Novosibirsk ERL-based FEL as User Facility

G. N. Kulipanov, B. A. Knyazev, V. V. Kubarev, V. M. Popik, M. A. Scheglov, O. A. Shevchenko, and N. A. Vinokurov

Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

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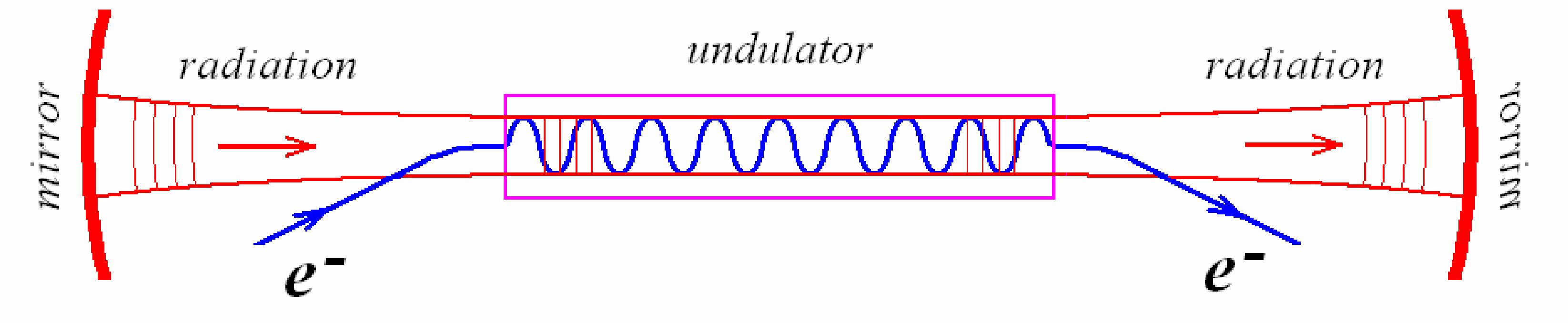
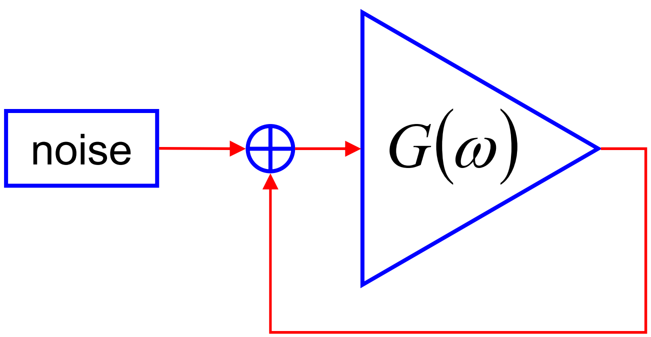
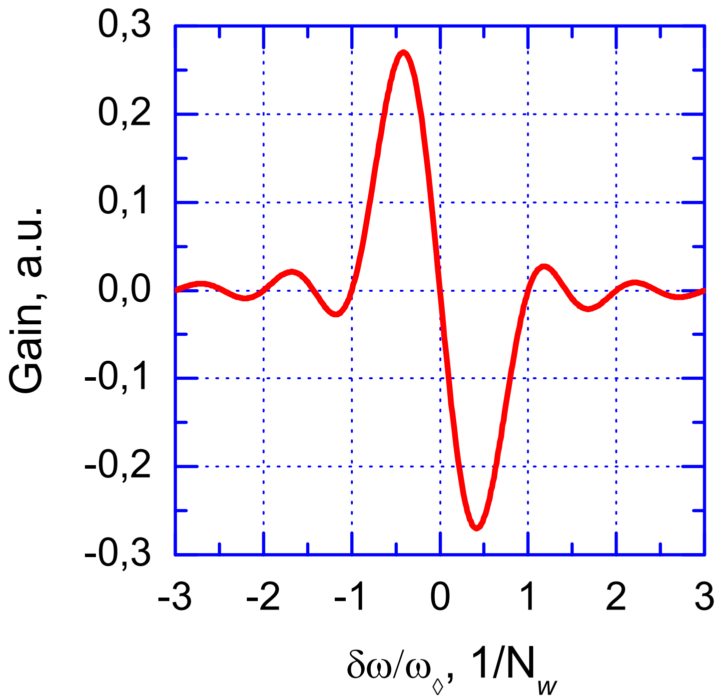
Scheme of the Free Electron Laser oscillator



Equivalent scheme of FEL oscillator

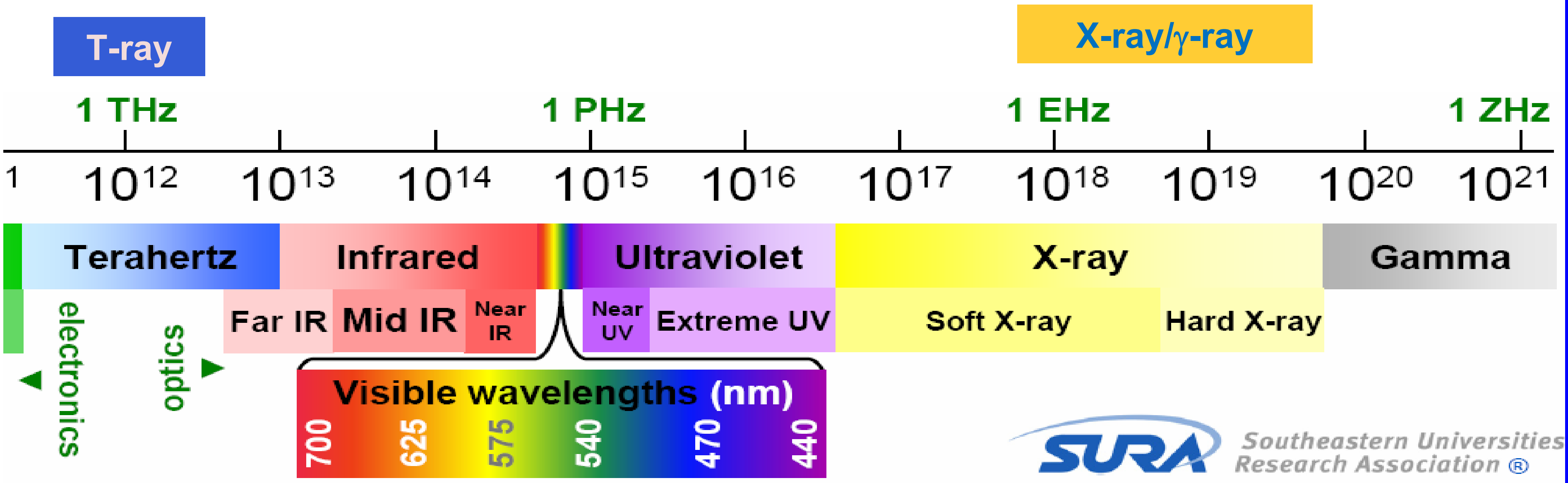




Narrow bandwidth amplifier with feedback

$\delta\omega/\omega$, $2/N_w$ - for optimal Gauss beam

The most attractive ranges for FELs are at very short and at very long wavelength, where there are no other lasers



FEL with ERL

- Electron efficiency of FEL is rather low (~1%), therefore energy recovery is necessary for a high power FEL.
- Energy recovery:

- decreases radiation hazard and

- makes possible operation at high average current.

II. Status of NovoFEL

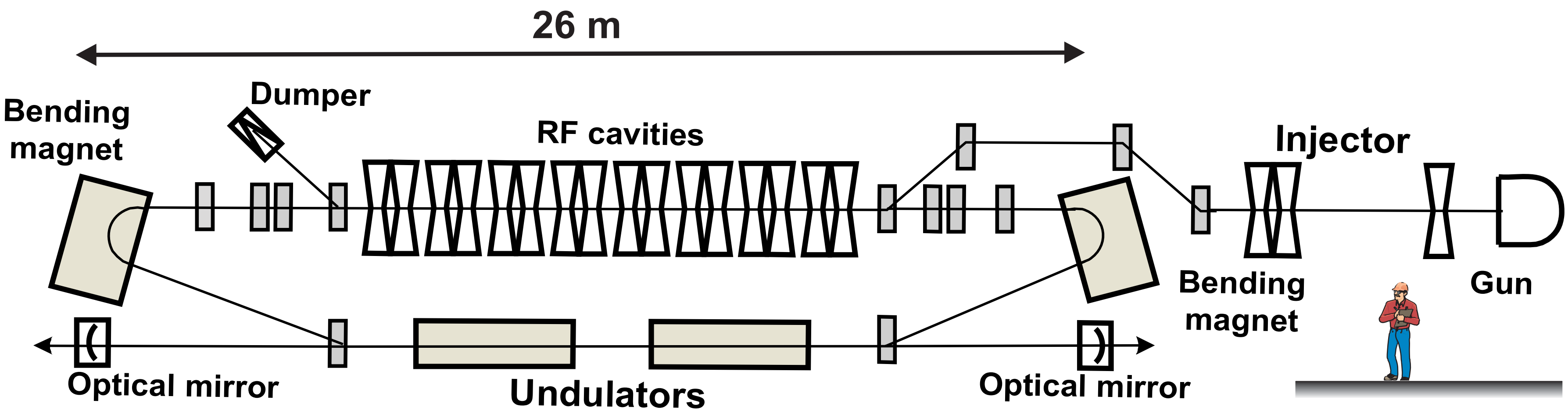
- The first stage of Novosibirsk high power free electron laser (NovoFEL) based on one track energy recovery linac (ERL) working in spectral range (110 – 240) μm was commissioned in 2003.

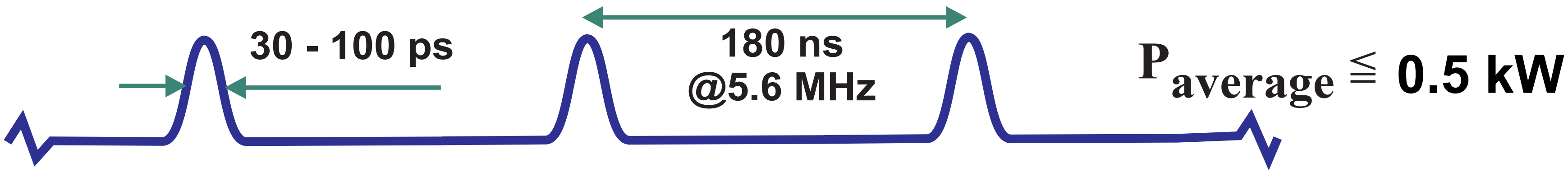
- The second stage of NovoFEL based on two track energy recovery linac, working in spectral range (40 – 80) μm, was commissioned in 2009.

- Creation of powerful FEL based on four-track energy recovery linac with a maximum energy of 40 MeV is close to completion. As result the planned range of wavelength will be between 240 and 5 μm, the expected radiation power varies from 1 kW in the long-wave range up to 10 kW in the short-wave range.

Layout of the Novosibirsk THz FEL (1st stage of NovoFEL)

