Terahertz and mm-wave applications at ENEA-Frascati

G. P. Gallerano, S. Ceccuzzi, A. Doria, E. Giovenale, G. L. Ravera, M. Zerbini,
G. Galatola-Teka[2]

[1]ENEA – Fusion Physics Division – Radiation Sources, Antennas and Diagnostics Laboratory
Via E. Fermi 45, 00044 Frascati – Italy, gianpiero.gallerano@enea.it
[2]ENEA Phd Student

Frequencies in the THz region are usually considered as too high for electronic devices, due to the technological limits in reducing the size of components as frequency increases, and too low for photonic devices, since the corresponding photon energy is comparable to those of thermal excitations at room temperature. A variety of applications of THz radiation are being developed worldwide. The majority of applications exploits the spectral fingerprints of the chemical species contained in the material under investigation and takes advantage from the fact that THz radiation can penetrate through plastic, cardboard and clothes, without causing the hazards of ionizing radiation (X-ray) and suffering at the same time less scattering than near-infrared radiation.

This wide variety of applications requires an equally wide range of sources and radiation characteristics. This is the reason why two Free Electron Lasers (FELs) have been designed, developed and realised at the ENEA Frascati Research Centre [1]. Thanks to their intrinsic generation mechanism they have the peculiar advantage of being tunable sources.

The ENEA Compact FEL is based on a microtron electron accelerator capable of generating a relativistic beam at an energy of 2.3 MeV with a current of 300 mA, in 4 μs pulses. A magnetic undulator, designed and realised by ENEA, made of 8 permanent magnets (SmCo) periods, provides the generation of radiation in the range 100-150 GHz with a peak power of 1.5 kW over the macropulse. Due to the RF nature of the accelerator, a sub-structure inside the pulse generates a train of micro-pulses of about 60 ps duration, equally spaced by 330 ps, with a peak radiation power of about 10 kW. The average CW power can be varied according to the repetition rate of the RF system driving the accelerator providing about 15 mW at 2.5 Hz (Fig. 1).

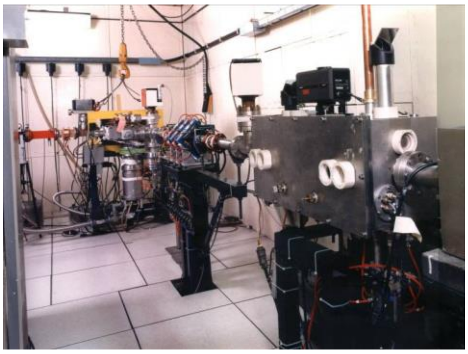

Fig. 1. The ENEA Compact FEL

The second ENEA FEL source is named FEL-CATS (Compact Advanced THz Source) and it is a unique device in the FEL panorama. It is a compact source based on a Linac type accelerator (2.3 MeV of energy and 250 mA of average current over 5 μs). It includes an additional RF device (called PMD), placed downstream the Linac, capable of manipulating the electrons in the longitudinal phase-space in such a way to create an adequate level of order in the bunch, to enhance the electromagnetic generation mechanism. This unique source, due to the presence of the PMD, does not make use of an optical resonator, thus extending its tuning capability over almost one octave. In fact, it generates radiation from 400 μm (0.7 THz) to 700 μm (0.4 THz) with a power level of several kW over the microsecond pulse duration (see Fig. 2).

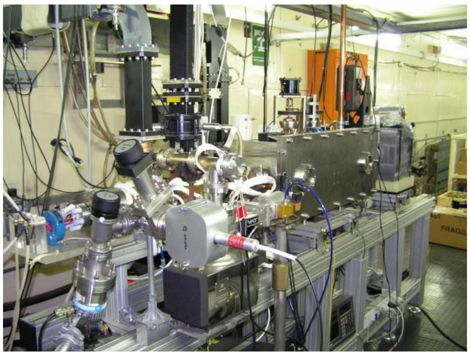

Fig. 2. The ENEA FEL-CATS source

Beside FEL sources, our laboratory has been equipped with an extensive assortment of other coherent sources, both lasers and electron devices as a part of the Center of Excellence for Terahertz Radiation and Applications (CETRA). A Far InfraRed (FIR) gas laser based on a CO_2 laser, pumping a gas cell, is available as well as a Ti:Sa laser oscillator that generates a train ultra-short pulses (about 130 fs) in the Near InfraRed (NIR) with an average CW power in excess of 1W. Other compact, portable, solid state sources are available in the THz laboratory to cover the low frequency spectrum: two YIG oscillators that emit in the ranges 8-20 and 20-40 GHz respectively, with an average CW power of 5-10 mW; an IMPATT diode at 97 GHz with about 80 mW of output power and a second IMPATT diode emitting at 140 GHz with about 20 mW of power. Finally a frequency multiplier in the range 220-330 GHz is also available to test high frequency components.

