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LACED PERMANENT MAGNET QUADRUPOLE DRIFT TUBE MAGNETS*

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Abstract

Twenty-three laced permanent magnet quadrupole drift tube magnets have been constructed, tested, and installed in the SuperHILAC heavy ion linear accelerator at LBL, marking the first accelerator use of this new type of quadrupole. The magnets consist of conventional tape-wound quadrupole electromagnets, using iron pole-pieces, with permanent magnet material (samarium cobalt) inserted 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 individual quadrupole magnets in a drift tube linac is never reversed, we can take advantage of this asymmetrical saturation to provide about 20% greater focusing strength than is available with conventional quadrupoles, while replacing the vanadium permendur poletips with iron poletips. Comparisons between these magnets and conventional tape-wound quadrupoles will be presented.

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] and the performance of a proof-of-principle magnet has also been presented.[2] In this paper we present a short review of the principles of this type of 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 of the laced quadrupole. The fundamental 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 four small-radius regions between the pole-pieces are 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. Since the entire path for the magnetic flux due to the permanent magnets is contained in the iron, for infinitely permeable iron the magnets 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. This reduces the field in the iron, which allows higher quadrupole gradients before saturation occurs.

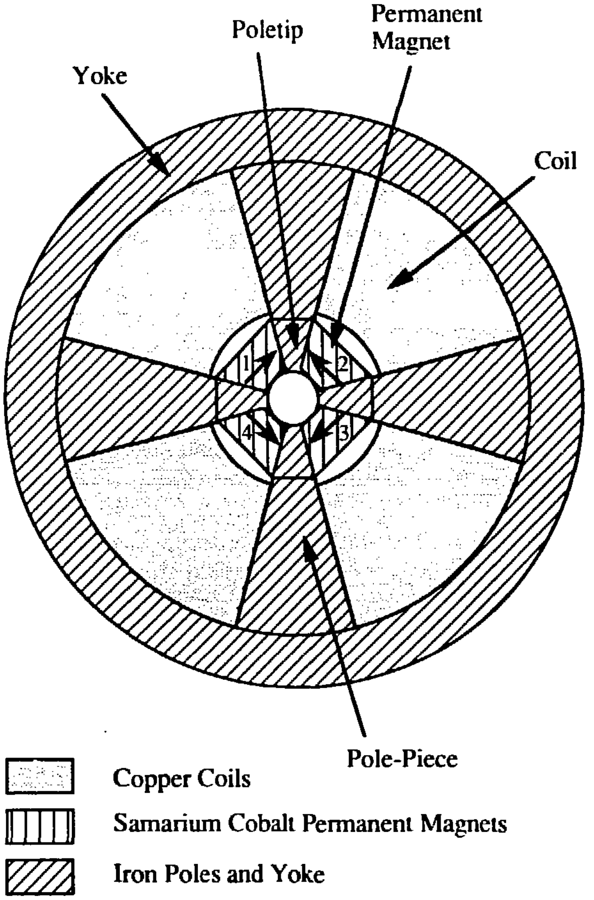

Fig. 1 - Schematic of the laced permanent magnet quadrupole. The poles are smaller and the coil starts at a larger radius than in a conventional quadrupole, leaving room for the permanent magnets between the poles.

The effect of the permanent magnet material is apparent in the curve of focusing strength (B'L) versus current-turns product (NI), 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.

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 magnet size due to the insertion of the quadrupoles 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-turns

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product 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 higher strength quadrupoles. The number of turns does not change much with this new design; turns near the center of the coil must be removed to make room for the permanent magnets, but the inner diameter of the yoke can be increased due to the reduced flux in the iron, leaving room for extra turns at large radii. The smaller polepieces allow more current per turn without increasing the current density in the copper.

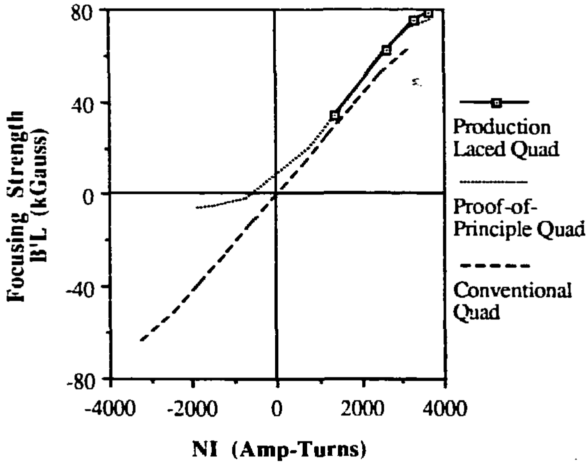

Fig. 2 - Focusing strength (B'L) as a function of current. The solid curve (with the data points) is for the production laced quadrupole, the dotted curve is for a proof-of-principle laced quadrupole (to show the asymmetry), and the dashed curve represents a conventional quadrupole.

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 minimize the saturation of the iron. 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 shorter section, located in the coil window, would become saturated. Figure 4 shows the assembled magnet. The permanent magnet pieces (with the arrows drawn on them) are located between the poletips, almost completely filling the available trapezoidal space. They are the same length as as the poletips.

Operation of the magnets was limited to 110 Amperes, the maximum design current of the magnets, to avoid demagnetization of the permanent magnet material. Rare earth permanent magnets behave in a linear fashion if the applied demagnetizing field is not too strong. If a critical value is exceeded, a permanent loss of strength will result. This can reduce the focusing strength of the magnet, and, even more importantly, can destroy the field quality as the loss is not uniform azimuthally. Samarium cobalt was chosen over neodymium iron, even though neodymium iron is linear at higher demagnetizing fields, because samarium cobalt has a higher Curie temperature, and is less sensitive to radiation. Care must be taken in the operation of the power supplies, however, not to exceed the maximum current.

