NovoFEL
(Novosibirsk Free Electron Laser)
and opportunities for Russia – EC
scientific and technological cooperation

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Opportunities for Russia - EC
scientific and technological cooperation
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- NovoFEL as user's facility.
- Development of THz range experimental equipment. Experiments with THz radiation.
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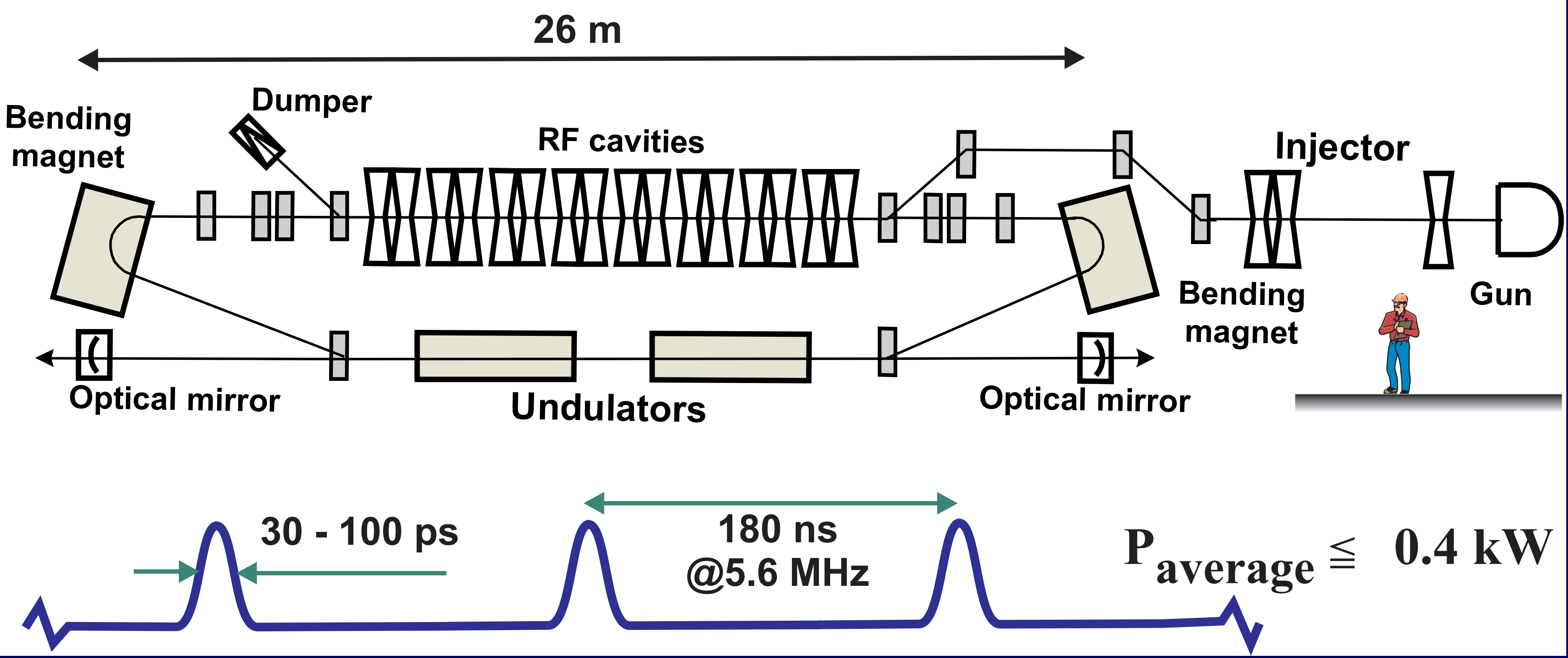
- Conclusion.

1.
The powerful terahertz range FEL for the Siberian Center of Photochemical Research

At present, at the Budker Institute of Nuclear Physics (Budker INP SB RAS, Novosibirsk), the powerful terahertz and IR range FEL are being developed, manufactured and put into operation for the Siberian Center of Photochemical Research.

The first stage project have a one track accelerator-recuperator with a maximum energy up to 14 MeV.

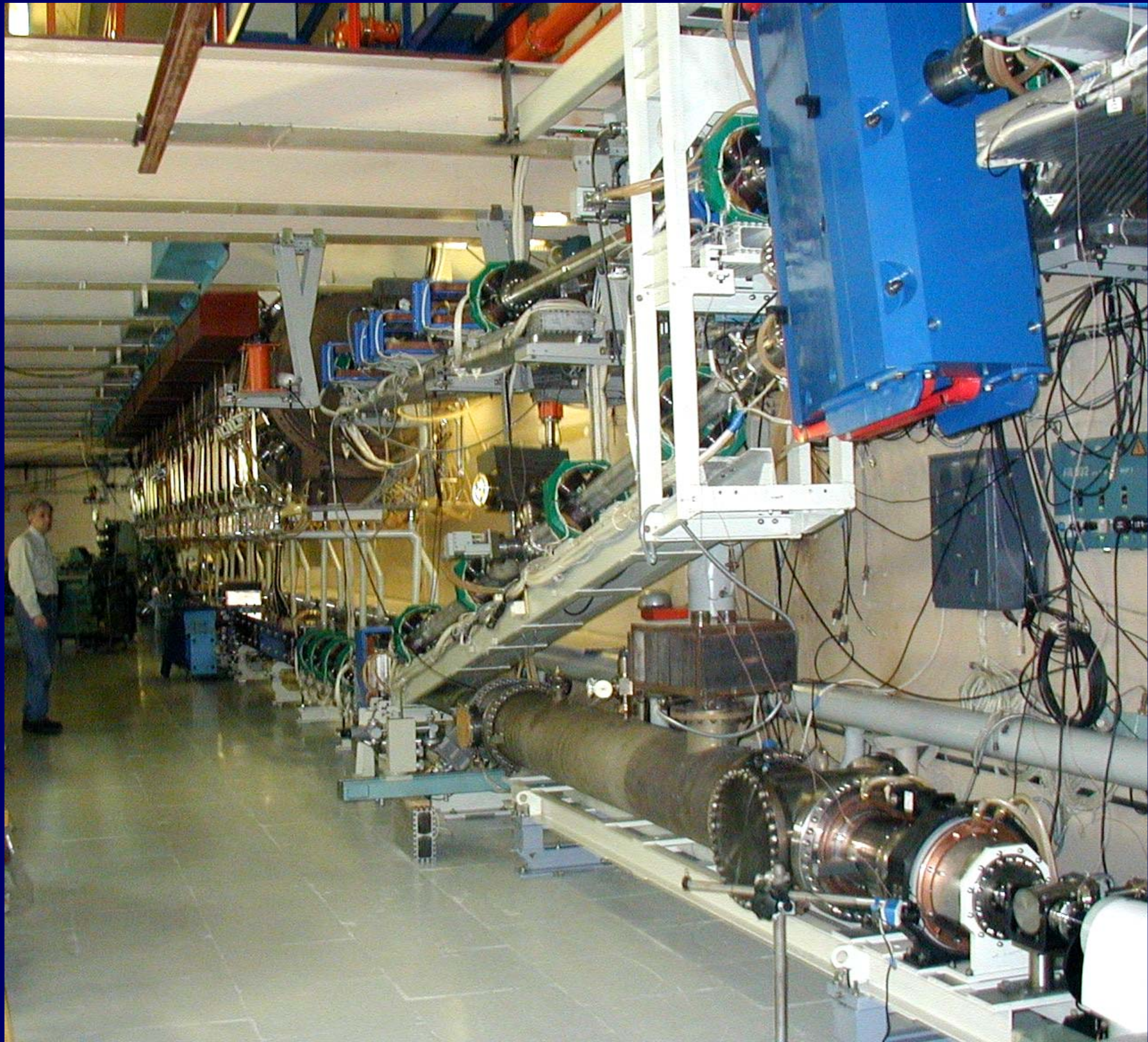
Layout of the Novosibirsk FEL (1st stage)



Electron beam from the injector after its passage through the buncher (a bunching RF cavity), drift section, 2 MeV for-accelerating cavities and the main accelerating structure is directed to the undulator, where a fraction of its energy is put into the laser radiation.

After that, the beam returning to the main accelerating structure in a decelerating phase, looses its energy practically to its injection value (2 MeV) is dropped into the absorber.

General view of NovoFEL (1st stage)



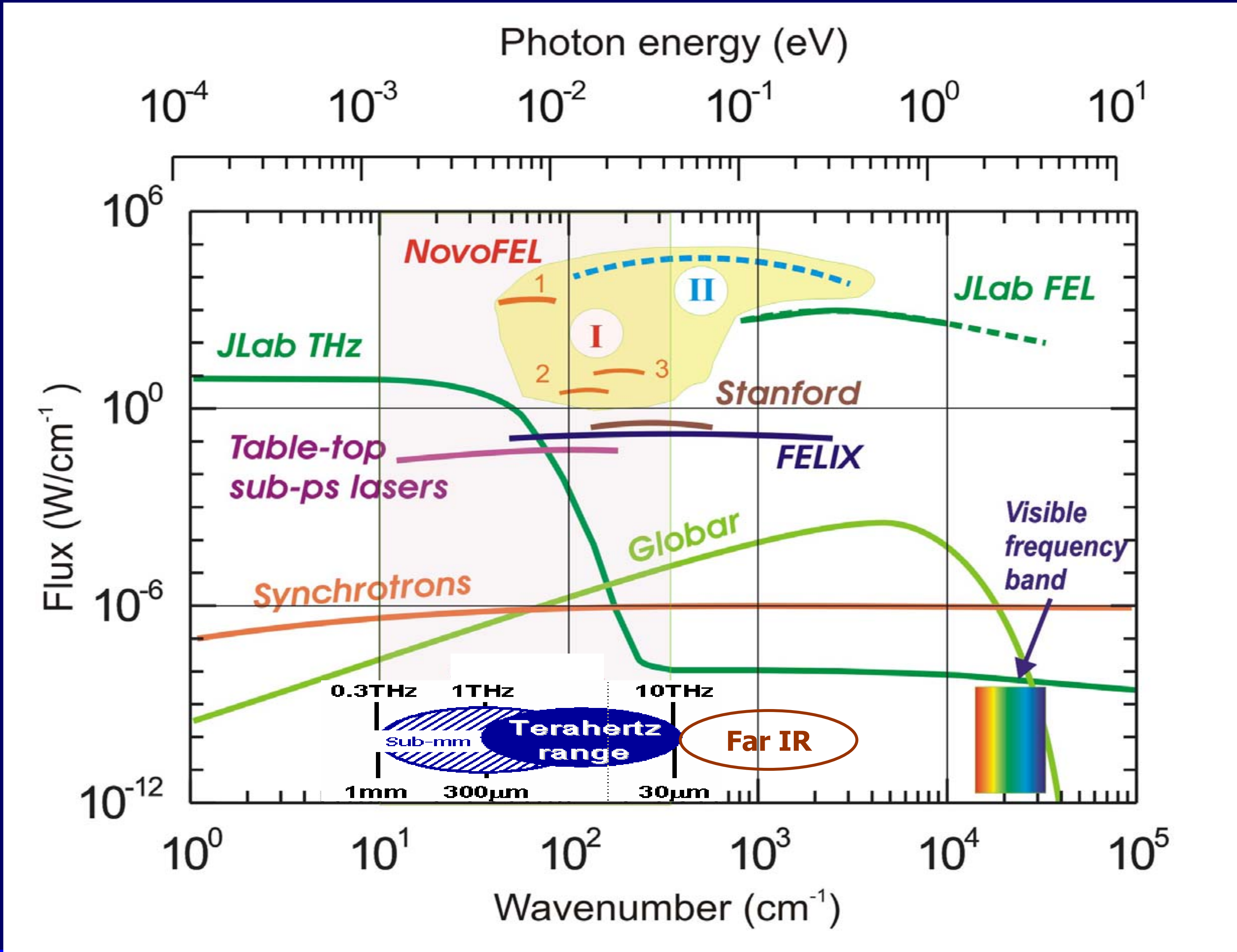
On April 4, 2003, a lasing in the range of 120 μm was obtained at a 1st stage FEL. At present, this FEL is the most powerful generator of the terahertz radiation with tunable wavelength (120-235 μm).

Radiation parameters of the 1st stage NovoFEL

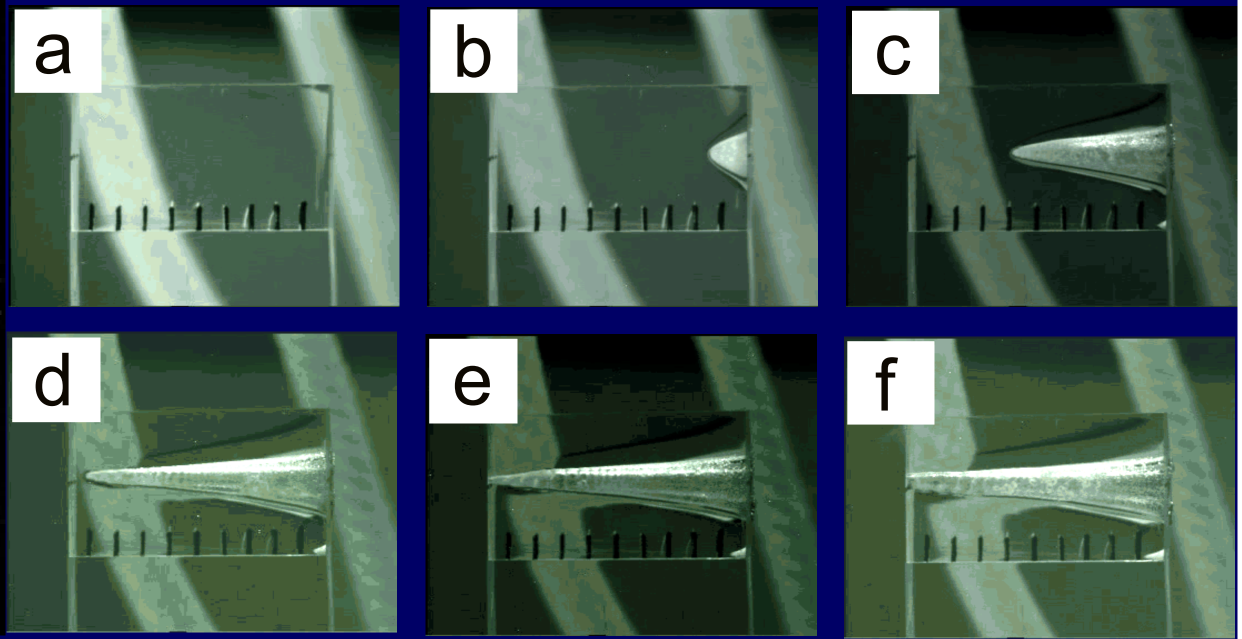
	1st harmonic	2nd harmonic	3rd harmonic
Wavelength, μm	**120 - 235**	**60 - 117**	**40 - 78**
Relative line width at a half-height, %	**0.3 – 1.0**	**0.2 - 1**	**0.1 - 1**
Maximum average power, W	**400**	**6**	**2.4**
Maximum peak power, kW	**600**	**9**	**3.6**
Pulse duration, ps	**40 - 100**	**40 - 70**	**40 - 70**
Pulse repetition rate, MHz	**2.8 - 5.6 - 11.2**		
Linear polarization degree, %	**> 99.6**		
Gaussian beam diameter at the user stations, mm	**60**		

The power and relative line width obtained in a terahertz region are the record parameters.