The CETRA Laboratory has realised an extensive variety of applications in different scientific and technological fields, like living plants biology, human biology, solid state physics and cultural heritage protection. The most notable activity was the pioneering THz BRIDGE project (2001 – 2004), a European project that opened the way to the study of the interaction of THz radiation with biological systems following a streamline of increasing complexity, from bio-molecules to living cells and tissues. At present the utilization capability of the laboratory resources takes place mainly in the context of scientific collaborations funded through national or international projects.

Recent applications in the biomedical field, are carried out in the frame of the GREAM project [2-3], financed by the Italian Ministry of Defence, and was realised in collaboration with the Scientific Department of Army Medical Center of Rome, and the Universities of Rome “La Sapienza”, “Tor Vergata” and “Roma Tre”. It focused on the study of potential genotoxic effects induced on different kind of human fibroblasts, after irradiation with the Compact FEL source, in the 100-150 GHz frequency range, and with the YIG source at 25 GHz. In order to correctly characterize the sample exposition, a preliminary study on the Specific Absorption Rate (SAR) has been performed, also by means of simulations, as reported in Fig. 3.

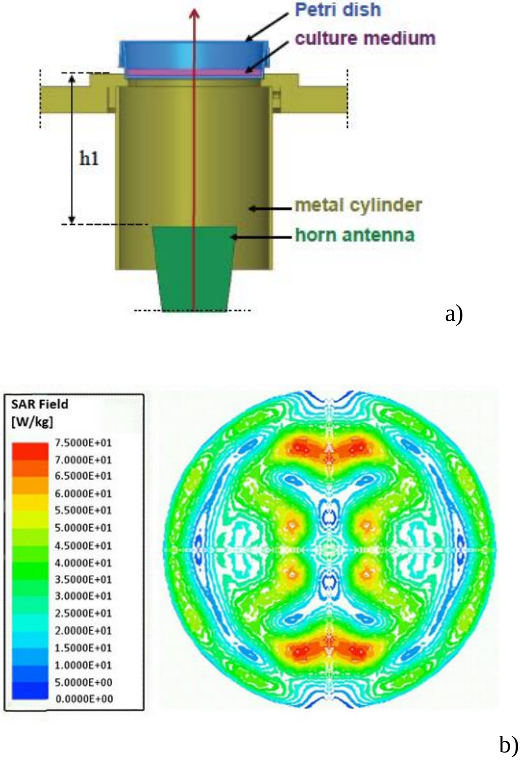

Fig. 3. (a) Detail of the setup showing the position of the petri dish; (b) SAR distribution on the cell layer at the bottom of the petri dish

In the field of Cultural Heritage preservation, a specific project, THz-ARTE, was carried out in the frame of a bilateral collaboration between Italy and Japan. For this project the CETRA Laboratory has realized an innovative imaging system [4] for the analysis of artwork samples, which were prepared by the NICT Institute in Tokio and by the CNR-IFAC Institute in Florence (see Fig. 4).

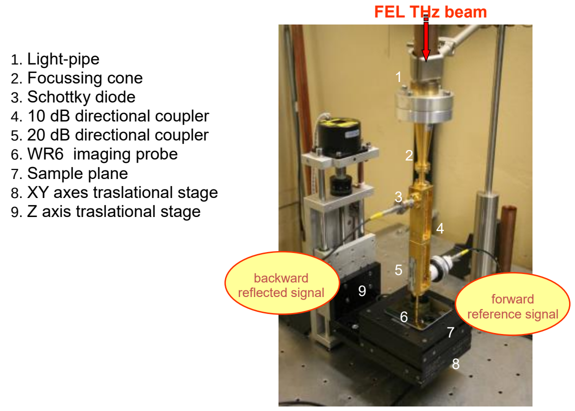

Fig. 4. The ENEA FEL Imaging System

A second reflective imaging system, employing the 97 GHz IMPATT source, has been realised to be suitable for “on field” operation. It exploits the penetrating features of the MM wave radiation together with a phase sensitive detection technique. This imaging system has been successfully operated on real ancient paintings (see Fig. 5).

