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NOVOSIBIRSK ERL FACILITY*

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Abstract

The first project of the four turn ERL for Novosibirsk FELs (NovoFEL) was proposed at FEL’90 Conference. Later the project was modified, but the base lines kept: a four turn normal conductance linac with energy recovery, low RF cavities (180 MHz), grid controlled DC gun (Q~1nC, τ=1 nsec, f_{rep} = 10 kHz–50 MHz). The ERL can operate in the three modes, providing an electron beam for the three different FELs (from 300 µm up to 5 µm). Construction and commissioning four-track ERL was divided on three stage: the first stage NovoFEL working in spectral range (90–240) µm, based on one track energy recovery linac (ERL) with energy 12 MeV and current 30 mA, was commissioned in 2003. The second stage of NovoFEL working in spectral range (35–80) µm, based on two track energy recovery linac with energy 22 MeV and current 7 mA, was commissioned in 2009. The third stage of NovoFEL working in spectral range (8–15) µm, based on four track energy recovery linac with energy 42 MeV and current 5 mA was commissioned in 2015.

INTRODUCTION - ERL ACTIVITY IN BUDKER INP

The Energy Recovery Linac (ERL) concept for the free electron laser (FEL) was proposed at Budker INP by N. Vinokurov and A. Skrinsky in 1978 [1]. The first project of the four-turn race-track microtron-recuperator for the FEL was proposed at the FEL’90 Conference (1990) [2].

Later the project was modified, but the base line kept: a four-turn normal conductance linac with energy recovery; normal conducting RF cavities (180 MHz); a grid-controlled DC gun with bunch charge about 1nC, duration 1 nsec, and bunch frequency 10kHz–50 MHz.

Advantages of the low frequency (180 MHz) RF system: high threshold currents for instabilities; operation with long electron bunches (for narrow FEL linewidth); large longitudinal acceptance (good for operation with large energy spread of used beam); relaxed tolerances for orbit lengths and longitudinal dispersion.

Today, the ERL can operate in three modes, providing an electron beam for the three different FELs, from 300 µm up to 5 µm [3,4].

The first stage of the Novosibirsk FEL (NovoFEL) works in the spectral range (90–240) µm, based on a one track Energy Recovery Linac (ERL) with energy 12 MeV, was commissioned in 2003 [5]. It is the most powerful radiation source in terahertz region.

The second stage works in infrared spectral range (35–80) µm, based on two track Energy Recovery Linac with energy 22 MeV, was commissioned in 2009 [6].

The third stage working in spectral range (8–15) µm, based on four track energy recovery linac with energy 42 MeV, was commissioned in 2015 [7].

From 1997 the using an ERL for a fully spatially coherent X-ray source has been discussed at BINP [8]. The feasibility study of the 5.6 GeV machine with two split super-conducting accelerating sections (similar to CEBAF accelerator [9]) was presented at ERL-11 conference in 2011 [10]. The same accelerating scheme was supposed for the project of compact 13.5 nm FEL based on 800 MeV ERL facility for extreme ultraviolet lithography in 2010 [11, 12].

NOVOFEL ACCELERATOR

The NovoFEL facility includes three FELs. All the FELs use the electron beam of the same electron accelerator, a multi-turn energy recovery linac. 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.

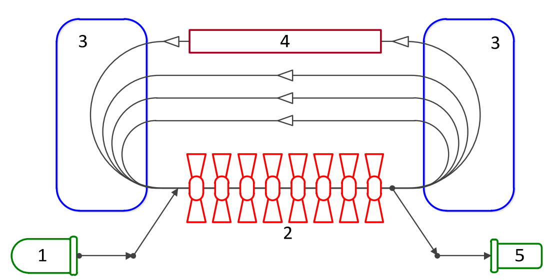

Figure 1: Simplified multi-turn ERL scheme:
1 – injector, 2 – linac, 3 – bending magnets,
4 – undulator, 5 – dump.

