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Hybrid Quadrupole Lens for the Focusing Channel of the DARIA Complex

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Abstract—The results of synthesis and electromagnetic calculation of a hybrid quadrupole lens for a proton linear accelerator of the DARIA compact neutron source are presented. The lens includes a permanent magnet quadrupole with a fixed magnetic field gradient and an auxiliary electromagnetic quadrupole excited by a pulsed current. The permanent magnet quadrupole is made of a radiation resistant rare-earth magnet and the electromagnetic quadrupole is designed to compensate for permanent magnet magnetization losses resulting from radiation degradation as neutron fluence accumulates during accelerator operation. A hybrid quadrupole lens can be applied for fast adjustment of the focusing channel as well as for transporting the accelerated ion beams with different ion mass-to-charge ratios.

Keywords: quadrupole, neutron generator, hybrid lens, electromagnetic calculation, ion beam, proton accelerator, electromagnetic lens, permanent magnet quadrupole

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INTRODUCTION

The DARIA (Dedicated to Academic Research and Industrial Application) project provides for the development and creation of a compact university-class neutron source designed to solve scientific problems, improve neutron techniques, for applied research, educational purposes and industrial applications, and for launch into mass production [1]. The DARIA complex, the scheme of which is shown in Fig. 1, can be applied in universities, scientific centers and industrial enterprises. In terms of the scale of tasks to be solved in one research and production complex, the DARIA multipurpose facility is, in essence, a megascience facility.

I.M. Kapchinsky was one of the first to propose the use of a linear ion accelerator as a neutron source driver. The scheme and preliminary parameters of a facility containing an accelerating section with spatially uniform quadrupole focusing, i.e., radio-frequency quadrupole (RFQ) and a drift tube linac (DTL) are described in [2]. The beam is focused by permanent magnet quadrupole lenses located inside the drift tubes. At present, a linear accelerator, which is an integral part of the DARIA complex [3], is under development at the Kurchatov Complex for Theoretical and Experimental Physics. The linac operates at a high frequency of 162.5 MHz and produces a pulsed proton beam with an energy of 13 MeV: current 100 mA and pulse duration 100 μs at a repetition rate of 100 Hz. It consists of an ion source and two accelerating sections, RFQ ≈5.4 m long and DTL ≈5.9 m long (Fig. 1). The low-energy beam transport channel brings proton beams from the ion source to the RFQ section inlet and provides the best proton capture during the acceleration. An intermediate channel that performs six-dimensional beam matching delivers an ion beam, preliminarily accelerated in the RFQ section, into the DTL section. Protons accelerated to the final energy are moved through various channels into experimental boxes by means of a magnet-manipulator.

The developed accelerator is designed to operate in the low duty-cycle mode (the duty cycle in the case under consideration is a significant value of 1%), which imposes additional restrictions on the accelerating structures. A feature of accelerators with this mode of operation is the requirement for almost 100% transmission (virtually no losses) of both the DTL channel and other accelerating structures, especially at high ion energies. In this case, it will be possible to avoid excessive activation of the accelerator in the DTL section. Under such conditions, quadrupole lenses of the focusing channel can be made on the basis of permanent magnets, which reduces the cost of electricity during operation of the installation. The experience of developing focusing channels with permanent magnet quadrupole lenses for high-current

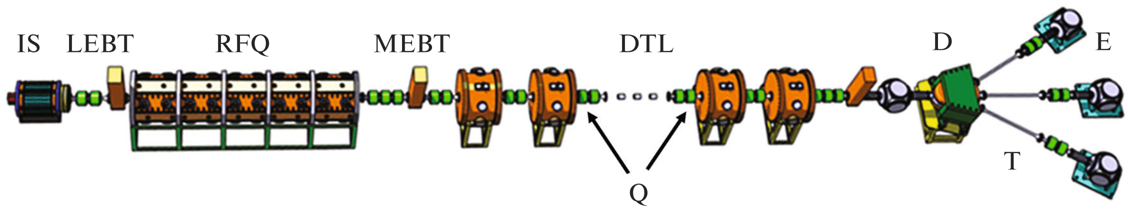

Fig. 1. Scheme of the DARIA accelerator complex: IS is the ion source; LEBT is the low-energy beam transport channel; RFQ is radio frequency quadrupole; MEBT is the medium energy beam transport Channel; DTL is the drift tube linac; D is the magnet manipulator; T is the channels for distributing the beam into the experimental boxes; E is the experimental boxes; Q is the quadrupole lenses of the focusing channel.

linear ion accelerators has confirmed the reliability and efficiency of using permanent magnets in accelerator technique [4, 5].

