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CHARGED PARTICLES ACCELERATORS FOR NUCLEAR TECHNOLOGIES

Quadrupole Lens for DTL Linac

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Abstract—This article considers the possibility of using a hybrid permanent magnet quadrupole lens with correcting coil for a linear accelerator. The design of the lens was developed and its optimization was carried out to obtain a magnetic field gradient of sufficient magnitude in the aperture. Calculations were carried out in a specialized software package to determine whether the characteristics of the lens meet the requirements. The influence of variation of permanent magnet magnetization on the field quality was investigated.

Keywords: hybrid quadrupole, DTL linac, permanent magnets

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INTRODUCTION

The DARIA project (neutron source Dedicated to Applied Research and Industrial Applications) is aimed at developing compact neutron generators for universities, research centers, and industry [1–4]. As part of the project, a linear proton accelerator is being developed for which a lens that corresponds to the parameters specified in the second column of Table 1 is required. It is important to note that a high magnetic field gradient of 49 T/m is required, with the ability to adjust it up to 30%, and the geometric length of the lens should not exceed 130 mm.

The need to comply with size restrictions imposes special conditions on the choice of lens type and materials for it. In this case, a permanent magnet quadrupole or an electromagnetic quadrupole can be used. For the electromagnetic quadrupole, the field gradient can be adjusted and mass production is available. But this type of magnet needs a power source. And to achieve the required field characteristics in a large aperture, the electromagnetic quadrupole will have a large size and power consumption, which will cause difficulties in conditions of limited space according to the specification. The permanent magnet lens is compact and does not require a power source to operate. The disadvantages of such a quadrupole are the lack of a convenient way to tune the field and temperature instability [5, 6].

The work proposes a lens option that combines the advantages of using electric windings and permanent magnets. A similar lens was also considered in [7]. In the proposed design, permanent magnets are used to create the main magnetic flux and create 80% of the required field value. Windings are placed on the poles of the magnet to create an additional 20% of the magnetic field and its possible change.

Table 1. Comparison of parameters of the designed lens and specification requirements

Parameter	Specification	Project
Magnetic aperture	47 mm	47 mm
Integral of magnetic field gradient	6.3 T, 30%	6.2 T, 30%
Magnetic field gradient MAX/MIN	49 T/m, 30% planned	46 T/m, 30%
Maximum lens length	130 mm	130 mm (Effective length 134 mm)
Field nonlinearity for 75% aperture	≤0.7	0.3
Pole profile	Hyperbola	Hyperbola
Lens dimensions	450 × 450 × 130, mm	340 × 340 × 130, mm
Permanent magnet type	SmCo, B_r = 1.1 T	SmCo, B_r = 1.1 T

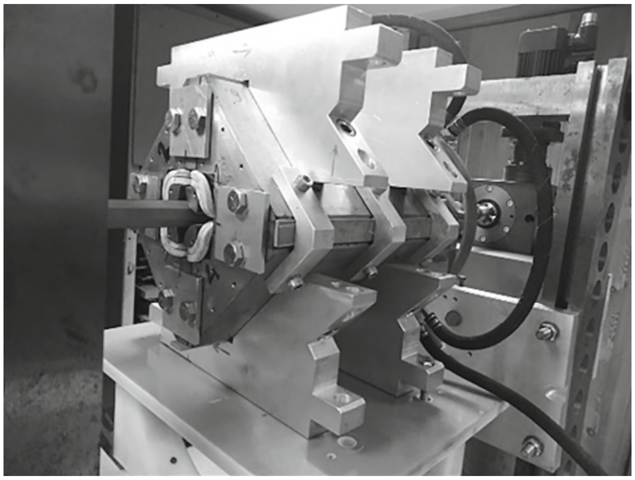

Fig. 1. Prototype of hybrid lens.

