DOI 10.1007/s11141-017-9727-9
Radiophysics and Quantum Electronics, Vol. 59, No. 8–9, January–February, 2017
(Russian Original Vol. 59, No. 8–9, August–September, 2016)

NOVOSIBIRSK FREE ELECTRON LASER: RECENT ACHIEVEMENTS AND FUTURE PROSPECTS

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UDC 621.384.6+621.373

Free electron lasers (FELs) are unique sources of electromagnetic radiation with tunable wavelength. A high-power FEL has been created at the G. I. Budker Institute for Nuclear Physics. Its radiation frequency can be tuned over a wide range in the terahertz and infrared spectral ranges. As the source of electron bunches, this FEL uses a multi-turn energy-recovery linac, which has five straight sections. Three sections are used for three FELs which operate in different wavelength ranges (90–240 μm for the first, 37–80 μm for the second, and 5–20 μm for the third ones). The first and the second FELs were commissioned in 2003 and 2009, respectively. They are used for various applied and research problems now. The third FEL is installed on the last, forth accelerator loop, in which the electron energy is the maximum. It comprises three undulator sections and a 40 m optical cavity. The first lasing of this FEL was obtained in the summer of 2015. The radiation wavelength was 9 μm and the average power was about 100 W. The design power is 1 kW at a pulse repetition rate of 3.75 MHz. Radiation of the third FEL will be delivered to user stations from the protected hall in the near future. The third FEL commissioning results are presented and the current status of the first and second FELs as well as their future development prospects are described.

1. INTRODUCTION

Free electron lasers (FELs) are unique sources of monochromatic electromagnetic radiation (see, e. g., [1–3]). The principle of operation of FELs is based on the effect of amplification of an electromagnetic wave during its interaction with an electron beam in the undulator. The synchronism condition, under which the energy can be transferred from the electrons to the radiation, connects the radiation wavelength with the electron energy, as well as with the amplitude and period of the magnetic field in the undulator.

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By varying these parameters, it is possible to tune smoothly the wavelength in a fairly wide range. This is the main advantage of the FELs over the conventional lasers. There are two types of FELs: single-pass, high-gain FEL amplifiers, in which an external signal or spontaneous radiation of the electron beam is fed to the input, and FELs with feedback, which are also called FEL oscillators. Feedback is usually provided by using an optical cavity.

A unique free-electron laser (Novosibirsk FEL) with an average radiation power of about 0.5 kW, a peak power of about 1 MW, and wavelength tuning in a range of 5 to 240 μm was created at the G. I. Budker Institute for Nuclear Physics. This laser belongs to the class of FEL oscillators. Currently, it significantly outperforms foreign facilities in its characteristics (see [4]). Other types of narrow-band radiation sources also operate in the terahertz frequency range. They include gyrotrons with kilowatt pulse power at frequencies of up to 1.3 THz [5], frequency tunable backward-wave oscillators with a power of about 1 mW and a frequency of up to 1.4 THz [6], semiconductor lasers with frequencies of about 10 THz and a power of up to 1 W, water-vapor lasers with a power of about 1 mW at some frequencies of about a few terahertz, and some other lasers. High peak and average radiation powers of the FELs combined with the possibility of the wavelength tuning make them attractive for scientific and technological applications.

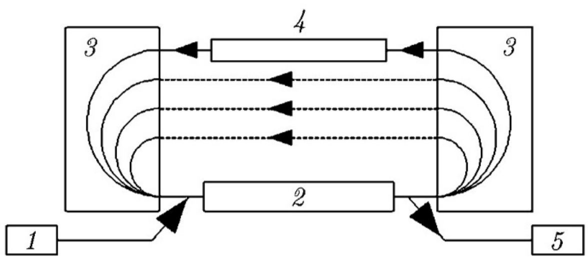

Fig. 1. Simple scheme of the multi-turn energy-recovery linac: *1* is the injector, *2* is the accelerating structure, *3* are the pivot magnets, *4* is the undulator, and *5* is the absorber.

The main part of any FEL is an electron accelerator. An FEL uses accelerators of different types, but for the creation opf high-power lasers the most successful solution is the use of a special class of electron accelerators — high-frequency energy-recovery linacs (ERLs), which were invented by A. N. Skrinsky and N. A. Vinokurov in 1978. In the FEL, only a small part of the energy is transferred from the electron beam to the radiation; therefore, to obtain a high average power of radiation it is needed to use beams with a high average current. This raises the waste-beam recovery problem. The latter can be partially solved by the beam energy recovery in the accelerating structure, which is provided in the ERL scheme (Fig. 1). In this scheme, the beam is accelerated at first, then it is used in the FEL and after that is slowed down and enters the absorber. Also, due to a slight complication of the structure, the beam energy can be increased on the last loop using a multiple pass of the beam through the accelerating structure at the acceleration phase.

