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First lasing at the high-power free electron laser at Siberian center for photochemistry research

E.A. Antokhin, R.R. Akberdin, V.S. Arbuzov, M.A. Bokov, V.P. Bolotin, D.B. Burenkov, A.A. Bushuev, V.F. Veremeenko, N.A. Vinokurov*, P.D. Vobly, N.G. Gavrilov, E.I. Gorniker, K.M. Gorchakov, V.N. Grigoryev, B.A. Gudkov, A.V. Davydov, O.I. Deichuli, E.N. Dementyev, B.A. Dovzhenko, A.N. Dubrovin, Yu.A. Evtushenko, E.I. Zagorodnikov, N.S. Zaigraeva, E.M. Zakutov, A.I. Erokhin, D.A. Kayran, O.B. Kiselev, B.A. Knyazev, V.R. Kozak, V.V. Kolmogorov, E.I. Kolobanov, A.A. Kondakov, N.L. Kondakova, S.A. Krutikhin, A.M. Kryuchkov, V.V. Kubarev, G.N. Kulipanov, E.A. Kuper, I.V. Kuptsov, G.Ya. Kurkin, E.A. Labutskaya, L.G. Leontyevskaya, V.Yu. Loskutov, A.N. Matveenko, L.E. Medvedev, A.S. Medvedko, S.V. Miginsky, L.A. Mironenko, S.V. Motygin, A.D. Oreshkov, V.K. Ovchar, V.N. Osipov, B.Z. Persov, S.P. Petrov, V.M. Petrov, A.M. Pilan, I.V. Poletaev, A.V. Polyanskiy, V.M. Popik, A.M. Popov, E.A. Rotov, T.V. Salikova, I.K. Sedliarov, P.A. Selivanov, S.S. Serednyakov, A.N. Skrinsky, S.V. Tararyshkin, L.A. Timoshina, A.G. Tribendis, M.A. Kholopov, V.P. Cherepanov, O.A. Shevchenko, A.R. Shteinke, E.I. Shubin, M.A. Scheglov

Budker Institute of Nuclear Physics, Acad. Lavrentyev Prospect 11, 630090 Novosibirsk, Russia

Abstract

The first lasing near wavelength 140 μm was achieved in April 2003 on a high-power free electron laser (FEL) constructed at the Siberian Center for Photochemical Research. In this paper, we briefly describe the design of FEL driven by an accelerator–recuperator. Characteristics of the electron beam and terahertz laser radiation, obtained at the first experiments, are also presented in the paper.

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Keywords: Free electron laser; Energy recovery linac

*Corresponding author. Tel.: +7-3832-394003; fax: +7-3832-342163.
E-mail address: vinokurov@inp.nsk.su (N.A. Vinokurov).

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1. Introduction

A new source of terahertz radiation was commissioned recently in Novosibirsk. It is CW FEL based on an accelerator–recuperator, or an energy recovery linac (ERL). It differs from the earlier ERL-based FELs [1,2] in the low-frequency non-superconducting RF cavities and longer wavelength operation range. The terahertz FEL is the first stage of a bigger installation, which will be built in 3 years and will provide shorter wavelengths and higher power. The facility will be available for users in 2004. The first radiation study results are discussed in this paper.

2. Accelerator–recuperator

Full-scale Novosibirsk free electron laser is to be based on multi-orbit 50 MeV electron accelerator–recuperator. It is to generate radiation in the range 3 μm–0.3 mm [3,4]. 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. 1. The 2 MeV electron beam from an injector passes through the accelerating structure, acquiring 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 FEL is installed in a long straight section of a single-orbit accelerator–recuperator. It consists of two undulators, a magnetic buncher, two mirrors of the optical resonator, and an outcoupling system. 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. One can use one or both undulators with or without a magnetic buncher. 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 identical, spherical, 15 m curvature radius, made of gold plated copper, and water cooled. In the center of each mirror there is a 3.5 mm diameter hole. It serves for mirror alignment (using He–Ne laser beam) and output of small amount of radiation. The distance between mirrors is 26.6 m. The outcoupling system contains four adjustable planar 45 copper mirrors (scrapers). These mirrors cut the tails of Gaussian eigenmode of the optical resonator and redirect radiation to calorimeters. This scheme preserves the main mode of optical resonator well and reduces amplification of higher modes effectively.