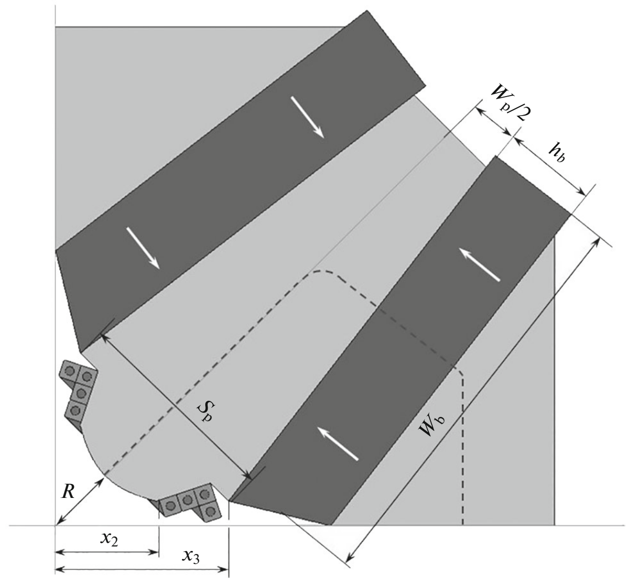

Fig. 2. Schematic view of lens and contour of integration.

This study will provide a description of the lens design, its characteristics, and an analysis of compliance with specifications. Using calculations carried out in a software package, it was verified that, under the given boundary conditions of operation of the lens as part of a linear accelerator, the required parameters are achieved: the integral of the field gradient and the homogeneity of the gradient.

HYBRID QUADRUPOLE DESIGN

A prototype of a hybrid quadrupole lens has been developed and created at the Budker Institute of Nuclear Physics (INP). The magnetic aperture of the prototype is 36 mm; the length of the lens is 240 mm. The dimensions of the prototype are larger than the dimensions shown in the specifications. At the same time, the magnetic field gradient of the lens is 65 T/m, which makes it unsuitable for the requirements for the DTL linac project, but confirms the experience of the INP in designing and manufacturing hybrid quadrupoles. A photo of the prototype is shown in Fig. 1.

For the DTL linac project, a lens design with permanent magnets made of radiation- and thermally resistant SmCo material is proposed. To ensure the required range of gradient adjustment, a full coil current of 2400 A-windings must be provided. A 6 mm × 6 mm bus bar with a total cross sectional area of 144 mm^2 is used for the coil.

In order to optimize the field force line distribution and increase the field concentration in the pole region, minimization of the fluxes through the coil and the scattering fluxes described by Eqs. (1) and (2) is necessary.

The magnetic circuit of a hybrid quadrupole is described as follows:

$$\frac{1}{\mu_0}\int_0^R B_r dl + \frac{1}{\mu}\int_{\text{core}} B_{\text{st}} dl + \frac{1}{\mu_0}\int_{\text{pm}} B_{\text{pm}} dl = NI + Mh_b, \quad (1)$$

where B_r is the field in the aperture, B_{st} is the field in the steel, B_{pm} is the field in the permanent magnet, M is the magnetization of the permanent magnet, and NI is the number of ampere-windings of the correcting coil. The integration contour is shown in Fig. 2 by the dotted line.

Neglecting the magnetic potential drop in the steel, we obtain the expression

$$\frac{GR^2}{2} = \mu_0 NI + H_M h_b, \quad (2)$$

where H_M is the field magnetization inside permanent magnet.

Simultaneously with Eqs. (1) and (2) for the field strength, the condition of conservation of magnetic flux from the permanent magnet block must be satisfied:

$$B_b w_b = \int_{x_2}^{x_3} B_0 dx + \int_0^{x_2} Gx dx + \int_0^{w_p/2} B_{w_p} dx. \quad (3)$$

Equation (3) describes the magnetic flux balance generated by the permanent magnet unit. Here $B_b w_b$ is the flux across the surface of w_b.

The surfaces for magnetic flux conservation are also shown in Fig. 2.

