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

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Abstract

The paper presents a comprehensive study of a compact 540° magnetic buncher designed for an upgrade to the Novosibirsk Free Electron Laser (NovoFEL). A key feature of the proposed scheme is its remarkably high (about 1 m) longitudinal dispersion R_{56}, which allows efficient bunch compression down to a target bunch length of approximately 10 ps with a peak current exceeding 100 A. For the first time reported are new quantitative results on the space charge effects at the tightest spatial bottleneck of the system—inside the post-buncher short-focusing longitudinal lens. The numerical solutions to the Kapchinskij–Vladimirskij envelope equations and 3D CST Particle Studio simulations performed across a wide range of peak currents (from 50 to 150 A) demonstrate perfect agreement, confirming that the space charge forces cause no envelope degradation or blurring. The results confirm the feasibility and high efficiency of the proposed permanent-magnet bunching system.

INTRODUCTION

Many applications of accelerator technology require electron bunches with length of about 10 picoseconds, peak current exceeding 100 amperes, and normalized emittance less than 100 mm·mrad. To achieve these parameters with an initial bunch duration exceeding 100 ps, a magnetic buncher design with bending angle of 540° has been proposed for the Novosibirsk FEL (NovoFEL) [1, 2]. The key feature of this design is its remarkably high (approximately 1 m) longitudinal dispersion R_{56}, which enables efficient compression of a long bunch. Furthermore, the entire magnetic system is based on permanent magnets. Compared to conventional electromagnetic options, this approach significantly reduces both manufacturing and operational costs. The design of the 540° magnetic buncher started several years ago at the Budker INP FEL facility [3]. The buncher will be installed in the 1.5-MeV electron injection channel at the NovoFEL facility.

The buncher consists of two 30° magnets with parallel edges and two magnetic mirrors (see Fig. 1). The radii of the electron trajectories in the bending magnets and the distances between the magnets are chosen so as to ensure an achromatic bend. A calculation of the trajectory, longitudinal dispersion, and transverse focusing of particles is described in [4]. After passing through a 30° parallel-edge magnet, the magnetic mirrors, the other 30° parallel-edge magnet, and a quadrupole magnetic lens, electrons enter a focusing lens with a longitudinal magnetic field and sharp edge. The latter is necessary for the transverse size of the electron beam to be small.

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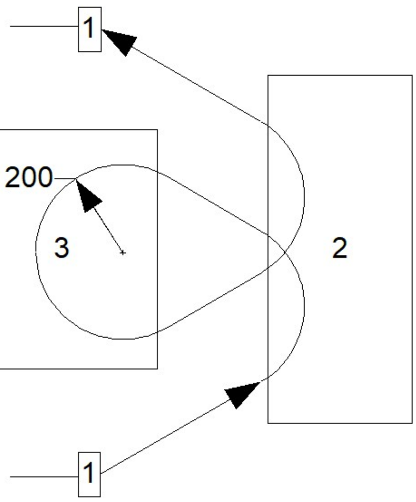

Figure 1: Scheme of 540° bend magnetic electron buncher: 1—30° magnets, 2—large magnetic mirror, 3—small magnetic mirror. Solid curve: reference trajectory of electrons.

The 30° magnets and the quadrupole lens have already been produced. Therefore, this paper presents only the designs and results of calculation of the field of the magnetic mirrors and the axisymmetric lens with a longitudinal field.

The longitudinal dynamics in the 540° magnetic buncher is mainly determined by its significant longitudinal dispersion $R_{56} \approx 1$ m. To achieve longitudinal compression, the electron beam is prepared with an initial correlation of energy and longitudinal coordinate (energy chirp), which means that trailing particles have slightly less energy than leading ones. As a bunch traverses the magnetic mirrors, these lower-energy particles travel along tighter trajectories with smaller bending radii, which results in a shorter physical path. This systematic path difference allows the bunch tail to rapidly catch up with the bunch head. Consequently, an initially long bunch is transformed into a highly compressed, high-peak-current state right at the exit of the magnetic system, satisfying the strict requirements for applications.

