

The Novosibirsk Free-Electron Laser Facility

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Abstract—The Novosibirsk FEL facility has three FELs installed on the first, second, and fourth orbits of the multiturn energy recovery linac (ERL). The first FEL covers the 90–240 μm range of wavelengths at an average radiation power of 0.5 kW with a pulse repetition rate of 5.6 or 11.2 MHz and a peak power of 1 MW. The second FEL operates in the 40–80 μm range of wavelengths at an average radiation power of 0.5 kW with a pulse-repetition rate of 7.5 MHz and a peak power of around 1 MW. These two FELs are the world’s most powerful (in terms of average power) sources of coherent narrow-band (less than 1%) radiation in their wavelength ranges. The third FEL was commissioned in 2015 to cover the 5–20 μm range of wavelengths. The Novosibirsk ERL is the world’s first and only multiturn ERL. Its distinctive features include a normally-conductive 180 MHz accelerating system, a direct current (DC) electrostatic electron gun with a control grid and thermionic cathode, three operating modes of the magnetic system, and a compact (6 \times 40 m) design. The Novosibirsk FEL facility has been in operation for users of terahertz radiation since 2004.

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THE ACCELERATOR

The Novosibirsk FEL facility [1, 2] includes three FELs. The undulators of these FELs are installed in different tracks of the same multiturn energy recovery linac (ERL). A simplified layout of the four-turn ERL is shown in Fig. 1. Low-energy electrons from injector 1 travel to high-frequency accelerating structure 2. Having passed four times through the accelerating structure, the electrons arrive at the last track and lose a small part of their energy in FEL undulator 4. The electron beam is decelerated in the same accelerating structure and arrives with low energy at beam dump 5.

An electrostatic gridded thermionic cathode electron gun is used as the source of electrons. The voltage applied to the accelerating tube of the electron gun is 300 kV. This electron gun allows the generation of electron bunches with durations of 1 ns, charges of up to 1.5 nC, and a normalized emittance of around 20 μm . The electron bunch repetition rate can vary from 0 to 22.5 MHz. Downstream of a bunching resonator that operates at a frequency of 180.4 MHz, the bunches are compressed in a gap with around 3 m long. They are then accelerated to an energy of 2 MeV

by two accelerating cavities, pass through the injection channel, and are injected into the main accelerating structure of the ERL (see Fig. 2).

The accelerating structure consists of 16 normal conducting radio-frequency cavities connected to two waveguides. The cavities’ operating frequency is 180.4 MHz. The low frequency allows operation with long bunches and large beam currents.

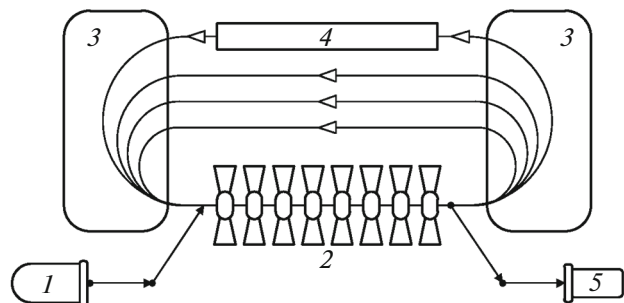


Fig. 1. Simplified layout of the multiturn ERL: (1) injector, (2) accelerating structure, (3) bending magnets, (4) undulator, (5) beam dump.

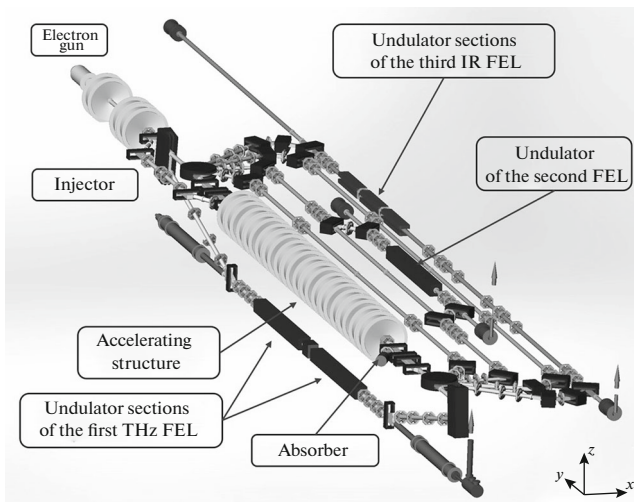


Fig. 2. Novosibirsk ERL with three FELs (plan view).