When developing the DTL channel, a concept was adopted, according to which this section would consist of a chain of separate, individually phased accelerating cavities with focusing magnetic quadrupoles located between these cavities.

In an accelerator with a single type of accelerated ion, there is no need to vary the gradients of the focusing channel quadrupoles during operation until external factors, such as changes in the operating temperature, aging, or radiation exposure, lead to significant changes in the magnetization of the magnetic material.

The destabilizing effect of the first two factors can usually be neutralized by the simplest means: artificial aging of the magnetic material and stabilization of the operating temperature [6]. To do this, it is often sufficient to apply natural convection if the lens operates in air, and not in a drift tube or in high vacuum of cavities. The third factor requires special care if the accelerator is of the high current type and, in addition, is designed to accelerate ions to a significant output energy. The situation becomes much more complicated if the accelerator operates in the ion factory mode, when a huge fluence of accelerated ions is accumulated on the irradiated objects in the experimental boxes over several decades. Then the loss of the accelerated beam in the accelerating channel could cause significant radiation degradation of the magnetic material [7, 8]. In order to increase the service life of the focusing channel, in this case, it is necessary to introduce additional means: protection of permanent magnets from direct impact by a scattered accelerated beam, a decrease in the neutrons yield from the vacuum chamber walls [9], the use of the most radiation-resistant magnetic materials, for example, a permanent magnet made of the Sm_2Co_{17} alloy. In particular, it is precisely for these reasons that it is preferable to bend the accelerated beam before it enters the hot area so that the backscattering of neutrons towards the accelerator and its equipment becomes impossible. If these measures are not enough, then to compensate for the loss of magnetization, a permanent magnet lens with mechanical gradient adjustment or lenses of a hybrid design by introducing an additional electromagnet operating in the direct current or the pulsed modes can be used.

DARIA PROJECT: DTL ACCELERATING SECTION

In the developed DTL section, as the particle energy increases, the focusing period multiplicity decreases: $K_F = 5 \rightarrow 3.6$, since only the lengths of the drift tubes increase, while the lengths of the lenses remain constant. A reduction in the multiplicity K_F makes it possible to gradually reduce the phase increment of transverse oscillations of particles; the beam radius and channel acceptance do not decrease. By choosing the rule of change of the phase increment, one can reduce the gradient of the magnetic lens and ensure the required acceptance, as well as find conditions under which the gradient and the magnetic lens lengths are constant along the entire channel. In particular, with a linear decrease in the phase shift $85°\downarrow 60°$, the absolute value of the magnetic lens gradient remains constant along the DTL channel and equal to 14.64 T/m (Table 1). This way opens up the possibility of making a focusing channel from completely identical lenses both in terms of geometric and magnetic parameters, which radically simplifies the fabrication of the channel and reduces the cost of the accelerator.

A period of the FOD type (method of alternating focusing and defocusing lenses and drift gaps) satisfies the requirements for the developed DTL section. When using five-gap cavities, it is possible to increase the focusing period to $5\beta\lambda$ (β is the relative proton velocity and λ is the wavelength of the high frequency field) and provide the required normalized acceptance. Table 1 lists the main parameters of the DTL section of the DARIA complex. As can be seen from Table 2, the developed DTL channel consists of six focusing periods of the FOD type. Each of them contains a five-gap cavity and two permanent magnet quadrupole lenses with constant gradients of 14.64 T/m, which differ only in sign. This channel provides an acceptance of 15 π mm mrad at an output energy of 13.2 MeV.

