

Novosibirsk Free Electron Laser—Facility Description and Recent Experiments

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Abstract—The design and operational characteristics of the Novosibirsk free electron laser facility are described. Selected experiments in the terahertz range carried out recently at the user stations are surveyed in brief.

Index Terms—Biology, chemistry, free electron laser, optics, spectroscopy, terahertz range.

I. INTRODUCTION

THE free electron laser (FEL) facility at Budker INP is based on the normal conducting CW energy recovery linac (ERL) with a rather complicated magnetic system. It is the world's only multi-orbit ERL so far. It can operate in three different regimes providing electron beams for three different FELs. Its commissioning was naturally divided into three stages.

The first stage ERL includes only one orbit in a vertical plane and serves as an electron beam source for the terahertz FEL, which started working for users in 2003. The radiation of this FEL is used by several groups of scientists, including biologists, chemists and physicists. Its high peak and average powers and the capability of wavelength tuning is utilized in experiments on material ablation, biological objects modification, and ultrafast single-pulse gas spectroscopy. The second stage ERL has two

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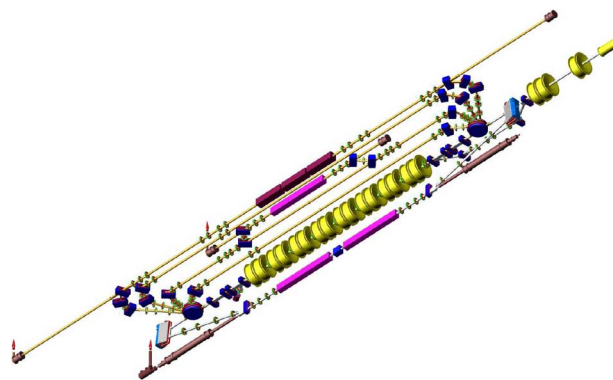


Fig. 1. Novosibirsk ERL with three FELs (3-D bottom view).

orbits in a horizontal plane. The second stage FEL is installed on the bypass of the second orbit. The first lasing of this FEL was achieved in 2009. The last stage ERL has four orbits. The commissioning of the third FEL is in progress now.

II. FREE ELECTRON LASER (FEL)

The Novosibirsk FEL facility is based on the multiturn energy recovery linac (ERL), the scheme of which is shown in Fig. 1. In this scheme the beam goes through the linac several times before it enters the undulator. As a result, the final electron energy can be increased.

At present, the Novosibirsk ERL is the only multiturn ERL in the world. It has a rather complicated lattice, as can be seen from Fig. 1. The ERL can operate in three modes, providing electron beam for three different FELs. The whole facility can be treated as three different ERLs (one-turn, two-turn and four-turn), which use the same injector and the same linac. The one-turn ERL is placed in a vertical plane. It works for the THz FEL, the undulator and optical cavity of which are installed on the floor (see Fig. 2). This part of the facility is called the first stage. It was commissioned in 2003 [1].

The four ERL orbits are placed in a horizontal plane at the ceiling. There are two round magnets in the common track. By switching these magnets on and off, one can direct the beam either to the horizontal or to the vertical beamlines. The 180-deg bending arcs also include smaller bending magnets with parallel edges and focusing quadrupoles. For reduction of the sensitivity to the power supply ripples, all magnets on each side are connected in series. The quadrupole gradients are chosen so that all the 180-deg bends are achromatic. The vacuum chambers with water-cooling channels inside are made of aluminium.



Fig. 2. General view of accelerator hall.

TABLE I
BASIC ERL PARAMETERS

Injection energy, MeV	2
Main linac energy gain, MeV	10
Charge per bunch, nC	1.5
Normalized emittance, mm·mrad	20
RF frequency, MHz	180.4
Maximum repetition rate, MHz	90.2

The second horizontal track has a bypass with the second FEL undulator. The bypass adds about 0.7 m to the length of the second orbit. Therefore, after passing the bypass, the beam returns to the linac in a decelerating phase and after two decelerations it finally comes to the dump. This second FEL has been in operation since 2009. The third FEL is installed on the last (fourth) track. It is under commissioning now.

The basic beam and linac parameters common for all the three ERL operation modes are listed in Table I.

Depending on the number of turns, the maximum final electron energy can be 12, 22 or 42 MeV. The bunch length in the one-turn ERL is about 100 ps. In the two and four-turn ERLs, the beam is compressed longitudinally down to 10–20 ps. The maximum average current achieved in the one-turn ERL is 30 mA, which is still the world's record for ERLs.

One essential difference of the Novosibirsk ERL as compared with other facilities [2]–[4] is the use of low-frequency non-superconducting RF cavities. On the one hand, this increases the linac size, but on the other hand, this also allows increasing the transverse and longitudinal acceptances, which in turn enables operation with longer electron bunches with large transversal and longitudinal emittances. Moreover, there are no beam break-up instabilities at the Novosibirsk ERL, and the average beam current is limited now by the electron gun power. The location of different parts of the facility in the accelerator hall is shown in Fig. 2.

