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ELECTRON OUTCOUPLING SYSTEM OF NOVOSIBIRSK FREE ELECTRON LASER FACILITY– BEAM DYNAMICS CALCULATION AND THE FIRST EXPERIMENTS

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Abstract

The radiation power of the FEL with optical cavity can be limited by the overheating of reflecting mirrors. In the electron outcoupling scheme electron beam radiates the main power at a slight angle to the optical axis. For this, it is necessary to divide undulator by dipole magnet at least for two parts – the first for the electron beam bunching in the field of the main optical mode, and the second for the power radiation by deflected beam.

Electron outcoupling system is installed on the third FEL based on the multiturn energy recovery linac of the Novosibirsk Free Electron Laser facility (NovoFEL). It consists of three undulators, dipole correctors and two quadrupole lenses assembled between them. There are two different configurations of the system since the electrons can be deflected in either the second or the third undulator.

The electron beam dynamics calculations and the results of the first experiments are presented.

INTRODUCTION

Free electron lasers (FELs) are the unique source of monochromatic electromagnetic radiation. Radiation is generated due to motion of relativistic electron bunches into the magnetic field of undulator. In contrast to types of lasers, FEL allows to receive radiation of any given wavelength in the operating range, and this wavelength can be relatively quickly tuned [1]. The efficiency of FEL is tenths of a percent of the electron beam average power therefore the use of the energy recovery linacs (ERLs) seems to be the most optimal. The maximum achievable power of an FEL with an optical cavity, aside from the parameters of the electron beam, can be limited by the overheating of reflecting mirrors. To prevent this effect there was proposed the electron outcoupling system [2,3]. Numerical calculations of the such configurations were carried out by various groups of researchers [4-7].

The main idea of the electron outcoupling scheme is to radiate the main part of the power into the small angle to the FEL optical axis, thereby avoiding mirrors overheating. The principle of operation of the schemee is the following (Fig. 1): the electron beam (1) is turned by the dipole magnet (2) into the undulator (3); bunched by interaction with electromagnetic field of the fundamental mode (6) and then deflected by small angle (5) direct to the next undulator (4); emits the main power of the radiation (8). This radiation transported (7) to the user stations. Then the used electron bunch (9) is removed from the system by magnet (2).

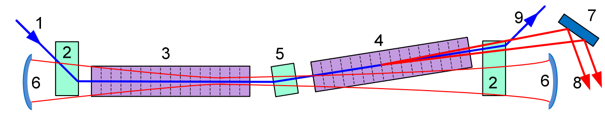

Figure 1: 1 – initial electron beam; 2 – bending magnets; 3 – bunching undulator; 4 – radiating undulator; 5 – beam rotation magnet; 6 – optical mirrors and fundamental mode; 7 – electron outcoupling mirror; 8 – main radiation power; 9 – used electron beam.

NOVOFEL FOUR-TRACK ERL

NovoFEL (Fig. 2) is the high-power terahertz and infrared radiation source [8]. Radiation can be generated by three different FELs using an electron beam of three different ERL configurations. The main parameters of the third FEL based on four-track ERL (Fig. 3) are presented in Table 1. The third FEL operates as user facility since 2015. It consists of three permanent magnet undulators with the variable gap (see Fig. 4) and an optical cavity. This undulator separation into three parts was made, in particular, for experiments with electron outcoupling system. For this purpose, the quadrupole lenses and additional dipole correctors are installed in the empty spaces between the undulators and at the ends of the undulators (Fig. 5). The feasibility study of using this scheme in the NovoFEL facility was described in [9].