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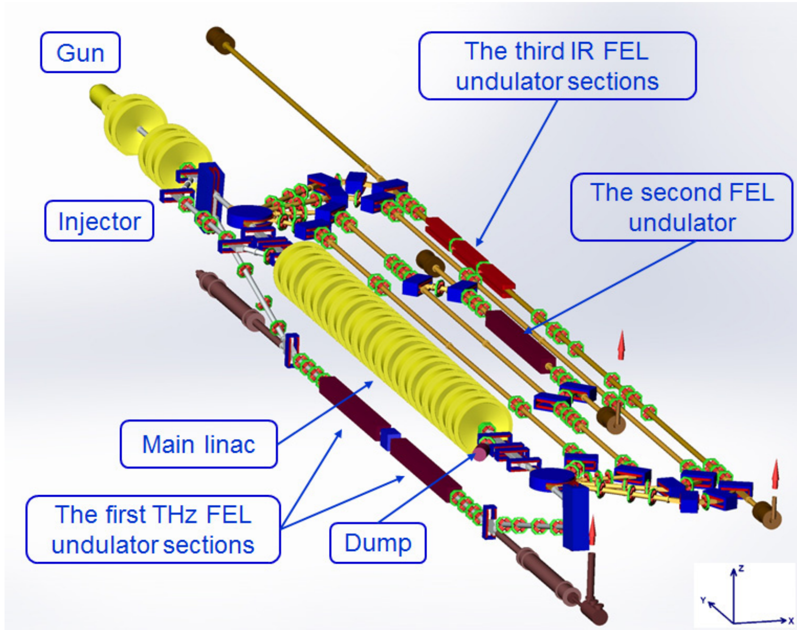

Figure 2: The Novosibirsk ERL with three FELs (top view).

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). Parameters of the accelerator is presented in Table 1.

Table 1. NovoFEL accelerator parameters

Modes:	1st	2d	3d
RF frequency, MHz	180.4		
Gun working freq., MHz	5.6-22.4	7.52	3.76
Energy, MeV	10-14	22	42
Average current, mA	30	7.5	3
Recuperation efficiency, %	>95		
Wavelength, µm	90-240	40-80	8-11
Electron efficiency, %	0.6	0.3	0.2

The Magnetic Structure

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 energy of 12 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.

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 energy of 22 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.

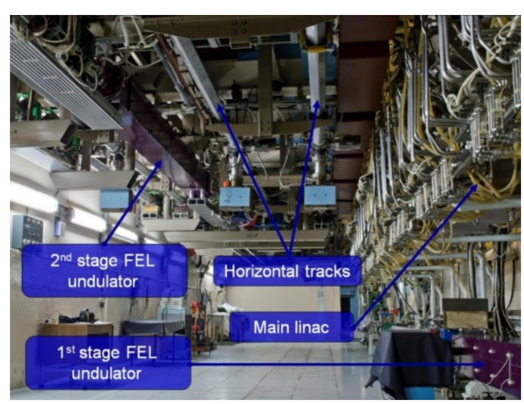

Figure 3: Accelerator hall

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The RF System

The main accelerating structure consists of 16 normal-conducting RF cavities, connected by two waveguides. The operation frequency is 180.4 MHz. Such a low frequency allows operation with long bunches and high currents. Even and odd cavities are united into two groups. Each group of cavities is fed from its own RF generator. Project power of each RF generator is 600 kW.

In the RF system, bi-metal copper clad stainless steel cavities are used [13]. The electrical parameters of cavities are given in Table 2.

Table 2. NovoFEL RF cavity parameters

Operating frequency, MHz	180.4
Tuning range, kHz	320
Characteristic impedance, Ohm	133.5
Quality factor	40000
Shunt impedance, MOhm	5.3
Operating gap voltage, kV	950
Power dissipation, kW	85
Transit time factor	0.9

Each RF generator (Fig. 4) consists of four stages. First and second stages of the amplifier are made of tetrodes GU-92A. Third stage is based on GU-101A tetrode, fourth stage is made of modules based on TH-781 tetrodes.

The modular design of the RF generator [14] essentially simplifies the power addition from several tubes, and simplifies manufacturing and adjustment of the whole generator. The 600 kW output stage is assembled with four modules. The single module is used as a third stage of the generator.

Figure 4. NovoFEL generators hall

The feeder system (Fig. 5) is made of rectangular waveguides and coaxial lines. Also it provides power distributing between the cavities in the groups.

The control system adjusts amplitude and phase of the RF voltage of the accelerating cavities, tunes the cavities, and removes RF excitation from the generator in emergency conditions.

Each channel was tested at 7500 kV on the gaps of 8 cavities. The RF power was 630 kW per channel. The efficiency factor of the output stage is 57 %.

Now, the accelerating RF system operates at 13600 kV on 16 cavities. Total power of generators is 1100kW.

Figure 5. NovoFEL feeder system

FELS

The first FEL has been in operation since 2003 [5]. 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. [15 – 20].

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. 6.

Figure 6. Optical beamline for FELs. Radiation of all FELs is delivered to the same user stations. Switching between FELs is done using retractable mirrors

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).

