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QUADRUPOLE LENSES WITH PERMANENT MAGNETS

V.A. Bovda, A.M. Bovda, I.S. Guk, V.N. Lyashchenko, A.O. Mytsykov, L.V. Onischenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: guk@kipt.kharkov.ua

The paper presents an overview of up-to-date design and conception of permanent magnet quadrupole lense. The overview covers two classes of magnetic systems that used in the beam transport facilities of accelerators as quadrupoles with fixed gradient and lenses with the field tuning in the wide range.

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INTRODUCTION

Magnetic dipoles and quadruples are key components of traditional transporting systems of the charged particles in the closed type accelerators. Dipole magnetic systems are used for the beam steering and quadruple ones are for the beam size and angel setting. The actual dipole and quadruple magnetic systems involve compact and low consumption layout. The discovery of new family of high performance rare-earth permanent magnets as SmCo magnets in 70s of twenties century and NdFeB magnets ten layers later developed the new approaches in the design of dipole and quadruple magnetic device [1–3]. As the result of high scientific interest, a lot of experimental magnetic systems were designed [4–9] that were used both in accelerators and other fields of physics.

Traditional concept of quadruple lenses introduces two layouts with permanent field and with alternating field gradient.

1. QUADRUPLE WITH PERMANENT FIELD

The broad literature overview of permanent magnets application in the accelerators technologies up to 90s of previous century was written by Robert H. Klaus Jr elsewhere [1]. The first analytical approach revealed by K. Halbach in 1980 showed the advantages of SmCo alloys for the forming quadruple lenses with high magnetic field gradients (please see [10]). Halbach quadruple lens consists of several segments. Each of magnetic segment has a specific magnetization direction (Fig. 1).

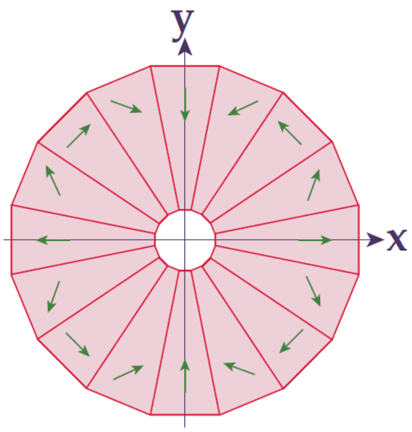

Fig. 1. The cross-section of Halbach quadruple assembled of 16 segments [2]

Magnetization of such quadruple can be expressed as [2]:

$$\underline{B}^*(\underline{z}_0) = \frac{\underline{z}_0}{r_1} B_r 2\left(1-\frac{r_1}{r_2}\right)K_2 \,,$$

$$K_2 = \cos^2\left(\frac{\pi}{M}\right)\frac{\sin(2\pi/M)}{2\pi/M} \,, \qquad (1)$$

where r_1 and r_2 – inner and outer radii of Halbach ring, M – number of segments, B_r – remanence.

Magnetic field for different number of segments is shown in Table [2]:

M	4	8	12	16	20	24
K_2	0.32	0.77	0.89	0.94	0.96	0.97

A typical remanence Br of about 0.95 T gives the gradient up to 6 T/cm for the quadruple with the radii of 2 and 10 mm that is not achievable for the traditional quadruple with the large aperture [2].

The experimental setup of 16 segments cylinder [10] is in good agreement with theoretical model elsewhere [2, 10]. Measurements of magnetic field are well consisted with the theoretical estimations.

The discovery and mass production of new generation of high-performance permanent magnets provided the wide development of Halbach conception. Modified Halbach cylinders are realized in various quadruple magnetic systems with fixed magnetic fields [9, 11–24].

For example, the quadruple with fixed magnetic field is used in the optical system of proton microscope at LANSCE proton beam facility of 800 MeV [9]

High-gradient quadruple are shown in (Fig. 2). The Halbach quadruple consists of 16 segments structure with the actual size of the lens of 1.5 inch, inner daimeter of 1.375 inch and outer diameter of 4.0 inch. The use of NdFeB magnetis with Br = 1.2 T gives the gradient of 71.6 T/m.

