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A STUDY OF A 90° BENDING MAGNET FOR H^- BEAMS*

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Abstract

Three different magnetic pole face configurations with field indices $\neq 0$ have been studied to minimize second-order magnetic focusing aberrations. One pole face with a substantial second-order magnetic field inhomogeneity ($\beta = 1.14$) reduces the measured $A_1 = \partial^2\phi_f/(\partial\theta_f\partial y_f)$ aberration coefficient to zero. A calculation using first- and second-order ion optics provides a qualitative explanation for the aberration variations seen in these magnets. The pepper pot emittance measurement technique was used; although these measurements are sensitive to the A_1 term, they are not very sensitive to the $A_2 = \partial^2\phi_f/(\partial x_f\partial y_f)$ contribution.

Introduction

Previous emittance measurements[1] with a Dudnikov-type H^- ion source showed that a bow tie pattern existed in the y plane phase space. (See Fig. 1 for the coordinate system definition.) The x and y plane phase-space angles are θ and ϕ. Pepper pot measurements revealed a dominant second-order coupling of the form

$$\delta^2\phi_f = A_1\theta_f y_f \quad (1)$$

where the subscript f refers to the final (pepper pot) coordinates. Our goal is to examine how the A_1 and A_2 aberrations affect $\delta^2\phi_f$.

Experiment

Magnet Designs

To focus an extracted ion beam of 1 cm by 0.05 cm (emission slit size) into an approximately circular 1- to 2-cm-diam beam, a 90° magnet of central radius 8 cm and a field index of about 0.9 is used. Three different pole face shapes with the required field indices are outlined vs x in Fig. 1. Label I corresponds to the original pole face,[1] II corresponds to a design that yields $dB_y/dx \approx$ constant, and III is the pole face shape that empirically gives $A_1 \approx 0$. Field shaping is achieved by removing or adding metal in the range of the radii lengths from 8.5 cm to 11.4 cm. All pole faces are mounted on identical coil and yoke assemblies.

The field indices, $n = -(\rho/B_0)dB/dx$, derived from the field maps are also shown in Fig. 1. Solid lines for I and II are theoretical calculations from the POISSON[2] computer program that was used to determine the contour II. A smooth curve has been drawn through the case III data. Table I summarizes the field index parameter n and the second derivative $\beta = (\rho^2/2B_0)(d^2B_y/dx^2)$ for the three cases.

A Dudnikov-type ion source[3,4] provided a 1-mA dc H^- beam for these experiments. The ion source is mounted so that the extraction slit is at the entrance to the dipole field, thus introducing a small uncertainty in the correct treatment of magnetic field at this position.