OPTIMIZATION OF MAGNETIC SYSTEM ELEMENTS

The process and results of the calculation and optimization of the magnetic mirrors are described in detail in [5]. The schemes of the magnetic mirrors and the short-focus lens are shown in Figs. 2 and 3.

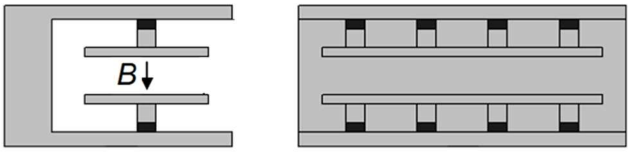

Figure 2: Scheme of magnetic mirror: left—side view, right—front view. Blocks of permanent magnet material are shown in black, iron magnetic cores are shown in grey, and arrow shows direction of field vector in working gap.

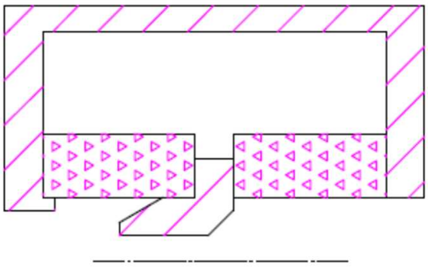

Figure 3: Longitudinal cross-section of axisymmetric lens with longitudinal field. Oblique shading: details of iron magnetic core; triangular shading: direction (along axis of symmetry) of magnetization of pucks made of neodymium-iron-boron material. Electron beam enters from left.

The computed magnetic field distributions of the elements are illustrated in Figs. 4 and 5.

The small mirror is designed with working gap of 84 mm, bending radius of 200 mm, and peak magnetic field of 33 mT, as confirmed by the field profile in Fig. 4. The large mirror features a qualitatively identical field configuration scaled to the target geometry.

The longitudinal focusing lens has the effective length L_{eff} = 50 mm with a peak magnetic field of 600 mT. Since the lens is thick and cannot be treated via a thin-lens approximation, the effective focal length F_{eff} is introduced. Owing to the conservation of the root-mean-square (RMS) emittance, this focal length is determined from the relation $\theta_{max} = \varepsilon / a_{min} = a_0 / F_{eff}$, where a_0 is the initial RMS beam size at the entrance, a_{min} is the minimum RMS beam size at the waist, θ_{max} is the maximum RMS angular spread, and $\varepsilon = \varepsilon_n / \beta\gamma$ = 8 mm·mrad is the geometric RMS emittance calculated from the normalized emittance ε_n = 32 mm·mrad for an electron kinetic energy of 1.5 MeV. This yields the effective focal length $F_{eff} = a_{min}\, a_0 / \varepsilon$ = 40 mm. On the beam envelope plot (Fig. 6), where the longitudinal coordinate z = 0 corresponds to the entrance face of the lens, the minimum beam size (waist) is reached internally at z_{min} = 62 mm. At this focal point inside the lens body, a foil target will be positioned to produce short bremsstrahlung pulses.

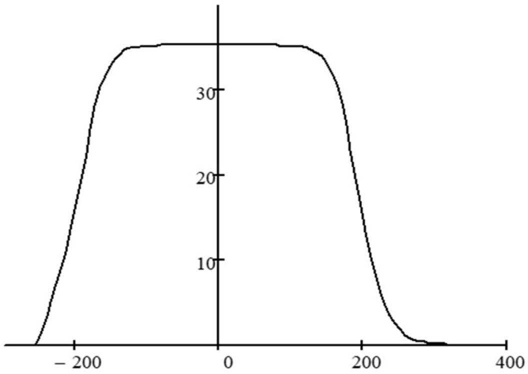

Figure 4: Calculated dependence of induction (mT) in median plane of small magnetic mirror on coordinate (mm) across edge (right slope) of magnet.