Average spectral power density of the light sources



High average power of radiation (up to 400 W) in combination with high peak power (up to 0.6 MW) enables performing high power density experiments

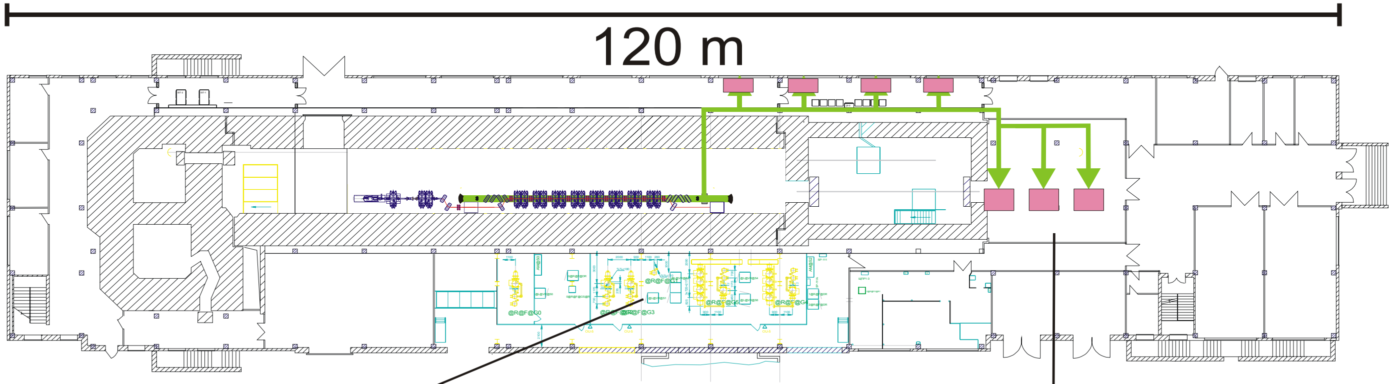


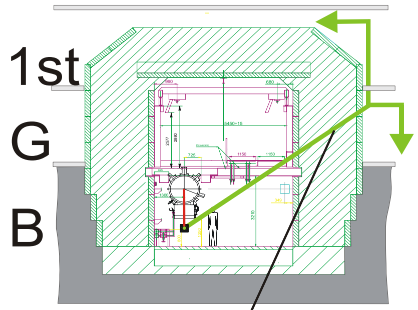
- ❑ Laser beam focused in the atmosphere with a parabolic mirror (f=1.0 cm) ignites a continuous optical discharge.
- ❑ Unfocused laser beam drills an opening in 50-mm organic glass slab within three minutes (ablation without burning).
- ❑ These fenomena can be used for many fundamental and applied experiments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

2.

NovoFEL as user's facility

Layout of terahertz FEL and user stations

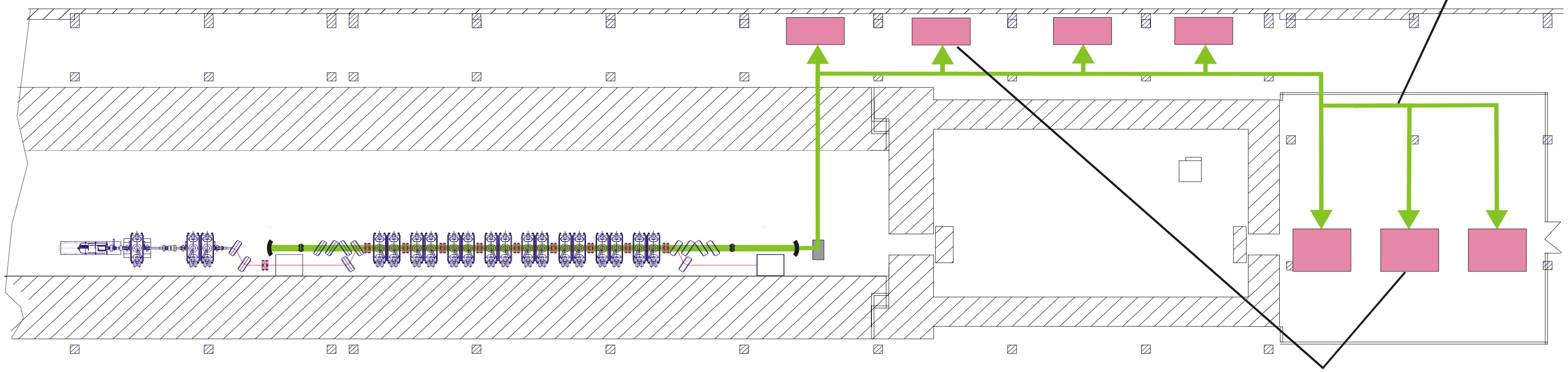




RF generator system
(ground floor)

Control room
(ground floor)

Beamlines for
radiation transport



Accelerator-recuperator and
Terahertz free electron laser (basement level)

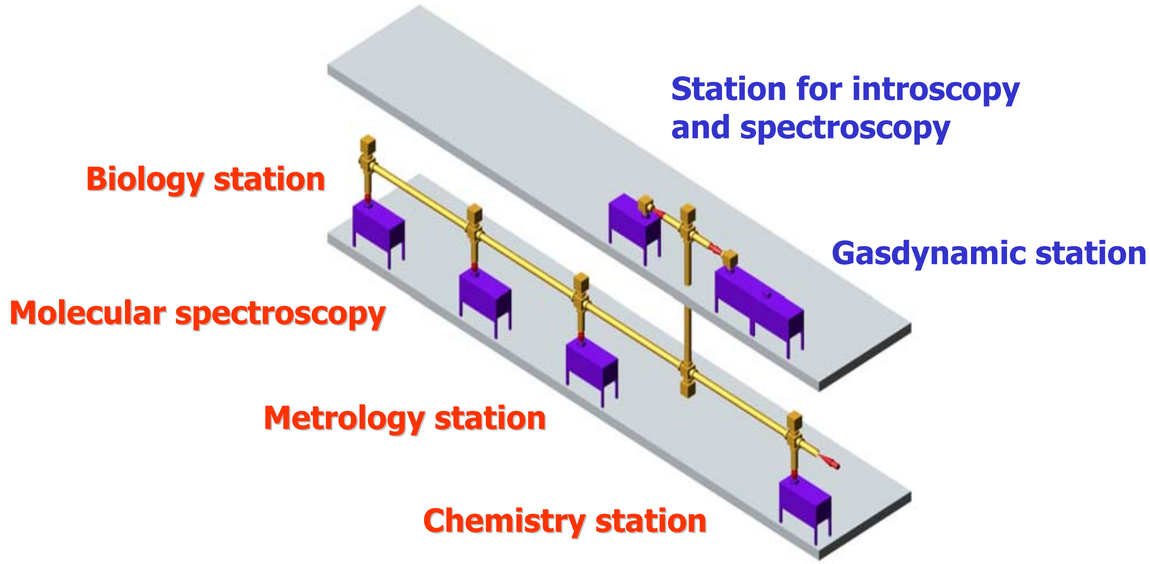
User Stations
(ground and first floors)

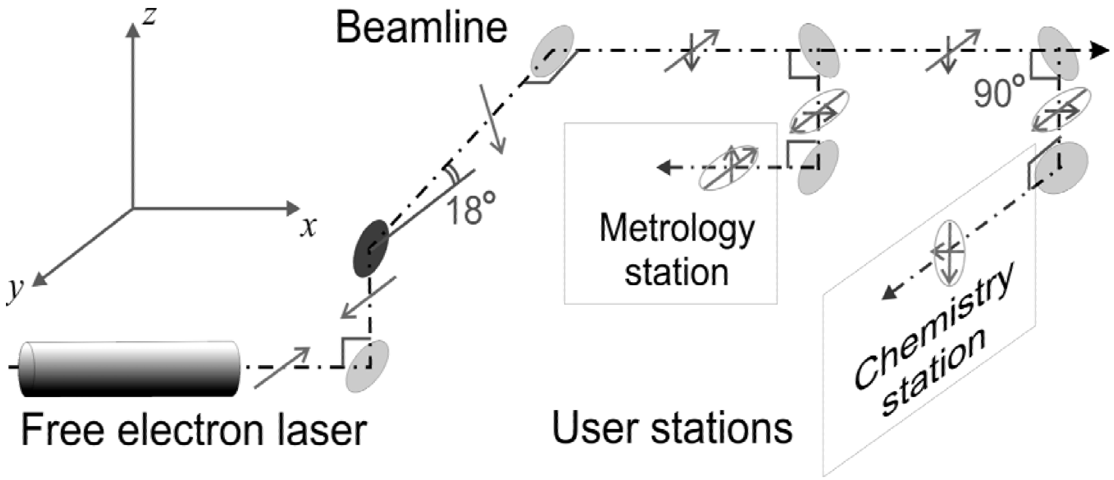
Beamlines and first stage user stations at NovoFEL

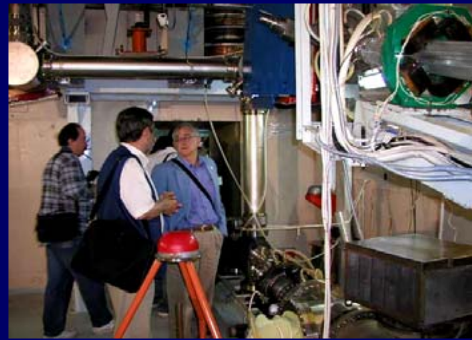
Laser radiation is transmitted through an optical beamline filled with dry nitrogen to the two experimental halls. Four user stations are now operating. Another two stations are under construction. The commissioning of this stations is in prospect of beginning of 2007.

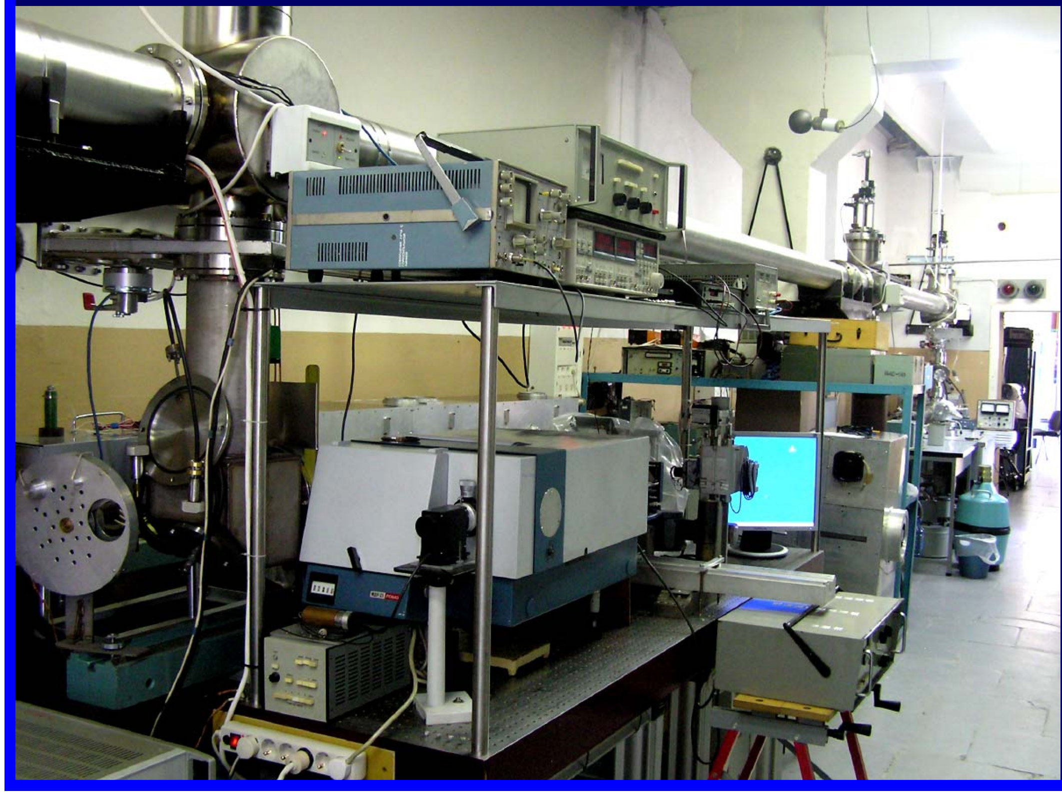
Station status:

1. **Operating**
2. **Under construction**

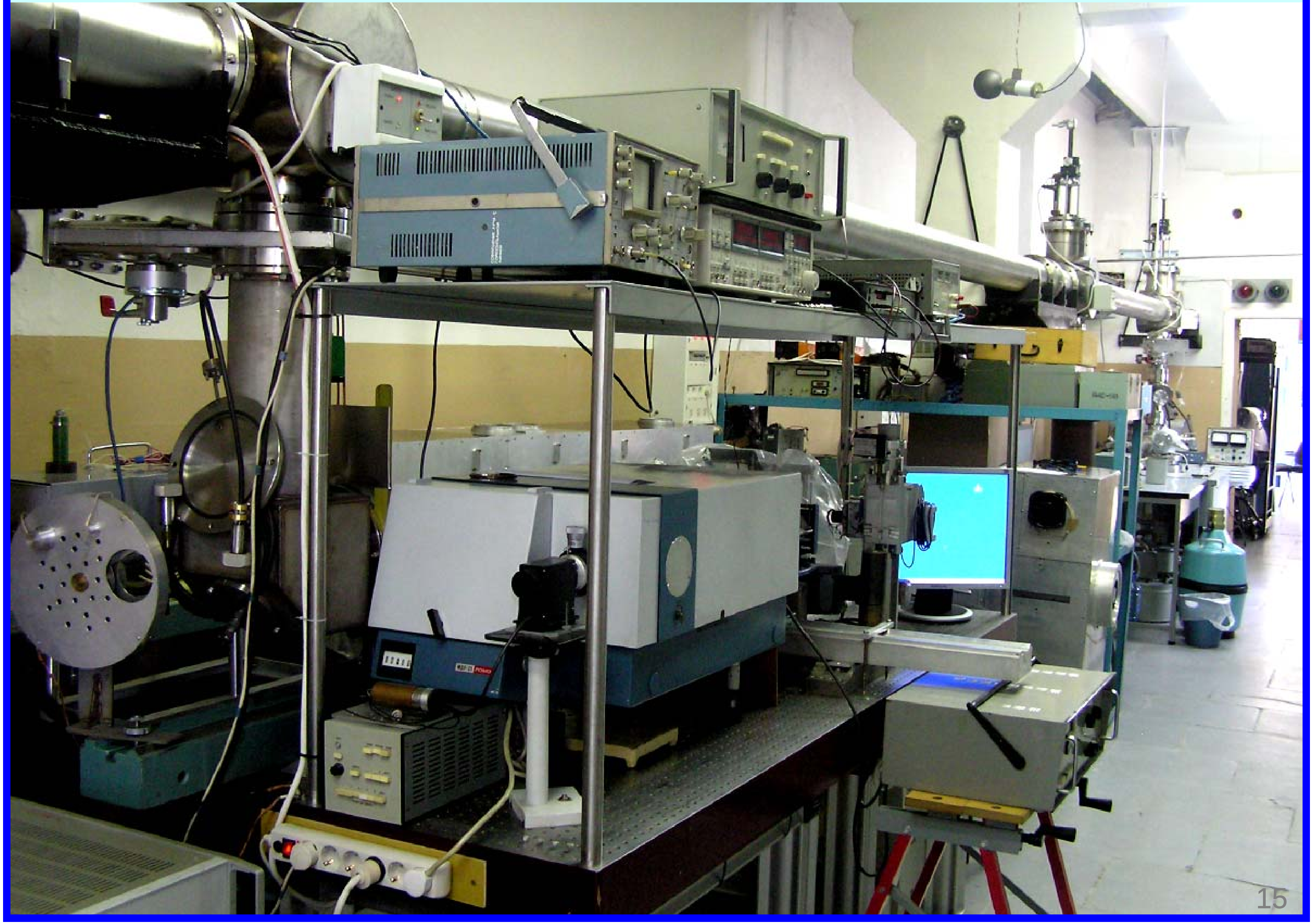








Four stations in the lower experimental hall



The features of the Novosibirsk THz FEL:

- Short pulse duration (40 - 100 ps)
- High pulse power (up to 0.6 MW)
- High average power (up to 400 W)
- Full space coherence
- High longitudinal coherence (~ 2 cm)
- Polarisation (degree of linear polarisation is more than 99 percents)

Some important specific features of THz-radiation:

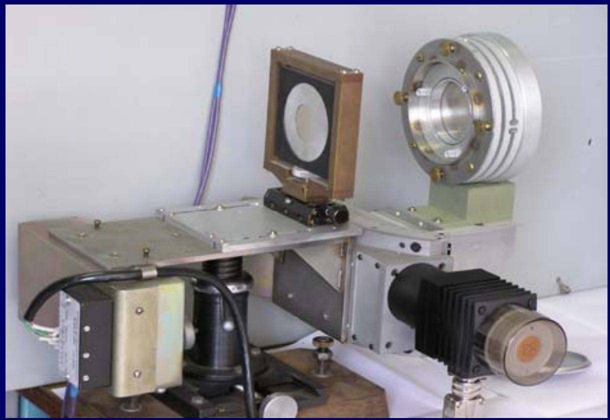
- Radiation is non-ionizing
- The Rayleigh scattering is suppressed ~ 1 / λ^4
- The eigen frequencies of many physical, chemical and biological systems are within this range (hydrogen bonds)
- Trasparency windows are different from windows for visible and IR radiation

3.

