Novosibirsk high-power terahertz free electron laser: instrumentation development and experimental achievements

Knyazev B.A.[1, 3, A], Kulipanov G.N.[1, B], Vinokurov N.A.[1, 3, C], Aseev A.L.[4], Cherkassky V.S.[3], Chesnokov E.N.[2], Chugui Yu.V[8]., Dem'yanenko M.A.[4], Esaev D.G.[4], Fomin V.M.[6], Gavrilov N.G.[1], Gerasimov V.V.[1, 3], Golod S.V.[4], Goryachkovskaya T.N.[5], Kolobanov E.I.[1], Kozlov A.S.[2], Kubarev V.V.[1, 3], Malyshkin S.B.[2], Matveenko A.N.[1], Medvedev L.E.[1], Merzhievsky L.A.[7], Miginsky S.V.[1], Mironenko L.A.[1], Naumova E.V.[4], Ovchar V.K.[1], Ovsyuk V.N.[4], Peltek S.E.[5], Petrov A.K.[2], Popik V.M.[1], Prinz V.Ya.[4], Salikova T.V.[1], Scheglov M.A.[1], Seleznev V.A.[4], Serednyakov S.S.[1], Shevchenko O.A.[1], Skrinsky A.N.[1], Stupak M.F.[8], Vlasenko M.G.[1], Yakovlev V.I.[6], Zhigach S.A.[7]

[1] Budker Institute of Nuclear Physics SB RAS, Novosibirsk, 630090 Russia
[2] Institute of Chemical Kinetics and Combustion SB RAS, Novosibirsk, 630090 Russia
[3] Novosibirsk State University, Novosibirsk, 630090 Russia
[4] Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, 630090 Russia
[5] Institute of Cytology and Genetics SB RAS, Novosibirsk, 630090 Russia
[6] Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, 630090 Russia
[7] Lavrentiev Institute of Hydrodynamics SB RAS, Novosibirsk, 630090 Russia
[8] Technological Design Institute of Scientific Instrument Engineering SB RAS, Novosibirsk, 630090 Russia
[a] knyazev@inp.nsk.su, [b] kulipanov@inp.nsk.su, [c] vinokurov@inp.nsk.su

Abstract

In this paper we describe the Novosibirsk terahertz free electron laser (NovoFEL) and present some of results obtained by many research groups working at the user stations of the NovoFEL.

Keywords: Free electron laser, terahertz radiation, imaging, spectroscopy, biomedical applications, metamaterials

1. Introduction

The exponentially-growing number of publications devoted to the development of terahertz sources and applications of terahertz radiation reflects the expectation of a breakthrough to new technologies involving this frequency band. The interest in the terahertz radiation is due to its following properties: it is a nonionizing radiation (the photon energy ranges from 0.04 eV to 0.004 eV); the radiation passes through opaque media and weakly dispersive materials relatively well owing to strong suppression of Rayleigh scattering ($1/\lambda^4$); the frequency range of the radiation covers the region of rotational spectra of molecules, vibrations of biologically important collective modes of DNA and proteins, and frequencies characteristic of intermolecular interactions; the terahertz radiation corresponds to the energy region of hydrogen bonds and van der Waals forces of intermolecular interactions.

The invention of broadband terahertz generators, which are based on femtosecond lasers, triggered researches in terahertz imaging and tomography, spectroscopy, biology and medicine, security, and other applications. For applications which require a tunable monochromatic coherent radiation the backward wave oscillators (in the millimeter and high submillimeter regions), injection-seeding parametric generators, and difference-frequency generators are commonly used. However, the average power of all the above mentioned generators is very low.

More intense terahertz radiation can be emitted using the sources based on the radiation of relativistic electrons in magnetic structures like synchrotrons and free electron lasers (FEL). The average radiation power of conventional terahertz free electron lasers at laboratories of Stanford, UCSB, FOM-Institute, Osaka and KAERI is close to one Watt. Because of the relatively low FEL efficiency a further increase in the output power can be achieved only using energy-recovery systems. The capability of such technique has been demonstrated on the near-infrared FEL (JFEL), which has recently been commissioned at Jefferson Laboratory and is based on an energy recovery linac. Now it generates a broadband radiation with the average power as high as 10 kW. The same facility is also used as a 100-W average-power radiation source, which emits broadband terahertz radiation when a subpicosecond electron bunch passes bending magnets (coherent synchrotron radiation in the THz region).

