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The Novosibirsk Free Electron Laser Facility

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Abstract. The Novosibirsk FEL facility includes three FELs operating in the terahertz, far-, and mid- infrared spectral ranges. It has rather long history, but its potential has not been fully revealed so far. The first FEL of this facility has been operating for users of terahertz radiation since 2004. It remains the world's most powerful sources of coherent narrow-band radiation in its wavelength range (90 – 340 μm). The second FEL was commissioned in 2009. Now it operates in the range of 35 – 80 μm, but we plan to replace its undulator soon with a new one, and its short wavelength boundary will be shifted down to 15 μm. The third FEL was commissioned in 2015 to cover the wavelength range of 5 – 20 μm. Its undulator comprises three separate sections. Such lattice is suited very well to demonstrate the new off-mirror way of radiation outcoupling in an FEL oscillator (so called electron outcoupling), which we also plan for near future. We also intend to improve the accelerator injection system. As a result, the average electron beam current and consequently the radiation power of all the three FELs will increase. In this paper, we present an overview of the facility and discuss our recent achievements and future plans.

INTRODUCTION

The sources of coherent electromagnetic radiation in the terahertz spectral range are of great interest to scientists in different fields of science including physics, chemistry, biology, medicine, and so on. High power terahertz radiation sources can also have some technological applications. Researches using terahertz radiation have become very active in recent decades with the appearance of new powerful coherent sources of terahertz radiation with adjustable wavelength that are based on free electron lasers (FELs) [1]. The Novosibirsk FEL facility is one of the first such sources, and it still has the world maximum average radiation power in its wavelength range. The facility has three FELs, which operate in three adjacent wavelength ranges (terahertz, far-, and mid- infrared). The first terahertz FEL covers the wavelength range of 90 – 340 μm, for which there are no other powerful sources. The

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second FEL operates in the range of 40 – 80 μm. The average radiation power of the first and second FELs is up to 0.5 kW and the peak power is about 1MW. 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.

Undulators of the FELs are installed on the first, second, and fourths orbits of the multi-turn energy recovery linac (ERL). The Novosibirsk ERL is the first multi-turn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and rather compact (6×40 m2) design.

The first FEL of the facility was commissioned in 2003; the lasing of the last (third) FEL was obtained in 2015. Now the radiation of all three FELs is available for users, but the accelerator and FEL scientific program has not been finished yet. One of the points of this program is demonstration of electron outcoupling [2]. The findings of this experiment will be of great value for the future high power FEL design. Another point is the modification of the injector, involving the installation of a new RF gun [3]. Using the new gun will increase the average current of the beam and consequently the average radiation power. We also plan to replace old FEL undulators with new variable period undulators [4]. It is a new type of undulators, which has never been tested on an FEL. The new undulators will expand the FEL tunability range.

DESIGN OVERVIEW

Accelerator

The NovoFEL accelerator has a rather complex design. One can treat it as three different ERLs that use the same injector and the same linac. A simplified scheme of the multi-turn ERL is shown in Fig. 1. Starting from low-energy injector 1, electrons pass several times through accelerating radio frequency (RF) structure 2. After that, they lose part of their energy in FEL undulator 4. The used electron beam is decelerated in the same RF structure, and the low-energy electrons are absorbed in beam dump 5.

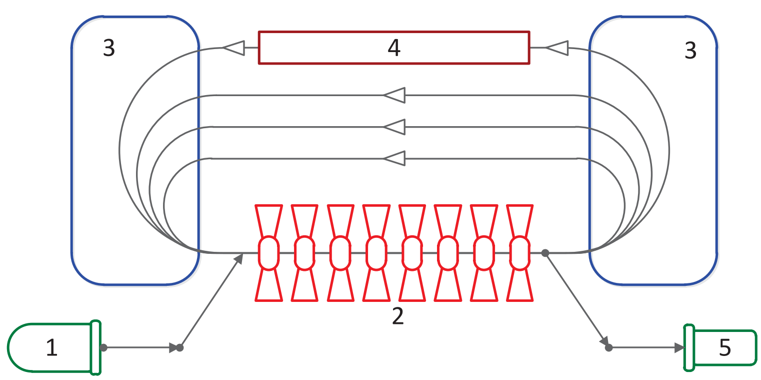

FIGURE 1. Simplified multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.