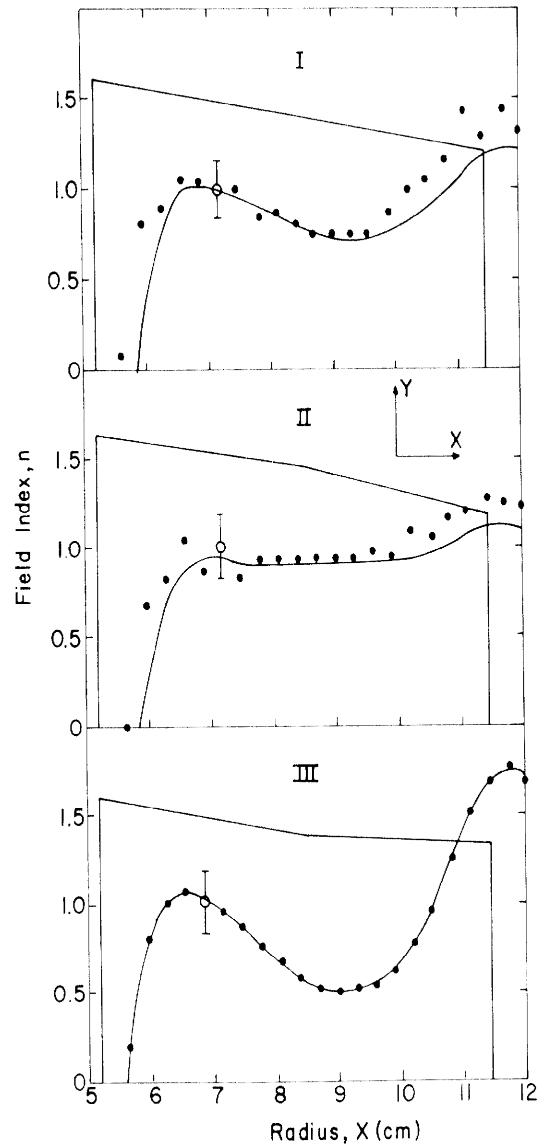

Fig. 1. Summarizes the measured field indices (n) vs the radial coordinate x. The pole face contours are also shown. Beam traverses the magnet in the x = 7 cm to 9 cm region. Representative error bars are shown for each case.

Pepper Pot Measurements

Pepper pot measurements were made on all three pole face configurations. A 13.2-keV H^- beam drifted 10 cm from the exit pole face edge to a pepper pot plate with 0.05-mm-diam holes spaced on a square grid with adjacent holes spaced 2.5 mm apart. Following the pepper pot plate is a 36-mm drift to a pyrex glass disk on which the beamlets burned a pattern. The strip appearance (see Fig. 2) is caused by the asymmetrical emission slit geometry. Angles and distances characterizing the pattern were then read directly from the glass using a microscope with a

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TABLE I

SUMMARY OF THE MAGNETIC FIELD PARAMETERS AND SECOND-ORDER ABERRATION COEFFICIENTS FOR THE THREE POLE FACE CONFIGURATIONS

Magnet	n	β	Experiment A_1 (mrad/cm)	Experiment A_2 (mrad/cm^2)	Theory A_1 K = 0.50 (mrad/cm)	Theory A_1 K = 0.36 (mrad/cm)	Theory A_2 K = 0.36 (mrad/cm^2)
I	0.88±0.04	0.67±0.06	0.20±0.01	7±5	0.15±0.03	0.17±0.03	0.1±1.8
II	0.93±0.03	-0.05±0.05	0.44±0.01	0±4	0.53±0.02	0.52±0.02	-23.4±1.6
III	0.71±0.03	1.14±0.12	0.0±0.01	10±5	-0.24±0.06	-0.17±0.06	21.0±3.9

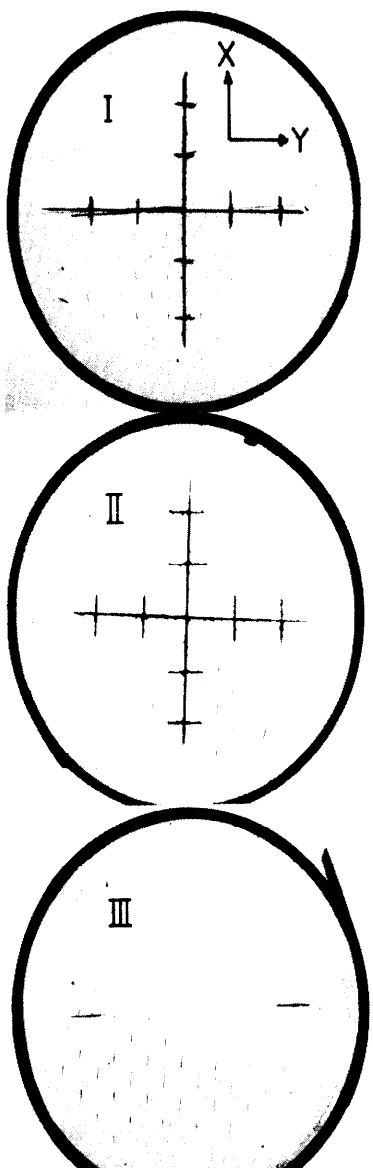

Fig. 2. Photographs of the pepper pot disks obtained from measurements with the three magnet poles. The large horizontal and vertical marks are scribe lines used to focus a camera; the vertical burn spots show $A_1 = 0$ for case III.

traveling base. Using this data and the pepper pot geometry we have derived second-order aberrations, emittances, and beam convergence-divergence properties. Experimental determinations of the A_1 and A_2 aberration coefficients are listed in columns 4 and 5 of Table I. The A_2 term is difficult to measure accurately from our pepper pot images and is extractable only with large errors. However A_2 apparently increases with β as A_1 decreases with β.

