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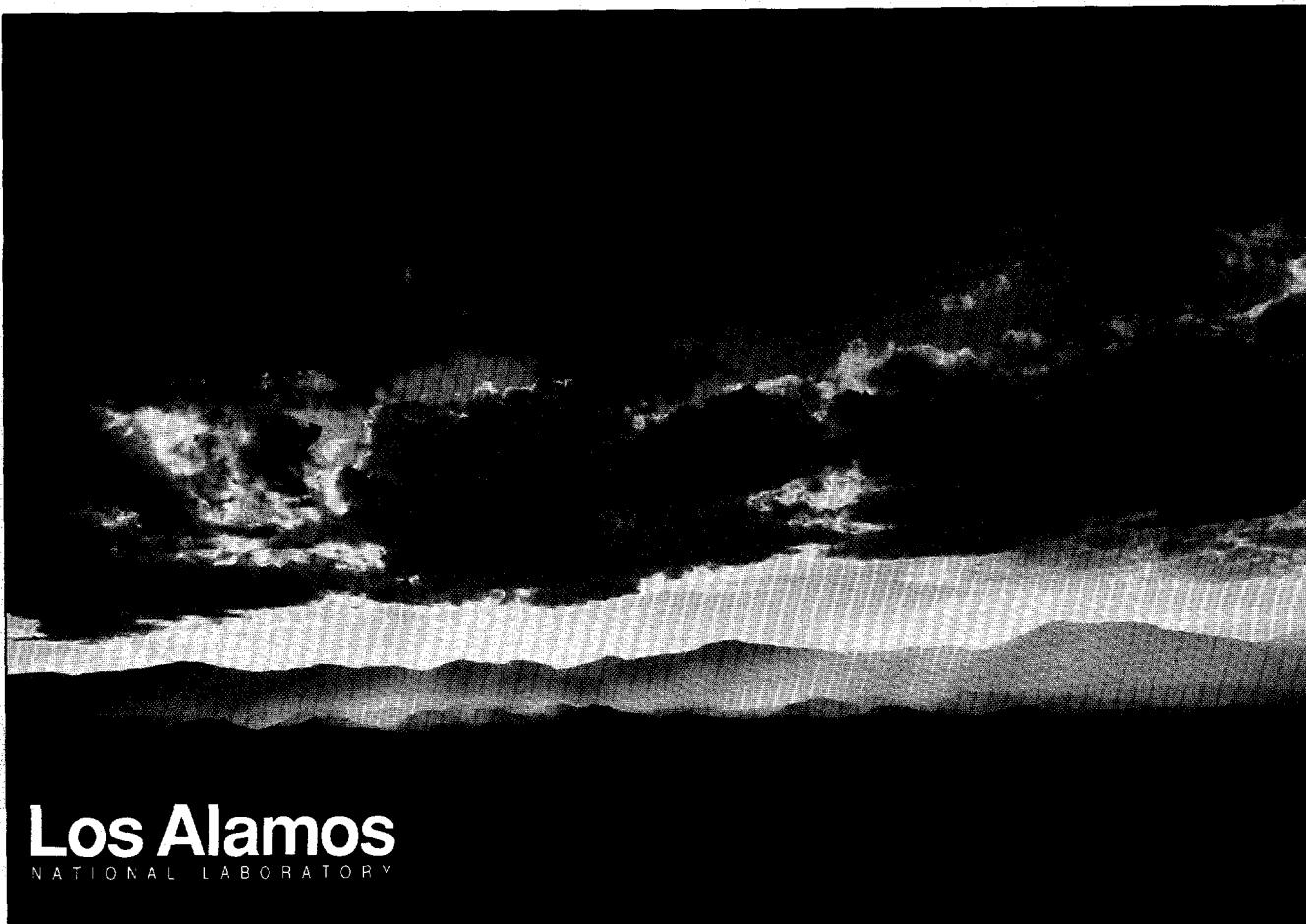
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MAGNETIC DESIGN AND MEASUREMENT OF NONLINEAR MULTIPOLE MAGNETS FOR THE APT BEAM EXPANDER SYSTEM*

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Abstract

Two prototype nonlinear multipole magnets have been designed for use in the 800-MeV beam test of the APT beam-expansion concept at LANSCE. The iron-dominated magnets each consist of three independent coils, two for producing a predominately octupole field with a tunable duodecapole component, and one for canceling the residual quadrupole field. Two such magnets, one for shaping each transverse plane, are required to produce a rectangular, uniform beam current density distribution with sharp edges on the APT target. This report will describe the magnetic design of these magnets, along with field measurements, and a comparison to the magnetic design.

