TUNING PERMANENT MAGNETS WITH ADJUSTABLE FIELD CLAMPS*

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Abstract

The effective length of a permanent-magnet assembly can be varied by adjusting the geometrical parameters of a field clamp. This paper presents measurements on a representative dipole and quadrupole as the field clamp is withdrawn axially or radially. The detailed behavior depends upon the magnet multipolarity and geometry. As a rule-of-thumb, a 3-mm-thick iron plate placed at one end plane of the magnet will shorten the length by one-third of the magnet bore radius.

Introduction

Although it is inconvenient to alter the optical properties of a magnetic element formed solely of permanent magnets, in accelerator applications it is often desirable to do so. In particular, it may prove necessary to alter the strength of the element, that is, the gradient-x-length integral for a quadrupole or the field-x-length integral for a dipole. For instance, the achievable magnet-fabrication tolerance (typically 1%) may be insufficiently precise for the intended use; the optimum beam tune might require trial-and-error variation around the theoretically predicted parameters; or a change in particle type, energy, or current would force an alteration in element parameters.

It is possible to conceive of various techniques for adjusting permanent-magnet optical elements, each technique having its own set of advantages and disadvantages. At one limit of sophistication, a design has been proposed for a drift-tube quadrupole[1] that is continuously tunable, *in situ*, over a broad strength range, and a prototype has been constructed.[2] At the opposite limit, the magnet construction technique may permit one to shim the position of the magnet blocks, thus achieving a degree of adjustment at the cost of some disassembly. It is the purpose of this paper to point out that the strength of an element may also be decreased simply by end plates, formed of ferromagnetic material, that I refer to as "field clamps" because of their geometric shape and location.

Field clamps have several advantages in practice, particularly if only a one-time, modest strength adjustment is desired. First, the end-plate material may be added without disturbing the existing magnet. This is especially attractive in a large magnet, built from multiple blocks, in which shimming individual blocks may be difficult or even hazardous. The magnet need not be removed from the beamline if experimental measurements to determine clamp parameters were obtained prior to installation. Second, as a nonadjustable clamp consists of an iron washer and some aluminum spacers, it is simple to fabricate and install. An important feature in using field clamps is that it is unnecessary to design for their presence ahead of time; therefore, they may be added to existing magnets. Finally, one can conceive of various mechanical devices that permit one to alter the clamp geometry *in situ*, resulting in a continuously tunable magnet.

The major disadvantage at present is that the clamp geometry cannot be calculated, but must be determined experimentally. The clamp certainly alters the shape of the magnet fringe fields, which may be important in certain applications. In addition, in designing a tunable system, it may be necessary to deal with fairly significant forces.

Qualitative Effect of a Field Clamp

Halbach has discussed the radial[3] and axial[4,**] variation of the magnetic field outside the permanent-magnet volume. Consider a 2N-pole magnet constructed of M blocks; N = 1 for a dipole, N = 2 for a quadrupole, etc. The two-dimensional field radially outside the magnet has angular symmetry of degree (M-N). If a steel tube is placed around the magnet, the tube will be magnetized with this angular pattern. For instance, if M = 8 and N = 2, (M-N) = 6; the tube will produce 12-pole and will not affect the quadrupole field in the beam region. Therefore, a tube will not serve to alter the strength of an optical element constructed of permanent magnets. The tube will act as a shield, but because the field outside the magnet volume varies with a radius like $r^{-(M-N+1)}$, the fields are very small and the shield is necessary only in special cases.

In the axial direction, however, significant magnetic fields exist to a distance of the order of one magnet bore diameter beyond the end planes. A piece of iron placed in this region will affect the fundamental multipole N and all harmonics. (Harmonics can be adjusted by controlling the symmetry of the iron.) The iron has two effects on the field distribution. First, like any field clamp, it "cuts off" the axial extent of the field to a degree that depends upon the axial position and bore radius of the field clamp. Second, by providing a low-reluctance path, the iron partially "shorts" the closest permanent-magnet blocks and reduces the field generated by them in the magnet bore. Thus, an iron washer in one magnet end plane can reduce the magnet strength by more than 50%.

This paper presents experimental measurements of several clamp configurations on one quadrupole and one dipole. The results are widely applicable, however. The magnets are both constructed of eight square blocks, as shown in Fig. 1. All such magnets are geometrically similar. It follows that the results, expressed in dimensionless coordinates, will be valid for all magnets constructed with eight square blocks. All dimensions are expressed as multiples of the bore radius r_1 of Fig. 1. All strengths are expressed as a fraction of the value obtained with the field clamp removed. Further, results for a single magnet disc of axial length L can be transformed into results for a magnet constructed of any number of such discs and, thus, into results for a magnet of arbitrary length.