Development of THz range experimental equipment.

Experiments with THz radiation

Some spectral devices developed or upgraded for NovoFEL

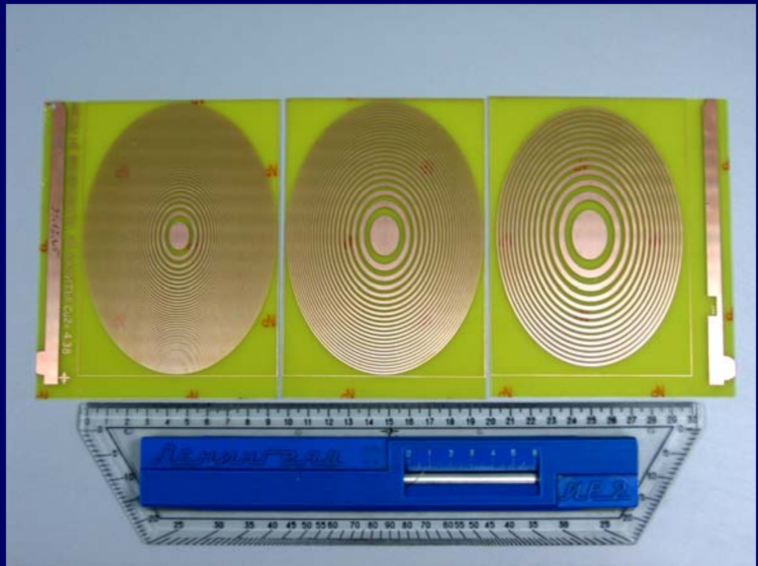


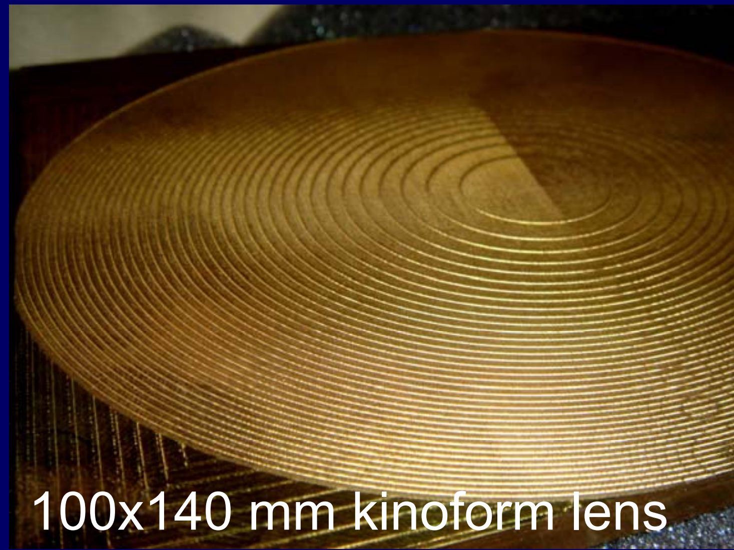
Mesh Fabry-Perot interferometer:
- a) high spectral resolution
- b) compactness and simplicity

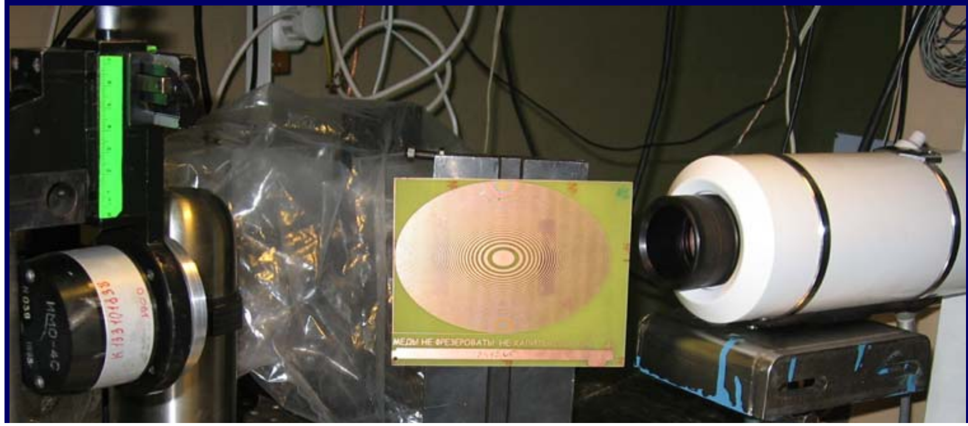
Upgraded MDR-23 monochromator:
- a) wide spectral range 0.3 - 300 μm
- b) real harmonic separation, on-line adjustment

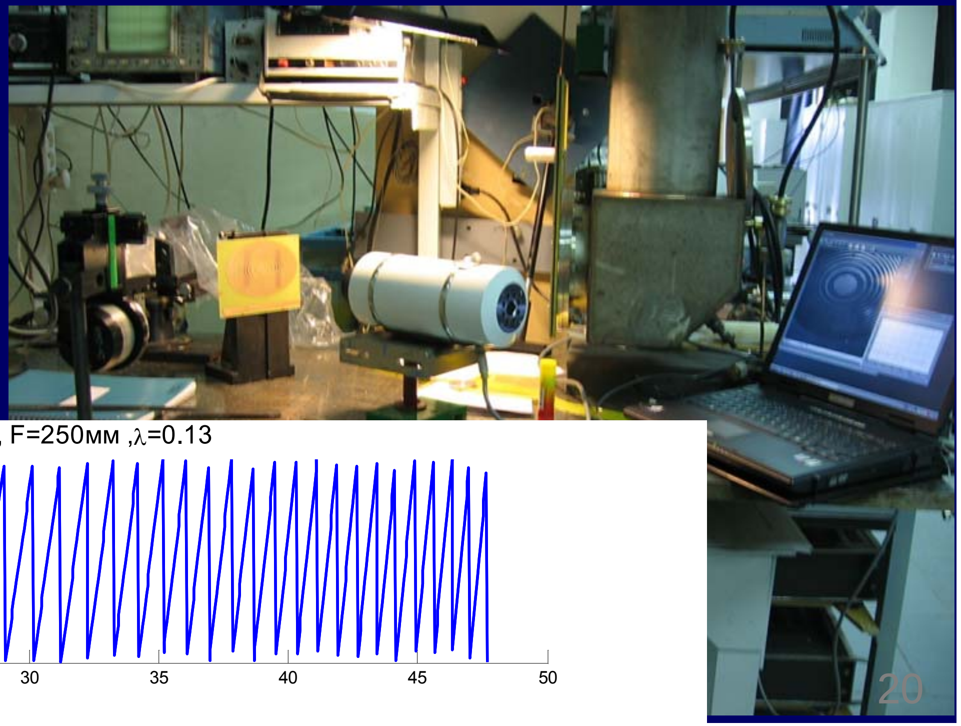
Bruker vacuum Fourier spectrometer IFS-66v:
- a) clear vacuum spectrums
- b) wide spectral range 1-1000 μm

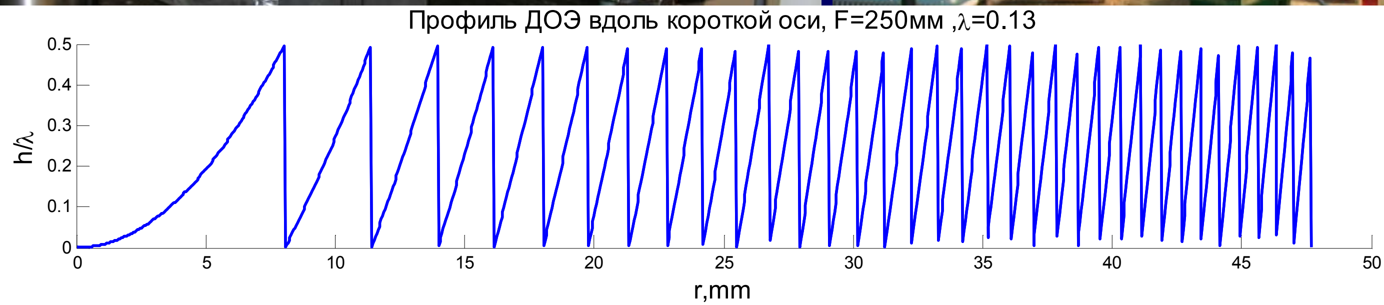
Zone Fresnel plates and kinoform lens for terahertz region









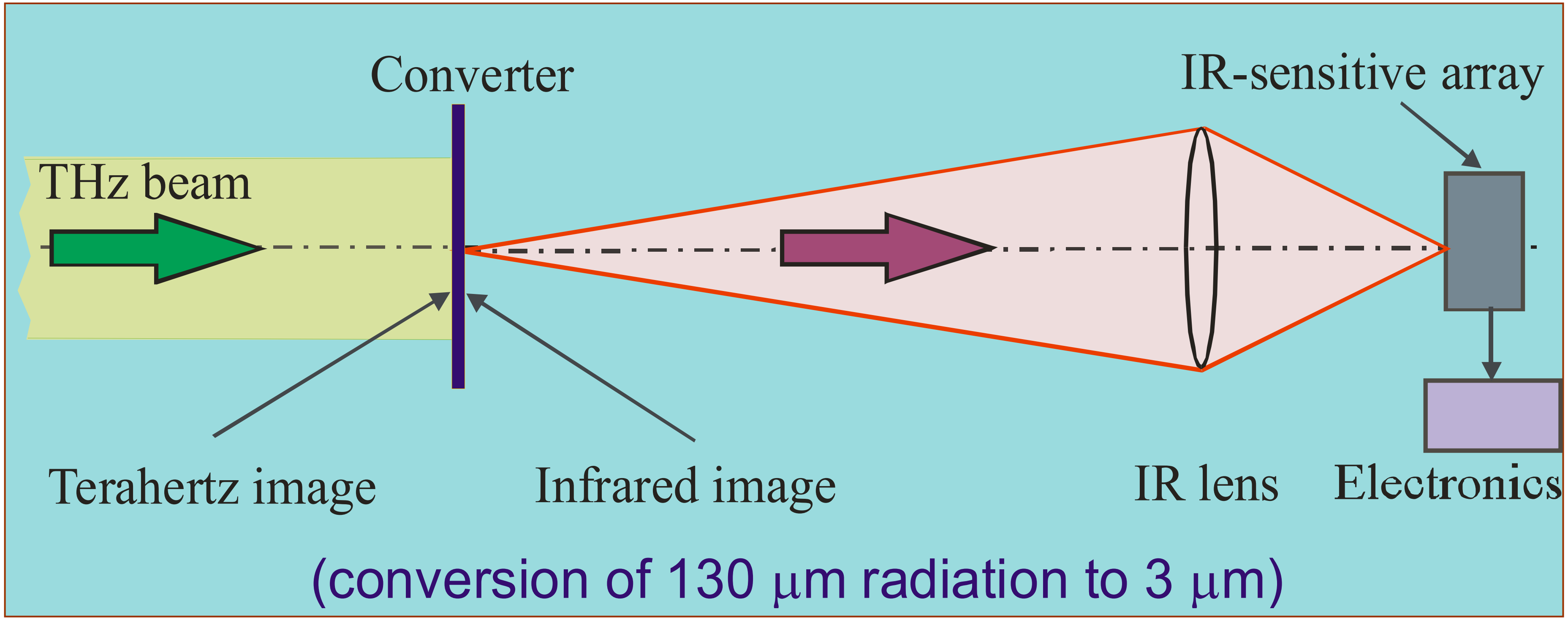


THz imaging with a high-power free electron laser

- High average power of the FEL enables development of imaging techniques based on the thermal effect of radiation

- We have developed and implemented several methods for THz radiation visualization based on the thermal effects

THz imaging with an IR thermograph



- Converter of THz radiation is a carbon paper
- Time resolution is limited by thermal relaxation time (about 1 sec for this screen)
- Converters with fast relaxation time are under consideration

THz imaging with the thermograph

Keys in an opaque paper envelope

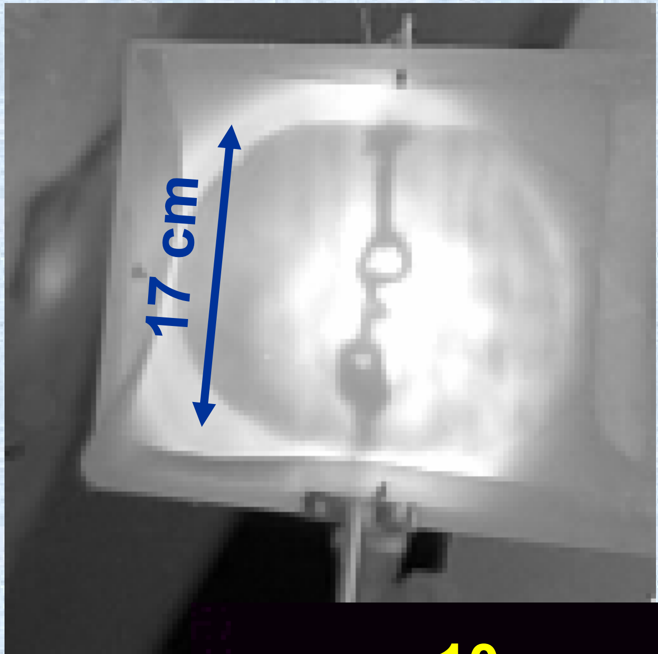
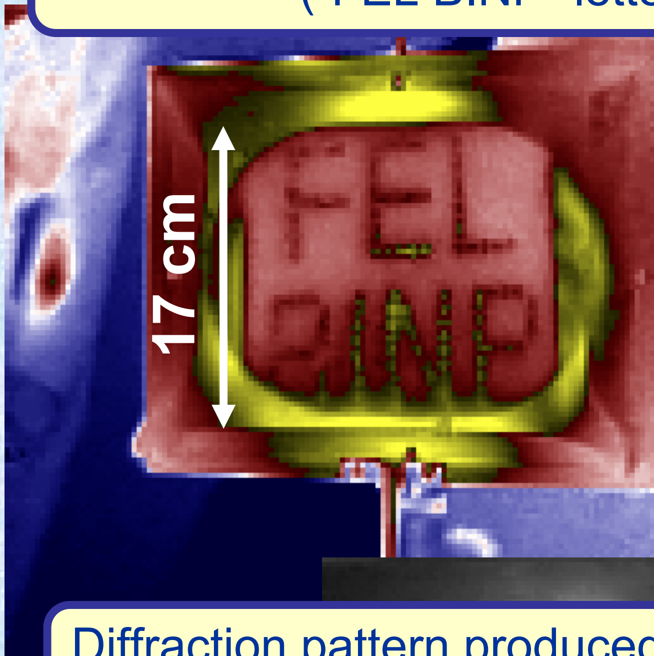
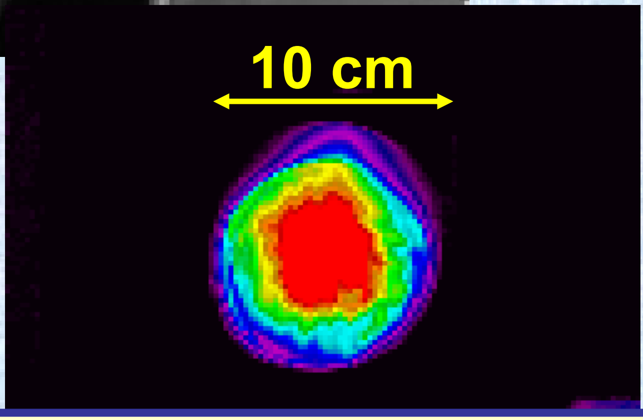


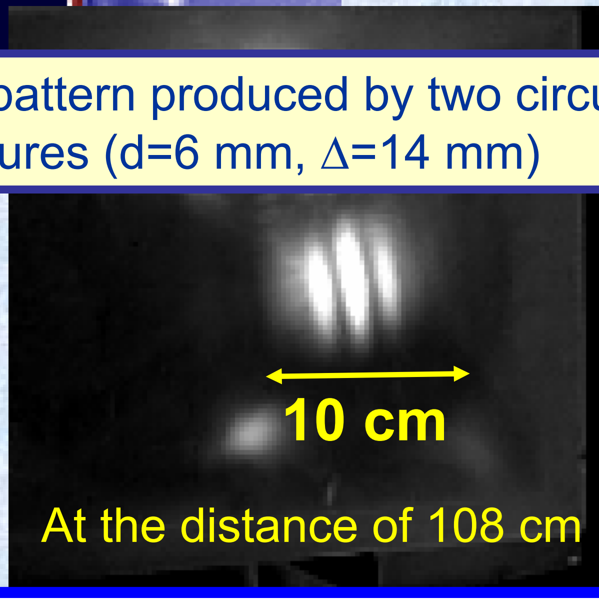
Image of 6-mm holes drilled in a metal plate (“FEL BINP” letters)