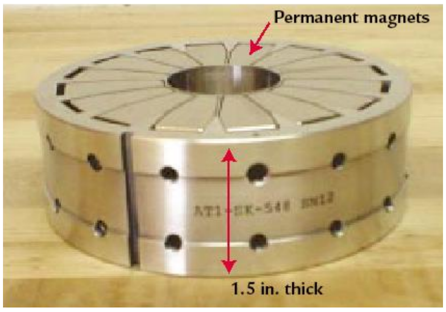

Fig. 2. Quadruple with 16 segments [9]

Optical system on the base of such quadruple lenses gives high-resolution pictures because of minimal chromatic aberrations.

Compact magnetic system with tiny lenses (Fig. 3) is used for the free-electron laser in the laser-plasma accelerator [11].

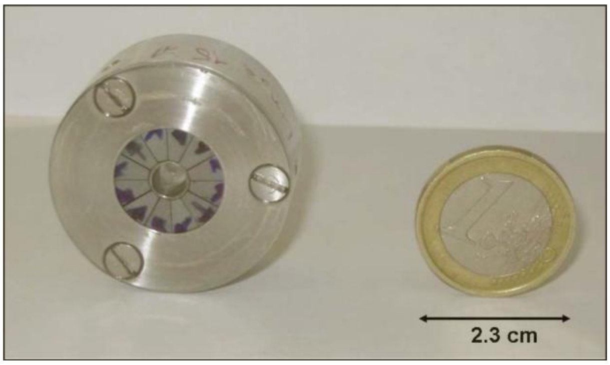

Fig. 3. General view of the compact lens [11]

The simple and efficient design of 12-segments Halbach quadruple assembly was designed with four radially magnetized NdFeB sectors making up the quadruple field and eight NdFeB sectors forming closed magnetic circuit [11]. The arrows in Fig. 3 show the magnetization direction of magnetic sectors. The inner radius of lens was 3 mm. A non-magnetic precision cylinder was embedded in the center of the lens to provide appropriate mechanical and magnetic field accuracy due to the high attraction force between four radially magnetized segments. Magnetic measurements showed good results withing whole lens aperture. A high accuracy of magnetic field with average gradient of (503 ± 6) T/m was obtained for ten lenses.

A triplet lines on the base of NdFeB magnets is developed for electron microscope [12]. Magnetic 35UH NdFeB wedges are cut by electrical discharge machine. Machined weges are assembled in 16-sector K. Halbach array with inner and outer diameter 3.5 and 7 mm correspondingly. The lines shows nearly 600 T/m field gradients. The triplet is located in special device (Fig. 4) that allows the adjust the individual position of each magnetic sector and obtain the image of input electron beam.

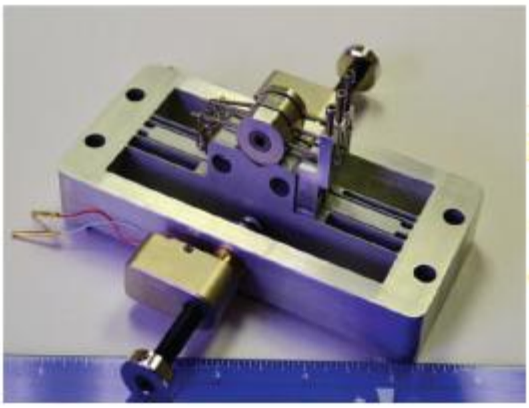

Fig. 4. Picture of the PMQ triplet setup [12]

Magnification ratios over 30x resulted in the development of short-time resolved electron microscopy and high-brightness electron beam [12].

The quick reconfiguration of the beam line with simultaneously high vacuum was achieved by the incorporating steel wedges into 16-section design and cutting the quadrupole along the steel [13] (Fig. 5). The maximum gradient obtained in a series of such lenses did not exceed 214 T/m.