Fig. 5. Portable ENEA Imaging system applied to a “Fresco” painting on the “tavella”—St. John Baptist—by Alessandro Gherardini (1655-1726)

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Ultrafast THz-pump & Electron-probe Facility (*ci-rcus*) at KAERI

Young Uk Jeong[1,2], Nikolay Vinokurov[3], Hyun Woo Kim[1,2], In Hyung Baek[1,2], Key Young Oang[1], Mi Hye Kim[1], Young Chan Kim[1], Kyu-Ha Jang[1,2], Kitae Lee[1,2], Seong Hee Park[4], Sergey Miginsky[1,3], Jungwon Kim[5], Fabian Rotermund[5], Sunglae Cho[6]

[1]Korea Atomic Energy Research Institute, Daejeon, Korea, yujung@kaeri.re.kr
[2]University of Science and Technology, Daejeon, Korea
[3]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[4]Korea University, Sejong, Korea
[5]Korea Advanced Institute of Science and Technology, Daejeon, Korea
[6]Ulsan University, Ulsan, Korea

We have developed a small-scale accelerator-based ultrafast-pump-and-probe facility for exploring dynamics of atoms and molecules in solid state or gas phase [1-3]. The main part of the facility is ultrafast electron diffraction (UED) beam lines as shown in Fig. 1 and 2.

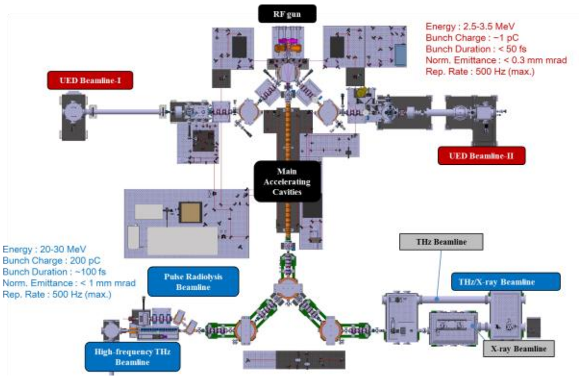

Fig. 1. Schematics of the KAERI ultrafast electron diffraction (UED) facility. The upper two beam lines are for UED experiments. UED beam line in the left part is for solid-state samples and the other beam line in the right part is for gas samples.

We developed two UED beam lines for gas and solid state samples. We have femtosecond-duration pumping sources with 267 nm, 400 nm, 800 nm, or wideband terahertz (THz), which are divided or converted from the 40-fs and 5-mJ laser pulses generated by a Ti:sapphire regenerative amplifier (Spitfire Ace-35F1K, Spectra Physics). The maximum pumping-pulse energy density is 4 J/cm^2 for 800 nm, and 500 mJ/cm^2 for 267 nm. THz pulse could be generated by a pulse-front tilting technique in $LiNbO_3$ crystal. The THz pulse energy and the peak electric filed of the focused THz pulse on sample are 1.7 μJ and ~25 MV/m, respectively. The THz pulses were also used for measuring the pulse duration and arriving timing jitter of the electron beam at the sample position.

The probe electron beam is generated from an S-band radiofrequency (RF) photoelectron gun by irradiating the 267-nm and 100-fs laser pulses divided and converted from the Ti:sapphire laser amplifier. The electron beam from the RF photogun has a kinetic energy of ~ 3 MeV. The UED beam lines consist with two 90-degree achromatic bends which are placed symmetrically. Each achromatic bend has two 45-degree circular-type bending magnets and two sets of triplet quadrupoles. The achromatic bend can compress electron beam from 100 fs to 40 fs and reduce the arriving timing jitter of the electron beam up to less than 20 fs at the sample position. We would like to emphasize that the short-bunch electron beam with low jitter was realized with high bunch charge of more than 1 pC.

With the ultrashort electron beam with extremely low jitter, we could measure the dynamics of photo-excited Bi poly-crystals with the temporal accuracy better than 50 fs in rms.

Fig. 2. Foreground of the KAERI ultrafast electron diffraction (UED) facility.

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THz science at FELBE

J. Michael Klopf[1], Harald Schneider[2]

[1]Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany, klopf@hzdr.de
[2]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

The FELBE User Facility at the ELBE Center for High Power Radiation Sources offers two FELs dedicated to optical studies of materials over a wide range of the THz and IR spectrum (1.2 – 60 THz / 5 – 250 μm). In 2017, the installation and commissioning of a new U37 undulator was completed, resulting in enhanced performance over the spectral range of 7.5 – 60 THz (5 – 40 μm). In this talk, we will present a brief facility status report and a review of some recent experiments which utilize the intense narrow-band THz fields and the high repetition rate of the free electron laser FELBE in Dresden, Germany.

The free electron laser (FEL) is an important source for THz and IR radiation. While there have been significant advances in tabletop THz and mid-IR sources, FELs still offer several advantages, such as wide and continuous spectral tuning, short pulses, high peak power, narrow spectral bandwidth, and high brightness.