Table 1
Accelerator parameters (the first stage)

RF wavelength (m)	1.66
Number of RF cavities	16
Amplitude of accelerating voltage at one cavity (MV)	0.7
Injection energy (MeV)	2
Final electron energy (MeV)	12
Bunch repetition rate (MHz)	1.4–22.5
Average current (mA)	2–40
Beam emittance (mm mrad)	1
Final electron energy spread (%)	1
Final electron bunch length (ns)	0.02–0.1
Final peak electron current (A)	40–10

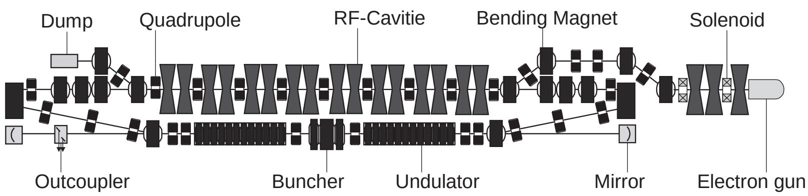

Fig. 1. Scheme of the first stage of Novosibirsk high-power free electron laser.

3. FEL commissioning

For FEL commissioning, we used both undulators. Beam average current was typically 5 mA at repetition rate 5.6 MHz, which is the round-trip frequency of the optical resonator and 32th subharmonics of the RF frequency $f \approx 180$ MHz. Most of measurements were performed without scrapers recording radiation flux from one of the mirror apertures. Instead of fine tuning of the optical resonator length we tuned the RF frequency. The tuning curve is shown in Fig. 2.

Typical results of spectrum measurement with rotating Fabri–Perot interferometer are shown in Fig. 3. They were used to find both wavelength and line width of radiation. Radiation wavelengths were in the range 120–180 μm depending on the undulator field amplitude. The shortest wavelength is limited by the gain decrease at a low undulator field, and the longest one—by the optical resonator diffraction loss increase. Relative line width (FWHM) was near $3 \cdot 10^{-3}$. The corresponding coherence length $\lambda^2/2\Delta\lambda = 2$ cm is close to the electron bunch length, therefore we, probably, achieved the Fourier-transform limit.

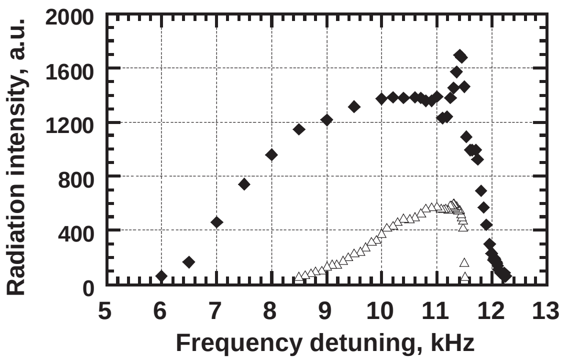

Fig. 2. Laser intensity vs RF frequency detuning f-180400 kHz (diamonds at repetition rate 5.6 MHz, triangles at repetition rate 2.8 MHz).

The loss of the optical resonator was measured with a fast Schottky diode detector [5]. Its typical output is the pulse sequence with 5.6 MHz repetition rate. Switching off the electron beam, we measured the decay time (see Fig. 4). The typical round-trip loss values were from 5% to 8%.

The FEL oscillation was obtained not only at $f_0 = 5.6$ MHz bunch repetition rate, but at $f_0/2$, $f_0/3$, $f_0/4$ and $2f_0/3$. The time dependence of intensity at bunch repetition rate $f_0/4$ is shown in Fig. 5. Radiation decay time (and therefore resonator loss) can also be measured from this dependence. The dependence of power on loss is shown in Fig. 6. For example, operation at bunch repetition rate $f_0/4$ corresponds to four time more loss per one amplification. It indicates that our maximum gain is about 30%.

