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A compact beam focusing and steering element using quadrupoles with independently excited poles

Geoffrey W. Grime

University of Surrey, Ion Beam Centre, Advanced Technology Institute, Guildford GU2 7XH, UK

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ABSTRACT

Beam steering elements for accelerator beam transport are conventionally and conveniently incorporated into beamlines by fitting magnetic dipole elements around the vacuum tube of the line. Two steerers in each plane (X and Y) together with a quadrupole doublet constitute a module providing full control of the direction, position and focus of the beam. In some installations however, there may be insufficient space on the beamline to mount separate steerer elements. To provide steering capabilities in such a situation we have used a magnetic quadrupole doublet with the coils of each pole independently excited to synthesise the desired combination of quadrupole, horizontal dipole and vertical dipole fields. This paper describes the quadrupole steerer and its multichannel power supply and presents calculated magnetic field distributions together with raytracing simulation of its performance.

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1. Introduction

Recent emphasis on microbeam applications at the 2 MV Tandetron laboratory at the Surrey Ion Beam Centre (IBC) has made it necessary to upgrade the high energy beam steering and focusing capability to optimise the beam transmission into the four microbeam lines. In order to achieve full control of the beam focus, position and direction in a quadrupole beam transport element, six independent parameters are required, two quadrupole fields and two axially separated dipole fields in each plane. Lack of space between the accelerator and the switcher magnet precluded the installation of separate dipole steerers and so the original electrostatic triplet lens has been replaced by a magnetic quadrupole doublet in which the dipole and quadrupole fields are synthesised by exciting independently the coils of the quadrupoles. This has proved very successful and a second identical unit is now in use as a beam transport element for the vertical beam line [1].

The idea of using unbalanced quadrupoles for beam steerers is not new [2], though the reported ways in which this has been implemented vary. Quadrupoles with additional separately excited steering coils on each pole are available commercially, for example the 'Combined Function Quadrupoles' offered by Radiabeam Technologies [3]. The unbalanced quadrupole field can also be created electronically using bypass transistors to divert the current in opposing quadrupole coils. This method was used for unidirectional beam scanning in the original Oxford triplet microbeam system [4] and has also been described for a beam steering application [5]. This paper describes a third method of synthesising dipole and quadrupole fields using four independently excited coils, investigates the nature of the resultant magnetic field and its effect on the beam and describes the multi-channel power supplies used to operate these devices.

2. The quadrupole-steerer (QS) element

In a conventional quadrupole magnet (shown schematically in Fig. 1) the magnitude of current in each of the coils (I_1–I_4) is identical, though the sense of flow alternates in order to generate a field with a quadrupole variation. This is usually achieved by exciting the coils in series from a single power supply. However by offsetting the value of the current in each coil by a suitable amount, it is possible to superimpose upon the quadrupole field dipole field components in both the horizontal and vertical directions, thereby combining beam deflection with focusing.

Using the pole labelling in Fig. 1, the required coil currents are:

$$\begin{aligned} I_1 &= Q + X + Y \\ I_2 &= -Q - X + Y \\ I_3 &= Q - X - Y \\ I_4 &= -Q + X - Y \end{aligned} \qquad (1)$$

where Q is the current required to generate the required quadrupole field, X is the current necessary to generate the vertical dipole field required for a given horizontal (X) beam deflection and Y is the current required for a given vertical (Y) deflection.

The quadrupole field gradient generated by this method can be shown to be

E-mail address: g.grime@surrey.ac.uk

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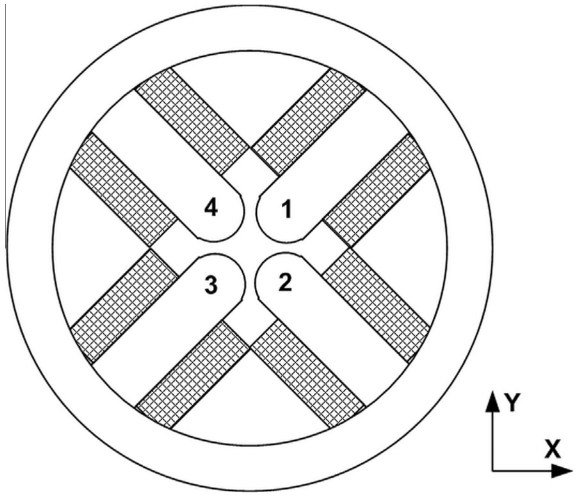

Fig. 1. Schematic cross section of a quadrupole magnet showing the pole numbering and coordinate system used in this paper.

$$g = \frac{2\mu_0 n Q}{r_0^2}$$

and the dipole fields are given approximately by

$$B_x = \frac{\sqrt{2}\mu_0 n Y}{r_0}$$
$$B_y = \frac{\sqrt{2}\mu_0 n X}{r_0}$$

where r_0 is the bore radius (distance from axis to pole tip) of the quadrupole and n is the number of turns on the coil of a single pole (assumed to be equal on all poles). Units are T m^{-1} for field gradient and T for dipole field if r_0 is in metres and the currents are in ampères.

3. Field modelling

In order to investigate the nature of the synthesised field, the magnetic circuit of a notional quadrupole magnet with circular pole profile, bore radius 7 mm and 500 turns per coil was modelled in two dimensions using FEMM 4.2 (Finite Element Method Magnetics [6]). The model permitted the currents in the coils to be specified independently.

