# NOVOSIBIRSK FOUR-ORBIT ERL WITH THREE FELS*

N. A. Vinokurov†[1], V. S. Arbuzov, K. N. Chernov, I. V. Davidyuk[1], O. I. Deichuly, E. N. Dementyev, B. A. Dovzhenko, Ya. V. Getmanov[1], Ya. I. Gorbachev, B. A. Knyazev[1], E. I. Kolobanov, A. A. Kondakov, V. R. Kozak, E. V. Kozyrev[1], S. A. Krutikhin, V. V. Kubarev[1], G. N. Kulipanov, E. A. Kuper, I. V. Kuptsov, G. Ya. Kurkin, L. E. Medvedev, S. V. Motygin, V. K. Ovchar, V. N. Osipov, V. M. Petrov, A. M. Pilan, V. M. Popik, V. V. Repkov, T. V. Salikova, M. A. Scheglov, I .K. Sedlyarov, S. S. Serednyakov[1], O. A. Shevchenko, A. N. Skrinsky, S. V. Tararyshkin, A. G. Tribendis[2], V. G. Tcheskidov, P. D. Vobly, V. N. Volkov, Budker INP SB RAS, Novosibirsk, Russia
[1]also at Novosibirsk State University, Novosibirsk, Russia
[2]also at Novosibirsk State Technical University, Novosibirsk, Russia

*Abstract*

The Novosibirsk FEL facility has three FELs, installed on the first, second and fourth orbits of the ERL. The first FEL covers the wavelength range of 90 – 240 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 5.6 or 11.2 MHz and a peak power of up to 1 MW. The second FEL operates in the range of 40 - 80 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 7.5 MHz and a peak power of about 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 wavelength range of 5 – 20 µm. The Novosibirsk ERL is the first and the only multiturn 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 a rather compact (6×40 m$^2$) design. The facility has been operating for users of terahertz radiation since 2004.

## ACCELERATOR

The Novosibirsk free electron laser (FEL) facility [1, 2] includes three FELs. All the FELs use the electron beam of the same electron accelerator, 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 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.

The electron source is a 300-kV electrostatic gun with a grid cathode. It 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 length), accelerated in the two 180.4-MHz accelerating cavities up to 2 MeV, and injected by the injection beamline and the chicane into the main accelerating structure of the ERL (see Fig. 2).

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 Novosibirsk ERL has three modes, one mode for operation of each 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 installation.

*Work supported by Russian Science Foundation project N 14-50-00080.
†email address vinokurov@inp.nsk.su

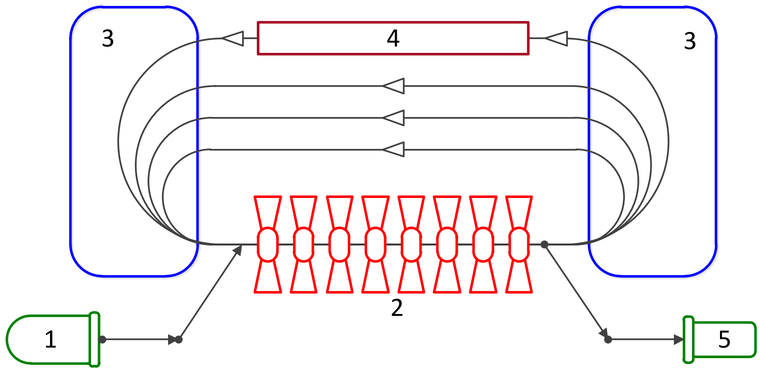


Figure 1: Simplified multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.