The absolute power measurements were performed in two ways. First we measured the power coming through the hole in the mirror without scrapers. Output coupling is very weak in this case, so the power was about 10 W. It corresponds to intra-cavity average power near 2 kW. Other measurements were performed with two (right

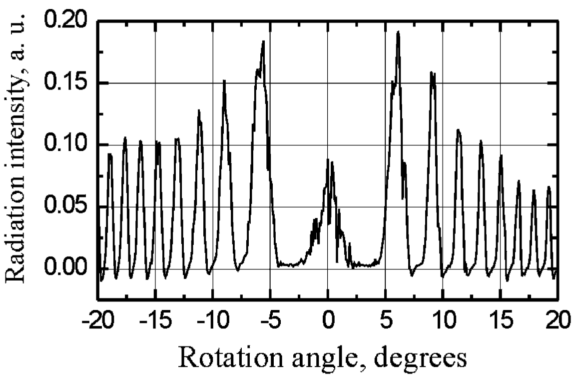

Fig. 3. Results of the Fabri–Perot interferometer rotation angle scanning (laser wavelength $\lambda = 136$ μm).

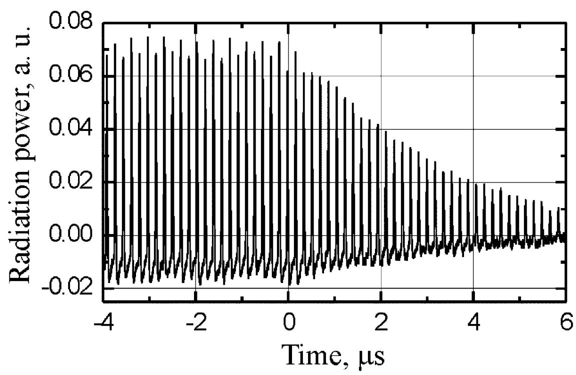

Fig. 4. Time dependence of the output radiation power after switching the electron beam off.

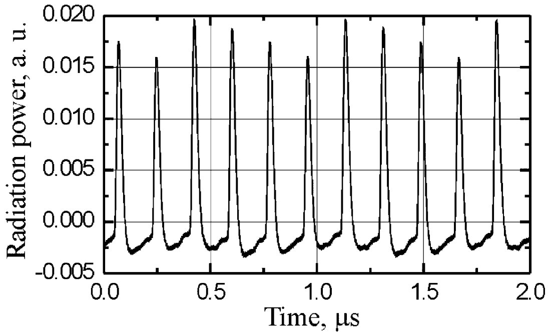

Fig. 5. The output radiation time dependence. Electron bunch repetition rate 1.4 MHz is four time less then the optical resonator round-trip frequency 5.6 MHz.

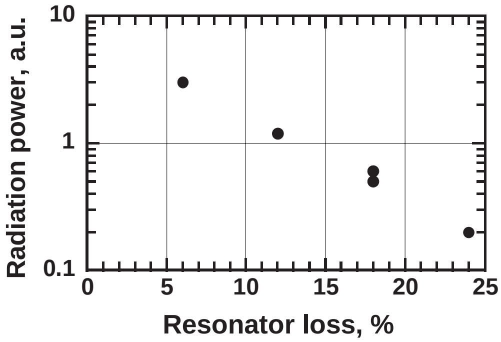

Fig. 6. Average intra-cavity power vs loss per one amplification.

and left) scrapers inserted. The insertion depth was chosen to decrease intra-cavity power twice. The measured power in each calorimeter was 20 W. Taking into account other resonator loss one can estimate the total power loss as 100 W. The electron beam power was 50 kW. Therefore, an electron efficiency is about 0.2%. The possible explanation of such a low value is too long undulator and high electron energy spread. Attempts to get oscillation with one undulator switched off are in progress. Possible way for decreasing of the energy spread—the installation of a 3rd harmonic (540 MHz) cavity—is under examination.

Table 2
Expected radiation parameters for users

Wavelength (mm)	0.11–0.18
Pulse length (ns)	0.1
Peak power (MW)	0.1
Maximum repetition rate (MHz)	5.6–22.5
Average power (W)	100

4. Further development

A beamline for transport radiation out of the accelerator hall to the user station rooms is under construction. The first experimental station is designed. The facility is to start operation for users in 2004. Expected radiation parameters for users are shown in Table 2.

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