ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2023, Vol. 20, No. 4, pp. 772–775. © Pleiades Publishing, Ltd., 2023.
Russian Text © The Author(s), 2023, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2023.

PHYSICS AND TECHNIQUE OF ACCELERATORS

# Experiments on the Short X-Ray Pulse Generation at the NovoFEL Facility

**Ya. V. Getmanov[a, b, *], V. M. Borin[a, b], N. A. Vinokurov[a, b], X. Ma[a], Yu. I. Maltseva[a], O. I. Meshkov[a, b], and O. A. Shevchenko[a]**

[a] *Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[b] *Novosibirsk State University, Novosibirsk, 630090 Russia*
**e-mail: y_getmanov@mail.ru*

Received November 18, 2022; revised December 16, 2022; accepted January 23, 2023

**Abstract**—The energy recovery linear accelerator of the Novosibirsk Free Electron Laser facility can be used as a source of short X-ray pulses. Bremsstrahlung is produced by the electron current of the accelerator passing through a thin foil with a bunch repetition frequency of several megahertz and a picosecond duration of an individual bunch. This article discusses the possibilities of creating such a source and the results of the first experiments.

**DOI:** 10.1134/S1547477123040301

## INTRODUCTION

To study fast processes, not only is a certain wavelength required, but so is the corresponding duration of electromagnetic pulses. The duration of X-ray pulses of many modern sources of synchrotron radiation exceeds 10 ps, which limits their applications, for example, in studies of the dynamics of chemical reactions and phase transitions [1]. The root-mean-square duration of bunches in the accelerator-recuperator (see Fig. 1) of the Novosibirsk Free Electron Laser (FEL) complex [2] can be less than 10 ps. Installing a thin foil in the orbit of the electron beam of the accelerator makes it possible to create a generator of periodic picosecond X-ray bremsstrahlung pulses with a high (several MHz) repetition rate. Other modern X-ray sources (accumulators, X-ray tubes, laser-plasma accelerators, and X-ray FELs) do not produce radiation with such parameters.

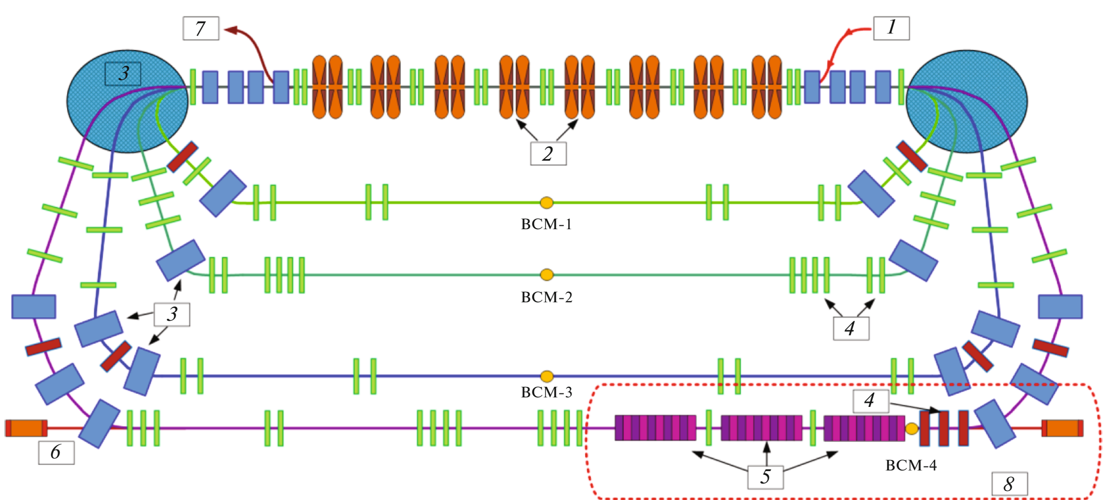


**Fig. 1.** Four-turn accelerator-recuperator of the Novosibirsk FEL: (*1*) injector, (*2*) accelerating structure, (*3*) bending magnets, (*4*) quadrupole lenses, (*5*) undulators, (*6*) optical cavities, (*7*) electron absorber, and (*8*) bremsstrahlung generation region; BCM indicates electron beam current monitor.

