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Status of the Novosibirsk high-power terahertz FEL

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Abstract

The first stage of Novosibirsk high-power free electron laser (FEL) was commissioned in 2003. It is based on the normal conducting CW energy recovery linac (ERL). Now the FEL provides electromagnetic radiation in the wavelength range 120–230 μm. The maximum average power is 400 W. The minimum measured linewidth is 0.3%, which is close to the Fourier-transform limit. Four user stations are in operation now. Manufacturing of the second stage of the FEL (based on the four-turn ERL) is in progress.

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Keywords: Recirculating linacs; Free electron lasers

1. Introduction

A new source of terahertz radiation was commissioned recently in Novosibirsk [1]. It is CW free electron laser (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. Full-scale Novosibirsk FEL is to be based on the four-orbit 40 MeV electron accelerator–recuperator (see Fig. 1). It is to generate radiation in the range from 5 μm to 0.24 mm [4,5].

2. Accelerator–recuperator

The first stage of the machine contains a full-scale RF system, but has only one orbit. Layout of the accelerator–recuperator is shown in Fig. 2. The 2 MeV electron beam from an injector passes through the accelerating structure, acquiring the 12 MeV energy, and comes to the FEL, installed in the straight section. After interaction with radiation in the FEL the beam passes once more through the accelerating structure, returning the power, and comes to the beam dump at the injection energy. Main parameters of the accelerator are listed in Table 1.

The electron source is the 300 keV DC gun with gridded cathode. Maximum charge per bunch is 1.7 nC.

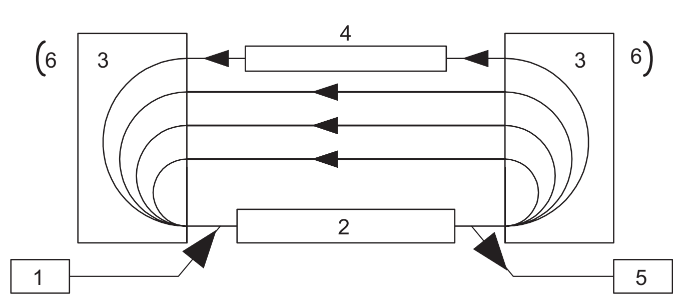

Fig. 1. Scheme of the accelerator–recuperator based FEL. 1—injector, 2—accelerating RF structure, 3–180° bends, 4—undulator, 5—beam dump, 6—mirrors of the optical resonator.

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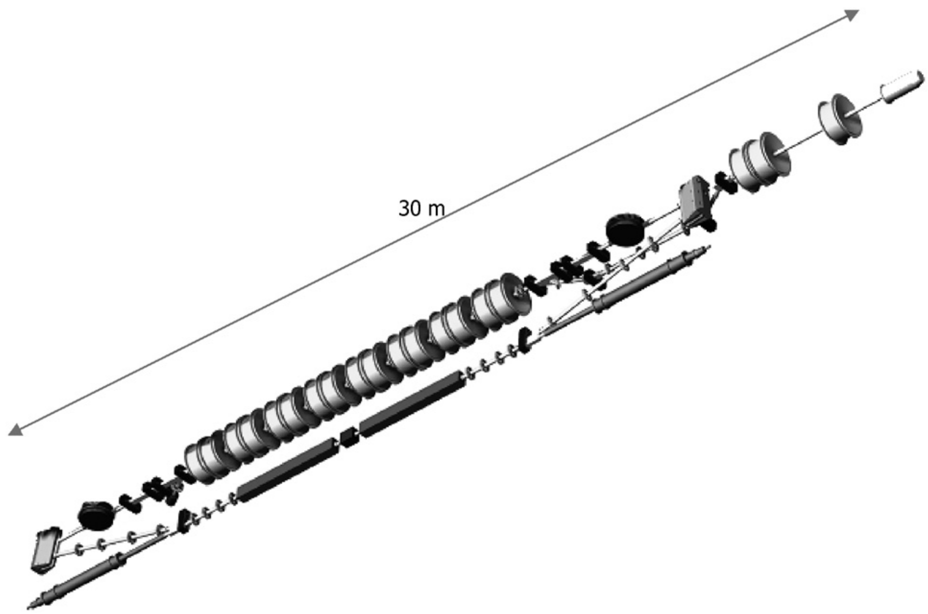

Fig. 2. Scheme of the first stage of the Novosibirsk terahertz FEL. The loop lies in the vertical plain.