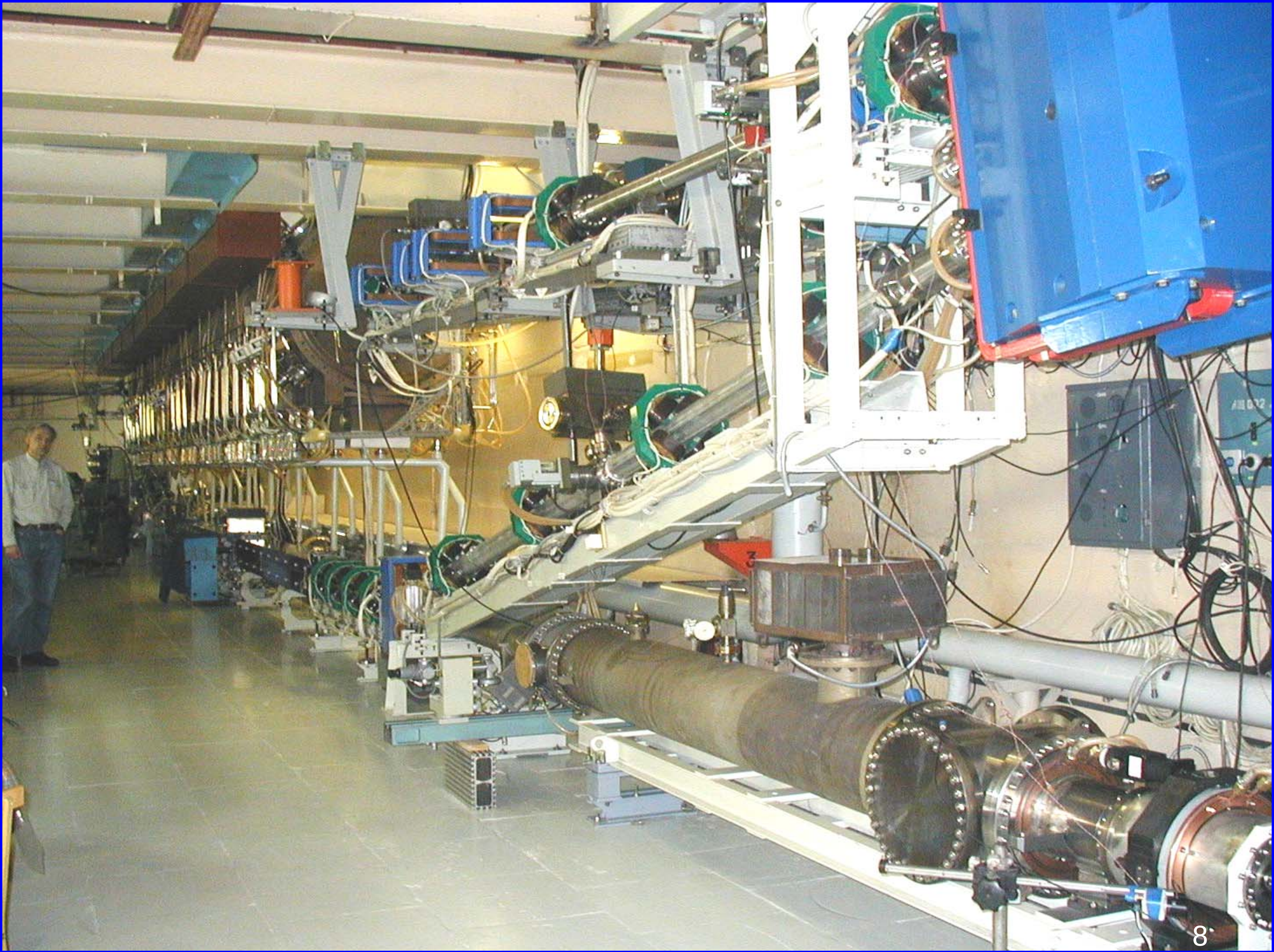
In operation since 2003



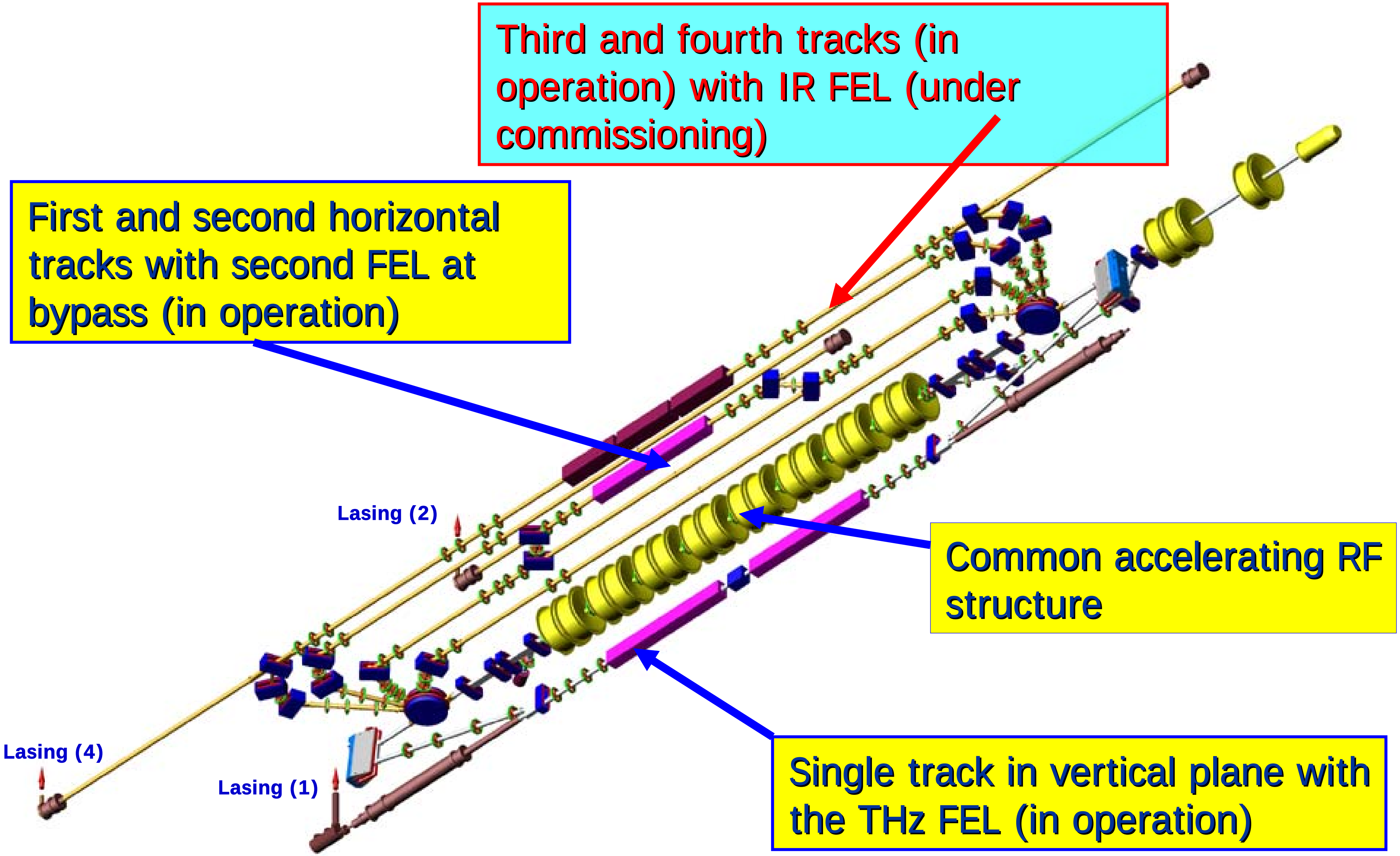


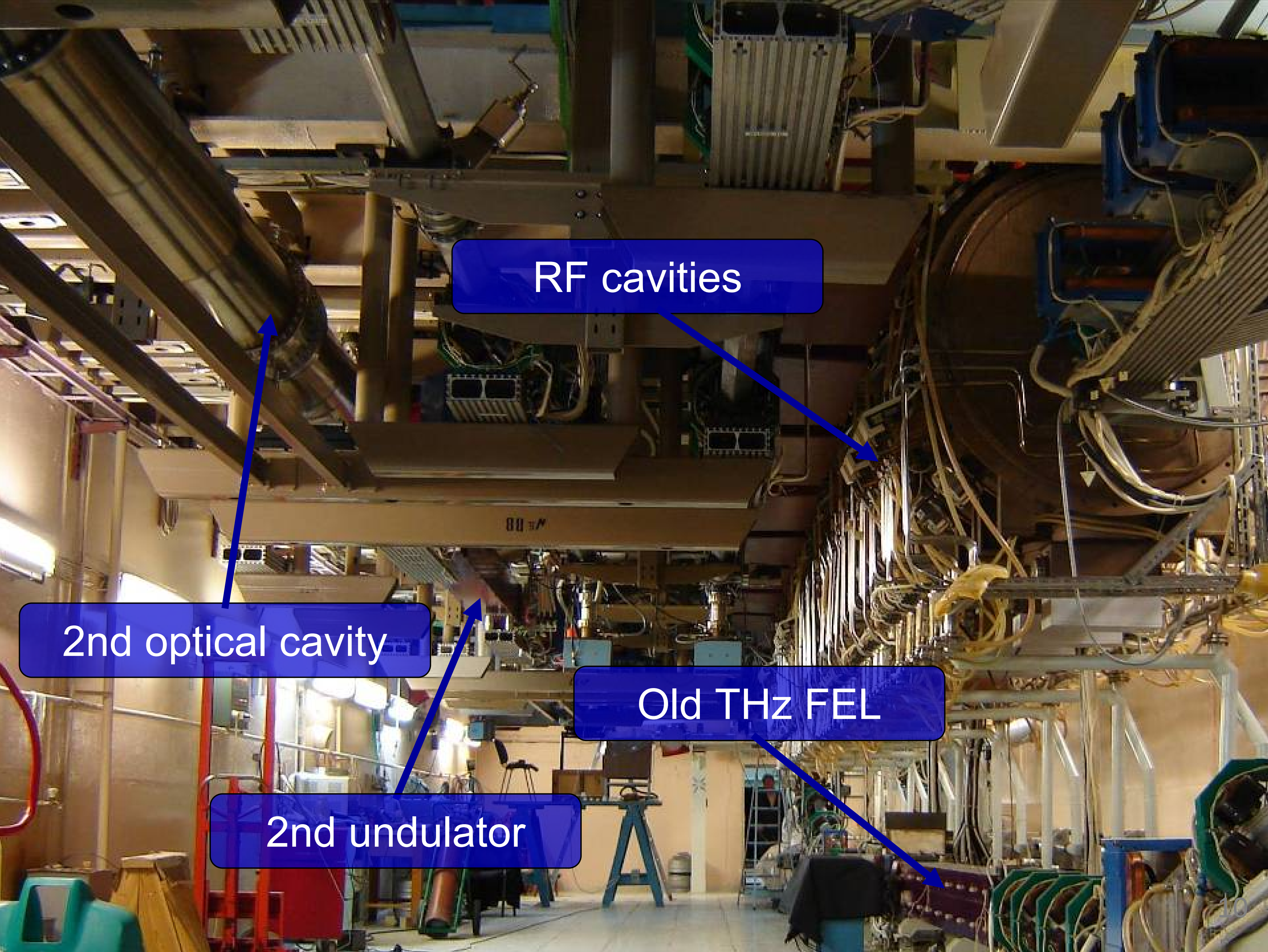
Electron beam from the gun passes through the buncher (a bunching RF cavity), drift section, 2 MeV accelerating cavities, the main accelerating structure and the undulator, where a fraction of its energy is converted to radiation.

After that, the beam returns to the main accelerating structure in a decelerating RF phase, decreases its energy to its injection value (2 MeV) and is absorbed in the beam dump.

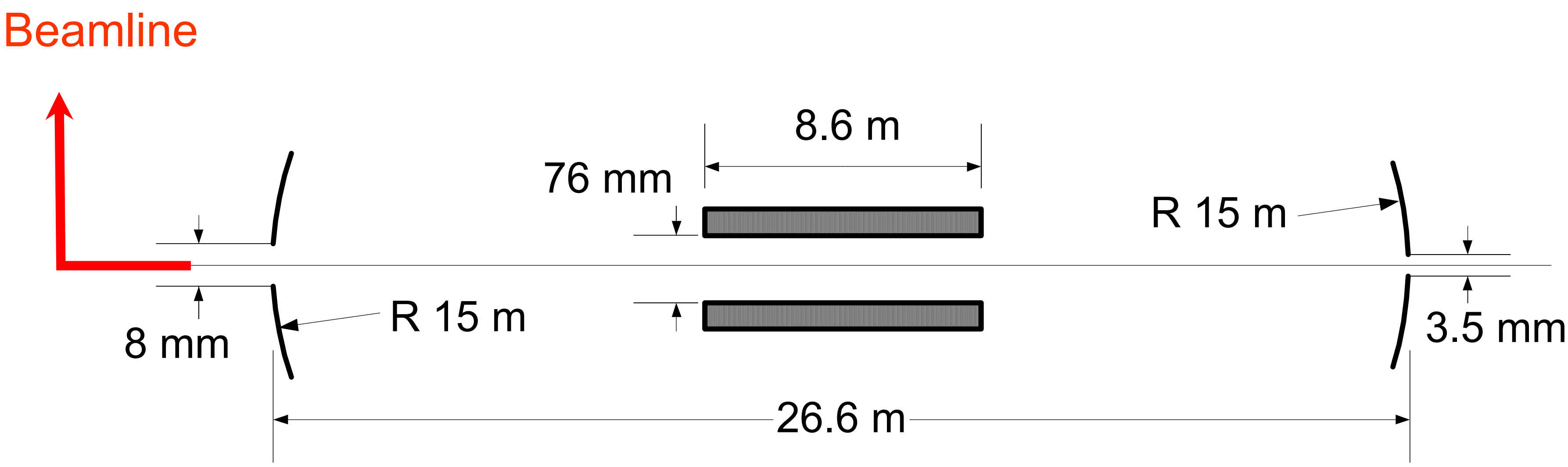


Novosibirsk ERL with 3 FELs (details in the talk of O. A. Shevchenko)




RF cavities
2nd optical cavity
Old THz FEL
2nd undulator

Layout of the optical resonator

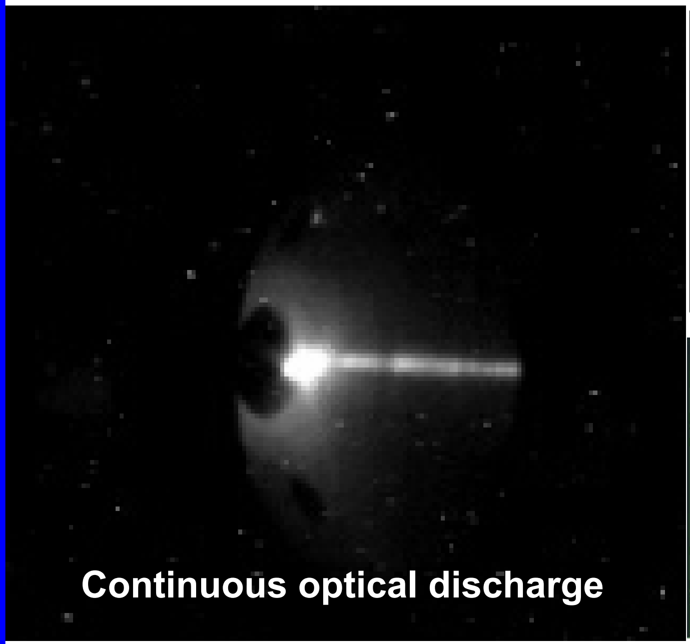


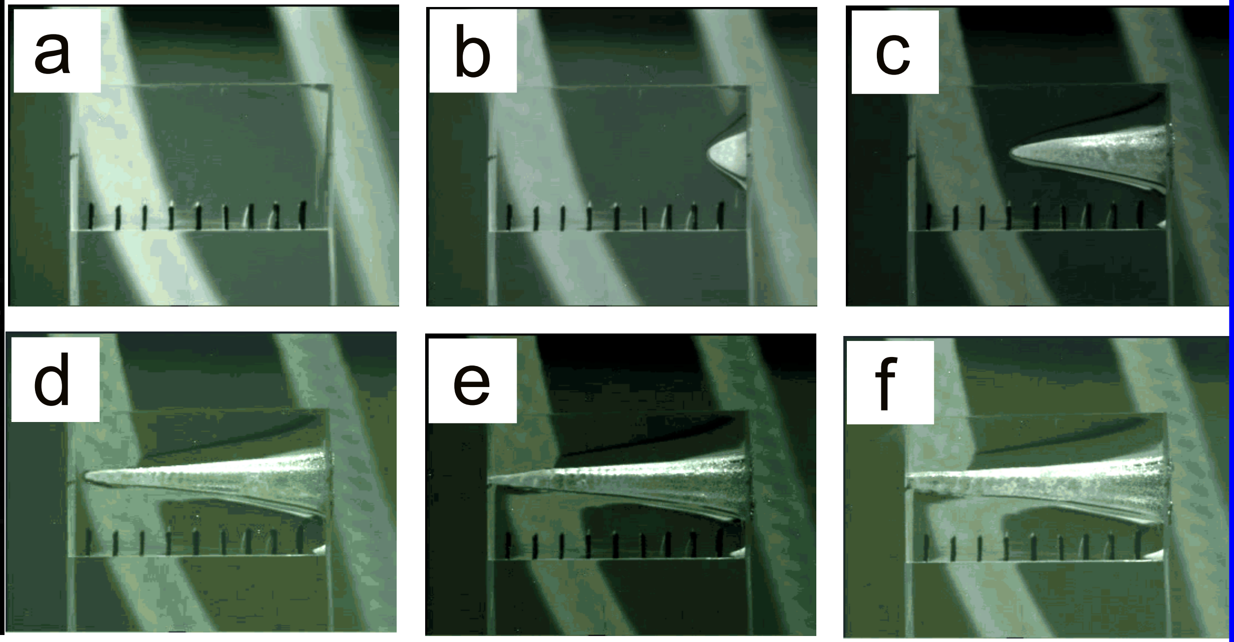
Radiation parameters of the 3 stages of NovoFEL

Stage	1st stage (1 track)	2nd stage (2 tracks)	3rd stage (4 tracks)
Status	In operation since 2003	In operation since 2009	Commissioning
Wavelength, μm	110 - 240	40 - 80	5 - 20
Relative line width (FWHM), %	0.2 – 2.0	0.2 - 1	0.1 - 1
Maximum average power, kW	0.5	0.5 - 1	10
Maximum peak power, MW	0.5	2.0	10
Pulse duration, ps	30 - 120	20 - 40	10 - 20
Pulse repetition rate, MHz	2.8 - 5.6 - 11.2 - 22.4	7.5 - …	3.8 - …
Linear polarization degree, %	> 99.6		

The power and relative line width obtained in the terahertz range (the 1st stage) are record parameters.

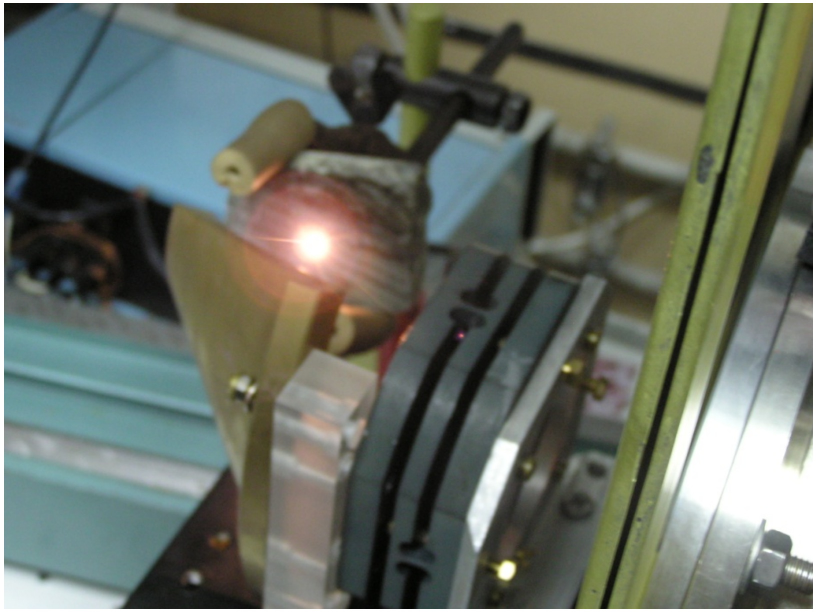
High average power of radiation (up to 500 W) in combination with high peak power (up to 1 MW) enables performing high power density experiments

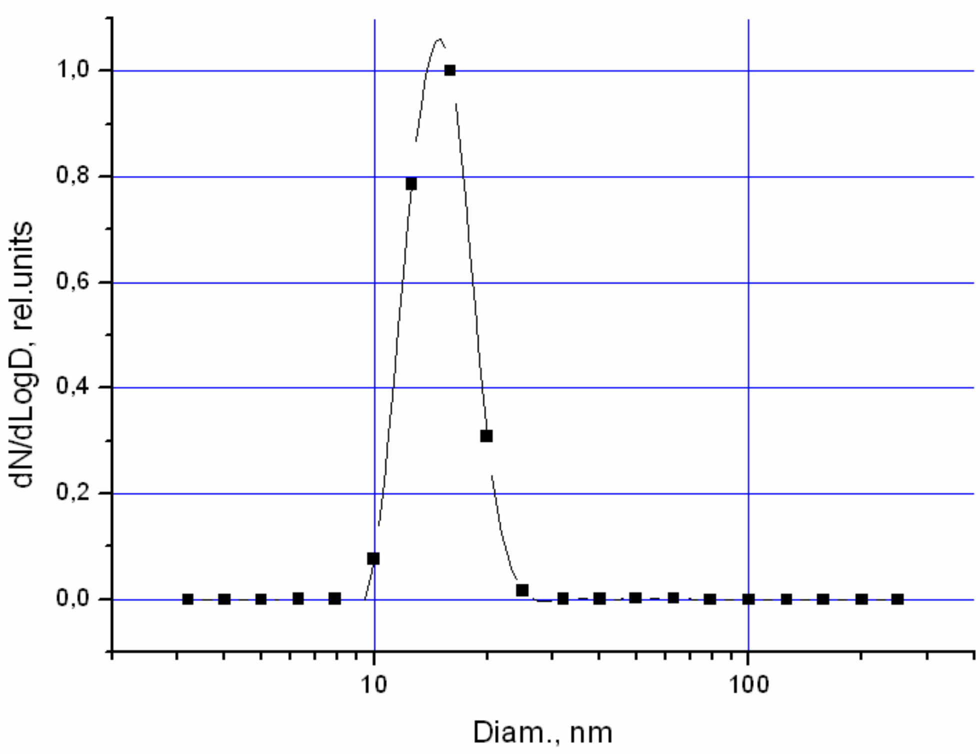




- Laser beam focused in the atmosphere with a parabolic mirror (f=1.0 cm) ignites a continuous optical discharge.
- Unfocused laser beam drills an opening in 50-mm organic glass slab within three minutes (ablation without burning).
- These phenomena can be used for many fundamental and applied experiments (plasma physics, aerodynamics, chemistry, material processing and modification, biology…)

Result of Treatment of Marble with THz radiation (bright light, ablation of nanoparticles)

