

CIRCULAR PERMANENT MAGNET QUADRUPOLES FOR HIGHER FREQUENCY AND HIGHER SHUNT - IMPEDANCE LINACS

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Abstract

A new version of rare-earth permanent magnet lenses is presented. They have been developed for higher frequency and higher shunt impedance linacs. These lenses have a circular form. Due to 100% filling by magnetic material in each lens module and continuous rotation of magnetization vector it is possible to achieve a higher field in comparison with discrete magnetization distribution lenses.

1 INTRODUCTION

At present there are several kinds of permanent magnet multipole (PMM) split-pole lenses. All of them (segmented-, rod- and hybrid-types) have a discrete character [1,2,3]. Though it seems to be more natural to develop the circular lens construction with continuous rotation of magnetization vector, we don't know about such practical propositions. On the other hand there are rich literature describing some methodic and technological items and improvements of discrete type lenses.

The discrete designs allowed to remove a number of engineering difficulties, which were arose during manufacturing of the ring-type lens and to realize all advantages of split-pole lenses in comparison with electromagnetic ones. However the lenses with small number of discrete elements have a big loss of magnetic field and compactness. The procedure of its manufacturing and assembling are vastly complicated. When the elements number is increasing so ring-type lens becomes again more preferable.

The essential preference of the ring-type lenses - small overall dimensions - allows to decrease considerably sizes of drift tubes in Alvarez linacs. Thus the possibilities are opened for increasing of the working frequency and shunt-impedance of the cavity.

2 RING-TYPE PMM CONSTRUCTION

Ring-type lens is a solid magnet, which is magnetized according to the law:

$$\vec{I} = I(\vec{n}\cos k\varphi + \vec{\tau}\sin k\varphi), \quad (1)$$

where \vec{n} , $\vec{\tau}$ - are unit vectors of the cylindrical coordinate system r, φ, z ; k - is multipolarity of the lens ($k=1$ - dipole, $k=2$ - quadrupole etc.); I - is modulus of the magnetization of material. $I = \text{const}$ in the whole volume of the ring with the bore radius R_1 and outer radius R_2 (Fig. 1a).

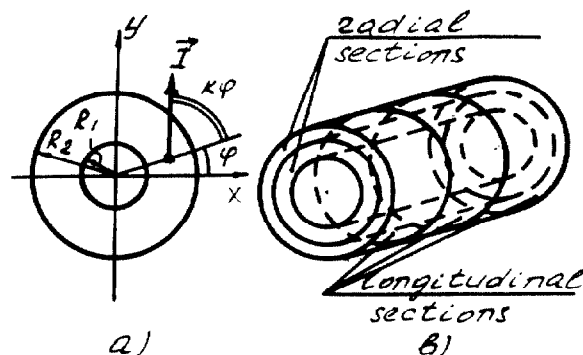


Figure 1: The rule of magnetization vector rotation in ring-type PMM - (a) and module PMM construction - (b).

The field configuration and dependence of the field value on R_1 , R_2 in the lens with infinite length $L \rightarrow \infty$ are well known. For lens with finite length (particularly for very short lens) due to influence of the edge effects widely known expressions for calculations of the fields give too large error. Taking into account the edge effects and with the only assumption that magnetization \vec{I} doesn't depend on the field, it is possible to show that longitudinal distribution of the gradient on the axis of the permanent magnet quadrupole lens (PMQ) is given by

$$G_a(z) = \frac{\mu_0 I}{8} [f(R_1, l, z) - f(R_1, -l, z) - f(R_2, l, z) + f(R_2, -l, z)], \quad (2)$$

where

$$f(R, l, z) = \frac{12R^2(z+l)^2 + 8(z+l)^4 + 3R^4}{R(z+l)[R^2 + (z+l)^2]^{3/2}}, \quad l = 0.5L. \quad (3)$$

(To calculate the gradient in the geometric ends of the lens in the expression (2) it is necessary to go to the limit at $z \rightarrow \pm l$.)

Creation of necessary magnetization distribution (1) is performed during pressing of magnetic alloy powder. Special multipole magnet is inserted to the inner volume of matrix in order to give right orientation of magnetic particles. Particles are fixed by magnet forces until the pressing finish.

Lens is suggested to be built from thin circular modules (Fig. 1b). This way is necessary to provide tolerances which occur in accelerator technology for precise lenses and to repress influence of the magnetic properties spread in commercially available rings. A measurements of a great number of ring modules are carried out before lens assembly. After that module sets is selected to achieve compensation of undesirable field contribution from modules within each set.