The Novosibirsk ERL has three main ways of switching on the magnetic system, one configuration for each of the three FELs. The first FEL is installed under the accelerating structure (see Figs. 2 and 4). Having passed through the accelerating structure, the 11 MeV electron beam is thus bent by 180 degrees in the vertical plane. After it is used in the FEL, the beam returns to the accelerating structure in the decelerating phase. In this configuration, the ERL operates as a one-turn ERL.

To operate with the second and third FELs, two round bending magnets must be switched on. They bend the beam in the horizontal plane, as shown in Fig. 2. After passing four times through the main accelerating structure, the electron beam arrives at the undulator of the third FEL. The electron energy in the third FEL is 42 MeV. The beam is then decelerated four times and arrives at the beam dump with low energy.

With four magnets switched on in the second track (see Fig. 2), the 20 MeV beam passes through the undulator of the second FEL. Due to the correctly matched length of the track, the beam then arrives at the accelerating structure in the decelerating phase and disappears in the beam dump after two decelerations.

A photograph of the accelerating hall, in which we can see the accelerating structure and FEL undulators, is presented in Fig. 3.

It should be noted that all 180-degree turns are achromatic (in the first and second horizontal tracks, they are second-order achromatic) but not isochronous. This allows us to tune the longitudinal dynamics of the beam in order to increase the peak current in the FEL and optimize the beam's deceleration.

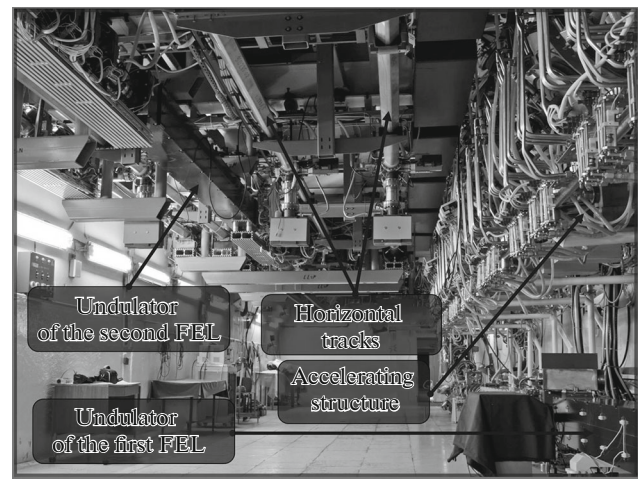


Fig. 3. Accelerating hall.

THE FEL

The first FEL was commissioned in 2003 [3]. It is a source of a narrow-band (linewidth, less than 1%) terahertz radiation, that is tunable in the 80–240 μm range of wavelengths, with an average power of up to 0.5 kW and a peak power of 1 MW (pulses with durations of 100 ps and a repetition rate of 5.6 MHz). In the last year, 30 research projects in different fields of science were performed with this FEL [4–9].

The radiation from all three FELs is transferred to the same user stations through an optical channel filled with dry nitrogen. The system that switches the radiation from different FELs is shown in Fig. 4.

The second FEL generates narrow-band radiation (linewidth, less than 1%) in the far-infrared wavelength range of 40 to 80 μm with an average power of

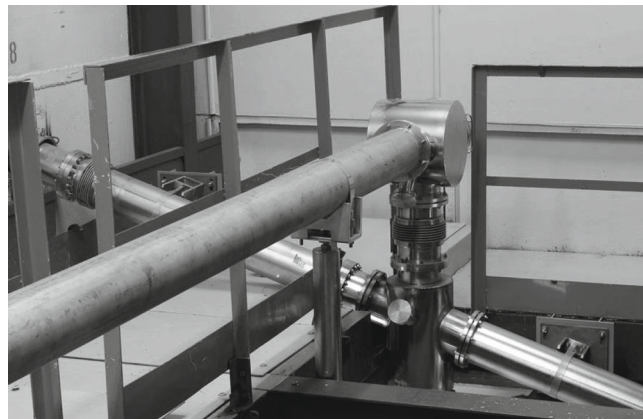


Fig. 4. Optical channels of FEL radiation outcoupling. The radiation from all FELs is transferred to the same user stations. Switching between FELs is done by means of removable mirrors.