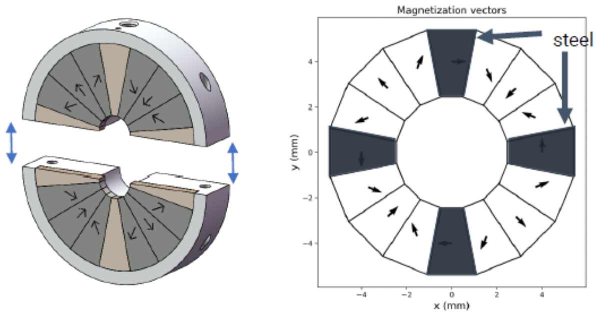

Fig. 5. Hybrid quadruple lenses [13]

Special manufacturing approaches were used for the fabrication of high-compact quadruples in the focusing systems with several lenses [14]. A long trapezoidal wedge with high remanence of Br = 1.22 T were machined to a specified design shape from a larger magnet block through an high precision cutting process, wire electrical discharge machining (EDM). The 16 magnetized sectors were then attached together carefully into an equally long aluminum keeper tube. Magnet wedges were installed inside the keeper and neighboring magnets additionally joined with each other by special glue to ensure structural stability of the system under extreme magnetic repulsion. The long assembly is then cut into six identical quadruples with mechanical length of 10 cm, to ensure consistent performance between all of them.

The inner diameter of bore is ground to the specified value of 5 mm with a diamond cutter.

Such manufacturing approach provides almost identical quadruple characteristics with the field gradient of 560 T/m. An illustration which schematically summarizes the quadruple manufacturing procedure is shown in Fig. 6.

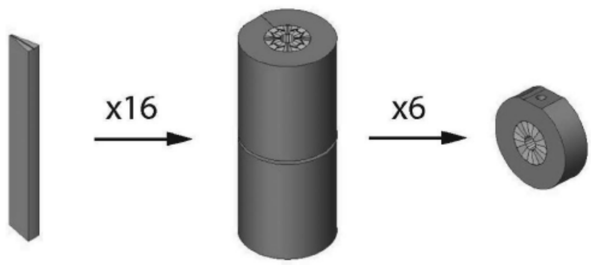

Fig. 6. Scheme of quadruple manufacturing procedure [14]

The advantage of above-mentioned technology was avoidance of measuring magnetic properties of very small magnets and sorting hundreds of magnetic sectors.

Quadruple lenses described in [2, 3, 9–14] have the fixed magnetic field parameters. Focusing system of such quadruples is adjusted by the position within axis beam as in traditional optical systems.

It was shown (Fig. 7) that soft magnetic inserts into K. Halbach wedges-structure increased the magnetic field generated by permanent magnets [15, 16].

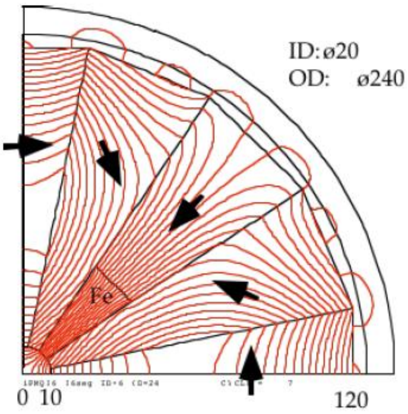

Fig. 7. Saturated iron permanent quadrupole magnet [16]

The gradient of magnetic field was improved from 2.2 to 2.4 T/cm by iron-wedge inserts. The gradient over 2.5 T/cm could be achieved with permendur.

The quadruple lens with permanent magnets was chosen as one of the favorites for the lens in the outlet system of liner collider [15]. The lens prototype was produced (Fig. 8) and demonstrated to have an integrated strength of 28.5 T with an overall length of 10 cm and a 7 mm bore radius. Additionally, special method was proposed to compensate negative thermal coefficient of magnetic field of permanent magnet material.

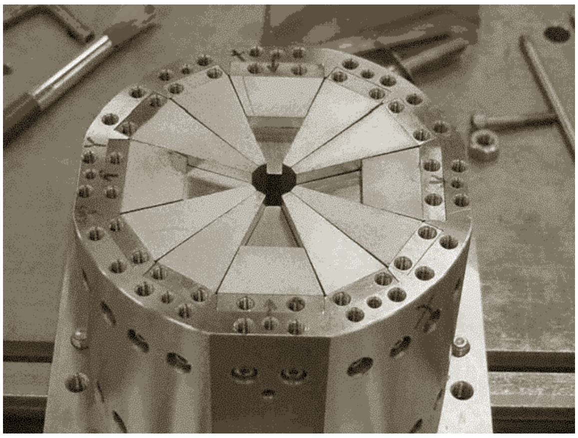

Fig. 8. Quadruple prototype [15]

Despite compact construction, zero power consumption and other advantages for the design of collider outlet, the fixed magnetic field of the system imposes some limits to the conception. The precise adjustment of magnetic field strength was made by cutting several sectors within the axis beam of the lens and rotating them to 90° without any skew component being introduced (Fig. 9).

