

# Compact Strong Permanent Magnet Symmetric Lens

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## Abstract

A compact strong Permanent Magnet Symmetric (PMS) lens which produces the axial magnetic field is studied. The proposed lens has no iron pole piece except for the return poles on both ends which are required for magnetic field shielding purpose in some applications. It can produce the magnetic field on the axis more than the remanent field of the magnet material by the perpendicular field superimposition.

## I. INTRODUCTION

A 7-MeV proton linac was constructed at Institute for Chemical Research, Kyoto University.[1,2] The linac is consisting 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. Unfortunately, the entrance side of the RFQ is occupied by the vacuum port and the final focus element has to be installed into the hole in the end plate of the RFQ. The hole has diameter of 40 mm and the depth of 60 mm. A compact focusing device which can fit in this size had to be devised.

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". 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 superimposition.

## II. PERPENDICULAR FIELD SUPERIMPOSITION

Let us consider the anisotropic magnet configuration in the two dimensional space as shown in Figure 1. The magnetic field has the direction of Z on the Z axis, and the maximum at the center. The analytical expression for the maximum field is calculated as follows;

$$B_{\max} = \frac{Br}{\pi} \left\{ \log \left( 1 + \frac{l^2}{b^2} \right) - \log \left( 1 + \frac{l^2}{r^2} \right) \right\}. \quad (1)$$

It can be shown that the value is not finite when  $l/b \rightarrow \infty$  keeping  $l/r$  finite. Because the produced field is perpendicular to the easy axis of the magnet material, the operating point in the B-H curve will stay in the upper half. If the magnet material has no knee in the second quadrant of the B-H curve, which is easy requirement for almost all rare earth magnet

materials, no demagnetization is expected. Although it is only a logarithmic increase, the field strength seems to have no limitation in this respect.

The field concentration by perpendicular filed superimposition is verified by a rough experiment. Eight pieces of 10 x 10 x 30 mm magnets made of NEOMAX 35H, which has Br of 1.1 [T], are placed as shown in Figure 1. One block is consisted of four pieces which attract each other. Two of the blocks are fixed on jaws of an iron vice, and put close by pressing with the vice to the gap of about 2 mm. The maximum field is measured by an axial Hall probe as 1.6 [T] which is more than the Br. The Hall probe has the thickness of 2 mm.

Neglecting the second term of the equation (1) which express the contributions from the outer surfaces and substituting the values for l and b, we get  $B_{\max}=1.6$  [T]. Because the jaws of vice is made of iron, it acts like return yoke and reduces the effects of the outer surfaces. The magnetic field produced by the magnets with the iron return yoke is also calculated by PANDIRA [6] as shown in Figure 2. It also shows the value 1.6[T] as a maximum.

According to the result of above experiment, the perpendicular superimposition can hold good for producing at least 1.5 Br. Further study is needed to clarify the demagnetization process in the perpendicular direction and a limitation.

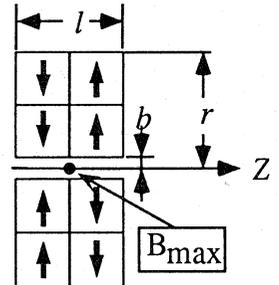


Figure 1. Geometry for field concentration test.

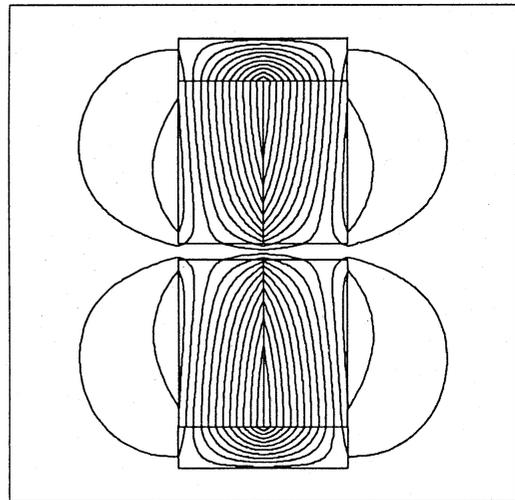


Figure.2 Flux plot calculated by PANDIRA

### III. 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

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

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 twice as large as that of the remanent field. On the other hand, this property can also be used as a focal strength adjustment by means of the temperature control. The typical temperature coefficient of the Nd-B-Fe magnet is  $0.1\% / ^\circ\text{C}$ .

### IV. MAGNETIC FIELD PRODUCED BY A RADIALLY MAGNETIZED MAGNET

Let us consider a radially oriented permanent magnet ring as shown in Figure 3.

