APPLICATION OF PERMANENT MAGNETS FOR FORMING SOLENOIDAL FIELDS

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In the paper the possibility of forming a solenoidal magnetic field with the help of the permanent ring-shaped magnets is considered. The results of modeling a magnetic field for the magnets with the various inside diameter is shown. The possibility of the magnitude control of the magnetic field by the passive and active methods is investigated. In the work the estimation of the cost, mass and size of various magnets was done.
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1 INTRODUCTION

For some problems, for example, beam shaping in magnetron guns with secondary-emission cathodes [1, 2] it is necessary to have an enough homogeneous magnetic field of great magnitude. Now such fields form with the help of solenoids, powered direct current. The advent of new magnetic material enables to expand an area of application of permanent magnets. One of such possibilities is generation of the strong (~0.3-0.4T) solenoidal fields for klystrons on the basis of magnetron guns with secondary-emission cathodes and transporting of a charged beams in various systems.

2 MATHEMATICAL MODEL

For description of a magnetic field B we shall use the known relation [3]:

$$\mathbf{B} = \mathrm{rot}(A)\,, \tag{1}$$

where A is the vector potential equal [3]:

$$\mathbf{A} = \oint\limits_V \frac{\mathbf{M}\times\mathbf{S}}{S^3}\,dV\,, \tag{2}$$

where **S** is the vector, directed from the point Pm, in the neighbourhood of which is the volume dV, to the observation point P; **M** is the vector of magnetization of the volume element dV.

The formula (2) is valid on a sufficient distance of the point Pm from P.

For description of a field created by cylindrical magnetics we shall use a frame and labels shown in Fig. 1.

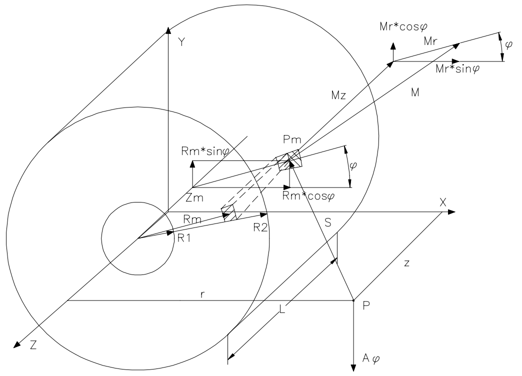

Fig. 1. Definition of a vector- potential (2).

Using the convention shown in Fig. 1 it is possible to show, that a vector potential of an infinitely thin ring with the radius Rm, each segment of which has only longitudinal (Mz), and radial (Mr) components of magnetization, in a view point P(z, r) looks like:

$$\mathbf{A}_\varphi = \frac{2\left(-\zeta_1 E\left(-4rRm/\zeta_3\right)+\zeta_2 K\left(-4rRm/\zeta_3\right)\right)}{\sqrt{\zeta_3}\,r\left(r^2 - Rm^2 + (z-Zm)^2\right)^2}\,, \tag{3}$$

where:

$$\zeta_1 = MzRm\left(Rm^2 - r^2 + (z-Zm)^2\right) + Mr(z-Zm)\left(Rm^2 + r^2 + (z-Zm)^2\right),$$

$$\zeta_2 = MzRm\left(Rm^2 + r^2 + (z-Zm)^2\right)^2 + Mr(z-Zm)\left((r-Rm)^2 + (z-Zm)^2\right)\left((r+Rm)^2 + (z-Zm)^2\right),$$

$$\zeta_3 = (r-Rm)^2 + (z-Zm)^2\,.$$

As the problem is axial, a potential has only the φ-component and does not depend on an angle φ. It is known [2], that in areas, where there are no sources (namely such a field we consider) the axial-symmetric field is completely determined by the value of the field on the axis.