Table 1. Main calculated parameters of the DTL section

Accelerated ions	p^+
Beam energy, MeV	3.3–13.2
Injection current, mA	99.5
Beam duration, μs	100
Beam pulse repetition period, ms	10
Ratio of the channel acceptance to the beam emittance at the injection point into the section	3
Focusing period structure	FOD
Number of focusing periods	6
Lens aperture, mm	60
Focusing field gradient, T/m	14.64
Number of magnetic quadrupole lenses	12
Focusing period multiplicity	5–3.6

Table 2. Design parameters of the quadrupole lens for the DTL of DARIA complex

Number of lenses in the DTL	Material	Number of sectors	Aperture radius, mm	Outer radius, mm	Length, mm	Gradient integral, T
12	Sm_2Co_{17}	24	31	51	120	3.1

A very valuable property of the chosen type of focusing period is the small range of gradients of magnetic lenses; in practice, they differ from each other only in sign.

FIXED-GRADIENT QUADRUPOLE

At present, the DARIA project provides for the acceleration of proton beams only. Therefore, to ensure focusing in the DTL channel, it is proposed that a quadrupole lens be used based on permanent magnets made of the Sm_2Co_{17} alloy, which was developed at the Institute for Theoretical and Experimental Physics, 120 mm long, with a radius of the inner aperture of the vacuum chamber of 30 mm, and a maximal gradient integral of 3.1 T (Table 2). Initially, the theory and design of such lenses were described in [10–12].

To carry out dynamic calculations, a 3D distribution of the magnetic field in a quadrupole lens of the sector type made of Sm_2Co_{17} alloy with a remanent induction of $B_r = 1.05$ T, which is provided by the current level of production of permanent magnets of this class, was obtained. The distribution of magnetization in a lens with $N_s = 24$ sectors is shown in Fig. 2a. In the case of the magnetic aperture r_a, outer radius r_{out} and length L_{quad} (Table 2) in ideal case a magnetic field gradient of $G_{ideal} = 2B_r\left(1/r_a - 1/r_{out}\right) = 26.6$ T/m can be achieved, and the gradient integral would be $G_{ideal}L_{quad} = 3.19$ T.

In a sector quadrupole, due to the discreteness of the magnetization distribution, the gradient and the gradient integral are somewhat smaller. In the case under consideration, with the selected number of magnetic elements, the calculated gradient integral, which does not take into account the errors in the geometry and orientation of the magnetization in the

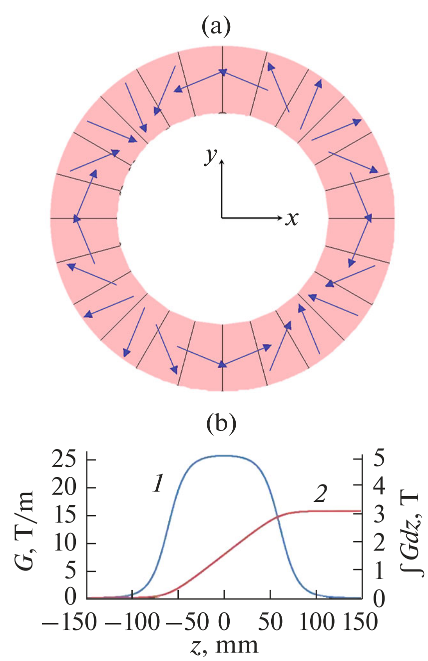

Fig. 2. Distribution of magnetization in a quadrupole lens (a), as well as the longitudinal distribution of the gradient (*1*) and the gradient integral (*2*) (b).

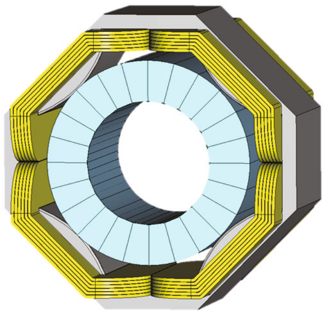

Fig. 3. Hybrid with a salient-pole electromagnet.

manufacture of sectors, is 3.12 T (Fig. 2b), which is only ~2% below the ideal one. Since the field on the aperture surface is only ~0.82 T, it is sufficient to use a samarium-cobalt permanent magnet with a low coercivity $H_{CI} \geq 1.2 \times 10^6$ A/m. The area of the magnetic field extension is of about 200 mm long. The selected regime is much lower than that achieved at present [13]: at a gradient of more than 120 T/m, the magnetic flux density at the pole tip is more than 1.8 T.