Since ten such quadrupoles are supposed to be placed on the 2-m section of the final part of the focusing system, the focusing power can be changed in 1% increments due to the rotation of the segments.

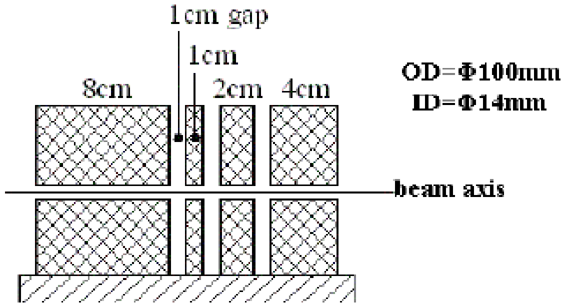

Fig. 9. Quadruple cross-section [15]

Sophisticated focusing systems on the base of double ring structures were developed in quadrupoles with variable magnetic field [15, 17].

Compact quadrupole with the strong gradient was constructed for the synchrotron facility [18]. The magnetic layout composed of rectangular magnetic blocks and soft magnetic yokes. The wide aperture in the horizontal plane provide the accommodation of x-ray port, a typical constraint in storage ring-based light sources. The quadrupole prototype is shown in Fig. 10.

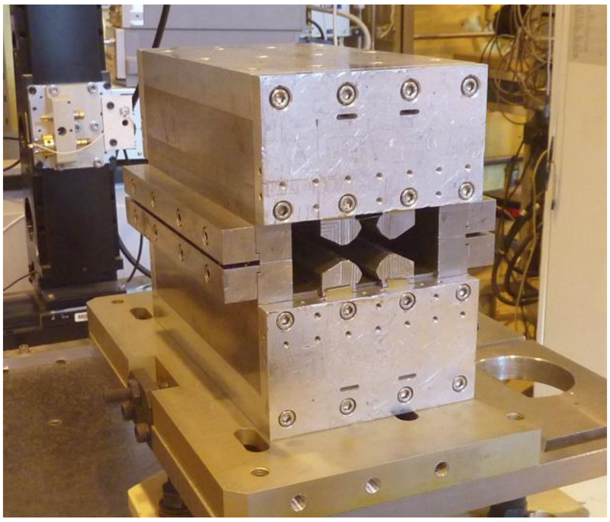

Fig. 10. Quadrupole prototype [18].

The outside dimensions of the quadrupole prototype are 210x160x230 mm. Three aluminum plates fixes the poles and magnetic blocks in the stable position. The upper part of the quadrupole can be dismanteled. The upper gap between the poles is 10 mm. The total weight of the device is 45 kg including 12 kg of magnets. The gradient is about 82 T/m. The configuration of the system composing of soft magnetic poles yields good compensation of the permanent magnet's inhomogeneity. The quality of magnetic field that mostly depends on mechanical errors could be improved by more effective pole shape and layout. The use of special iron-type shims results in considerable enhancement of the field quality. A gradient homogeneity better than 10^{-3} was obtained after installation of these shims.

A several types of quadrupole lenses on the base of 16-segment K. Halbach cylinders were constructed for Cornell-Brookhaven energy recovery linac test accelerator (CBETA) [19–23] (Fig. 11).

Magnetic field distribution at the focusing QF and defocusing QD magnets depicts the magnetic configuration of quadrupole lens (Fig. 12). The fixed component of BD magnets (Fig. 13) provides the much less use of magnetic material.