The first stage FEL includes two 3.5 m long electromagnetic undulators with a period of 12 cm, a phase shifter and an optical cavity. The chosen undulator pole shape provides equal

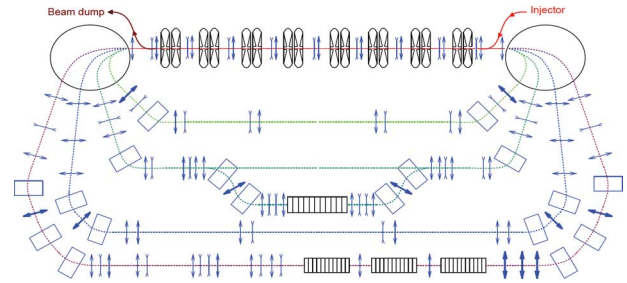


Fig. 3. Scheme of horizontal tracks. The second FEL undulator is installed on the bypass of the second track, and the third FEL undulators are at the fourth track.

electron beam focusing in the vertical and horizontal directions. The matched beta-function in the undulators is about 1 m. The phase shifter is installed between the undulators and is used for phasing of the radiation of two undulators. The optical cavity is composed of two copper mirrors covered by gold. The radius of the mirror curvature is 15 m, and the mirror diameter is 190 mm. The distance between the mirrors is 26.6 m, which corresponds to a round-trip frequency (and a resonance electron repetition rate) of 5.64 MHz. The radiation is outcoupled through the holes in the mirrors centers. The optical beamline is separated from the vacuum chamber by a diamond window installed at the Brewster angle.

The laser system of the first stage FEL generates coherent radiation tunable in the range of 80–240 micron as a continuous train of 40–100 ps pulses at a repetition rate of 5.6–22.4 MHz. The maximum average output power is 0.5 kW; the peak power is 0.8 MW [5], [6]. The minimum measured linewidth is 0.2%, which is close to the Fourier-transform limit.

The second stage FEL includes one 4-m long electromagnetic undulator with a period of 12 cm and an optical cavity. The undulator is installed on the bypass, where the electron energy is about 22 MeV. Therefore the FEL radiation wavelength range is 40–80 microns. The undulator design is similar to that of the first stage, but it has smaller aperture and higher maximum magnetic field amplitude. The optical cavity length is 20 m (12 RF wavelengths). Therefore the bunch repetition rate is 7.5 MHz. The maximum gain is about 40% which enables lasing at 1/8 of the fundamental frequency (at a bunch repetition rate of about 1 MHz).

A significant (percent) increase in the beam losses took place during the first lasing runs. Then sextupole corrections were installed into some of the quadrupoles for making the 180-deg bends second-order achromatic. That increased the energy acceptance for the electron beam. The output power is about 0.5 kW at a 9 mA ERL average current. This world's first multiturn ERL has operated for the far infrared FEL since 2009.

In the third stage ERL, the electron beam is accelerated four times. The third FEL undulators are installed on the last track, where the beam energy is 42 MeV. In this FEL, three permanent magnet undulators with periods of 6 cm and variable gap are used. The wavelength range will be 5–30 microns. The scheme of the third stage ERL with the FEL undulators is shown in Fig. 3. The 40 m optical resonator of the FEL has classical open scheme, but the electron outcoupling [7] is planned to be tested here.

TABLE II
RADIATION PARAMETERS

Stage	1 st stage (one track)	2 nd stage (two tracks)	3 rd stage (four tracks)
Status	In operation since 2003	In operation since 2009	Under commissioning
λ , μm	90 – 240	30 – 90	(5 – 30)
$\delta\lambda/\lambda$	0.2 – 2 %	0.2 – 1 %	(0.1 – 1) %

The four-turn ERL operates with a repetition rate of 3.76 MHz and an average current of 3.2 mA, which is sufficient for lasing. In the nearest future we plan to commission the third stage ERL. The optical cavity assembly is in progress.

Another important issue we are working on now is the operation stability and improvement in the existing FEL parameters. A new power supply is being prepared for the existing electron gun. A new CW RF gun [8] was tested successfully. A project of a variable-period permanent magnet undulator [9] to replace the electromagnetic undulator of the second FEL is being developed.

Parameters of the laser radiation for the three laser systems of NovoFEL are presented in Table II, where λ is wavelength; $\delta\lambda/\lambda$ is the relative linewidth; $\langle P \rangle$ is the maximum average power; P_{peak} is the maximum peak power; τ is the pulse length; f_{opt} is the round-trip optical cavity frequency. The radiation is linearly polarized.

III. USER STATIONS AND INSTRUMENTATION

A. Radiation Characteristics

The NovoFEL radiation is extracted from the optical cavity through an opening of 8 mm in diameter in the tail-end mirror and enters into the beamline passing an 1 mm thick diamond output window. Drayed air-nitrogen mixture is continuously circulated inside the beamline to avoid absorption of terahertz radiation by water vapor. After several reflections from plane and toroidal metal mirrors, the laser beam arrives through a polypropylene-film window at one of the user stations via a port equipped with a movable plane mirror. The beam has a Gaussian profile, $I = I_0 \exp(-2r^2/w^2)$ and diffraction-limited divergence. The total length of the beamline is equal to 80 meters.

Six user (Fig. 4) and two diagnostic stations are in operation now. Another four are under construction. A small fraction of radiation is split to a spectrometer, which allows continuous measurement of the radiation spectrum while users are performing their experiments. Other radiation diagnostics include a Fourier spectrometer, a thermograph, microbolometer arrays, a pyroelectric array, and a fast Schottky diode coupled to a 20 GHz oscilloscope. The last one is used for time-resolved measurements. It allows recording the laser pulse shape and other signals with time resolution up to 15 ps.

All the stations are available to external users and well equipped with devices and instrumentation, both standard and homemade. Because of the high average power of the laser beam, the role of the homemade equipment is crucial for many experiments. Below we describe instrumentation developed at the user stations.