At the ELBE Center for High Power Radiation Sources, two IR/THz FELs provide the primary radiation sources for the FELBE User Facility. In 2017, FEL1 was upgraded with a new undulator built by Research Instruments GmbH. Installation of the new U37 undulator took place in early 2017, and commissioning was completed in the summer of 2017. First lasing was established quickly and the performance matched well to simulations. Careful measurements were made of parameters such as cavity detuning, gain/loss, and FEL pulsewidth before resuming User operations in the Fall of 2017.

The new U37 undulator provides greater spectral overlap with the U100 of FEL2, allowing for better operational performance and flexibility in the range of 18 – 40 μm. More important, the improved magnetic structure of the new U37 allows for a very large spectral tuning range for a given electron beam energy. Users can rapidly take spectrally resolved measurements over a wide range by simply adjusting the gap of the undulator. This can be implemented manually or programmatically. The important parameters of the FELBE FELs are presented in Table 1.

The FELBE beamline directs FEL beam to eight User Labs with dedicated instrumentation and synchronized tabletop lasers and THz sources (i.e. Ti:Sa oscillators, regenerative amplifiers, OPAs, SFG/DFG sources) for pump-probe experiments. Optical cryostats and an 8 T split coil magnet are available for low temperature and field dependent measurements.

Furthermore, the FELBE beamline has been extended into the adjacent Dresden High Magnetic Field Laboratory (HLD), enabling measurement techniques such as Electron Spin Resonance (ESR) spectroscopy in pulsed fields up to 70 T [1].

Table 1: FELBE Parameters

	FEL1 (U37)	**FEL2 (U100)**
Spectrum	7.5 – 60 THz (5 – 40 μm)	1.2 – 16.7 THz (18 – 250 μm)
Avg. Power	≤ 44 W (13 μm)	≤ 65 W (42, 83 μm)
Pulsewidth (shortest)	0.7 – 4 ps	1 – 25 ps
Max. Pulse Energy	3.4 μJ	5 μJ
Peak Field	up to 4 MV/cm	up to 500 kV/cm
Bandwidth $\Delta\lambda/\lambda$	0.4 – 3.4%	0.4 – 2 %
Repetition Rate	13 MHz	13 MHz

The spectral tuning range and ultrashort pulses of the two FELs are ideal for the study of ultrafast dynamics, particularly in 2-D materials [2], semiconductor nanostructures [3], and correlated systems [4]. The high repetition rate (13 MHz) is an important feature of the FELBE FELs. This results in very high average power, excellent S/N and data statistics, and has also enabled revolutionary methods for spectrally resolved nanoscale imaging by scattering-type scanning near-field infrared microscopy (s-SNIM) [5], even down to cryogenic temperatures [6, 7].

This talk reviews in particular, some recent experiments using intense narrow-band THz fields from the free-electron laser FELBE in Dresden, Germany.

For example, in Landau-quantized graphene, degenerate four-wave mixing and pump-probe experiments have been conducted, respectively, to investigate the coherent third-order nonlinear polarization [8] and to provide evidence of supercollisions [9]. At low temperatures, a long-lived (several ps) pump-induced anisotropy of the carrier distribution was also observed [10]. In GaAs quantum wells, intense narrow-band THz fields have been exploited for dressing elementary electronic excitations. We will present THz-induced dressing of excitons [11, 12], exciton-polaritons [13].

The recently upgraded FELBE FEL provides exceptional performance for a wide range of measurements across the THz and IR spectrum. FELBE is an open access international FEL User Facility, and proposals for beamtime are invited from users twice a year through the FELBE website (https://www.hzdr.de/FELBE).

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Novosibirsk Free Electron Laser Facility

O.A.Shevchenko[1], N.A.Vinokurov[1,2], V.S.Arbuzov[1], K.N.Chernov[1], I.V.Davidyuk[1,2], O.I.Deichuly[1], E.N.Dementyev[1], B.A.Dovzhenko[1], Ya.V.Getmanov[1,2], Ya.I.Gorbachev[1], B.A.Knyazev[1,2], A.A.Kondakov[1], V.R.Kozak[1], E.V.Kozyrev[1,2], S.A.Krutikhin[1], V.V.Kubarev[1,2], G.N.Kulipanov[1], E.A.Kuper[1], I.V.Kuptsov[1], G.Ya.Kurkin[1], L.E.Medvedev[1], S.V.Motygin[1], V.K.Ovchar[1], V.N.Osipov[1], V.M.Petrov[1], A.M.Pilan[1], V.M.Popik[1], V.V.Repkov[1], T.V.Salikova[1], M.A.Scheglov[1], I.K.Sedlyarov[1], S.S.Serednyakov[1,2], A.N.Skrinsky[1], S.V.Tararyshkin[1], A.G.Tribendis[1,3], V.G.Tcheskidov[1], P.D.Vobly[1], V.N.Volkov[1]