The Novosibirsk FEL uses the multi-turn energy-recovery accelerator scheme, which is advantageous in that a higher energy of the beam can be obtained with a shorter accelerating structure. At the same time, the scheme has a significant drawback: the same loops should be used for the beam at the acceleration and slowing-down stages, which makes the accelerator tuning much more difficult. This problem can, in principle, be solved by using a slightly more complex scheme with two accelerating structures [7].

2. GENERAL SCHEME AND MAIN PARAMETERS OF THE ACCELERATOR

At present, the Novosibirsk FEL is a world unique multi-turn ERL. It has a fairly complex structure, the scheme of which is presented in Fig. 2. The whole facility can conventionally be divided into three energy-recovery linacs (one-, two, and four-turn ones), which have a common injector and a common accelerating structure. Operating mode of the accelerator is chosen by switching the pivot magnets. Undulators of three free electron lasers with different wavelength tuning ranges are mounted on the straight sections of the ERL.

A single-pass recovery accelerator includes a common injector and an injection channel, as well as an accelerating structure and one loop located in the vertical plane. The beam generated in the electron gun has a charge of about 1 nC and a duration of about 1.5 ns. The kinetic energy of electrons is 300 keV. Then the beam is bunched, accelerated up to an electron energy of 2 MeV, and injected into the main accelerating structure. The injector uses an electrostatic gun with hot cathode, which is connected to a high-voltage

TABLE 1. Main parameters of the accelerator.

Injection energy, MeV	2.0
Energy pickup in the accelerating structure, MeV	11.0
Electron bunch charge, nC	1.5
Normalized emittance, mm·mrad	30.0
HF oscillator frequency, MHz	180.4
Maximum repetition rate, MHz	90.2

source with a voltage of 300 kV and a maximum current of 50 mA. In prospect, we also plan to use a high-frequency gun, which is currently under development at the G. I. Budker Institute for Nuclear Physics. Undulators of the first laser operated in the terahertz range of the frequency spectrum are mounted on the lower loop of the ERL. The laser was commissioned in 2003 and is currently used for applied and research work [8].

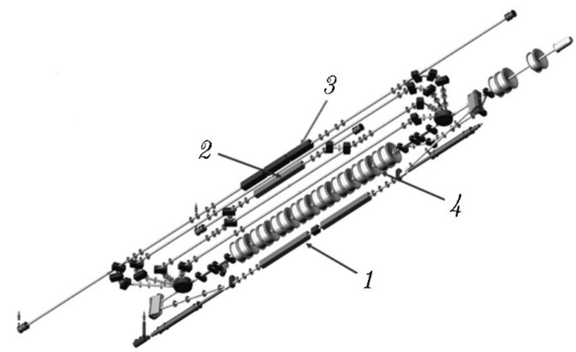

Fig. 2. Scheme of the Novosibirsk energy-recovery linac with three free electron lasers (bottom view): *1* the first FEL, *2* the second FEL, *3* the third FEL, *4* common accelerating structure for all the lasers.

The loops of two other recovery accelerators are located in the horizontal plane. Two round pivot magnets are mounted on a common loop where the main accelerating structure is located. When these magnets are switched on, the electron beam moves along the horizontal loops. The part of the magnetic system, which is responsible for rotation of the beam by 180°, also includes small pivot magnets with parallel edges and quadrupole lenses. To decrease the system's sensitivity to current pulsations, all the magnets are connected in series. The gradients of the magnetic field in quadrupole lenses are chosen from the achromatic rotation condition. Vacuum chambers of the horizontal loops are made of aluminum and have cooling channels inside.

The second horizontal loop has a bypass on which the undulator of the second laser is mounted. Due to lengthening the trajectory by 0.7 m during passage of the electron beam through a bypass, there occurs a time delay resulting in that the beam comes back to the accelerating structure in the slowing-down phase, and enters the absorber after two slowing-down cycles. The second laser was commissioned in 2009. The third laser, whose first action was achieved in 2015, uses all the four horizontal loops of the accelerator.

