COMMISSIONING STATUS AND FURTHER DEVELOPMENT OF THE NOVOSIBIRSK MULTITURN ERL*

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Abstract

The Novosibirsk ERL is used as a source of electron beams for the powerful Free Electron Laser. It is based on the normal conducting RF structure which operates in CW mode. The third stage of this facility which is the first in the world four-turn ERL has been commissioned recently. More than 90% of electrons were transported to the beam dump, which allowed to increase the average beam current up to 5 mA. The obtained parameters are sufficient to get lasing at the third stage FEL which will be installed at fourth track in the nearest future. In this paper we report the commissioning status and talk about further development of the Novosibirsk ERL and FEL facility.

ACCELERATOR DESIGN

The Novosibirsk FEL facility is based on the multiturn energy recovery linac (ERL) which scheme is shown in Fig. 1. In this scheme the beam goes through the linac several times before it enters undulator. As the result one can increase the final electron energy.

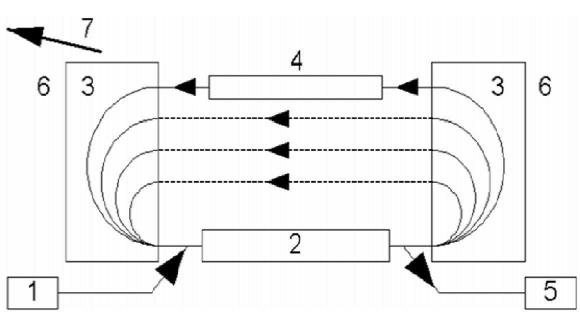

Figure 1: Simplest multiturn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.

Multiturn ERLs look very promising for making ERLs less expensive and more flexible, but they have some serious intrinsic problems. Particularly in the simplest scheme shown in Fig.1 one has to use the same tracks for accelerating and decelerating beams which essentially complicates adjustment of the magnetic system. This problem can be solved by using more sophisticated scheme based on two linacs [1].

At present the Novosibirsk ERL is the only one multiturn ERL in the world. It has rather complicated lattice as it can be seen from Fig. 2. The ERL can operate in three modes providing electron beam for three different FELs. The whole facility can be treated as three different ERLs (one-turn, two-turn and four-turn) which use the same injector and the same linac. The one-turn ERL is placed in vertical plane. It works for the THz FEL which undulators are installed at the floor. This part of the facility is called the first stage. It was commissioned in 2003 [2].

The other two ERL orbits are placed in horizontal plane at the ceiling. At the common track there are two round magnets. By switching these magnets on and off one can direct the beam either to horizontal or to vertical beamlines. The 180-degree bending arcs also include small bending magnets with parallel edges and quadrupoles. To reduce sensitivity to the power supply ripples, all magnets on each side are connected in series. The quadrupole gradients are chosen so that all bends are achromatic. The vacuum chambers are made from aluminium. They have water-cooling channels inside.

The second horizontal track has bypass with the second FEL undulator. The bypass provides about 0.7 m lengthening of the second orbit. Therefore when the beam goes through the bypass it returns back to the linac in decelerating phase and after two decelerations it finaly comes to the dump. This part (the second stage) was commissioned in 2009. The final third stage will include full-scale four-turn ERL and FEL installed on the last track.

The basic beam and linac parameters common for all three ERLs are listed in Table 1.

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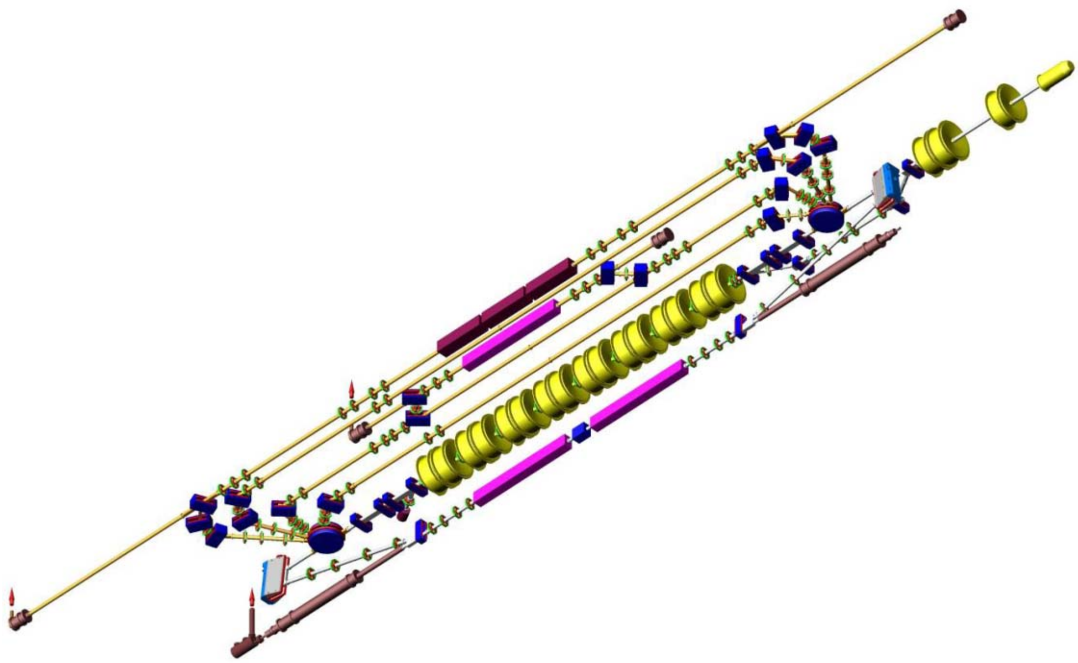