[1]Budker INP SB RAS, Novosibirsk, Russia, O.A.Shevchenko@inp.nsk.su
[2]Novosibirsk State University, Novosibirsk, Russia
[3]Novosibirsk State Technical University, Novosibirsk, Russia

The Novosibirsk FEL facility has three FELs, installed on the first, second and fourth orbits of the ERL. The first FEL covers the wavelength range of 90 – 240 μm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 5.6 or 11.2 MHz and a peak power of up to 1 MW. The second FEL operates in the range of 40 - 80 μm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 7.5 MHz and a peak power of about 1 MW. These two FELs are the world's most powerful (in terms of average power) sources of coherent narrow-band (less than 1%) radiation in their wavelength ranges. The third FEL was commissioned in 2015 to cover the wavelength range of 5 – 20 μm. The Novosibirsk ERL is the first and the only multiturn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and a rather compact (6×40 m2) design. The facility has been operating for users of terahertz radiation since 2004.

Accelerator

The Novosibirsk free electron laser (FEL) facility [1, 2] includes three FELs. All the FELs use the electron beam of the same electron accelerator, a multiturn energy recovery linac (ERL). A simplified scheme of the four-turn ERL is shown in Fig. 1.

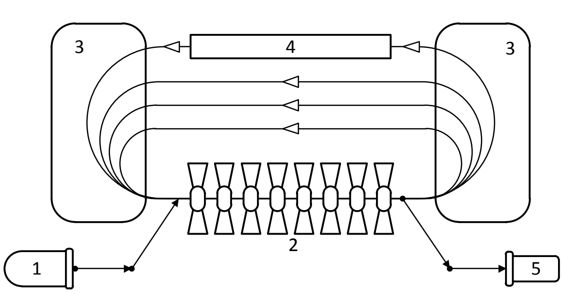

Fig. 1. Simplified multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump

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.

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).

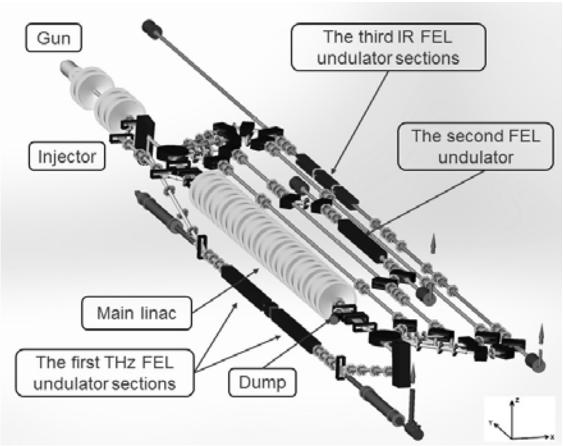

Fig. 2. The Novosibirsk ERL with three FELs (top view)

The accelerating structure consists of 16 normal-conducting RF cavities, connected to two waveguides. The operation frequency is 180.4 MHz. Such a low frequency allows operation with long bunches and high currents.

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 Fig. 2). Therefore, after the first passage through the RF structure, the electron beam with an energy of 11 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 are switched on, the beam with an energy of 20 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.

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.

FELs

The first FEL has been in operation since 2003 [3]. 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. [4 – 9].

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). The new variable-period undulator [10] is being prepared to replace the old electromagnetic one of this FEL [11]. It will allow us to expand significantly the wavelength tuning range.

The undulator of the third FEL is installed on the fourth track. 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.

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 [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.

The new RF gun

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun [13] was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved recently [14]. The injection beamline for the RF gun will be manufactured this year.

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From millimeter to microns – IAP RAS powerful sources for various applications

M. Yu. Glyavin, G. G. Denisov, E.A. Khazanov

Institute of Applied Physics RAS, Nizhny Novgorod, Russia, glyavin@appl.sci-nnov.ru

The last decade has contributed to the rapid progress in the development of THz sources, in particular gyrotrons. Although in comparison with the classical microwave tubes the gyrotrons are characterized by greater volume and weight due to the presence of bulky parts (such as superconducting magnets and massive collectors where the energy of the spent electron beam is dissipated) they are much more compact and can easily be embedded in a sophisticated laboratory equipment (e.g. spectrometers, technological systems, etc.) than other devices with a comparable value of Pf^2 such as free-electron lasers (FELs) and radiation sources based on electron accelerators. All these advantageous features have opened the road to many novel and prospective applications of gyrotrons as radiation sources in a great number of high power THz technologies, advanced spectroscopic techniques, plasma science and materials processing, fusion research as well as in many other scientific and technological fields.