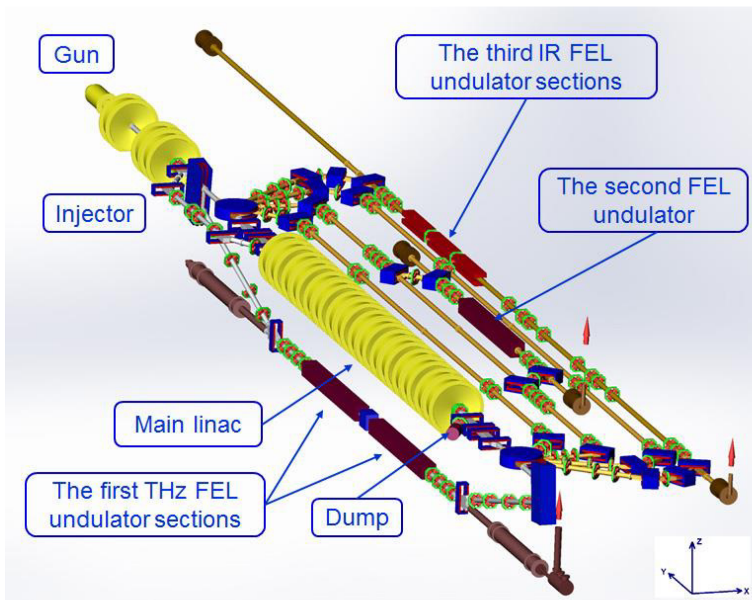


Figure 2: The Novosibirsk ERL with three FELs (top view).

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. 2. 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. 2) 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.

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

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. It enables beam longitudinal "gymnastics" to increase the peak current in the FELs and to optimize deceleration of the used beam.




ISBN 978-3-95450-182-3

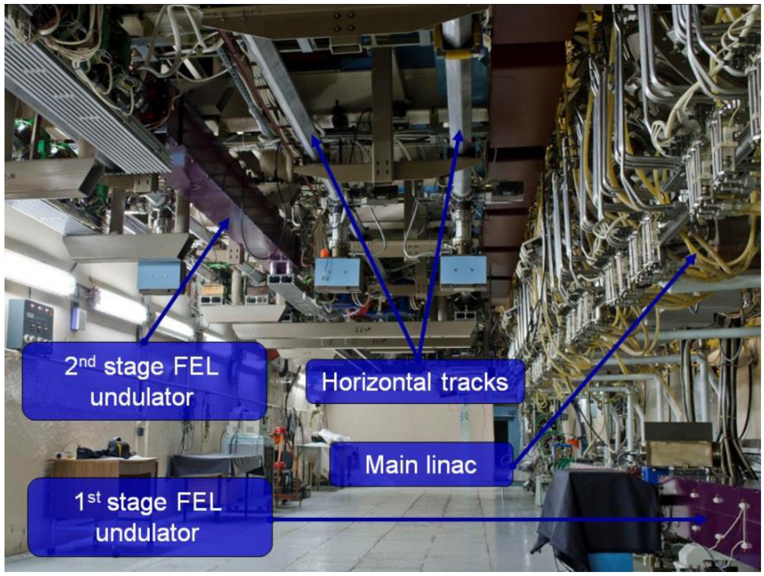


Figure 3: Accelerator hall.

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

## FELS

The first FEL has been in operation since 2003 [3]. 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. [4 – 9].

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.

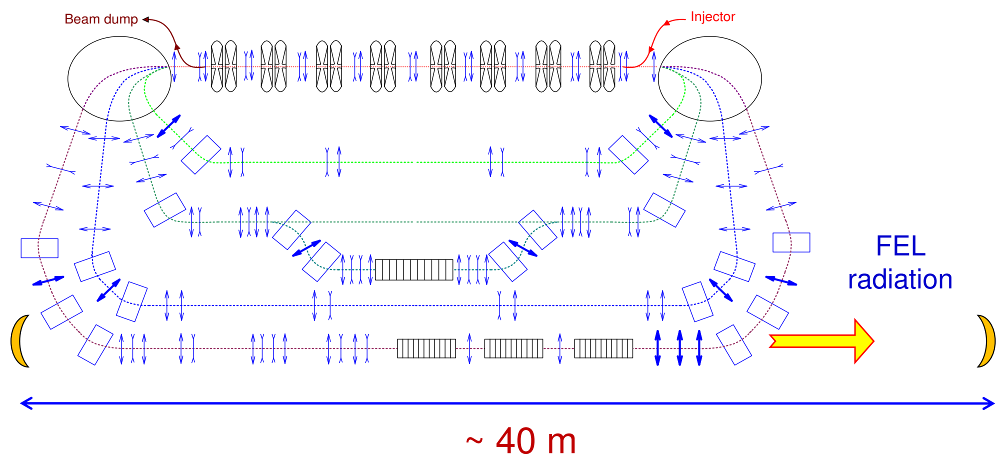


Figure 5: The third stage ERL with FEL undulators and optical cavity.

