AXIAL MAGNETIC FIELD PRODUCED BY RADIALLY MAGNETIZED PERMANENT MAGNET RING

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Abstract

Axial magnetic field produced by a radially magnetized permanent magnet ring was investigated. The magnet ring can produce a magnetic field on the axis higher than the remanent field of the magnet material based on the perpendicular field superposition. Because of the direction of the magnetization, the magnet system can be covered by an iron case, and then the stray flux outside the case is small. The magnet system has no iron pole piece except for the return poles of the iron case on both ends which are usually required for magnetic field shielding. A compact strong Permanent Magnet Symmetric lens was fabricated and the measured magnetic field agreed with PANDIRA calculation. For wider usage, it is desirable that the strength of the lens can be varied. One method to give the strength variability is presented. The axial magnetic field may also be applicable to the mirror field of the ECR (Electron Cyclotron Resonance) ion source. One example for that purpose is also presented.

Introduction

A 7-MeV proton linac was constructed at Institute for Chemical Research, Kyoto University.[1,2] The linac consists of a 2-MeV RFQ linac and a 7-MeV Alvarez (DTL). The operating frequency is 433.3 MHz and the structure dimension is compact. In order to match the RFQ acceptance, the input beam has to be focused strongly to the RFQ. For future study of the simultaneous acceleration of both positive and negative ions, a magnetic lens which produces the magnetic field of axial symmetry was picked up. The field can be produced by a "solenoid" coil, but the size cannot fit in the space and the power dissipation will be intolerably large. Applications of anisotropic magnet have been studied for charged particle beam manipulations [3,4,5]. With a careful study of the radially oriented anisotropic magnets, it was found that a compact strong Permanent Magnet Symmetric (PMS) lens can be fabricated in the limited size by application of the perpendicular field superposition[6]. The configuration allows a design of a magnet system producing strong axial magnetic field with very small leakage flux. A PMS lens using three radially magnetized rings designed for the final focusing lens to the RFQ is described.

Usually the magnetic field produced by permanent magnets has fixed strength and its application is limited. A simple method to add the variability of the strength is described.

If the large negative rebounds of the axial magnetic field in outer regions are permissible, the radially magnetized permanent magnet rings are also suitable for making mirror field of the Electron Cyclotron Resonance (ECR) ion source. One example is given in the last section.

Property of Magnetic Field Lens

The focal strength $1/f$ for charged particles with the energy of eV in a magnetic field lens of axial symmetry is given by

$$\frac{1}{f}=\frac{e}{8m_0V^*}\int_{-\infty}^{\infty}B^2dz \quad [\mathrm{m}], \qquad V^*=V\left(1+\frac{|eV|}{2m_0c^2}\right), \tag{1}$$

where e and m_0 are the charge and the mass of the particles at rest respectively.[7] It should be noted that the focal strength is proportional to B^2 and 20% increase in the focal strength will be obtained by 10% increase of the remanent field which will be achieved by material developments. The drawback is that the temperature coefficient of the focal strength is also twice as large as that of the remanent field.

Magnetic Field Produced by a Radially Magnetized Magnet

Let us consider a radially magnetized anisotropic permanent magnet ring as shown in Fig. 1.

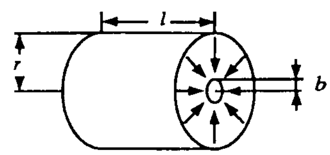

Fig. 1 Radially magnetized permanent magnet ring

Integrating over the magnetic dipole, the magnetic field on the axis of the magnet is given as

$$B(z)=\frac{Br}{2}\left\{\frac{1}{r_l}-\frac{1}{b_l}-\frac{1}{r_0}+\frac{1}{b_0}+\log\frac{(1+r_0)(1+b_l)}{(1+b_0)(1+r_l)}\right\}, \tag{2}$$

$$r_0=\sqrt{1+\left(\frac{z}{r}\right)^2},\; b_0=\sqrt{1+\left(\frac{z}{b}\right)^2},\; r_l=\sqrt{1+\left(\frac{z+l}{r}\right)^2},\; b_l=\sqrt{1+\left(\frac{z+l}{b}\right)^2}$$