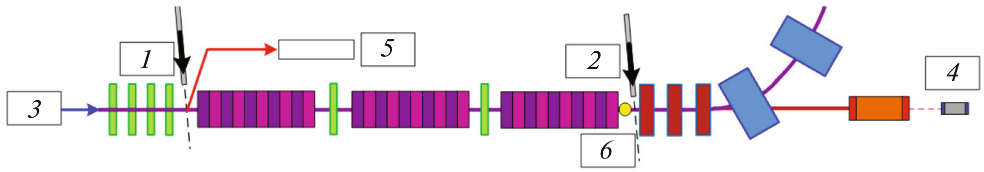


**Fig. 2.** Scheme of the experiment. X-ray generation area: (*1, 2*) foil input devices, (*3*) electron beam, (*4*) X-ray detector (PMT), (*5*) radiation-resistant chamber, and (*6*) beam current monitor.

## INTERACTION OF AN ELECTRON BEAM AND FOIL

At sufficiently high electron energies, bremsstrahlung in the low-frequency range is described by the classical approximation [3]. Total photon flux with frequency ω and emission line width Δω/ω, radiated by the average electron current $I$ equals (α is the fine structure constant, $r_e$ is the classical electron radius, γ is the relativistic factor, $Z$ is the atomic number, $L$ is foil thickness, $n$ is the density of atoms in the foil, and $e$ is the electron charge)

$$\dot{N}_{\omega,\mathrm{tot}} \approx \frac{16\alpha Z^2 r_e^2 n L}{3}\frac{I}{e}\ln\left(\frac{2\gamma^2 c}{\omega Z r_e}\right)\frac{\Delta\omega}{\omega}. \qquad (1)$$

During the passage of a thin foil by an ultrarelativistic electron beam, the energy losses of electrons are negligible. The main effect is to increase the angular spread due to multiple scattering

$$\theta_{\mathrm{rms}} = \sqrt{\frac{4\pi}{\gamma^2} n r_e^2 Z^2 L \ln\frac{\rho_{\max}}{\rho_{\min}}}, \qquad (2)$$

where $p_{\max}$ and $p_{\min}$ are the maximum and minimum impact parameters [4]. To keep small (of order 1/γ) of the angular divergence of the radiation, it is desirable that it does not exceed the root-mean-square angular spread of electrons.

## SCHEME AND PARAMETERS OF THE RADIATION SOURCE

On the last (fourth) track of the accelerator-recuperator (electron energy is about 40 MeV), two foil inlets are installed before and after the FEL undulators (Fig. 2). Initially, graphite foil 25 μm in thickness was installed in each bushing. The choice of graphite foil as a target is associated with the possibility of heating it to a high temperature, which ensures good heat removal due to radiation.

Subsequently, the graphite foil in the first input was replaced with aluminum, which is better suited for measuring the size of the electron beam by observing transition radiation [5], but scatters the electron beam much more strongly. Both foils are installed on the emerging frames and deployed at an angle of 45° to the orbit. The passage of the electron beam is controlled by electron current monitors installed in the accelerating channel. Radiation was registered using a PMT.

## PASSAGE OF AN ELECTRON BEAM

The accelerator of the Novosibirsk FEL complex uses an energy recovery scheme. One of its advantages is the ability to work with high average electron currents. The downside is the increased risk of heating the vacuum chambers due to the loss of the electron beam. This problem is especially manifested when using the installation as a radiation source. In the case of FEL generation, electron losses in the accelerator channel arise due to an order of magnitude increase in the energy spread caused by the effect of electron bunch microbunching in the undulator. In the case of bremsstrahlung, the loss is caused by an increase in the angular spread and, as a consequence, an increase in the emittance of the electron beam by several times after the foil. Since the types of losses are qualitatively different, it is necessary to significantly rebuild the regime of electron optics. The initial mode of the magnetic elements of the accelerator during the passage of the foil by the electron beam was modeled using the Elegant program [6]. The parameters of the electron bunch after passing through the foil are determined by formula (2).