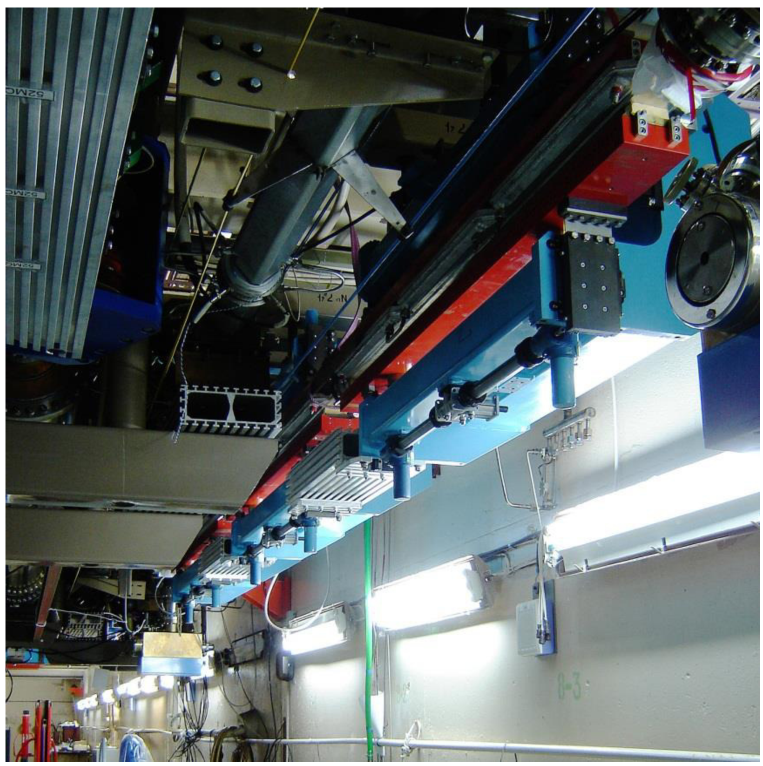

Figure 6: The third FEL undulators.

The second FEL 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). The new variable-period undulator [10] is being prepared to replace the old electromagnetic one of this FEL [11]. It will allow us to expand significantly the wavelength tuning range.

The undulator of the third 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 is 5-20 μm.

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 also plan to implement an electron out-coupling scheme here [12] (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.


ISBN 978-3-95450-182-3

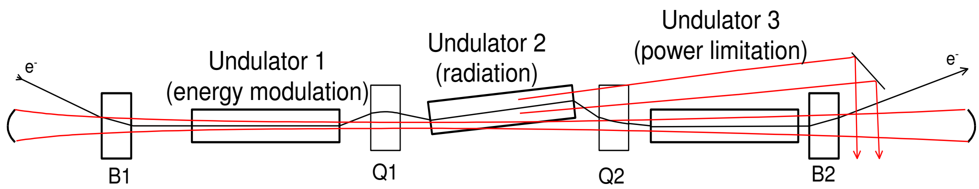


Figure 7: Electron out-coupling scheme.