The magnetic field has two maximums at z=0 and $-l$, where the end of the magnet is located. The maximum value is

$$B(0)=\frac{Br}{2}\left\{\frac{r}{\sqrt{r^2+l^2}}-\frac{b}{\sqrt{b^2+l^2}}+\log\frac{1+\sqrt{1+l^2/b^2}}{1+\sqrt{1+l^2/r^2}}\right\}. \tag{3}$$

It can be shown that the logarithm term is not finite if keeping l/r finite, and $l/b\to\infty$. In the real applications, two kinds of rings with different magnetization will be placed alternatively. In the case, the magnetic field should be superposed and the maximum field is doubled. The principle of the perpendicular field superposition should work here For example, a lens of two rings (b=5 mm, r=2 cm, and l=2 cm x2) has the maximum field of 1.22 Br.

PMS Lens with Fixed Strength

The two-ring PMS lens was fabricated [6]. The magnetic field was measured and compared with PANDIRA result. Three-ring PMS lens is designed for the final focusing device to the 2-MeV RFQ, which has a large bore hole at the entrance.

Two-ring magnet PMS lens

The magnet rings are azimuthally segmented to realize the radially oriented anisotropic property using the available material. The iron case is used as the return yoke around the magnet to reduce the leakage field on the axis particularly to the RFQ side. The corners of the magnets near the axis are rounded so that Bz has less *r* dependence and the lens has less aberration. The bore hole of the iron case at entrance side is made large to accept a beam with large diameter. The magnet material is NEOMAX 40 which has the remanent field Br of 1.29 T nominal.

Figure 2 shows the calculated flux plot and the magnetic field distribution on the axis of both the calculated value by PANDIRA and the measured value. The measured peak value is about 10 % smaller than the calculated one. The azimuthal segmentation may be the main reason of the reduction in this case.

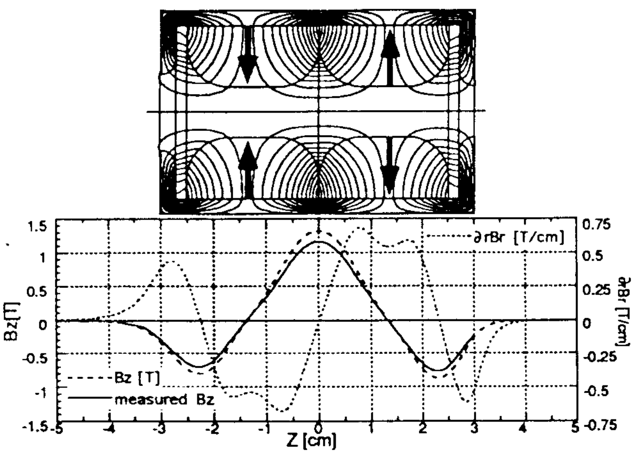

Fig. 2. Magnetic field distribution of two-ring PMS lens

Three-ring magnet PMS lens

The three-ring PMS lens has two small rings which will fit in the endplate of the RFQ and one large ring which will be outside of the endplate. (See Fig. 3) The total length is 110 mm. The outer diameters of the case are ø90 mm and ø60 mm. The inner diameter of each ring is ø30 mmø, ø24 mm, and ø15 mm, respectively, because the beam size shrinks towards the RFQ entrance. Figure 4 shows the radial orbits of the proton beam along the PMS lens. Five beams come from left hand side with 2 mm radially equal spacing. Bz and Br/r at r=2 mm and those which outermost particle feels are also shown in the figure. The distribution in the X-X' phase space at the z=-12 cm and z=5 cm is shown in the box. The RFQ vane starts at the coordinate of z=4 cm in the figures. With stronger magnet material and larger bore size in the entrance, the aberration will be reduced. The space charge effect is not included in this calculation. Although some leakage flux is seen in the outer region of the lens, the magnetic field at the RFQ entrance is small.

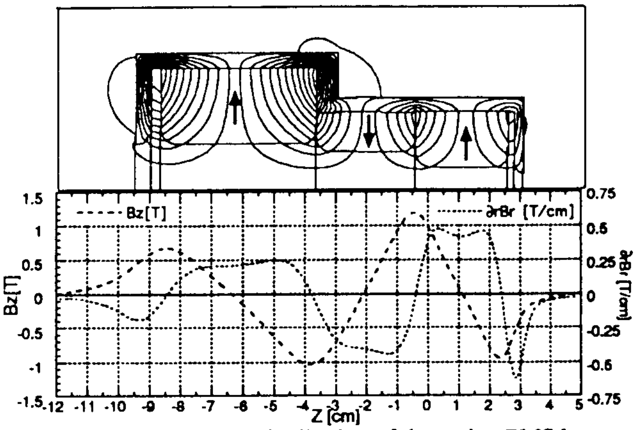

Fig. 3. Magnetic field distribution of three-ring PMS lens. Only the upper half is shown.