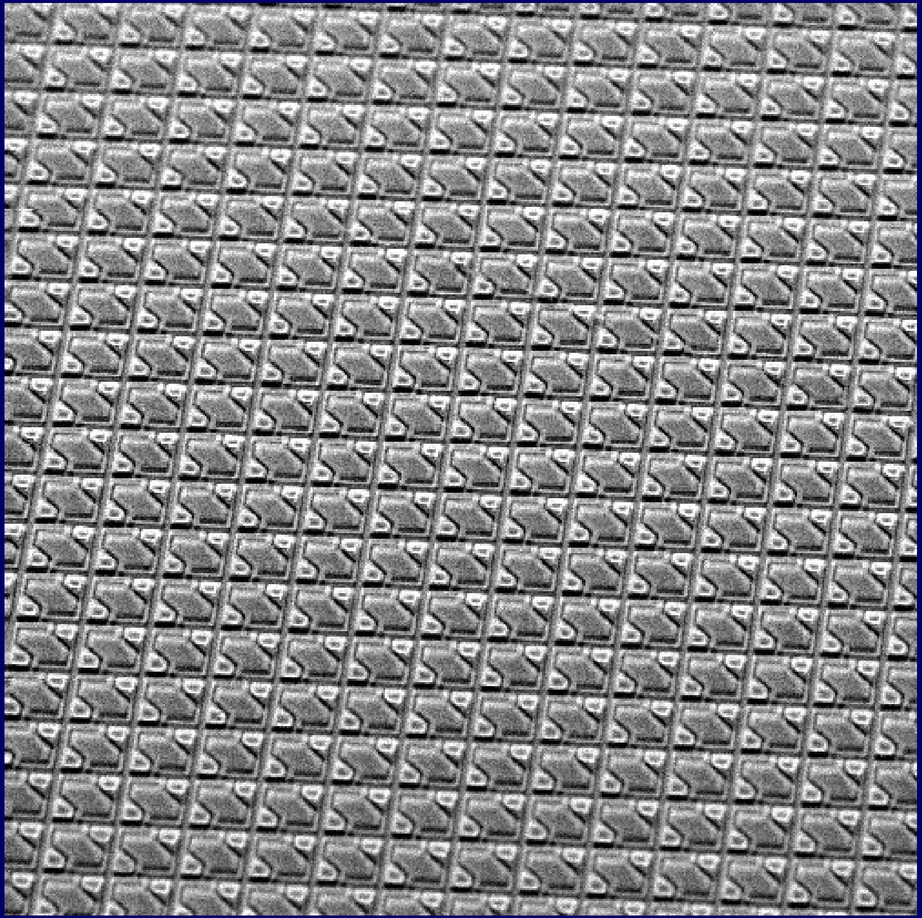
THz laser beam cross-section at the beamline output (13 meters from the laser)

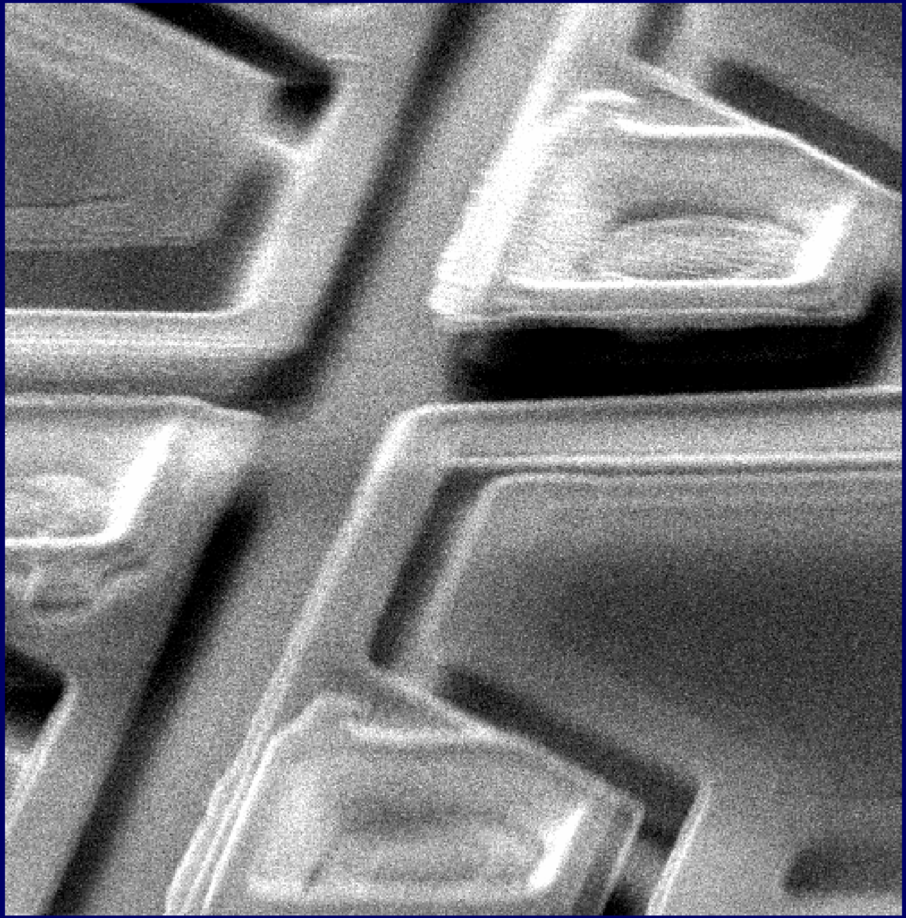
Diffraction pattern produced by two circular apertures (d=6 mm, Δ=14 mm)



Room-temperature microbolometer matrix for terahertz region

(V. Shashkin et al. Institute of Semiconductor Physics SB RAS, Novosibirsk)





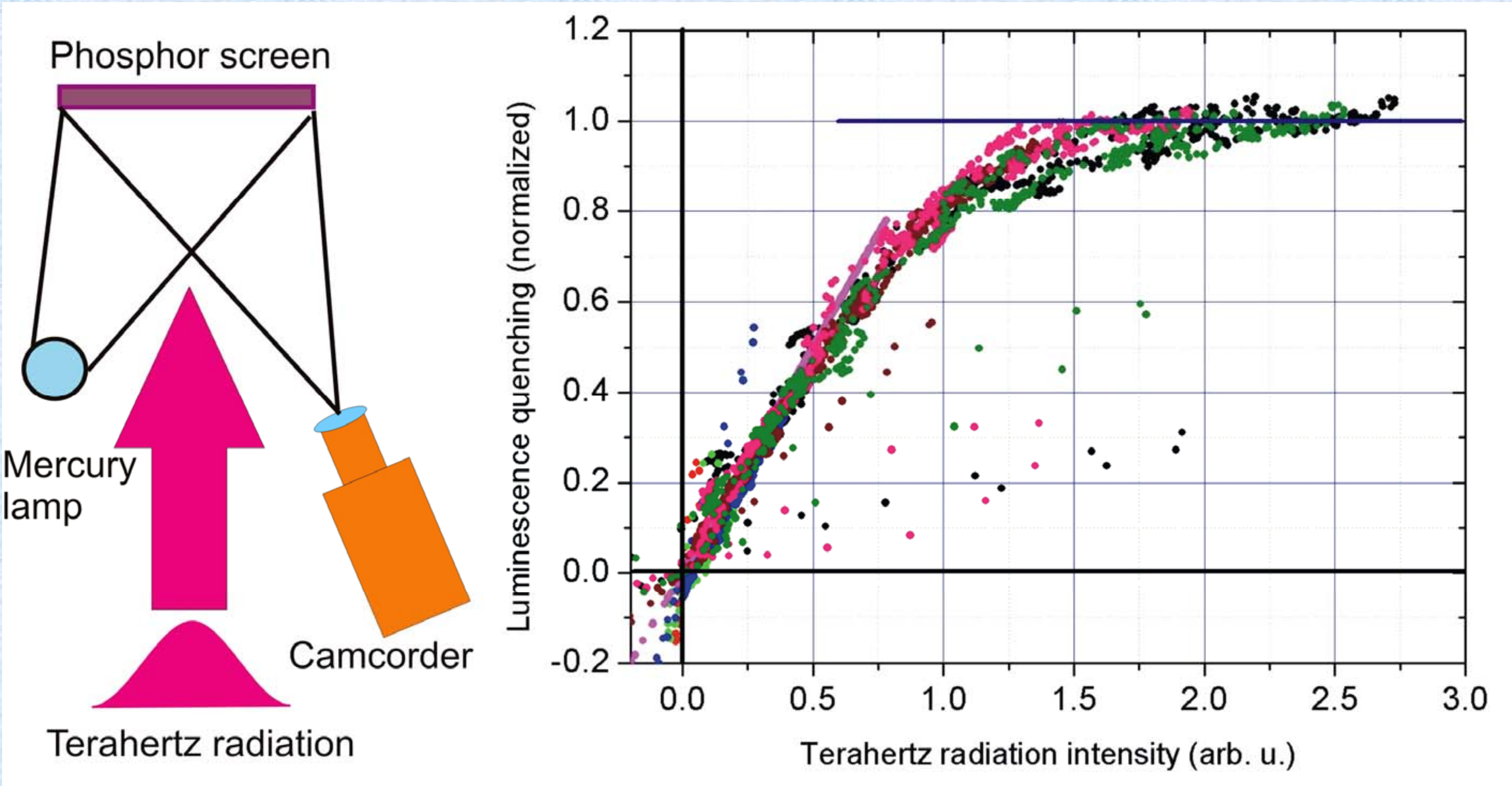
Vanadium oxide matrix

Size – 20x20 mm^2, number of pixels 169x120

THz imaging with “Thermal Image Plate” (TIP)

Thermal image plate, Mickan Instruments

Calibration of thermal image plate using terahertz radiation from NovoFEL.



THz imaging with "Thermal Image Plate" (TIP)

Thermal image plate, Mickan Instruments

Red – out of THz beam area (B)
Blue – in the area of THz beam (A)

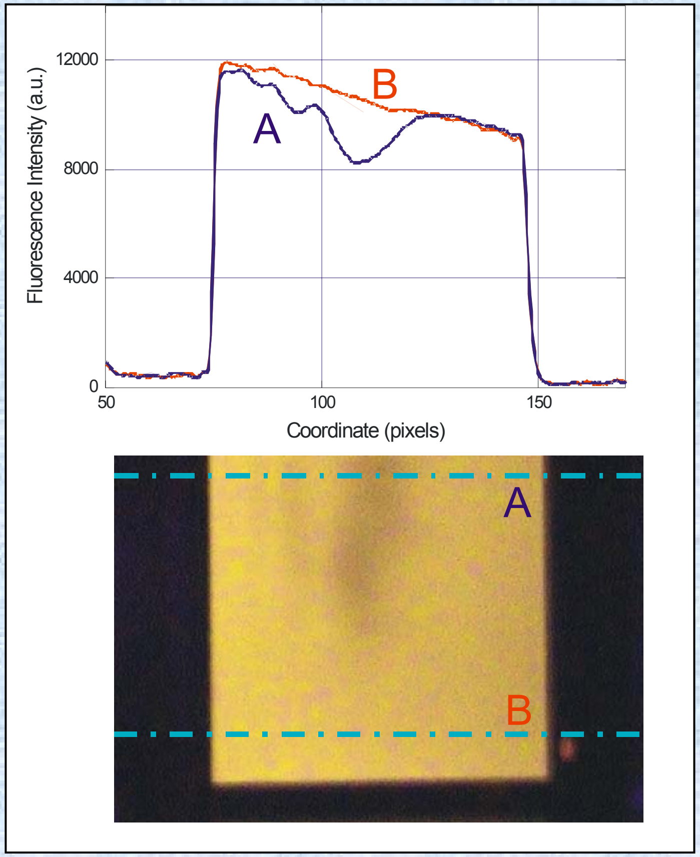
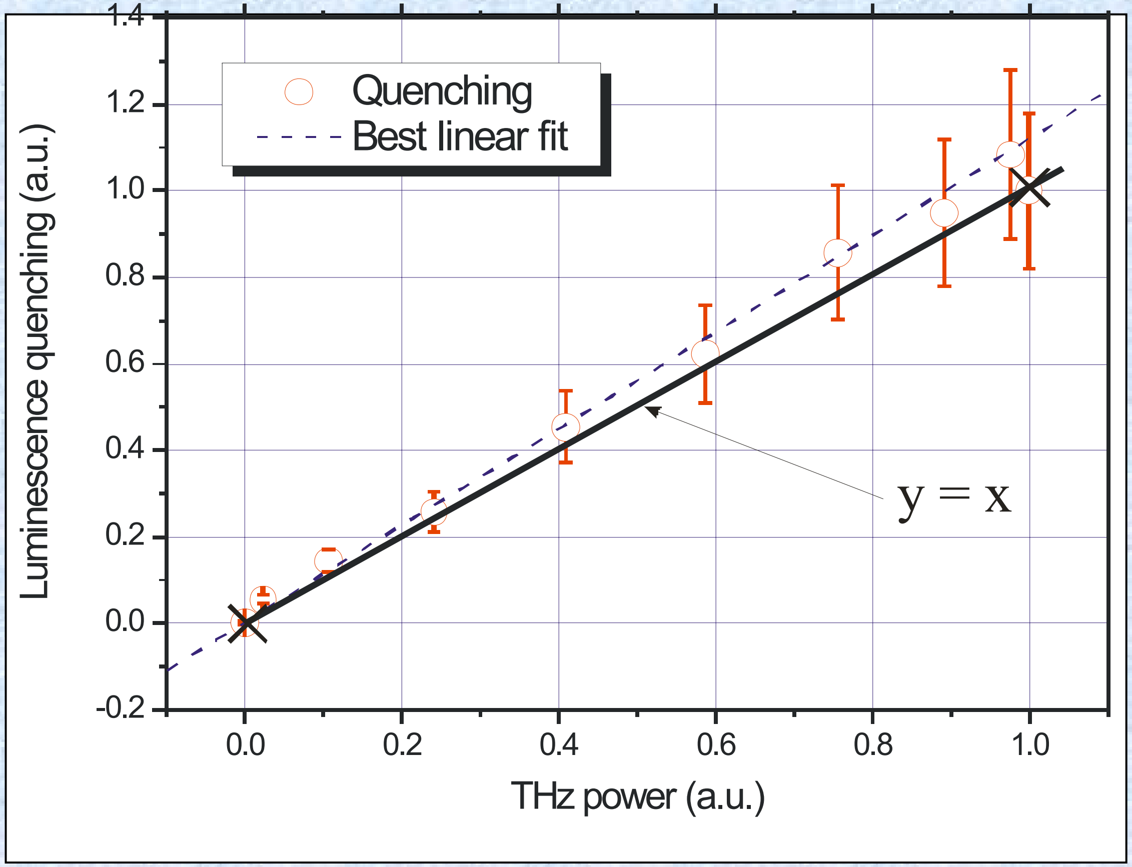


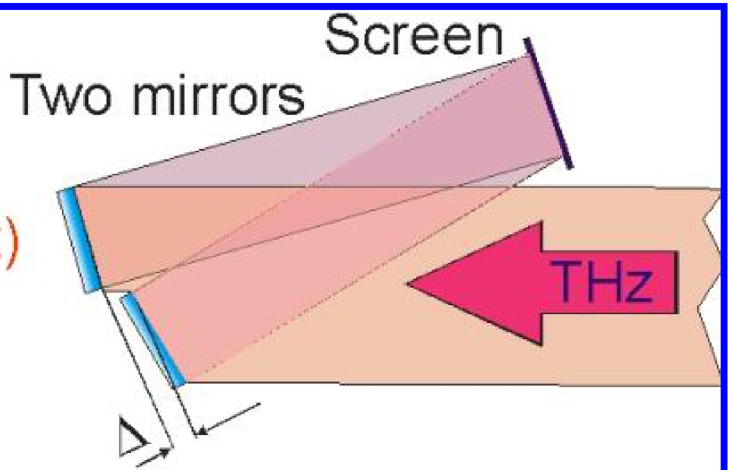
Image of a diffraction pattern.