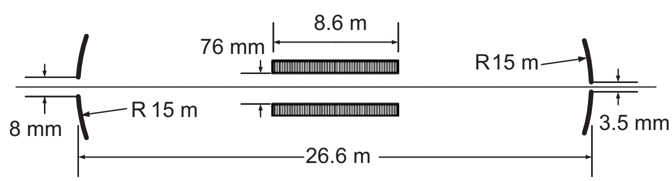

Fig. 3. Scheme of the optical resonator.

Table 1
Accelerator parameters (first stage)

RF frequency (MHz)	180
Number of RF cavities	16
Amplitude of accelerating voltage at one cavity (MV)	0.7
Injection energy (MeV)	2
Final electron energy (MeV)	12
Maximum bunch repetition rate (MHz)	22.5
Maximum average current (mA)	20
Beam emitance (mm mrad)	2
Final electron energy spread, FWHM (%)	0.2
Final electron bunch lengt (ns)	0.1
Final peak electron current (A)	10

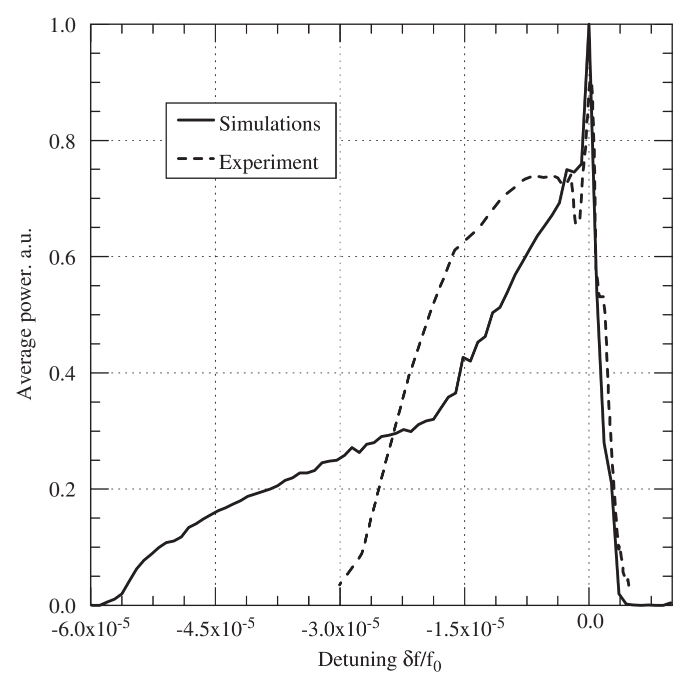

Fig. 4. Dependence of the average power on the RF frequency detuning.

3. FEL

The FEL is installed in a long straight section of a single-orbit accelerator–recuperator. It consists of two undulators, a magnetic buncher, and optical resonator. Both electromagnetic planar undulators are identical. The length of an undulator is 4 m, period is 120 mm, the gap is 80 mm, and deflection parameter K is up to 1.2. The buncher is simply a three-pole electromagnetic wiggler. It is necessary to optimize the relative phasing of undulators and is used now at low longitudinal dispersion $N_d < 1$.

Both laser resonator mirrors are spherical, 15 m curvature radius, made of the gold-plated copper, and water cooled [6]. In the center of each mirror there is a hole. It serves for mirror alignment (using the He–Ne laser beam) and output of small amount of radiation. The distance between mirrors is 26.6 m. The forward mirror has the hole with the diameter 3.5 mm, and the rear one with the diameter 8 mm (see Fig. 3). The calculated transparency of the mirror with the 8-mm hole, at the wavelength 150 μm, is 1.5%. At this wavelength the measured round-trip loss are near 7%. The output radiation passes through two windows, which separated the FEL and accelerator vacuum from the atmosphere. After the forward mirror the additional iris and the normal-incidence quartz window are installed. After the rear one there is a diamond window, tilted at the Brewster angle.

4. Radiation study

The first measurements of radiation parameters were reported before [1]. Instead of the fine tuning of the optical resonator length we tuned the RF frequency. The tuning curve is shown in Fig. 4. The preliminary simulation results [7] demonstrated a reasonable agreement with measured data. The experimental curve is wider, which may be explained by the shortening of the optical resonator due to mirror heating.

The average radiation power, passed through the hole at the rear mirror, was about 400 W. Taking into account of the 7% loss, one gets approximately 2 kW of power, extracted from the electron beam. The electron beam power was 200 kW. Therefore, an electron efficiency is about 1%. The radiation parameters are listed in Table 2.