The first ERL of the facility has only one orbit. It is placed vertically (see Fig. 2). The second and the third ERLs are two and four-turn ERLs, respectively. Their beamlines are placed horizontally. The injector is common for all the ERLs. It includes an electrostatic gun and one bunching and two accelerating cavities, as shown in Fig. 2. The gun voltage is 300 kV, which is applied to the grid-controlled thermionic cathode. The gun provides 1-ns bunches with a charge of up to 1.5 nc, a normalized emittance of about 20 μm, and a repetition rate of zero to 22.5 MHz. After the 180.4-MHz bunching cavity, the bunches are compressed in the drift space (about 3 m long), accelerated up to 2 MeV in the two 180.4-MHz accelerating cavities, and injected by the injection beamline and the chicane into the main accelerating structure of the ERL (see Fig. 3). The accelerating structure consists of 16 normal-conducting RF cavities, connected to two waveguides. The operation frequency is 180.4 MHz. Such a low frequency allows operation with long bunches and high currents.

The choice of the working ERL and corresponding FEL is determined by commutation of bending magnets. The first FEL is installed under the accelerating (RF) structure. Therefore, after the first passage through the RF structure, the electron beam with an energy of 11 MeV is turned by 180 degrees in the vertical plane. After being used in the FEL, the beam returns to the RF structure in the decelerating phase. In this mode, the ERL operates as a single-orbit installation.

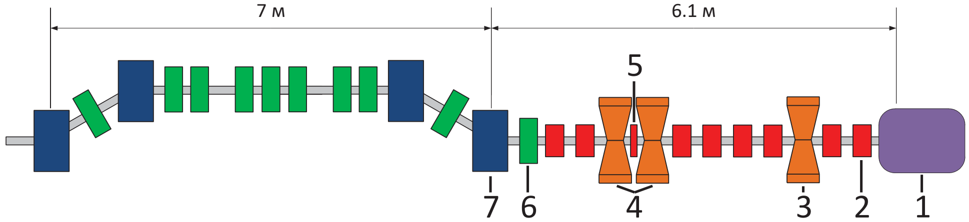

FIGURE 2. Injector layout: 1 - electron gun; 2 - electromagnetic solenoids; 3 – bunching cavity; 4 – accelerating cavities; 5 – permanent magnet solenoid; 6 – quadrupoles; 7 – merger bending magnet.

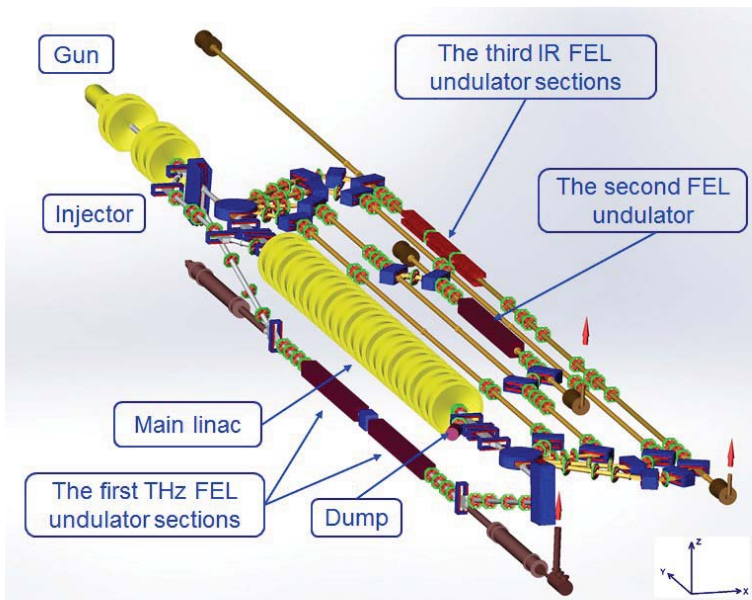

FIGURE 3. Novosibirsk ERL with three FELs (top view).

