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PHYSICS AND TECHNIQUE OF ACCELERATORS

Current Status of the Novosibirsk Infrared FEL and the Third Stage Lasing[1]

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Abstract—Novosibirsk FEL facility is based on the first in the world multi-turn energy recovery linac (ERL). It comprises three FELs (stages). FELs on the first and the second tracks were commissioned in 2004 and 2009 respectively and operate for users now. The third stage FEL is installed on the fourth track of the ERL. It includes three undulator sections and 40-meters-long optical cavity. The design tuning range of this FEL is from 5 to 20 microns and the design average power at bunch repetition rate 3.74 MHz is about 1 kW. Recent results of the third stage FEL commissioning are reported.

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OVERVIEW OF THE NOVOSIBIRSK FEL FACILITY

Accelerator Design and Basic Parameters

The Novosibirsk FEL facility is based on the multiturn energy recovery linac (ERL) which scheme is shown in Fig. 1. The advantage of this scheme is that high energy electrons can be obtained with shorter linac as the beam goes through the linac several times before it enters undulator.

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.

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 [1].

The other two ERL beamlines 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

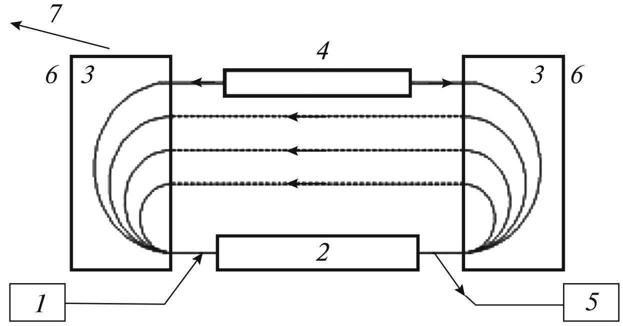

Fig. 1. Simplest multiturn ERL scheme: *1*—injector, *2*—linac, *3*—bending magnets, *4*—undulator, *5*—dump.

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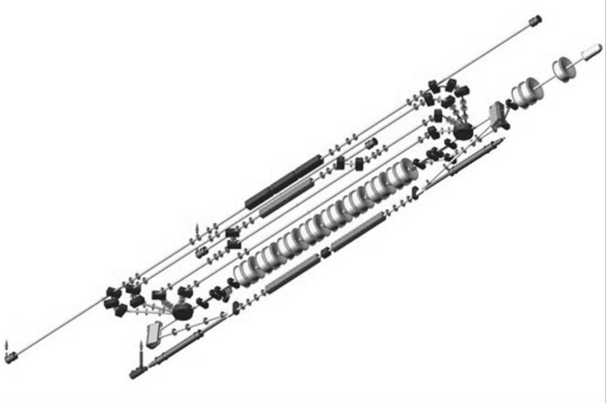

Fig. 2. The Novosibirsk ERL with three FELs (bottom view).

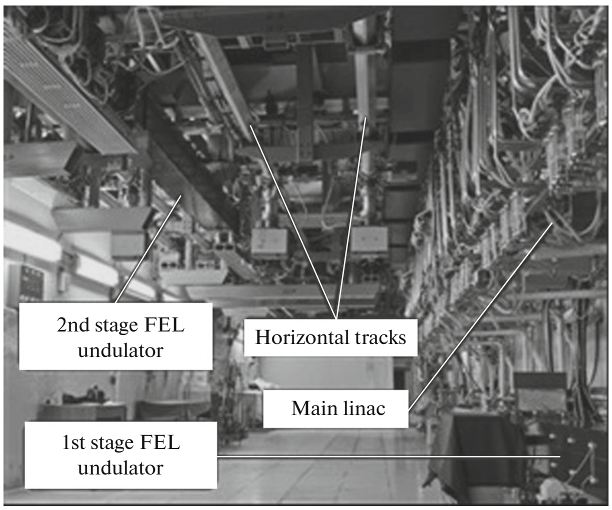

Fig. 3. Accelerator hall (bottom view).The first stage FEL.

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.

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

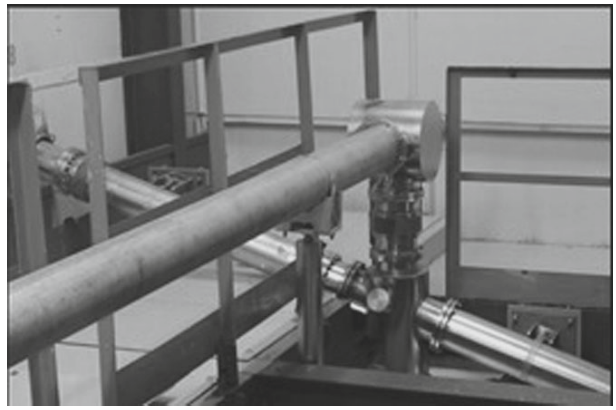

Fig. 4. Optical beamlines for the first and the second stage FELs. Radiation of both FELs is delivered to the same user stations. Switching between FELs is done by retractable mirror.

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 [2, 3] 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 emittance.

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

The First Stage FEL

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 repetition rate 5.64 MHz. Radiation is outcoupled 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.