Table 2
The radiation parameters

Wavelength (mm)	0.12 … 0.23
Minimum relative linewidth FWHM	0.003
Pulse length, FWHM (ns)	0.05
Peak power (MW)	1
Repetition rate (MHz)	11.2
Maximum average power (kW)	0.4

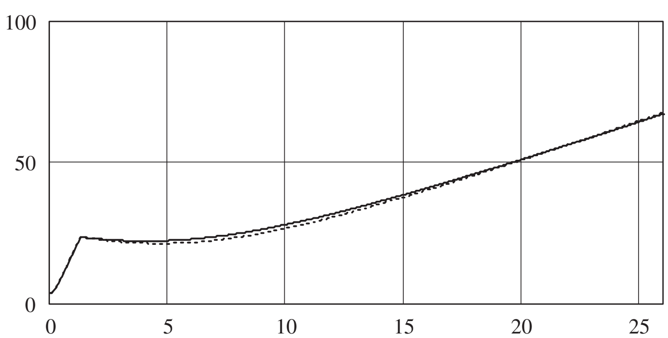

Fig. 5. Calculated sizes of equivalent Gaussian beam (mm) vs. distance along the beamline (m). The solid line is for the size, which is initially vertical, and the dotted line is for the size, which is initially horizontal.

5. Beamline and user stations

To transmit the radiation from the rear mirror hole to user stations, the beamline from the accelerator hall to the user hall was built. As the diffractional angular divergence $1.22\lambda/D = 0.03$ (for 200 μm) is high, the spherical mirror is used to transform the radiation beam to almost parallel one. The incidence angle is only 7°, therefore astigmatism is negligible (see Fig. 5). Other five mirrors are flat. The beamline is filled by dry nitrogen. It is separated from the accelerator vacuum by the diamond window, and from the air by the polyethylene window. After installation of nitrogen dryer we obtained almost complete transparency of the beamline.

Now radiation may be delivered to five stations. Two of them are used for measurement of radiation spectrum, and other three—for users. In particular, the terahertz ablation of DNA and other biologically relevant molecules was performed [8]. It was shown that transfer from surface occurred without molecular destruction.

6. Further developments

We plan to increase further the output power. The electron gun upgrade for the increase of the average current up to 0.1 A is in progress.

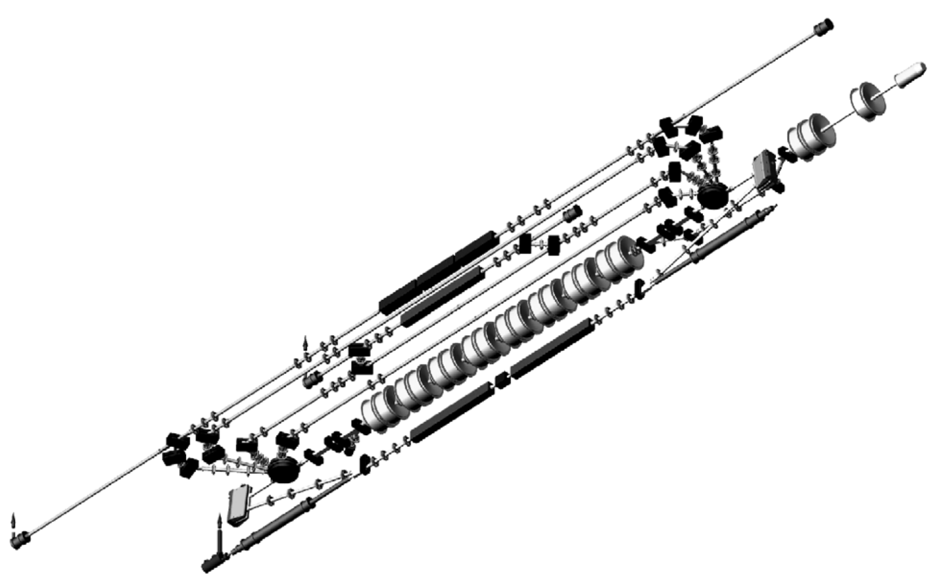
Fig. 6. Scheme of the second stage of the Novosibirsk terahertz FEL. The terahertz FEL orbit lies in the vertical plain. Other four orbits lie in the horizontal one.

The design and manufacturing of the full-scale four-turn ERL is underway. An artistic view of the machine is shown in Fig. 6. The existing orbit with the terahertz FEL lies in the vertical plane. The new four turns are in the horizontal one. One FEL is installed at the fourth orbit (40 MeV energy), and the second one at the bypass of the second orbit (20 MeV energy).

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