IMPROVEMENT OF FIELD QUALITY OF GLASER MAGNETS USED FOR FOCUSING ION BEAMS

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Glaser magnets used for focusing charged particle beams show appreciable aberrations. These aberrations can be reduced by making the magnetic field uniform in the median plane. This can be done by increasing the pole gap, which, however, reduces the focal power also. We have shown that a better way of improving the field quality in Glaser magnets is to taper the poles outwards. The saturation characteristics also are better in tapered poles.

1 Introduction

Various types of magnets are used for focusing charged particles in beam lines. Quadrupoles are extensively used for this purpose. Dipole magnets with rotated pole edges, or having field gradients also act as focusing elements. Another type of focusing magnet which is sometimes used is the Glaser magnet. Glaser magnets are basically solenoidal magnets with iron yoke and pole pieces. These provide a strong axial magnetic field giving a strong focusing action on a charged particle beam.

A number of Glaser magnets have been used in the external injection line of the Electron Cyclotron Resonance (ECR) ion source at the Variable Energy Cyclotron Centre, Calcutta [1]. Two high power Glaser magnets are used in tandem to match the size of the beam. Three other smaller magnets are used in the vertical section of the beam line. The external injection line at KFA, Julich also uses such magnets [2]. The low energy beam lines at LBL, California [3] and the Cyclotron Laboratories at MSU [4] and Texas A and M University [5] use these magnets for focusing and transporting the beam from the ion source to the cyclotron. Apart from their extensive use in electron devices, solenoid magnets have other uses also e.g., the emittance degradation of polarized H ion beams can be reduced by using properly shaped solenoid fields [6]. The advantage of a Glaser over other magnets is that it is a cylindrically symmetric magnet which focuses the beam in all the meridian planes. Also, it is compact in nature and one does not require doublets. Obviously, astigmatic errors are absent in a Glaser magnet. However, spherical aberration is large in such magnets. These errors can be reduced by improving the field quality of the magnet. Not much attention appears to have been paid in this regard. In this work we have made an attempt to improve the field quality of Glaser magnets by shaping the pole pieces.

2 Field in a Glaser magnet and its improvement

The magnetic field in a Glaser type of magnet has the general form [8]

$$B(r,z) = B(z) - \frac{r^2}{4}B''(z) + \frac{r^4}{64}B^{IV}(z) - \dots \quad (1)$$

where $B(z)$ is the field along the axis as a function of the axial distance z. Glaser [7] gave the following model for $B(z)$

$$B(z) = \frac{B_0}{1+\frac{z^2}{a^2}} \quad (2)$$

where B_0 is the field at the centre and a is the axial distance from the centre where the field falls to half its maximum value. The radial equation of motion of a particle in the field is

$$\ddot{r} = -\left(\frac{qB_z}{2m}\right)^2 r \qquad (3)$$

where r is the radial distance. Focusing will be good if the factor B_z^2 is uniform with respect to r. However, one can see that B contains terms with r^2 , r^4 etc. Because of these terms the equation (3) will take the form

$$\ddot{r} = -\left(\frac{qB_z}{2m}\right)^2 \left(r - \frac{1}{2}\frac{B''(z)}{B(z)} r^3 + ...\right) \qquad (4)$$

and so there will be aberration due to the presence of r^3 and higher order terms. This leads to emittance growth also. So, generally one takes the paraxial approximation in which one assumes that the beam moves very near the axis and hence r is small. But this limits the available aperture of the magnet and so the magnet requires a large ampere-turn.

In this work we have taken a different approach. Instead of limiting the radial distance we try to reduce the term $B''(z)$ in equation (3), i.e., we make the longitudinal field $B(z)$ more uniform in the median plane. This can be easily achieved by increasing the pole gap, but in this process the focal power of the magnet decreases. The focal power of a Glaser is proportional to the square of the field times the length. Increasing the length by a factor of 2 reduces the field by about the same factor thereby reducing the focal power. We have tried to reduce the term B'' in a different way. We have done this by tapering the cylindrical pole pieces so that the pole gap goes on increasing outwards (Fig. 1). It has, however, to be noted that it is not possible to reduce $B''(z)$ at all z.

