NOVOSIBIRSK FREE ELECTRON LASER FACILITY: TWO-ORBIT ERL WITH TWO FELS

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Abstract

The Novosibirsk ERL has rather complicated magnetic system. One orbit (11-MeV) for terahertz FEL lies in the vertical plane. Other four orbits lie in the horizontal plane. The beam is directed to these orbits by switching on of two round magnets. In this case electrons pass through RF cavities four times, obtaining 40-MeV. At the fourth orbit the beam is used in FEL, and then is decelerated four times. At the second orbit (20 MeV) we have a bypass with another FEL. When the bypass magnets are switched on, the beam passes through this FEL. The length of bypass is chosen to provide the delay necessary to realize deceleration at the third pass through accelerating cavities. In 2008 two of four horizontal orbits were assembled and commissioned. The electron beam was accelerated twice and then decelerated down to low injection energy. First multi-orbit ERL operation was demonstrated successfully. In 2009 the first lasing at the second FEL, installed on the bypass of the second track, was achieved. The wavelength tunability range is 40 - 80 micron. Energy recovery of a high energy spread used electron beam was optimized. Third and fourth orbit assembly is in progress.

THE FIRST ORBIT FEL

A source of terahertz radiation was commissioned in Novosibirsk in 2003 [1]. It is CW FEL based on an accelerator–recuperator, or an energy recovery linac (ERL). It differs from other ERL-based FELs [2, 3] in the low frequency non-superconducting RF cavities and longer wavelength operation range. The one-turn ERL (which is the first stage of the full-scale four-turn ERL) parameters are listed in Table 1, and its scheme is shown in Fig. 1.

Table 1: Parameters of the first stage of Novosibirsk ERL.

Beam energy, MeV	11
Maximum average electron current, mA	30
RF frequency, MHz	180.4
Maximum bunch repetition rate, MHz	22.5
Bunch length, ps	100
Normalized emittance, mm·mrad	30
Charge per bunch, nC	1.5
RF cavities Q factor	$4\cdot10^4$

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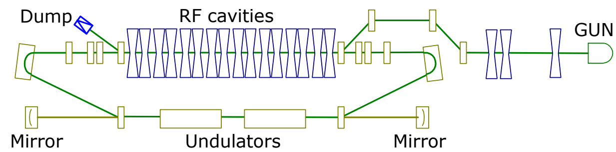

Figure 1: Scheme of the Novosibirsk terahertz free electron laser.

This first stage of the Novosibirsk free electron laser generates coherent radiation tunable in the range 120-240 micron as a continuous train of 40-100 ps pulses at the repetition rate of 2.8 - 22.5 MHz. Maximum average output power is 500 W, the peak power is more than 1 MW [4,5]. The minimum measured linewidth is 0.3%, which is close to the Fourier-transform limit. The third harmonics lasing was obtained recently. It was achieved by suppression of the first harmonics lasing using aperture-decreasing scrapers.

Five user stations are in operation now. Two other are in progress.

THE SECOND STAGE OF ERL AND FEL

Full-scale Novosibirsk free electron laser facility is to be based on the four-orbit 40 MeV electron accelerator-recuperator (see Fig. 2). It is to generate radiation in the range from 5 micrometer to 0.24 mm [6, 7].

Manufacturing, assembly, and commissioning of the full-scale four-turn ERL are underway. The orbit of the first stage with the terahertz FEL lies in the vertical plane. The new four turns are in the horizontal one. One FEL will be installed at the fourth orbit (40 MeV energy), and the second one is already installed and works at the bypass of the second orbit (20 MeV energy).

The bypass provides about 0.7 m lengthening of the second orbit. Therefore, when the bypass magnets are switched on, the deceleration of beam take place at the third passing through the accelerating system, and after that electrons come to the first orbit and, after the second deceleration, to the beam dump.

All 180-degree bends are achromatic. To reduce sensitivity to the power supply ripples, all magnets are connected in series. To simplify the mechanical design, all non-round (small) magnets are similar and parallel-edge. Water-cooled vacuum chambers are made from aluminium.