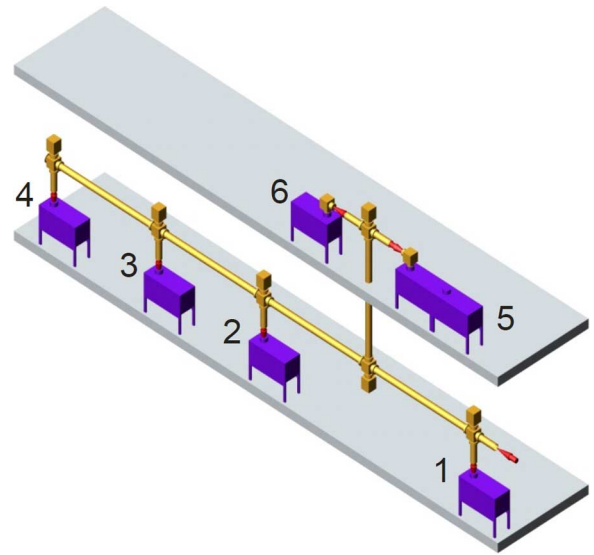


Fig. 4. User stations: 1—chemistry station, 2—metrology station, 3—molecular spectroscopy station, 4—biology station, 5—vacuum station, 6—station for spectroscopy and imaging.

B. Optical Elements

Optical elements for manipulation and shaping of laser radiation, as well as for experiments on terahertz imaging, were designed and fabricated. A limited number of substances are suitable for use as “optical quality” transparent materials in the terahertz range. High-numerical-aperture kinoform lenses [10] made of high-density polypropylene 0.8 mm thick, which turned out to be resistant to intense THz radiation, enabled obtaining images with a diffraction-limited resolution [11]. Another radiation-resistant material, high-resistivity silicon, has better mechanical characteristics and many technological processes can be applied to its treatment. These capabilities were used in the creation of a set of binary diffraction optical elements (DOEs) [12], [13]. That enabled splitting the laser beam into three beams, shaping of the laser beam into given volumes, transformation of laser beam modes, uniform illumination of a square area, and, finally, formation of beams with orbital angular momentum. The problem of strong Fresnel reflection (the silicon refractive index is $n = 3.42$) was radically solved via deposition of an anti-reflection Parylene C layer.

C. Imaging Devices

Uncooled 160×120 and 320×240 microbolometer arrays (MBA) [14], [15] with a pixel size of $51 \times 51 \mu\text{m}$ and a repetition rate of up to 90 frames per second have been adapted to the terahertz imaging. The sensitivity of an array with a germanium window to terahertz radiation at $\lambda = 130 \mu\text{m}$ was found to be 30 nW/pixel, which proves the array to be a rather sensitive imager with an excellent wavelength-limited spatial resolution.

These microbolometer arrays with VOx sensitive elements were initially developed for the mid-IR spectral range, where their sensitivity was one to two orders higher. We found that VOx did not absorb THz radiation, and the radiation was detected via the antenna mechanism, i.e., oscillations of induced current through the VOx bridge. For this reason, in contrast to

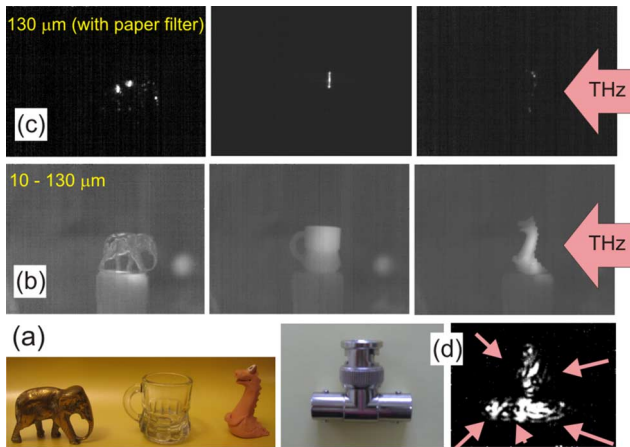


Fig. 5. (a) Images of metal, glass and ceramic objects recorded with visible range CCD camera. Images of same objects illuminated unidirectionally with THz laser radiation, recorded by 160×120 MBA with germanium window equipped with germanium objective (b) and with additional paper filter (c). (d) Images of BNC Tee connector in visible range and under diffuse illumination by $130 \mu\text{m}$ radiation reflected from rough metal surface.

the mid-IR, in the THz region the array demonstrates polarization sensitivity that drastically depends on the conductor geometry. This feature can play both a negative and a positive role. In particular, radiation polarization can be sensed simply by MBA rotation.

The MBAs have found numerous applications in image registration devices. Application of MBA to imaging of sites illuminated with coherent laser radiation enabled us to detect first THz speckles in the space domain [16], which had been detected previously only in the time domain [17], to investigate terahertz speckle statistics, and to demonstrate feasibility of THz speckle metrology. However, speckles significantly degrade the quality of images in optical systems and in radioscopy systems. Examples of images recorded with MBA under unidirectional and diffuse radiation are given in Fig. 5. In the first case (Fig. 5(c)), the camera detected only laser beam reflexes from objects at $\lambda = 130 \mu\text{m}$ (the radiation with a wavelength less than $35 \mu\text{m}$ was blocked by the paper filter), whereas at $\lambda = (10 - 14) \mu\text{m}$ one could see the thermal radiation from the objects, the right-hand sides of which (for the dielectric objects) had higher temperatures because of heating by the intense THz beam [see Fig. 5(b)].

One way to improve the quality of images in the terahertz range is the application of the holography technique [18], which enables employing an individual diffraction pattern as a source for reconstruction of images for a number of planes at different distances. Examples of the in-line holographic imaging, including detection of concealed objects, are presented in Fig. 6. One more device used for THz imaging was Pyrocam III.