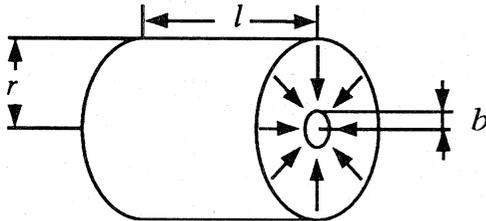


Figure 3. Radially oriented permanent magnet ring

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

$$B(z) = \frac{Br}{2} \left\{ \frac{1}{r_1} - \frac{1}{b_1} - \frac{1}{r_0} + \frac{1}{b_0} + \log \frac{(1+r_0)(1+b_1)}{(1+b_0)(1+r_1)} \right\},$$

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

$$r_1 = \sqrt{1 + \left(\frac{z+l}{r}\right)^2}, \quad b_1 = \sqrt{1 + \left(\frac{z+l}{b}\right)^2} \quad (3)$$

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

$$B(0) = \frac{Br}{2} \left\{ \frac{r}{\sqrt{r^2+l^2}} - \frac{b}{\sqrt{b^2+l^2}} + \log \frac{1+\sqrt{1+l^2/b^2}}{1+\sqrt{1+l^2/r^2}} \right\}. \quad (4)$$

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

### V. PMS LENS

For fabrication of the real magnet, several constraints had to be considered. The ring should be azimuthally segmented to realize the radially oriented anisotropic property using the available material. The return iron yoke has to be located around the magnet to reduce the leakage field on the axis particularly to the RFQ side. It is achieved by the iron case of the magnet. The corners of the magnets near the axis are rounded so that the  $B_z$  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. The final dimensions are shown in Table 1. Photo 1 shows the assembled PMS lens.

number of ring	2
outer radius of a ring magnet	17 mm
length of a ring magnet	25 mm
number of segments in a ring	16
bore radius	5 mm
corner radius of a segment	8 mm
outer radius of iron case	20 mm
length of iron case	60 mm
corner radius and thickness of lids	3 mm
bore radius of entrance lid	7.5 mm

Table 1. Model PMS dimensions

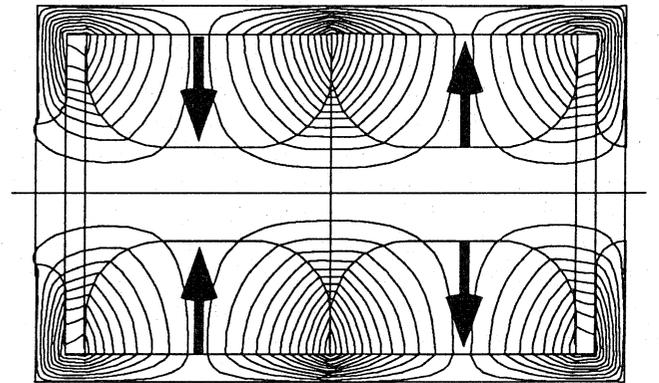


Figure 4 PANDIRA result

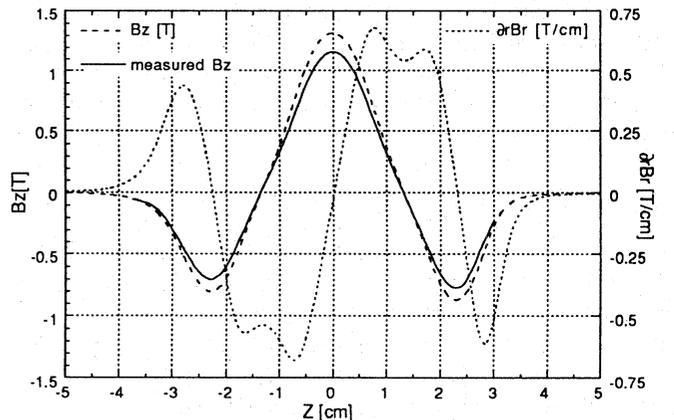


Figure 5 Magnetic field distribution

The field calculated by PANDIRA is shown in Figure 4. Figure 5 show the magnetic field distribution plots on the axis 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 is thought to be the main reason of the reduction in our model magnet case.