To compensate for scattering fluxes from the outer sides of the permanent magnet blocks, the tiles are approximated to each other by an amount of $w_p/2$. In this case, the width of the pole S_p in Fig. 2 should be optimized on the basis of two opposing factors:

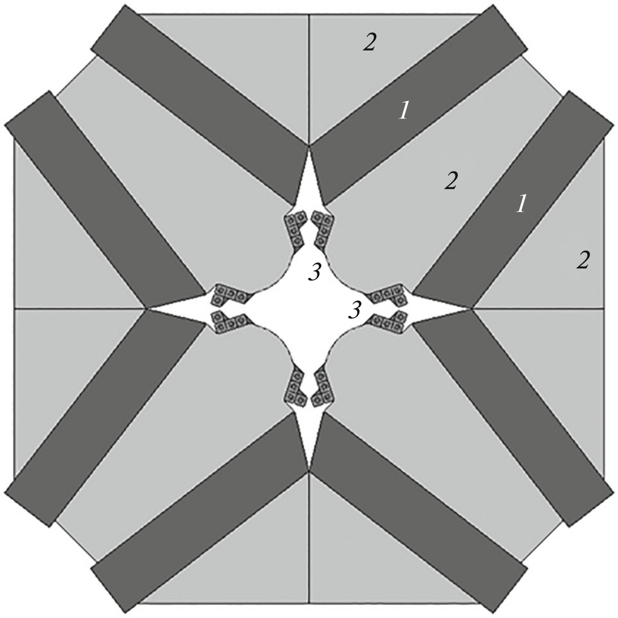

Fig. 3. Hybrid quadrupole design: (*1*) permanent magnets, (*2*) steel St-10, (*3*) winding.

(1) minimizing the width of $x_3 - x_2$ to reduce the scattering flux through it, but providing sufficient space for the correction coil;

(2) selection of sufficient width of S_p pole at which saturation of steel does not occur.

Minimizing the scattering fluxes leads to the magnetic quadrupole design shown in Fig. 3.

RESULTS OF LENS SIMULATION

The lens was simulated using a specialized software package based on the finite element method. The results are shown in Figs. 4–8. Figure 4 illustrates the distribution of the magnitude of the magnetic field induction vector in the cross section of the lens. The field lines in the lens contour are shown in Fig. 5. The greatest concentration of force lines and, consequently, the largest field magnitude are observed in the pole region.

Table 1 compares the lens requirements defined in the specification and the parameters of the designed lens confirmed by the results of lens modeling. Table 1 shows that the basic requirements are met, including the geometric length of the quadrupole and the resulting magnetic field gradient.

The influence of the variation of permanent magnet magnetization on the Fourier series coefficients describing the quadrupole field was investigated. A Fourier series expansion of the $B_\varphi(r)$ component was performed at a radius of 85% of the aperture at 128 points.