2. The Novosibirsk free electron laser

The NovoFEL facility consists of an energy recovery linac ("accelerator-recuperator") with an RF-power supply, undulators with optical resonators, beamlines for transmission of laser radiation, and user stations [1].

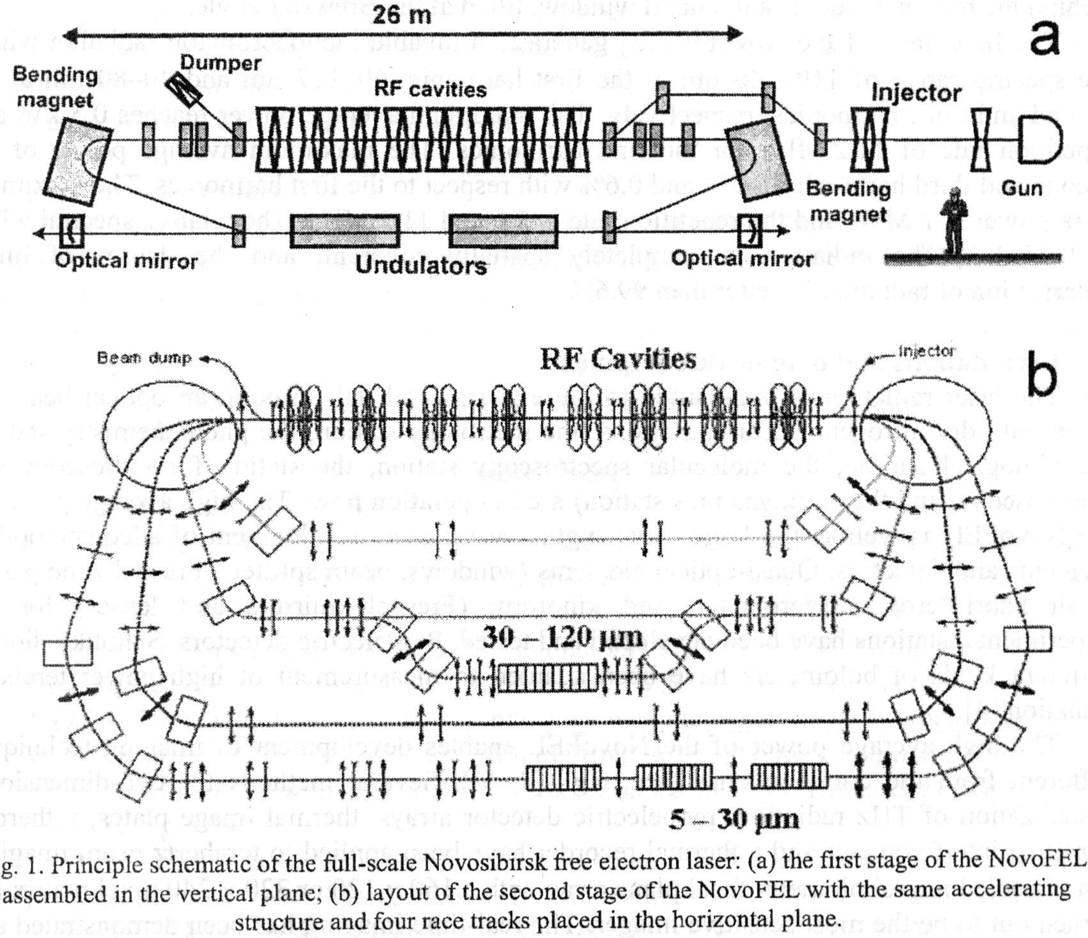

Fig. 1. Principle schematic of the full-scale Novosibirsk free electron laser: (a) the first stage of the NovoFEL, assembled in the vertical plane; (b) layout of the second stage of the NovoFEL with the same accelerating structure and four race tracks placed in the horizontal plane.