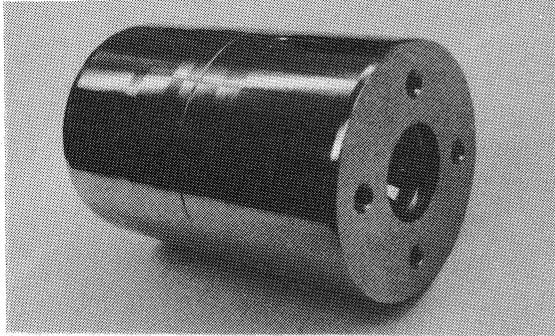


Photo. The assembled PMS lens

## VI. BEAM OPTICS

The beam dynamics simulations based on the calculated magnetic field distribution by PANDIRA are performed. The equations of motion in the cylindrical coordinate are

$$\begin{cases} m_0 \dot{v}_r = -q v_\theta B_z + m_0 v_\theta^2 / r, \\ m_0 \dot{v}_\theta = -q (v_z B_r - v_r B_z) - m_0 v_r v_\theta / r. \end{cases} \quad (5)$$

The equations are integrated numerically. For less aberration, the  $r$  dependence of  $B_z$  and  $\partial r B_r$  should be small. One typical result is shown in Figure 6. The parallel beams with 0.5 mm even spaced radii start at  $z=-6$  cm ( left edge ), and go through the PMS whose center is located at  $z=0$ .  $B_z$  and  $\partial r B_r$  at 8 different radii which correspond to the initial positions of the beams are shown on the Z axis. The  $x-x'$  phase space plots are also shown at the initial point and the focal point

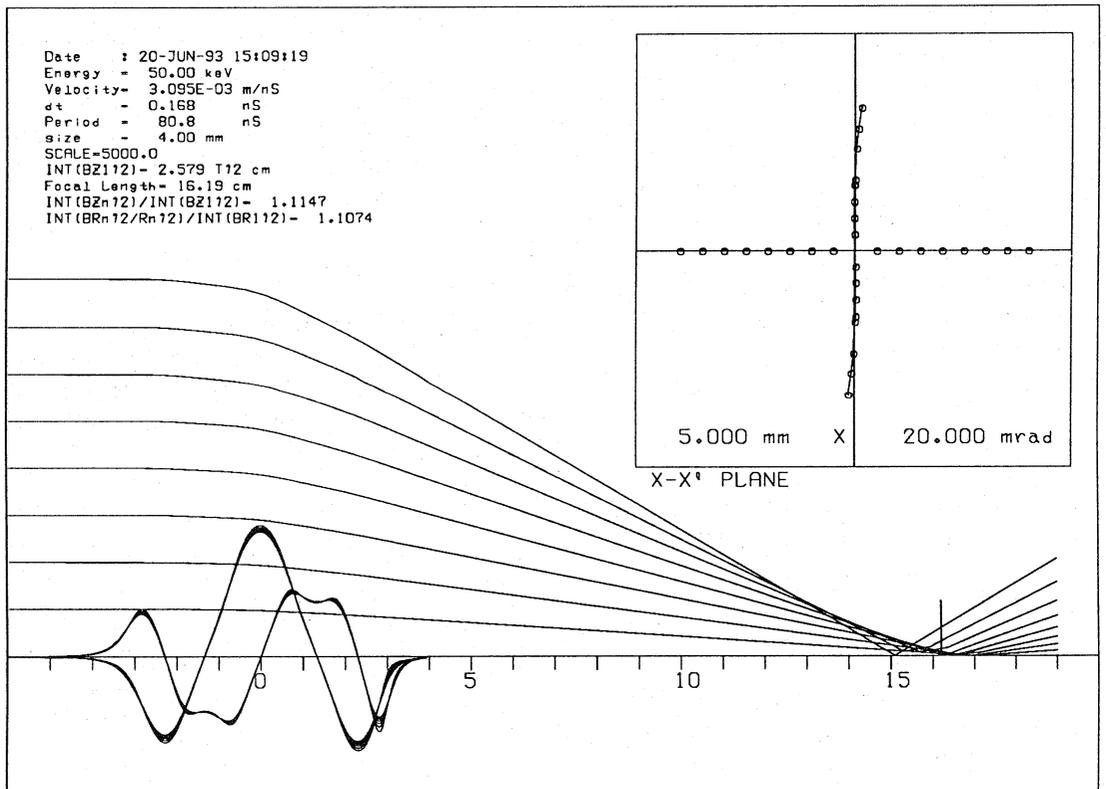


Figure 6 Beam dynamics simulation based on PANDIRA result.

calculated by equation (2). Because the integral over  $B_z$  on the axis of PMS lens is zero (Ampère's law), the image does not rotate. In this calculation, the space charge effect is not included yet. The space charge effect will be included in further study.

## VII. ACKNOWLEDGMENT

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## VIII. REFERENCES

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