$$Br = \sum_{k=1}^{\infty} \frac{(-1)^k B^{(2k-1)}(z)}{k!(k-1)!}\left(\frac{r}{2}\right)^{2k-1} = -B'(z)\frac{r}{2} + B'''(z)\frac{r^3}{16} - \ldots; \tag{4}$$

$$Bz = \sum_{k=1}^{\infty} \frac{(-1)^k B^{(2k)}(z)}{(k!)^2}\left(\frac{r}{2}\right)^{2k} = B'(z) - B''(z)\frac{r^2}{4} + B^{(4)}(z)\frac{r^4}{64} - \ldots.$$

Therefore let us determine only the z-component of the field on an axis. It essentially simplifies the expression:

$$\mathbf{B}z = \frac{1}{r}\frac{\partial\left(rA_\varphi\right)}{\partial r}\bigg|_{r=0} = -2\pi\,Rm\times$$

$$\times\frac{Mz\left(Rm^2 - 2\left(z-Zm\right)^2\right) + 3MrRm\left(z-Zm\right)}{\left(Rm^2 + \left(z-Zm\right)^2\right)^{5/2}} \tag{5}$$

In Fig. 2 the dependence of the magnitude B_z along the axis z at different directions of "elementary" ring magnetization is shown.

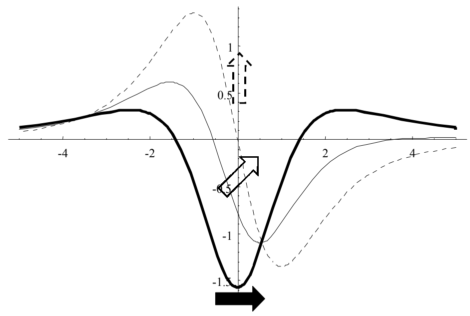

Fig. 2. Field on the axis of the ring composed of the magnet with a magnetization direction designated by the corresponding arrows.

ВОПРОСЫ АТОМНОЙ НАУКИ И ТЕХНИКИ. 2001. №5.
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3 FIELD OF THE SYSTEM OF RINGS

Using above-mentioned expressions one can calculate the system of rings, the field on an axis of which has a certain preset value. Let us suppose that there is a ring with the inner radius R_1, and outer radius R_2 and the length L_0. Make also a system from several rings packed along the axis z. At the top of such a cylinder we lay a similar system of rings with an inner radius R2 and outer radius R3 (see Fig. 3). In Fig. 3 the half of the cylinder composed from the separate homogeneous magnetized rings is shown. The second half is ambidextrous concerning a plane 0, R.

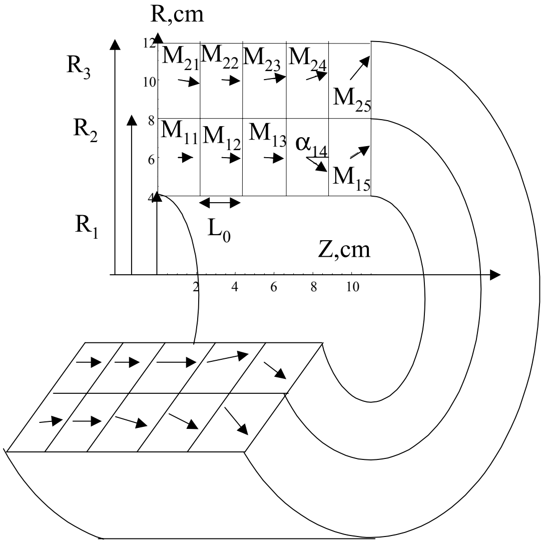

Fig. 3. Half of cylinder composed from separate homogeneous magnetized rings.

Varying number of rings in a consist of the cylinder and the directions of their magnetization at its given magnitude, were selected such parameters, which allowed to realized the preset field in the indicated area with a pointed exactitude. One of variants, which allows to make the field of 3кGs in area ±8cm, with the exactitude 1% represented in the Fig. 3. The angles α_{ij} of a magnetization of separate rings in this variant are:

$$\alpha_{i,j} = \begin{pmatrix} 1.96745 & -4.81172 \\ -5.32708 & 0.282978 \\ -1.6347 & 5.61662 \\ -36.4057 & 21.4499 \\ 26.8962 & 47.2088 \end{pmatrix} \circ .$$

The geometrical parameters of a ring were obtained analytically with usage of expression (4). The magnet with the analytically obtained parameters by the program PANDIRA (part of POISSON [5]) was calculated. The outcomes of these evaluations are shown in a Fig. 4. In both calculations was supposed, that the material of a ring is characterized in following parameters (see Fig. 5):

Br=1053Gs; Hc=-1053; the permeability in a perpendicular direction to easy magnetization is 1.