Both the devices have a shortcoming of relatively small physical size ($16.36 \times 12.24 \text{ mm}$ for the MBA), which may be insufficient for some applications. Due to the high power of NovoFEL, for such applications we used [19] temperature-sensitive “thermal image plates” developed for mid-IR by Macken Instrument, Inc. Most THz radiation comes through the phosphor layer and is reflected from the base aluminum sheet, which decreases the device sensitivity, but the large sensitive area of

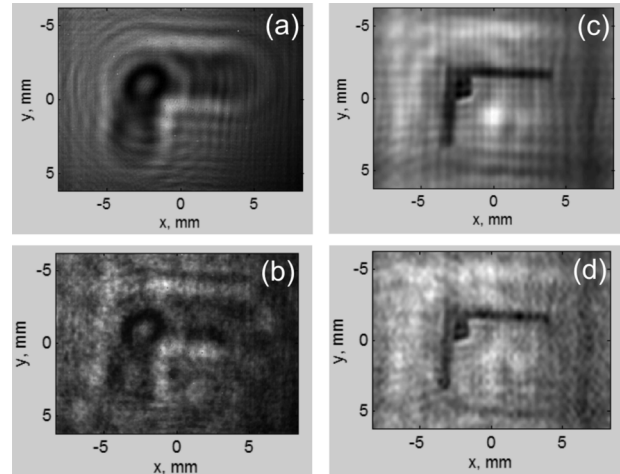


Fig. 6. In-line holograms recorded with 320×240 MBA with silicon window. (a) Hologram of object made of aluminum foil. (b) hologram of same object inside paper envelope. The distance between the object and the hologram was 28 mm . (c), (d) Images reconstructed using Rayleigh–Sommerfeld convolution algorithm.

75×75 or $150 \times 150 \text{ mm}$ and a wide linear response (up to 60% luminescence quenching) enables recording wide-field images.

D. One-Channel Radiation Detectors

The user stations are equipped with a large collection of one-channel THz radiation detectors. Besides the above mentioned fast Schottky diodes, pyroelectric and bolometer detectors are used. Albeit the FEL radiation is very intense, in some experiments very low radiation flows are to be measured. Slow measurements are performed with TYDEX optoacoustic Golay cells, whereas a hot-electron cryogenic bolometer [20] is used for measurements with one-pulse time resolution. GeGa- and Si-photoresistors in liquid helium are used in our experiments on study scattering of THz radiation by distant water fog and aerosols.

IV. SELECTED EXPERIMENTS

A. Quasi-Continuous Terahertz Optical Discharge

Nonlinear interaction of the high-power terahertz radiation of the Novosibirsk FEL with matter demonstrates an interesting phenomenon of terahertz optical discharge. It was attained immediately after commissioning of the Novosibirsk FEL and spectacularly demonstrated the high pulse power of the latter. Currently, experiments with such discharge are systematically carried out at the Novosibirsk FEL. They are of both metrology character (measurement of the discharge occurrence and maintenance thresholds for different gases and substances) and research nature (search for useful applications of this type of discharge). With short pulses of the Novosibirsk FEL (70 ps), a terahertz optical discharge occurs with pulsed fields of focused radiation of $\sim 1 \text{ MV/cm}$ and pulse intensities of $\sim 1 \text{ GW/cm}^2$ and, unlike other terahertz laser sources, the discharge can be quasi-continuous. The discharge dynamics is complex and diverse. In particular, gas dynamic auto-oscillations and plasma oscillations arise in it at nonlinear frequencies [21].

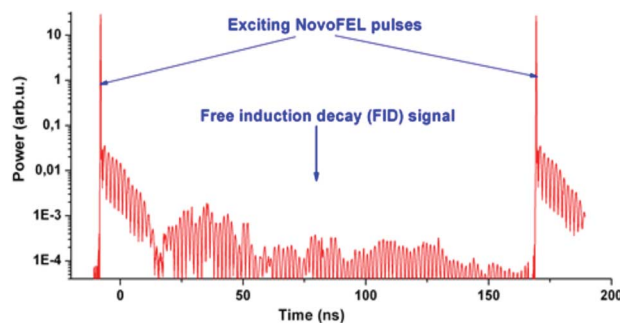


Fig. 7. Free induction decay signal of HBr (0.4 Torr, 60 cm) excited by NovoFEL line (central frequency: 66.71 cm^{-1} , FWHM width: 0.2%).

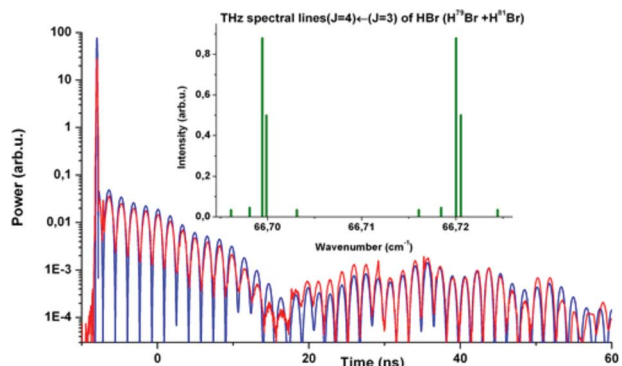


Fig. 8. Comparison of experimental FID signal from Fig. 1 (red line) and calculated FID signal for reference data of HBr lines shown in insert (green lines).

B. Ultra-Fast High-Resolution Spectroscopy

Ultra-fast high-resolution spectroscopy is an important field of research at the Novosibirsk terahertz free electron laser (NovoFEL). It uses almost all the advantages of the NovoFEL radiation (wavelength tuning, high pulsed power, and continuous pulse train). This spectroscopy is based on the measurement of signals of free-induction decay (FID) of emission by molecules excited with short (70–100 ps) NovoFEL pulses. Such signals are measured via slow step-by-step scanning in all time-domain spectrometers. The high pulse power of NovoFEL enabled first real-time measurement of terahertz signals with specially developed ultrafast detectors [22], [23]. This allows ultrafast single-pulse terahertz spectroscopy, which is the only possible in study of single and non-recurring processes, creation of spectrographic “movies” on the basis of the NovoFEL pulse-periodic radiation etc.