The effect of tapering on the field can be understood in the following way. One can visualize a Glaser magnet as a cylindrical dipole magnet with a bore in the middle. Because of this bore, the field at the centre becomes less than the field at the periphery and this is what gives rise to a non-uniformity of the field in the median plane. It is easy to understand that when the pole is tapered the magnetic potential lines get modified to be denser near the axis and this leads to the radial uniformity of the field.

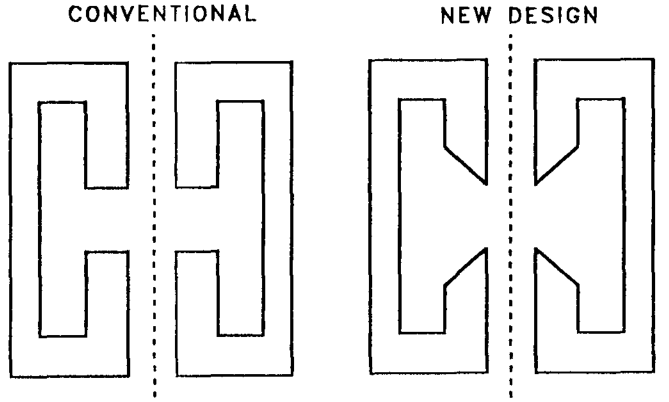

Fig.1. Pole shapes in conventional and modified Glaser magnets

3 Field calculation and results

Magnetic field has been calculated by using the well known code POISSON for a cylindrical geometry. For comparing the various pole geometries, the magnet aperture (5 cm) and the ampere-turn (15000) have been kept fixed. Calculations have been done for pole gaps of 3.6 cm, 4 cm, 5 cm, 6 cm and 7 cm. By the term pole gap we mean the minimum distance between the poles. For each gap the tapering angle has been varied from 0^0 (no tapering) to around 45^0 . Fig. 2 shows the variation of the magnetic field as a function of the radial distance for conventional Glasers (no tapering). As is expected, the field becomes more uniform as the pole gap is

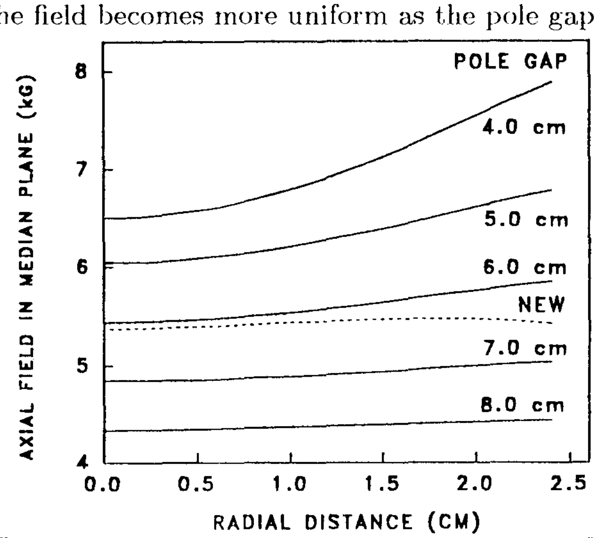

Fig.2. Variation of the axial component of the magnetic field in the median plane with the radial distance for conventional Glasers of various pole gaps. The dotted curve is for a tapered pole (44^0) with a gap of 5cm.

increased. It also shows that with the increasing pole gap the field decreases because of which the strength of the magnet decreases. A similar effect can be seen by tapering the pole pieces instead of increasing the pole gap. Fig. 3 shows the field uniformity for various tapering angles for a fixed pole gap of 4 cm. The field uniformity is found to improve with the tapering angle. Thus we see that pole tapering and increasing the pole gap both have qualitatively the same effect on the field uniformity.

