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PHYSICS AND TECHNIQUE OF ACCELERATORS

Development of a 540° Magnetic Buncher Based on Permanent Magnets

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Abstract—To obtain short electron bunches with a large charge, special magnetic systems with a strong dependence of the time of flight on the particle energy, so-called magnetic bunchers, are used. This paper considers one of the variants of such a system and describes its main elements: magnetic mirrors. Permanent magnets are used to simplify the design and increase the stability of the magnetic field.

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INTRODUCTION

For many technological and research purposes, it is necessary to obtain short (picosecond) electron bunches with a large charge. In this case, the normalized emittance of the electron beam should also be small. Such bunches can be obtained by the bunching (longitudinal compression) of electron bunches with a lower peak current. To overcome Coulomb repulsion, bunching should be carried out at relativistic electron energies in a special magnetic system with a strong dependence of the time of flight on the energy of particles—a so-called magnetic buncher. A few years ago at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, an original scheme of such a device was proposed [1]; one of the variants is shown in Fig. 1.

The buncher consists of two 30° magnets with parallel edges and two magnetic mirrors. Passing successively through the first parallel-edged magnet, the large magnetic mirror, the small magnetic mirror, the large magnetic mirror, and the second parallel-edged magnet, the electrons rotate through 30° + 120° + 24° + 120° + 30° = 540°. The radii of the trajectories in the bending magnets and the distances between the magnets are chosen so that the bend is achromatic. This means that the horizontal angle and coordinate of the electron leaving the last bending magnet do not depend (in a linear approximation) on the deviation of the energy of this electron from the calculated energy (i.e., the energy of the reference particle). The buncher is supposed to be installed in the electron injection channel with a kinetic energy of about 1.5 MeV at the Novosibirsk FEL facility [2]. Thirty-degree magnets already exist, so this article only presents the design and results of calculating the field of magnetic mirrors.

DESCRIPTION OF MAGNETS

To obtain the high stability of the magnetic field and reduce the cost of the system in the design of mag-

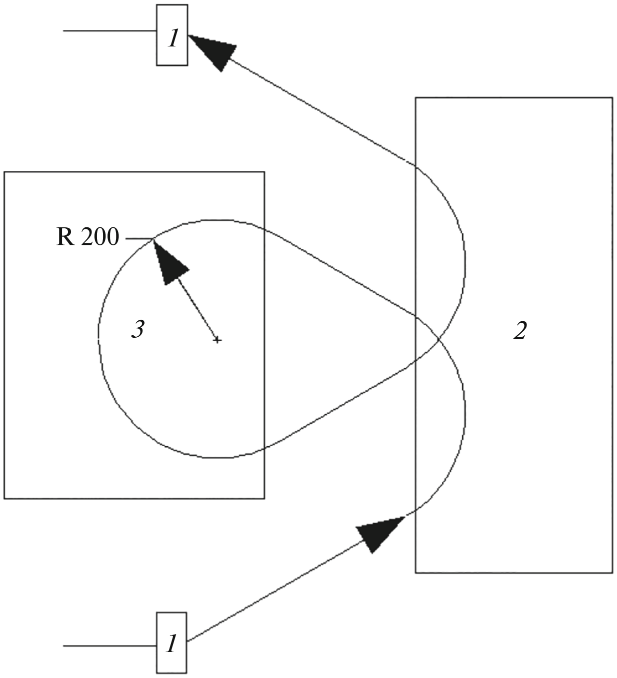

Fig. 1. Scheme of a bunching magnetic system with a rotation of 540°: (*1*) 30° magnets, (*2*) large magnetic mirror, and (*3*) small magnetic mirror. The reference trajectory of electrons is shown as a solid curve.

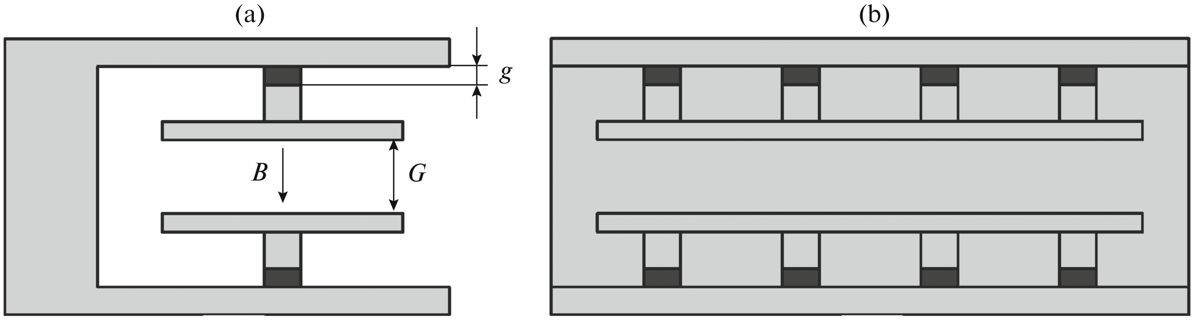

Fig. 2. Scheme of a magnetic mirror: (a) side view and (b) front view. Tiles of the magnetic material are in black, the iron magnetic cores are in gray, and the arrow shows the direction of the field vector in the working gap.

netic mirrors, permanent magnets made of neodymium–iron–boron alloy with residual induction. B_r about 13 kG and the energy product $(BH)_{\max}$ about 40 MG Oe are used. With such parameters of the magnets, in order to minimize their number (the total volume of the magnetic material), it is necessary to obtain an induction in the magnets of about 7 kG. In this case, the required field in the working gap of the magnets is much smaller (about 300 G). Therefore, in order to obtain a sufficiently large induction in permanent magnets, an iron magnetic circuit must ensure the concentration of the magnetic flux passing through the working gap in the volume occupied by permanent magnets. When developing the geometry of the magnetic cores, standard tiles of magnetic material with dimensions of 40 × 40 × 20 mm^3 with magnetization along short edges were chosen. The scheme of the magnetic mirror is shown in Fig. 2.