HYBRID QUADRUPOLE FOR DARIA

The above mentioned risk of a decrease in the magnetization of a permanent magnet due to radiation degradation stimulates us to take measures to restore the given lens gradient integral. Mechanical adjustment has a limited resource and requires additional efforts to reduce the influence of displacement of the magnetic axis of the lens relative to the optical axis of the accelerator channel upon the beam dynamics. Electromagnetic adjustment in this sense is preferable.

Figure 3 presents a hybrid in which the main magnet is the same as in the case discussed above (Fig. 2a), and the electromagnet is represented by a salient-pole quadrupole lens located outside the permanent magnet quadrupole. In this design, due to the remote location of the magnetic poles from the working area, early limitation of the maximum gradient occurs, so that the hybrid efficiency can be practically achieved in a small (up to ±20% of the average) range of adjustment of the gradient integral compared to its average value.

The specified range of adjustment of the field is reached at a current per pole up to 5 kA. In a coil conductor with 24 turns, the current density is 36 A/mm^2. Under these conditions, to reduce the average power, a pulsed power supply is required, and in order to ensure the frequency mode and duty cycle of the accelerator (Table 1) a trapezoidal shape of the excitation current pulse with a flat top with a duration of 100 μs and a minimum at the base is required [14]. This solution will reduce power dissipation by 30–50 times (Table 3), although it will require enhanced convection.

Figure 4 shows the results of electromagnetic calculation. The shape of the distribution curves of the total field gradient and the electromagnetic quadrupole contribution can be optimized by adjusting the length of, for example, the permanent magnet quadrupole. The difference between the forms of these distributions is insignificant. Superposition of the fields of the permanent magnet and electromagnetic quadrupoles arises due to the negligibly weak dependence of the magnetic state of the permanent magnet on the external field of the electromagnetic quadrupole. Therefore, it does not respond to multiple pulsed impacts of the electromagnetic quadrupole field, although it requires preliminary preparation of the magnetic elements of the permanent magnet quadrupole before assembling the lens to stabilize the return curves.

It should be noted that all elements of the electromagnetic quadrupole in the hybrid lens are moved a considerable distance from the working area, so the additional nonlinearity of the field due to the contribution of this lens is significantly weakened [15]. Therefore, on the one hand, the nonlinearity of the hybrid is practically determined by the discreteness of the permanent magnet quadrupole, and on the other hand, there is no need to use a special shape of the pole profile: it can be given the simplest shape, for example, a cylindrical one. This increases the efficiency of the electromagnetic quadrupole. Indeed (Fig. 4b), on the reference radius, which is 75% of the aperture radius, the nonlinearity of the electromagnetic quadrupole field is less than 0.1%.

Table 3. Hybrid lens parameters

Magnetic aperture of the electromagnetic quadrupole, mm	107
Geometric length, mm	120
Hybrid field gradient, T/m	30
Gradient integral, T	3.7
Nonlinearity at 75% of r_a, %	Less than 0.7
Excitation current, A	210
Dissipation power (direct current), kW	5

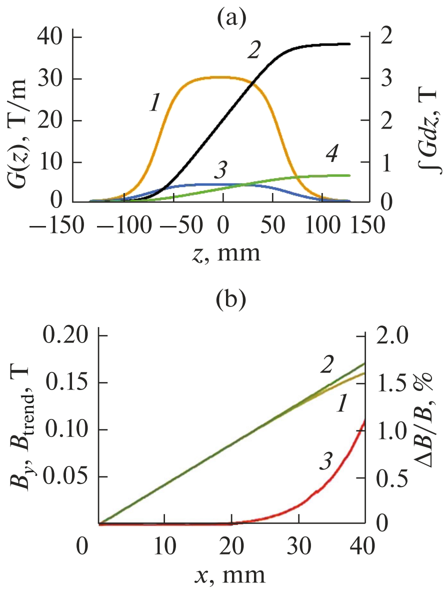

Fig. 4. Longitudinal distribution of the magnetic field gradient in the hybrid (*1*) and its integral (*2*), as well as the contribution of the electromagnet field gradient (*3*) and its integral (*4*) (a). Actual B_y (*1*) and linear B_{trend} (*2*) distributions of the field, as well as the deviation of the distributions $\Delta B/B$ (*3*) (b).