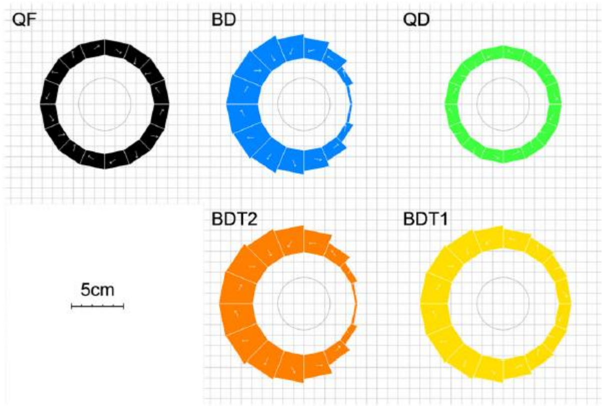

Fig. 11. Permanent magnet cross-sections [19]

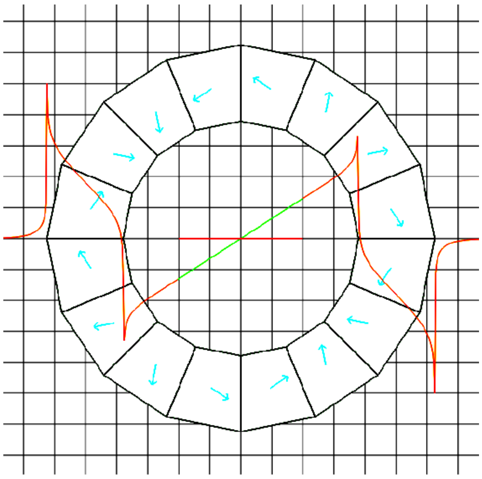

Fig. 12. Cross-section of the quadrupole 'QF' magnet. Blue arrows show magnetisation direction of the PM blocks. The orange line graphs the mid-plane field By'x; 0º, with green highlighting the good field region and red showing the beam position range in the accelerator [22]

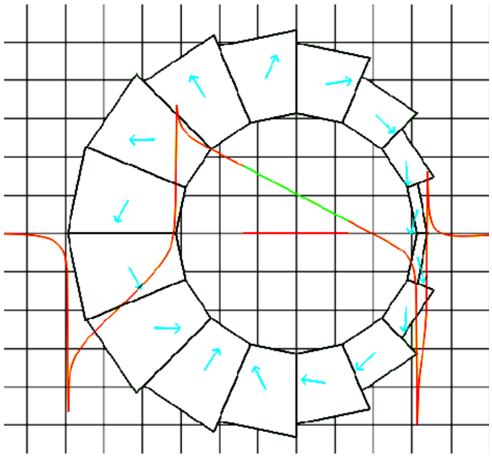

Fig. 13. Cross-section of the BD magnet [22]

Six quadrupoles with the gradient of 23.62 T/m and 19.12 T/m with dipole component of 0.377 T were developed [22]. Permanent magnet wedges of the quadrupoles were confined in 3D-printed plastic form. To guarantee high mechanical stability, the system fixed by outer aluminum tube. The special 3D-ptinted holder with pieces of iron wire was located in the bore. The pieces of wire were used for the correction the field quality of the quadrupole. The general view of the magnets can be seen in Figs. 14 and 15.

Fig. 14. QF magnet [17]

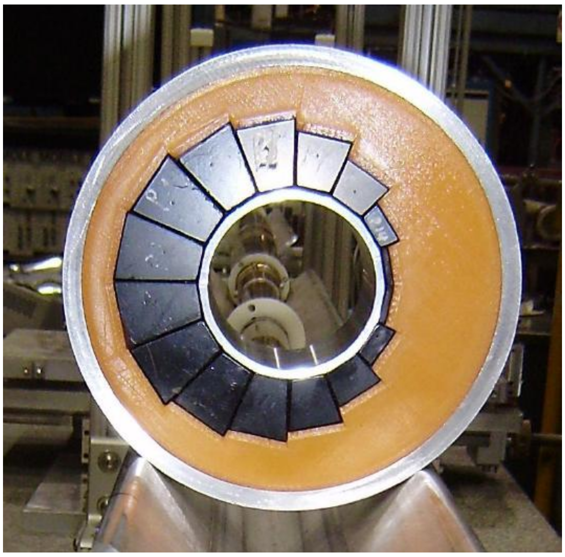

Fig. 15. BD magnet [17]

Water cooling system (T=85 F and high precision control about ±0.2 K) was used to stabiles magnetic field of the quadrupole due to negative temperature coefficient of NdFeB magnets of $-1.1 \cdot 10^{-3}$/K.