Such performances are representative of rare-earth materials (for example samarium-cobalt).

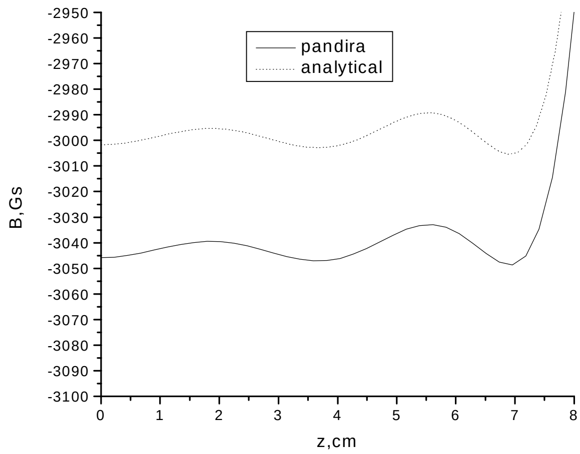

Fig. 4. Comparison of calculation results of the magnetic field by analytical methods ((4) application) and by numerical program PANDIRA.

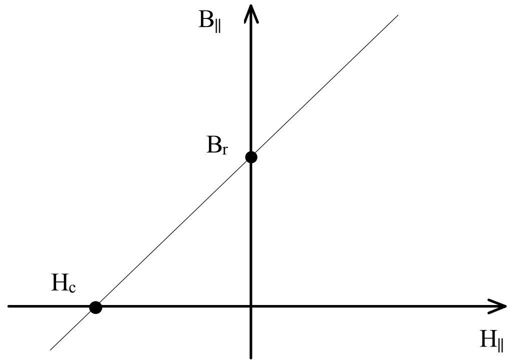

Fig. 5. The coercive force H_c (in Oersteds) and the remanent field B_r (in Gauss) for fields parallel to the axis.

4 CONTROL OF A FIELD

Let us consider influence of the presence of the material with the penetrability different from 1 on the field of inside and outside the cylinder.

In Fig. 6 the model of the magnetic cylinder with the location of magnetic screens is shown. Radius of an orifice is 4 cm, outside radius of the cylinder is 12 cm, barrel length is 10 cm. This figure maps a dextral half-plane of the magnetic cylinder, as it is symmetrically dichotomized by a vertical axis. In first case, the calculations were done for outside screens of 1 cm thickness, one of which is parallel to the axis (Armco1), the second screen is arranged perpendicularly to the axis (Armco2). In the second case the calculations were done for two interior screens (Armco 3) and (Armco 4) 0.5 cm thick.

In Fig. 7 the dependence of the field for the magnetic cylinder (Fig. 3) are shown at the presence of iron outside of the cylinder (see Fig. 6). The curve 1 corresponds to availability of two screens (Armco 1) and (Armco 2), the curve 2 corresponds to availability of a perpendicular axis of the screen (Armco 2), the curve 3 corresponds to availability of a parallel axis of the screen (Armco 1). In Fig. 8 the similar dependence for presence of iron inside the cylinder (see Fig. 6) is shown. The figures above are demonstrate that a field inside the cylinder can be controlled by the presence of iron. These are the bare bones of a passive method. In application of permanent magnets for making magnetic fields in magnetron guns it is very important, as the variation of the value and longitudinal allocation of a magnetic field disable generation of a beam coupling [1].

There is one more apparent possibility to control a field inside the magnetic cylinder i.e. current windings. Their application is easily described in an analytical aspect as at absence of nonlinear devices a magnetic field is equal to superpositions of fields of magnetic rings and current.