On the fourth track, two foil inlets are built into the vacuum chamber of the accelerator (Fig. 2). They are separated by a group of undulators with a relatively narrow vertical aperture. Considering that the angular spread is the same in the vertical and horizontal directions, it is rather problematic to conduct the electron beam without losses after the introduction of the first foil even in numerical simulation. Figure 3 shows the calculation of the transmission mode for the case of introducing the second foil: the structure functions and their limitations for passing at the level of three standard deviations of the normal distribution and a circular aperture of the vacuum chamber. In the calculation, it was assumed that the electron beam could be focused on the foil to a size corresponding to beta functions equal to 0.5 m. Strict restrictions imposed on the admissible values of the structure functions lead to the need for maximum focusing of the electron beam on the emitting foil.

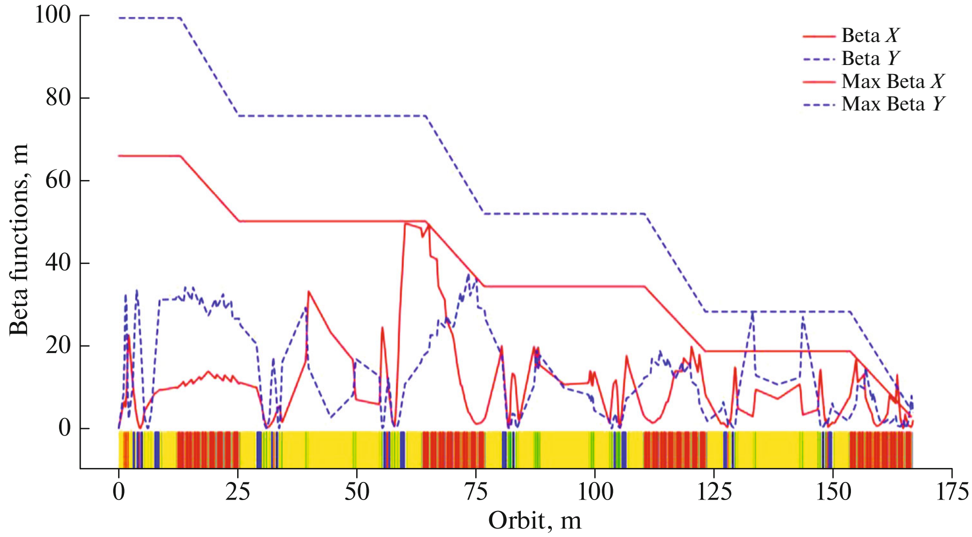


**Fig. 3.** Estimated mode of electron beam passage with the second foil inserted. The solid line is the horizontal beta function and its constraint; the dotted line is the vertical one.