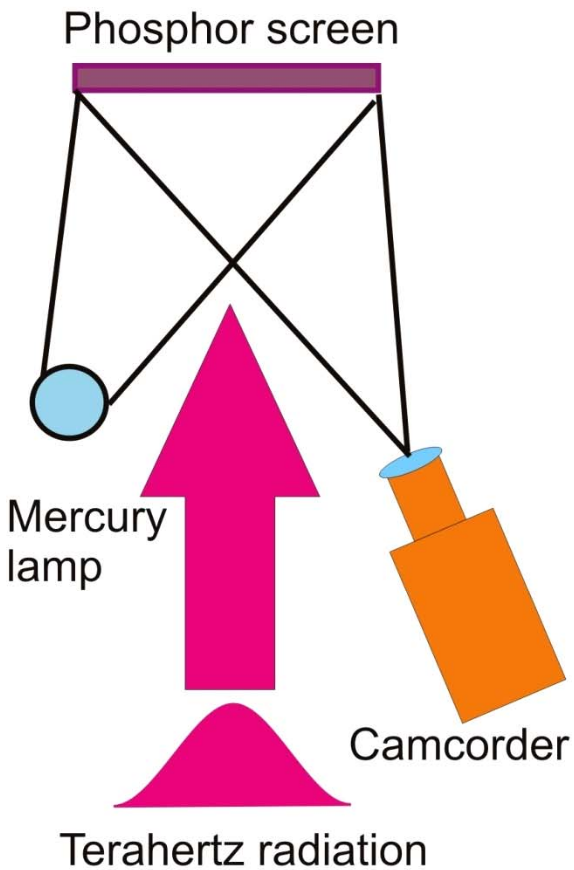


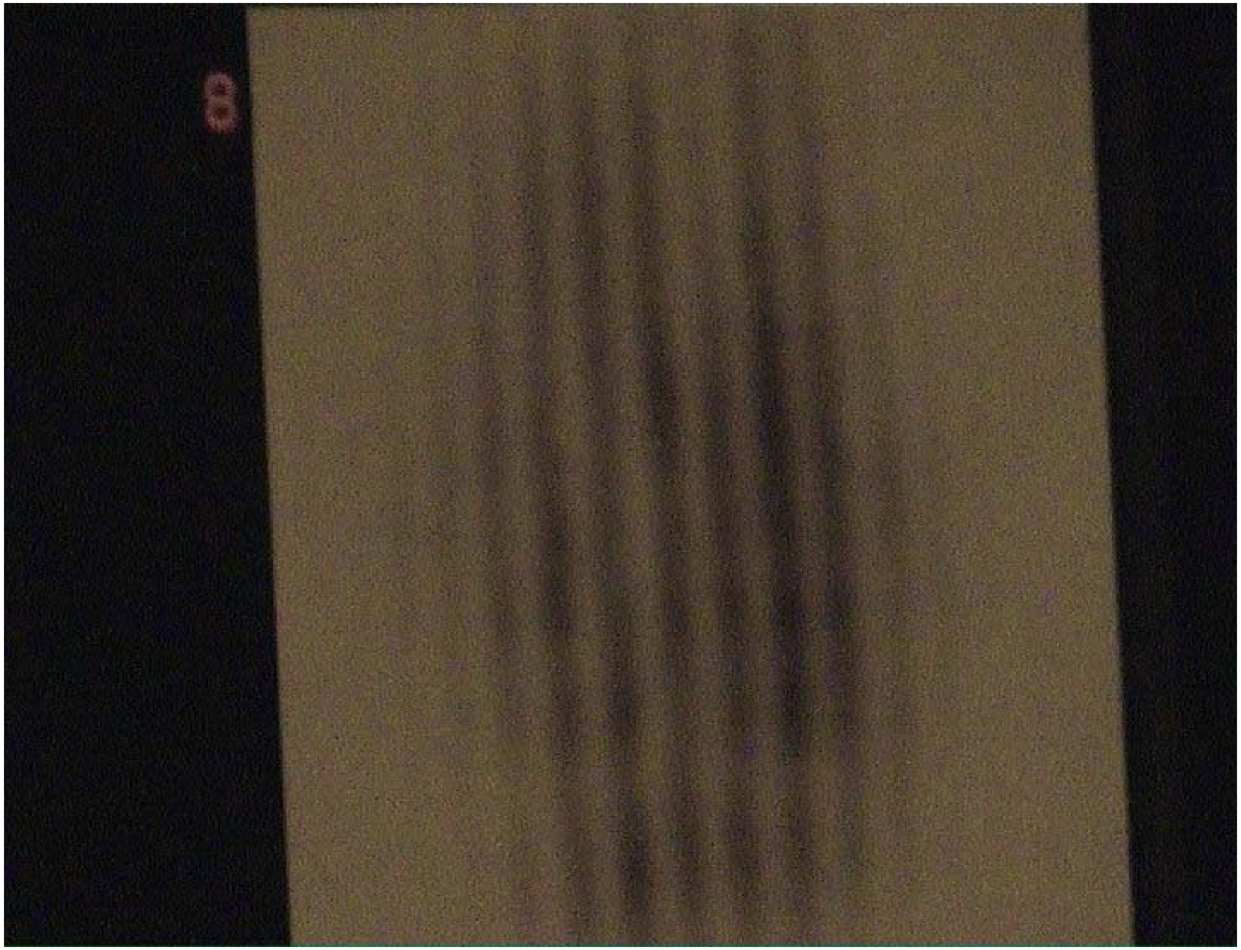


THz imaging with “Thermal Image Plate” (TIP)

Thermal image plate, Mickan Instruments

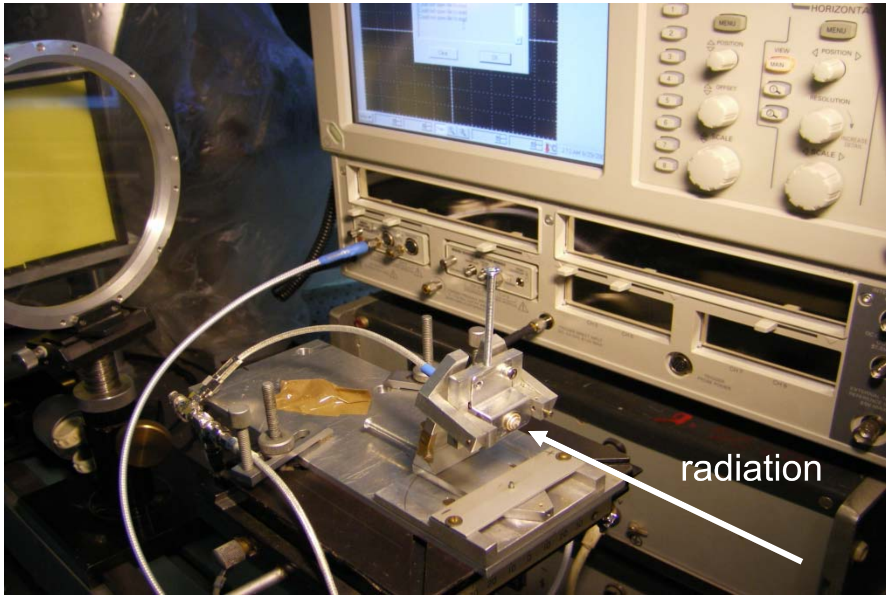
Measurement of the coherence length by Freshel bi-mirror method
Diffraction picture for the mirror displacement Δ = 0

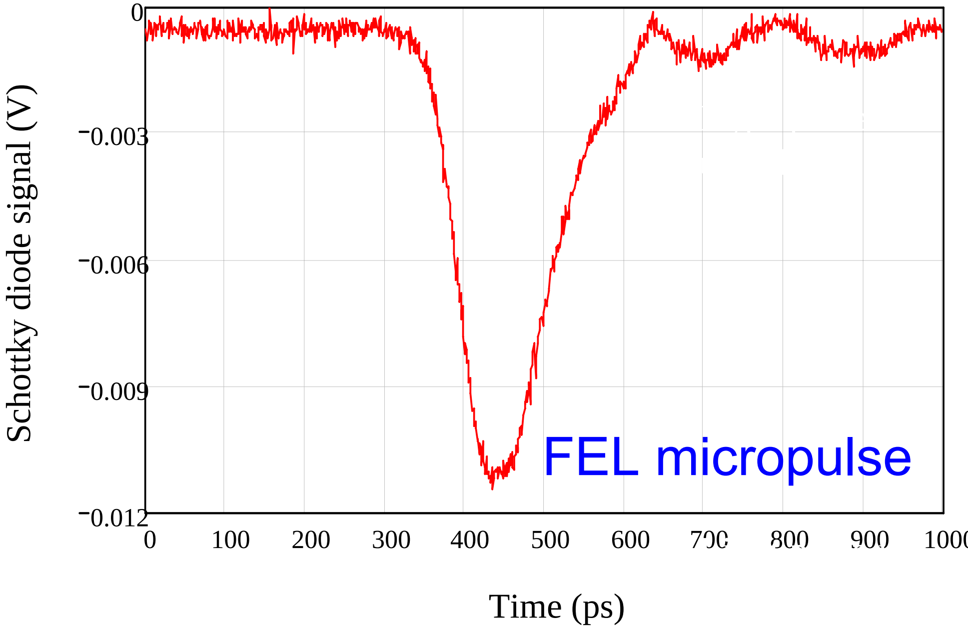




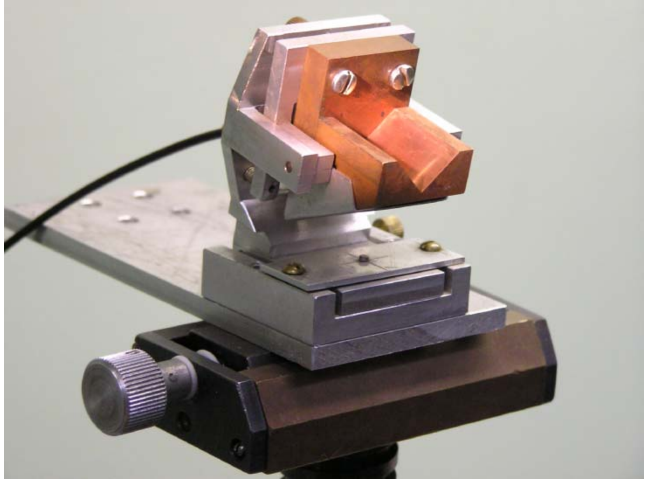
Schottky diode detectors

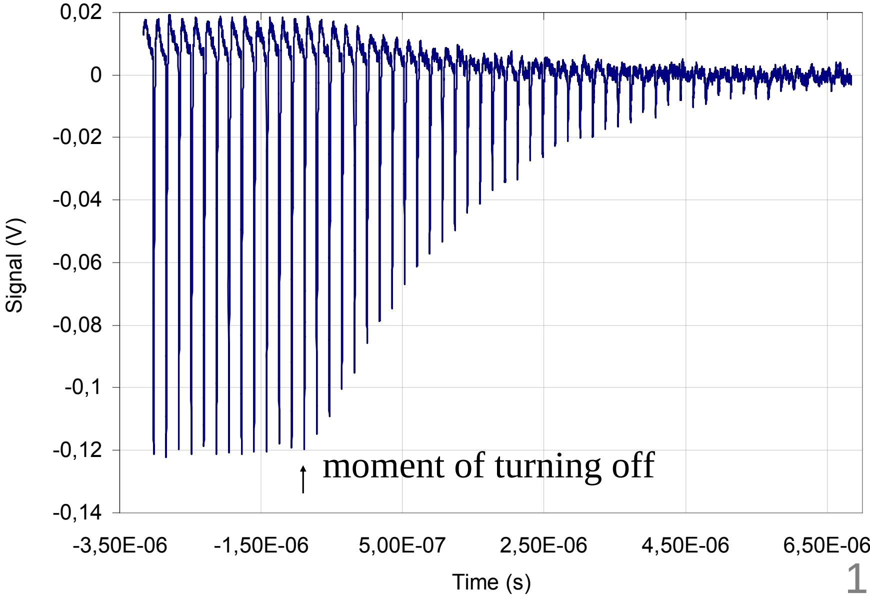
Ultra-fast Schottky diode detector



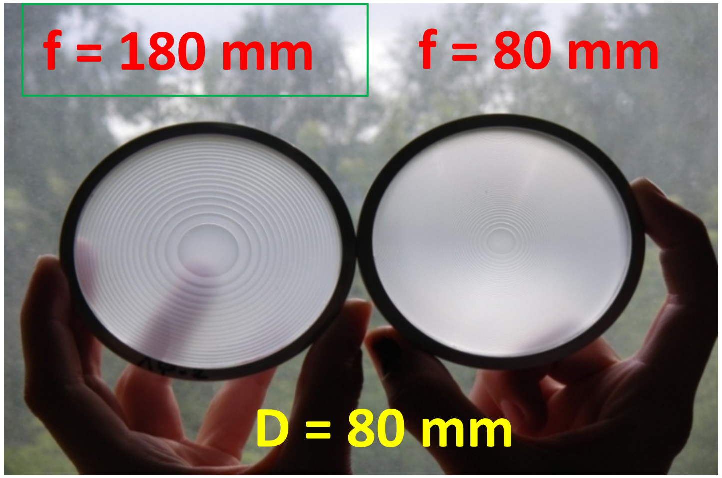


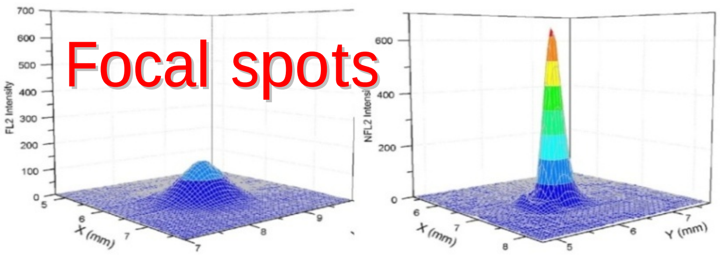
High-sensitive Schottky diode detector





0.8-mm thick polypropylene kinoform lenses (KL)





$d_{1/2}$ = 0.8 mm **$d_{1/2}$ = 0.3 mm**

Technological Design Institute of Scientific Instrument Engineering SB RAS, Novosibirsk

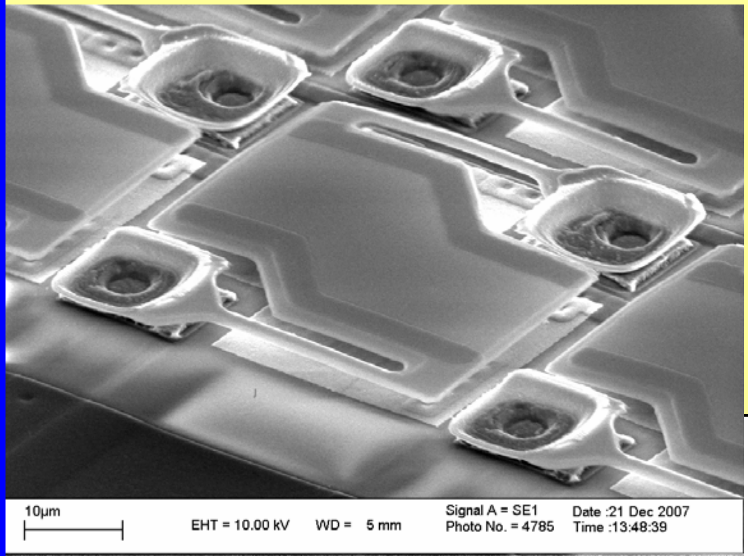
Two samples of microbolometer FPA

320x240 focal plane array with a repetition rate up to 90 fps

M.A. Dem'yanenko, D.G. Esaev, B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov. "Imaging with a 90 frames/s microbolometer focal plane array and high-power terahertz free electron laser". Appl. Phys.Lett., V. 92, 131116, 2008.

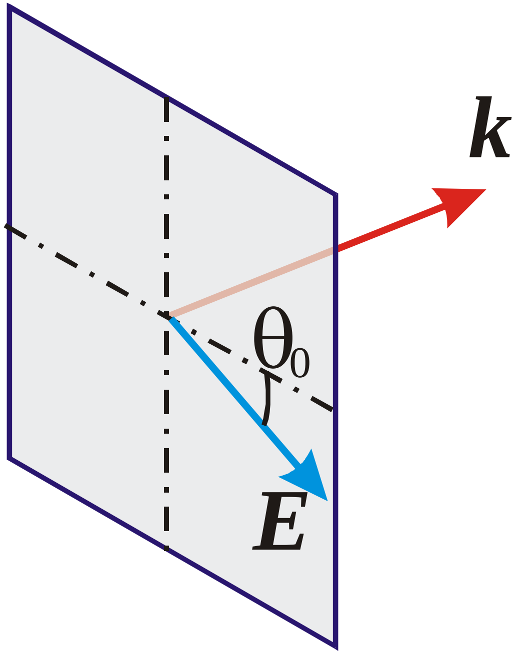
Focal plane array characteristics

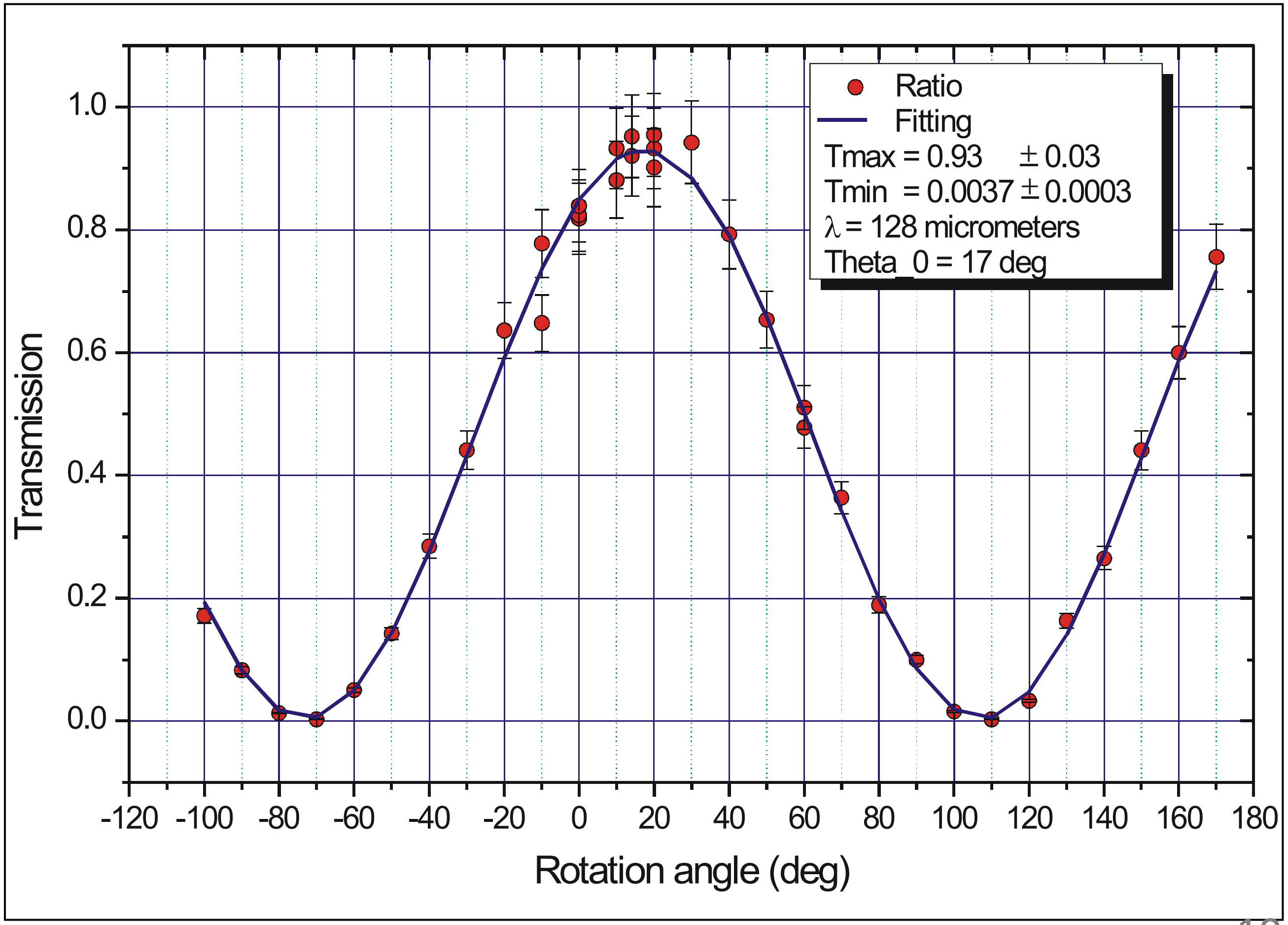
FPA responsivity @ λ = 2.3 THz (V/W)	$S = 1.6 \cdot 10^4$
Sensitivity threshold (W/cm^2)	$P = 1.3 \cdot 10^{-3}$
Optical noise equivalent power ($pW/Hz^{1/2}$)	$\mathrm{NEP} = 200$
Signal-to-noise ratio	$\mathrm{SNR} = 4000$
Frame rate (frames/s)	up to 90
Pixel size (μm)	51×51