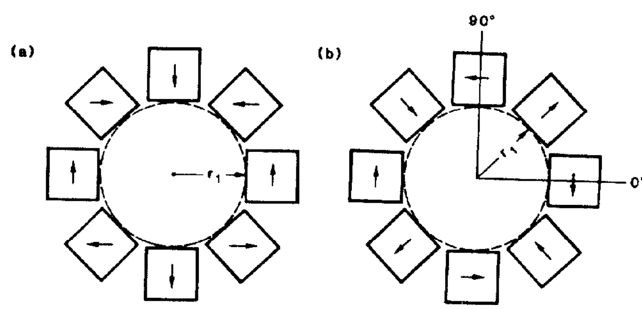

Fig. 1. Arrangement of eight, square, permanent-magnet blocks, showing easy axis of magnetization for (a) dipole and (b) quadrupole. The block inner radius, r_1, is used as a reference dimension in analyzing the experimental results.

Experiment: Quadrupole

The quadrupole magnet was constructed of eight $Nd_2Fe_{15}B$ blocks, 2.54 cm square by 1.27 cm thick, mounted in an aluminum holder so as to establish a block inner radius of 3.51 cm. Quadrupole strength as a function of field clamp parameters was determined by using a

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**Formulas for fringe fields from dipoles are given in unpublished lecture notes.

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spectrum analyzer to measure the voltage generated by a "Morgan[5] coil," radius 2.31 cm, rotating at 10.0 Hz. This arrangement also determined harmonic content.

The first experiment used a solid-steel washer 0.32 cm thick, with a 3.51-cm inner radius, and a 7.62-cm outer radius at one end of the magnet. Figure 2 shows the normalized magnet strength S as a function of the normalized spacing $Z=z/r_1$, where z was measured between proximal surfaces of the field clamp and magnet blocks. The field clamp is not quite thick enough and saturates at Z=0. Doubling the field clamp thickness further reduces S to 0.45 at Z=0.

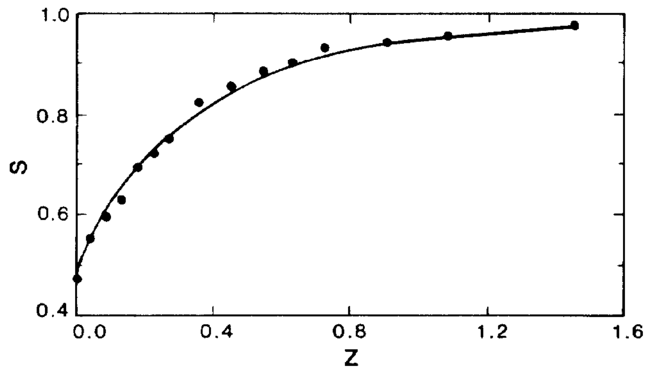

Fig. 2. Fraction of quadrupole strength vs normalized spacing of field clamp. Clamp is moved axially from one end of 1.27-cm-long magnet. Points are experimental data connected by a smooth curve.

The lowest "allowed harmonic" in an iron-free, eight-block, permanent-magnet quadrupole is n=10. The field clamp introduces duodecapole, n=6, familiar from conventional magnets with iron poles. Figure 3 shows the fraction of n=6 at radius 2.31 cm as a function of Z. The large values at small Z are also a result of saturation. The harmonic content can be controlled by removing iron at the field clamp i.d. at azimuthal positions 0°, 180°, and ±90° in Fig. 1(b). This also reduces the effect of the field clamp on strength, however.

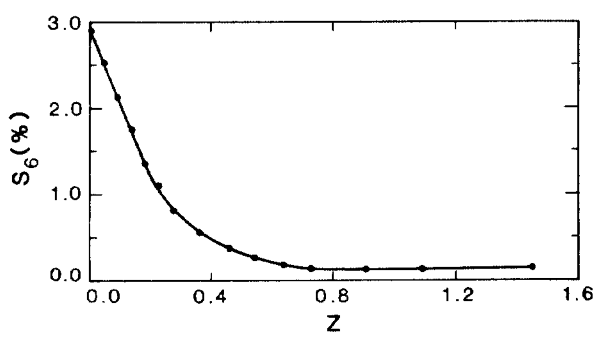

Fig. 3. Fraction of harmonic n=6 vs normalized spacing of field clamp. Clamp is moved axially from one end of 1.27-cm-long magnet. Points are experimental data connected by a smooth curve.