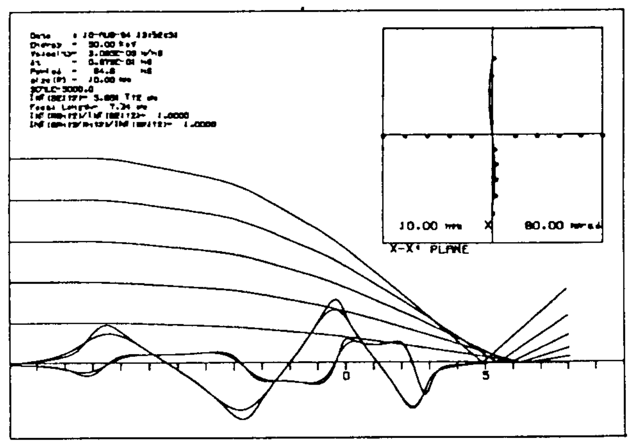

Fig. 4 Proton orbits along the three-ring PMS lens.

PMS Lens with Variable Strength

Because the magnet geometry of the PMS lens with fixed strength achieves the maximum strength, the strength can only be reduced to have the variation capability. A method to give the capability is dividing each magnet ring into two short rings and changing the distance between them. The highest magnetic field strength is obtained when they are put close each other. Because two separated short rings from a ring have the same magnetization, they repel each other and then more energy is stored at highest magnetic field strength. Another way to reduce the strength may be to change the distance between rings of different magnetization. This method is simple because of the smaller number of rings, and is applicable when plural magnet rings are used. Unfortunately, this method has smaller effect on the focal strength, because two rings of different magnetization attract each other and then less energy is stored when they are put close each other.

The variable PMS lens should have extra gap for the movement of the magnet rings and then it will be longer than fixed one to have the same strength. The appropriate gap length for the movement is comparable to the bore radius. An example of the variable PMS lens is listed in Table 1. Figure 5 shows the calculated magnetic field plots and Bz on the axis with two configurations; one gives the highest strength and the other gives the smallest strength. The peak field value of 1.5 [T] is achieved in this configuration, which is more than the remanent field of 1.2 [T]. The focal strength can be reduced to about 54% of the highest value in this example. When the thinner magnet ring is used, which reduces the absolute strength, the strength range will be extended.

outer radius of a ring magnet	45	mm
length of a ring magnet	20	mm
bore radius	10	mm
outer radius of iron case	55	mm
length of iron case	130	mm

Table 1
Variable PMS Dimensions

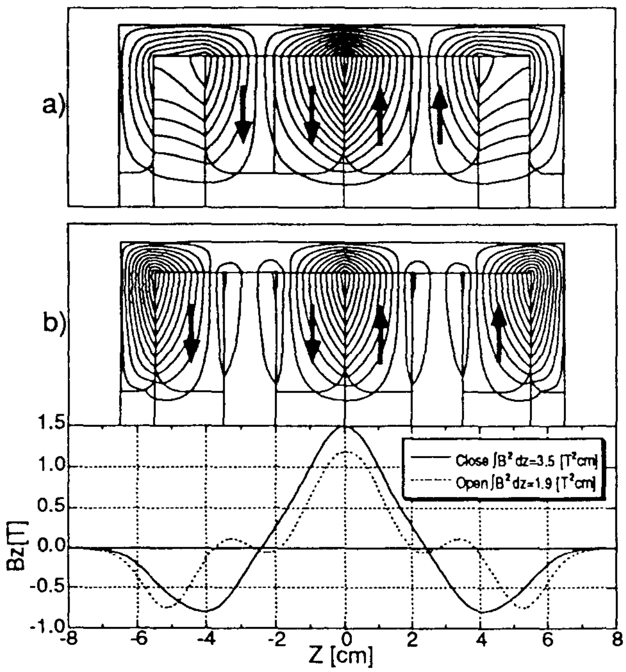

Fig. 5 Variable PMS Lens with three peak fields.
a) The strength is maximum. S=3.5[T^2cm]
b) The strength is minimum. S=1.9 [T^2cm]