Polarizers:

Transmission of the QMC Instruments Ltd polarizer
(metal stripes on the mylar film)
This result was obtained for average power of 25 W
The polarizer was tested for the maximum power density up to 8 W/cm^2

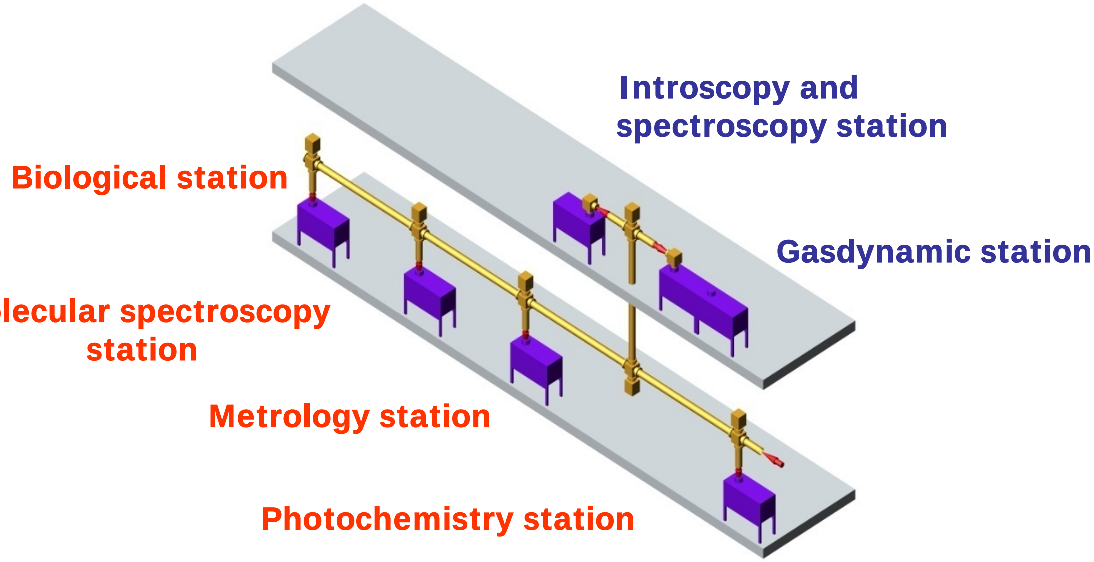




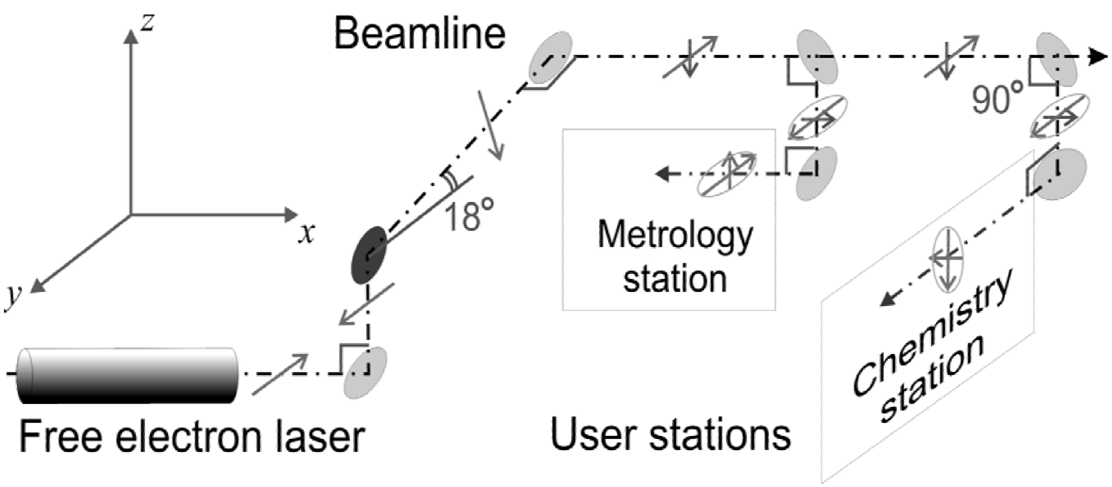
III. NovoFEL as user’s facility

Siberian center of photochemical research based on Novosibirsk high power THz FEL

Laser radiation is transmitted through an optical beam line filled with dry nitrogen to the two experimental halls. Six user stations are now operating.



Scheme of transmission of THz radiation beam to user's stations



User stations at Novosibirsk FEL

Gas dynamics

Introscopy and spectroscopy

Metrology

Biology

Molecular spectroscopy

Why terahertz radiation?

- This is a non-ionizing radiation: the photon energy is ($10^{-1} \div 10^{-3}$) eV;
- The radiation passes well through turbid media and fine materials due to suppression of the Rayleigh scattering ($1/\lambda^4$);
- This is the region of the rotational spectra of molecules, oscillations of biologically important collective modes of DNA and proteins, and oscillations of solid-state plasma;
- Atomic spectra of highly excited Rydberg states lie in the terahertz region;
- This is the area of hydrogen bonds and van der Waals forces of intermolecular interaction;
- The energy of terahertz radiation photon lies in the energy gap of superconductors.

Participating organizations

1. Budker Institute of Nuclear Physics (Novosibirsk)
2. Institute of Chemical Kinetics and Combustion SB RAS (Novosibirsk)
3. Novosibirsk State University (Novosibirsk)
4. Rzhanov Institute of Semiconductor Physics SB RAS (Novosibirsk)
5. Institute of Cytology and Genetics SB RAS (Novosibirsk)
6. Technological Design Institute of Scientific Instrument Engineering SB RAS (Novosibirsk)
7. Lavrentyev Institute of Hydrodynamics SB RAS (Novosibirsk)
8. Scientific and Technological Center of Unique Instrumentation of RAS (Moscow)
9. Khristianovich Institute of Theoretical and Applied Mechanics SB RAS (Novosibirsk)
10. Nikolaev Institute of Inorganic Chemistry (Novosibirsk)

Participating organizations

11. Novosibirsk State Technical University
12. Moscow State University
13. Korean atomic energy research Institute (Daejeon, Korea)
14. Terawave Institute (Daejeon, Korea)
15. Vieworks Co. Etd (Gyeonggi-do, Korea)
16. Boreskov Institute of Catalysis (Novosibirsk)
17. Limnological Institute SB RAS (Irkutsk)
18. Institute of Solid State Chemistry and Mechanochemistry (Novosibirsk)
19. Patrice Lumumba Peoples' Friendship University (Moscow)
20. Institute of Atmospheric Optics (Tomsk).

The themes of works using NovoFEL THz radiation in 2012-2013:

1. Using THz ablation for study fractional composition of vaccines and for measurement of molecular weight of synthetic polymers

2. Study of the spectrum of electronic states in Si / CaF_2 BaF_2 / PbSnTe:In nanoheterostructures.

3. Investigation into the interaction of THz radiation with new functional resonant metamaterials for devices controlling the polarization, phase, intensity and direction of propagation of radiation.

4. Investigation into the interaction of THz radiation with materials based on carbon nanotubes.

5. Production of carbon nanostructures with the help of NovoFEL radiation.

6. Spectroscopy of attenuation total reflection (ATR) and plasmon spectroscopy of surfaces and films.

The themes of works using NovoFEL THz radiation in 2011-2012:

11.Development of tomography, holography and metrology using a source of coherent monochromatic THz radiation.

12. Development of methods for flame diagnostics using the THz FEL.

13. Study of the impact of THz radiation on genetic material.

14. Exploration of the impact of THz radiation on stress-sensitive biological cell systems.

15. THz radiation influence of the katG and E.coli dps genes.

16. Study of the integrated proteomic response of E.coli to exposure by terahertz radiation.

17. Ellipsometric measurements in THz region.

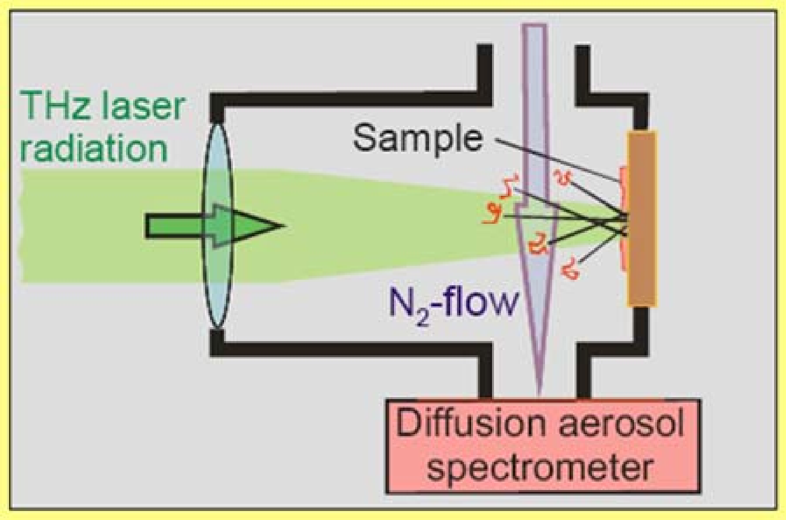
19. Investigation of H_2-O_2 combustion using THz radiation tuning over H_2O absorbtion lines.

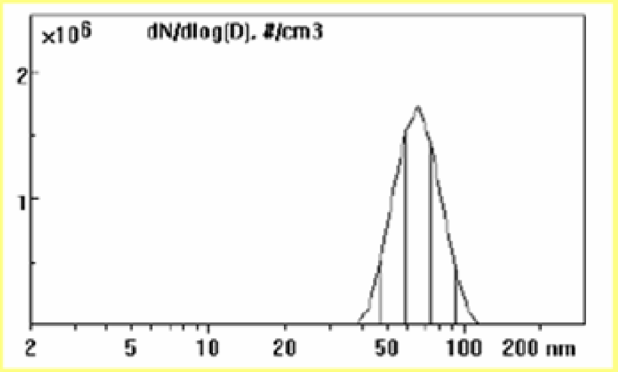
The themes of works using NovoFEL THz radiation in 2011-2012:

22. Investigation of the explosion and detonation in gas mixtures.
23. Measurements of the concentration of H_2O vapor in flames.
24. Ultrafast high-resolution THz time-domain spectroscopy.
25. Demonstration of imaging and detection of concealed objects.
26. Speckle photography and speckle interferometry.
27. Talbot metrology.
28. Experimental study of photoeffect for noble gas atoms in strong terahertz field.

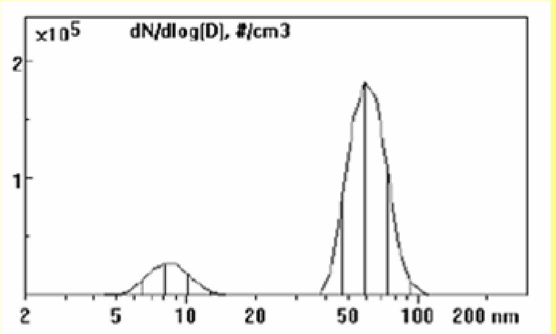
IV. Examples of experiments using NovoFEL THz radiation

Ultra-soft laser ablation of DNA (2005, ICK&C and BINP)





Phage DNA



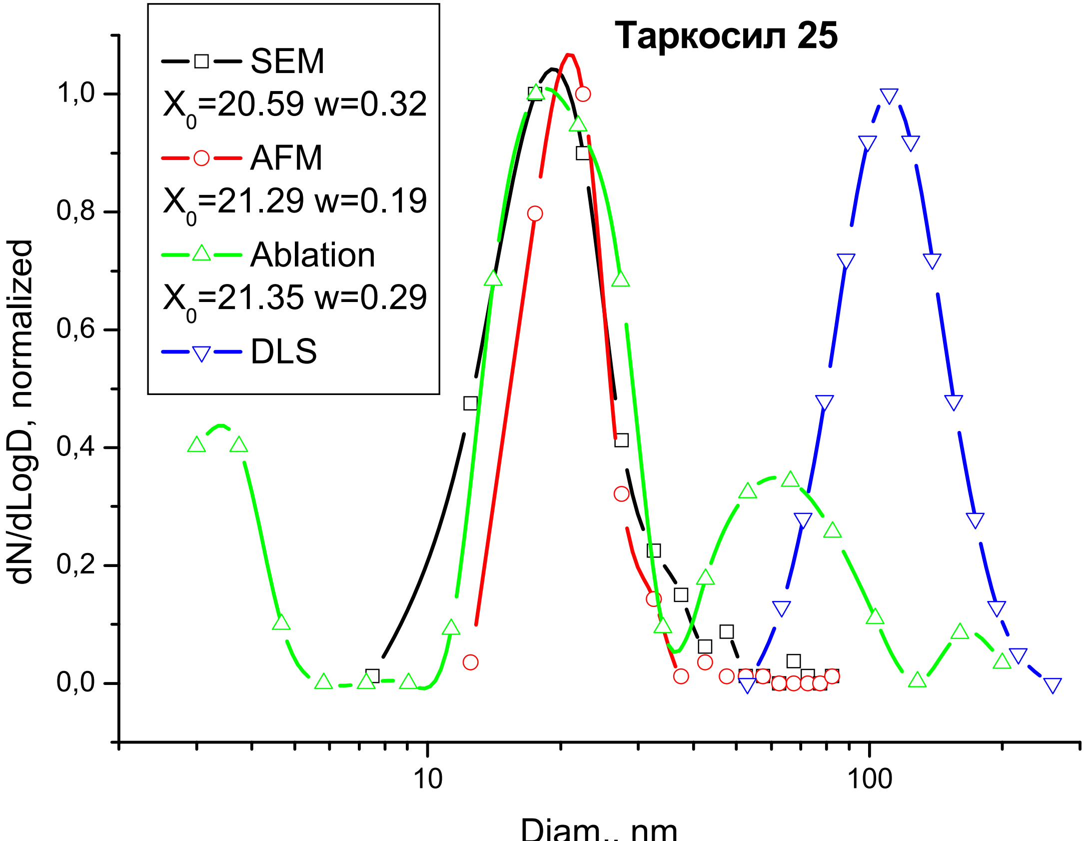
Phage DNA + plasmide DNA

Demonstration of ultra-soft ablation of DNA samples without defragmentation: when the power density of THz radiation is optimal, particle size spectra contain only the peaks corresponding to the initial particles.

Effect of soft ablation of biological macromolecules was discovered in our Center. It consists in transfer of molecules and clusters into aerosol phase under the influence of FEL radiation. Thus pure substances form a single fraction of particles, binary and ternary mixtures - two and three, respectively. Decomposition of molecules into smaller fragments of different size is not observed. Chemical structure and biological activity of the initial samples is not changed. Measurements are carried out by means of aerosol spectrometer, which detects macromolecule, as aerosol nanoparticles.

A.K. Petrov, A.C. Kozlov et al. Doklady Academii Nauk. – 2005. - T.404, №5. - C.698-700.

THz FEL ablation: measurement of fractional composition of artificial silica nanopowder



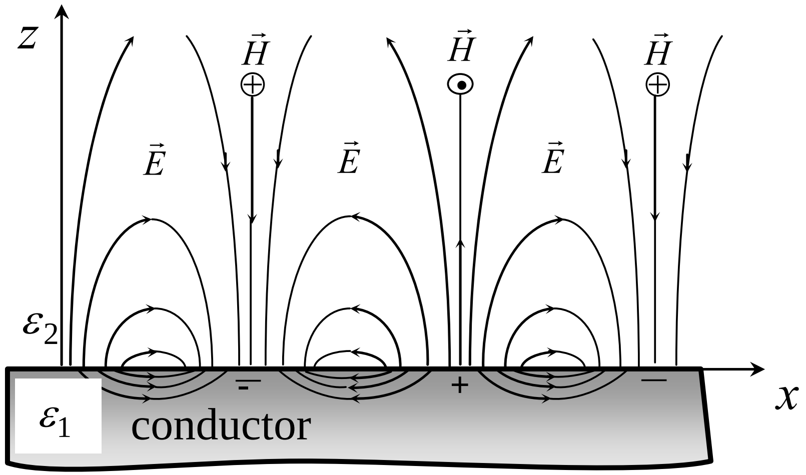
The slide presents an example of size distributions for silica nanopowder produced in BINP. Soft ablation demonstrates the excellent agreement for main fraction of particles and aggregates and confidently registers a difficult fraction of 3-5 nm. It should be noted that the method of soft ablation do not require complex and time-consuming steps of sample preparation and analysis. Single measurement takes 4 minutes.