The main parameters of the accelerator and the electron beam, which are common for the three ERLs, are presented in Table 1.

Depending on the number of turns, the maximum finite energy of electrons is 12, 22, or 42 MeV. Duration of the electron bunch on the last loop in a one-turn ERL is equal to about 100 ps. In a two- or four-turn ERL, the bunch is contracted in the longitudinal direction down to 10–20 ps. The maximum average current obtained in a one-turn ERL is 30 mA, which is the world record at present.

One significant difference of the Novosibirsk ERL from other facilities [9, 10] is the use of normally conducting low-frequency cavities. This, on the one hand, leads to an increase in size of the accelerating structure, but, on the other hand, increases the longitudinal and transverse acceptances and, as a result, makes it possible to use longer electron bunches with a greater transverse emittance.

Location of various parts of the facility in the acceleration hall is shown in Fig. 3.

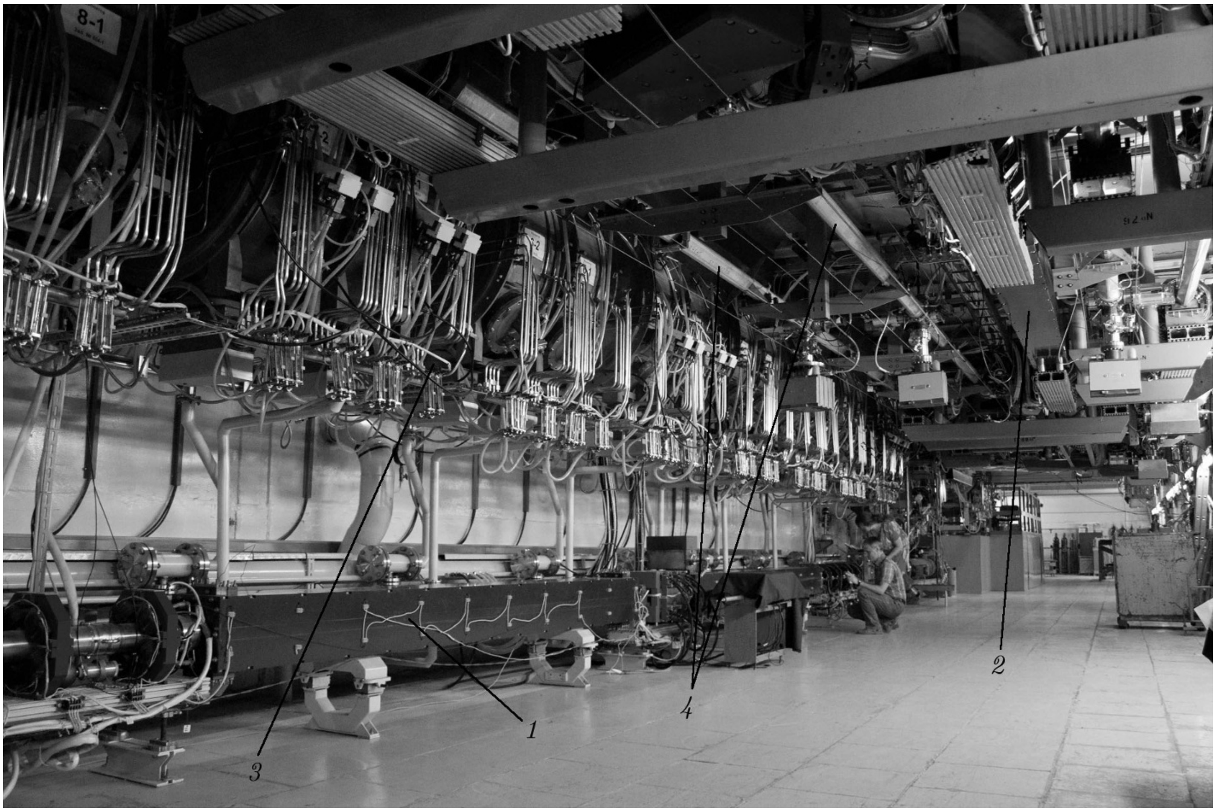

Fig. 3. Location of the facility elements in the acceleration hall: *1* and *2* are the undulators of the first and the second FEL, respectively, *3* is the accelerating structure, and *4* are the horizontal loops.