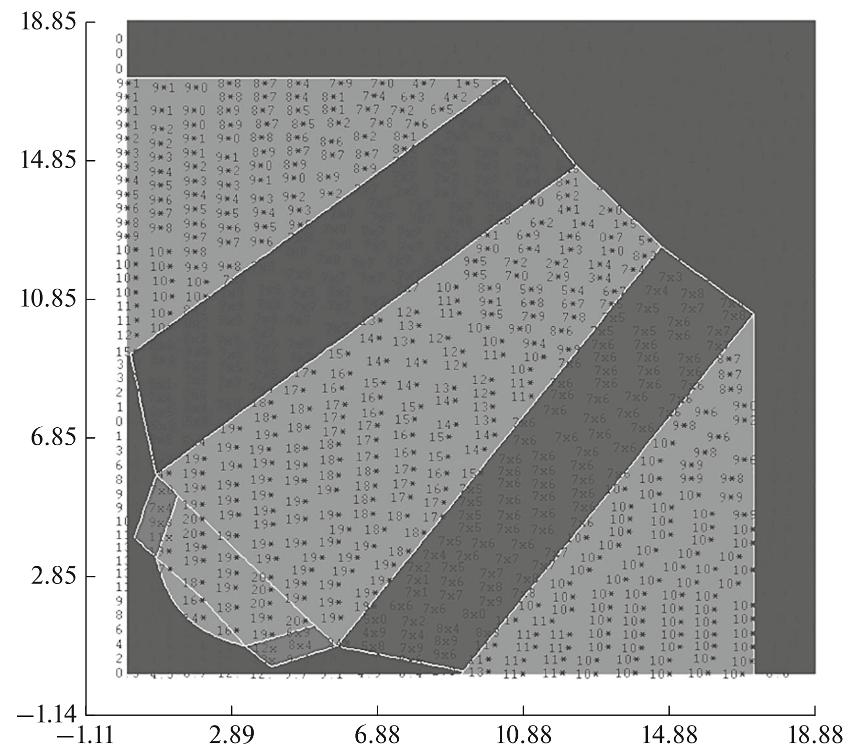

Fig. 4. Map of the module of the induction vector of magnetic field in lens cross section.

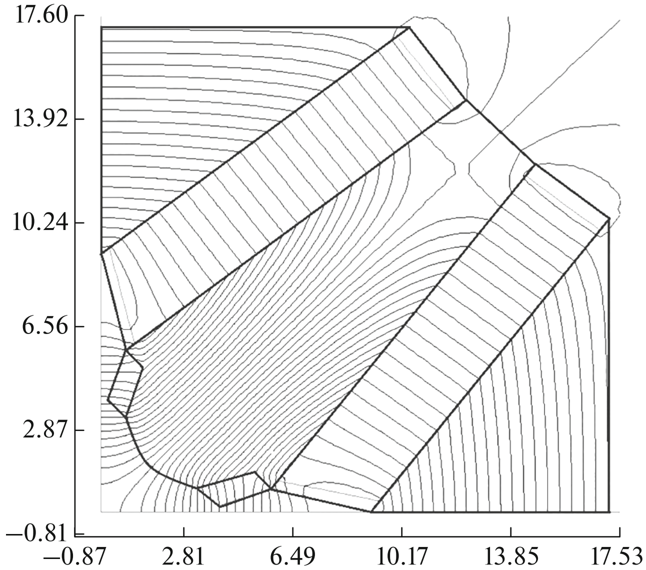

Fig. 5. Force lines of the field of quadrupole lens.

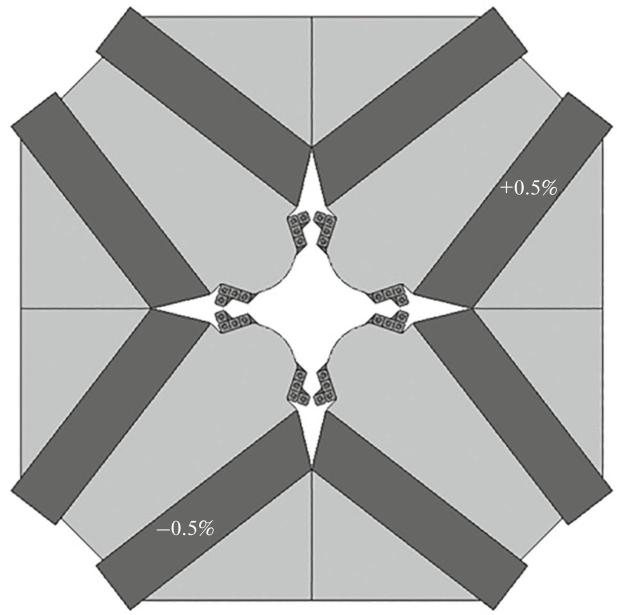

Fig. 6. Variation of magnetization in permanent magnet tiles.