Kozlov A.S., Petrov A.K., Kulipanov G.N. et al, KONA Powder and Particle Journal. 2010. No.28, P.219

Study of surface plasmons using THz radiation (MSU and BINP)

Surface plasmon (SP) is a combination of TM evanescent EM wave and a wave of free charges, propagating along the conductor-dielectric interface

A snapshot of SP field distribution



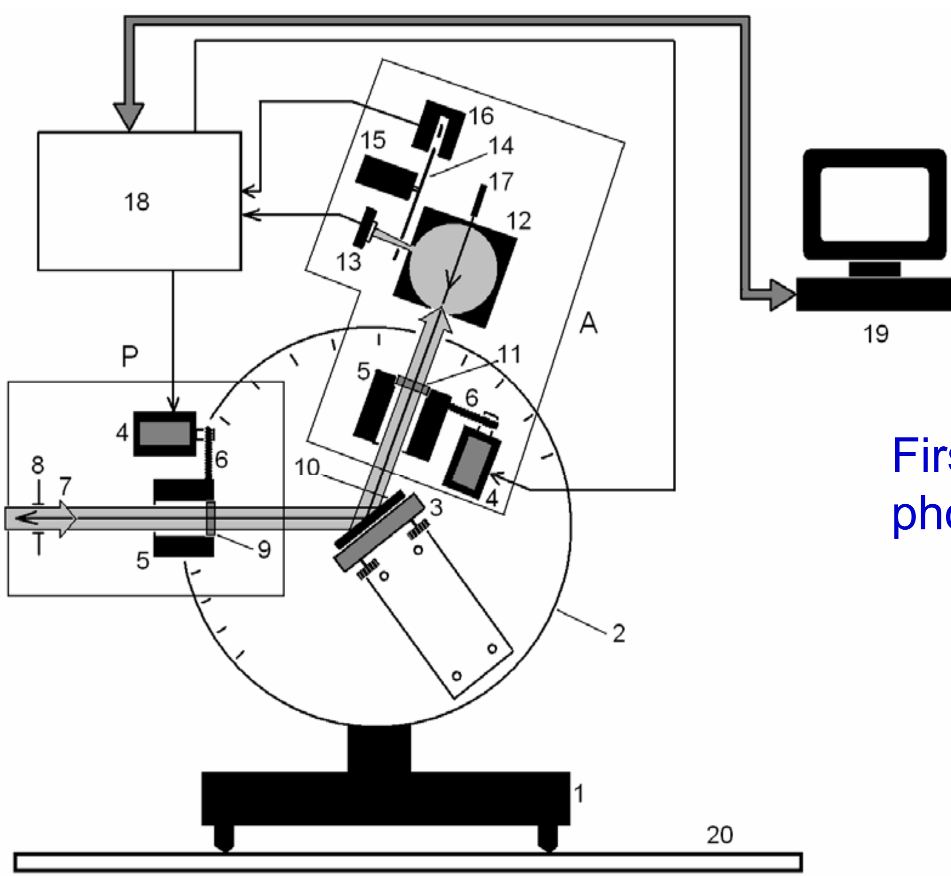
In the THz range SPs were examined using the time-domain spectroscopy technique with wideband THz source. Experimental results obtained by different authors were rather contradictory!

Using monochromatic radiation of NovoFEL, surface plasmons were studied on plane and curved metal-dielectric interfaces

Potential applications of SPs in the THz spectral region:

- investigation of conducting surfaces
- spectroscopy of thin layers on metal surfaces

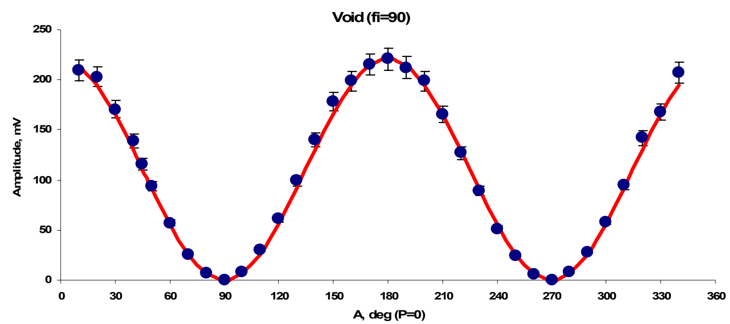
Ellipsometer in the THz region (TDISIE and BINP)



Ellipsometry measures the complex reflectance ratio, ρ, of a system, which may be parametrized by the amplitude component Ψ and the phase difference Δ .

$$\rho = \frac{r_p}{r_s} \qquad \rho = \tan(\Psi)e^{i\Delta}$$

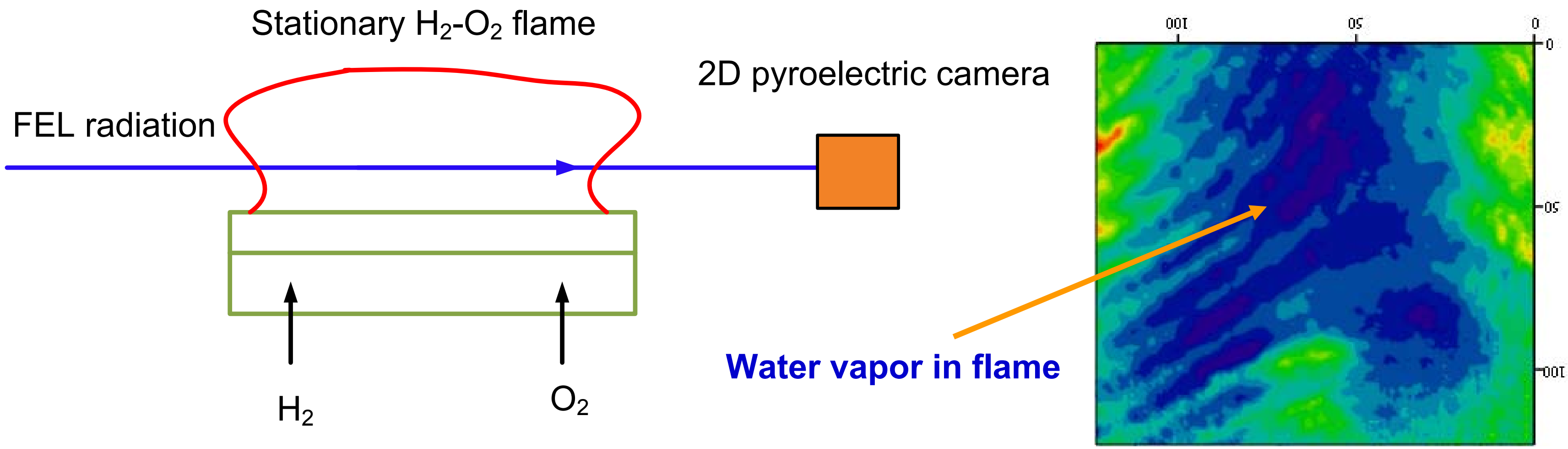
First experiments identified an accuracy of photometric measurements of about 5%.

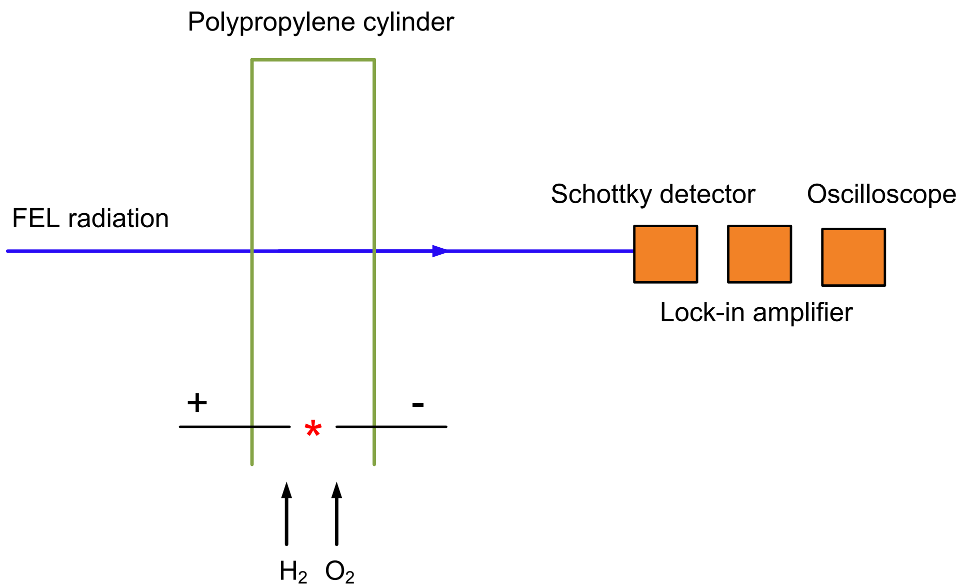


1-support, 2-goniometric circle with 5-degree discretisation of the incidence angle, 3-objective stage, 4-stepper motors, 5-polarizer arbor, 6-worm-gear,
7-FEL beam, 8-entrance aperture, 9-polarizer, 10-measured sample,
11-analyzer, 12-spherical depolarizer, 13-pyroelectric detector, 14-chopper,
15-gearmotor, 16-optocoupler, 17-red set-up laser, 18-electrical controller, 19-computer, 20-base plate.

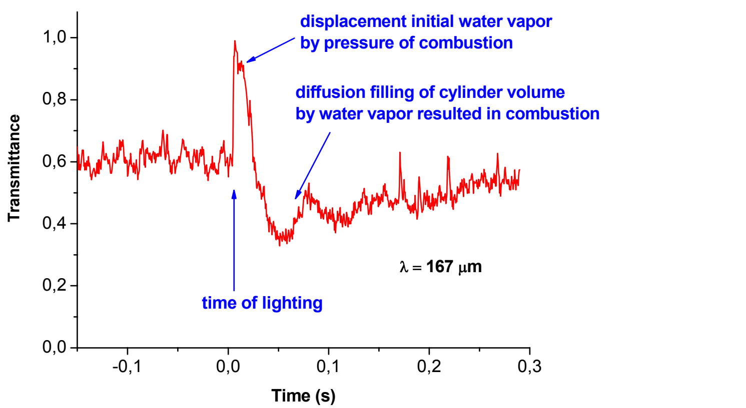
TERA-2012, Poster:. Azarov, V. Shvets, Y. Choporova et al. "Ellipsometric measurements system using THz NovoFEL"

Investigation of H_2 - O_2 combustion by THz NovoFEL radiation tuned on H_2O absorbing lines (ICK&C and BINP)



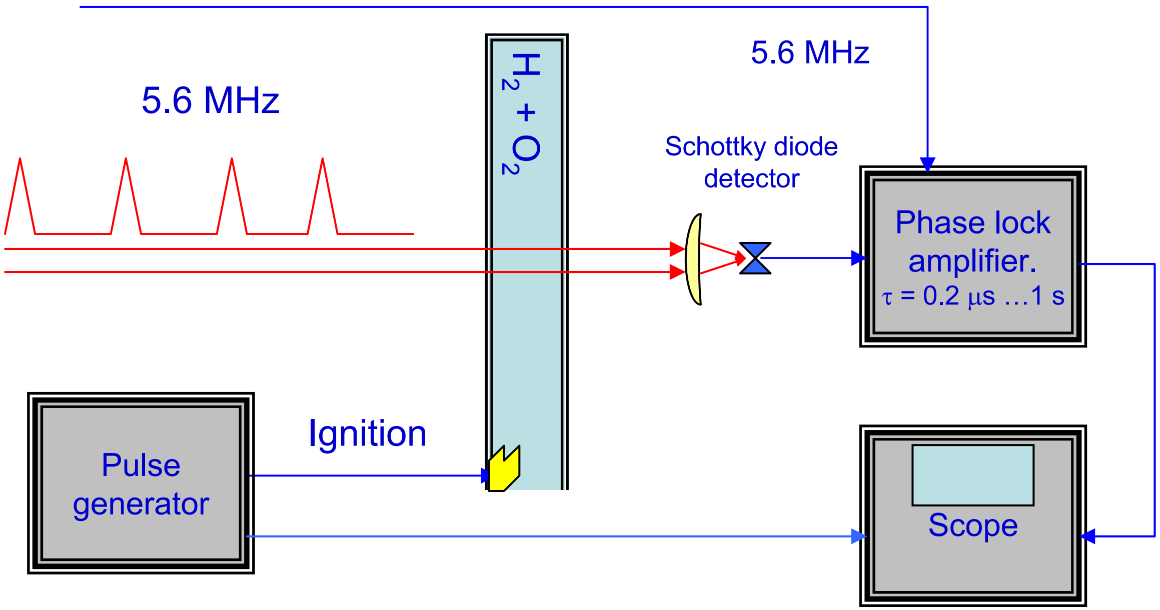


Combustion H_2- O_2 mixer in ∅40×200 mm polypropylene cylinder

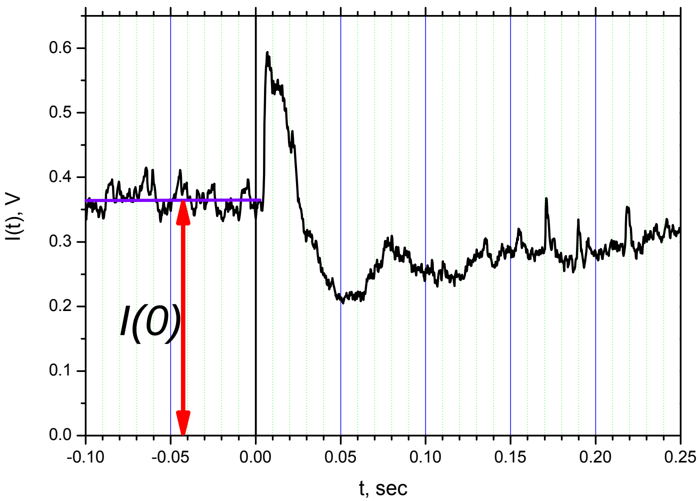


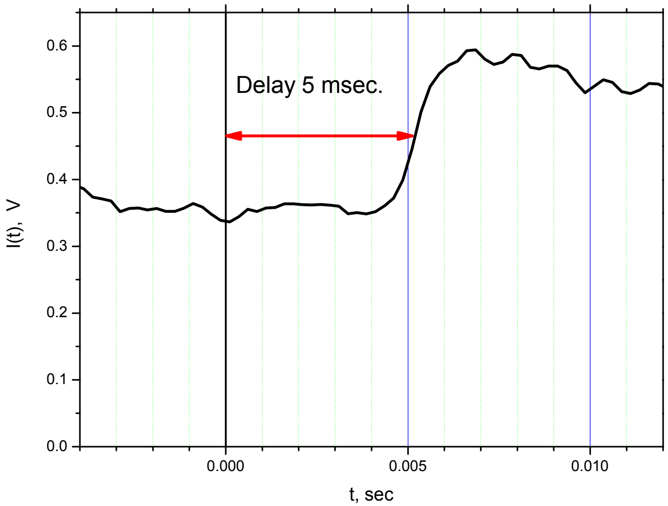
V. Kubarev, E. Chesnokov et al. (Budker INP, ICKC, LIG)

Investigation of the explosion and detonation in gas mixtures



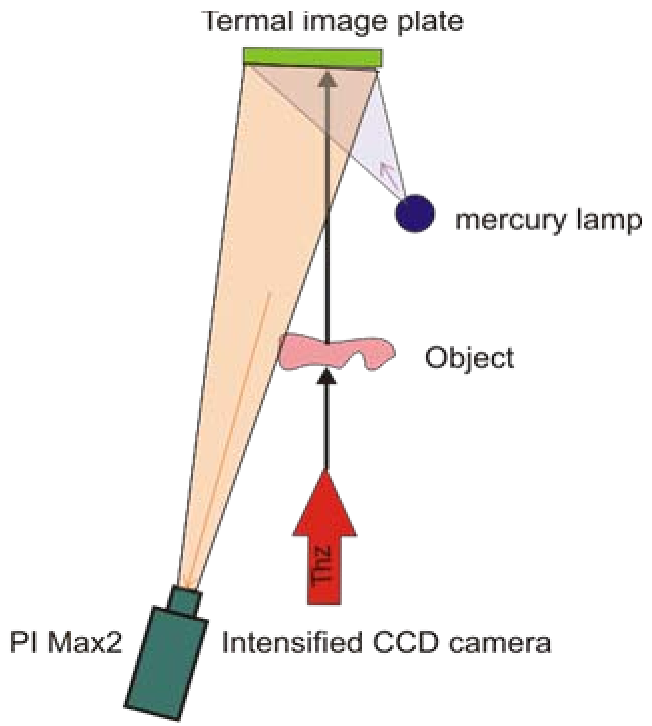
Signal at 167 µm. H_2O absorption line $6_{24} \leftarrow 6_{15}$





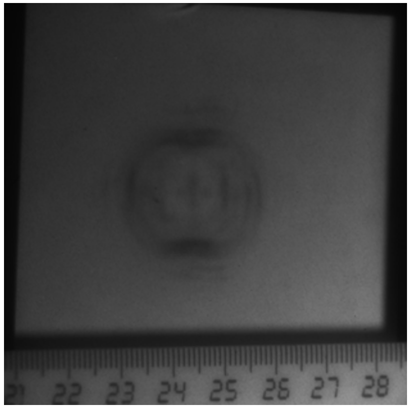
publ: V. Kubarev, E. Chesnokov et al. (Budker INP, ICKC, LIG) to be published in Vestnik NSU

In-line (Gabor) holography in the THz region

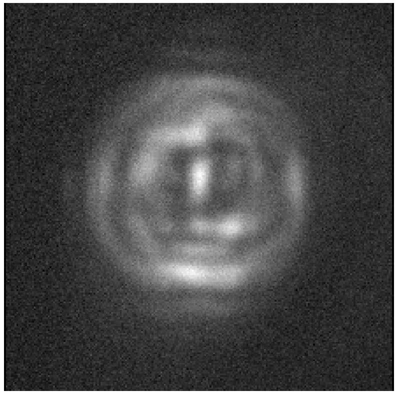


Experiments have been performed using classical scheme in line (Gabor) holography.
Holograms were recorded using temperature sensitive phosphor image plate with a CCD camera and then numerically reconstructed by calculation the Fresnel-Kirchhoff integral in the real image plane.