Basic ERL parameters

Injection energy, MeV	2
Main linac energy gain, MeV	11
Charge per bunch, nC	1.5
Normalized emittance, mm mrad	30
RF frequency, MHz	180.4
Maximum repetition rate, MHz	90.2

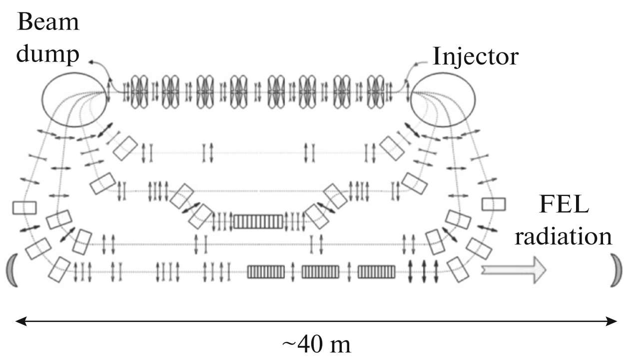

Fig. 5. The third stage ERL with FEL undulators and optical cavity.

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 [4]. The minimum measured linewidth is 0.3%, which is close to the Fourier-transform limit.

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).

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.

The optical beamline (Fig. 5) 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. In future we consider an option to use the new type of undulators with variable period [5] at this FEL. It will allow us to increase significantly the wavelength tuning range.

THE THIRD STAGE FEL DESIGN

Energy of electrons in the third stage ERL is about 42 MeV as the beam is accelerated four times. Undulator of the FEL is installed on the fourth track as it is shown in Figs. 5, 6. The whole undulator is composed of three 28 period sections. Each of them is a permanent magnet undulator with period 6 cm and variable gap. The wavelength range of this FEL will be 5–30 microns. The optical cavity of this FEL is about 40 meters long. It is composed of two copper mirrors (Fig. 7).

The radiation is outcoupled trough the holes in the mirror center. But we also have an option to implement electron outcoupling scheme here (see Fig. 8) [6].

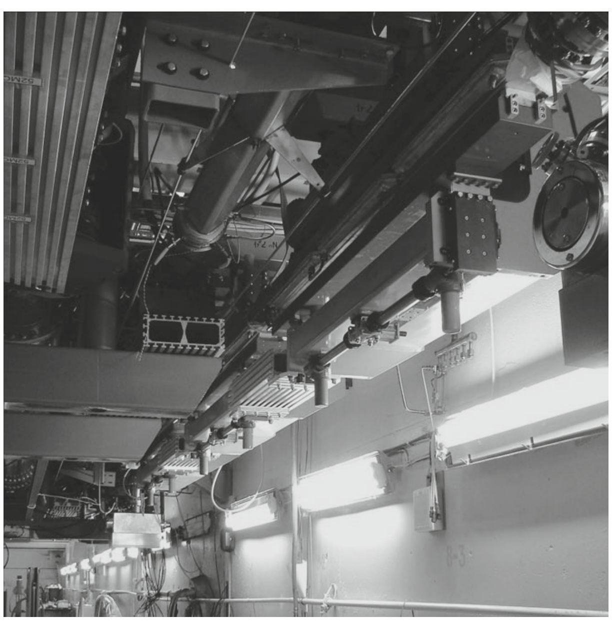

Fig. 6. The third stage FEL undulator sections.

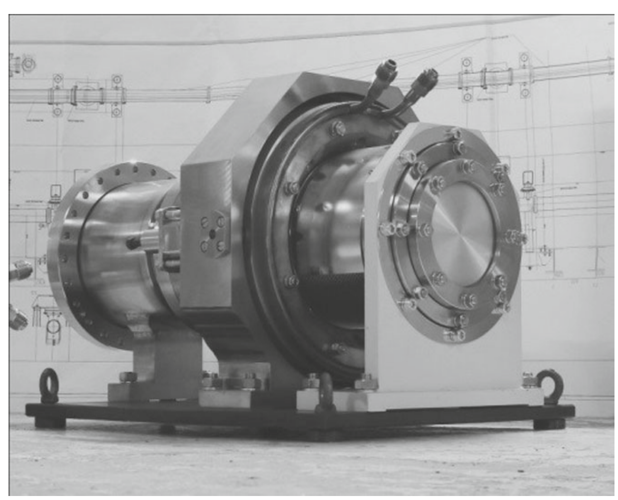

Fig. 7. Copper mirrors.

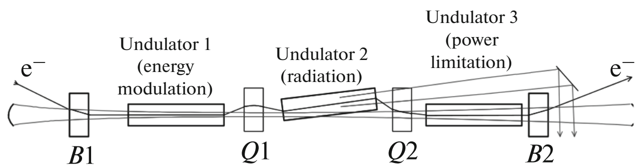

Fig. 8. Electron outcoupling scheme.

COMMISSION CHALLENGES AND FIRST EXPERIMENTS WITH THE NEW FEL RADIATION

Commissioning of the third stage FEL could not be possible without solution of some physical and technical problems. The first one was obtaining of high recovery efficiency in multiturn ERL. Without it one could not get the high enough bunch repetition rate which is required for lasing. Adjustment of the ERL lattice allowed to decrease beam losses down to 10%. As the result the average current 3.2 mA was obtained. The other problem was alignment of 40 meters long optical cavity. The distance between mirrors had to be adjusted with accuracy better than 0.3 mm. One also had to align the beam trajectory in undulator with submillimetric accuracy. When all requirements were fulfilled getting lasing became a simple task. The first experiment with FEL radiation included measurement of radiation power and wavelength. The maximum power was 100 watts at wavelength about 9 microns. Future experiments at the third stage FEL will include study of selective photochemical reactions, infrared laser catalysis and separation of isotopes.

FUTURE PROSPECTS

Concerning the third stage FEL in the nearest future we plan to improve X-ray and neutron radiation shielding, install remote control units for undulator gap and optical cavity mirror angles, deliver FEL radiation to existing user stations, decrease beam losses and increase average current, increase DC gun voltage and improve beam quality in injector, optimize electron efficiency of FEL. The regular user shifts at the first stage FEL will be also continued.

ACKNOWLEDGMENTS

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