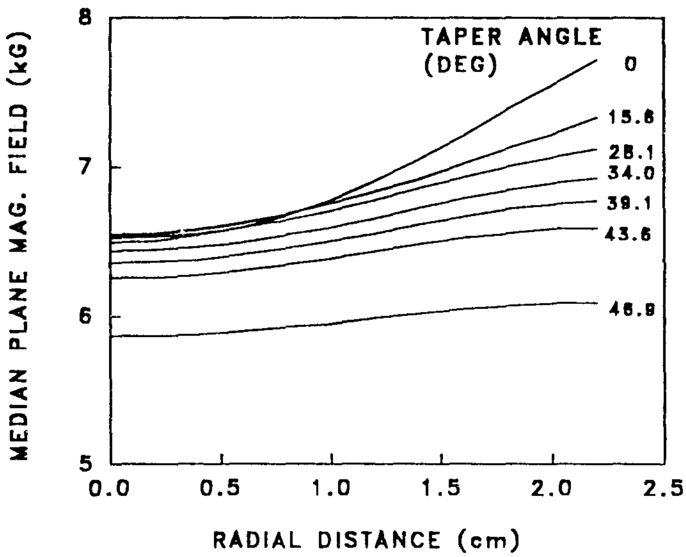

Fig.3. Variation of the axial magnetic field in the median plane with the radial distance for various tapering angles. The pole gap is 4 cm.

In order to decide which is more benificial, we have calculated the focal length for a 15 keV deuteron for various geometries. The focal length f for a particle of mass m and energy qV is given by [9]

$$\frac{1}{f} = \frac{q}{8mV} \int_{\infty}^{\infty} B_z^2 dz \qquad (5)$$

Fig. 4 shows the maximum field deviation (near the maximum aperture) for various pole gaps and taper angles. All the curves show the same trend of getting more uniform at higher taper angles. But at the same time the focal power also decreases. The dotted curves in Fig. 4 show the variation of focal length as a function of the taper angle. Given a maximum allowed field deviation (for any particular application) the taper angle and the pole gap can be decided from Fig. 4. One can have a particular maximum field variation for various pole gaps but the lower gap (with a higher taper angle) will give larger focal power. This can further be seen from Fig. 5 where the focal length has been plotted as a function of the maximum field deviation.

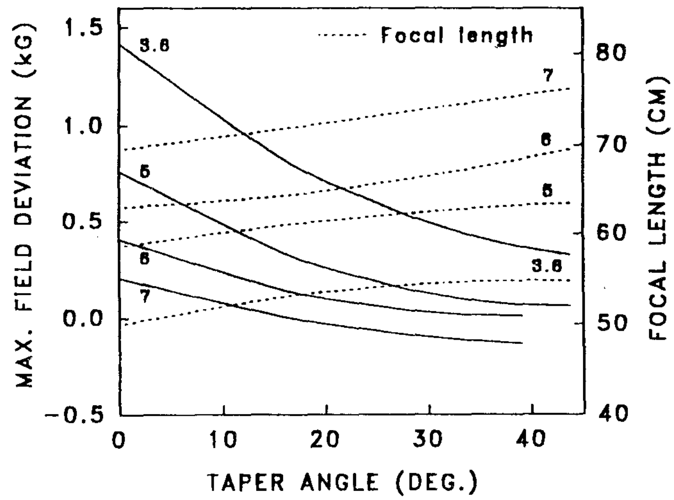

Fig.4. Plot of the maximum field deviation (solid curve) and the focal length (for a 15 keV deuteron, dotted curve) as a function of the taper angle. The pole gaps in cm are indicated on the lines.

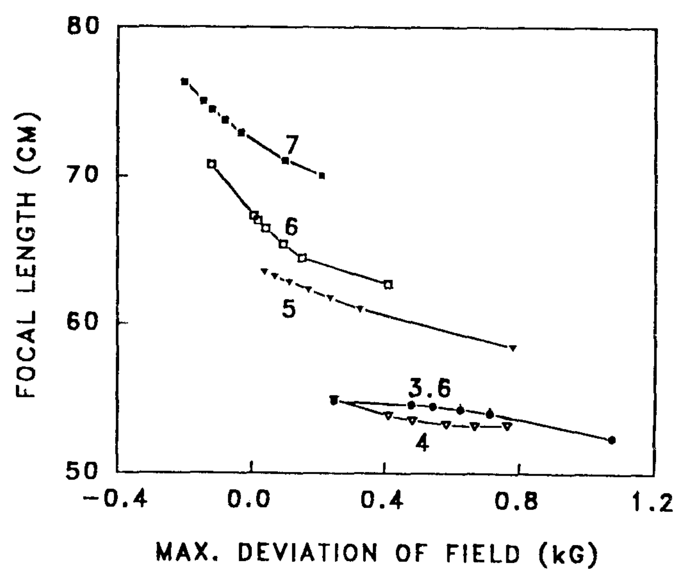

Fig.5. Plot of the focal length (for a 15 keV deuteron) as a function of the maximum deviation of field for various pole gaps. The field deviation, in turn, depends on the taper angle.