For operation with the second and third FELs, two round magnets (a spreader and a recombiner) are switched on. They bend the beam in the horizontal plane, as shown in Fig. 3. After four passes through the RF accelerating structure, the electron beam gets in the undulator of the third FEL. The energy of electrons in the third FEL is about 42 MeV. The used beam is decelerated four times and goes to the beam dump.

If the four magnets on the second track (see Fig. 3) are switched on, the beam with an energy of 20 MeV passes through the second FEL. After that, it enters the accelerating structure in the decelerating phase due to the choice of the length of the path through the second FEL. Therefore, after two decelerations the used beam is absorbed in the beam dump.

It is worth noting that all the 180-degree bends are achromatic (even second-order achromatic on the first and second horizontal tracks), but non-isochronous. That enables beam longitudinal "gymnastics" to increase the peak current in the FELs and to optimize deceleration of the used beam.

Undulators, optical cavities, and FEL operation

Undulators of the first and the second FELs are electromagnetic ones with a period of 12 cm. The first FEL undulator is composed of two 4-meter long sections. There is a phase shifter between them. The FEL radiation wavelength is tuned by variation of the field amplitude or by choosing the beam energy. The radiation power is different for different wavelengths. It depends on the ratio of the FEL gain to the optical cavity losses. The maximum power is obtained around a wavelength of 130 μm, as seen in Fig 4a. The irregular undulator lattice slightly complicates the wavelength tuning procedure. If the beam slippage in the drift space between the undulator sections is incorrect, then the radiation power and wavelength change with the undulator field amplitude as shown in Fig. 4b.

The second FEL undulator has only one section and thus the wavelength tuning is much simpler in this case. In the third FEL, we use a permanent magnet undulator with a period of 6 cm and a variable gap. This undulator has three sections, which can be tuned independently. Each section contains 28 periods. They are installed on the forth track (see Fig. 5).

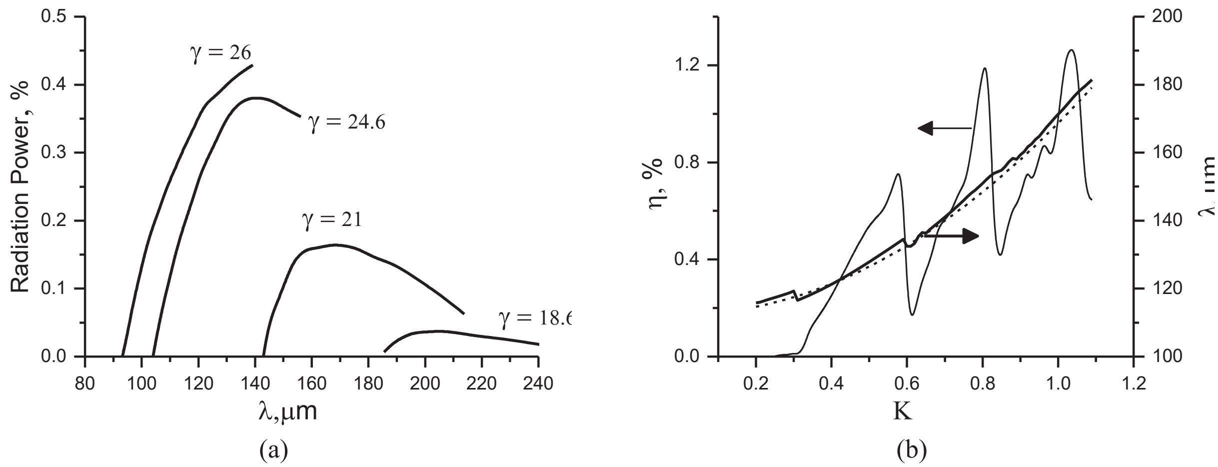

FIGURE 4. (a) Calculated outcoupled radiation power (relative to electron beam power) vs. wavelength for different beam energies and (b) electron efficiency and wavelength vs. undulator deflection parameter in first FEL of NovoFEL facility. Dashed curve: case of continuous undulator.