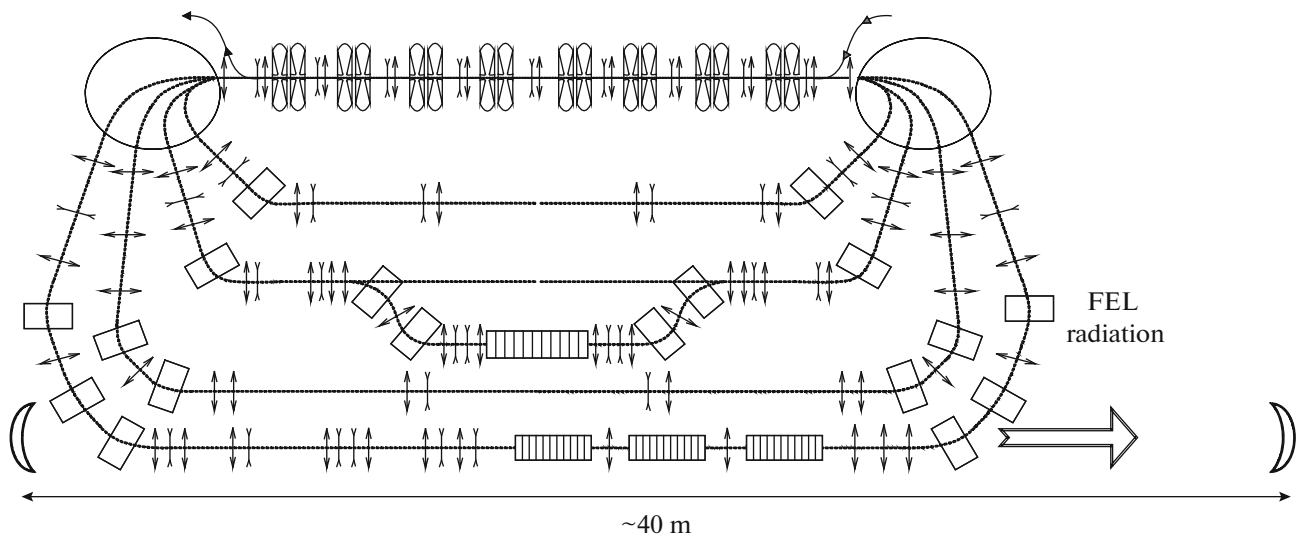


Fig. 5. ERL with undulators and the optical cavity of the third FEL.

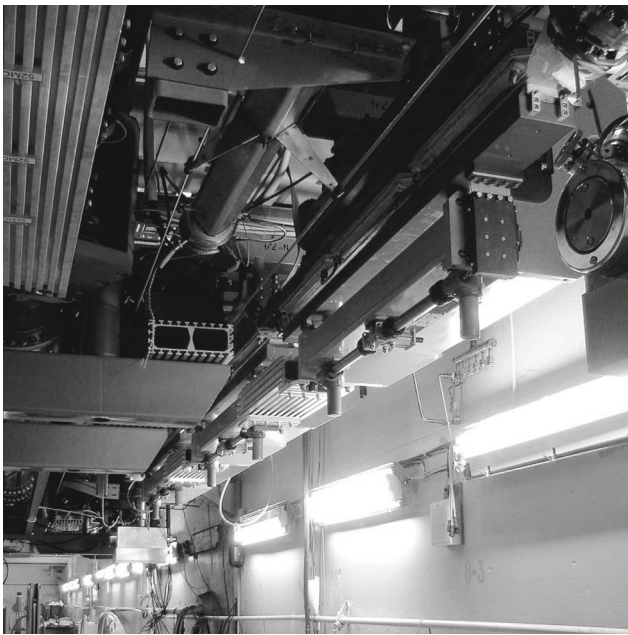


Fig. 6. Undulators of the third FEL.

0.5 kW and a peak power of 1 MW (pulses with durations of 50 ps and a repetition rate of 7.5 MHz). In the near future, we plan to replace the old electromagnetic

undulator with a new variable-period undulator [10, 11]. This will allow us to extend the range of wavelength tuning.

The undulator of the third FEL is installed in the fourth track, as is shown in Figs. 5 and 6. This undulator consists of three 28-period sections. Each section is a separate permanent-magnet undulator with a period of 6 cm and a variable gap. The gaps are tuned independently, so the middle section can also be used to phase two side sections. The range of wavelength tuning in this FEL is 5–20 μm .

The optical cavity of the third FEL is around 40 m long. The cavity is composed of two copper mirrors. Radiation is currently outcoupled from the cavity through holes in the mirror center. We plan to implement the electron outcoupling scheme in [12] (see Fig. 7). In this scheme, the beam is focused in the first undulator through its interaction with intracavity radiation. Using achromatic bending, it is then deviated by a small angle in the transverse direction so that its radiation from the second undulator exits at some angle with respect to the optical cavity axis without passing through the front mirror. It should be noted that this scheme has advantages only for radiation with high average power. As a rule, users do not need high power; the radiation outcoupling through the holes in the mirrors is much simpler.