Our subsequent measurements [24] showed that FID signals can be up to 180 ns long, which enables a spectral resolution of about 6 MHz ($3 \cdot 10^{-6}$) (Fig. 7).

The free induction emission by molecules is well described by the Lorentz linear dispersion theory, which can be used both for analytical spectroscopy and for determination of parameters of emitting junctions and their relaxation cross sections. Fig. 8 shows an example of comparison of the theory and experiment.

Simplest analytical spectroscopy of molecules (spectroscopy of transitions known *a priori*) can be performed by just measurement of free induction signals. In many cases, the molecular

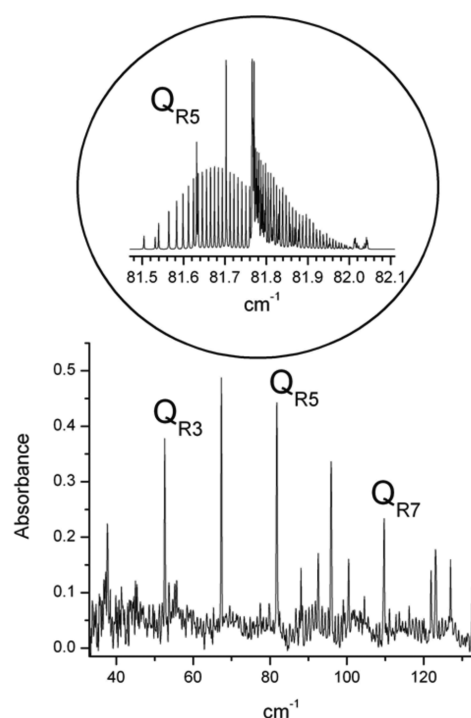


Fig. 9. Low resolution rotation spectra of NO_2 ($L = 50 \text{ mm}$, 70 Torr). Insert: internal structure of Q_{R5} band calculated from spectroscopic data.

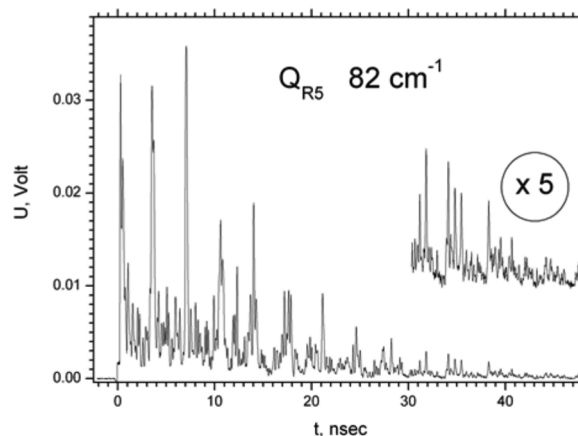


Fig. 10. FID signal of NO_2 at Q_{R5} branch. Length of gas cell: 100 cm; pressure: 1 Torr.

lines have an individual complex fine structure of a few dozen lines (Fig. 9). In the time domain, this assemblage of junctions results in a complex signal with a variety of typical individual echo peaks caused by interference of comparable frequencies (the effect of commensurate echo) (Fig. 10) [25].

A more complex general-type ultrafast spectroscopy (the spectra are not known *a priori*) was performed at NovoFEL with a special polarization spectrometer [26], [27]. This spectrometer was successfully used for diagnostics of so-called side-band modes, arising because of modulation instability in certain NovoFEL operation regimes [28]. A single-pulse measurement of the NovoFEL radiation spectrum with a resolution of 10^{-3} will be carried out in a time of 0.4 ns.

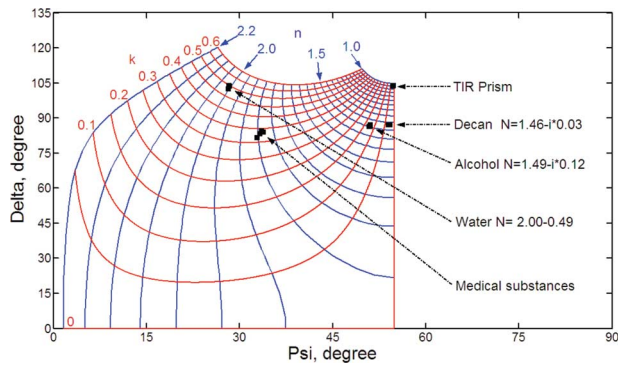


Fig. 11. Calculated nomograms for ψ and Δ . The coordinate system (red and blue lines) is formed with the isolines of the refractive and absorption indices. The dark dots present experimental data for the silicon prism and for decan, ethanol, water and dry blood and blood serum applied to the top surface of the silicon prism.

C. THz Ellipsometric System

Study of liquid sample characteristics is very important for biological and medical applications. Nowadays there is no reliable equipment for measurement of the absolute values of the complex refractive index of liquids in the THz range. Ellipsometry is generally known as the most precise and sensitive technique for measurement of optical properties of substances. Most biological substances contain water, which is highly absorbing throughout the THz range. For the purpose of study of highly absorbing media, we have developed an ellipsometric system with a silicon-prism internal reflection system. The arrangement of the ellipsometric system is based on a classic PSA (polarizer–surface–analyzer) scheme. The ellipsometric parameters Ψ and Δ are measured using a static photometric algorithm in the multiangle analyzer mode. The highest precision of the measurement of the ellipsometric parameters is 0.3° for ψ , and 0.01 was achieved for $\cos(\Delta)$, which allowed us to measure the absolute values of the refractive index and the absorption coefficient for diluted water solutions with a precision of 0.01 [29].