Figure 2: The Novosibirsk ERL with three FELs (bottom view).

Table 1: Basic ERL parameters

Injection energy, MeV	2
Main linac energy gain, MeV	10
Charge per bunch, nC	1.5
Normalized emittance, mm·mrad	30
RF frequency, MHz	180.4
Maximum repetition rate, MHz	90.2

Depending on the number of turns the maximum final electron energy can be 12, 22 or 42 MeV. The bunch length in one-turn ERL is about 100 ps. In two and four-turn ERLs the beam is compressed longitudinally up to 10-20 ps. The maximum average current achieved at one-turn ERL is 30 mA which is still the world record.

One essential difference of the Novosibirsk ERL compared to other facilities [3,4] is using of the low frequency non-superconducting RF cavities. On one hand it leads to increasing of the linac size but on the other hand it also allows to increase transversal and longitudinal acceptances which allows to tolerate longer electron bunches with large transversal and longitudinal emittances.

The location of different parts of the facility in the accelerator hall is shown in Fig. 3.

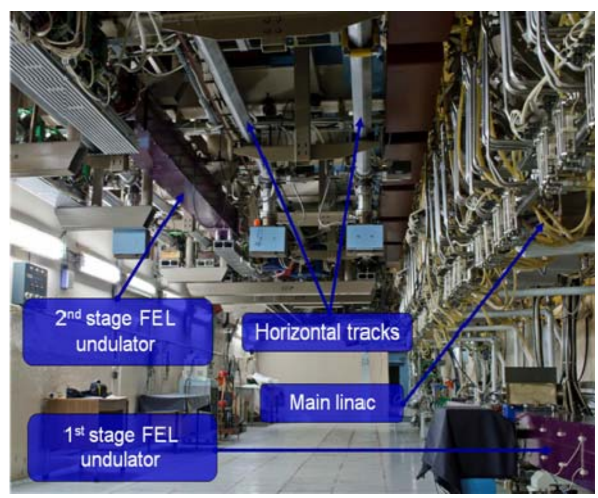

Figure 3: Accelerator hall (bottom view).

THE FIRST STAGE FEL

Design and Basic Parameters

The first stage FEL includes two electromagnetic undulators with period 12 cm, phase shifter and optical cavity. Undulator pole shape is chosen to provide equal electron beam focusing in vertical and horizontal directions. The matched beta-function is about 1 m. The phase shifter is installed between undulators and it is used to adjust the slippage. The optical cavity is composed of two copper mirrors covered by gold. The distance between mirrors is 26.6 m which corresponds to the round-trip frequency (and the resonance electron repetition rate) 5.64 MHz. Radiation is outcoupled

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through the hole made in the mirror center. The optical beamline is separated from the vacuum chamber by diamond window. The beamline pipe is filled with dry nitrogen.

The FEL generates coherent radiation tunable in the range 120-240 micron as a continuous train of 40-100 ps pulses at the repetition rate of 5.6 - 22.4 MHz. Maximum average output power is 500 W, the peak power is more than 1 MW [5,6]. The minimum measured linewidth is 0.3%, which is close to the Fourier-transform limit.

Operation Experience

For the last two years about 30 experiments were carried out at the Novosibirsk THz FEL. They include: pioneering works on THz ablation; study of micro- and nanoparticles, vaccines, polymers, metamaterials; production of nanotubes and nanostructures; composite diagnostics; terahertz radioscopy, imaging, detection of concealed objects; interferomety, holography & tomography; speckle and Talbot metrology; ellipsometry; fast water vapor detection; flame and gas detonation study; impact of THz radiation on genetic materials; impact of THz radiation on cells; study of integrated proteomic response; coherent effects in gases; ultrafast time-domain spectroscopy; interaction of atoms with strong THz EM-field.

Five user stations are in operation now. Two other are in progress. The new spectrometer has been installed recently. It allows to measure continuously radiation spectrum not interrupting user experiments (Fig. 4). Other radiation diagnostics include Fourier spectrometer, thermograph, microbolometer matrix, Shottky diode together with wideband oscilloscope. The last one is used for time-resolved measurements. It allows to detect longitudinal power distribution of radiation pulses.