Although this experiment was performed on a single quadrupole disc 1.27 cm thick, it can be used to calculate the effect on a magnet constructed by axial stacking of multiple discs. With reference to Fig. 2, a washer at Z=0 reduces the strength of the nearest magnet disc to S=0.47. The next magnet disc, 1.27 cm from the washer, or Z=0.362, has its strength reduced to S=0.81, and so forth. In general, consider a magnet consisting of discs labelled from i=1 to i=I and a clamp at distance Z from disc i=1. The spacing between the clamp and disc i is

$$Z_i = Z + 0.362(i - 1) .$$

The strength of this disc is read from Fig. 2 as $S(Z_i)$, and the strength reduction is $[1 - S(Z_i)]$. The total strength reduction for the magnet assembly is

$$\Delta S = \sum_{i=1}^{i=I} [1 - S(Z_i)] .$$

The quantity ΔS=1.00 is equivalent to removing a length of 1.27 cm from a magnet with r_1 =3.51 cm. In general, the decrease ΔL in magnet effective length is

$$\Delta L = 1.27\, \Delta S\, (r_1/3.51)\ \text{cm} .$$

Figure 4 presents the quantity (1.27 ΔS) for a very long magnet. Figures 2-4 all refer to the effect of a single field clamp. The effects will be additive if a field clamp is used at both ends of the magnet.

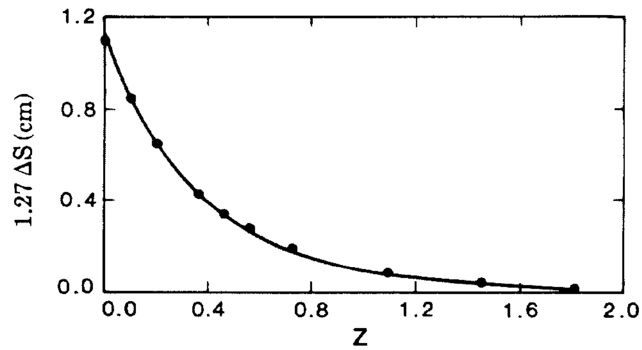

Fig. 4. Decrease in effective length of a very long quadrupole vs normalized spacing of field clamp. Curve calculated from data in Fig. 2.

The above calculation could also be performed to predict the n=6 component, using the data of Fig. 3. The fraction of n=6 becomes quite small as magnet length increases because of the rapid decrease in S_6 with Z.

In a second experiment, the above field-clamp washer was sawed into four, pie-shaped segments and mounted on a fixture so that the segments could be withdrawn radially. The apparatus is pictured in Fig. 5. The same quadrupole disc was employed as above. Figure 6 shows data for normalized strength S as a function of radial position R, again expressed as a fraction of magnet-block inner radius; R=1.00 corresponds to all segments inserted to a radius of 3.51 cm; R=2.00 corresponds to a further outward displacement of 3.51 cm. Because of the saw kerf visible in Fig. 5, the segments do not quite fill the entire

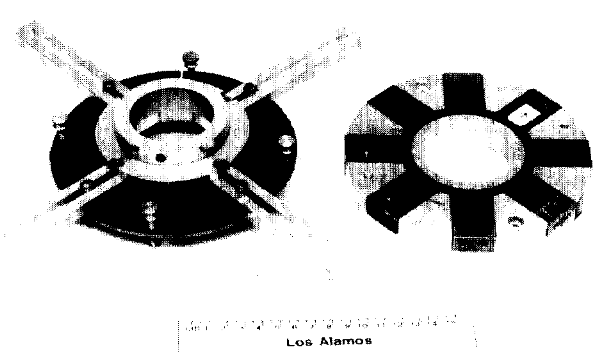

Fig. 5. Apparatus for determining effect of radial and angular clamp motions on quadrupole strength. The angular orientation pictured is that of the 0° curve in Fig. 6.

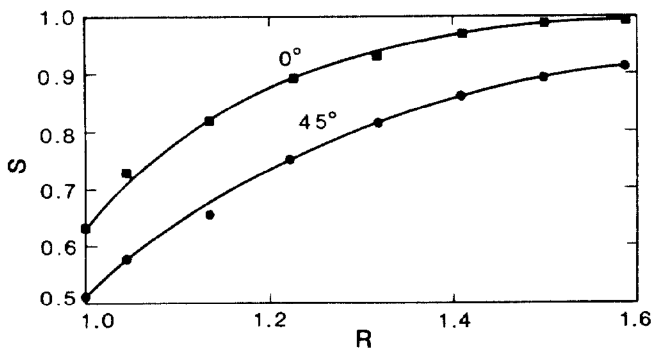

Fig. 6. Fraction of quadrupole strength vs normalized radial position of field clamp; two orientations of gaps between clamp pieces with respect to axes in Fig. 1(b). Clamp and magnet shown in Fig. 5.

ring at R = 1.0, and the S value is not as low as in Fig. 2. The gaps between the segments become wider as the segments are withdrawn, and there is some dependence of S on the orientation of these gaps. In Fig. 6, the curve labelled 0°, means that the gaps between segments occur at angles 0, 180, and ±90° as defined in Fig. 1(b). The curve labelled 45° means that the gaps occur at ±45° and ±135°.