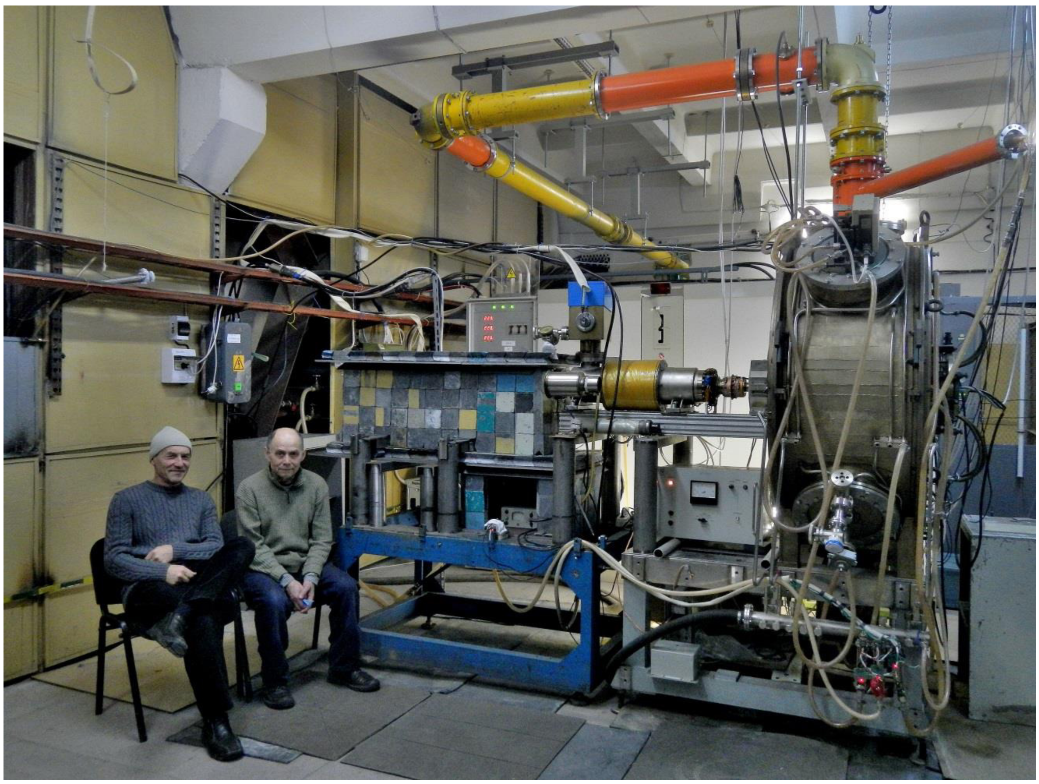

Figure 8: New electron RF gun for Novosibirsk ERL.

## THE NEW RF GUN

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun [13] (see Fig. 8) 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 [14]. The injection beamline for the RF gun will be manufactured this year.

## ACKNOWLEDGMENT

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

The work was done using the infrastructure of the Shared-Use Center "Siberian Synchrotron and Terahertz Radiation Center (SSTRC)" of Budker INP SB RAS.

## REFERENCES

[1] G. N. Kulipanov *et al.*, “Novosibirsk Free Electron Laser - Facility Description and Recent Experiments”, *IEEE Trans. on Terahertz Science and Technology*, 5(5) (2015) 798–809.

[2] O. A. Shevchenko *et al.*, “The Novosibirsk Free Electron Laser – unique source of terahertz and infrared coherent radiation”, *Phys. Procedia*, 84 (2016) 13-18.

[3] E. Antokhin *et al.*, “First lasing at the high-power free electron laser at Siberian center for photochemistry research”, *Nucl. Instr. and Meth.* A 528(1) (2004) 15–18.

[4] B. A. Knyazev *et al.*, “Generation of Terahertz Surface Plasmon Polaritons Using Nondiffractive Bessel Beams with Orbital Angular Momentum”, *Phys. Rev. Lett.*, 115(16) (2015) 163901.

[5] Yu. Yu. Choporova *et al.*, “Classical Holography in the Terahertz Range: Recording and Reconstruction Techniques”, *IEEE Trans. on Terahertz Science and Technology*, 5(5) (2015) 836–844.

[6] M. S. Komlenok *et al*., “Fabrication of a multilevel THz Fresnel lens by femtosecond laser ablation”, *Quantum Electronics*, 45(10) (2015) 933–936.
[7] A. N. Agafonov *et al*., “Control of transverse mode spectrum of Novosibirsk free electron laser radiation”, *Applied Optics*, 54(12) (2015) 3635.
[8] E. N. Chesnokov *et al*. “Non-Faraday rotation of the free induction decay in gaseous NO”, *Chem. Phys. Lett.*, 636 (2015) 203–207.
[9] V. V. Gerasimov *et al*., “Experimental investigations into capability of terahertz surface plasmons to bridge macroscopic air gaps”, *Optics Express*, 23(26) (2015) 33448.
[10] N. A. Vinokurov *et al*., “Variable-period permanent magnet undulators”, *Phys. Rev. ST Accel. Beams*, 14(4) (2011) 040701.
[11] I. Davidyuk *et al*., “Modeling and designing of variable-period and variable-pole-number undulator”, *Phys. Rev. Accel. Beams* 19 (2016) 020701.
[12] A. Matveenko *et al*., “Electron outcoupling scheme for the Novosibirsk FEL”, *Nucl. Instr. and Meth*. A 603 (2009) 38 – 41.
[13] V. Volkov *et al*., “Thermocathode radio-frequency gun for the Budker Institute of Nuclear Physics free-electron laser”, *Physics of Particles and Nuclei Letters* 13 (7) 796 - 799 (2016).
[14] V. Volkov *et al*., “New RF gun for Novosibirsk ERL FEL”, *Phys. Procedia*, 84 (2016) 86-89.




ISBN 978-3-95450-182-3