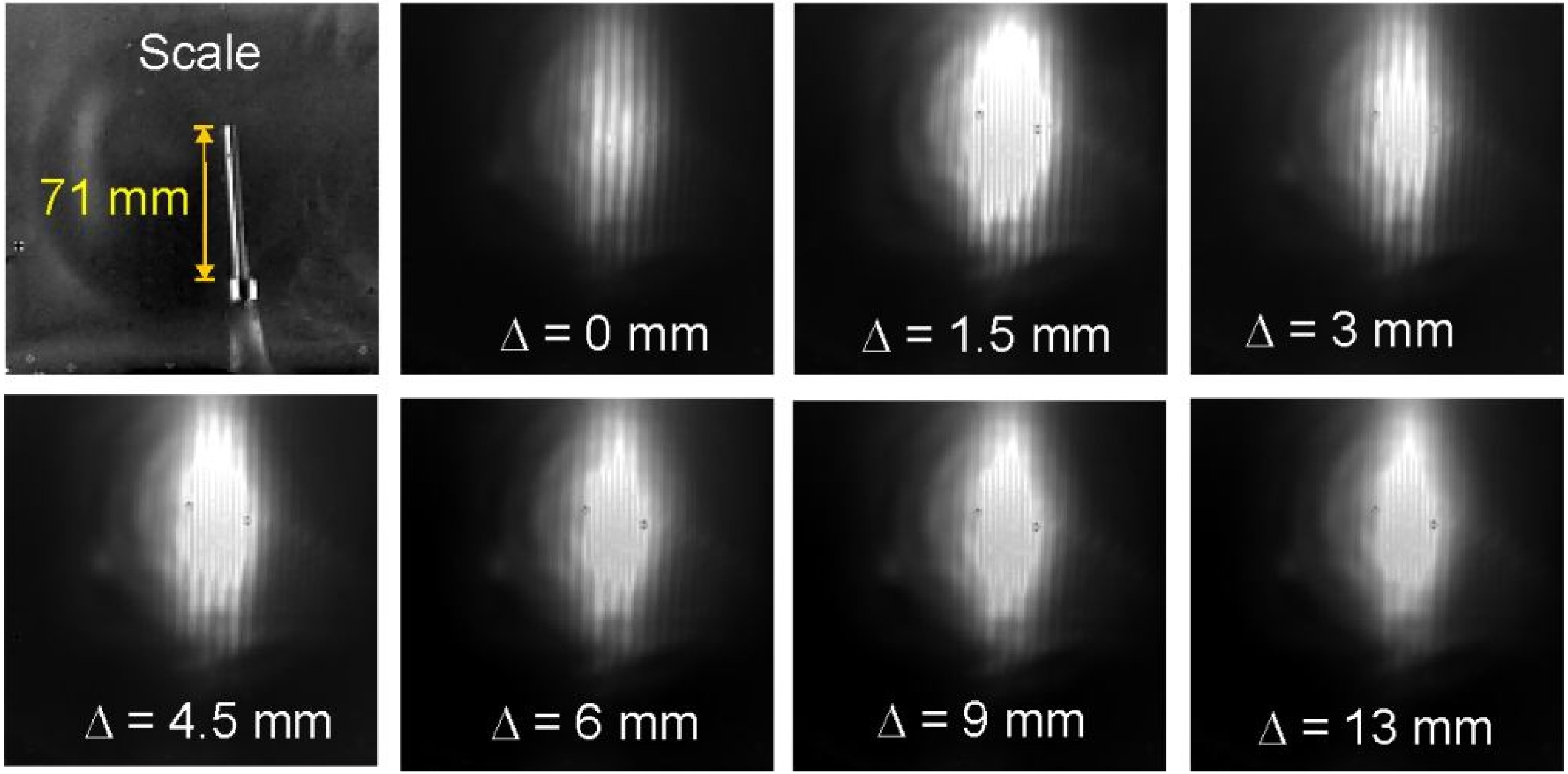


Calibration of TIP sensitivity vs. THz beam intensity.

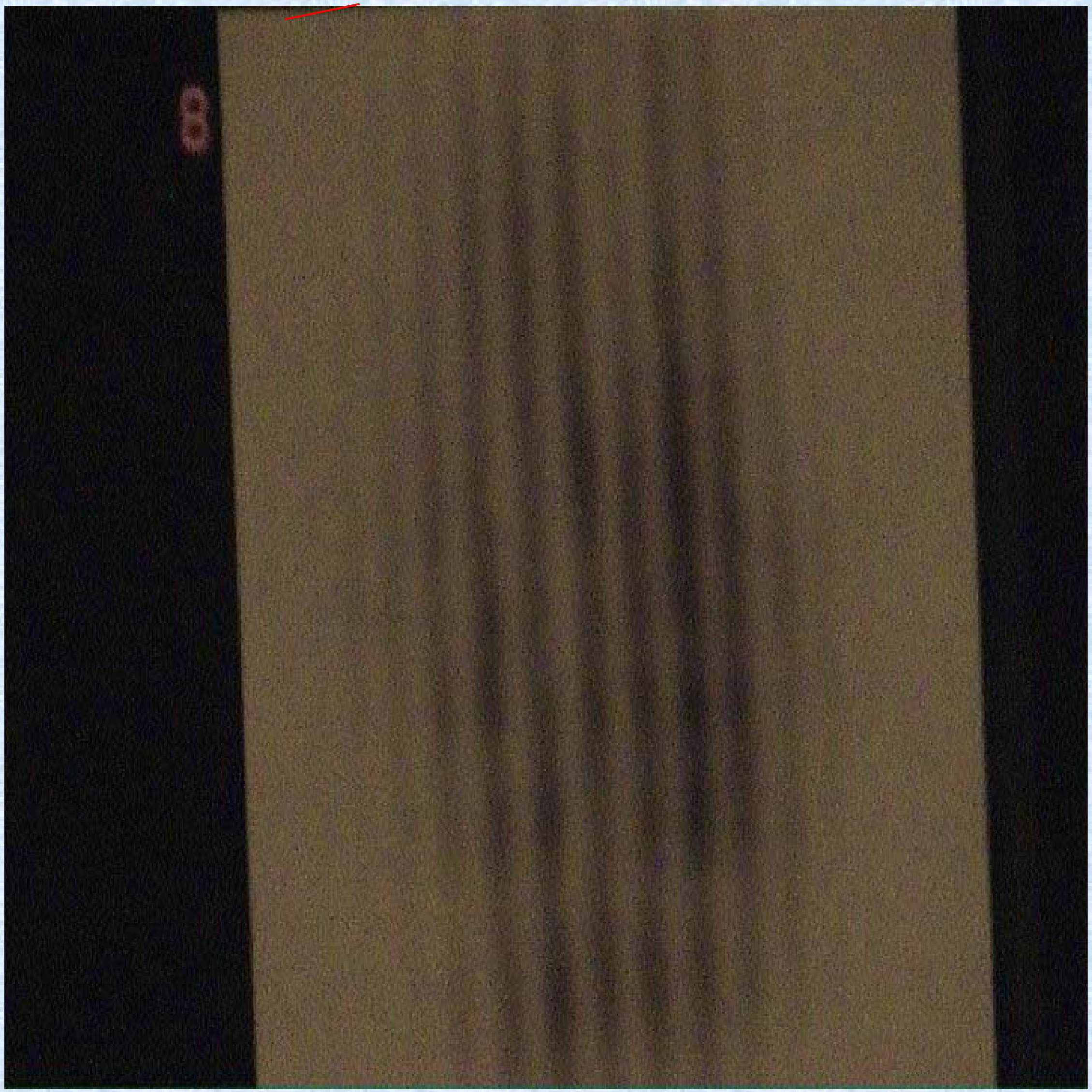
Space and temporal coherence

Measurement of the coherence length with
a Fresnel bi-mirror Δ is a mirror displacement)
Recording with the IR thermograph





Measurement of the coherence length by Freshel bi-mirror method

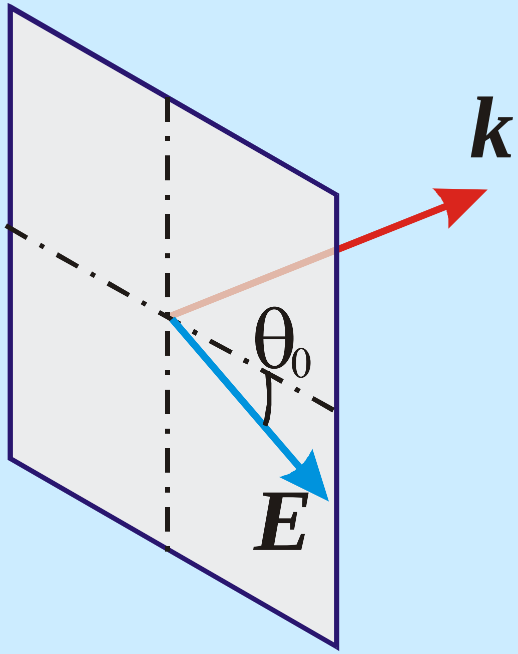


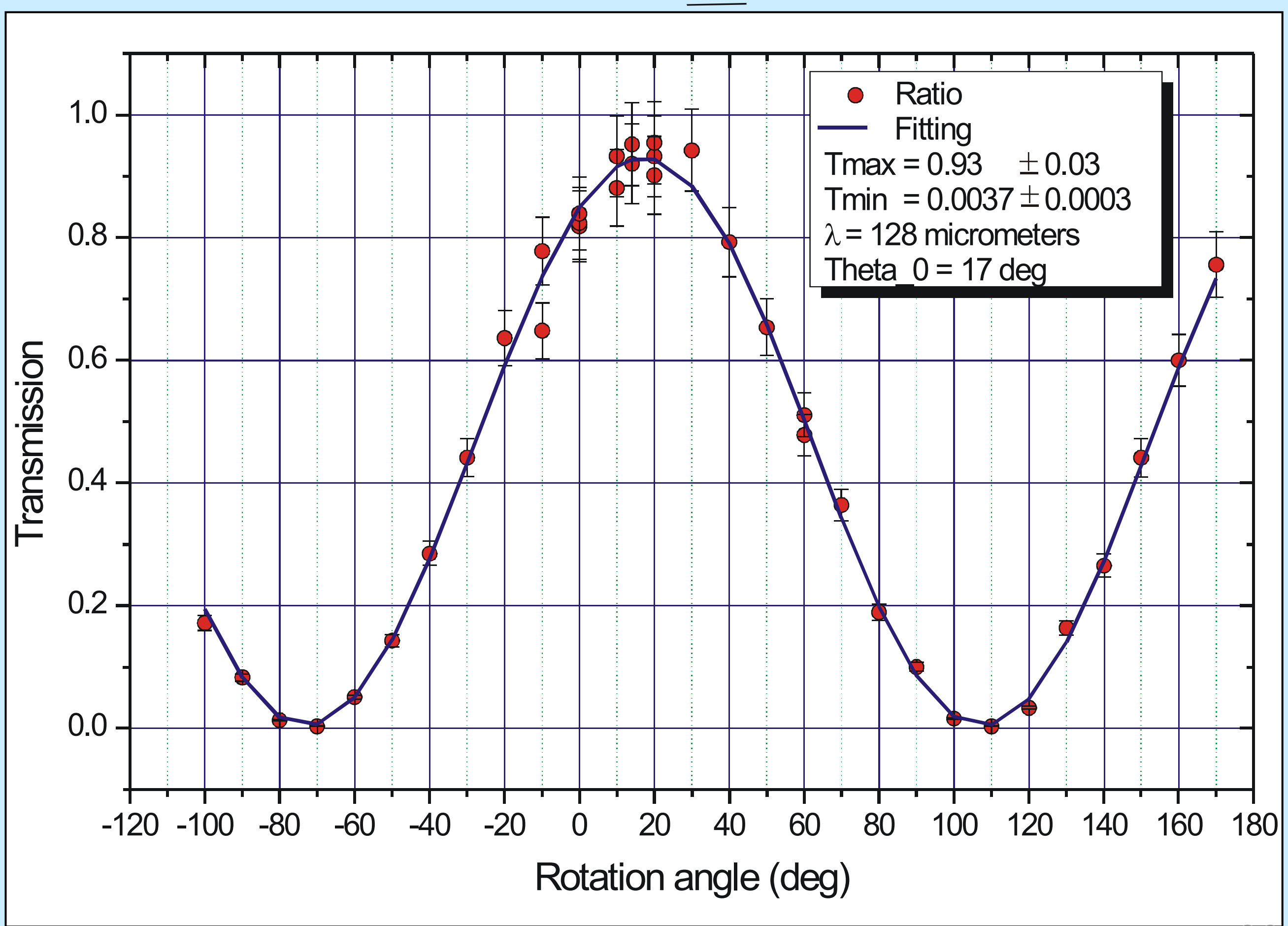
Diffraction picture for the mirror displacement Δ = 0

Image with thermal image plate (luminescence quenching)

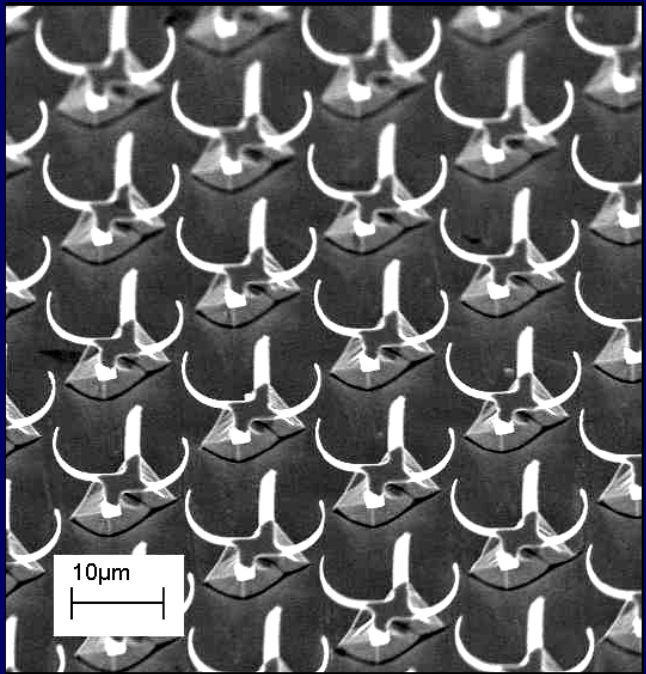
Linear polarization of radiation from THz FEL

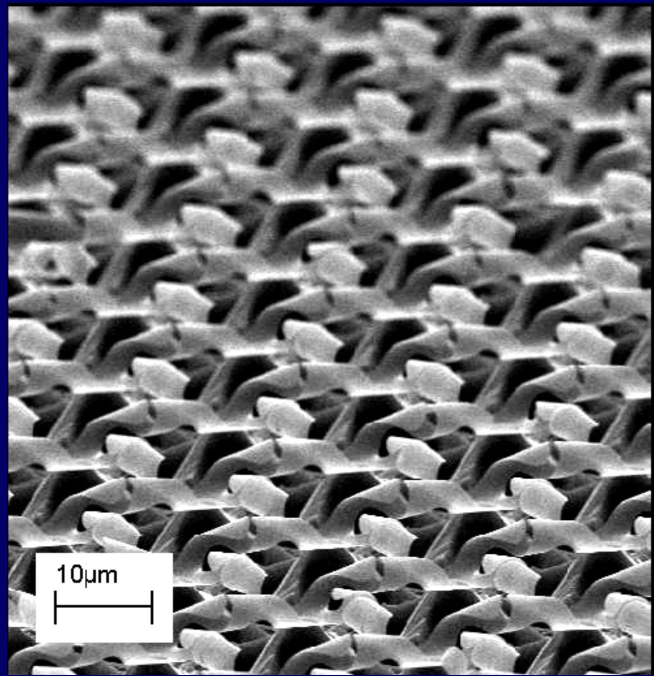
Transmission of the QMC Instruments Ltd polarizer
(metal stripes on the mylar film)
This result was obtained for average power of 25 W
The polarizer was tested for the maximum power density up to 8 W/cm²