Mirror Field for an ECR Ion Source

Another application of the magnet configuration is the mirror field for ECR (Electron Cyclotron Resonance) ion source[8]. Because $\int_{-\infty}^{\infty} Bz\, dz$ is zero (the Ampère's law), the large negative rebounds of the axial magnetic field in outer region is inevitable when no solenoid coil is used. If such rebounds are permissible on the extracted beam axis, it is possible to configure the radially magnetized permanent magnets for the mirror field for ECR ion source. One example using the radially magnetized permanent magnet rings with remanent field of 1.2 [T] is shown in Fig. 6. It can produce the peak magnetic field of 0.6 [T] with the mirror ratio of 2, which corresponds to more than the ECR frequency of 10GHz. Because of the radially magnetized magnets, the magnet system can be shielded by the iron case, and has very small leakage flux around it. The small sub-ring magnets are used to enhance the peak mirror field. When the main magnets are separated further, the peak field can be changed by adjusting the separation between the main- and the sub-magnet.

There is large vacant space at the middle of the magnet. When an additional solenoid coil is available in the space to back up and change the field, the size of the magnet system

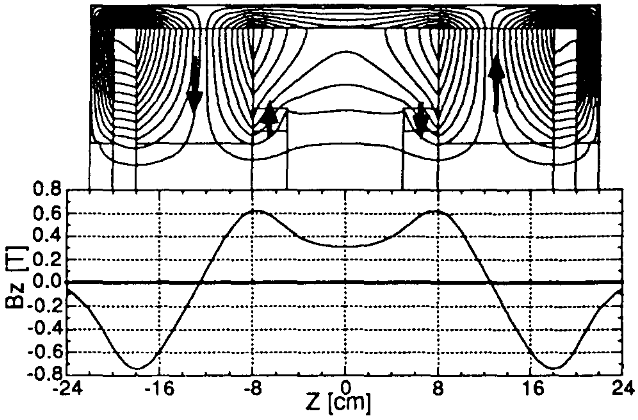

Fig. 6. An example of the mirror magnet for ECR ion source.

and the rebound of the magnetic field can be reduced. On the other hand, the rebound is taken as a focusing element, and the beam optics should be designed including its existence.

Summary and Discussion

The radially magnetized permanent magnet ring makes it possible to fabricate a compact strong axial magnetic field lens with very small leakage flux. One method to give the adjustability of the strength is presented. The calculations show that the strength range of as much as two fold is possible. Utilizing this method, the application of the PMS lens will be widened.

It is also applicable to the mirror magnetic field for plasma confinement. Because of the small leakage flux, the magnet will be easy to handle. Even the turbo-molecular pump (TMP) can be placed very close to the magnet. This feature should be very useful when the magnet is used for ECR ion source.

Acknowledgment

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References

[1] Y. Iwashita, et. al."7MeV PROTON LINAC", Proc. 1990 Linear Accel. Conf., Albuquerque, p.74
[2] A. Noda, et. al. "Improvement of the Proton Accelerator System", Bull.Inst.Chem.Res.Kyoto Univ. Vol.70,No.1 (1992)
[3] O. C. Dermois, "The external injection system for the Groningen cyclotron", Proc. Fifth Int. Cyclotron Conf. Oxford, 620 (1969)
[4] K. Halbach, "Physical and Optical Properties of Rare Earth Cobalt Magnets", Nucl. Instr. and Meth., 109 (1981)
[5] K. Halbach, "Magnet Innovations for Linacs ", Proc. 1986 Linac Conf., Stanford, SLACReport303, 407 (1986)
[6] Y. Iwashita, "Axial Magnetic Field Lens with Permanent Magnet", Proceedings of the 1993 Particle Accelerator Conference", 3154 (1993)
[7] C. Fert and P. Durandeu, "Magnetic Electron Lenses" in "Focusing of Charged Particles", Edited by A. Septier; Academic Press, 309 (1967)
[8] P.Ludwig, R.Geller and G.Melin, "The 10-GHz NEOMAFIOS upgraded electron cyclotron resonance ion source", Rev. Sci. Instrum. Vol.63, No.4, 2892 (1992).