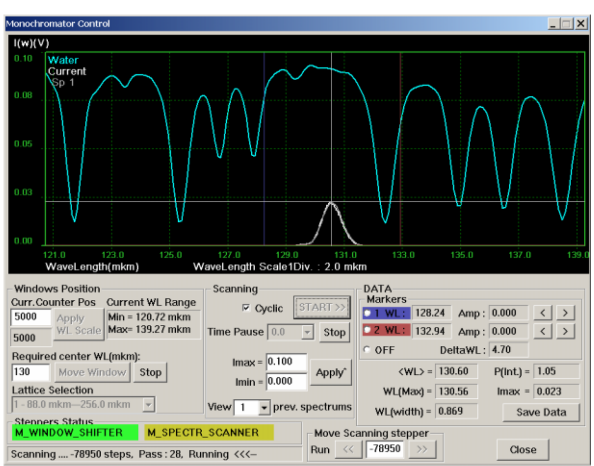

Figure 4: Spectrum measurement diagnostic control (white line - the measured FEL radiation spectrum, blue line - water absorption spectrum).

Recently the third harmonics lasing was obtained. It was achieved by suppression of the first harmonics lasing using aperture-decreasing scrapers installed inside the optical cavity and proper adjustment of the phase shifter. The measured detuning curves for the first and third harmonics lasing are shown in Fig. 5.

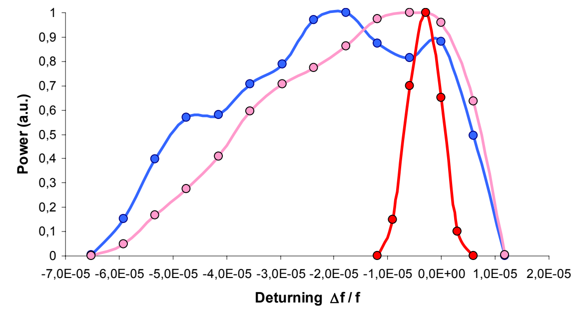

Figure 5. Normalized detuning curves for the lasing at the first (blue) and third (red) harmonics and the detuning curve for the amplified spontaneous emission at the third harmonic (pink).

THE SECOND STAGE FEL

The second stage FEL includes one electromagnetic undulator with period 12 cm and optical cavity. The undulator is installed on the bypass where the electron energy is about 22 MeV. Therefore the FEL radiation wavelength range is 40 - 80 micron. The undulator design is identical to the first stage one but it has smaller aperture and higher maximum magnetic field amplitude. The optical cavity length is 20 m (12 RF wavelengths). Therefore the bunch repetition rate for initial operation is 7.5 MHz.

The first lasing of this FEL was achieved in 2009. The maximum gain was about 40% which allowed to get lasing at 1/8 of the fundamental frequency (at bunch repetition rate ~1 MHz).

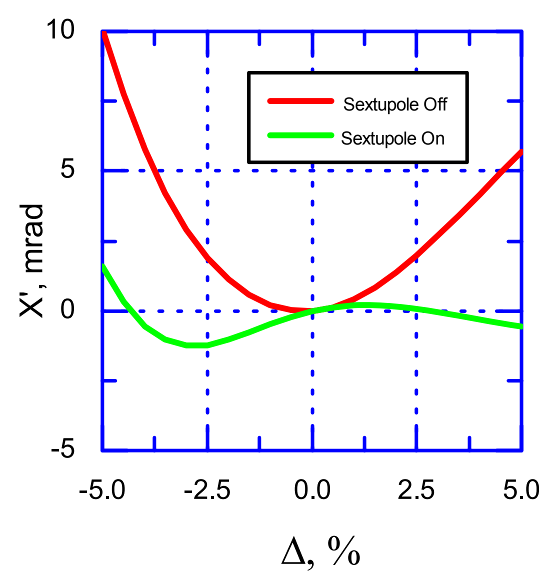

Figure 6: Compensation of quadratic dependence of the bending angle on energy by sextupoles in the first orbit bending arcs.

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The significant (percents) increase of beam losses took place during first lasing runs. Therefore sextupole corrections were installed into some of quadrupoles to make the 180-degree bends second-order achromatic. It increased the energy acceptance for used electron beam (Fig. 6).

The optical beamline (Fig. 7) which delivers radiation from new FEL to existing user stations is assembled and commissioned. The output power is about 0.5 kW at the 9 mA ERL average current. Thus, the first in the world multiturn ERL operates for the far infrared FEL.

Figure 7: Optical beamlines for the first and the second stage FELs. Radiation of both FELs is delivered to the same user stations. Switching between FELs is done by retractable mirror.