Fig. 2 shows the calculated field distribution in the absence of quadrupole (i.e. $Q = 0$) and for different combinations of X and Y currents of 0.1 A. The arrow indicates the direction of the dipole component on the beam axis. The simulated value of the y field in the case of Fig. 2(a) is 9.5 mT, compared with a value 12.6 mT from Eq. (2). This discrepancy is assumed to be due to flux leakage to adjacent poles and will depend on the details of the pole profile.

Fig. 3 shows how the field in Fig. 2(c) is modified when the quadrupole component of the field is excited, in this case with $Q = 0.2$ A. This shows clearly that the effect of unbalancing the field is to displace the magnetic centre of the quadrupole. The amount of displacement can be calculated by rewriting the composite y field ($B = B_y + gx$) as $B = g(x + B_y/g)$. That is, the displacement of the quadrupole magnetic axis is simply the ratio of the induced dipole to the quadrupole field gradient. This may offer a way of modelling the steering effect of the QS device (as a displaced quadrupole element), but this breaks down when g is small or zero.

The uniformity of the induced dipole field is important in determining the quality of the transported beam. Non-uniformities result from errors in the 4-pole geometry of the magnetic circuit and also from deviations of the excitation of individual poles from that implied by Eq. (1). The uniformity of the induced dipole fields was investigated by plotting the ratio of the magnitude of the field to its value on the axis along the diameters indicated by red lines in Fig. 2(a)–(c). This is shown in Fig. 4, where distance is expressed as a ratio to the quadrupole bore radius, r_0. In both cases the field changes with distance off axis, though in opposite directions. The exact form of this variation will depend on the details of the pole profile. With the pole geometry assumed here, the field remains within 10% of its value on axis up to a radius of 0.375 r_0.

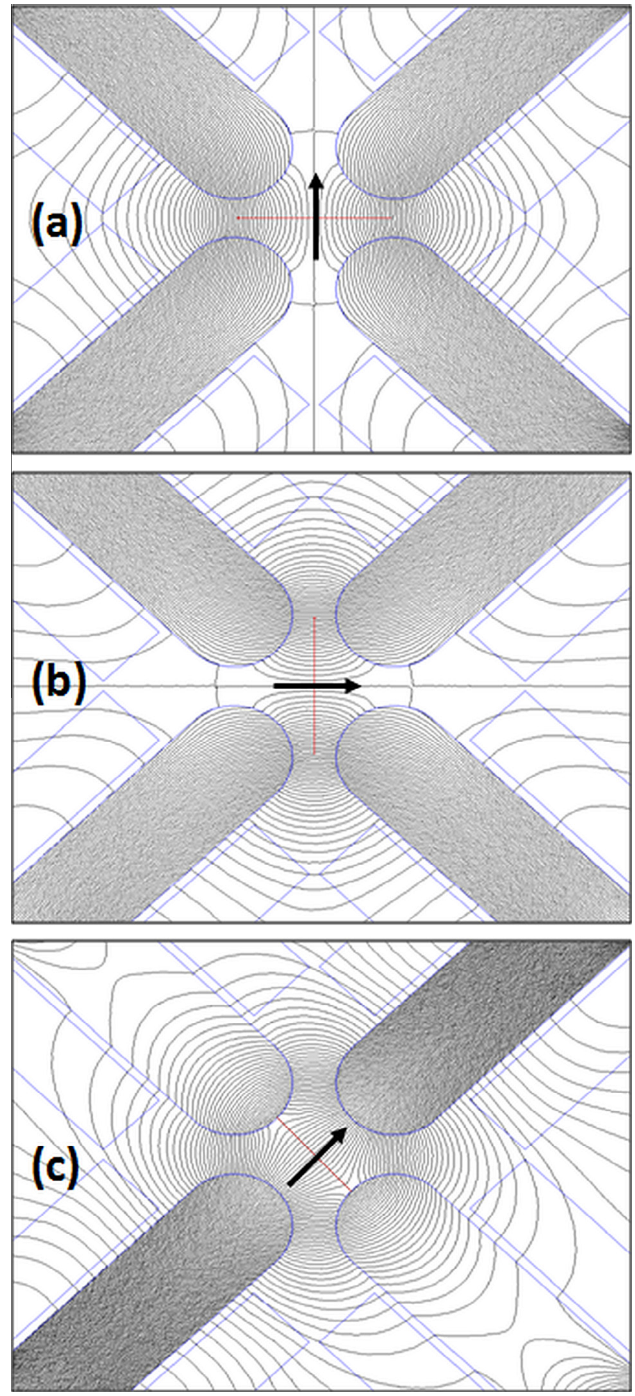

Fig. 2. FEMM simulations of the dipole field created with currents generated from Eq. (1) using $Q = 0$ A and (a) $X = 0.1$ A, $Y = 0$ A, (b) $X = 0$ A, $Y = 0.1$ A, (c) $X = Y = 0.1$ A. The arrow indicates the direction of the dipole field component.

Higher order multipoles (6-pole, 8-pole, etc.) will be introduced into the synthesised field by the effect of pole excitation errors

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