The optical constants were measured for a number of liquids (Fig. 11). For distilled water, the complex refractive index measured was $N = 2.00 - i \cdot 0.49$. The refractive indices of decan and ethanol, which are versatile solvents, were $N = 1.46 - i \cdot 0.03$ and $N = 1.49 - i \cdot 0.12$, respectively. The complex refractive index of dry blood and blood serum of healthy people and people with diseases varies from $N = 1.81 - i \cdot 0.31$ to $N = 1.88 - i \cdot 0.35$.

D. Terahertz Surface Plasmon Polaritons

Surface plasmon polaritons (SPPs) attract growing attention in modern photonics, in particular, because of the feasibility of realization of two- and three-dimensional integration circuits [30]. Such devices are of special interest in the THz range for communication systems, chemical and biological sensors and material study. Characteristics of SPPs are well investigated in the visible and near-infrared regions [31], whereas in the terahertz range the knowledge about SPPs is far from being complete.

We experimentally studied propagation of SPPs along “gold-zinc sulfate (ZnS)–air” interfaces and their diffraction at the surface edge, varying the ZnS thickness from zero to 3 μm

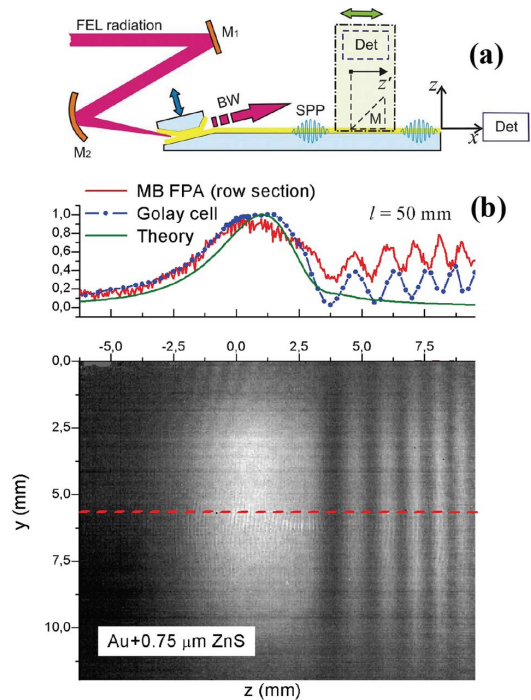


Fig. 12. Intensity distribution of diffracted wave at $l = 50$ mm beyond the edge obtained with Golyay cell (blue dots in plot) and with microbolometer FPA (frame below and red curve on plot).

[32]. The SPPs were launched by the waveguide [33], [34] or end-fire coupling techniques using radiation of NovoFEL at wavelengths of 130–140 μm . Upon reaching the surface edge, the SPPs diffracted into the free space [see Fig. 12(a)], where either a 320×240 microbolometer focal plane array (MBFPA) or a Golyay cell with a 0.2 mm slit were applied for detection of the decoupled electromagnetic field. An example of the intensity distributions of the diffracted wave for Au with 0.75 μm ZnS coverage 50 mm beyond the edge recorded with these detectors is shown in Fig. 12(b). The experimental and theoretical distributions [35] were found to be in reasonable agreement. Deposition of a very thin (~ 10 – 3λ) dielectric layer substantially decreased the width of intensity distribution of the diffracted wave [35].

The SPP propagation length and decay length measured using a movable inclined mirror also drastically depended on the ZnS thickness. The experimentally determined decay lengths (few millimeters) were in good agreement with the Drude theory, whereas the propagation lengths (a few centimeters) were about three orders less than the theoretical one [36]. This contradiction is well-known in literature and still requires thorough investigation. In the experiments we observed SPP “jumping” across air gaps up to 100 mm long between two conducting layers [37].

E. Electron Paramagnetic Resonance Study of Paramagnetic Species Under THz Radiation

Electron paramagnetic resonance (EPR) spectrometer placed in the user station hall makes it possible to study the influence of high-power THz radiation on paramagnetic species via excitation of their electric or/and magnetic dipole transitions. The station has a conventional X-band EPR spectrometer, operable in a continuous wave (CW) or a time-resolved (TR) mode. The

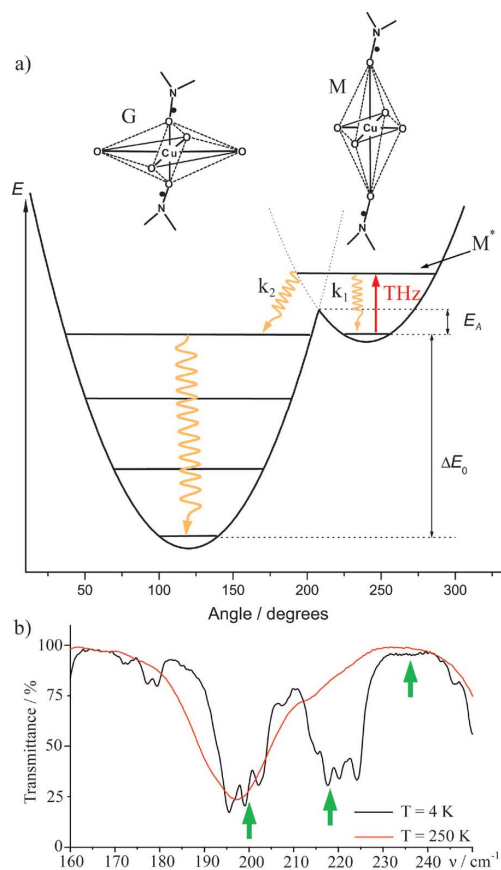


Fig. 13. (a) Schematic circular section of potential energy surface associated with two Jahn–Teller valleys in $\text{Cu}(\text{hfac})_2\text{LPr}$ compound. Structures corresponding to ground (G) and metastable (M) geometries are sketched on top. The expected mechanism of reverse conversion by THz radiation is shown. (b) Far IR spectra of $\text{Cu}(\text{hfac})_2\text{LPr}$ compound at temperatures of 250 K and 4 K. The arrows show the frequencies at which the sample was irradiated with THz light.