THIRD STAGE ERL AND FEL

The scheme of the third stage ERL with FEL undulators is shown in Fig. 8. Electron beam in the third stage ERL is accelerated four times. The third FEL undulators are already installed on the last track (Fig. 9) where the beam energy is 42 MeV. In this FEL three permanent magnet undulators with period 6 cm and variable gap will be used. The wavelength range will be 5-30 microns. The electron outcoupling is planned to be used here [7].

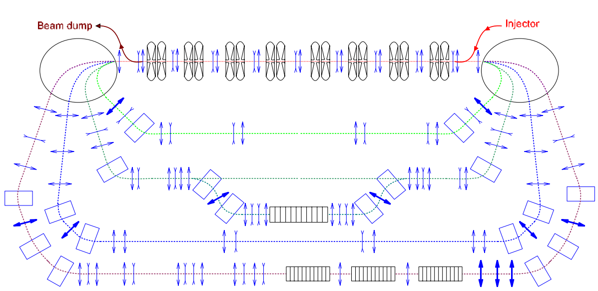

Figure 8: The third stage ERL with FEL undulators.

All magnetic system elements and vacuum chambers of the third stage ERL are assembled and installed. The first shifts for lattice adjustment took place and 95% of the injector beam current has been dumped already.

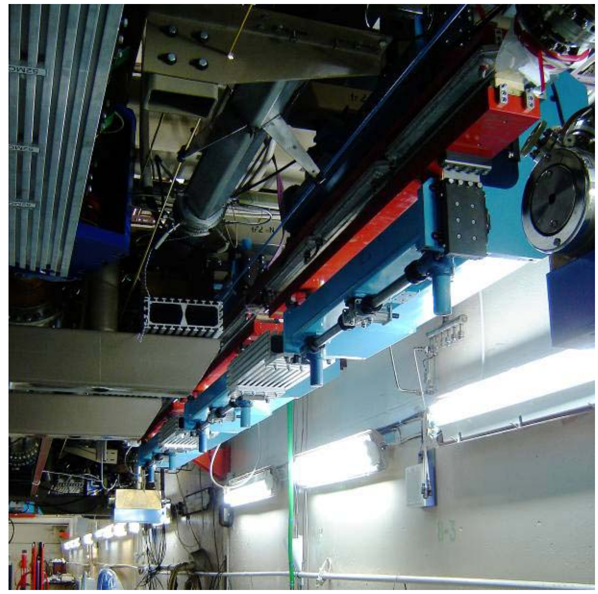

Figure 9: Three permanent magnet undulators with variable gap installed on the last track.

The signal from the BPM installed in the accelerating structure near the dump is shown in Fig. 10. All eight peaks here correspond to the same beam at different stages – the first four are in accelerating phase and the last four - in decelerating phase. One can see that the first and the last peak amplitudes do not differ significantly. It means that the beam losses mostly take place near the dump.

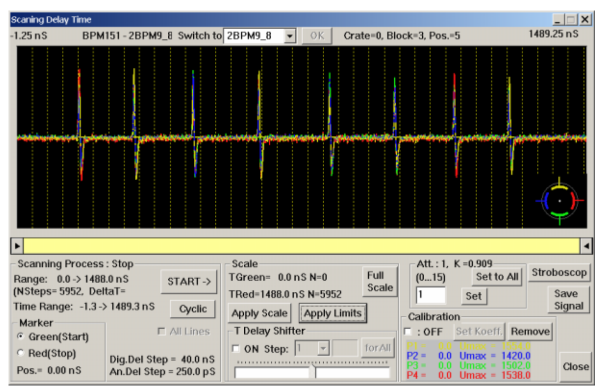

Figure 10: Signal from the BPM installed in the accelerating structure.

The obtained level of beam losses allowed to increase the average current up to 5 mA. The minimal repetition rate required to get lasing has been demonstrated.

FUTURE PROSPECTS

In the nearest future we plan to continue the third stage ERL commissioning. The third FEL optical cavity will be assembled and the lasing of this FEL will be obtained shortly. After that the main problem will be optimization of the longitudinal acceptance for recuperation of the beam with large energy spread. To solve this problem we

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are planning to optimize the lattice and to install additional sextupole correctors.

The other important issue which we are working on now is the operation stability and improvement of the existing FEL parameters. We plan to make some improvements of the RF system. We also plan to increase accelerating voltage amplitude and stability of the DC gun. For this purpose the new power supply is being commissioned now. In distant prospect we consider an option to replace DC gun by new RF gun which is being developed in our institute. The test setup for this gun is in operation already (Fig. 11).

Figure 11: RF gun test setup.

By now one has achieved the following beam parameters from this gun: bunch charge – 1.5 nQ, pulse duration – 1 ns, average beam current – 25 mA.

More serious modernization e.g. using the new type of undulators with variable period [8] is also considered.

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