1 INTRODUCTION

Static beam-expansion systems made up of a combination of linear and nonlinear magnets have been proposed for various accelerator-driven neutron sources such as the Accelerator Production of Tritium (APT) facility[1]. The static beam-expansion system proposed for APT accepts a nearly round Gaussian beam with a mean radius of a few millimeters and produces a 0.16 m by 1.6 m rectangular beam distribution on the target. Inside the rectangle, the current density is nearly constant, while outside, the current density drops off sharply to essentially zero. The nonlinear expansion is accomplished in a two-stage process. Quadrupoles and drifts are first used to produce a beam that is highly elongated in the y direction, with a waist in the x - z plane. The first nonlinear magnet is placed at this waist. The leading term in the multipole expansion for the central field of this magnet is an octupole term; the higher terms that are present modify the octupole behavior at larger distances from the axis. The effect of the first nonlinear magnet is to fold in the tails of the distribution in y - y' phase space, while leaving the x phase-space distribution substantially unchanged. The first nonlinear magnet is followed by quadrupoles and drifts that produce a beam that is elongated in the x - x' phase space, with a waist in the y - z plane. A nonlinear magnet at the second waist that is similar to the first one, but somewhat larger and rotated 90°, folds in the tails of the x - x' phase-space distribution. Finally, quadrupoles and drifts are used to produce the desired expanded beam size on the target.

As a test of this concept, two nonlinear magnets have been designed and built for use in a beam-expansion experiment using the 800-MeV proton beam of LANSCE.

2 FIELD DESCRIPTION

In initial particle-tracking simulations of the beam expander, the fields of the nonlinear magnets were described by truncated multipole expansions with a leading octupole term followed by higher order terms, i.e.,

$$B^* = B_x - iB_y = -ig_8 z^3 (1 + az^2 + bz^4 + cz^6), \quad (1)$$

where $z = x + iy$, g_8 is the octupole gradient, a adds a duodecapole component, etc[2]. The coordinates in Eq. 1 refer to the local magnet coordinates; they are the same as the beamline coordinates for the second nonlinear magnet and are rotated 90° for the first nonlinear magnet. Typical values of the parameters for the two magnets that gave good results for particle-tracking simulations of the 800 MeV beam expansion experiment at LANSCE are listed in Table I, along with the magnet lengths and clear beam apertures. Since the magnets are long in comparison to their apertures, a two-dimensional field description is entirely adequate for simulation purposes. The nonlinear magnets built for the experiment at LANSCE and planned for APT are variable-profile magnets for which Eq. 1 can be only an approximate description of the various possible field profiles. Indeed, apart from the leading octupole behavior and the fact that the field strength levels off to a value lower than a pure octupole field at larger x , there is nothing fundamental about the form of Eq. 1. From the point of view of the present beam-expansion scheme it is merely a convenient form to use for field-profile optimization. For the parameter values of both the LANSCE experiment and the APT design, contours of constant flux-density around the axis for the two magnets are oval-shaped and elongated in the same direction as the beam cross section. It would not be feasible to produce these fields with round-aperture magnets. Fortunately this is not necessary in view of the elongated beam profiles. Since the magnets have an aperture with a large width-to-height ratio, a single power-series expansion, e.g. Eq. 1, cannot

Table I
Field shape parameters, dimensions of the beam envelope, and length of the two nonlinear magnets.

Magnet	First	Second
g_8	$6.498 \times 10^4 \text{ T/m}^3$	$1.979 \times 10^4 \text{ T/m}^3$
a	$-1.847 \times 10^3 \text{ 1/m}^2$	$-7.072 \times 10^2 \text{ 1/m}^2$
b	$1.279 \times 10^6 \text{ 1/m}^4$	$1.876 \times 10^5 \text{ 1/m}^4$
c	$-3.936 \times 10^8 \text{ 1/m}^6$	$-2.211 \times 10^7 \text{ 1/m}^6$
beam height	3 mm	5 mm
beam width	25 mm	40 mm
length	500 mm	500 mm

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be used to describe the field over the entire volume occupied by the beam because the radius of convergence is limited to the distance from the origin to the nearest iron. Accordingly, a more sophisticated field description has been developed to parameterize the two-dimensional field in a way that can be used in particle-tracking simulations[3]. This field description uses a set of overlapping triangular dipole density distributions uniformly distributed on the surface of fictitious poles. The poles are planes of infinite extent and permeability and are located outside the beam envelope, but not substantially more than the minimum magnet gap. Weights for the triangle source elements are found by a least-squares fit to the field data.

