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The Novosibirsk Free Electron Laser – unique source of terahertz and infrared coherent radiation

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Abstract

The high-power free electron laser (FEL) facility NovoFEL has been created at Budker INP. Its wavelength can be tuned over a wide range in terahertz and infrared spectrum regions. This FEL uses a multi-turn energy recovery linac with five straight sections as a source of electron beam. Three sections are used for three FELs which operate in different wavelength ranges (the first at 90-240 μm; the second at 37 – 80 μm; the third at 5 – 20 μm).

The first and second FELs were commissioned in 2003 and 2009, respectively. They operate for users now. The third FEL is installed on the fourth accelerator track, which is the last one; the electron energy is maximal here. This FEL 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. Radiation of the third FEL was delivered to the user stations, and the first user shifts were performed recently. The results of the commissioning of the third FEL, the current status of the first and second FELs and future development prospects are presented.

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Keywords: free electron laser, energy recovery linac, terahertz radiation

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1. Overview of the Novosibirsk FEL facility

1.1. Accelerator and two old FELs

The Novosibirsk FEL facility [Kulipanov et al. (2015)] includes three FELs. All the FELs use the electron beam of the same electron accelerator. It is a multi-turn energy recovery linac (ERL). A simplified scheme of the four-turn ERL is shown in Fig. 1. Starting from low-energy injector 1, electrons pass four times through accelerating radiofrequency (RF) structure 2. After that they loose part of their energy in FEL undulator 4. The used electron beam is decelerated in the same RF structure, and low-energy electrons are absorbed in beam dump 5.

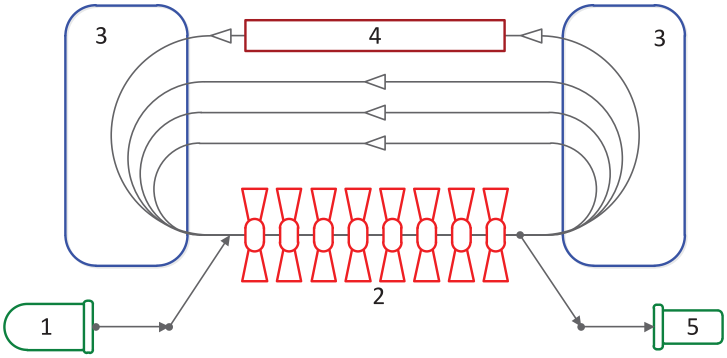

Fig. 1. Simplest multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.

The Novosibirsk ERL has three modes, one mode for operation of one of the three FELs. The first FEL is installed under the accelerating (RF) structure (see Figs. 2 and 3). 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 the use in the FEL, the beam returns to the RF structure in the decelerating phase. In this mode, the ERL operates as a single-orbit linac.

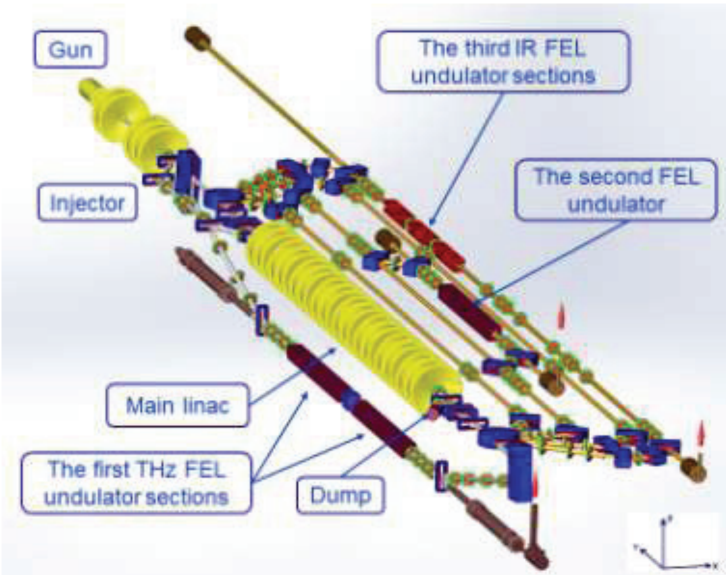

Fig. 2. The Novosibirsk ERL with three FELs (top view).