In order to provide right magnetization of ring module it is necessary to ensure coincidence between configuration of magnetizing field and magnet texture direction (1). It is known that split-pole electromagnet which has azimuthal current distribution in its coil in accordance with law $\sin k\varphi$ has right field configuration. However, field value of such electromagnet decreases fast. In the case of great ratio R_2/R_1 there is a problem to reach limit hysteresis loop for outer layers ($r \rightarrow R_2$) of ring module. This problem can be overcome by division of modules in radial direction. As a rule, for small size PMQ in linear accelerator focusing channels this ratio is about 1.5 - 2.0. Thus the number of radial sections may be not greater than three.

At first modules are manufactured in thin wall cylinder in such a way that their pole planes are coincided. After that lens with required outer diameter is assembled from these cylinders. Pole planes of these cylinders must be coincided if it is necessary to reach maximum field value. Azimuthal rotation of one cylinder around others allows us to make precise adjustment at field value on arbitrary intermediate level.

Module construction of circular lens give wide possibilities to get a field with required harmonic content, adjusting of field strength and correction of spatial field distribution. This can be fulfilled by combining of modules with various dimensions, multipolarity and magnetization.

3 COMPARATIVE ANALYSIS

In discrete split-pole lenses the continuous law of magnetization distribution (1) is substituted by elements with homogeneous magnetization. Due to this substitution it became possible to avoid difficulties of forming curvilinear texture (mentioned above) and realize the main advantages of PMQ over electromagnetic analogues. However the deviation of magnetization distribution with respect to distribution (1) results magnetic field value losses and distortions in magnetic field configuration.

In segmented lens the magnetic material filling approaches to 100%. If the number of segments per magnetization vector rotation period (1) is few, field value losses reach 20% and distortions of magnetic field configuration make this lens useless. In practice 16-segments lens construction is used for PMQ manufacturing for linacs [2]. In this case magnetic field losses is reduced to 6% and nonlinearity - to 0.3 - 0.5% at 75% aperture. At the same time the number of dimension types increases and it becomes more complicated to manufacture segments to select them in sets and assemble the lens finally.

In rod-type lens construction all magnetic elements have equal sizes. Using them we can manufacture lenses of arbitrary size. The technique of magnet selection of rods and lens assembling are very effective and well developed now [5]. However rod-type lens has one disadvantage: its field value is 20 -22% less than the field value of ring lens because of filling by magnetic material is not entire.

In ring module lens construction we also have to use nonmagnetic materials to orient and to fix modules. Nevertheless it is not difficult to approach 97% field value in comparison with continuous circular construction. The important advantage of ring module lens construction is the fact that necessary azimuth magnetization distribution in a module is already formed. To assemble such lenses we should only preliminarily select modules with proper field distribution and ensure correct orientation of modules in a lens.

4 RINGS MAGNETIZATION

Two types of coils that make magnetic field configuration in the ring approximating distribution (1) are used to magnetize the PMQ rings.

The first type coil having the azimuthal distribution of the wind density that satisfy the law $\sin k\varphi$ [6] is put into the ring aperture. Its external field configuration approaches distribution (1) in the whole volume of the ring. But the field value decreases according to $1/r^3$ that makes difficult to saturate the most remote layers of the ring and causes the necessity of the ring radial sectionalization. Nevertheless since the compact lens has a small aperture (as a rule bore radius is 5-15 mm) the first type coil turns out very thin but at the same time the necessary magnetization current for the Fe-Nd-B and Sm-Co₅ rings ($\mu_0 H_{CI} = 1.0-1.5$ T) even with the ratio $R_2/R_1 = 1.5$ is in order of some dozens of kiloamperes.

The magnetization experiments with the tested samarium-cobalt modules show that with the current of 20 kA it is possible to obtain the field of 2.5 T (the mean value in the interval $R_1 \leq r \leq R_2$) that leads as a rule only to the partial ring magnetization.

The second type coils allow to obtain the higher magnetization field. They have the flat coil winding which embrace the median region of the ring or placed closely to magnet pole. In this way the local magnetization of the median (Fig.2a) and the poles regions of ring (Fig.2b) is obtained. Almost 100% of the rings can be lead by this method up to the limit hysteresis loop with the necessary current being 15 kA. But the field configuration of this coil doesn't give satisfactory approximation of required field distribution. This fact causes growth of the nonlinear harmonic values in the module field.

Analysis of the results leads to the attractive idea of using the superconductive split-pole coils to magnetize the ring lens because in this case it is possible to expect 5-7 T on the coil surface.