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.

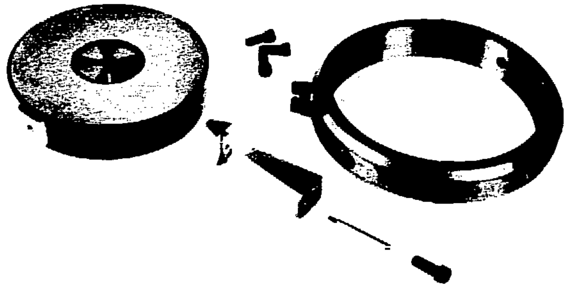

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Fig. 3 - Photograph of the partially assembled laced quadrupole magnet. Note that the polepiece is composed of two sections with the poletip longer than the section surrounded by the coil. The copper coil is coated with epoxy to prevent shorts.

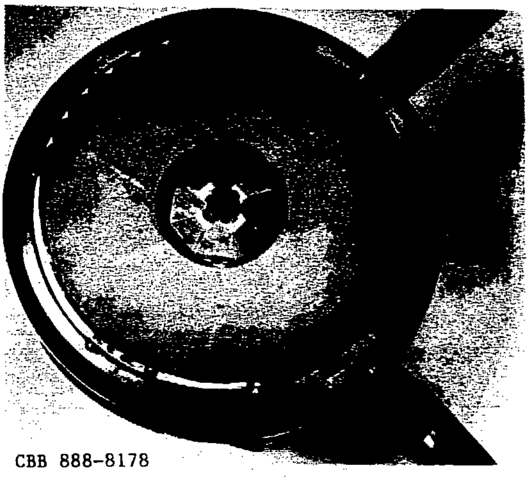

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Fig. 4 - Photograph of the laced quadrupole magnet. The diameter of the magnet is 10". Samarium cobalt permanent magnets (with arrows) fill the space between the poletips. The shell of the drift tube is welded to the yoke in a complete assembly.

Magnetic Measurements

The primary aim of these tests was to confirm the high focusing strengths of each of the laced quadrupoles, and to check the field quality of the magnets. Two groups (I and II) of magnets were made. Group I is shorter and has a smaller aperture radius (0.711 cm) than Group II (0.813 cm). Figure 2 compares the performance of one of the Group I magnets with a conventional drift tube magnet of the same size. The maximum focusing strength of a typical laced quadrupole is 19% higher than that of the conventional quadrupole run at the same number of ampere-turns, and 22% higher run at the same current.

In addition to the focusing strength, the field quality was measured for these magnets. 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, in addition to matching the polepiece properties.

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. 3 for a detailed study of errors in multipole magnets.

To minimize the unequal excitation of opposite poles the permanent magnet blocks between the polepieces were 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. The blocks were sorted in the order of strength and used in pairs on opposite sides of the magnets.

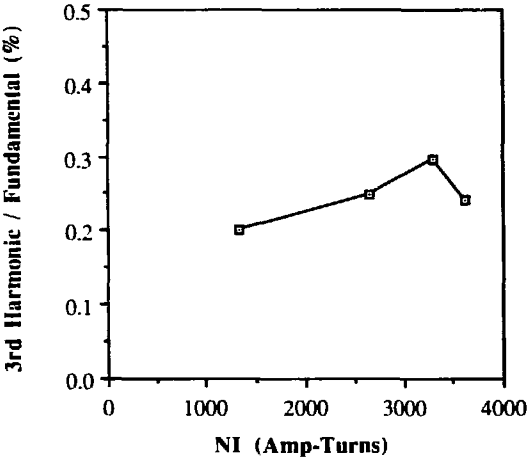

Fig. 5 - Graph of the ratio of the third harmonic multipole to the fundamental as a function of excitation current.

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, for a typical laced quadrupole. As can be seen, the field error is much less than 1% for operation at all currents in the normal operating range.

Accelerator Applications

Twenty-three of these magnets have been 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 (typically U^{13+}), means that the drift tube quadrupoles must be adjustable. Operations were limited by the focusing strength of the conventional quadrupoles. These quadrupoles replace the smallest two groups of prestripper magnets. The drift tubes at the entrance to the linac have the smallest aperture, and therefore benefit the most from the high focusing strength.

The installation of these magnets necessitated the installation of stem stiffeners in the linac. Each drift tube is held in place using two stems made of copper plated steel tubing, $1^3/_8$" in diameter and approximately five feet long, placed 90° apart. Figure 4 shows where the stems attach to the magnet yoke. The increase in poletip length, combined with the increase in field strength, resulted in forces between adjacent magnets sufficient to draw the magnets together. Stem stiffeners, consisting of two halves of steel tubing, four feet long and 2" in diameter, were copper plated and clamped to each stem of the first several drift tubes. This allowed the operation of the magnets at full focusing strength.

Installation of this type of magnet in the prestripper has resulted in a substantial transmission increase for the heaviest beams. While our operating schedule has not yet enabled us to precisely quantify the improvement, we have observed a substantial decrease in tuning time needed to achieve usable beam intensities.

Conclusion

Twenty-three laced permanent magnet quadrupole drift tube magnets have been built and installed in the SuperHILAC prestripper. These magnets performed as expected magnetically, delivering the desired 20% increase in focusing strength over the conventional drift tube magnet, with field errors in the same range as the conventional quadrupoles. The installation of these magnets has increased transmission of the prestripper by up to a factor of two over previous operation for the heaviest beams, such as uranium. This increase in transmission has substantially decreased the tuning time needed to get acceptable beam intensities, resulting in increased beam time on target.

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