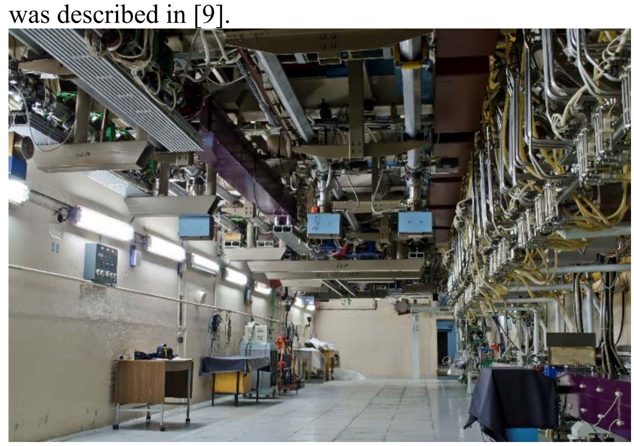

Figure 2: Accelerator hall and the tracks (on the ceiling) of the four-pass NovoFEL ERL.

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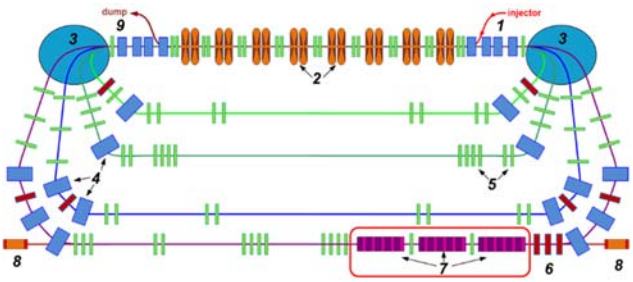

Figure 3: Scheme of NovoFEL installed on a four-track ERL:1- electron injector, 2 - NRF cavities, 3 – round dipole magnet, 4 - rectangular magnets, 5 – quadrupole lenses with dipole correctors, 6 - quadrupole lenses, 7 - undulators of the electron outcoupling system, 8 - mirrors of the optical cavity, 9 - electron dump.

Table 1: NovoFEL Facility Parameters

parameter	value
Electron energy	39 MeV
Average current	3 mA
Peak current	100 A
Norm. Emittance	30 µm×rad
Wavelength	~9 µm
Energy spread	~2%
Number of undualtors	3
Undulator periods	28
Period length	0.06 m
Outcoupling angles diapasons (horizontal. and vertical)	1.76 – 5.24 mrad -3.23 – 3.23 mrad
Optical cavity loss	0.135
Optical cavity length	40 m

Figure 4: Undulators of the third FEL (7 on the Fig. 3).

CONTINIOUS BENDING REGIME

In contrast with the scheme on the Fig.1 in the NovoFEL electron outcoupling system the electron bunches are supposed to turn out from the optical axis while the undulators are mounted on it. In this case, one of the important conditions for lasing into the outcoupling angle is the conservation of the electron bunching in the turn between bunching and radiating undulators. It can be achieved by using the achromatic bend.

The magnetic system of the bend in presented on Fig. 5. Since the quadrupole lens is not symmetrically with respect to the location of the dipole correctors and moreover, the reference trajectory of the electrons depends on deflecting angles, it is necessary to introduce an additional dipole component of the magnetic field in the quadrupole. In other words, to achieve achromatic constraints it is required to shift the quadrupole lens from optical axis. On the facility the lens was shifted by 2 cm. That displacement does not significantly affect the operation in ordinary laser regimes for users, since in such configurations the currents of quadrupole lenses between undulators are usually small.

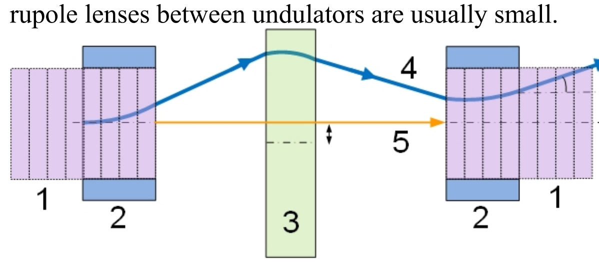

Figure 5: Electron bunch trajectory in the magnetic system between undulators: 1 – undulator, 2- dipole corrector, 3 – shifted quadrupole lens, 4 – electron bunch, 5 – light beam, 6 – outcoupling angle.