The optical cavities of all three FELs are similar. They are composed of copper mirrors covered with gold. The radiation is outcoupled through the holes in the mirror center. The second FEL has the shortest cavity, about 20 m long. The third FEL cavity is the longest one, about 40 meters long (see Fig. 5), and has a smaller mirror diameter, as the wavelength is shorter and the diffraction size is smaller in this case.

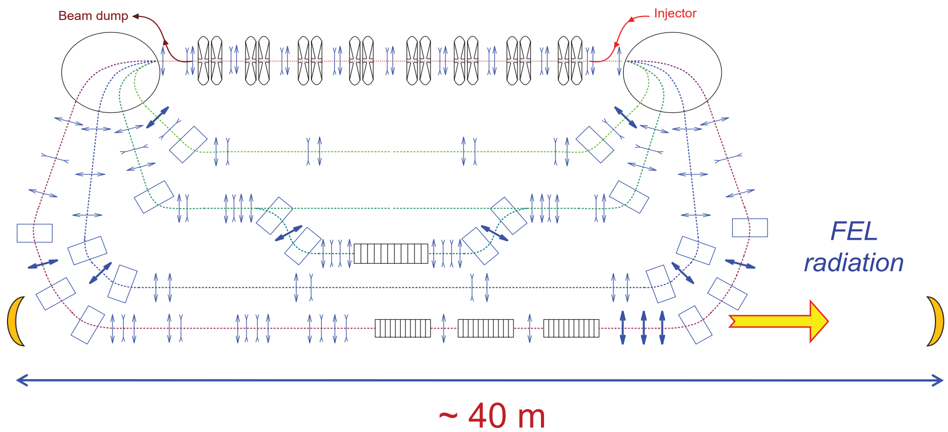

FIGURE 5. Third ERL with FEL undulators and optical cavity.

CURRENT STATUS AND RECENT ACHIEVEMENTS

The radiation of all three FELs is available for users now. It can be delivered to the same user stations through the nitrogen-filled beamline. The radiation combiner is shown in Fig. 6.

FIGURE 6. Optical beamline for FELs. Radiation of all FELs is delivered to the same user stations. Switching between FELs is done using retractable mirrors.

The basic accelerator and FEL parameters for all FELs already obtained in the experiment are listed in Table 1.

TABLE 1. Basic accelerator and FEL parameters

	1st FEL	2nd FEL	3rd FEL
Beam energy , MeV	8.5 – 13.4	21 -22.8	39 - 42
Peak current, A	10	30	50
Average current, mA	30	10	4
Wavelength, μm	90 - 340	37 - 80	8 - 11
Average radiation power, kW	0.5	0.5	0.1
Electron efficiency, %	0.6	0.3	0.2

The long wavelength boundary of the first FEL tunability range was increased recently from 240 to 340 μm. It was done mainly by decreasing the beam energy. The lasing at a long wavelength turned out to be possible thanks to reduced optical cavity losses. Preliminary measurements showed the optical cavity round trip losses to be 30 % at a wavelength of 337 µm. It is two times less than predicted by a simplified theory [5], which was not intended for this case.

The possibilities for users to conduct their experiments have been significantly expanded recently by implementation of the new operation mode [6]. In this mode, single or periodic radiation macropulses of duration of down to 10 µs can be obtained. The radiation power modulation is done electronically by controlling the FEL lasing, and it can be triggered by an external signal.

FUTURE PLANS

Electron outcoupling experiments

We plan to implement an electron out-coupling scheme on the third FEL [2] (see Fig. 7). In this scheme, the beam is bunched in the first undulator and then the achromatic bend slightly deflects it in the transverse direction so that its radiation in the second undulator goes off the axis and passes by the front mirror. It should be noted that this scheme is advantageous only with high power radiation. Typically, the users do not need much power and the out-coupling through the holes is much simpler. So, the main purpose of electron outcoupling experiment at NovoFEL is demonstration of its feasibility.