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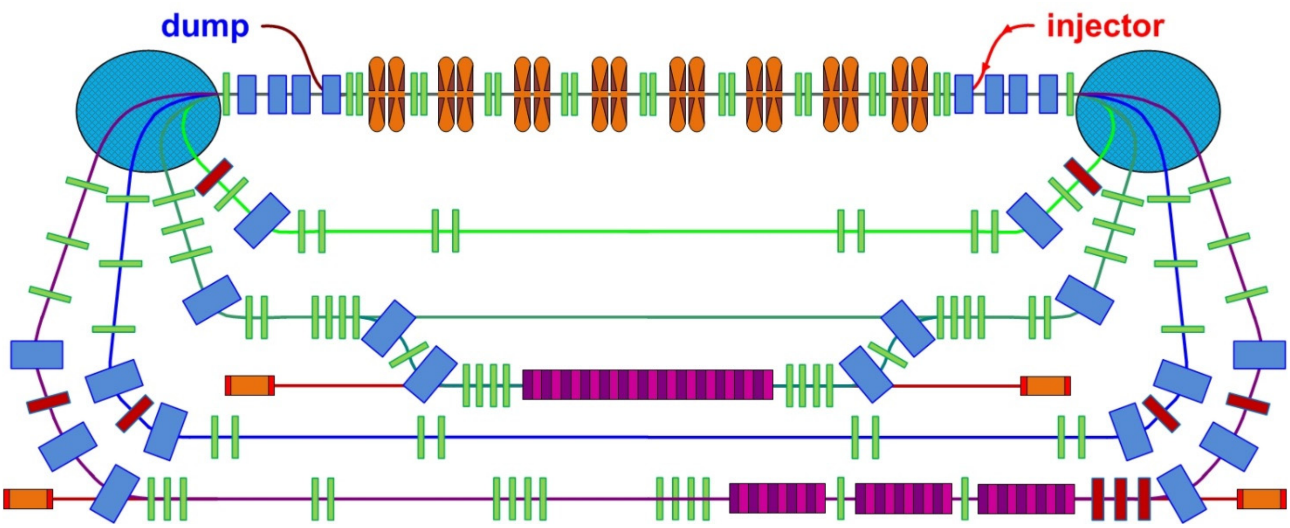

Figure 7. The second and third stages ERL with FEL undulators and optical cavities

The undulator of the third FEL is installed on the fourth track, as shown in Fig. 7 and Fig. 8. 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.

Figure 8. The third FEL undulators

Table 3. NovoFEL radiation parameters

Modes:	1^{st}	2^{d}	3^{d}
Wavelength, µm	90–240	40–80	5–20
Max. radiation power, kW	0.5	0.5	0.1
Max. peak power, MW	1	2	10
Min. pulse duration, ps	70	20-50	10-20
Length between pulses, ns	180	133	267
Rel. linewidth (FWHM), %	0.3–1	0.2–1	0.1–1

FUTURE PLANS

In the future it is planned to improve the x-ray and neutron radiation shielding for regular users operation on high energy mode, install the new variable-period undulator, new injection beamline for RF gun and optical diagnostics of electron beam parameters. Moreover, it is expected to implement an electron out-coupling scheme on the four-turn ERL.

The New RF Gun

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun [21] (see Fig. 10) was built and tested. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved recently [22]. The injection beamline (see Fig. 9) for the RF gun will be manufactured this year.

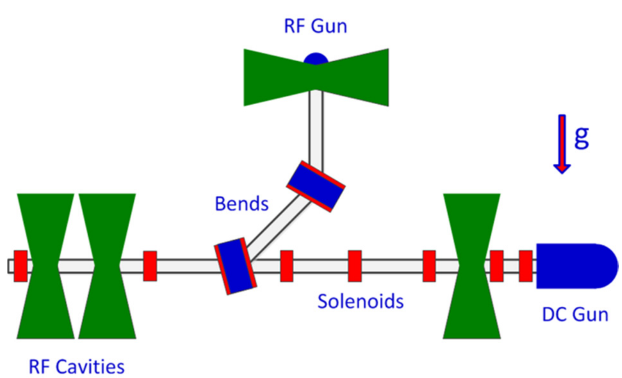

Figure 9.Scheme of NovoFEL injector with new gun

Table 4. Measured RF gun parameters

Energy, keV	100–320
Pulse duration(FWHM), ns	≤ 0.6
Bunch charge, nQ	0.3–1,5
Repetition rate, MHz	0.01–90
Average current, mA	102 max