As well as electron bunch deflected from axis of symmetry, the additional dipole field component in quadrupole should be taken into account in achromatic conditions calculation. They form two equations for transport matrix elements

$$R_{16}(\alpha_1, \alpha_2(K_1, \alpha_1), \alpha_3, K_1) = 0, \quad (1)$$

$$R_{26}(\alpha_1, \alpha_2(K_1, \alpha_1), \alpha_3, K_1) = 0, \quad (2)$$

where R – transport matrix between two undulators, α_1, α_3 – deflecting angles in dipole correctors and α_2 – in the dipole field component of the quadrupole. This field component depends of course on K_1 strength parameter of the lens, which itself influences on dispersion condition in the bend. The deflecting angels should give in total the outcoupling angle α_0

$$\alpha_0 = \alpha_1 + \alpha_2(K, \alpha_1) + \alpha_3. \quad (3)$$

The outcoupling scheme can be realized by two different options. The electrons can be deflected in the second or in the third undulator (Fig. 6). In the case second undulator the bended electron beam should return back to the optical axis at the third undulator to enhance the main radiation mode of the optical cavity. This adds an additional condition to the system of equations (1-3), because the electron gets extra horizontal deviation while moving through the second undulator with outcoupling angle. It looks hard to satisfy all these limitations with today's magnetic fields of

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dipole correctors. Therefore, at this time, we concentrate on the outcoupling scheme from the third undulator.

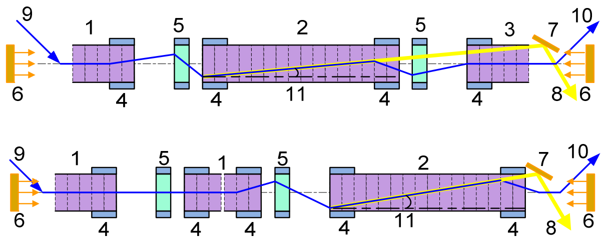

Figure 6: Two possible variants of electron outcoupling scheme – deflecting in the second (top figure) or in the third undulator (bottom figure): 1 – bunching undulator, 2 – radiation undulator, 3 – undulator, 4 – dipole correctors, 5 – quadrupole lenses, 6 – optical mirrors and fundamental mode, 7 – mirror for main radiation, 8 - main radiation, 9 – initial electron beam, 10 – used electron beam, 11 – deflection angle.

The experience in tuning the FEL regime with a deflected beam shows that lasing on two undulators is a feasible but rather difficult goal [10]. Since the Twiss parameters at the beginning of the undulator's system are not well defined the calculated optic regime may not provide enough amplification for lasing. Therefore, to facilitate the adjustment of the structure, it was proposed to make a continuous achromatic bend from zero to the angle of electron outcoupling (Fig. 5). In this case, the lasing starts in more simplified mode with three undulators then slightly tune to the regime with deflected electron beam at the last undulator. The continuous bend regimes were calculated by Elegant code (Fig. 7) [11]. As it shown by calculations to achieve the achromatic conditions the much higher magnetic fields of the dipole correctors are necessary than to obtain only deflection angle.

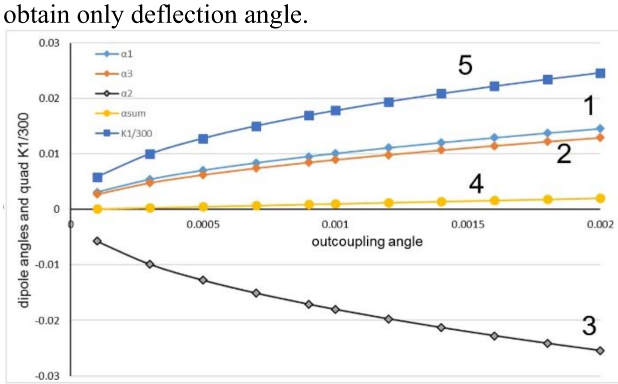

Figure 7: Achromatic bends parameters for the different outcoupling angles: 1,2 – dipole corrector's angles, 3 – angle of the shifted quadrupole, 4 – total angle, 5 – K_1 parameter of the quadrupole.