In the hybrid quadrupole (Fig. 5a) the electromagnet is made nonsalient-pole type. The turns of its winding are set so that the dependence of the current on the azimuth angle φ complied with the rule sin 2φ (Fig. 5b) [16–19]. Moreover, in line with the conclusion with respect to nonlinearity of the field of the electromagnetic quadrupole when analyzing the distribution shown in Fig. 4b, the winding space near the bisector of the first (and all other) quadrants is filled with electrotechnical steel. That is, four cores are formed, which, together with the cylindrical part of the magnetic circuit, significantly increase the efficiency of the electromagnetic quadrupole.

In the presented design, a similar resulting field as in the hybrid (Fig. 3) is achieved in the mode when the current in the conductor is up to 2.3 kA, and the same field adjustment range is possible with a current per pole up to 6.9 kA. Then in the conductor of a coil with three turns at a current density of 55 A/mm^2 the power dissipation is 31 kW. However, the inductance of such a lens is two orders of magnitude smaller, which will make it possible to shorten the fronts of the supply current pulse and bring its shape closer to rectangular. In addition, the overall size of such a lens is much smaller and amounts to 140 mm.

The list of possible designs, both electromagnetic and permanent magnet, which can be combined within a hybrid lens, is not limited to those indicated above. It can also include others, such as those described in [20–22], in which there is no restriction on the cross-sectional shape of the work region.

CONCLUSIONS

In the DTL section of the linear proton accelerator of the DARIA complex, it has been proposed to carry out focusing by permanent magnet nonsalient-pole quadrupoles. To increase the service life of the channel, the lenses will be made of rare-earth alloy Sm_2Co_{17}. The conditions for the functioning of lenses in the accelerator are considered. In order to compensate for a decrease in lens rigidity, which arises as a result of radiation degradation in the magnetization of a hard-magnetic material, it is proposed to use a hybrid quadrupole lens, in which it is possible to implement a gradient integral readjustment depth of up to 40%. Such a design can realize fast tuning of the DTL channel for ion beams in a small range of the mass-to-charge ratio. When the lens multipolarity is substituted by one, the function of a magnet manipulator can be provided (Fig. 1).

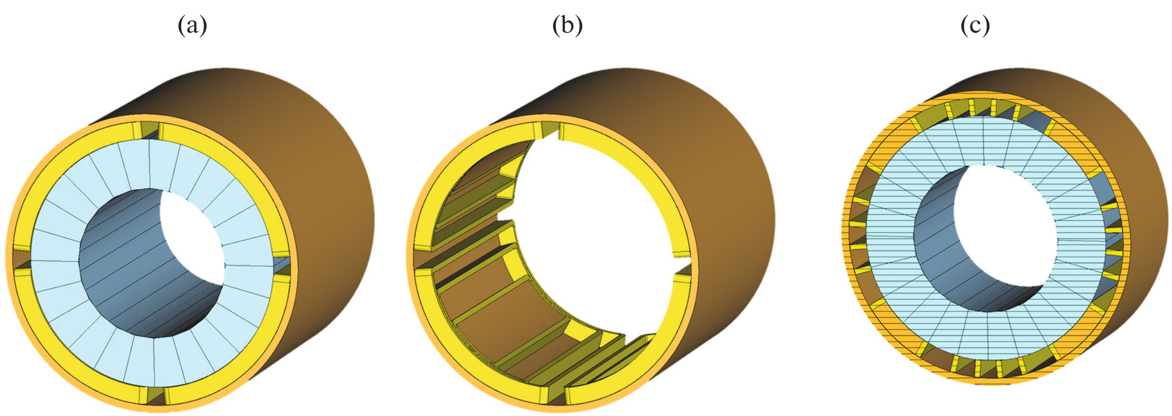

Fig. 5. Hybrid with an nonsalient-pole electromagnet (a), the structure of its winding (b) and a cross section (c).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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