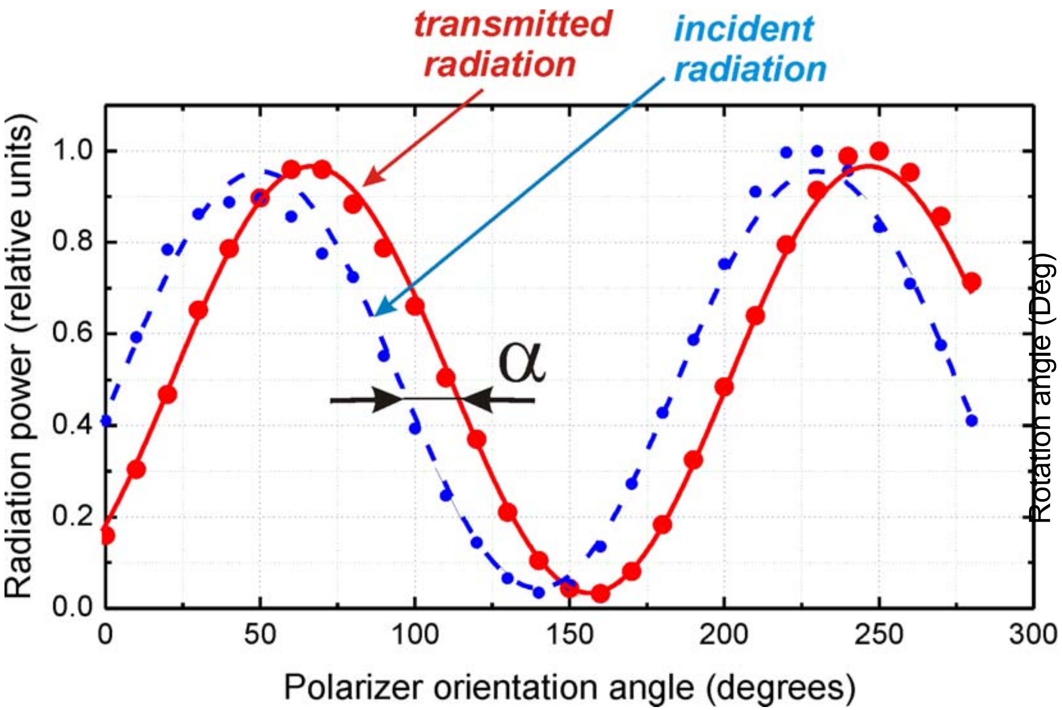
Rotation of the polarization plane by helical structutes



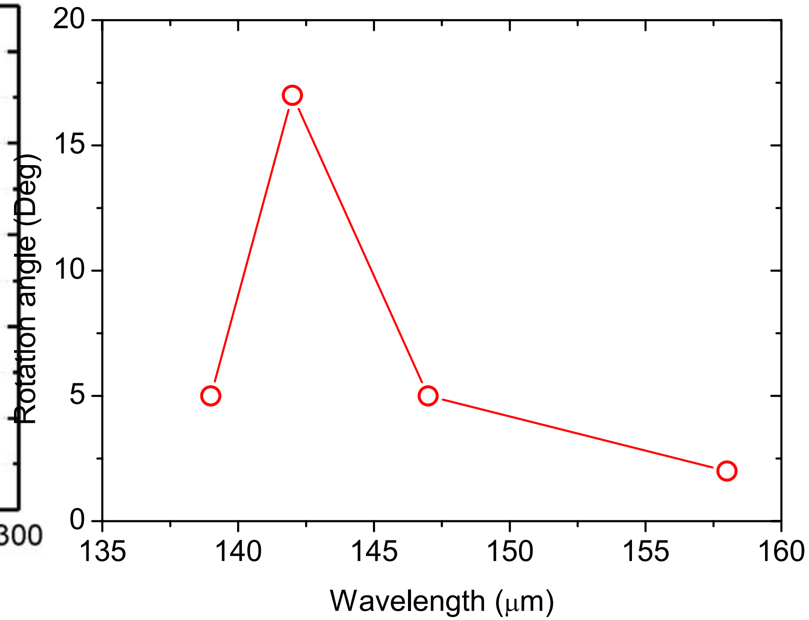


Started studying of rather unusual novel objects. In ISP SB RAS suggested novel technology allowing fabrication of precise 3D shells of various shapes and arrays on their basis.
Some examples of realized 3D shell-structures are presented on the next figures.
Such structures can be made of different materials including metals and doped semiconductors.
Multiformity of configurations, repeatability of shapes, scalability of sizes make arrays of such shell-structures very attractive as a basis for novel artificial composite media with tailored electromagnetic properties for different spectral ranges including THz one.

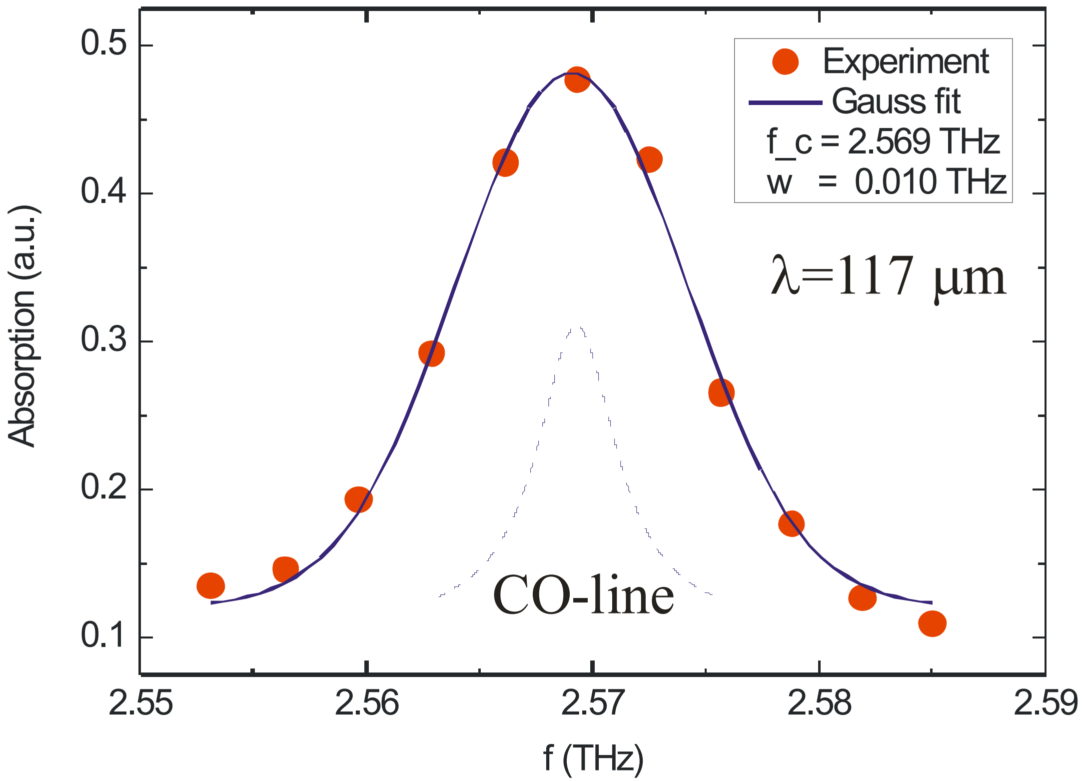
Rotation of the polarization plane by helical structures



Maximum of rotation corresponds to the length of structure elements of 75 μm that close to a half wavelength for λ=142.8 μm



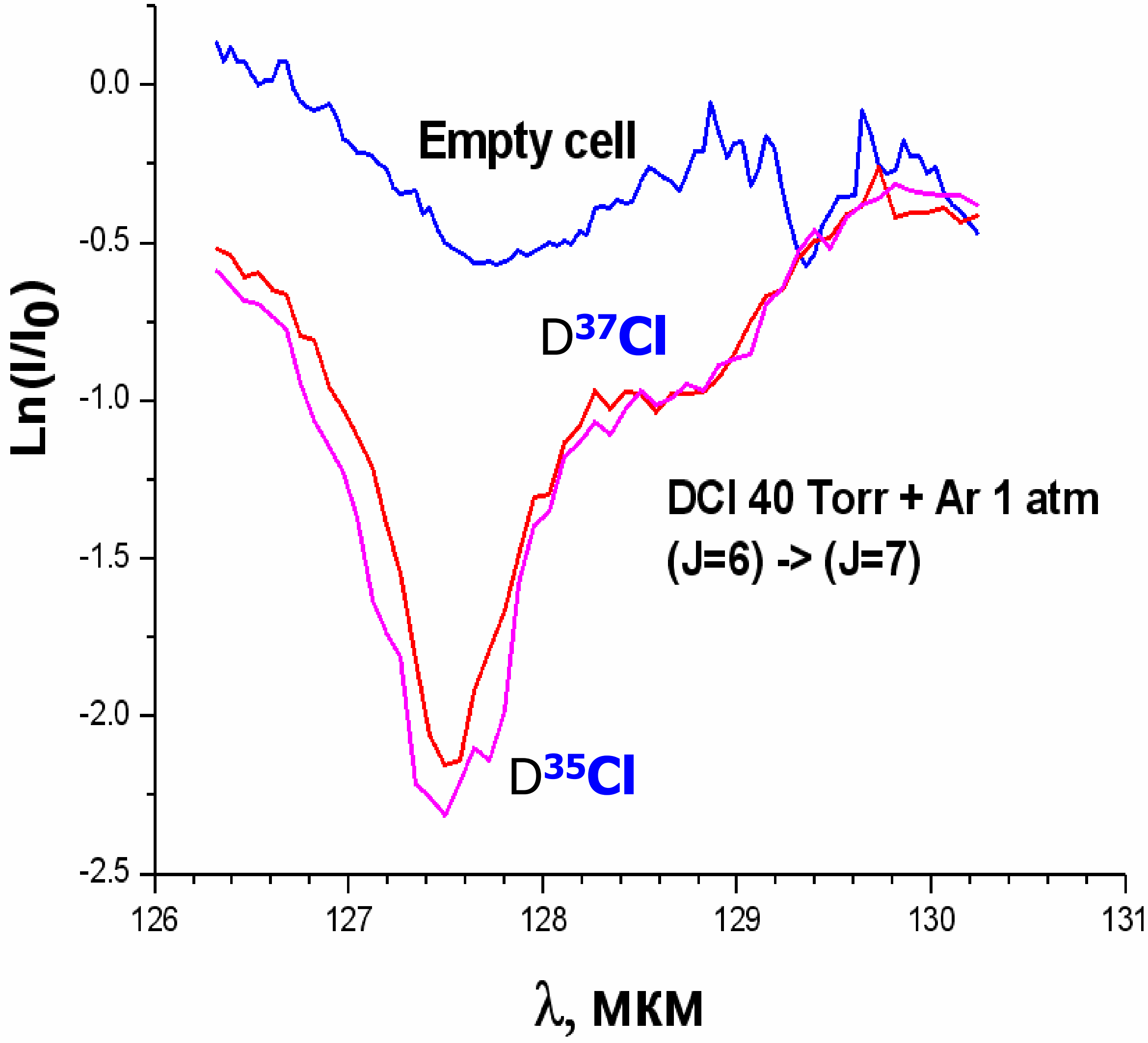
The single layer of metal-semiconductor helices with the thickness just about 1/15th of the wavelength rotates the polarization plane by 17 degrees.



Absorption in CO gas cell vs. laser wavelength; the dash line is calculated profile of CO-molecule transition.

Using of tunability of NovoFEL.

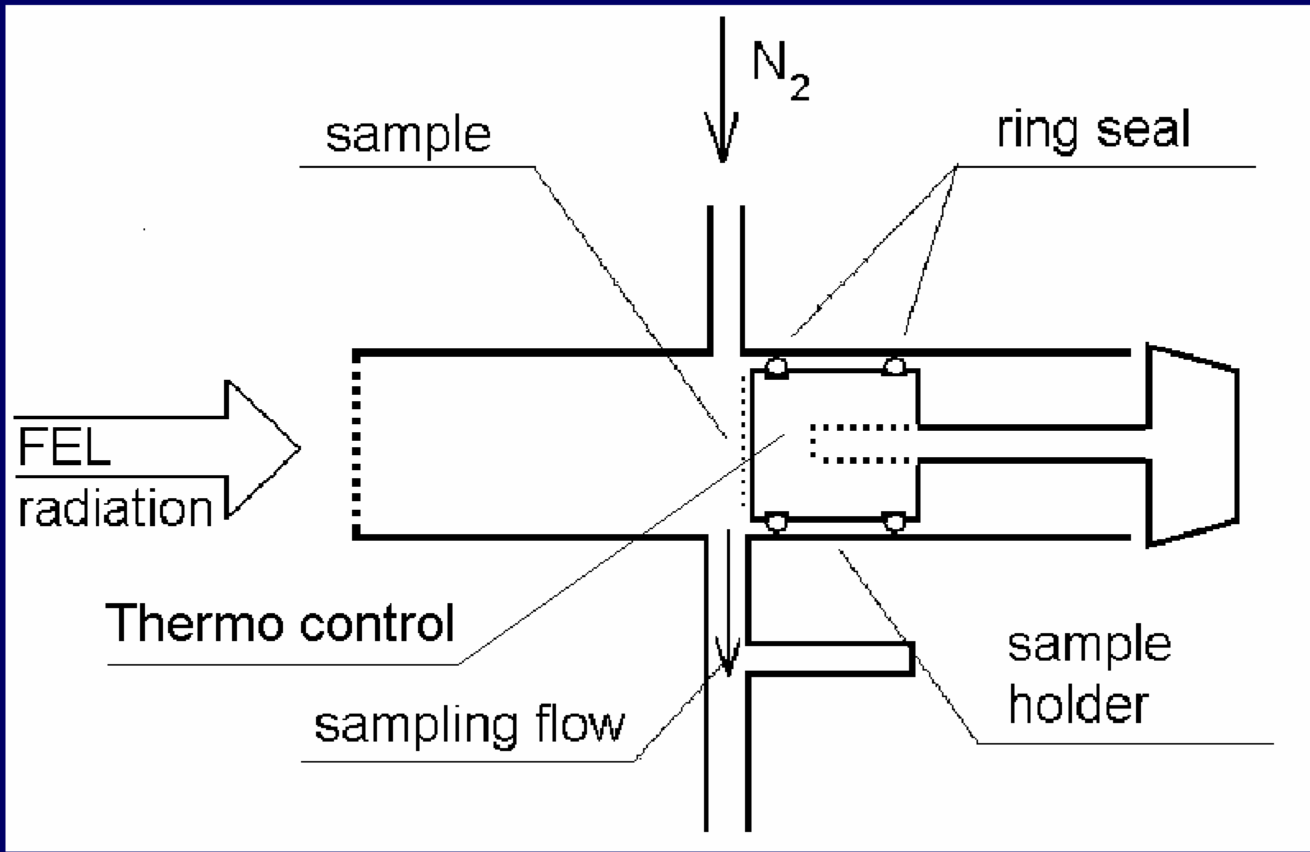
Separation of Cl isotopes in absorption spectrum.



