This error configuration will shift the value of the magnetic equipotential on the symmetry axis between the adjacent poles, but will not affect the magnet quality. However, unequal excitation of opposite poles violates the 90° rotational symmetry and contributes odd harmonics to the field. See Ref. 2 for a detailed study of errors in multipole magnets.

To minimize the unequal excitation of opposite poles the permanent magnet blocks between the polepieces should be arranged so that, referring to Fig. 1, the excitation strengths of blocks 1 and 3 are matched and the excitation strengths of blocks 2 and 4 are matched. For this test magnet no attempt was made to match the strengths of the blocks. If a large number of magnets were being constructed the blocks could be sorted in the order of strength and matched appropriately.

Field harmonics were evaluated at the poletip radius for the laced quadrupole. Of the odd harmonic errors the third harmonic is the most detrimental. Figure 5 shows the third harmonic, normalized to the fundamental, as a function of current. As can be seen, although there is an increase in this ratio for the highest current, showing the effect of unequal saturation, the field error is still much less than 1% for high current operation. The field errors at low current are due to the strong preloading of flux in the iron, and are not significant since the magnets are typically run in the upper half of their range.

Plans

This type of magnet is currently being installed 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, needed to accelerate beams ranging from hydrogen (H_2^+ is used) to uranium, means that the drift tube quadrupoles must be adjustable. Operations are now limited by the focusing strength of the conventional quadrupoles.

This quadrupole is designed to be the smallest of the different size magnets needed in the prestripper. The drift tubes at the entrance to the linac have the smallest aperture, and therefore benefit the most from the high focusing strength. Installation of this type of magnet in the prestripper is expected to result in a transmission increase of about a factor of two for the heaviest beams.[3] Twenty three magnets similar to the proof-of-principle magnet have been constructed, for installation in the entrance section of the prestripper during the summer and fall of this year.

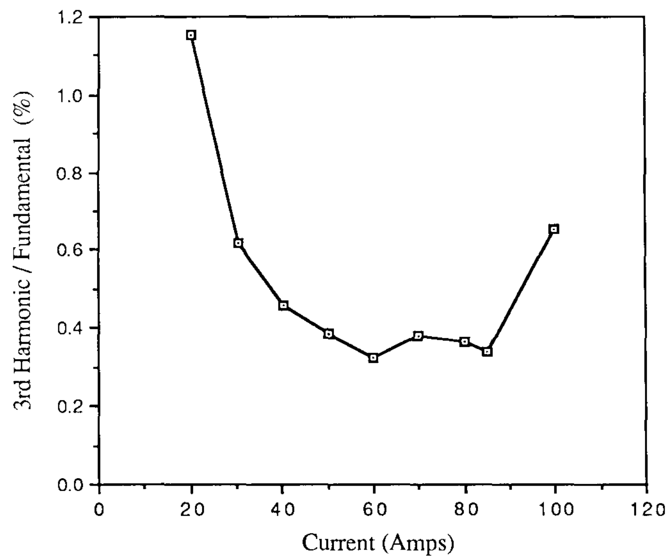

Fig. 5 - Graph of the ratio of the third harmonic multipole to the fundamental as a function of excitation current.

Conclusion

A laced permanent magnet quadrupole drift tube magnet has been built as a proof-of-principle test. This magnet behaved as expected magnetically, delivering more than the desired 20% increase in focusing strength over the conventional drift tube magnet. There was some indication of increased field errors due to the use of the laced permanent magnet technology, which should be alleviated by the proper sorting of individual permanent magnet blocks when several magnets are being constructed. This type of magnet is being installed in the SuperHILAC prestripper during the summer and fall of 1988. It is expected that installation of these magnets will increase transmission of the prestripper by as much as a factor of two over present operation for the heaviest beams, such as uranium.

Acknowledgements

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References

1. K. Halbach, "Magnet Innovations for Linacs", 1986 Linear Accelerator Conference Proceedings, June 1986, SLAC-Report-303 (1986) 407.
2. K. Halbach, "First Order Perturbation Effects in Iron-Dominated Two-Dimensional Symmetrical Multipoles," Nuclear Instruments and Methods, 74, 147 (1969).
3. K. Halbach, B. Feinberg, M.I. Green, R. MacGill, J. Milburn, and J. Tanabe, "Hybrid Rare Earth Quadrupole Drift Tube Magnets," IEEE Trans. Nucl. Sci., NS-32, 3643 (1985).