Experiment: Dipole

The dipole magnet was constructed of eight blocks of $SmCo_5$, each 1.52 cm square by 1.27 cm thick, mounted with a block inner radius of 2.06 cm. The field-clamp washer was 0.32 cm thick with a 1.91-cm inner radius and a 4.45-cm outer radius. Dipole strength measurements were made using an integrating fluxmeter and a long, multiwire coil rotated 360° in the dipole field; harmonics were not measured. All data were corrected for the earth's field. Figure 7 shows the normalized dipole strength S as a function of normalized spacing Z. Spacing was measured between the proximal surfaces of the magnet blocks and field clamp and is expressed as a fraction of block inner radius. Some field-clamp saturation is evident at Z = 0. As for the quadrupole, these data can be integrated to provide a result for a magnet of arbitrary length.

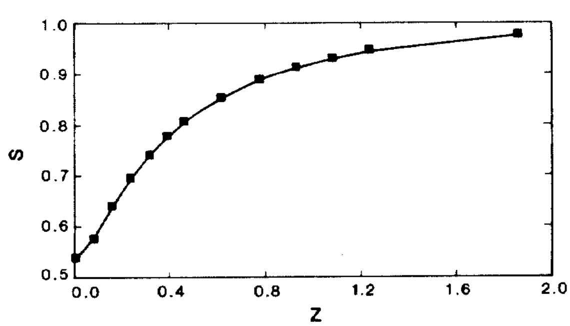

Fig. 7. Fraction of dipole strength vs normalized spacing of field clamp. Clamp is moved axially from one end of 1.27-cm-long magnet. Points are experimental data connected by a smooth curve.

Practical Example: Dipole

Recently, we were required to produce a bending magnet with a strength of 0.0160 T-m by axially stacking four of the above dipole discs. Further, it was required that the dipole strength over a cylindrical region outside of the magnet be as close as possible to the earth's field. This region was 1.9 cm in diameter, centered 10.0 cm from the magnet axis.

The solution was to enclose the magnet assembly in a steel cylinder, as indicated in Fig. 8. Tuning was accomplished by varying the diameter of the holes in the end plates and the axial position of the magnet inside the cylinder. The steel cylinder, with a wall 0.64 cm thick, has an ID of 8.89 cm that just slips over the OD of the magnet holders. The cylinder is 2.54 cm longer than the magnet assembly.

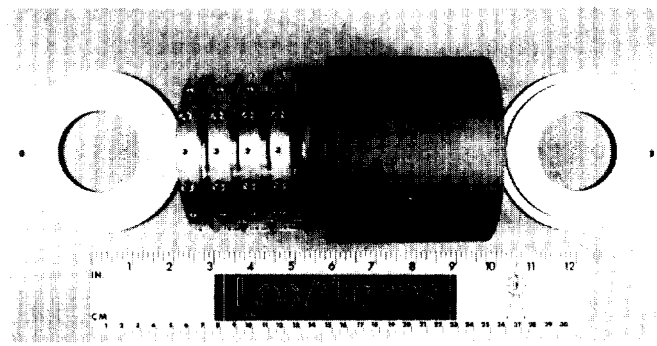

Fig. 8. Dipole with fringe-field shielding tube and end clamps.

The bare magnet assembly had a strength of 0.01738 T-m. With the magnet centered axially in the cylinder but without end caps, the strength increased to 0.01750 T-m. End caps with holes 3.81 cm in diameter reduced the strength to 0.01520 T-m. Finally, using end caps with holes 5.08 cm in diameter, the strength could be varied between 0.01638 T-m and 0.01602 T-m as the magnet was moved axially from center to within 0.32 cm of one end cap.

Summary

The strength of permanent-magnet dipoles and quadrupoles can be adjusted simply by the use of iron field clamps at the magnet ends. Critical clamp parameters are the ID and axial spacing, expressed in terms of the magnet ID. If the field clamp does not form a complete circle, angular orientation is important. Clamp thickness has a small effect under extreme conditions. Clamp OD is unimportant if it is larger than magnet-block OD.

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