The large and small magnetic mirrors differ only in some dimensions and in the magnitude of the field in the working gap.

The first stage in the development of an electron-optical circuit consisted of a preliminary estimate of the field strength, made using the method of approximate analytical calculation (Rothers method) [3]. This method is based on the well-known statement from electrostatics [4] that an electric dipole with moment *d,* introduced into a flat capacitor with a capacitance C and gap g, creates a potential difference

$$U = \frac{d\cos\theta}{gC}, \tag{1}$$

where θ is the angle between the direction of the dipole moment and the normal to the inner surface of the conductor. Because iron has a large magnetic permeability at fields that are not too high, iron magnetic circuits can be considered magnetic equipotentials and formula (1) can be used to calculate the potential difference, replacing electric dipoles with magnetic ones. For hard magnetic materials, the dipole moment per unit volume (magnetization) is approximately equal to $B_r/(4\pi)$ and the field in a flat working gap with a height G (see Fig. 2) is found by dividing the scalar magnetic potential of the iron pole by half the height of the gap

$$B = \frac{B_r S}{2\pi C G}, \tag{2}$$

where S is the total area of the magnetic material tiles in the upper half of the magnet, and it is assumed that the height of these tiles is equal to height g of the gap between the iron pole and the shield at zero potential; C is the equivalent capacitance of one (for example, upper) pole. For calculations of the magnetic field, magnetic conductivity $4\pi C$ is usually used instead of capacitance C. The magnetic conductivity is equal to the ratio of the magnetic flux flowing from the pole in the absence of permanent magnets at a given scalar magnetic potential to the magnitude of the potential. This value depends on the shape of the magnetic circuits and is fairly easy to estimate [3]. For example, for a gap filled with permanent magnets (“flat capacitor”), the magnetic conductivity is approximately equal to S/g, that is, the ratio of the area of the gap to its height. The flux flowing out of the upper pole is the sum of the flux through the plane of symmetry of the magnet and the flux leaving to the screen. A significant portion of the second flux passes through a relatively small permanent magnet gap. Therefore,

$$4\pi C = \frac{2S_G}{G} + \frac{S}{g} + 4\pi C_p, \tag{3}$$

where S_G is the effective area of the working gap and C_p is the parasitic equivalent capacitance describing part of the flow from the pole to the screen. Substituting (3) into (2), we obtain the final expression for the field in the working gap

$$B = \frac{B_r}{S_G/S + G/(2g) + 2\pi C_p G/S}. \tag{4}$$

Using field B and thickness g of the tiles of magnetic material, one can find the required area of tiles

$$S = \frac{S_G + 2\pi C_p G}{B_r/B - G/(2g)}. \tag{5}$$

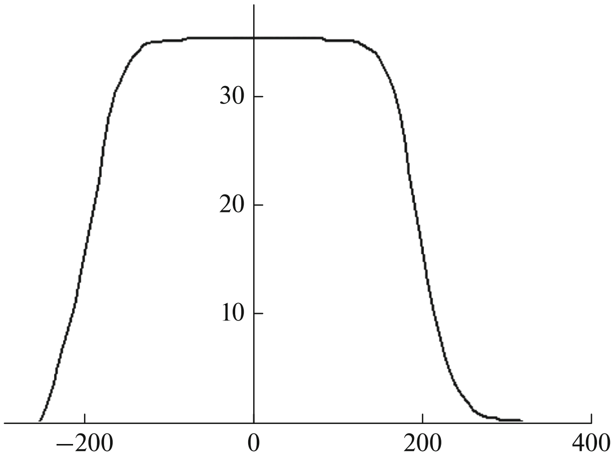

Fig. 3. Calculated dependence of the induction (mT) in the median plane of a large magnetic mirror on the coordinate (mm) across the edge of the magnet.

As was noted above, field B in the working gap should be much smaller than the residual induction B_r, so the area of the magnetic material tiles is relatively small and they are connected to the poles by separate iron spacers, as is shown in Fig. 2.

CALCULATION AND OPTIMIZATION OF THE MAGNETIC SYSTEM

The next stage of work was to calculate the field using CST-Studio, a software package that implements the functions of a computer-aided design system and electromagnetic simulation. At the same time, the dimensions of the magnetic circuit elements were optimized to obtain the required field in the working gaps of both magnetic mirrors using the minimum volume of magnetic material. In addition, the location of the permanent magnet tiles was optimized to obtain the required field homogeneity in the working gap. One of the calculation results is shown in Fig. 3. With working gap $G = 84$ mm, characteristic values of B fields in the median plane are approximately 330 and 220 G for small and large magnetic mirrors, respectively. The dependence of the field on the distance to the edge of the magnet will be used to refine the shape of the trajectory shown in Fig. 1.

CONCLUSIONS

A design of magnetic mirrors for an electron buncher using permanent magnets has been developed. The use of permanent magnets made it possible to significantly reduce the cost of magnetic mirrors, since there was no need to use expensive direct current sources with high stability and manufacture copper windings. In addition, the weight of magnetic mirrors on permanent magnets is much lower than for the electromagnetic version.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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