The gyrotron developed at IAP RAS jointly with GYCOM Ltd (Nizhny Novgorod) provides CW radiation with a power from 1W up to 300 kW in the frequency range 0.26-0.52 THz [1,2] and up to 1 MW at frequencies 0.14-0.17 THz [3]. It is important, that power up to 10W needed for spectroscopy applications can be obtained at low voltage about 1.5 kV or low beam current – tens mA.

The experiment on frequency stabilization was carried out using a continuous-wave (CW) gyrotron operating at a frequency of 263 GHz and an output power of up to 1 kW with an electron beam formed by a triode-type magnetron injection gun. The phase lock loop control of anode voltage has been used and the width of the frequency spectrum was decreased to 1 Hz [4], which corresponds $\Delta f / f = 3{*}10^{-12}$ with measurement time of a few seconds. The long-term stability was defined by reference clock ($\delta f / f \sim 10^{-9}$ for quartz clock and up to $\delta f / f \sim 10^{-12}$ for rubidium clock).

It is interesting, that the same scheme can be used for quick power modulation and data transmitting. Experiment was made based on 1kW/0.26THz tube and linear dependence between control (anode) voltage and output frequency was observed. As a result, high quality transmission of sound and pseudo random bit sequence (with a speed up to 1.5Mbit/s) has been obtained [3,5].

The prototype of CW 250GHz/200 kW gyrotron has been successfully developed. The power up to 300 kW in 40 microsecond pulses with efficiency more than 30% was demonstrated [6] with a full accordance with theoretical estimation. The gas discharge experiments, initiated by mentioned microwaves, demonstrate unique plasma parameters. The installation diamond window, needed for CW tests, is in progress.

The gyrotrons with pulsed magnetic fields operating at the fundamental harmonic produce up to 100 kW power level at 0.7 THz [7] and 1 kW at 1 THz frequency [8]. The future rising of operating frequency (especially excitation of high harmonics due to limit of reasonable magnetic field) needs improved methods of mode selection, which can be divided to electron-optical and electro-dynamical ones. The most successful realization of electron-optical methods is a gyrotron with axis-encircling electron beam (see, for example [9]). The paper [9] presents the pulsed third harmonic 1THz tube with a power level several hundred Watts. The CW version of LOG based on the cryomagnet is under tests at the moment.

The second harmonic CW gyrotron with improved mode selection based on double electron beam has been tested [10] jointly with FIR UF (Fukui, Japan). The wide step tuning of frequency by excitation of various modes was demonstrated in the range 0.4-0.75 THz. The stable operation at the frequency 0.76 THz on the second harmonic with power level about few Watts has been obtained, which useful for modern NMR/DNP spectroscopy applications.

The feasibility of a high-power sub-THz gyrotron with smooth wideband frequency tuning suitable for direct measurement of the positronium hyperfine structure is demonstrated numerically using both averaged equations and PIC-code simulations. Analytical estimates show that the frequency tuning through the excitation of axial modes can be achieved in a gyrotron with a short cavity driven by an electron beam with a high current. Simulations [11] and preliminary experiments demonstrates possibility of wide (about 10%) fine frequency tuning. An output power of 0.5-1 kW can be obtained at a frequency of about 0.2 THz within a 10-GHz band, which are the parameters needed for testing of quantum electrodynamics predictions through the spectroscopy of positronium.

The pulsed gyrotrons have been used successfully for initiation of localized gas discharges. Such a plasma is promising for development of both a point source of multi-charged ions and a source of high-energy ultraviolet (extreme ultraviolet EUV or XUV) [12,13]. The gas discharge has been successfully obtained also with 0.26 THz/CW IAP RAS gyrotron mentioned above.

The gyrotron looks as a most promising source for the high-resolution molecular spectroscopy in a gas mixture. A significant improvement of spectrum quality due to power growth in contrast with traditional BWO has allowed observing the theoretically predicted earlier transitions in SO_2 molecule [14]. Sensitivity of a radio-acoustic detector was increased about three orders due to high power. It is important to mention, that during last experimental company we use not only power on fundamental harmonic, but also gyrotron radiation produced due to nonlinear effects at high harmonic simultaneously with the fundamental. Though the generated power at the second and third harmonics is two orders and three orders, respectively, lower than at the first one, such a power level (1-10 W) is significantly higher than in other sources. In this experiment, the SO_2 spectrum line was measured at the frequency range 0.26-0.8 THz.