Quadrupole system of the same design was used in the outlet beam channel of proton therapy apparatus [24].

2. QUADRUPLE WITH ADJUSTABLE MAGNETIC FIELD

The basic principle of dipole and multipole magnets with smooth adjusting of the field gradient in the gap was presented by K.Halbach quadrupole elsewhere [25] (Fig. 16).

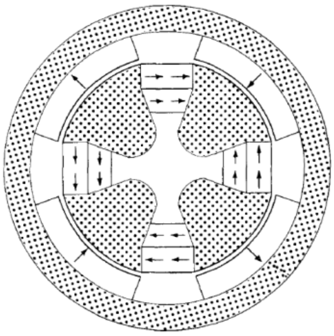

Fig. 16. Schematic cross section of a variable strength permanent quadrupole magnet [25]

The variation of the field in the quadrupole is carried out by the rotation of outer steel circle with fixed aligned magnetic sectors and four steel poles between magnets kept immovable. Fig. 17 depicts the quadrupole based on this K. Halbach conception [26].

Fig. 17. Photograph of the magnet assembly [26]

Laser-plasma acceleration of electrons [27] was studied by permanent magnet based QUAPEVA triplet lenses with adjustable gradient [28]. The scheme of magnetic field variation at these lenses is shown in Fig. 18.

QUAPEVA consists of K. Halbach ring with four NdFeB magnet cylinders.

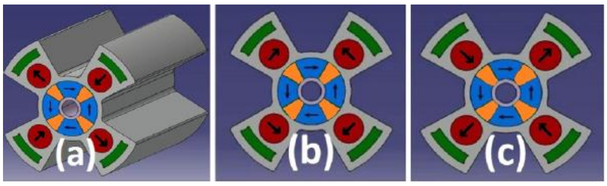

Fig. 18. Scheme of the QUAPEVA: Permanent magnet blocks (blue) and rotating cylinders (red), Vanadium Permendur magnetic plates (green) and poles (orange), and Aluminum support frame (grey). Maximum (a), intermediate (b), and minimum (c) gradients [28]

Four Fe-Co plates were placed behind cylinders to improve magnetic flux and gradient of the quadrupole aperture. Magnetic system is firmly secured in the aluminum frame to support magnetic elements due to the high magnetic force.

The variation of the gradient is done by the rotation of cylinders with the radial orientation of magnetic moment through drives. The general view of the quadrupole is presented in Fig. 19.

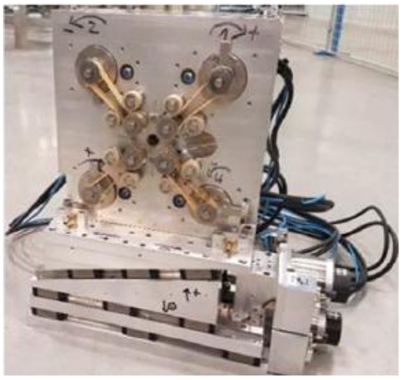

Fig. 19. Quadruple QUAPEVA [28]

The lens prototype has the length of 100 mm and the bore of 12 mm. The gradient of the lens can be adjusted in the range from 110 to 210 T/m.

Permanent magnet quadruple of the Next Linear Collider was designed by another principle [29]. The quadrupole consists of four independent assemblies driven by motors (Fig. 20).

Fig. 20. Схема магнита [29]

The device has a pole length of 42 cm and bore of 13 mm. The integral field gradient can be varied from 7 to 68.7 T. The soft magnetic poles (deep blue) and temperature compensating inserts (light blue) are shown in Fig. 20.

The principle of gradient variation via magnetic blocks displacement was used for numerous applications.

For example, for 42 km long CLIC Drive Beam Decelerator with beam energy in the range of 2.4 GeV…240 MeV, two porotypes of lens were developed. Each lens was designed for one of the ends of accelerator (ZEPTO project) [30, 31].

The layout of the quadrupole for the low energy outlet of the accelerator is shown in Fig. 21.