The first FEL has been in operation since 2003 [Antokhin et al. (2004)]. It provides a narrow-band (less than 1%) terahertz radiation in the wavelength range of 80 – 240 μm at an average power of up to 0.5 kW and a peak power of up to 1 MW (100-ps pulses at a repetition rate of 5.6 MHz). About 30 user research projects in different fields of science were carried out at the facility in recent years [see e.g. Knyazev et al. (2015), Choporova et al. (2015), Komlenok et al. ((2015), Agafonov et al. (2015), Chesnokov et al. (2015), Gerasimov et al. (2015)].

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. 2. After four passes through the RF accelerating structure, the electron beam is in the undulator of the third FEL. The used beam is decelerated four times and goes to the beam dump.

If four magnets on the second track (see Fig. 2) are switched on, the beam with an energy of 20 MeV passes through the second FEL. It generates a narrow-band (less than 1%) far infrared radiation in the wavelength range of 40 – 80 μm at an average power of up to 0.5 kW and a peak power of up to 1 MW (50-ps pulses at a repetition rate of 7.5 MHz). We plan to consider an option of using a new type of variable-period undulator at this FEL [Vinokurov et al. (2011)]. It will allow us to expand significantly the wavelength tuning range.

Unlike other ERLs [Neil et al. (2000), Minehara (2002)], the Novosibirsk one is the world's only multi-turn ERL.

A photo of arrangement of the accelerator hall with accelerating RF cavities and the FELs is shown in Fig. 3.

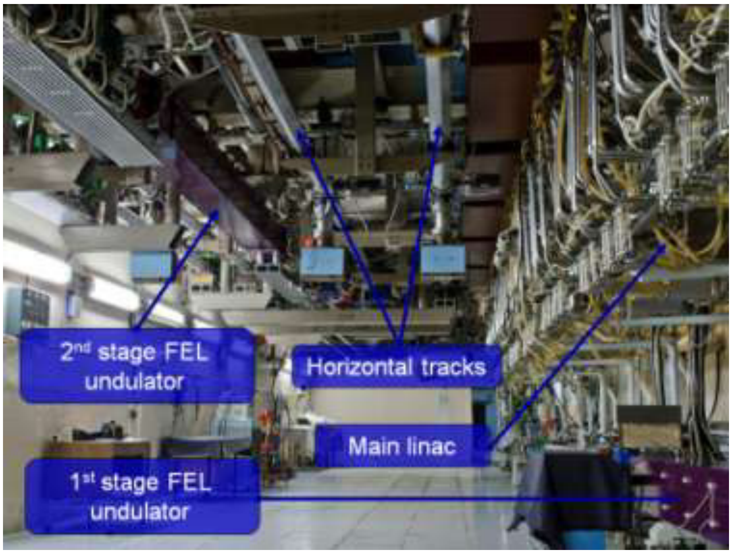

Fig. 3. Accelerator hall (bottom view).

The radiation of all the three FELs is directed to the same nitrogen-filled beamline to the user stations. The radiation combiner is shown in Fig. 4.

Fig. 4. Optical beamline for FELs. Radiation of all FELs is delivered to the same user stations. Switching between FELs is done using retractable mirrors.

1.2. The third FEL design

The energy of electrons in the third FEL is about 42 MeV as the beam is accelerated four times. The undulator of the FEL is installed on the fourth track, as shown in Fig. 5 and Fig. 6. The whole undulator is composed of three 28-period sections. Each of them is a permanent magnet undulator with a period of 6 cm and a variable gap. Now the section in the middle is used for phasing of the two other sections.

The wavelength range of this FEL will be 5-20 μm.