One more interesting feature of powerful sub-THz radiation is high speed production of pure nanopowders by material evaporation and condensation. The use of a subterahertz gyrotron setup with output frequency of 263 GHz and a nominal power of 1 kW as a radiation source to obtain nanoscale particles of metal oxides by the evaporation-condensation technique is demonstrated. An increase in the substance evaporation rate by more than three times compared with similar experiments using a technological gyrotron setup with a frequency of 24 GHz and a nominal power of 7 kW (the power density on the sample surface was about 13 kW/cm^2) as a radiation source was demonstrated. An increase in the radiation frequency leads to the improvement of the heating efficiency due to an increase of the absorption coefficient and provides a greater power density due to a better focusing of the radiation [15].

Despite the requirement for strong operating magnetic fields, mode competition, high ohmic losses, etc., the THz frequency range has been already achieved both by the pulse and CW gyrodevices. A number of applications rapidly increase with the development of radiation sources.

The basic distinguishing feature of the IAP RAS approach to creating powerful femtosecond laser complexes is the use of optical parametric chirped pulse amplification (OPCPA) instead of conventional laser amplification. The femtosecond laser complex PEARL created at IAP RAS is based on these principles. This complex generate pulses with power up to 0.56 PW. The experience gained in creating PEARL and its principles are currently used for constructing at IAP RAS of the laser complex PEARL-10 with a power over 5 PW. The concept of an exawatt laser system - the XCELS project [16] - has been developed. Appearance of such sources opens up absolutely new horizons for basic research and unique applications. Generation of high-energy, highly collimated bunches of charged particles and creation of secondary sources of powerful X-ray and gamma radiation during the interaction of superintense laser radiation with matter are the most topical problems of modern science. Present-day high-power laser complexes can lay the basis of a new compact technology of particle acceleration and generation of coherent X-ray and gamma radiation. Such technologies have great promise for use in diverse fields of science and engineering. In medicine, high-energy bunches of protons and ions are used for therapy of a variety of cancers. Electron bunches can be used for injection into free-electron lasers.

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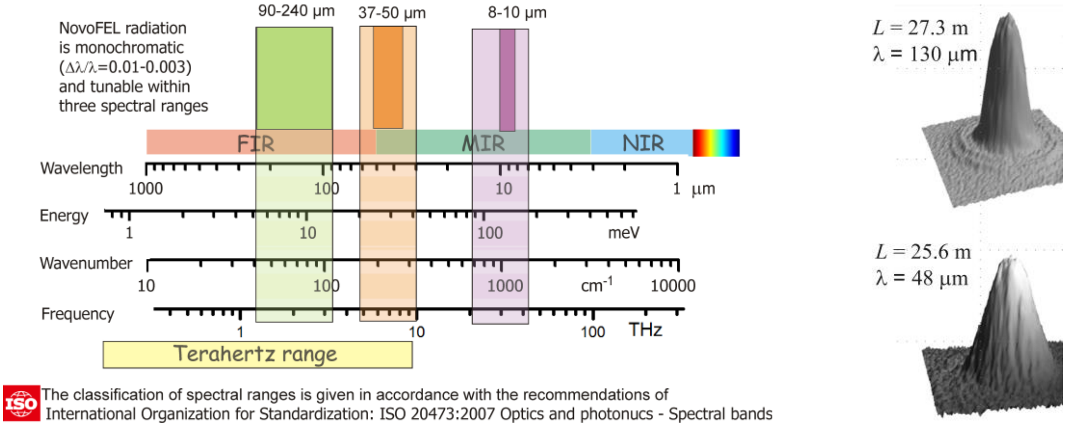
Recent experiments at NovoFEL user stations

B. A. Knyazev[1,2], I. A. Azarov[3], E. N. Chesnokov[4], Yu. Yu. Choporova[1,2],
V. V. Gerasimov[1,2], Ya. I. Gorbachev[1], Ya. V. Getmanov[1,2], B. G. Goldenberg[1],
O. E. Kameshkov[1,2], P. V. Koshlyakov[4], I. A. Kotelnikov[1,2], A. S. Kozlov[4], V. V. Kubarev[1,2],
G. N. Kulipanov[1], S. B. Malyshkin[4], A. K. Nikitin[2,5], P. A. Nikitin[6], N. D. Osintseva[1],
V. S. Pavelyev[1,7], S. E. Peltek[8], A. K. Petrov[4], V. M. Popik[1], T. V. Salikova[1],
M. A. Scheglov[1], S. S. Serednyakov[1], V. N. Shastin[9], O. A. Shevchenko[1], V. A. Shvets[1,2],
D. A. Skorokhod[1], A. N. Skrinsky[1], S. L. Veber[10], N. A. Vinokurov[1,2], V. B. Voloshinov[6],
R. Kh. Zhukavin[9]