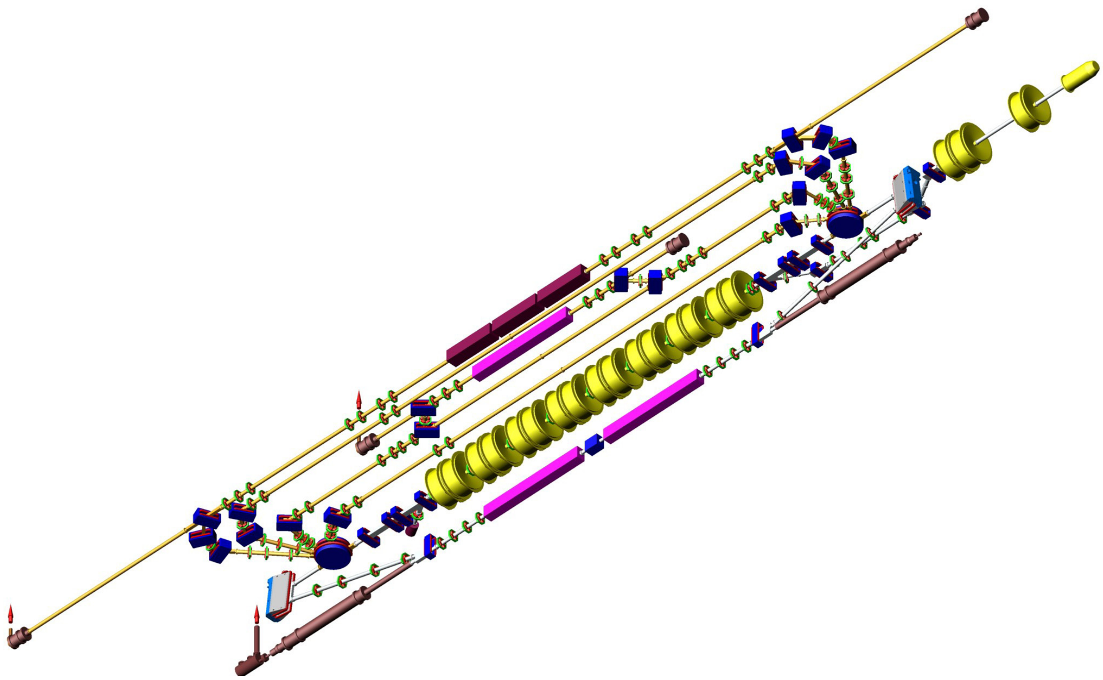

Figure 2: The full-scale Novosibirsk ERL with 3 FELs (bottom view).

The bypass magnetic system contains four bending magnets, quadrupoles, and undulator. The second orbit undulator is very similar to the old undulators of the first-orbit FEL, but its gap is lower. It is fixed-gap electromagnetic undulator. The main parameters of the undulator are listed in Table 2.

Table 2: Parameters of the second orbit undulator.

Period, mm	120
Gap, mm	70
Maximum field amplitude, T	0.12
Total length, m	3.9
Maximum bus current, kA	2.2
Maximum power consumption, kW	30

The undulator poles have the concave shape to equalize focusing in both transverse coordinates. It is necessary, as at 20 MeV this focusing is strong (matched beta function at the 0.12 T field amplitude is 1.1 m only).

The optical resonator length is 20 m (12 RF wavelengths). Therefore the bunch repetition rate for initial operation is 7.5 MHz (24th subharmonics of the RF frequency). Mirrors are made of copper, water-cooled, and covered by gold. Outcoupling holes (3 and 4 mm diameter) serve also for alignment by visible reference laser.

The location of two FELs in accelerator hall is shown in Fig.3. The first lasing of the FEL at bypass was achieved in 2009. The radiation wavelength range is 40 - 80 micron. The maximum gain was about 40%. The significant (percents) increase of beam losses took place during lasing. Therefore sextupole corrections were installed to some of quadrupoles to make 180-degree bends second-order achromatic. It will increase the energy acceptance for used electron beam.

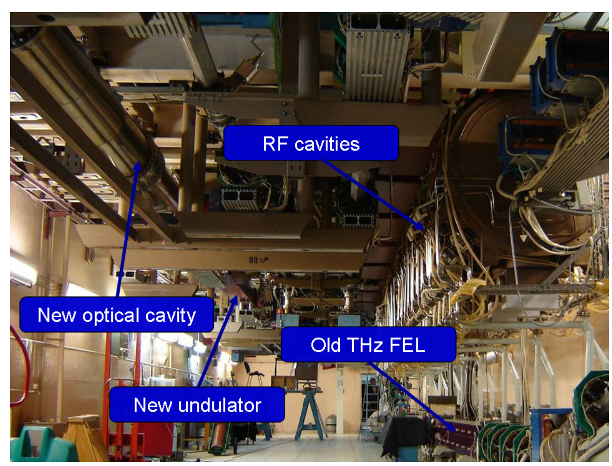

Figure 3: The location of two FELs in accelerator hall.