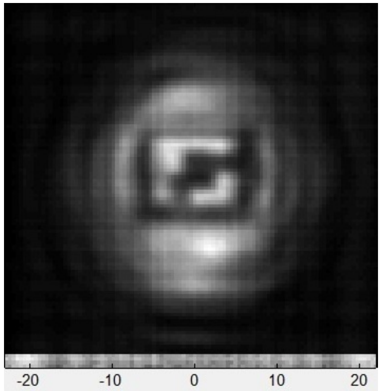
Photo from the CCD



Digital hologram



Reconstructed image



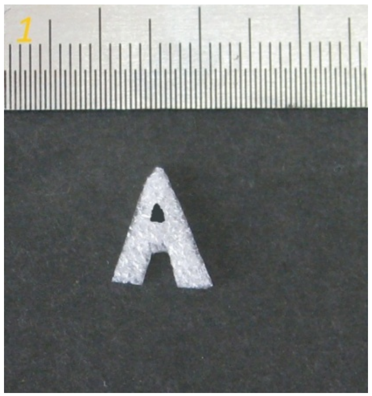
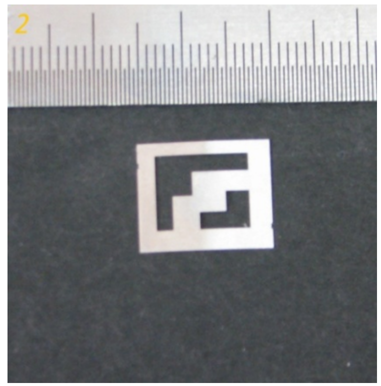
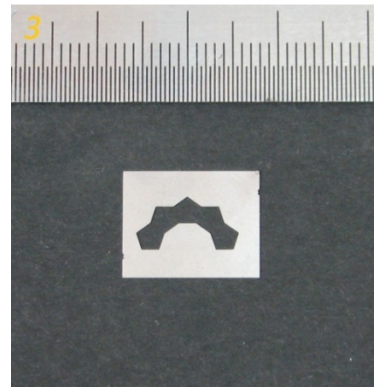
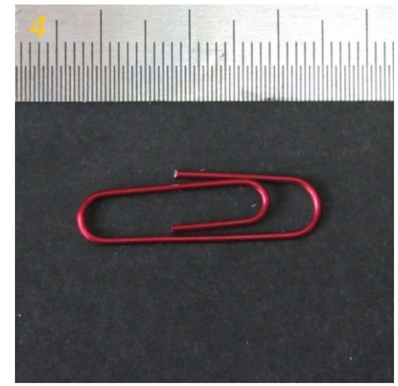
In-line (Gabor) holography in the THz region

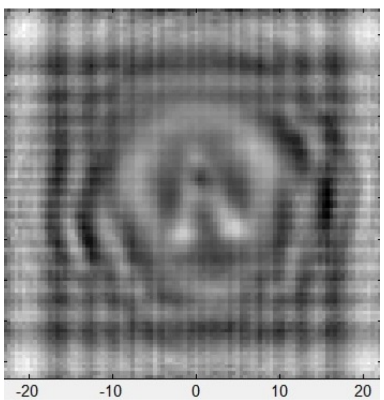
Both the amplitude and phase information of the object can be reconstructed from hologram. The spatial resolution was achieved to be about 0.4 mm at a radiation wavelength of 0.13 mm.

shaped foam polyethylene

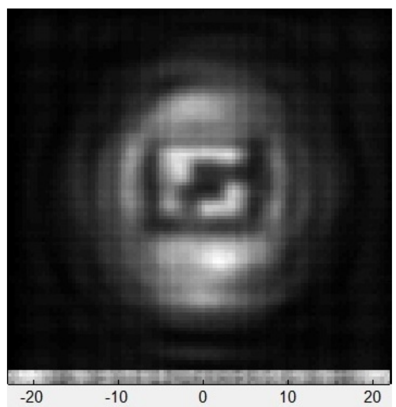
Metal masks, d=100 мкм

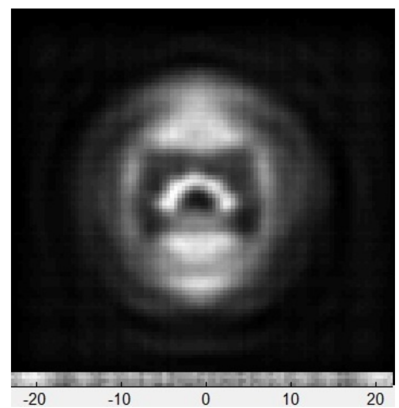
Metal clip

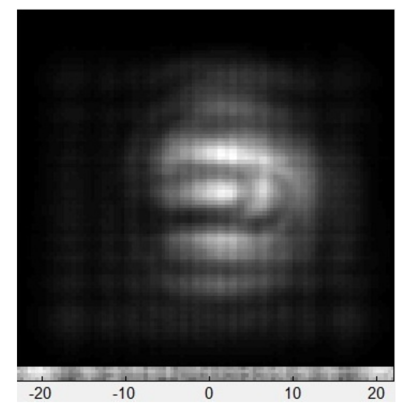







Phase distribution in the image plane

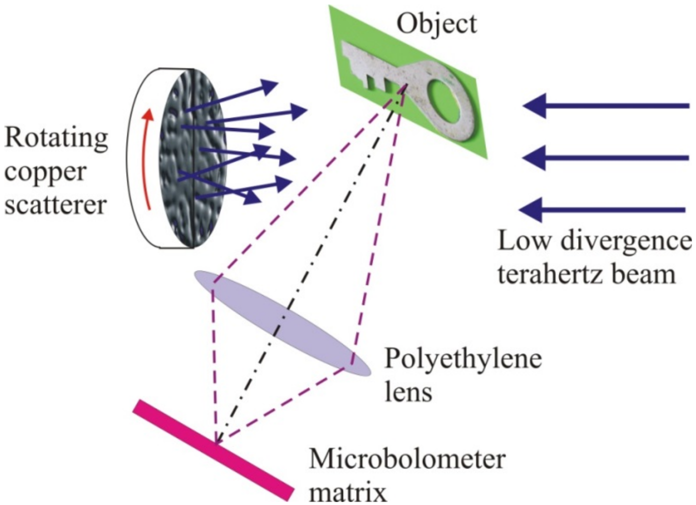


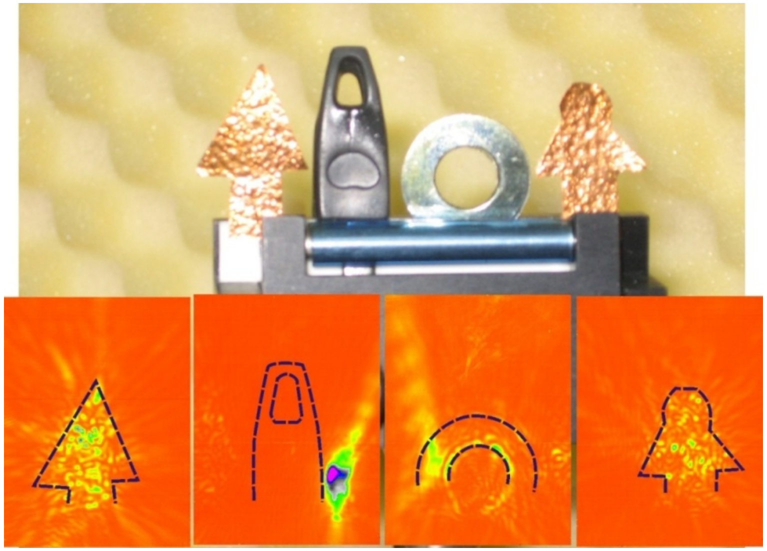


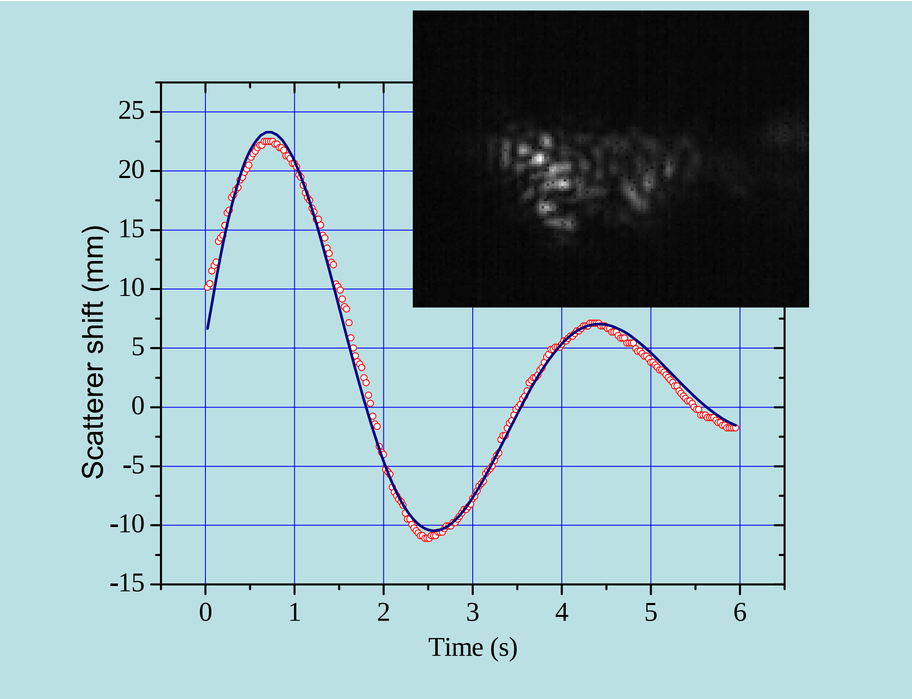


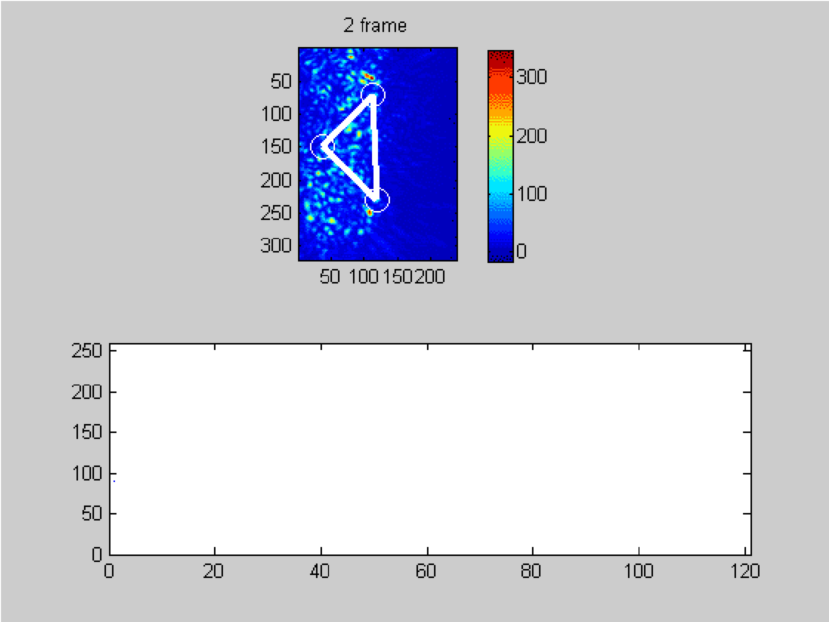
Amplitude distribution in the reconstructed real image plane

Speckles in the THz region: monitoring of displacement (including concealed objects)







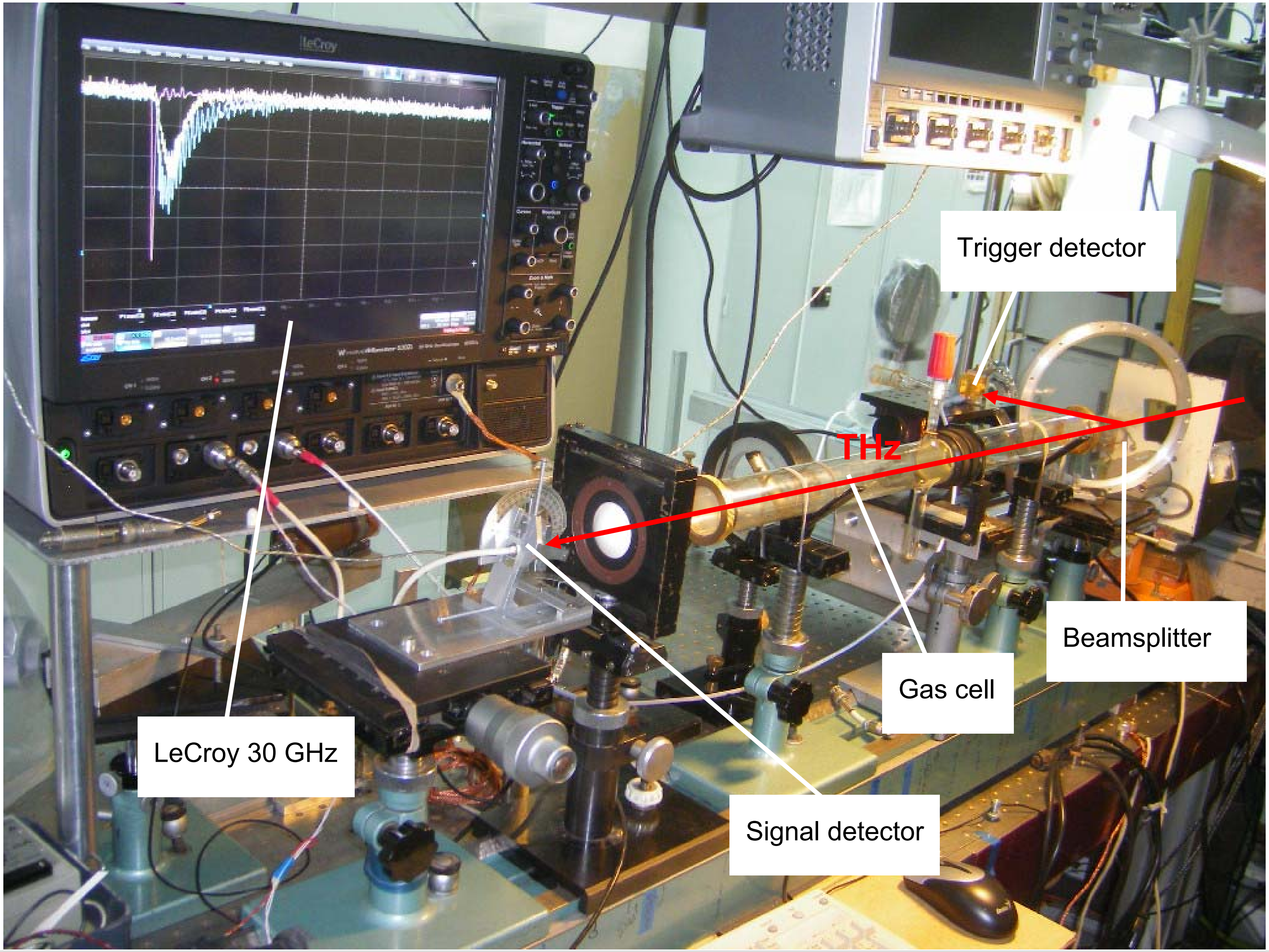


V. Selected experiments performed in 2011-2012

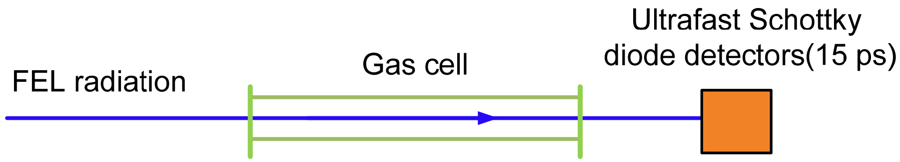
- Free induction decay of rotational transitions in molecules;
- Study of influence of THz radiation on biological materials.