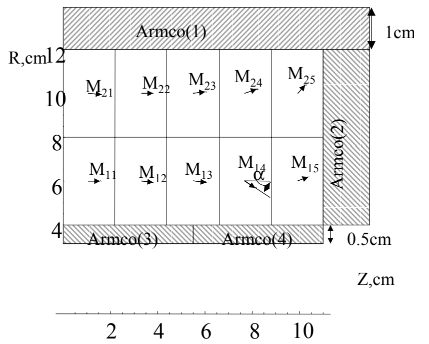

Fig. 6. The magnetic cylinder in environment of iron.

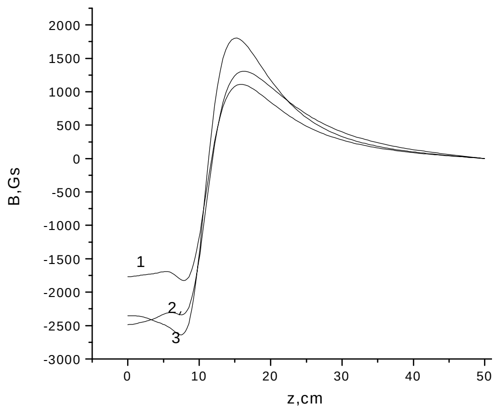

Fig. 7. The field distribution along the axis in the presence of iron outside of cylinder. 1 - armco (1) + armco (2); 2- armco (2); 3-armco (1).

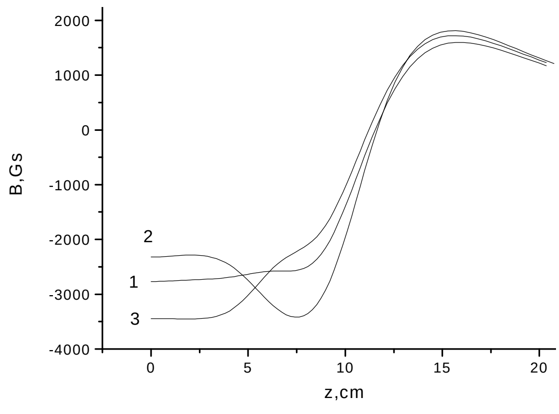

Fig. 8. The field distribution along the axis in the presence of iron inside of cylinder. 1 – armco(3)+ armko(4); 2–armco(3); 3-armco(4).

5 ECONOMICAL PARAMETERS OF MAGNETS

To estimate the economic efficiency of usage of permanent magnets for generation of solenoidal fields we shall estimate material consumption by a current solenoid in this process and compare them with expenditures on the permanent magnets. In Table 1 shown are the mass, leading dimensions and electro-technical parameters of permanent magnets and current solenoids with the help of which the field in the area ±8см of different radius, with a heterogeneity ΔB/B~1 % is realized.

Table 1. Main specifications of magnets

Inner radius cm	Outer radius, cm			Mass, кg			Dispersed power of the current solenoid, kW.	
	Permanent magnet	Solenoid		Permanent magnet	Solenoid			
		With cooling	Without cooling		With cooling	Without cooling	With cooling	Without cooling
0.5	4	5	18	8	14	125	2.2	0.9
1.	5	5.5	18	11	14	130	2.2	0.9
2.	8	6.5	20	31	19	145	2.8	1.
3.	10	7.5	20	50	22	153	3.4	1.
4.	12	8.5	21	79	27	161	4.	1.1

When evaluating the parameters of solenoids it was supposed, that the current in the noncooled solenoid is 10 A and the run on a wire by cross-section is 7 mm^2. In the chilled solenoid the current 500 A flows past a bus 8.5×8.5∅4. In both cases the solenoids should be iron-clad (penetrability ~1000, thickness 1 cm).

6 CONCLUSION

In each concrete case the application of permanent magnets or solenoids is determined by service conditions, infrastructure etc. At high diameters of an orifice a weight and the cost of a magnetic material can exceed a weight, cost of manufacture and operation of current solenoids. The application of permanent magnets for generation of solenoidal fields can be preferential when it is necessary to create a long solenoidal field and relative small radius (1-2 cm).

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