EPR spectrometer is equipped with a He cryostat, a Nd:YAG laser system and a THz waveguide; thus, both the radiation sources (NovoFEL or Nd:YAG laser) could be used during the EPR experiment for sample irradiation. Recently, this station was used for study of the influence of vibrational excitation on relaxation processes in the light-induced metastable state of $\text{Cu}(\text{hfac})_2\text{LPr}$ molecular magnet [38]. The $\text{Cu}(\text{hfac})_2\text{LPr}$ molecular magnet undergoes thermo- and light-induced magnetostructural transitions [39], [40] and at temperatures less than 20 K can be switched from a ground state (G) to a metastable state (M) by near-IR–vis light [Fig. 13(a)] [41]. The activation energy E_A of the $M \rightarrow G$ relaxation processes is about 20 cm^{-1} [42]. This value is much smaller than the energy of vibrational bands achievable with the high-power NovoFEL radiation (Fig. 13(b)); thus, excitation of the vibrational bands of $\text{Cu}(\text{hfac})_2\text{LPr}$ can significantly change the $M \rightarrow G$ relaxation rate. However, the $M \rightarrow G$ relaxation rate was found to be insensitive to the excitations chosen in experiment performed [the green arrows in Fig. 13(b)]. This result can be explained by the fast intermodal vibrational relaxation $M^* \rightarrow M$ in comparison with the $M^* \rightarrow G$ conversion ($k_1 \gg k_2$). However, it is also possible that the vibrations excited by THz radiation in these experiments are not associated with the reaction coordinate of the $M^* \rightarrow G$ conversion. Taking this into account, in the near

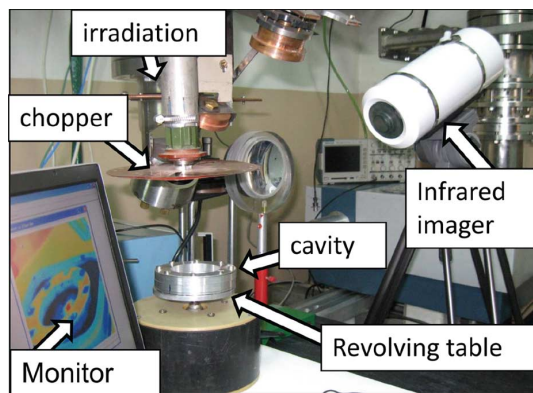


Fig. 14. Experimental station for irradiation of biological samples.

future we intend to probe other vibrational bands achievable at NovoFEL.

F. Non-Thermal Influence of Terahertz Radiation on *Escherichia Coli* Cells

Work is underway to study the non-thermal effects of the terahertz radiation of the Novosibirsk free electron laser (NovoFEL) on various living objects (from the archaea and bacteria, blue-green algae, and crustaceans to the human stem cells) and different levels of their structural and functional organization (from DNA and RNA to changes in the proteome).

The experiments are carried out at the biological station of the Siberian Center for Synchrotron and Terahertz Radiation at BINP SB RAS (Fig. 14). The Novosibirsk FEL radiation is delivered to the station via a special beamline. The objects are irradiated in a special cuvette with polypropylene windows, which are transparent in the terahertz range. $50 \mu\text{l}$ samples are placed between two stretched polypropylene films of 50 mm in diameter and $40 \mu\text{m}$ thick. The thickness of the irradiated layer of liquid is $40 \mu\text{m}$.

The THz radiation beam forms an elliptic spot on the cuvette surface, the radiation intensity distributed normally along both axes ($\sigma_x = 8 \text{ mm}$; $\sigma_y = 15 \text{ mm}$). Within the ellipse, the mean radiation intensity is 1.4 W/cm^2 and the peak radiation intensity is 4 kW/cm^2 . For uniform exposure of the sample throughout the volume, the cuvette is placed on a turntable. The average radiation power is adjusted using a chopper, which consists of two copper discs of 20 cm in diameter that have a common axis of rotation and are turned by a motor. Each disc has an opening occupying 1/30 of the disc area. Turning the discs relative to each other, one can regulate the area of the resulting opening and thus the average power of the irradiation of samples. During the experiment, the temperature of the medium in the cuvette was maintained at $35 \pm 2 \text{ }^\circ\text{C}$. The temperature was monitored using the thermal imager TKVr SVIT101 [43].

We investigated the non-thermal influence of terahertz radiation on *Escherichia coli* cells. This bacterium is a convenient and thoroughly studied model object for molecular biology. For detection of the dynamical response of biological systems to terahertz radiation it is convenient to use biosensor structures (biosensors). There is a variety of biosensor cells based on this bacterium. Biosensor is an artificial genetic reporter system, which contains a sensitive element, i.e., a promoter of a sensor

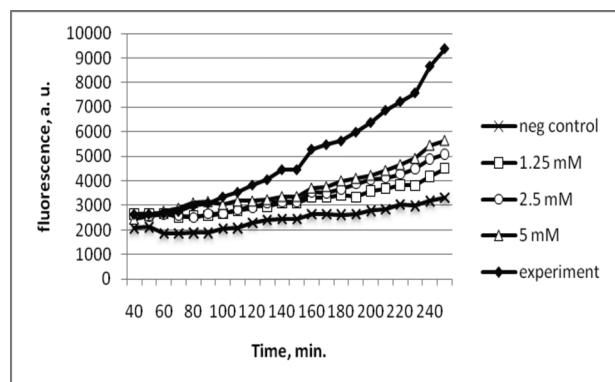


Fig. 15. Fluorescence intensity of the GFP protein in *E.coli/pKatG-gfp* biosensor cells after 15 min exposure to terahertz radiation at the wavelength of 130 microns. Neg. control—unexposed cells, H_2O_2 —inducer (positive control).

gene that is activated in response to external influence. A reporter gene that is under regulatory control of the sensor gene and encodes the green fluorescent protein (GFP) is an important part of this system. Currently there is a range of rather effective biosensor constructs based on promoters of *E. coli* genes, which are key parts of bacterial response to stress [44].