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

An assembly of third and fourth orbits is in progress.

THE PROSPECTS

During the commissioning of the two-orbit ERL and its FEL several problems appeared. As the result of this operation experience, the new multiturn ERL configuration was proposed [8]. The main idea was to

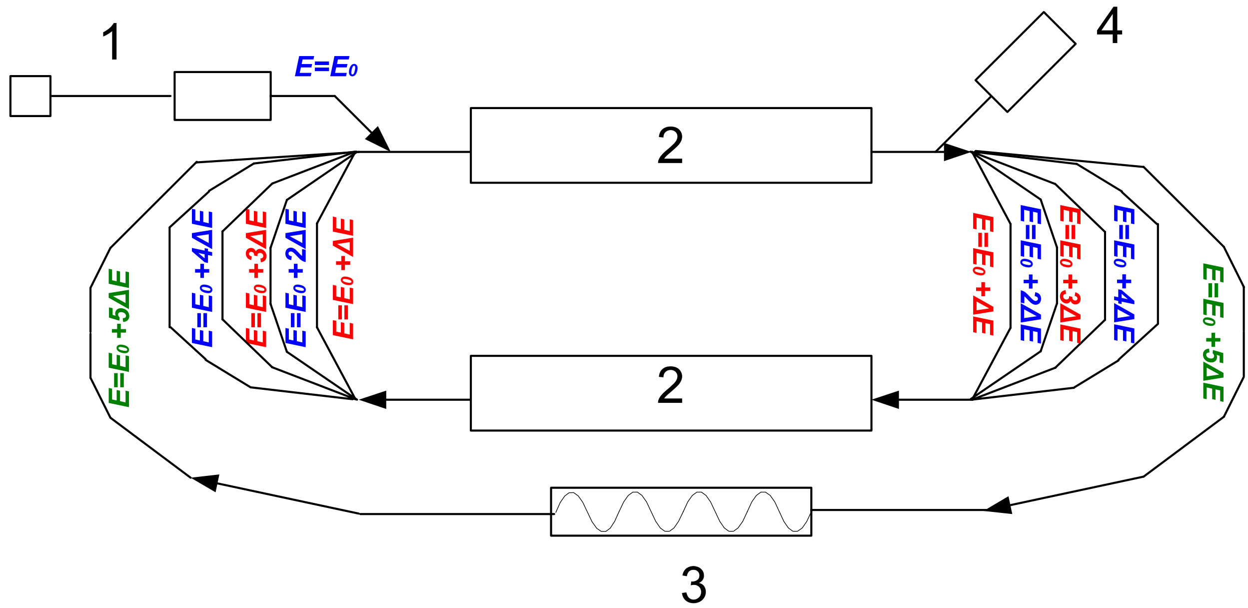

Figure 4: Simplest multiturn ERL with separated accelerated and decelerated beams. 1 – injector, 2 – RF accelerating cavities, 3 - undulator or other "user" device, 4 – beam dump.

separate accelerated and decelerated beams. It may be achieved using split accelerating structure, as it was done at TJNAF (USA).

One of the simplest schemes for ERL with separated accelerated and decelerated beams is shown in Fig. 4. Electrons with injection energy E_0 passes trough the accelerating sections 2 five times obtaining energy $E_0 + 5\Delta E$. After that, the beam is used in device 3 and enters the first accelerating section. The last orbit length is chosen to provide deceleration of electrons. Then after the first deceleration electrons have energy $E_0 + 4\Delta E$, which differs from energies $E_0 + \Delta E$, $E_0 + 3\Delta E$, and $E_0 + 5\Delta E$ of accelerated beams. Then separating magnet directs decelerated beam to its own arc for energy $E_0 + 4\Delta E$. During further deceleration electron energy differs from other beam energies not less than ΔE. It makes possible to have only one beam at each arc. Therefore one can adjust each arc length, optics, and trajectory steering independently.

The optical requirements for accelerating and decelerating beams may be very different. If ERL works for FEL, it needs to provide emittance conservation and optimal bunching during acceleration, but maximum energy acceptance (with longitudinal "gymnastics") during deceleration. Beam diagnostics also is simplified for separated beams. Splitting of RF system decreases the length of section with unseparated beams, making easier the focusing problem.

Other ERL configurations with beam separation are possible. E. g., different energy gain in accelerating sections and splitting of accelerating structure to three or more sections may be used.

The full arc flexibility makes possible to obtain femtosecond electron bunches in multiturn ERLs and use them to generate femtosecond x-ray and terahertz pulses.

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