Results using pole face I were equivalent to those obtained in Ref. 1. The next experiment used the magnet pole face with $\beta = 0$ (case II). Pepper pot measurements showed that the A_1 aberration is about twice as severe as in case I. The case III pole faces were shimmed in an antipodal fashion to case II. Field mapping revealed this shape has the largest β of the three cases studied. Photographs of the three pepper pot disks are shown in Fig. 2 and the A_1 coefficient is seen to be virtually eliminated in case III.

Analysis

These experiments provide data on three sets of n and β. Calculations were made using second-order coefficients from TRANSPORT[5,6] that are transformed to expressions for A_1 and A_2 at the final coordinates corresponding to the pepper pot position, thus enabling a direct comparison with experimental results. (For our beam conditions, only ϕ is substantially affected by aberrations.) Expressions for A_1 and A_2 are then sums of products of the first- and second-order TRANSPORT matrix elements.

Theoretical results are given in the final three columns of Table I. Because A_1 and A_2 are linearly related[5] to β, these coefficients are derived conveniently from the theory in Fig. 3 using the known n and β values and the relations

$$A_1 = F + \beta G$$

$$A_2 = f + \beta g \quad . \qquad (2)$$

The quoted errors come from uncertainties in determining β from the field map data in Fig. 1. Two columns for the A_1 results correspond to K = 0.36 and K = 0.50 where K is the integral measuring the finite extent of the fringing field.[5] We evaluated K = 0.36 from experimental measurements of the fringing field along z. The K = 0.50 case is included to demonstrate the sensitivity of the calculation to this effect; every A_1 prediction agrees better with experimental results when K is reduced from 0.50 to 0.36. Both the A_1 and A_2 calculations follow the experimental trend with the A_1 predictions being in better agreement.

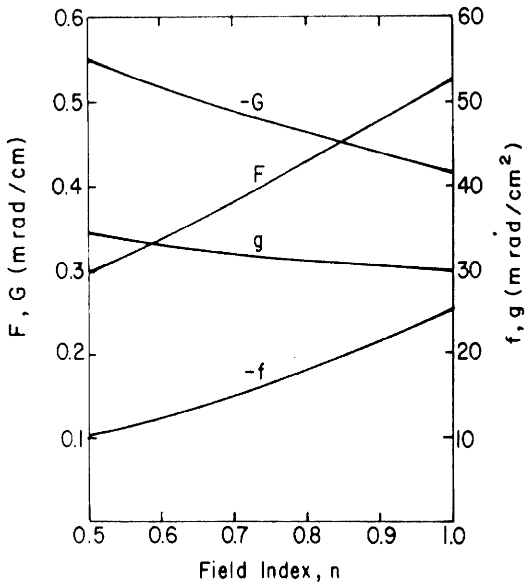

Fig. 3. Plot of F,G and f,g coefficients vs the field index. These parameters are derived from second-order TRANSPORT calculations.

Conclusions

We have studied three magnet pole face configurations to reduce second-order aberrations in ion source magnetic focusing systems. The pepper pot technique, as used here, is sensitive to the A_1 aberration but insensitive to the A_2 term. Second-order ion optics calculations qualitatively explain the data. Further, the experiment for $\beta = 0$ and theoretical calculations show that second-order aberrations mostly come from the fringe field transition and that these are reducible by having $\beta \neq 0$ in the bending field. For our beam conditions ($x_f = 0.6$ cm, $\theta_f = 21$ mrad, $y_f = 1.2$ cm) at $n = 0.9$ the optimum β is calculated to be 0.8 resulting in a maximum $\delta^2\phi$ of 4 mrad.

Acknowledgment

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