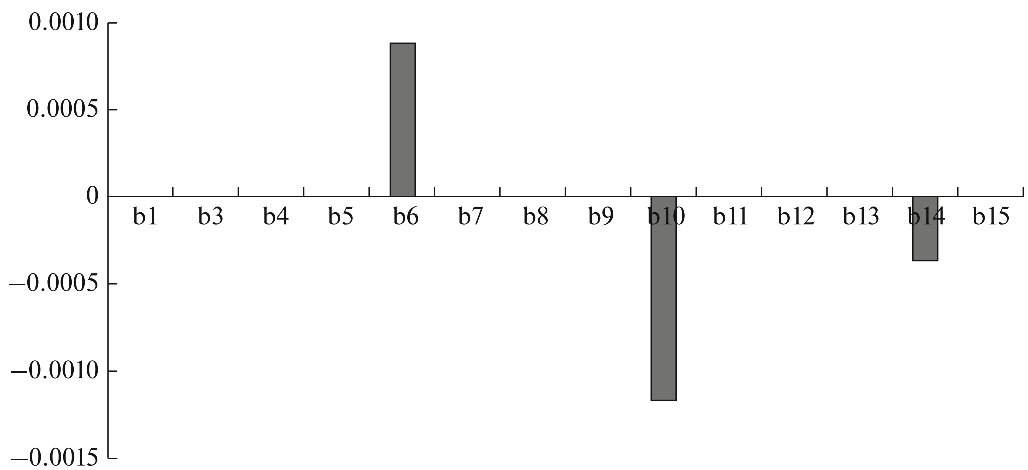

Fig. 7. Fourier series coefficients without magnetization scattering.

Several extreme cases were considered in which the magnetization varied by ±0.5%, which is an acceptable deviation in the production of permanent magnets. Figure 6 shows one of the considered cases of change in magnetization. Several more cases were analyzed using the same principle.

Figure 7 illustrates the distribution of terms of the Fourier series in the absence of magnetization scattering. Figure 8 shows that a dipole component appears in the field expansion in the case of magnetization deviation shown in Fig. 6. In this case, the distortion of the field components is the highest. In the remaining considered options, the values of the Fourier coefficients are within the range between the ideal case and the case in Fig. 6.

CONCLUSIONS

A prototype of a quadrupole hybrid-type lens has been designed and developed at the Institute of Nuclear Physics. The characteristics and dimensions of the prototype do not allow it to be used in a linac project for DARIA, but confirm that it is possible to create a lens with suitable parameters.

Simulation of the design hybrid quadrupole lens was carried out using a software package. The simula-

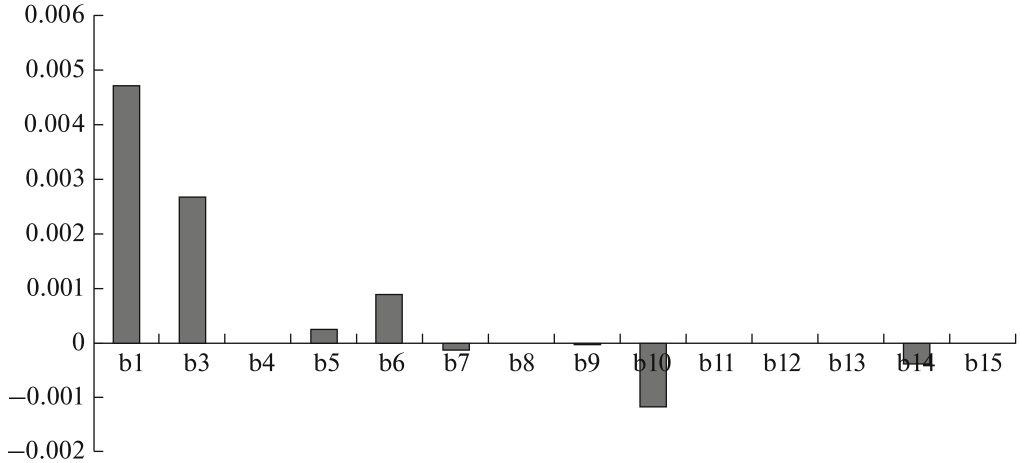

Fig. 8. Fourier series coefficients with magnetization scattering.

tion results show that the properties of the lens meet the requirements.

The influence of the scattering of magnetization of permanent magnets on the Fourier coefficients calculated for the lens field has been studied. The greatest possible distortion of the field under the influence of magnetization deviations has been determined, namely, the appearance of a dipole component. This component is responsible for the displacement of the magnetic axis of the lens and is not a problem, since it is easily compensated by the general movement of the lens. Other components occurring as a result of the violation of quadrupole symmetry of the field do not lead to a violation of the required homogeneity of the gradient.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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