The first stage of the Novosibirsk high-power free electron laser (NovoFEL) was commissioned in 2003 (Fig. 1, a). The accelerator is a continuous wave FEL based on a non-superconducting, low frequency (180 MHz), single-pass accelerator-recuperator with the following parameters: the electron energy is 12 MeV, charge per bunch is 1,5 nC, the bunch repetition rate is 5.6–22.5 MHz, the maximum average current is 30 mA, the bunch duration is 40–100 ps.

Two undulators are installed in a long straight section of the single-orbit energy recovery linac (ERL). Both the electromagnetic planar undulators are identical and 4 m long, the period is 120 mm, the gap is 80 mm, and the undulatory parameter K is up to 1.2. To optimize the relative phasing of the undulators a buncher was installed between them, the buncher,being just a three-pole electromagnetic wiggler, which is now used at a low longitudinal dispersion $N_d < 1$.

The laser resonator [2] consists of two spherical mirrors of a 15 m curvature radius, made of gold-plated copper and water-cooled. There is a hole in the center of each mirror. The hole is intended for mirror alignment (using the He-Ne laser beam) and output of small amount of radiation. The distance between the mirrors is 26.6 m. Both the front and rear mirrors has an opening with a diameter of 3.5 mm and 8 mm, correspondingly. The calculated transparency of the mirror with the 8-mm hole at a wavelength of 150 microns is 1.5 %. At this wavelength, the measured round-trip loss is near 7%. The output radiation passes through two windows, which separate the resonator and accelerator ultrahigh vacuum system from the atmosphere. Behind the front mirror, an additional iris and a normal-incidence quartz window are installed. Behind the rear one there is a diamond window, tilted at the Brewster angle.

The first stage of the NovoFEL [3] generates a tunable monochromatic radiation within the spectral range of 110–240 μm at the first harmonic, 60–117 μm and 40–80 μm at the second and third harmonics, respectively. The maximum average power reaches 0.5 kW at a repetition rate of 11.2 MHz for the first harmonics. The maximum average power of the second and third harmonics is 2% and 0.6% with respect to the first harmonics. The maximum peak power is 1 MW, and the repetition rate is 5.6 and 11.2 MHz. The relative spectral width is 0.25–1%. The radiation is completely spatially coherent, and the degree of linear polarization of radiation is better than 99.6%.

3. User stations and diagnostic equipment

The laser radiation is transmitted to the experimental hall through an optical beamline filled with dry nitrogen. Six user stations (the metrology station, the photochemistry station, the biological station, the molecular spectroscopy station, the station for radioscopy and spectroscopy, and the aerodynamics station) are in operation now. The high average power of the NovoFEL as well as the large wavelength necessitates development of adequate optical elements and detectors. Quasi-optical elements (windows, beam splitters, Fresnel zone plates, mesh Fabri-Perot interferometer, and kinoform (Fresnel) mirrors and lenses) for the experimental stations have been developed and tested. Pyroelectric detectors, Schottky diodes, different kinds of bolometers have been adapted to measurement of high power terahertz radiation [4].

The high average power of the NovoFEL enables development of imaging techniques different from the common ones (see, e.g., [4, 5]). Several methods for two-dimensional visualization of THz radiation, pyroelectric detector arrays, thermal image plates, a thermal sensitive interferometer and a thermal recorder have been applied to terahertz beam imaging. An uncooled microbolometer focal plane array with a 160 × 120 or 320 × 240 pixel matrix has turned out to be the most sensitive imager. The real-time imaging has been demonstrated at a frequency as high as 90 frames/s [6].

4. Experiments at the user stations

The terahertz laser of the NovoFEL has operated as a user facility for the past four years. The high power of the NovoFEL radiation enables performing several experiments impossible on any other terahertz sources. A continuous optical discharge in the atmosphere and drilling of a PMMA solid block have been demonstrated. Impressive experiments on ablation of biological molecules and other substances have been carried out [7]. Precise tuning of the radiation energy, a regime when "biological" molecules (DNA, proteins, etc) are "evaporated" without defragmentation was achieved. In one of the experiments, horseradish peroxidase recollected after ablation from the aerosol phase onto a solid filter retained, at least partially, its enzymatic activity. These and other results clear the way to new biotechnologies.