In the next experiments it is supposed to configure the optimal Twiss parameters by the beam diagnostic system using the pictures from radiation-resistant camera.

The beam profile after the lasing can be measured by detecting the synchrotron radiation from the dipole magnet [12]. The diagnostic system for the electron bunch longitudinal distribution measurements is currently under installation and launching [13].

ELECTRON BUNCHING AND RADIATION

The numerical simulation of the electron beam dynamics and radiation in the undulators was made in the Genesis code [14]. Firstly, in the mode of the continuous electron beam the optimal Twiss parameters calculated by Elegant code were set (Fig. 7). The achieved electron beam distribution after each undulator transformed by transport matrix from optic regime. It should be noted that dipole correctors are installed directly on undulators, therefore, the transport matrix, calculated separately for rotation, must be converted to real geometry (Fig. 5)

$$M_b = M_{Ld}^{-1} M_{bend} M_{Ld}^{-1}, \tag{4}$$

where M_b – transport matrix between undulator, M_{LD} – drift matrix with length of the dipole corrector, M_{bend} – matrix of the bend.

The light beam between the undulators flies along a straight path, while the electron beam moves along a curved, and also with a speed βc. Therefore, the electron beam should get additional phase to the light with the following value

$$\Delta\varphi = \frac{2\pi}{\lambda}\left(\frac{Ltr - 2LD}{\beta} - Ldr\right), \tag{5}$$

where λ – radiation wavelength, Ltr – length of the electron trajectory in the bend, LD – length of the dipole corrector, Ldr – the distance between undulators. This phase shift can achieve the sufficient values, more than several pi, therefore the variation of the resonance radiation wavelength is necessary in the calculation.

The radiation obtained after the passage all three undulators was decomposed into the main mode of the optical cavity and the remaining field. The power of the fundamental mode was transferred to the beginning of the calculation (to the input of the first undulator) taking into account previously determined losses of the optical system [15]. This procedure was repeated until a stable radiation regime was achieved.

At the first, numerical simulation of the FEL lasing in ordinary operation modes was made (without deflection of the electron beam). The calculated angular distribution after third undulator is shown on the Fig. 8. Numerical simulations by Genesis code also confirm that the fundamental mode (1 at Fig. 8) does not effect on the outcoupling mirrors (area 3 at Fig. 8). In the opposite of the main radiation mode, the part of other high order modes (2 at Fig. 8) falls on the outcoupling mirror even without the electron deflection in undulator. These calculations are planned to be verified experimentally. In the special regime with short lasing pulses we are going to detect the radiation attenuation fronts after optical cavity and outcoupling mirror. Such FEL lasing mode is realized by special modulation regime of NovoFEL DC-gun [16].

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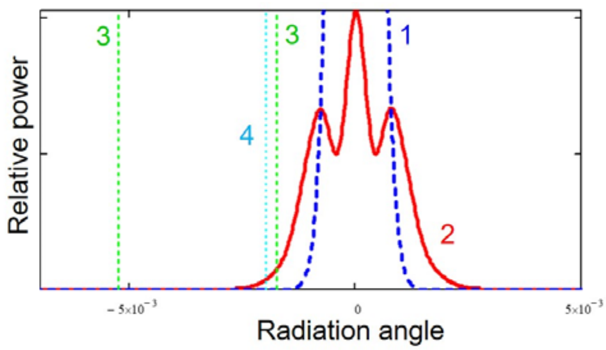

Figure 8: Angular power distribution of the electron beam in the FEL without deflecting in the undulator: 1 – fundamental mode, 2 – high order modes, 3 – area of the outcoupling mirror, 4 – electron outcoupling angle.

As already mentioned, the magnetic field of the dipole correctors should be much higher than requirements for total deflecting angle. Therefore, it is not possible to achieve the achromatic conditions at each angle. The obtainable outcoupling angle is 2 mrad. The angular power distribution in the regime with such deflection in the third undulator is shown on the Fig. 9. The enhancement of radiation power can be observed in the area of electron outcoupling mirror. However, the increasing is not significant relative to the rest of the power.