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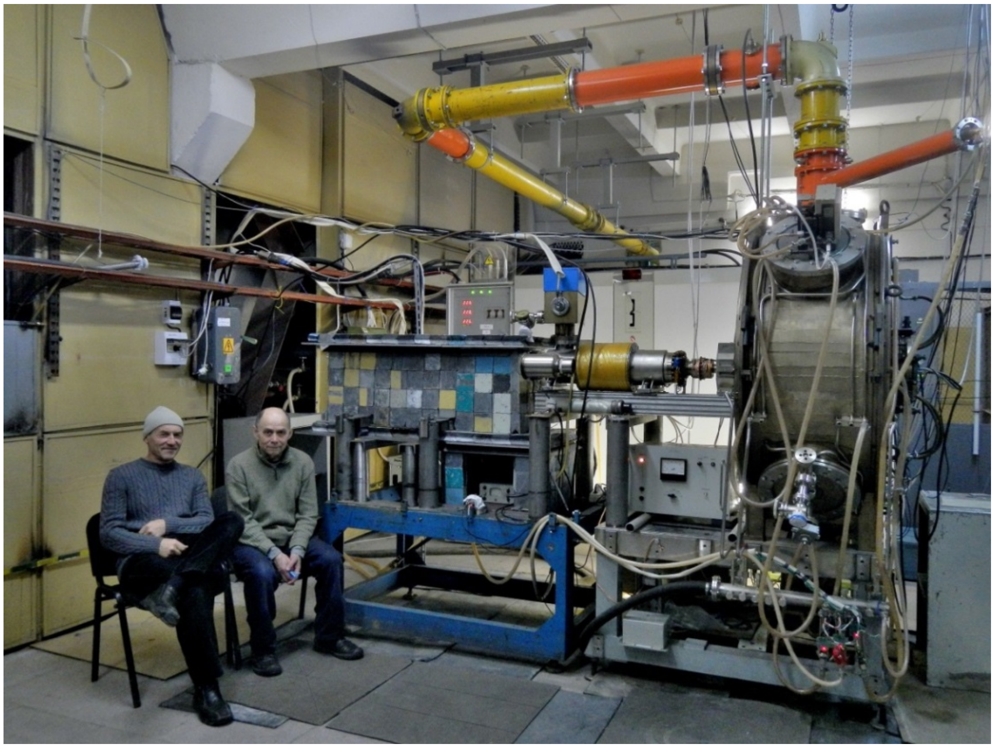

Figure 10: New electron RF gun for Novosibirsk ERL

Variable-Period Undulator

The new variable-period undulator [23] (see Fig. 11) is being prepared to replace the old electromagnetic one of the second FEL [24]. It will allow us to expand significantly the wavelength tuning range.

Figure 11. Variable Period Undulator λ_u=4.8–9.6 cm

FEL Outcoupling

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 [25] (see Fig. 12). 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.

Optical Diagnostics of Electron Beam Parameters

The beam energy at the last track of the ERL is 42 MeV. As a result, a significant part of synchrotron radiation from bending magnets is in the visible range. The transverse beam dimensions were measured with the optical diagnostics before and after the undulator applied for generation of mid-infrared coherent radiation (see Fig. 13 and Fig. 14). The obtained data is used to calculate the beam energy spread and emittance. The longitudinal beam dynamics was studied with electro optical dissector. [26]

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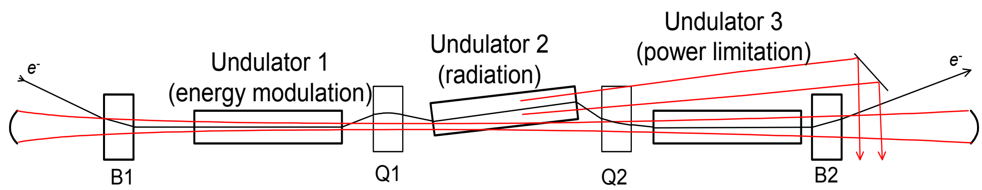

Figure 12: Electron out-coupling scheme

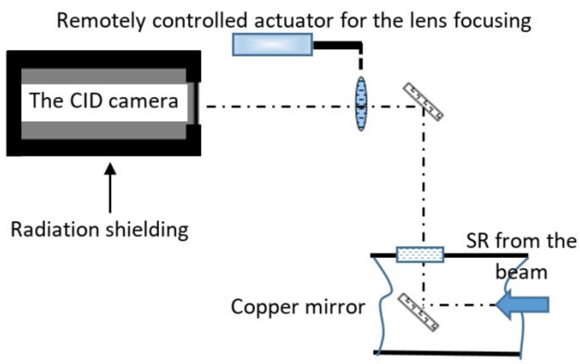

Figure 13. Layout of the diagnostics for acquisition of the transverse profile of the beam

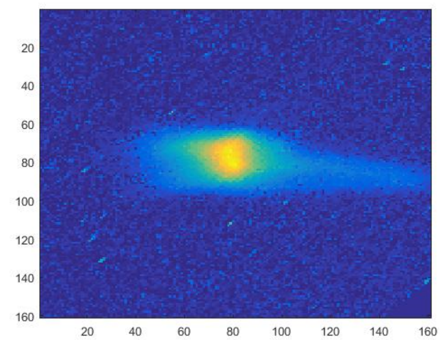

Figure 14. An example of the beam transverse distribution

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