3 MAGNETIC DESIGN

It is possible to design iron pole-piece magnets that produce a field that closely approximates the truncated power series of Eq. 1. for fixed parameter values g_8 , a , b , and c . The design approach is based on the fact that high-permeability pole pieces are very nearly contours of constant scalar magnetic potential. The scalar magnetic potential is the real part of the complex potential obtained by integrating Eq. 1, i.e.,

$$\Phi = -ig_8z^4 \left(\frac{1}{4} + a\frac{z^2}{6} + b\frac{z^4}{8} + c\frac{z^6}{10} \right), \quad (2)$$

Pole-tip profiles are obtained by choosing contours of constant real scalar potential that clear the beam pipe. Although the full plot of the scalar potential of Eq. 2 has 20 lobes, in practice only 8 lobes (two per quadrant) are needed for a practical magnet, since distant lobes affect the field inside the beam envelope negligibly. The ampere-turns required to excite the poles are obtained by dividing the respective scalar potentials by the permeability of free space. Unfortunately, an eight-fixed-pole magnet cannot be used if the parameters of Eq. 1 (or other field descriptions) are to be substantially varied by varying only the currents, since the constant-potential contours for one set of parameters do not coincide with the contours for another set of parameters. In order to allow field-profile variation, we have adopted a different design approach, employing twelve poles instead of eight in a variable-profile magnet that provides a range of leading octupole strengths and varying rates of departure from the octupole field at larger x . In the design of the 12-pole magnet, contours of constant scalar potential for the limits of parameter variation of Eq. 1 were plotted and initial pole-piece shapes that could, when appropriately energized, approximate the limiting contours were found. Flat pole-tip surfaces were used to simplify the modeling and fabrication of the magnet. The inner, middle, and outer poles were energized by inner, middle, and outer windings respectively. In finding the final pole-piece shapes, the midplane field was calculated for various combinations of currents with a two-dimensional finite-element code and compared with the desired range of field profiles. Since the

quadrupole component of field at the origin is supposed to be zero in the present expansion scheme, there are effectively two degrees of freedom in varying the field profile. The current in the inner winding required to null out the quadrupole field is very nearly a constant times the current in the middle winding and almost independent of the current in the outer winding. Incremental changes were made to the pole tip shapes until the difference between the desired and calculated fields was minimized over the width of the beam. The resulting cross section for the first magnet, including the conductors, is shown in Fig. 1. A comparison of the midplane field for the first magnet calculated with a finite-element code and the fields from Eq. 1 using the parameter values of Table I is shown in Fig. 2.

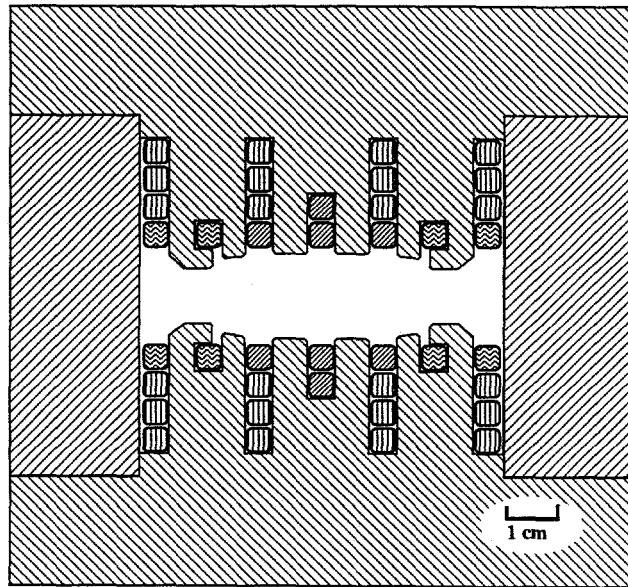


Fig. 1 Cross section of the first nonlinear magnet showing the inner, middle, and outer windings.

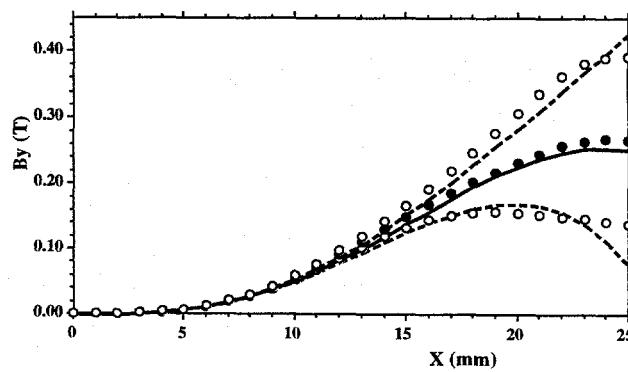


Fig. 2 Comparison of the desired and calculated midplane fields of the first nonlinear magnet for the nominal setting (solid curve and solid points respectively). Also shown are the desired and calculated midplane fields at the limits of the field profile variation (dashed curves and open points respectively). The normal field component (B_y) is antisymmetric in x .

The desired field shape of the second magnet was similar enough to that of the first that its pole-tip profile was simply a scaled-up version of that of the first magnet.