3. DESCRIPTION AND PARAMETERS OF THE FREE ELECTRON LASER

3.1. The first free electron laser

The first FEL comprises two electromagnetic undulators with a period of 12 cm, a buncher, and an optical cavity. The shape of the undulator poles was chosen so as to ensure an identical focusing of the beam in the vertical and horizontal directions. The consistent beta function of the undulator is about 1 m. The buncher is mounted between the undulators and is used for adjustment of the relative phase of the beam and the radiation. The cavity consists of two copper mirrors covered with gold. The distance between the mirrors amounts to 26.6 m, which corresponds to a repetition frequency of 5.64 MHz. The radiation is extracted through holes at the mirror centers. The channel for extraction of the radiation pulses is separated from the vacuum chamber by a diamond window and is filled with dry nitrogen.

This FEL is the source of coherent radiation with tunable wavelength in the range 90–240 μm. The radiation is generated in the form of a sequence of pulses with a duration of 40 to 100 ps and a repetition rate of 5.6 to 22.4 MHz. The maximum average power is 500 W, while the peak value exceeds 1 MW [11]. The minimum measured relative linewidth is 0.3%, which is close to the limit obtained by the Fourier transform.

3.2. The second free electron laser

The second FEL comprises an electromagnetic undulator with a period of 12 cm and an optical cavity. The undulator is mounted on the bypass of the second loop, where the electron energy reaches 22 MeV. The wavelength tuning range of this FEL is 35–80 μm. The undulator has about the same design as the undulator of the first FEL, but the amplitude of the magnetic field in it is increased due to the aperture decrease. The optical cavity is about 20 m long. The pulse repetition rate corresponding to this length is

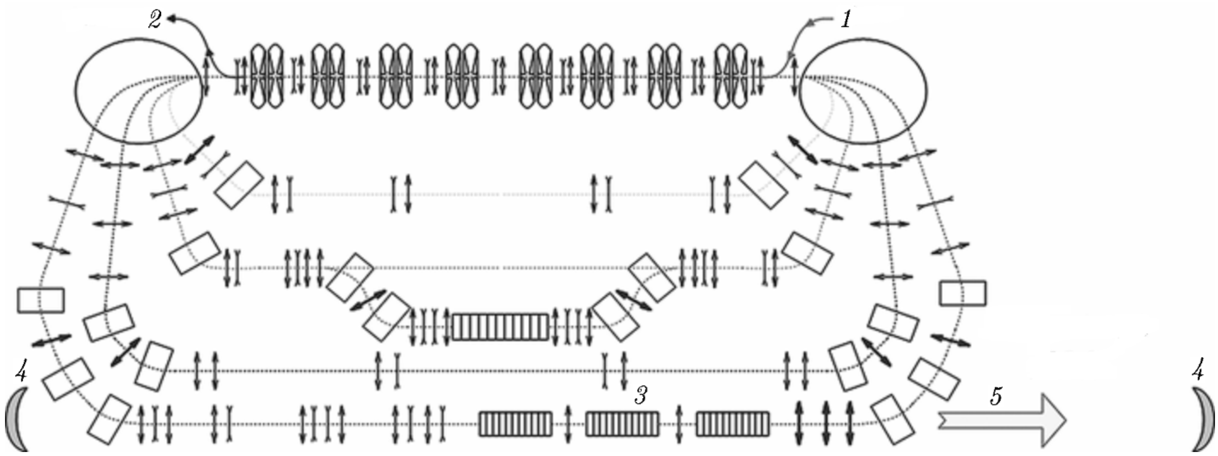

Fig. 4. Scheme of the third FEL with undulators and optical cavity: *1* is the injector, *2* is the waste beam, *3* are the undulators, *4* the optical-cavity mirrors, and *5* is the FEL radiation.

equal to 7.5 NHz. The first lasing of this FEL was achieved in 2009. The gain of the FEL at a wavelength of 50 μm exceeds 40%, and the radiation loss in the optical cavity in one pass at this wavelength is about 5%. This made it possible to achieve lasing when the the electron bunch repetition rate (about 1 MHz) is equal to 1/8 of the fundamental frequency of the optical cavity.

A significant beam loss caused by the additional electron energy spread occurs during the lasing. To reduce this loss, sextupole correctors were mounted in some quadrupole lenses, which made the 180° rotations achromatic in the second order. This increases the energy acceptance for the used electron beam.

The radiated power is 0.5 kW for an average beam current of 9 mA. In prospect, we plan to use a new type of undulator with variable period [12] to extend the wavelength tuning range in this FEL.