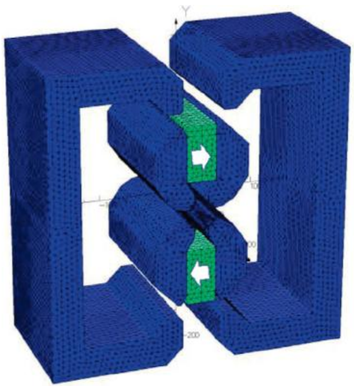

Fig. 21. Scheme of the quadrupole (ZEPTO project) [30]

The quadrupole consists of two blocks of permanent magnets that placed on the top and bottom of beam axis. Magnetic block can be moved adjusting the magnetic gradient within aperture.

The poles and yokes are made of iron. The bore and length of lens are 13.8 and 190 mm correspondingly. The magnets can be shifted to 75 mm that allow to vary the gradient from 2.9 to 43.8 T/m.

The quadrupole prototype was built at the STFC Daresbury Laboratory and magnetic measurements were performed at CERN (Fig. 22).

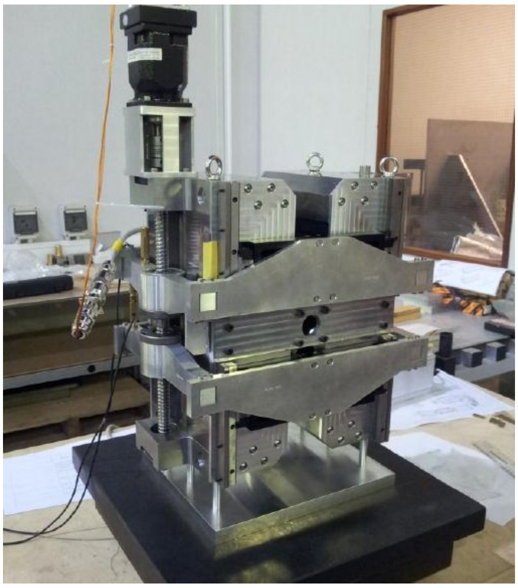

Fig. 22. The general view of the quadrupole [30]

The magnetic system of high energy outlet has different quadrupole design (Fig. 23) [31].

Two pairs of NdFeB magnetic blocks with the size of 18x100x230 mm possessing high remanence of 1.37 T are placed in the wagon. The wagon assisted by steel shim is located under and over poles. Blocks are moved up and down that leads to the variation of magnetic flux and, consequently, the alteration of quadruple field gradient. The poles remain fixed, which is a guarantee of the quality of the field. The lens length is 230 mm, the gap between the poles is 27.2 mm, the gradient varies from 15 to 60 T/m. The stroke of the moving part is 64 mm. The quality of the field in a gap of 23 mm changes by no more than 0.1%.

Fig. 23. The caption below figure

The sketch of the magnet is shown in Fig. 24.

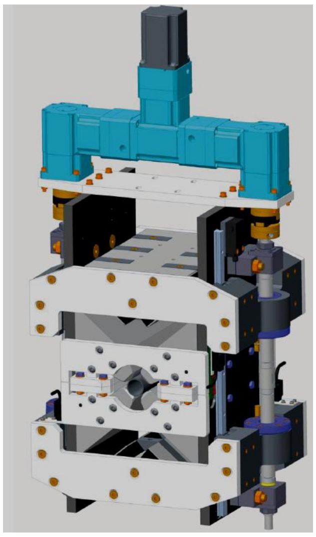

Fig. 24. Quadrupole design

A prototype quadrupole was also built at STFC Daresbury Laboratory.

CONCLUSIONS

The use of permanent magnets in the magnetic systems of accelerators enables the compact size design and low energy consumption of the facilities. In some cases, the permanent magnet design is the solely method to obtain specific parameters of magnetic field due to inability to get by the traditional quadrupoles. The choice of certain constructive solutions for lenses is dictated by the beam parameters and operation conditions of the equipment, and usually individual.

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КВАДРУПОЛЬНІ ЛІНЗИ З ПОСТІЙНИМИ МАГНІТАМИ

В.О. Бовда, О.М. Бовда, І.С. Гук, В.М. Лященко, А.О. Мициков, Л.В. Онищенко

Проведено огляд конструкцій квадруполів, побудованих із використанням постійних магнітів. Для роботи в системах транспортування пучків у прискорювачах використовуються квадруполі з постійним значенням градієнта поля та пристрої, що дозволяють змінювати його величину плавно в широких межах.