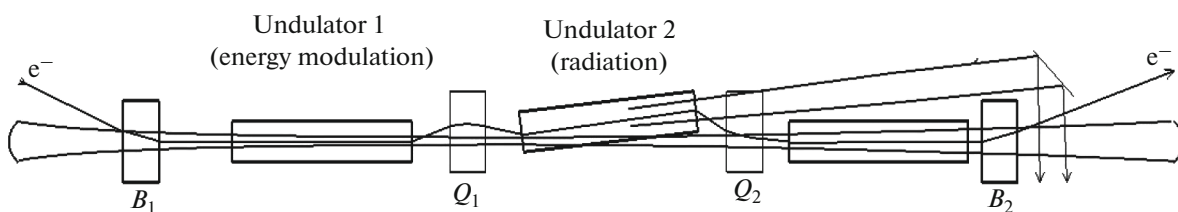


Fig. 7. Scheme of electron radiation outcoupling.

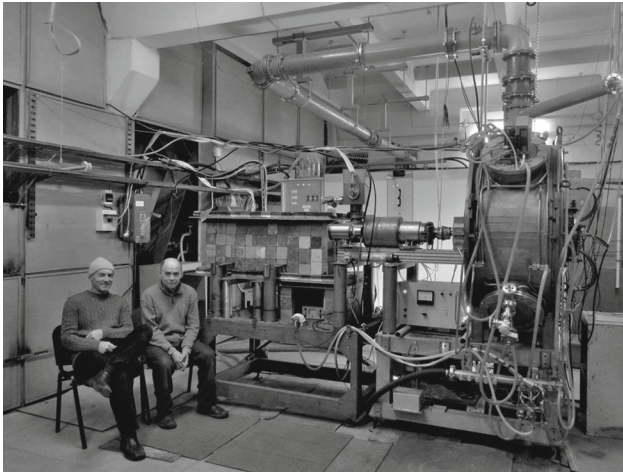


Fig. 8. New RF electron gun for the Novosibirsk ERL.

THE NEW RF ELECTRON GUN

The average beam current of the Novosibirsk ERL is currently limited by the electron gun. A new RF electron gun that operates at a frequency of 90 MHz has now been designed and tested (see Fig. 13) [13]. An average current exceeding 100 mA was obtained on this electron gun [14]. It is planned to build an injection channel for the RF electron gun at the test bench this year.

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REFERENCES

1. Kulipanov, G.N., et al., *IEEE Trans. Terahertz Sci. Technol.*, 2015, vol. 5, no. 5, p. 798.
2. Shevchenko, O.A., et al., *Phys. Proc.*, 2016, vol. 84, p. 13.
3. Antokhin, E., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2004, vol. 528, no. 1, p. 15.
4. Knyazev, B.A., et al., *Phys. Rev. Lett.*, 2015, vol. 115, no. 16, p. 163901.
5. Choporova, Yu.Yu., et al., *IEEE Trans. Terahertz Sci. Technol.*, 2015, vol. 5, no. 5, p. 836.
6. Komlenok, M.S., et al., *Quantum Electron.*, 2015, vol. 45, no. 10, p. 933.
7. Agafonov, A.N., et al., *Appl. Opt.*, 2015, vol. 54, no. 12, p. 3635.
8. Chesnokov, E.N., et al., *Chem. Phys. Lett.*, 2015, vol. 636, p. 203.
9. Gerasimov, V.V., et al., *Opt. Express*, 2015, vol. 23, no. 26, p. 33448.
10. Vinokurov, N.A., et al., *Phys. Rev. Spec. Top.—Accel. Beams*, 2011, vol. 14, no. 4, p. 040701.
11. Davidyuk, I., et al., *Phys. Rev. Accel. Beams*, 2016, vol. 19, p. 020701.
12. Matveenko, A., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2009, vol. 603, p. 38.
13. Volkov, V., Getmanov, Ya., Kenjebulatov, E., Kolo-banov, E., Krutikhin, S., Kurkin, G., Ovchar, V., Petrov, V.M., and Sedlyarov, I., *Phys. Part. Nucl. Lett.*, 2016, vol. 13, no. 7, p. 796.
14. Volkov, V., et al., *Phys. Proc.*, 2016, vol. 84, p. 86.

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