[1]Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia,
b.a.knyazev@inp.nsk.su
[2]Novosibirsk State University, Novosibirsk, Russia
[3]Rzhanov Institute of Semiconductor Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia
[4]Voevodsky Institute of Chemical Kinetics and Combustion, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia
[5]Scientific and Technological Center of Unique Instrumentation, Russian Academy of Sciences, Moscow, Russia
[6]Lomonosov Moscow State University, Moscow, Russia
[7]Samara State University, Samara, Russia
[8]Institute of Cytology and Genetics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia
[9]Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
[10]International Tomography Center, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia

The Novosibirsk free-electron laser (NovoFEL) is a source of monochromatic frequency-tunable radiation [1]. This facility belongs to the Siberian Synchrotron and Terahertz Radiation Center, which is open for Russian and foreign users. The NovoFEL consists of three laser oscillators, the supposed generation regions of which cover three regions of the spectrum, shown in Fig. 1 (a) with light rectangles. The spectral ranges of generation currently available to users are marked with darker rectangles. The first laser system of the facility, generating terahertz radiation in the range of 90 – 240 μm, was commissioned in 2003, and most studies performed by users to date relates to this range. Experiments using radiation of 40-50 μm have been started recently. The studies that had been performed at the first six workstations by 2015 are described in the review [2]. Since then, the facility was significantly upgraded, and now 11 workstations, the location of which is shown in Fig. 2, are in operation. Several more stations are under construction. The directions of research conducted at the stations are understandable from their names, but are not limited by them.

The laser beams at the inputs to the user stations are Gaussian beams (Fig. 1(b)). The radiation is an infinite sequence of 30-100 ps pulses with a standard repetition rate of 5.6 MHz and average power of up to 100-200 W. Regimes in which the radiation is coherent are described in [3]. Such parameters enabled the development of several superfast and high-resolution techniques of molecular spectroscopy [4,5], and the high pulse power allowed ignition of a continuous optical discharge in gases at the atmospheric pressure [6].



(a) (b)

Fig. 1. (a) Generation ranges of the Novosibirsk free electron laser; (b) beam shapes at the inputs to workstations (*L* is the distance from the laser oscillator).

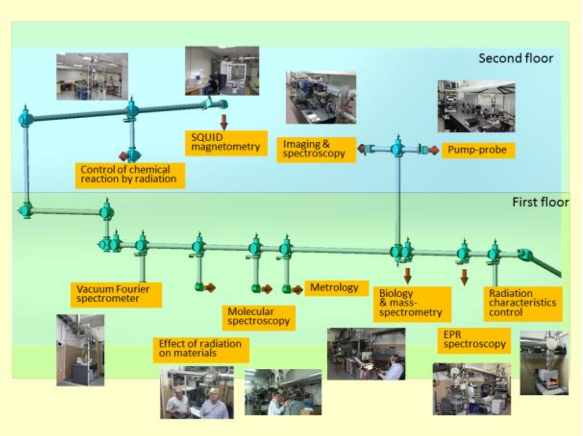


Fig. 2. Beamline (filled with dry nitrogen) and workstations at the Novosibirsk free electron laser facility.

Many applications require transformation of a Gaussian laser beam into beams of different mode structure or concentration of radiation in a predetermined volume or on an area. A number of diffractive optical elements made of diamond or high-resistivity silicon have been designed and fabricated for this purpose [7-8]. In particular, using diffractive optics made it possible to transform the laser radiation into Bessel beams with an orbital angular momentum ("vortex beams") [9-10]. The latter were converted into arrays of vortex beams via their diffraction on a 2D amplitude array of circular openings [11]. Acousto-optical deflection of a terahertz vortex beam was demonstrated in [12], and production of nanosized metal particles by acoustic waves generated in liquids by the NovoFEL pulsed-intermittent radiation was described in [13].

Classical holography with a monochromatic terahertz radiation source was first demonstrated in [14]. The NovoFEL radiation enabled achievement of record resolution for the terahertz range in the internal reflection ellipsometry [15]. Studies of terahertz surface plasmon polaritons on metal-dielectric-air interfaces revealed their particularities in comparison with the visible range plasmons [18-20].

The effect of THz radiation on biological objects, from cells to organisms, is under investigation at the biological station of NovoFEL (see, e. g., [21]). Two new workstations have been commissioned at the facility. A one-color pump-probe setup was applied to research on the relaxation time in semiconductors with shallow donors at cryogenic temperatures [22]. The electron paramagnetic resonance station [23] enables exploration of the influence of high-power THz or mid-IR radiation on spin systems.

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