Absorption spectrum of DCl gas (transition line J = 6,7)

NONDESTRUCTIVE TRANSFER OF COMPLEX MOLECULAR SYSTEMS INTO AEROSOL PHASE BY MEANS OF TERAHERTZ IRRADIATION OF FREE ELECTRON LASER (FEL)

Experimental cell cross-section

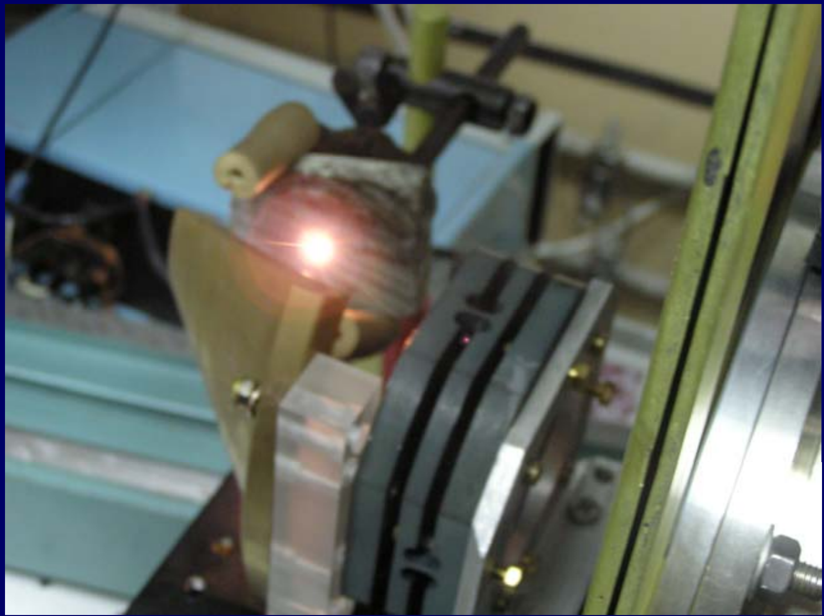


Equipment used for detection of aerosol products of ablation

- Automated diffusion battery
- Photoelectric particle counter
- Filter sampling
- Electronic microscopy
- Specific testing for biological activity

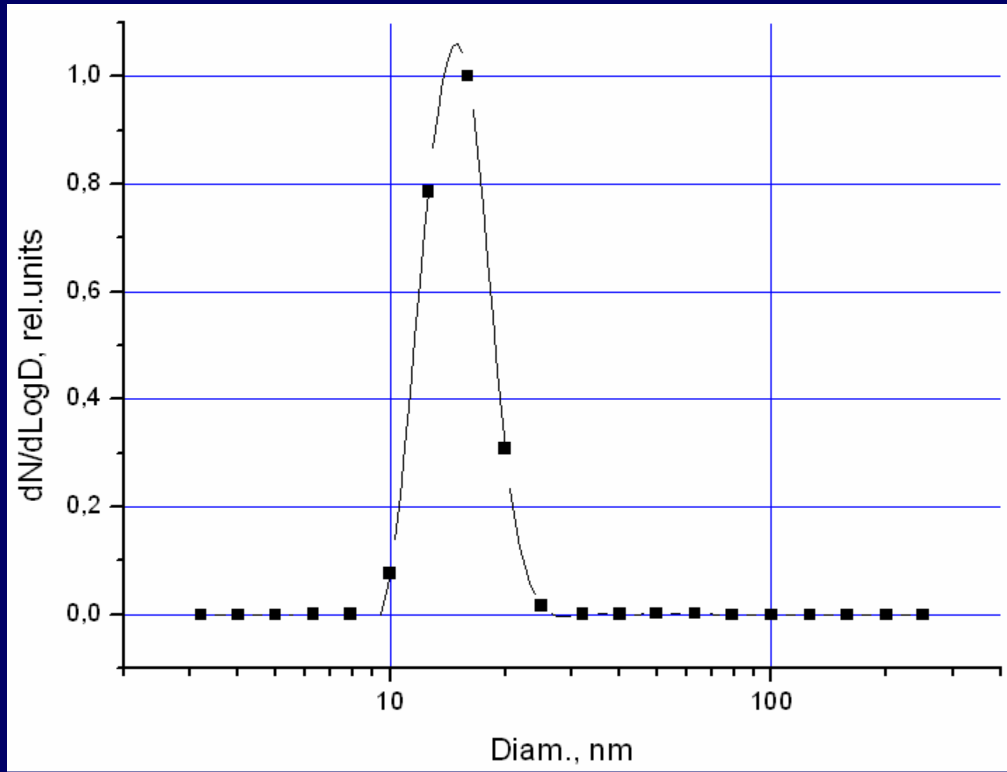
Size range covered: 3nm to 10µm   Measurement time: 4 min

Ablation of crystal minerals (marble)

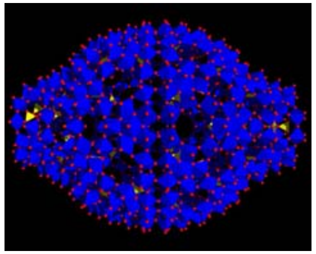


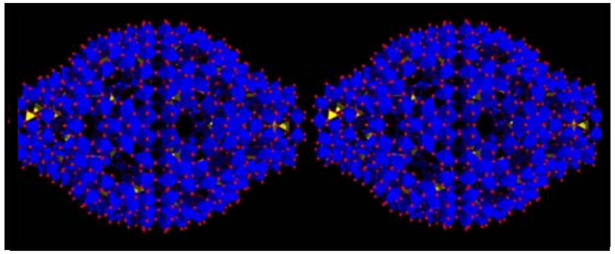
Ablation of marble

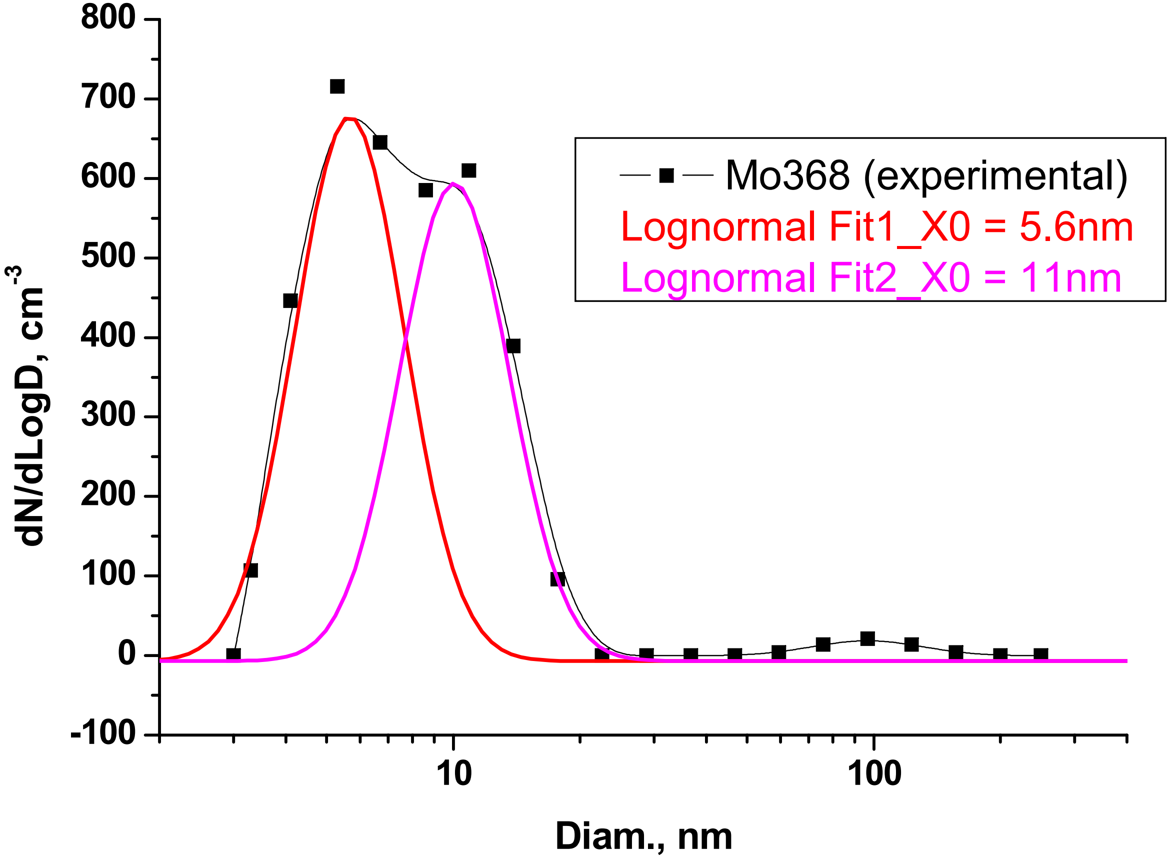
мрамор



Ablation of fullerenes

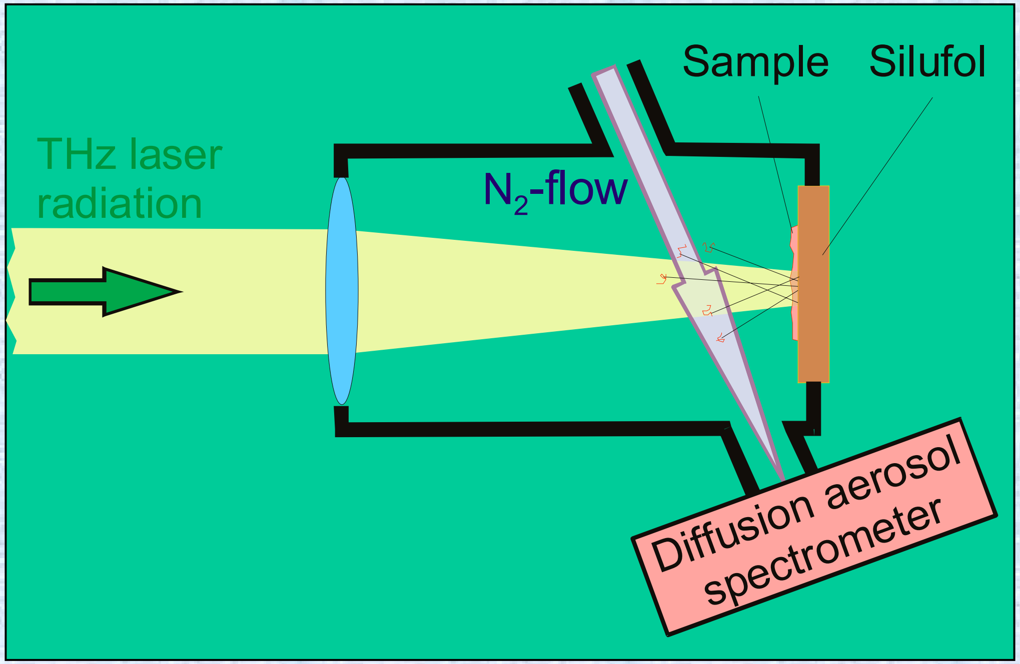


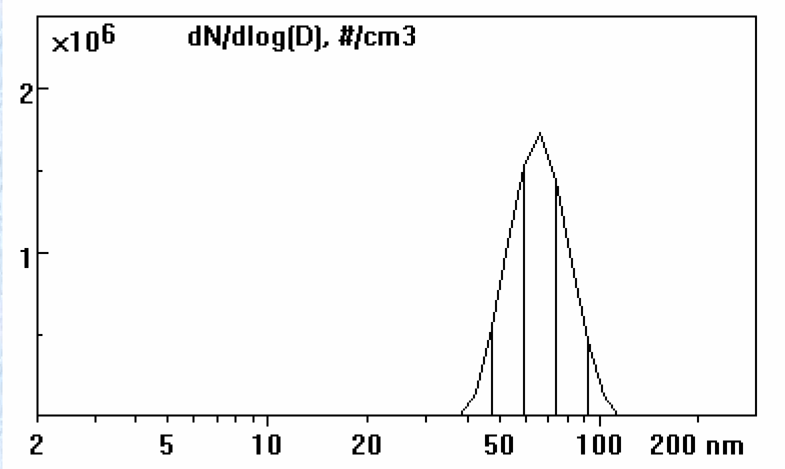




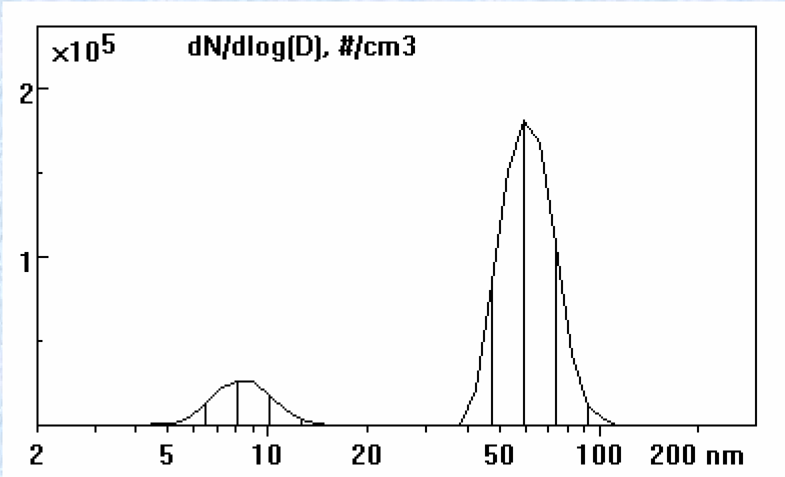
Mo_{368} – 5,6 нм; $\{Mo_{368}\}_2$ – 11,2 нм

Ultra-soft laser ablation of DNA





Phage DNA



Phage DNA + plasmide DNA

Demonstration of ultra-soft ablation of DNA samples without denaturation: when the power density of THz radiation is optimal, particle size spectra contain only the peaks corresponding to the initial particles. For higher power densities multi-peak spectra are observed.

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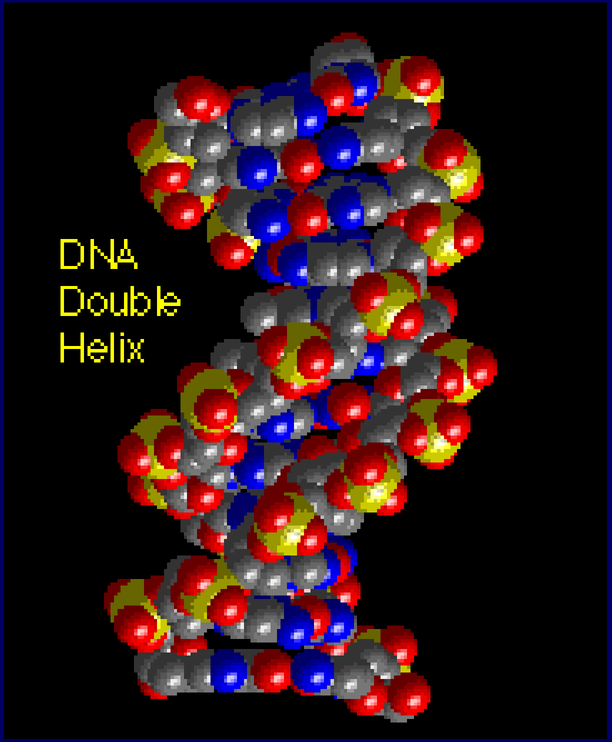
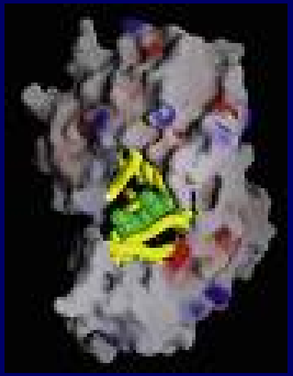
Alive after laser pulse



In order to reveal whether the enzymatic activity of ablation products is conserved, we carried out a test for histochemical coloring of the collected aerosol of horseradish **(хрен)** peroxidase.

The tests showed that this complicated enzyme and DNA (with the mean molecular mass of up to 60000 a.m.u.) remained active after ablation.

Horseradish peroxidase



We believe that this result is extremely important for biotechnology.

Alexander S. Kozlov et al. NONDESTRUCTIVE TRANSFER OF COMPLEX MOLECULAR SYSTEMS INTO AEROSOL PHASE BY MEANS OF SUBMILLIMETER IRRADIATION OF FREE ELECTRON LASER (FEL). Presented at this Conference.