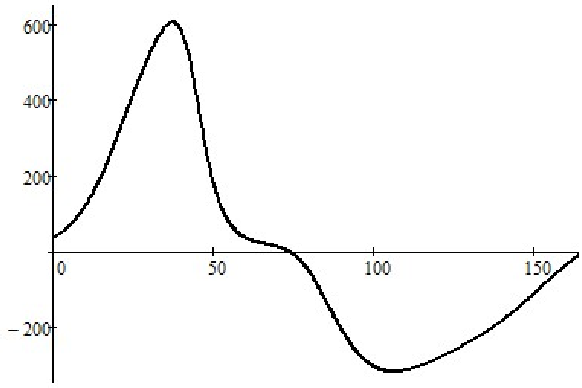

Figure 5: Calculated dependence of induction (mT) on coordinate (mm) on axis of symmetry of magnetic lens with longitudinal field.

STUDY OF SPACE CHARGE IMPACT ON FOCUSING OF BUNCHED BEAM

To quantify the space charge influence at the tightest bottleneck of the system, we analysed the beam transport through the short-focusing longitudinal field lens positioned right after the buncher, where the peak current reaches its maximum.

After the particles pass through the magnetic mirrors, the bunched electrons enter the focusing magnetic lens with a longitudinal axisymmetric field. This field is induced by the permanent magnets. For the electron beam to have minimum transverse sizes, the shape of the magnetic core in the lens (see Fig. 3) provides maximum steepness for the field dependence on coordinate at the entrance to the lens. Using this lens allows us to achieve a small effective focal length F_{eff} (see Fig. 6).

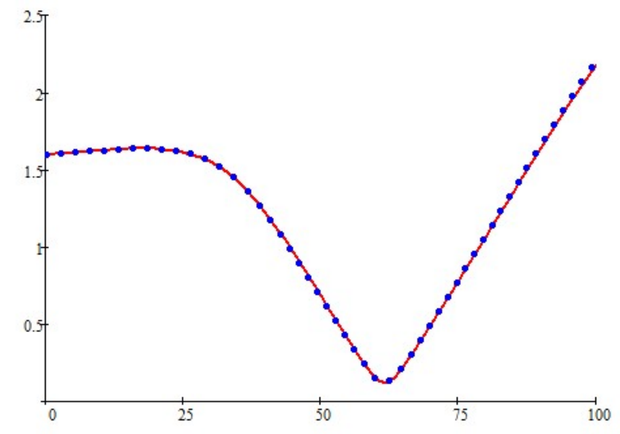

Figure 6: Dependence of standard deviation of transverse coordinate (mm) on longitudinal coordinate (mm) for axisymmetric permanent magnet lens: simulation (blue dotted line) and numerical solution (red line).

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

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

where I is the beam current; $\varepsilon_{KV} = 4\varepsilon$; $I_0 = mc^3/e$ is Alfvén current; $\beta\gamma = p/(mc)$; $R = pc/eB_z$; m, e, and p are the electron mass, charge, and momentum, respectively; c is speed of light.

Equation (1) was numerically solved for a given value of the peak beam current and for the magnetic field profile shown in Fig. 5. Both the numerical solutions to the Kapchinskij–Vladimirskij (K-V) equations were found and the CST particle tracking simulations were performed for a range of peak currents: 50 A, 100 A, and 150 A. For the benchmark case (peak current of 50 A, initial beam radius of 3.2 mm, emittance of 8 mm·mrad, and electron kinetic energy of 1.5 MeV), the K-V envelope results and CST data show perfect agreement (see Fig.6). Crucially, even at elevated peak currents of up to 150 A, the space charge forces cause no beam envelope degradation or blurring, ensuring stable and rapid beam focusing across the entire operational range.

Since the exact initial phase-space distribution in the CST particle tracking code may differ from the idealized K-V distribution, direct comparison of the maximum beam radii could be physically inconsistent. To ensure a rigorous and model-independent validation, the RMS envelopes were compared. For the K-V distribution, the RMS transverse size $a/2$ is equal to half of the maximum beam radius a. Therefore, the CST-simulated RMS sizes were benchmarked against $a/2$, obtained from the numerical solution of the K-V equation.

Thus, for such a strong focusing configuration, quantitative analysis confirms that the space charge forces do not cause any noticeable beam envelope broadening or beam degradation across the entire examined range of peak currents up to 150 A, showing consistent agreement between the analytical K-V model and 3D CST simulations

CONCLUSION

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

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

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