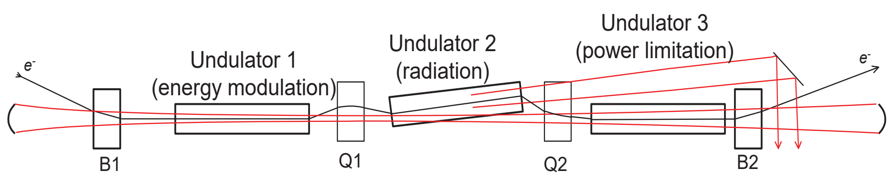

FIGURE 7. Electron out-coupling scheme.

Modification of injector

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun [3] was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved recently [7]. We plan to install this gun in the injector, the existing electrostatic gun kept there. The new gun with its beamline will be placed vertically and connected to the injector beamline via a 90-degree achromatic bend (see Fig. 8).

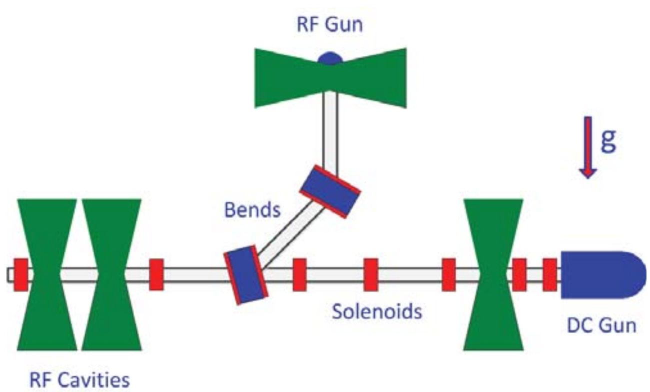

FIGURE 8. Injector modification scheme.

The RF gun beamline has already been manufactured and assembled on the test setup (see Fig. 9). The beam parameters were measured after the first bending magnet and at the beamline exit.

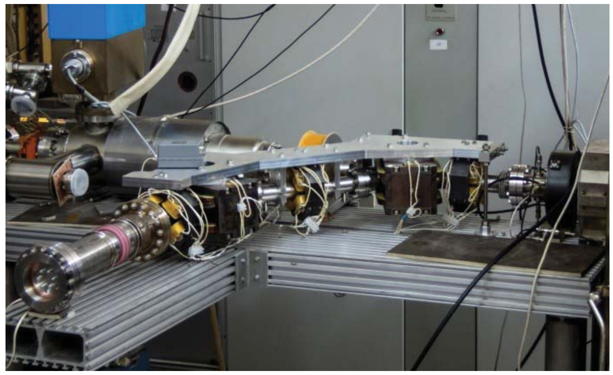

FIGURE 9. RF gun beamline.

Replacement of undulators

The existing electromagnetic undulator of the second FEL will be replaced with a new variable period undulator [4]. This replacement will allow us to expand the FEL tunability range toward the shorter wavelength region (see Fig. 10). The new undulator has already been assembled and magnetic field measurements are almost finished.

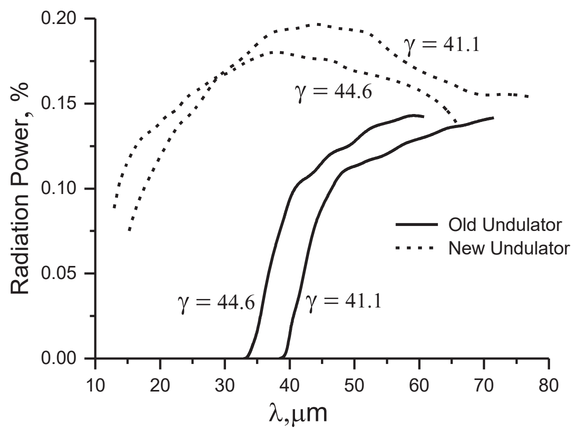

FIGURE 10. Second FEL outcoupled radiation power relative to electron beam power (results of simulations).

We also designed a new variable period undulator for the first FEL [8]. Its aperture is larger than the minimum period, but the field amplitude is relatively large. It was achieved by optimizing the magnet unit shape. Using this undulator will lift the long wavelength boundary of the FEL tunability range up to 450 μm and solve the problem of irregularity of the wavelength adjustment procedure.

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