Results overview
(new features in terahertz FEL application)

- **Nondestructive effect of terahertz FEL irradiation to biological systems**
- **Possibility of analysis of fraction content of disperse/colloid nanosystems**
- **Wavelength effect to the enzyme activity**

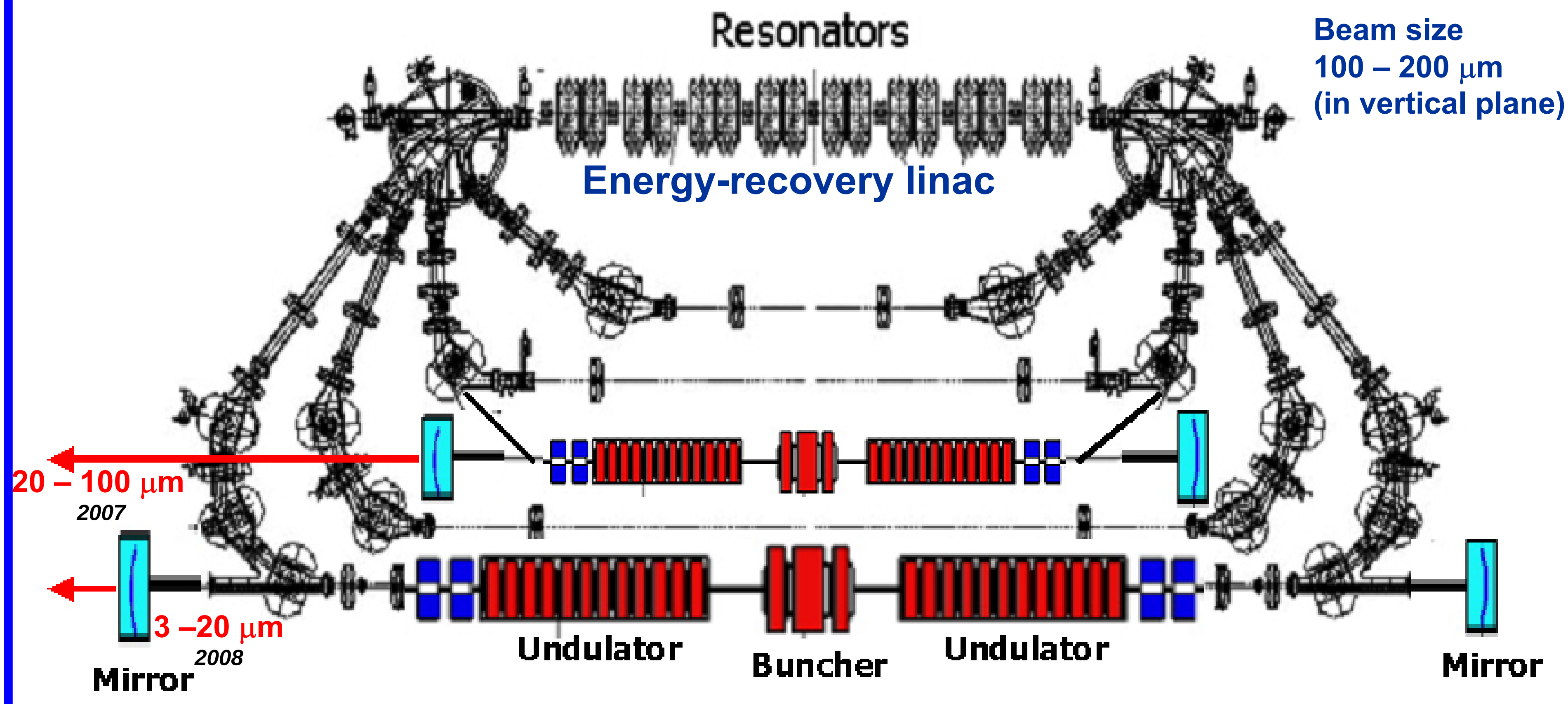
4.
Second stage of the Novosibirsk accelerator-recuperator and FEL

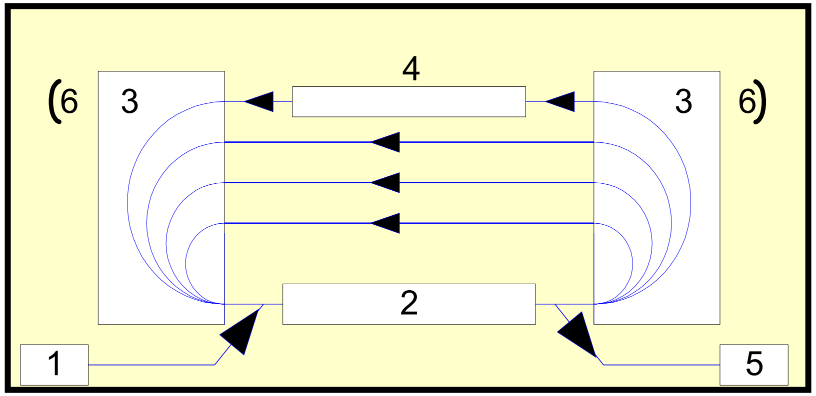
Second stage of accelerator-recuperator and FEL

A full-scale 4-track accelerator-recuperator uses the same accelerating structure as the accelerator-recuperator of the 1st stage but in contrast to the latter, it is placed in the horizontal plane. Thus, there is no need in dismounting one for installing another.

The choice of operation regime at one of two machines and one of three FEL will be achived by simple reswitching of the bending magnets.

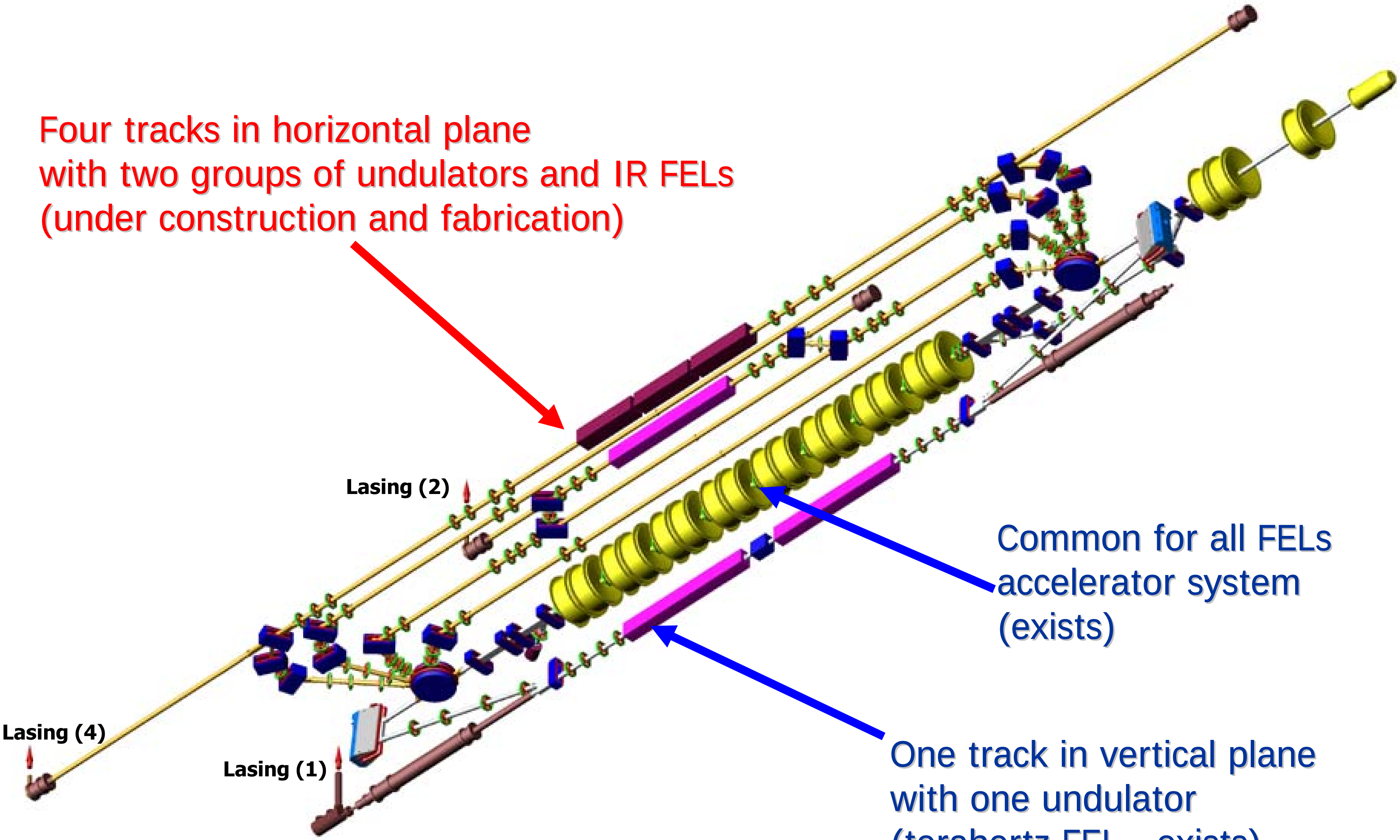
2-nd stage Novosibirsk FEL (under construction)



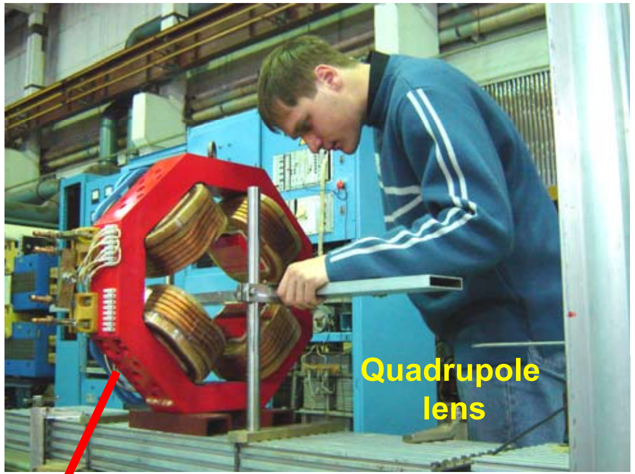


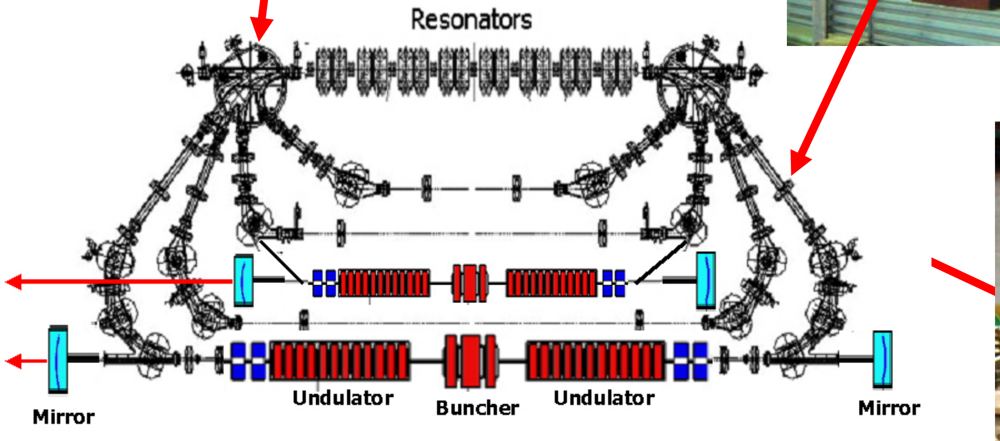
Radiation wavelength	3 – 100 μm
Average power	10 – 100 kW
E-beam energy	up to 50 MeV
Maximum repetition rate	90 MHz
Maximum mean current	150 mA

Full scale Novosibirsk FEL (bottom view)



2006-2007: fabrication and assembling of the components of 2-nd stage Novosibirsk FEL





The FEL under construction will generate the monochromatic radiation in the form of repeated micropulses of ~10 picosecond duration and energy of ~ millijoules with the wavelength retuning from 3 to 100 μm.

This will enable the resonance action at any oscillation in molecules. FEL will enable the unique experiments in the fields of physics, chemistry, biology and medicine.

For example, one can selectively excite or dissociate one kind of molecules in a mixture (isotopes, isomers, microadmixtures), study the influence of the oscillation excitation of molecules and radicals on the rate of biomolecular reactions, which is extremely important, in particular, for understanding the chemical processes in atmosphere, study the fast reactions and spectroscopy of excited states.

The most important applications of such a powerful and expensive machine are in the field of high technologies.

Technological applications of a powerful tunable IR FEL of continuous operation

- Separation of isotopes. The basic process is a selective multiphoton dissociation of molecules. The resonance wavelength range is 2—50 μm. The required pulse energy is not less than 0.1 mJ and monochromaticity of 10^{-2} — 10^{-4} depending on the type of reaction. Maximum pressure (and efficiency) in reactor is inversely proportional to the radiation pulse duration and at t ~ 10 ps it can exceed the atmospheric pressure.

- Mass production of stable isotopes:

$_{28}$**Si** –radiation resistant material (space, weapon industry, nuclear energetics). The thermal conductivity of the pure isotope is over 50% higher than that in the natural mixture. This circumstance provides a great gain in production of powerful semiconductor apparatuses and microchips. $_{28}$**Si** is also used in metrology and in the future technology - spin electronics.

$_{13}$**C** – is a spin mark for NMR-tomography in the development of new medications and in medical diagnostics.

$_{15}$**N** – is also the spin mark for the study and current control of use of nitrogen fertilizers in agriculture and agrochemistry.

Technological applications of a powerful IR FEL of continuous operation

- Treatment of polymer surfaces

The aim:

mechanical (sharp increase of surface area), chemical (transformation of the amides into amines groups) modification or pyrolysis (conversion into pure carbon) of surfaces of the polymer films and synthetic fibers.

New properties:

o Improvement of the film adhesion with respect to each other or other surfaces.

o Dull surface with no mirror reflection . More colorful when painting (mechanical modification)

o Anticeptic properties of a surface (chemical modification)

o Conducting surface (pyrolysis)

- Energy transfer to cosmos.

Research applications of a powerful tunable IR FEL of continuous operation

Physics:

• Semiconductors - admixture levels, excitation, recombination dynamics. Superconductivity-conductivity zones, admixtures.
• Optical reflecting surfaces and monomolecular layers.
• Physics of surfaces.
• Spectroscopy.
• Molecular rotating and oscillating transitions.
• Diagnostics of the combustion zones.
• Lidar.
• Calibration of IR-radiation detectors.

Chemistry:

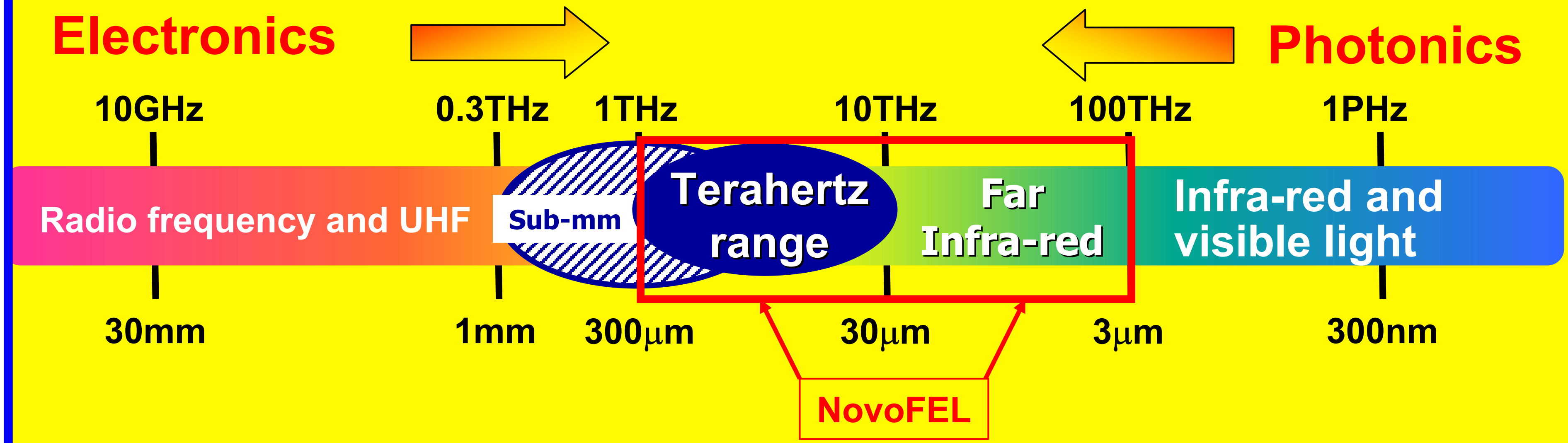
• Selective reactions and separation of isotopes.
• Dynamics of molecule excitations.
• Laser catalysis.

5.
Conclusion

At present, an intense work on creation of powerful FELs (> 1 kW of average power) is carried out worldwide. For the purposes of industrial technologies, it is necessary to reach the average power level of ~10 kW.

- In some cases, the problem is a rather wide line of generation (usually, no less that 1-3%). For some industrial applications (for example, separation of isotopes), the required monochromaticity should be not worse than a few hundredths of per cent.

Electromagnetic waves



1 THz ~ 1 ps ~ 300µm ~ 33 cm^{-1} ~4.1 meV ~ 47.6⁰K

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Novosibirsk High Power Terahertz Free Electron Laser

Summary

- Novosibirsk terahertz free electron laser becomes a user facility.
- Radiation transmission line to the user stations hall has been assembled.
- First user stations are under design and construction.
- New users from European Community are welcomed.

Novosibirsk High Power Terahertz Free Electron Laser

We invite the researchers,

who want to perform interesting experiments

with a high-power, monochromatic, coherent,

tunable THz radiation,

to do it in Novosibirsk.

Siberian Center of Photochemical Research

Thank you for your attention