4 MECHANICAL DESIGN AND FABRICATION

Both the nonlinear magnets were built with the same mechanical design and fabrication procedures. The pole tip profile was machined by electron-discharge machining (EDM) followed by a light grinding of the pole tips and other critical dimensions to achieve the desired tolerance on the pole tip profile and spacing. Due to limitations in the EDM machining the 50 cm-long iron core was machined in two 25 cm-long segments. After machining, the two segments were aligned and held together by stainless steel strongbacks. Iron yokes were added on either side to maintain the spacing between the top and bottom halves of the magnets. As shown in Fig. 1 the first nonlinear magnet was wound with just 1, 3, and 1 turns of hollow-core copper conductor for the inner, middle, and outer windings respectively. The larger size of the second nonlinear magnet made it possible to quadruple the number of turns per winding. The windings were formed on a mandrel, fit into their respective spaces, and potted with epoxy. The corresponding windings in each quadrant were connected in series allowing the magnet to be energized by three independent power supplies.

5 MAGNETIC MEASUREMENTS

The central field of the first nonlinear magnet was measured at the Los Alamos National Laboratory (LANL) using a small calibrated Hall probe mounted on a three-axis measuring machine. Measurements were made of the normal field component in the midplane at the center of the magnet for the three windings energized separately as well as simultaneously. Some typical measurement results for the first nonlinear magnet are shown in Fig. 3. Also included in Fig. 3 are the results of the two-dimensional field calculations for the nominal current settings. The fields from the three windings energized separately were found to vary linearly with current. This linearity implies that, to a good approximation, the field with all three windings energized simultaneously equals the sum of the fields with the windings energized separately. Hence it is sufficient to characterize the field for the windings energized separately. In addition to the Hall probe measurements, the integral field of the first nonlinear magnet was measured at the Brookhaven National Laboratory (BNL) using a rotating coil system. The rotating coil was wound with tangential windings at a radius of 7.4 mm from the axis of rotation. The rotating coil measured the integral field as it was stepped in 3 mm intervals across the width of the magnet. These measurements provided a harmonic description of the magnetic field, from which both the integral of the normal and transverse field components could be calculated at any point of interest over the area measured. As shown in Fig. 4 the rotating coil measurements are in good agreement with the two-dimensional field calculations on and above the midplane.

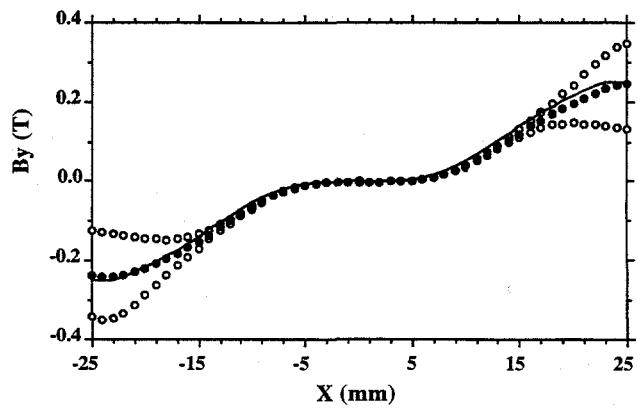


Fig. 3 Calculated and measured midplane field at the center of the first nonlinear magnet for all three windings at their nominal values (solid curve and solid points respectively). Also shown are the midplane fields measured at the limits of the current range of the outer winding, (open points).

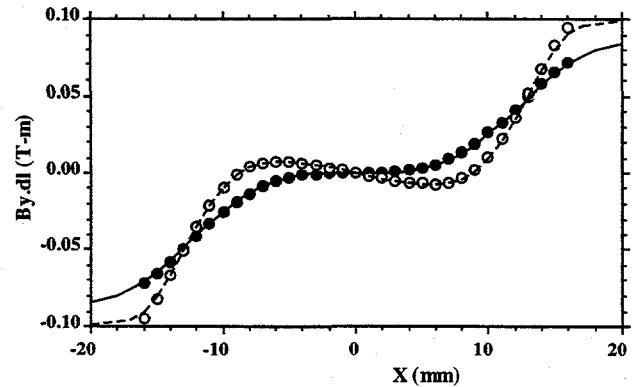


Fig. 4 Results of the rotating coil measurements of the first nonlinear magnet showing the integral field 5 mm above as well as on the midplane for a typical current setting (open and solid points respectively). Also shown are the integral fields for the same conditions estimated from the two-dimensional field calculations (curves). The integral fields were estimated from the two-dimensional results by multiplying by the 0.5 m length of the magnet.

The second nonlinear magnet was measured at LANL with a Hall probe and three-axis measurement machine with similar agreement between the measured and calculated fields.

6 CONCLUSIONS

Two nonlinear multipole magnets have been designed, fabricated and measured. The calculated and measured fields for both magnets were found to be in good agreement. The magnets are presently being installed in the first experiment at LANSCE.

7 REFERENCES

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