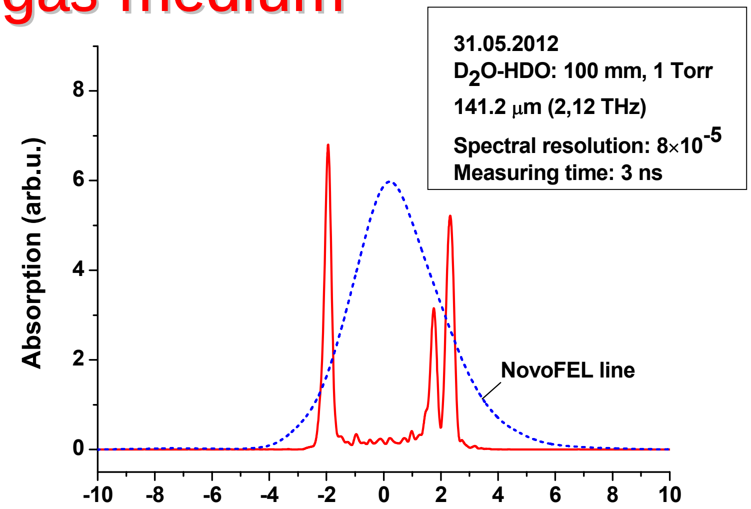
Free induction decay of rotational transitions in molecules

Experimental setup

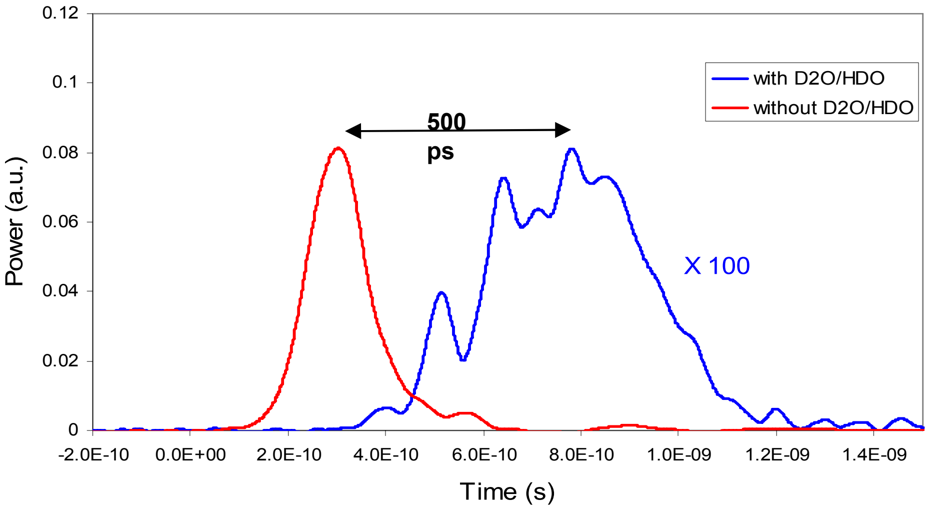


Dramatic slowing down of THz pulse in high-dispersion gas medium





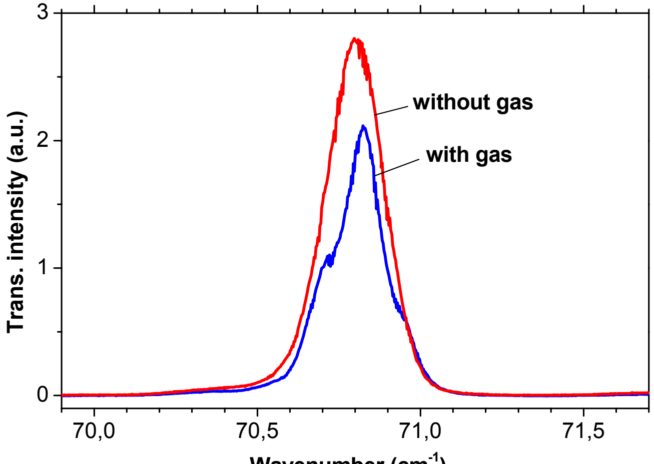
$$V_g = \frac{d\omega}{dk} = \frac{c}{n + \omega \frac{dn}{d\omega}} = 0.85c$$

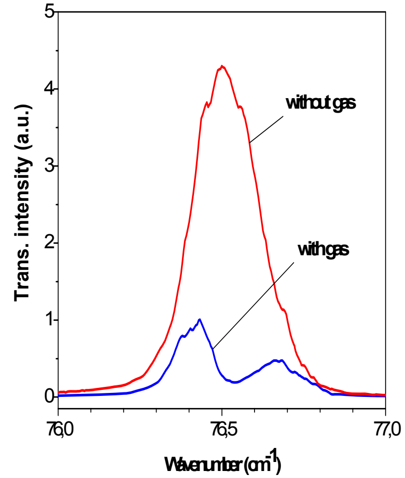


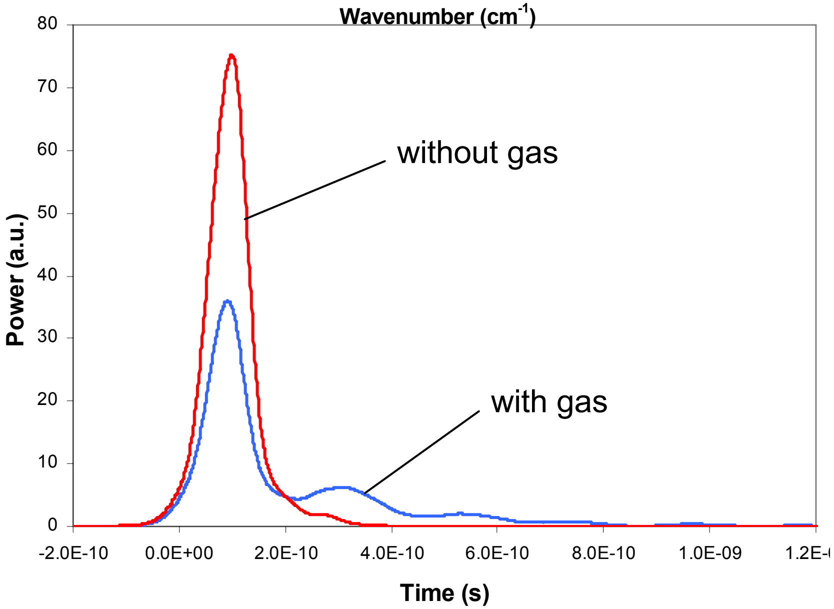
Free induction decay of D_2O-HDO

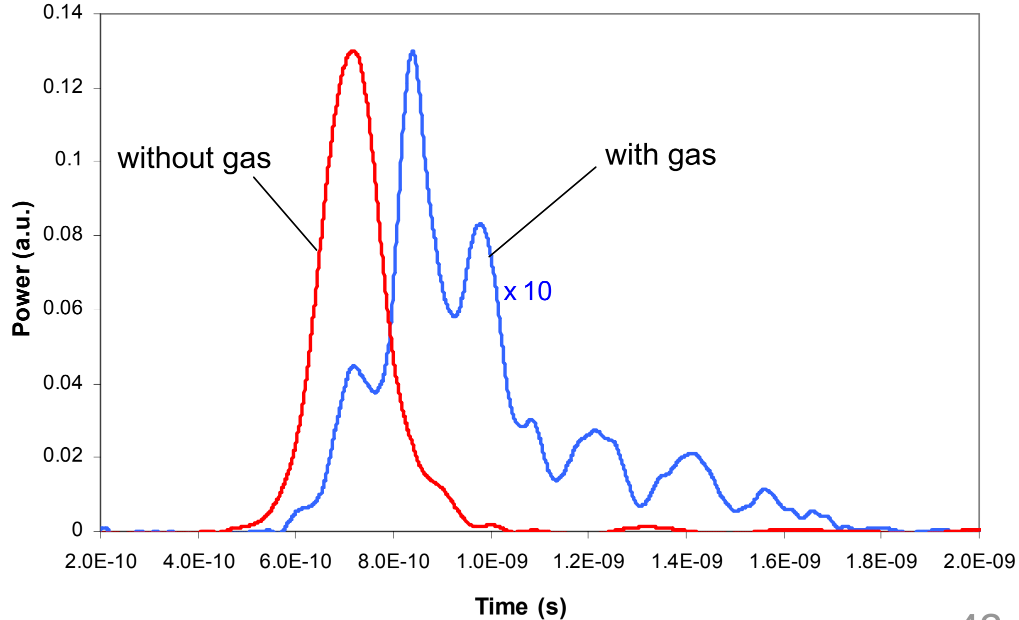
Low absorption:

High resonant absorption:

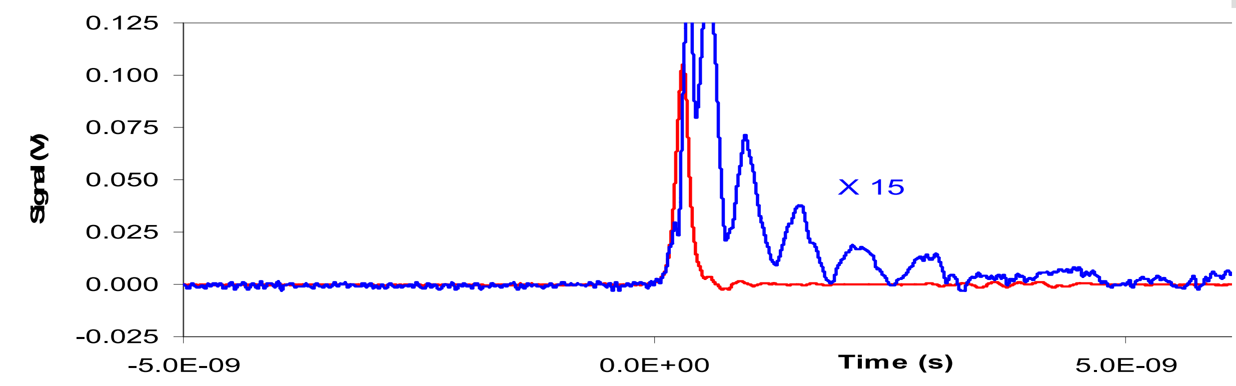




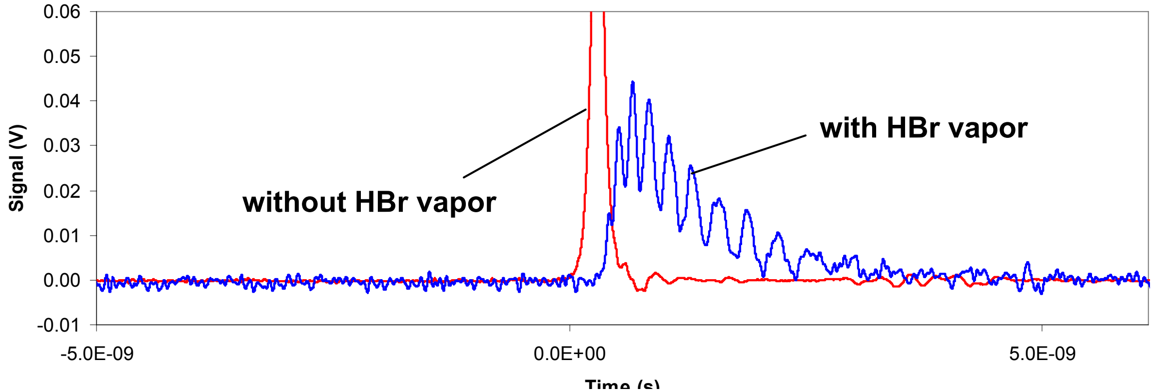




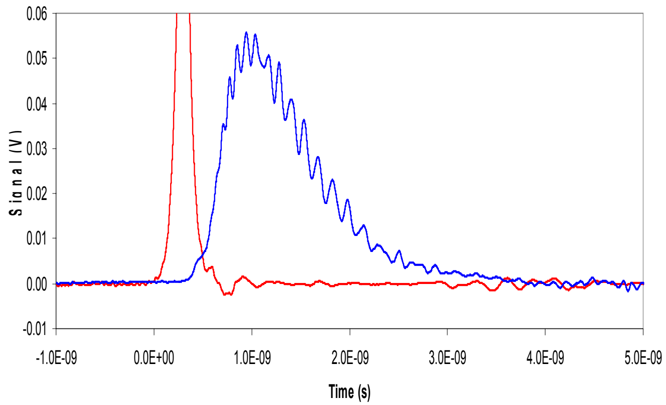
Free induction decay of HBr (doublet line 66.70/66.72 cm^{-1})



Low pressure
(0.6 torr)

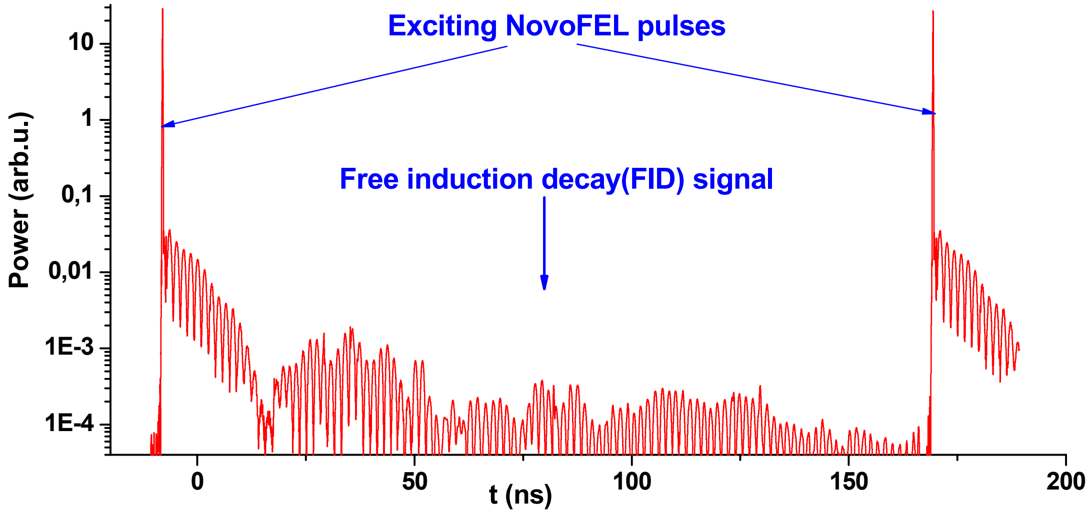


Middle pressure
(~10 torr)

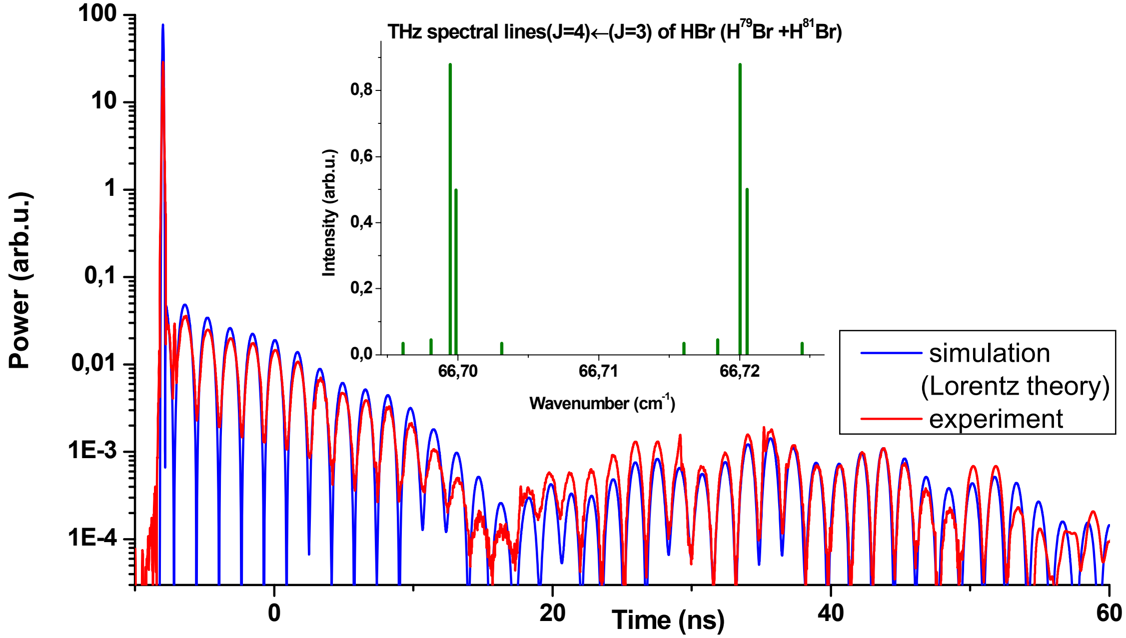


High pressure
(21 torr)

Long free induction decay of HBr



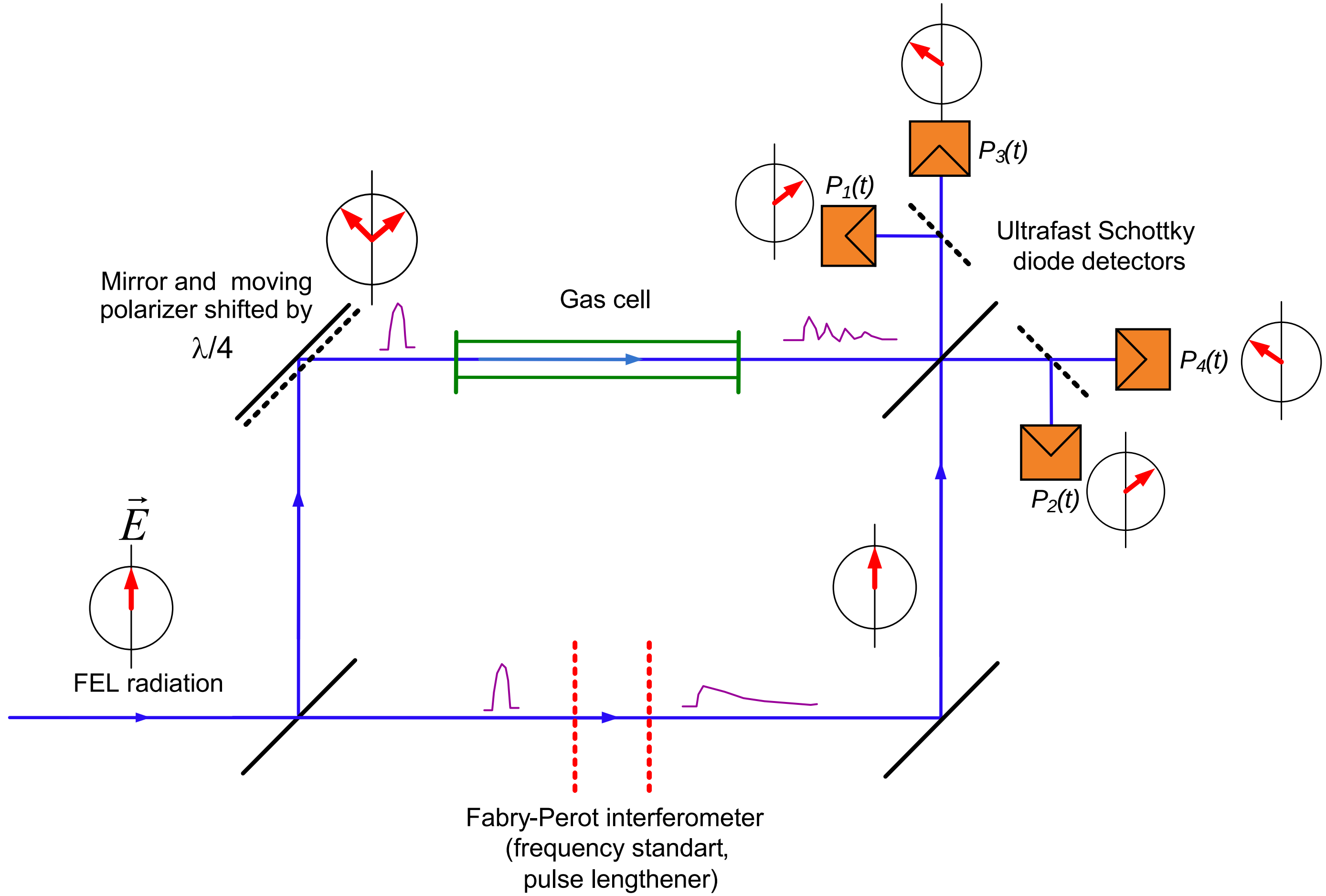
$(\Delta f / f)_{min}=(2\text{-}4)\cdot 10^{-6}$



Applications of free induction decay

- Time resolved ultrafast time domain spectroscopy
- Measure of cross-section of collisional broadening
- High-resolution spectroscopy ($\Delta f/f \sim 10^{-6}$)
- Ultra-fast spectroscopy of nonrepeatable phenomena
- Spectral “cinema” with a picture frequency up to 22.5 MHz