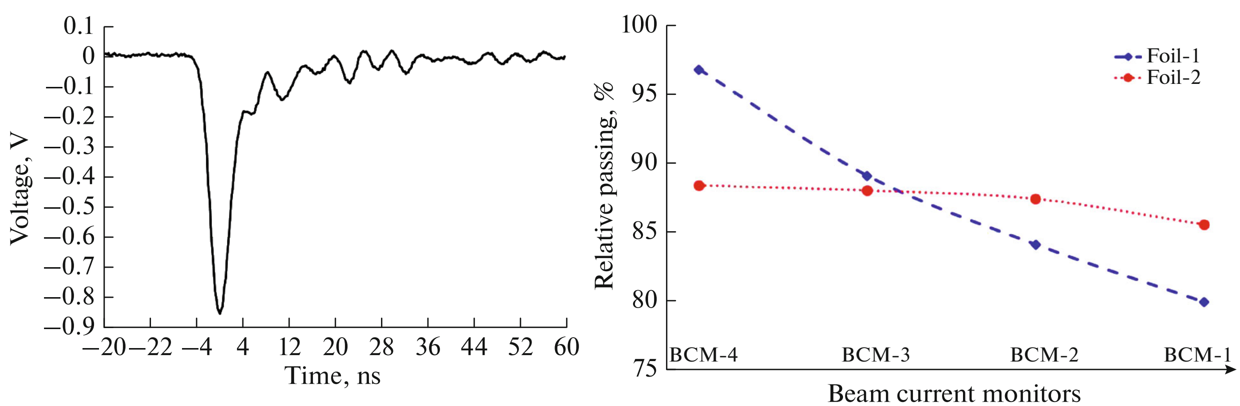


**Fig. 4.** Experiment results. On the left is a characteristic signal of a radiation pulse registered by a PMT. On the right is the passage of the used electron beam, calculated from the readings of the current meters.

## EXPERIMENTS

Two series of experiments were carried out using both targets and varying the parameters of the electron bunch. The passage through the system strongly depends on the dimensions of the electron beam on the foil. The minimization of this size can be controlled using optical diagnostics based on the detection of transition radiation using a radiation-resistant television camera located in the accelerator hall. Therefore, the first foil was also used in the experiments, with the help of which the possibility of maximum beam compression was studied. Experimentally, it was possible to obtain minimum beta functions of about 0.8 m, which is somewhat larger than the values obtained in the simulation, at which the electron beam passes in its entirety.

Bremsstrahlung gamma radiation was registered at the end of the radiation output channel, at a distance of about 30 m from the foil. Its signal, characteristic of all experiments, is shown in Fig. 4. The pulse duration is limited by the PMT resolution. The beam passage was measured using current monitors. The readings were compared on the same sensors during acceleration and deceleration with the foil inserted and withdrawn. In both cases, the final passage to the absorber is at a level of 80%. Despite the fact that the mode of operation with the second foil looks more promising, the decrease in losses was only 5–6%. One of the reasons is the lack of optical diagnostics in this place, which makes it possible to minimize the size of the electron beam. The resulting transmission makes it possible to operate at a repetition rate of electron bunches with a charge of 1 nC up to 100 kHz, but it is insufficient for the standard operation of an accelerator with a repetition rate of 3.75 MHz due to the danger of overheating of the vacuum chambers.

## CONCLUSIONS

The increase in the emittance caused by the scattering of electrons by target atoms significantly increases the losses of the electron beam and requires a reconfiguration of the regimes of the electron optics of the accelerator. During the experiments, short radiation pulses were obtained with a duration of less than 1 ns. The passage of electronic current, depending on the modes, is 75–85% of what is necessary for the stable operation of the installation. An average electron current of 0.1 mA has been reached. Strengthening focusing with undulators and installing additional quadrupole lenses will reduce the loss of electrons to an acceptable level. Measurements of the intensity and duration of X-ray pulses are planned.

## FUNDING

This work was supported by grant 21-12-00207 of the Russian Science Foundation.

## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

## REFERENCES

1. A. Zewail, "Femtochemistry: atomic-scale dynamics of the chemical bond using ultrafast laser (Nobel lecture)," Chem. Int. No. 39, 2586 (2000).
2. N. A. Vinokurov and O. A. Shevchenko, "Free electron lasers and their development at the Budker Institute of Nuclear Physics, SB RAS," Phys. Ups. **61**, 435–448 (2018).
3. L. D. Landau and E. M. Lifshits, *Quantum Electrodynamics* (Nauka, Moscow, 1989; Butterworth-Heinemann, 1982).
4. J. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975; Mir, Moscow, 1965)
5. Ya. Getmanov, V. Borin, V. Dorokhov, A. Matveev, O. Meshkov, A. Mickailov, D. Reshetov, O. Shevchenko, and N. Vinokurov, "Development and application of electron beam optical diagnostics for the multi-turn ERL of the Novosibirsk FEL facility," J. Istrum. **15**, 14 (2020).
6. M. Borland, "Elegant: A flexible SDDS-compliant code for accelerator simulation," LS-287 TRN: US0004540.