3.3. The third free electron laser

Due to the fact that the beam in the ERL of the third FEL is accelerated four times, the electron energy amounts to 42 MeV. This FEL uses three undulator sections, each having 28 periods, which are mounted on the fourth loop, as is shown in Fig. 4. Each section is a variable-gap permanent-magnet undulator. The wavelength tuning range of this FEL will amount to 5–20 μm. The optical cavity is 40 m long and consists of two copper mirrors (Fig. 5).

Fig. 5. The optical-cavity mirror unit.

Currently, the radiation is extracted through holes in the mirrors, but in future, we plan to use the electron output circuit shown in Fig. 6 [13]. This circuit uses an undulator consisting of three sections. In the first section, by the radiation stored in the optical cavity the density of the electron beam is modulated with period equal to the radiation wavelength. The beam enters the second section after the achromatic rotation by a small angle. The coherent radiation which arises in this section is oblique to the axis of the optical cavity and can easily be extracted to the outside by means of an additional mirror. The third section is used to control the electron-beam — cavity-mode coupling.

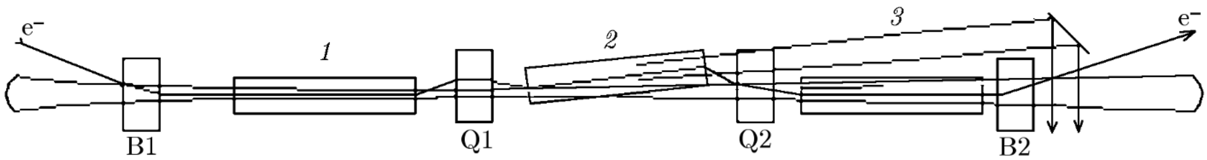

Fig. 6. The electron output circuit. In the undulator section *1*, the beam density is modulated at the radiation wavelength. In section *2*, coherent radiation is generated obliquely to the optical cavity axis. Section *3* is used for control of the electron-beam — cavity-mode coupling.