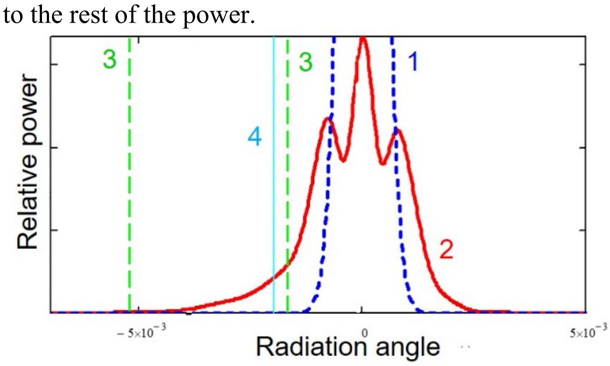

Figure 9: Angular power distribution of the electron beam in the FEL with deflecting in the third undulator: 1 – fundamental mode, 2 – high order modes, 3 – area of the outcoupling mirror, 4 – electron outcoupling angle.

The Fig. 10 shows the angular power distribution generated by electrons in the last undulator. The power is radiated to the desired angle, but it is much lower than scattered high order radiation modes from other two undulators. The possible reason is the electron bunching decreases rapidly while passing the last undulator (3 at Fig. 11). On the Fig. 11 is shown the bunching factor calculated by Genesis code along the optical axis (1, 2 and 4) and along the deflected beam trajectory (3). In spite of the achromatic bends, it changed at the areas 5 and 6 due to non-zero R_{56} elements of the transport matrix.

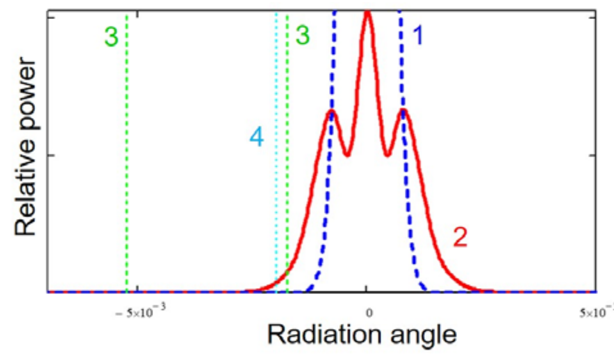

Figure 10: Angular power distribution: electron bunches achromatic bended before third undulator.

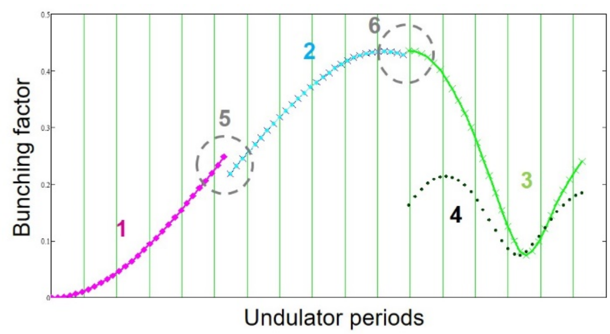

Figure 11: Bunching factor in the undulators system: 1 – first undulator, 2 –second undulator, 3 – bunching factor in the third undulator, calculated along the electron beam propagation axis, 4 – bunching factor, calculated along the optical axis by Genesis code, 5 – drift between 1-st and 2-d undulators, 6 – achromatic bend between 2-d и 3-d undulators.

CONCLUSION

The continuous achromatic bend from ordinary lasing regime to the desired deflected trajectory of the electron beam in the third undulator was calculated. Another issue related to this tuning is the compensation of the bunch perturbation due to the lasing the existing optics before the electrons return to the common track of the ERL.

The angular distribution of the radiation power in the system of electron outcoupling from the third undulator was calculated. It shows that the power of the high order modes from first and second undulators falling on the outcoupling mirror comparable with the radiation from deflected electron beam in the last undulator.

For ordinary FEL lasing regime with three undulators the radiation power of the high order modes at the outcoupling mirror is much higher than scattered on it fundamental optical cavity mode. The ration between these quantities is supposed to be checked in future experiments.

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