The feasibility of terahertz spectral selective radioscopy, holography and tomography has been demonstrated. The real-time terahertz imaging of objects illuminated with unidirectional and diffuse terahertz beams was under study. The speckle patterns, which were observed in the THz region for the very first time, were used for a demonstration of terahertz speckle photography [8]. Studies of solids, flames and gas flows using intense terahertz radiation are in progress.

The tunability of the NovoFEL radiation wavelength was employed in spectroscopy experiments. A resonant rotation of polarization plane by a chiral structure fabricated at the Institute of Semiconductor Physics SB RAS has been demonstrated in the THz range for the very first time [9]. Since many substances, especially biologically important ones, have a very strong absorption in the terahertz range, an attenuated total reflection imaging spectrometer has been developed for real-time spectroscopy.

5. Further development

We are planning to commission soon the second stage of the NovoFEL (Fig. 1, b), based on the four-track 40 MeV accelerator-recuperator, using the same accelerating RF structure as with the first stage. The FELs in the second and fourth tracks are to generate radiation in the spectral ranges of 5-30 μm and 30-100 μm, respectively. The expected average power of each FEL is more than 1 kW. By now, the electron beam has been transported through the first and second tracks, and lasing with a wavelength of about 50 μm has been achieved.

References

1. G.N. Kulipanov, N.G. Gavrilov, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, V.K. Ovchar, V.M. Popik, T.V. Salikova, M.A. Scheglov, S.S. Serednyakov, O.A. Shevchenko, A.N. Skrinsky, V.G. Tcheskidov, N.A. Vinokurov, M.A. Demyanenko, D.G. Esaev, E.V. Naumova, V.Y. Prinz, V.P. Fedin, A.M. Gonchar, S.E. Peltek, A.K. Petrov, L.A. Merzhievsky, V.S. Cherkassky. *Terahertz Sci. and Technol.* 2008, vol. 1, issue.2, 19 p. – http://www.thznetwork.org.cn/Journal/index.asp
2. V.V. Kubarev, B.Z. Persov, N.A. Vinokurov, A.V. Davidov. *Optical resonator of powerful free-electron laser.* Nucl. Instrum. Methods in Phys. Researches Sec. A. 2004, vol. A528, p. 199.
3. N.G. Gavrilov, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, A.D. Oreshkov, V.K. Ovchar, V.M. Popik, T.V. Salikova, M.A. Scheglov, S.S. Serednyakov, O.A. Shevchenko, A.N. Skrinsky, V.G. Tcheskidov, N.A. Vinokurov. *Nucl. Instrum. Methods in Phys. Researches Sec. A.* 2009, vol. 575, p. 54.
4. B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov. *J. Korean Phys. Soc.* 2007, vol. 51, p. 409.

5. N.A. Vinokurov, S.A. Zhigach, B.A. Knyazev, A.V. Konysheva, G.N. Kulipanov, L.A. Merzhievsky, I.A. Polskikh, V.S. Cherkassky. *Radiophysics and Quantum Electronics.* 2007, vol. 50, p. 803.
6. M.A. Dem'yanenko, D.G. Esaev, B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov. *Appl. Phys. Lett.* 2008, v. 92, 2008, 131116.
7. A.K. Petrov, A.S. Kozlov, S.B. Malyshkin, M.B. Taraban, V.M. Popik, M.A. Scheglov, T.N. Goriachkovskaya, S.E. Peltek. Nucl. Instrum. *Methods in Phys. Researches Sec. A.* 2007, vol. 575, p. 68.
8. O.I. Chashchina, B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov. *Nucl. Instrum. Methods in Phys. Researches Sec. A.* 2009 (in press).
9. E.V. Naumova, V.Ya. Prinz, V.A. Seleznev, S.V. Golod, V.V. Kubarev, B.A. Knyazev, G.N. Kulipanov, S.A. Kuznetsov, P.V. Kalinin, N.A. Vinokurov. *Proc. of Joint 31st International Conference on Infrared and Millimeter Waves and 14th International Conference on Terahertz Electronics.* Sept. 18-22, 2006, Shanghai, China.