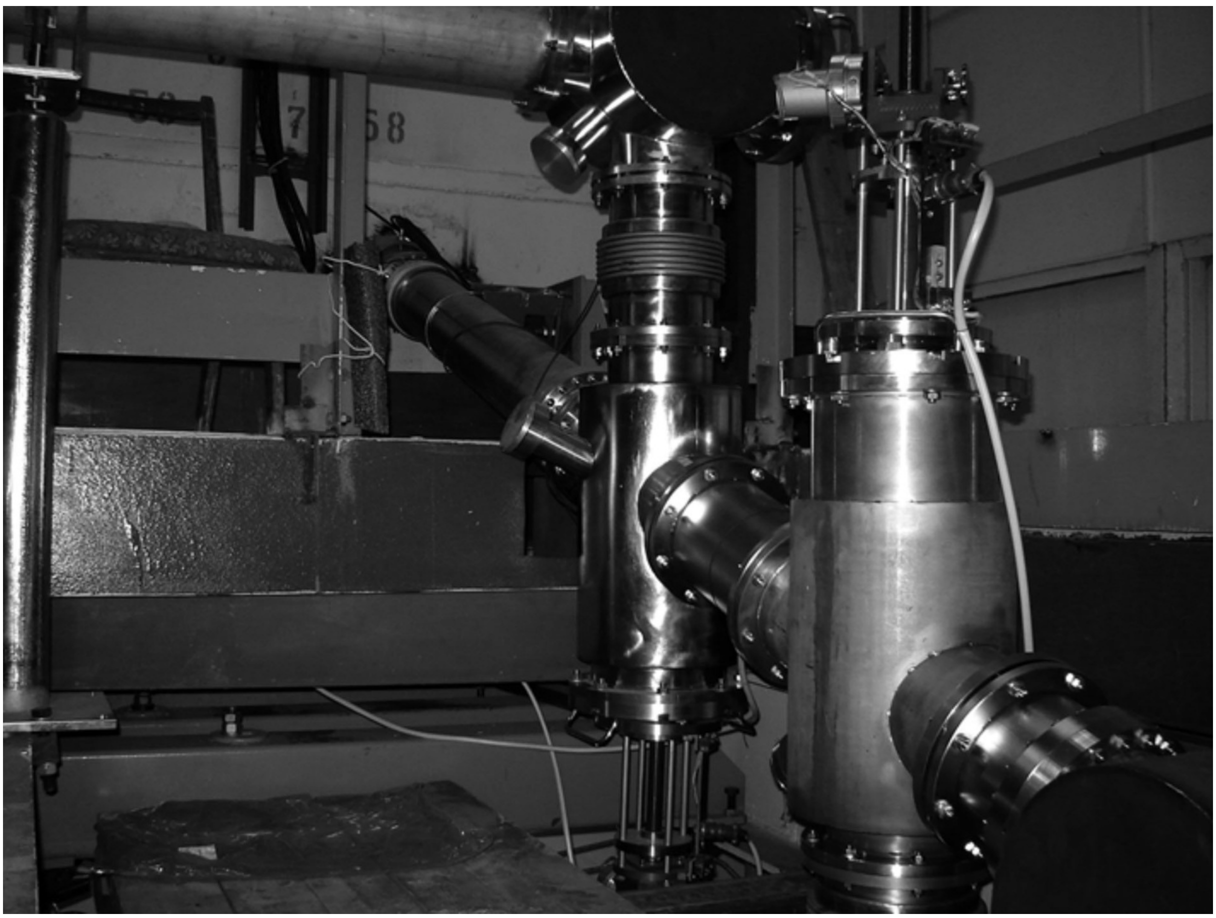

Fig. 7. Radiation extraction channel with a retractable-mirrors unit for switching among the first, second, and third FEL.

4. THE THIRD FEL COMMISSIONING RESULT

The radiation of all the three FELs is delivered to the same user stations. Switching among the stations is provided by output mirrors (Fig. 7). The main parameters of all the three FELs are given in Table 2. Design parameters for the third FEL are shown in the parentheses.

To obtain lasing of the third FEL, it was needed to solve a number of physical and technical problems. The main problem was the obtaining of a high degree of the electron beam recovery in a multi-turn energy-recovery linac. Without solving this problem it was impossible to increase the repetition rate of the electron bunches to the fundamental frequency of the optical cavity (3.75 MHz). By tuning the magnetic system of the accelerator, the beam loss was reduced to 10%, so that most of this loss falls on the last slowing-down stage with a fairly low energy. As a result, an average current of 3.2 mA was obtained. As was mentioned

TABLE 2. Main parameters of the FEL.

Parameters	First FEL	Second FEL	Third FEL
Electron energy, MeV	12	22	42(46)
Average current, mA	307	10	3(50)
Wavelength, μm	90.240	35.80	9(5.20)
Radiation power, kW	0.5	0.5	0.1(5)
Electronic efficiency, %	0.6	0.3	0.2(0.5)

above, the complexity of the solution of this problem is due to the fact that the intermediate loops of the accelerator are used for both the accelerated and slowed-down beams. This precludes independent tuning of the magnetic system for the latter. One solution is to make the focusing of the slowed-down beam mirror-symmetric with respect to the accelerator center by appropriately designing the magnetic system of the intermediate loops and correctly tuning the optical system on the last loop.

The other problem is associated with the adjustment of a 40-m optical cavity. It was needed to keep the distance between the mirrors to an accuracy of 0.3 mm. Also, it was necessary to transmit the beam through the undulator along the axis of the optical cavity mode with submillimeter accuracy. The position sensors in this place do not provide the necessary resolution; therefore, the trajectory is corrected so as to exclude deviation of the beam by quadrupole lenses.

After solving all the mentioned problems, the lasing achievement becomes very simple. The first lasing of this FEL was obtained in 2015. The radiation power (100 W) and wavelength (9 μm) were also measured at that time. The possible future experiments with this FEL include the study of selective photochemical reactions, infrared laser catalysis, and isotope separation.

5. FURTHER DEVELOPMENT PROSPECTS

The nearest plans related to work with the third FEL include the improvement of the radiation protection of the acceleration hall, installation of the remote control system for undulators and mirrors of this FEL, as well as delivery of its radiation to the existing user stations. It is also necessary to reduce the electron loss, raise the average current of the beam, and increase the electronic efficiency of the FEL. To do this, it is needed to improve the beam quality in the injector by increasing voltage in the electrostatic gun and optimize the operation regime of the magnetic system. In the further prospect, we plan to design and manufacture an injection channel from a high-frequency gun, as well as make and mount a mirror and a window to demonstrate extraction of the radiation from the third FEL. Regular research and applied work with the remaining two FEL will be continued.

This work was supported by the Russian Science Foundation (project No. 14–50–00080).

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