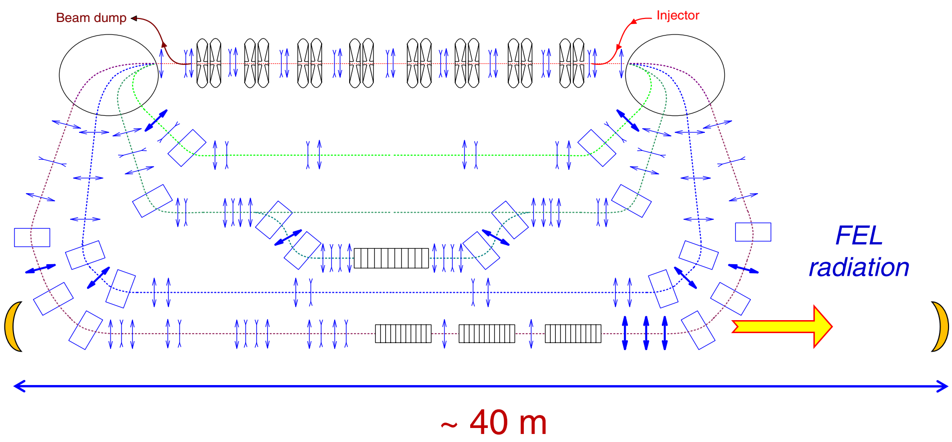

Fig. 5. The third stage ERL with FEL undulators and optical cavity.

Fig. 6. The third stage ERL with FEL undulators.

The optical cavity of this FEL is about 40 m long. It is composed of two copper mirrors. The radiation is out-coupled through the holes in the mirror center. We can also implement an electron out-coupling scheme here [Matveenko et al. (2009)] (see Fig. 7), and we are going to try it in future. 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 past the front mirror. It should be noted that this scheme is advantageous only with high power radiation. Usually, the users do not need much power and the out-coupling through the holes is much simpler.

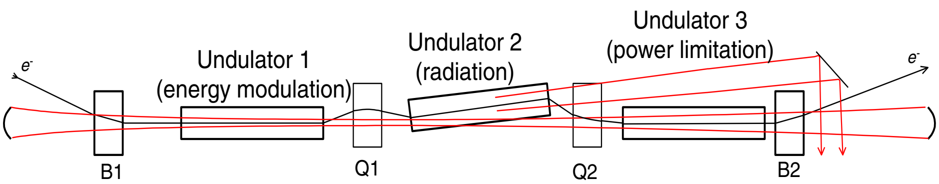

Fig. 7. Electron out-coupling scheme

2. Commissioning of the third FEL - challenges, first experiments and future prospects

The commissioning of the third stage FEL would be impossible without solutions to some physical and technical problems. The first task was attaining high recovery efficiency in the multi-turn ERL. Without it, the quite high bunch repetition rate, which is required for lasing, would be impossible. Adjustment of the ERL lattice made it possible to decrease the beam losses down to 10 %. As a result, an average current of 3.2 mA was achieved. It should be noted that the commissioning of this ERL was a challenge itself as being accelerated and decelerated bunches use the same tracks. The experience attained here can be used in design of future ERL-based facilities [Socol et al. (2011)].

Alignment of the 40-m optical cavity was another problem. The distance between the mirrors had to be adjusted with accuracy better than 0.3 mm. It was also necessary to align the beam trajectory in the undulator with submillimeter accuracy. When all the requirements were fulfilled, the lasing became a simple task.

The first experiment with the FEL radiation included measurement of the radiation power and wavelength. The maximum power was 100 W at a wavelength of about 9 μm. When we had installed remote control units for the undulator gap and delivered the FEL radiation to the existing user stations, the first user shift took place on the third FEL. The first use of this FEL radiation was done recently in experiments of our colleagues from the International Tomography Center (ITC SB RAS). They studied the influence of intense IR radiation on the spin state of a photoswitchable magnetoactive compound based on copper ions and nitroxide radicals. The spin state of the complex was controlled by EPR spectroscopy, the EPR spectra before and after IR excitation being compared. The obtained results are quite interesting, but they require further investigations. In these experiments we swept the IR-light wavelength in the range from 8.5 to 9.6 μm.

Future experiments at the third stage FEL will include study of selective photochemical reactions, infrared laser catalysis and separation of isotopes. In the nearest future, we are also going to improve the x-ray and neutron radiation shielding, decrease beam losses, increase the average current and the DC gun voltage, improve the beam quality in the injector, and optimize the electron efficiency of the FEL. The regular user shifts at the first stage FEL will be also continued.

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