STUDY OF BEAM DYNAMICS IN MAGNETIC ELECTRON BUNCHER FOR NOVOSIBIRSK FREE ELECTRON LASER

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Abstract

This paper presents the current state of buncher design for the Novosibirsk Free Electron Laser (FEL) and study of the impact of space charge on transverse dynamics of the bunched beam.

INRODUCTION

Many applications of accelerator technology require electron bunches with length of about 10 ps, the peak current exceeding 100 A and the normalized emittance being less than 100 mm·mrad. To produce such bunches, special electron-optical systems, known as magnetic bunchers, are widely used. Designing a 540° magnetic buncher has started several years ago at Budker INP FEL facility [1]. Such a device enables users to obtain extremely short bunches with large charge. Effective bunching is provided by the particularly strong dependence of the time of flight on the particle energy. In addition, for reduction of the maintenance costs, the whole electron-optical system is based on permanent magnets. The buncher is to be put into operation in the 1.5 MeV electron injection channel of the NovoFel facility.

The following tasks were performed during the development of the buncher.

- Development and optimisation of the electron-optical scheme of the buncher.
- Development and optimisation of the magnetic system elements.
- Study of the influence of the space charge on the electron beam parameters and the corresponding limitations of the minimum electron bunch sizes.

The device consists of two 30-degrees magnets with parallel edges and two magnetic mirrors (see Fig. 1). Radii of the electron trajectories in bending magnets and the distance between magnets are chosen in such a way to ensure the achromatic bend. The calculation of the trajectory, longitudinal dispersion, and the transverse focusing for particles is described in the article [2]. After passing through a 30-degrees magnet with parallel edges, magnetic mirrors, another 30-degrees' magnet with parallel edges and a quadrupole magnetic lens, electron enter a focusing lens with a longitudinal magnetic field with a sharp edge. The latter is necessary to obtain a small transverse size of an electron beam.

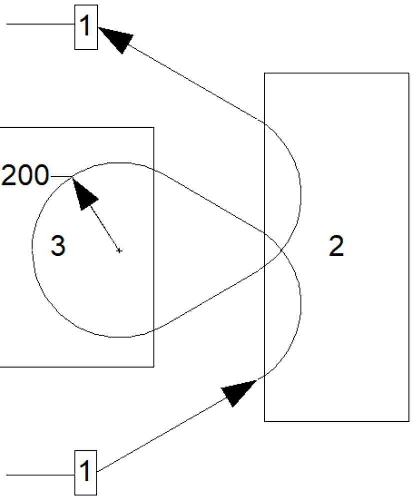

Figure 1: The scheme of the 540-degree bend magnetic electron buncher: 1 - 30-degree magnets, 2 - large magnetic mirror, 3 – small magnetic mirror. The reference trajectory of the electrons is shown by a solid curve.

30-degree magnets and a quadrupole lens already exist. Therefore, this paper presents only the designs and results of calculating the field of magnetic mirrors and an axisymmetric lens with a longitudinal field.

OPTIMIZATION OF THE MAGNETIC SYSTEM ELEMENTS

The process and results of calculation and optimization of magnetic mirrors are described in detail in the article [3]. The schemes of the magnetic mirror and the short-focus lens are shown in Fig. 2 and 3.

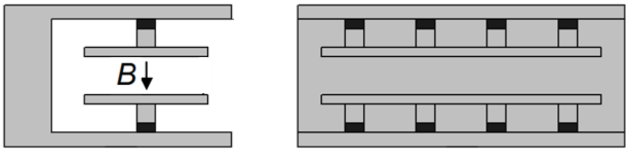

Figure 2: The scheme of a magnetic mirror: left – side view, right – front view. The blocks of the permanent magnet material are shown in black, the iron magnetic cores are shown in grey, and the arrow shows the direction of the field vector in the working gap.

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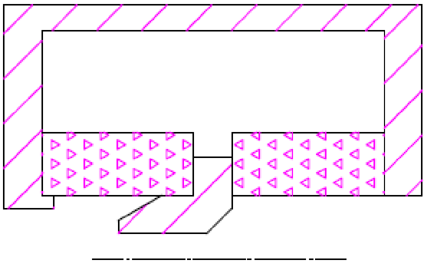

Figure 3: Longitudinal section of an axisymmetric lens with a longitudinal field. The oblique shading shows the details of the iron magnetic core, the triangular one shows the direction (along the axis of symmetry) of the magnetization of the pucks made of neodymium-iron-boron material. The electron beam enters from the left.

The result of calculating the magnetic field profile for one of the magnetic mirrors and the lens with a longitudinal magnetic field are shown in Fig. 4 and 5.