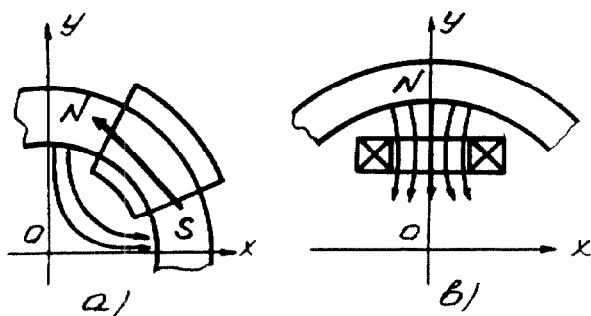


Figure 2: Two types of coil for local magnetization of median (a) and of pole (b) regions of ring-type PMQ

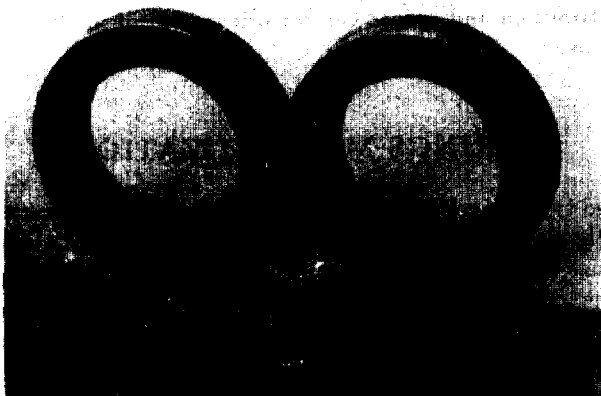


Figure 3: Experimental samarium-cobalt quadrupole modules for higher frequency and higher shunt-impedance linacs.

5 EXPERIMENTAL SAMPLES

Experimental samarium-cobalt samples of circular modules (Fig.3) have $R_1 = 11$ mm and $R_2 = 5$ mm. After magnetization a measurements of a magnet field were fulfilled in whole aperture space including fringe field regions.

Fig.4a shows the longitudinal gradient distribution along the ring axis (curve 1). The curve 2 was drawn according to the theoretical dependence (2); it fits to experimental distribution with accuracy 0.3 % (rms) when $\mu_0 I = 0.78$ T. This allows us to adopt obtained magnetization value as an average over ring volume. We come to the same value when the mathematical model is constructed by the method of integrating over magnet sources on the basis of experimental distribution.

Fig.4b shows the harmonic spectrum averaged on 5 ring modules. The spectrum for each ring was obtained by inductance method. Single-wind coil of the measurement device was placed on a cylindrical surface of 9.1 mm radius. It caught practically total ring field in longitudinal direction. One can see from this spectrum that amplitudes of some low frequency harmonics might be of some percents of the second quadrupole harmonic because of a uncontrollable fluctuations during rings manufacturing. The above mentioned method of dividing of the circular lens along

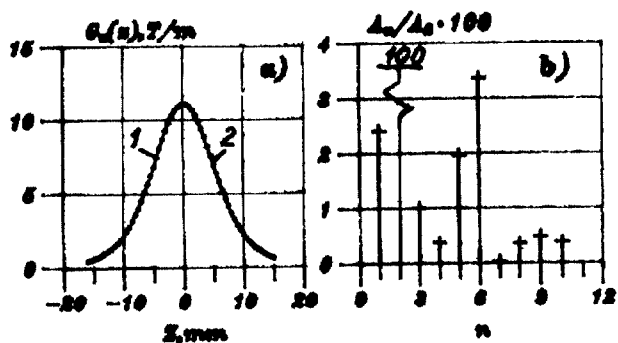


Figure 4: Longitudinal distribution of the gradient -(a) and harmonic spectrum -(b) in experimental modules.

its length into a sequence of short sections was proposed to eliminate these unquadrupole harmonics. Due to appropriate combination of rings one can reduce the average nonlinearity along the whole lens and bring it to agreement with a tolerance.

6 CONCLUSION

We have explored the magnet field distribution in quadrupole modules which are manufactured as a solid rings with smooth and continuous rotation of easy axis approaching to ideal law (1). The module construction of permanent magnet multipoles have been proposed for accelerator technics after we have analyzed numerical data of gradient and of nonlinear harmonics content. Particularly we have shown that module ring-type quadrupole lenses will allow to reduce significantly total sizes of drift tubes. This would give us possibility to use it in linear accelerators operating on higher frequency and with shunt-impedance being higher than in the case of discrete lenses.

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