We performed a series of exposures of *E.coli/pKatG-gfp* biosensor cells to terahertz radiation at wavelengths of 130, 150, and 200 microns. Fig. 15 presents GFP fluorescence values after a single exposure to terahertz radiation with a 1.4 W/cm^2 power density and 130-micron wavelengths for 15 minutes, as well as GFP fluorescence values in cells induced by hydrogen peroxide in various concentrations (positive control) and the basic fluorescence values in unexposed cells (negative control). The quantity of cells was roughly equal in all experiments, which indicates the increase of GFP synthesis in *E.coli/pKatG-gfp* biosensor cells. As illustrated in Fig. 15, exposure to terahertz radiation at 130 μm wavelengths induces expression of the GFP protein in *E.coli/pKatG-gfp* biosensor cells. Similar dynamics of stress response of the *E.coli/pKatG-gfp* biosensor were showed for other wavelengths. At the same time, exposure for 5 and 10 minutes did not evoke a pronounced increase in the fluorescence intensity.

Biosensor cells express GFP during five hours after exposure to terahertz radiation, which equals about eight life cycles. Work on the proteomic profiling of the response by *E.coli* cells and human stem cells to terahertz radiation influence is underway.

A study on the effect of terahertz radiation on human embryonic stem cells (ESCs) was also carried out. The genotoxic action of terahertz radiation on the frequency of induction of DNA double strand breaks in human stem cells was estimated. The ability of terahertz radiation to cause chromosomal aberrations in irradiated cells was studied [45].

The earliest cell responses to nuclear DNA damage include a cell-cycle block at the border of the G1/S and G2/M phases of the cell cycle, as well as at the S stage [46]. To study the effect of terahertz radiation on the cell cycle, we counted the number of cells at the stage of mitosis 16 hours after exposure of the cells. To detect mitotic cells we performed immunocytochemical staining with antibodies to histone H3 phosphorylated on serine 10. The results of the analysis of the mitotic

index revealed no difference between the irradiated and control ESCs; the average mitotic index was 3.2 ± 0.1 and 3.1 ± 0.4 , respectively.

To study the ability of terahertz radiation to induce DNA double strand breaks in a cell, we counted γH2AX foci 2 hours after irradiation. It was shown earlier that the spontaneous level of the γH2AX foci in ESCs is extremely heterogeneous and depends on the cell division phase [47]. The analysis results show that there is no significant difference in the number of γH2AX foci per nucleus in the irradiated and control ESCs; the average frequency of γH2AX foci per nucleus was 4.1 ± 1.4 and 3.7 ± 0.4 , respectively.

A cytogenetic analysis of unstable chromosomal aberrations the terahertz radiation induced in the ESCs was done. No significant differences in the number of aberrations per 100 cells in the irradiated and control ESCs were revealed.

Analysis of the expression profiles of the RNA of ESCs exposed to terahertz radiation revealed weak (less than 1%) modulation of gene expression, as well as increased transcription of mitochondrial genes.

The studies of the non-thermal effects of the Novosibirsk terahertz free electron laser on living objects and various levels of their structural and functional organization have shown that 1) THz radiation does not exert DNA-damaging, genotoxic or mutagenic influence on the genomes of ESCs; 2) THz radiation increases the transcription of genes in mitochondria in ESCs; 3) THz radiation elicits a response from the oxidative stress systems in *E.coli*; 4) the THz radiation influence on *E.coli* cells is pronouncedly dose-dependent.

In an investigation [48] it has been shown that irradiation with terahertz radiation during cultivation has no significant effect on the morphology, proliferation rate and differentiation ability of human epithelial and embryonic stem cells. It has been assumed that in these circumstances the cells are able to compensate for any effects caused by exposure to terahertz radiation. In another work [49] it has been shown, on the contrary, that the exposure of artificial human skin cells to pulsed terahertz radiation affects the level of expression of a number of genes associated with inflammatory and cancer diseases of skin.

V. SUMMARY

The experimental results presented in this review show that, using radiation from the free electron laser (FEL), scientists from different disciplines can perform exciting pioneering works. As a rule, for all researchers it is important to use a monochromatic, tunable over a wide spectral range spatially coherent radiation. For some experiments, a large pulse and average power turns out to be the most important.

The commissioning of the third stage of our FEL and generation of high-power (up to 10 kW) radiation in the far infrared region ($\lambda = 5 \div 30$ microns) will enable investigation into photochemical technologies (laser catalysis, selective chemical reaction, and isotope separation using infrared multiphoton dissociation). The use of these technologies in industry will require development of a new generation of FELs and significant cost reduction.

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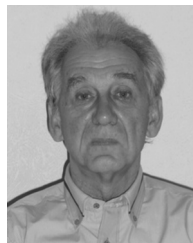
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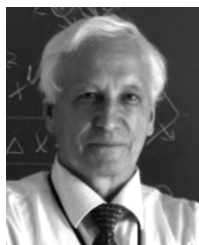


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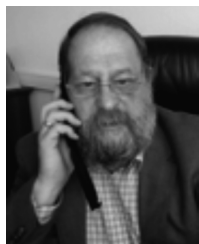
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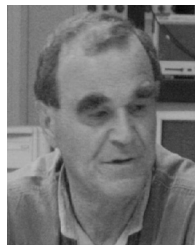
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