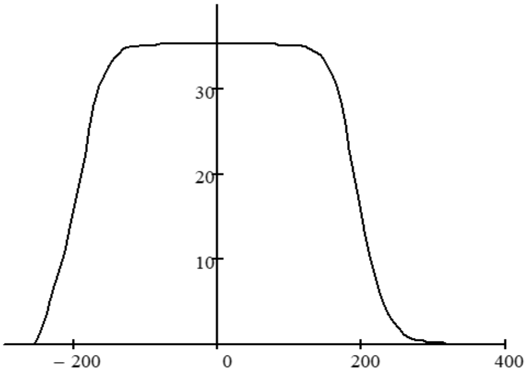

Figure 4: Calculated dependence of the induction (mT) in the median plane of the small magnetic mirror on the coordinate (mm), across the edge (right slope) of the magnet.

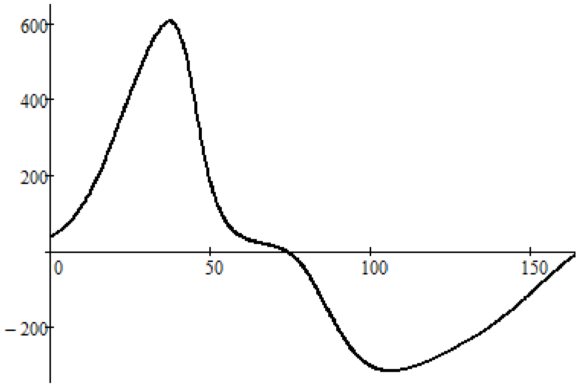

Figure 5: Calculated dependence of the induction (mT) on the coordinate (mm) on the axis of symmetry of the magnetic lens with a longitudinal field.

STUDY OF THE SPACE CHARGE IMPACT ON THE FOCUSING OF THE BUNCHED BEAM

After the particles pass through the magnetic mirrors, the bunched electrons enter a focusing magnetic lens with a longitudinal axisymmetric field, the source of which is permanent magnets. To obtain the minimum transverse sizes of the electron beam, the shape of the magnetic core of the lens (see Fig. 3) provides the maximum steepness of the field dependence on the coordinate field at the entrance to the lens. Using such a lens allows allows to achieve a small «focal length» (see Fig. 6).

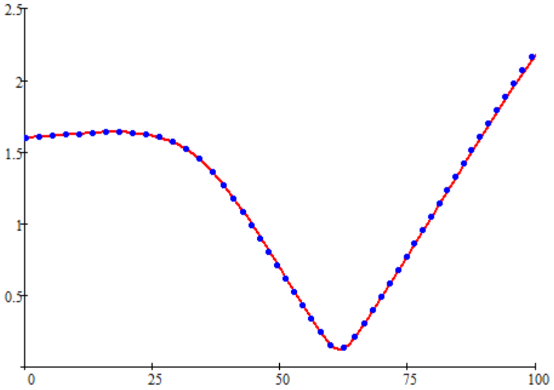

Figure 6: Dependence of the standard deviation in the transverse coordinate (mm) on the longitudinal coordinate (mm) for an axisymmetric permanent magnet lens for the NovoFEL, simulation (blue dotted line) and numerical solution (red line).

To evaluate the effects associated with the influence of space charge on the transverse dynamics of particles, the Kapchinskij-Vladimirskij equation for an axisymmetric beam of radius a in a longitudinal magnetic field B_z

$$a'' + \frac{a}{4R^2} - \frac{2I}{(\beta\gamma)^3 I_0 a} - \frac{\varepsilon^2}{a^3} = 0 \ , \qquad (1)$$

where I is the beam current, ε is the beam emittance, $I_0 = mc^3/e$ is Alfvén, current, $\beta\gamma = p/(mc)$, $R = pc/eB_z$, m, e and p are electron mass, charge and momentum, c is velocity of light, was used.

Equation (1) was solved numerically for a given value of the peak beam current and for the magnetic field profile shown in Fig. 5. To verify the numerical solution using the CST-Studio software package, a simulation of particle motion in the lens shown in Fig. 3 was performed. When comparing the numerical solution and the simulation results, the root-mean-square beam sizes, rather than radii a, were used. For an axisymmetric beam, the standard deviations in both coordinates are the same and equal to half of the maximum beam size with the Kapchinskij-Vladimirskij distribution. A comparison of the numerical solution of equation (1) and the simulation results is shown in Fig. 6. The values of the problem parameters in both cases were 50A for the beam current, 3.2 mm for the initial beam radius, 8 mm*mrad for the emittance and 1.5 MeV for electron kinetic energy. The plot shows a complete correspondence between the simulation results and the numerical solution.

For so strong focusing, the effect of space charge on the transverse dynamics of particles is small and does not change the beam envelope significantly.

CONCLUSION

The article provides an overview of the results of designing a magnetic buncher for the Novosibirsk free electron laser facility. At the moment, an electron-optical scheme of the magnetic system has been developed, the magnetic field has been modelled, the reference trajectory of particle motion has been calculated, the Kapchinskij-Vladimirskij equation for estimating the effect of spatial charge on focusing has been derived and solved, and particle motion in a magnetic lens with a longitudinal axisymmetric field has been simulated.

Further work will be aimed at measuring the actual values of the magnetic field after manufacturing the elements of the buncher magnets.

REFERENCES

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