4 Discussions

We have shown that the median plane field of a Glaser magnet can be made more uniform simply by tapering the pole pieces outwards. This reduces the aberrations in the magnetic lens. This is more effective than increasing the pole gap because the focal power decreases more sharply with the increasing pole gap than with the increasing tapering angle. A larger focal power (for the same NI) can be achieved by decreasing the pole gap and increasing the taper angle. There is, however, a limit to decreasing the pole gap. As shown in Fig. 5 focal lengths for pole gaps of 3.6 cm and 4 cm do not differ much.

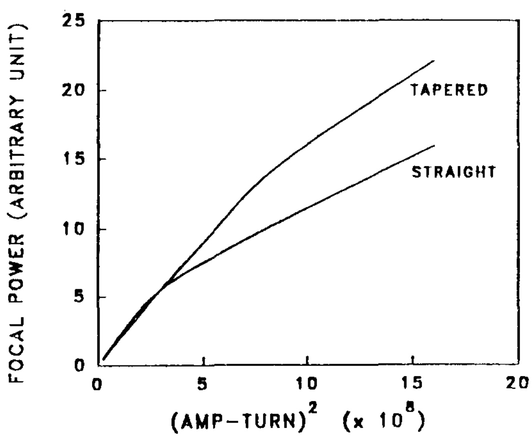

Fig.6. Effect of saturation. Variation of focal power with the square of the ampere-turn for a pole gap of 4 cm. Conventional Glasers get saturated more easily.

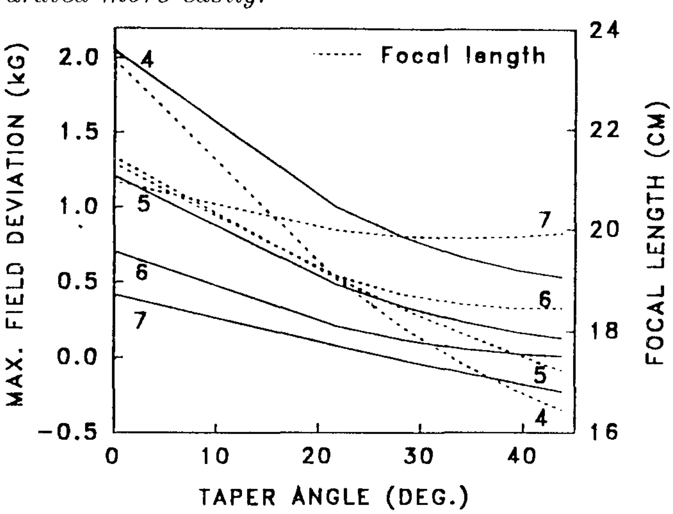

Fig.7. Plot of the maximum field deviation (solid curve) and the focal length (for a 15 keV deuteron, dotted curve) as a function of the taper angle (NI=30000). The pole gaps in cm are indicated on the lines.

It should be noted that people have earlier used partially tapered poles in Glaser lenses [10,11,12] but there the taper structure was used for reducing the saturation problem and no consideration was given to the field uniformity.

We have studied the effect of pole tapering on the magnet saturation also. Fig. 6 shows that magnets with untapered poles saturate more easily than those with tapered poles. This is because the total flux through untapered poles is large. The effect of pole tapering on the field deviation and the focal length is more prominent at higher ampere-turns as shown in Fig. 7 for NI=30000. It is clearly seen that as the taper angle increases, both the field deviation and the focal length decrease. Thus it appears that tapering of poles in Glaser magnets should be recomended.

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