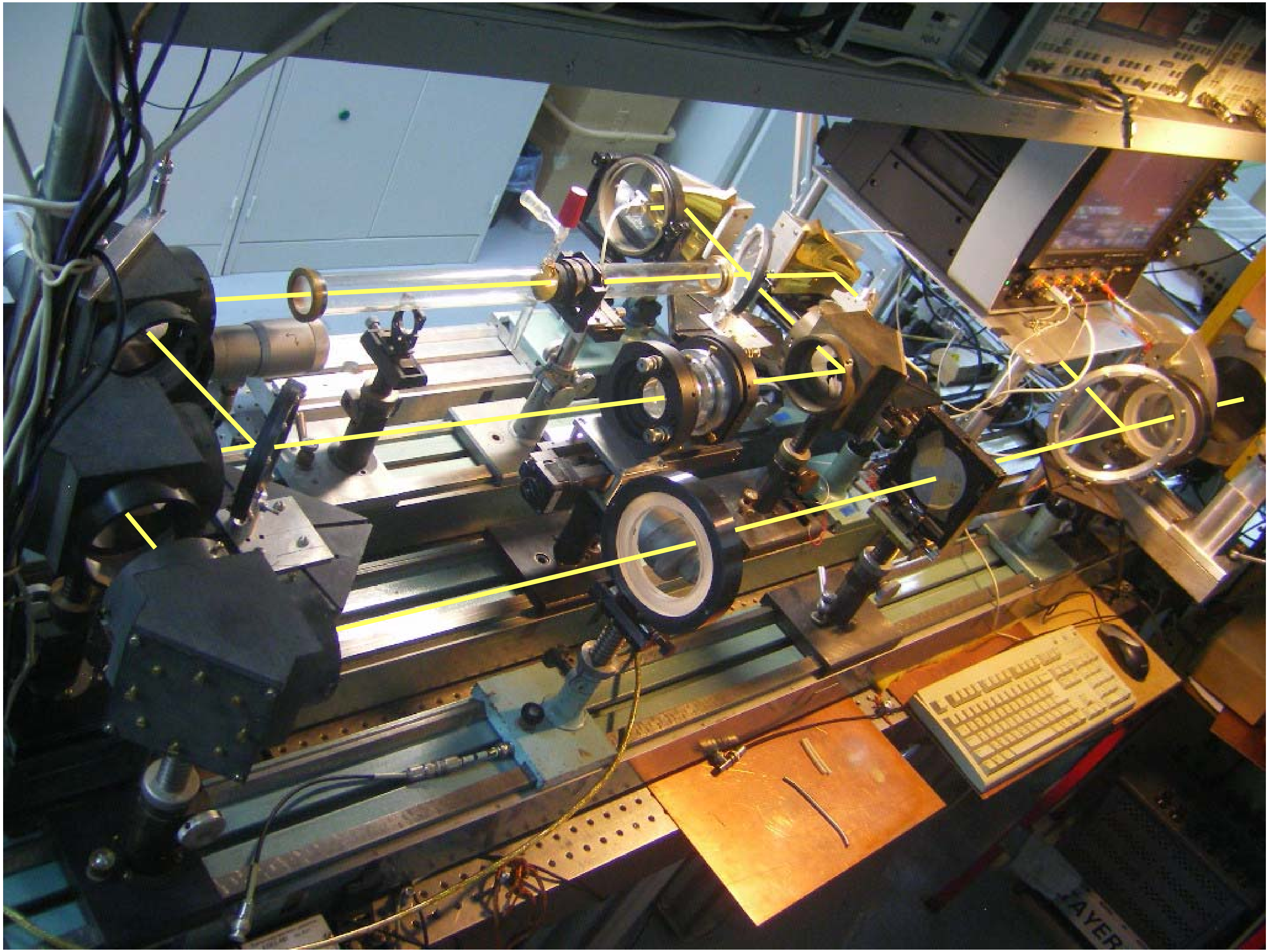
Scheme of the ultrafast time-domain spectrometer



$$E_x(t) = E(t)\cos\varphi(t) = \frac{P_1^{(0)}(t) - P_2^{(\pi)}(t)}{\sqrt{P_{FPI}(t)}};$$

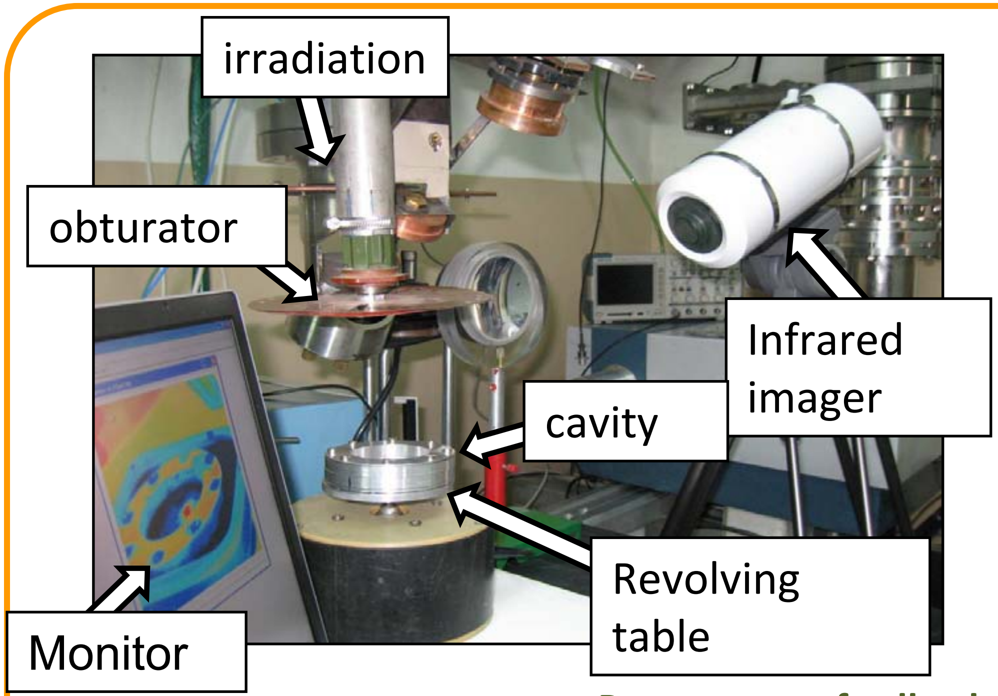
$$E_y(t) = E(t)\sin\varphi(t) = \frac{P_3^{(\pi/2)}(t) - P_4^{(3\pi/4)}(t)}{\sqrt{P_{FPI}(t)}}$$

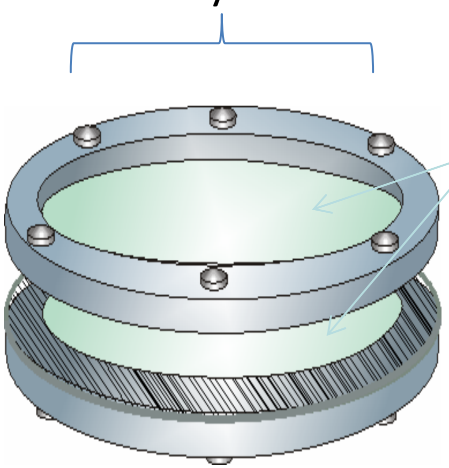
Experimental setup



Study of influence of THz radiation on biological materials

Experimental setup:





Parameters of cell culture irradiation:

Power density, W/cm^2 1.4

Wave length 70, 130, 150, and 200 µm

Temperature in cavity 35 ± 2ºC

Cell culture volume 50 µl

Biological objects for study of influence of terahertz radiation

- pUC 18 plasmid DNA
- stress sensitive cell systems using biosensor
- *E.coli* proteome using the 2D-electrophoresis followed by identification of proteins with the technique of the MALDI-TOF mass-spectrometry
- cultures of microorganisms

A comparative bioinformatics analysis was performed for the regulatory regions of genes promoters

Demidova EV, Goryachkovskaya TN, Malup TK, Bannikova SV, Semenov AI, Vinokurov NA, Kolchanov NA, Popik VM, Peltek SE. Studying the non-thermal effects of terahertz radiation on Ecoli/pKatG-GFP biosensor cells. *Bioelectromagnetics. 2012.*

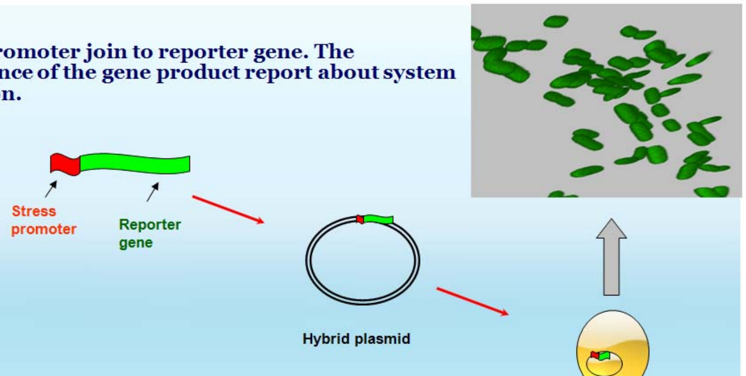
Result №1

No effect of THz radiation on the primary structure of DNA !!!

Wavelengths 70, 130, 150, and 200 μm,
the dose up to 1200 J/cm^2

Influence of terahertz radiation on stress sensitive cell systems using biosensor constructions

Stress promoter join to reporter gene. The appearance of the gene product report about system activation.

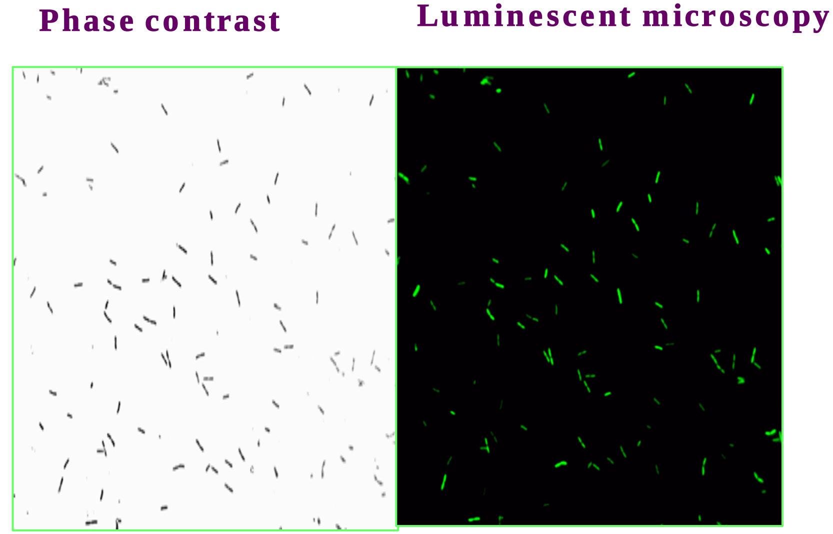


Bacterial cell

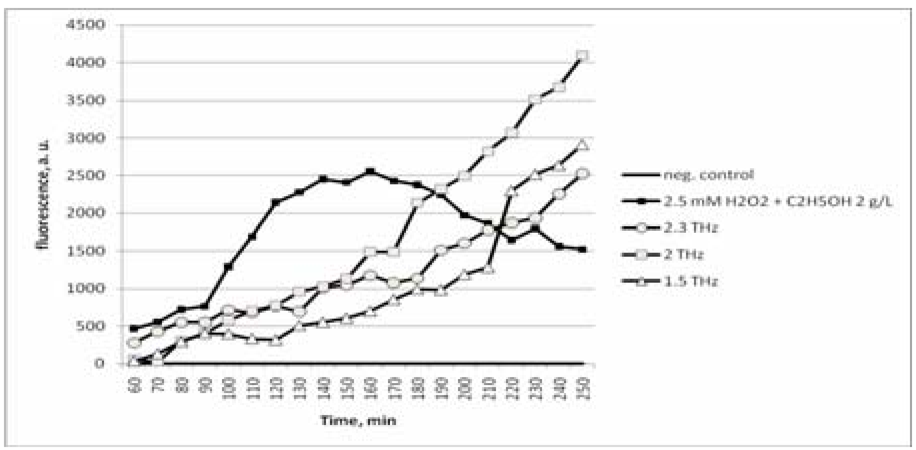
Genes of fluorescence and luminescence proteins are used as reporter genes.

The final component of the system is bacterial cell in which the construction are introduced.

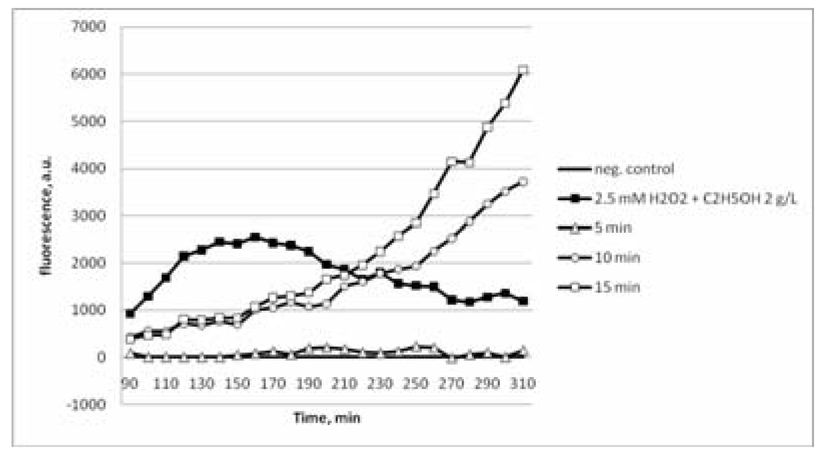
Design of biosensor



Microscopy control of reaction biosensor cell on the terahertz irradiation



Fluorescence intensity of the GFP protein in E.coli/pKatG-gfp biosensor cells after 15 min exposure to terahertz radiation at the wavelength of 1.5, 2.0 and 2.3 THz



Fluorescence intensity of the GFP protein in E.coli/pKatG-gfp biosensor cells after 5, 10 and 15 min exposure to terahertz radiation at the wavelength of 130 μm

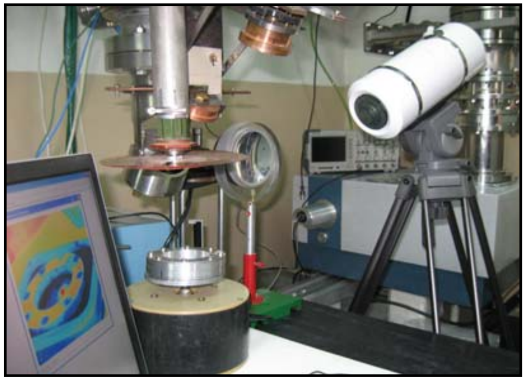
Result №2

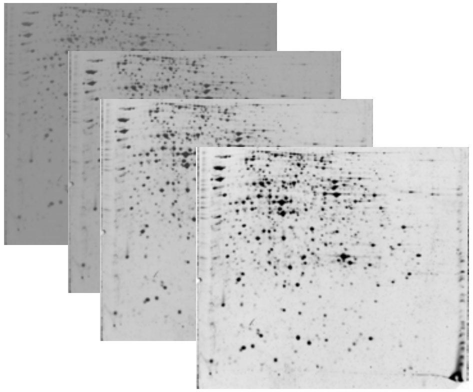
Observed activation of biosensors E.coli/pKatG-gfp, E.coli/pDps-gfp, E.coli/pCopA-gfp

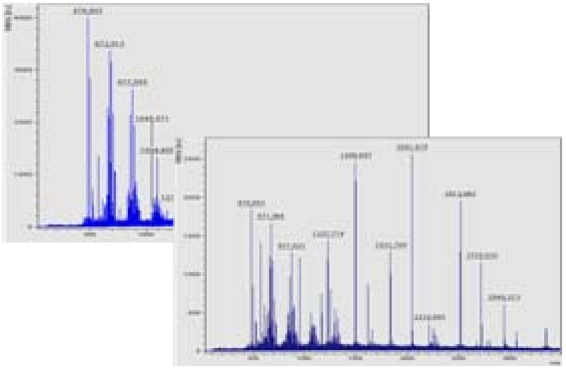
and no activation E.coli/pEmrR-gfp.

Influence of THz irradiation on E.coli proteome

Terahertz irradiation of *E.coli* → Protein separation in two-dimensional electrophoresis → Identification of proteins by MALDI mass-spectrometry of every selected protein fraction







Identified *E. coli* proteins which production induced by THz radiation (mass-spectrometry by MALDI TOF and ion-cyclotron resonance)

Upp	uracil phosphoribosyltransferase
rplY	50S ribosomal subunit protein L25
glnA	glutamine synthetase
manX	Component of mannose PTS permease
rbsA	Component of ribose ABC transporter
GltA	citrate synthase
RpoD	RNA polymerase, sigma 70 (sigma D) factor

Degp	serine protease Do
hlyE	hemolysin E
PurA	adenylosuccinate synthetase
Tsx	receptor of phage T6 and colicin K
cydA	cytochrome *bd*-I terminal oxidase subunit I
AppC	cytochrome *bd*-II terminal oxidase subunit I
AspC	aspartate aminotransferase, PLP-dependent

Result №3

14 proteins of E.coli cells were identificated which changed their expression under THz irradiation.

Bioinformatic analysis revealed that binding sites of the transcription factors OxyR and MarA are present in promoters of terahertz-induced genes.

Result №4

Object	Result of THz irradiation
Escherichia coli	Change of protein expression Weak stimulation culture grows
Chlorella vulgaris	Weak stimulation culture grows
Daphnia magna	No effect

VI. Summary

- Up to 500 W of average power at 110 – 240 and 40 - 80 micron wavelength range is available for users. Linewidth is less than 1%, maximum peak power is about 1 MW.
- Six experimental stations are in operation.
- The Novosibirsk terahertz free electron laser is becoming a user's facility. We invite those researches who want to perform interesting experiments with a high power monochromatic coherent tunable THz and FIR radiation to carry out them in Novosibirsk.

Thank you for your attention