Novosibirsk Free Electron Laser: Terahertz Radiation Generation and Applications

N.A. Vinokurov

CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

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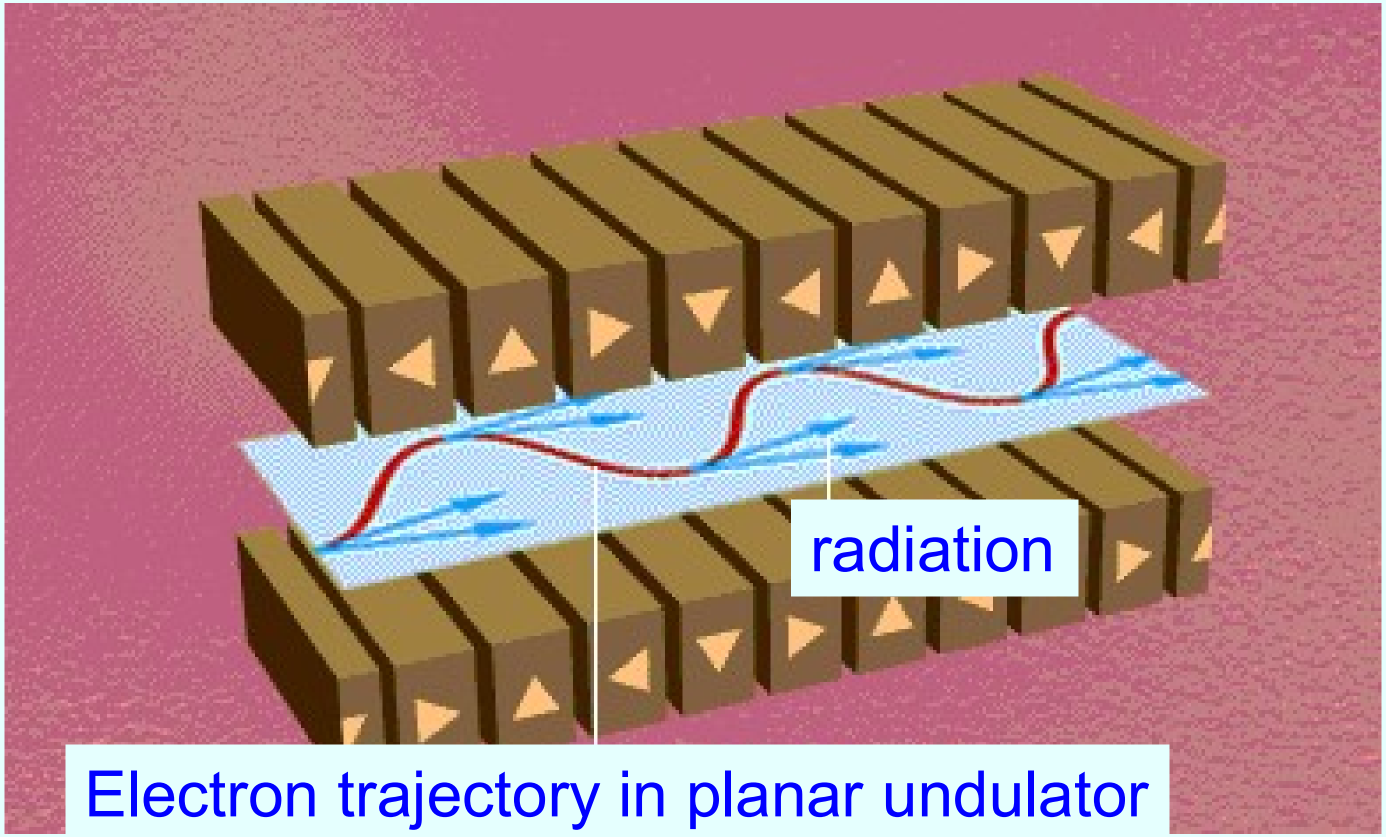
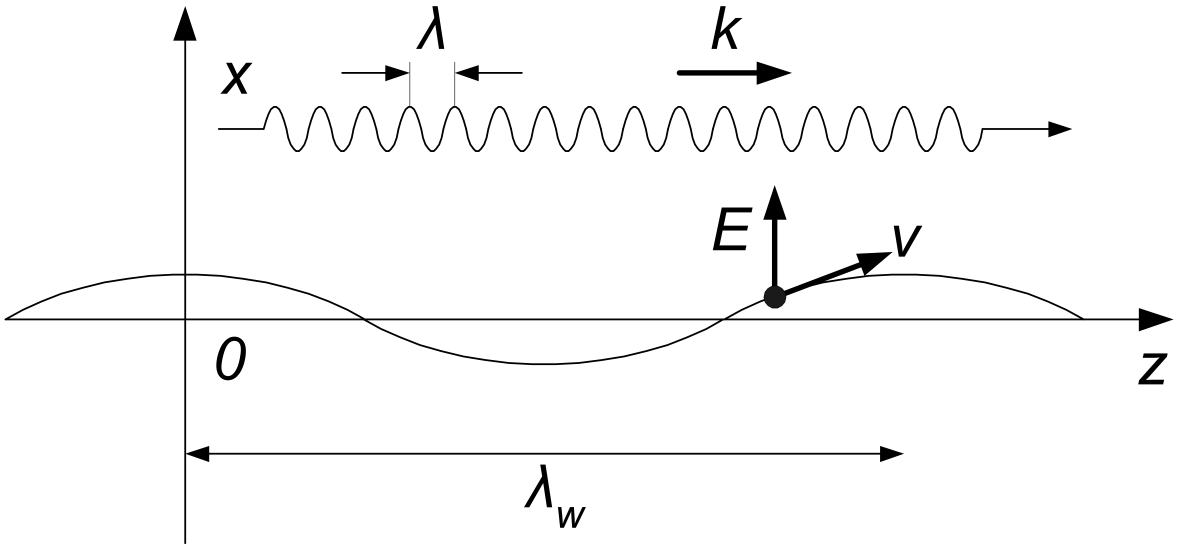
FEL principle of operation

Undulator (wiggler) is a magnetic system with spatially periodic transverse magnetic field. In such a field a relativistic electron may move along periodically bent trajectory (sinusoid or helix). It was invented by V. L. Ginzburg in 1947.



Electron trajectory in planar undulator
(permanent magnet undulator).

Undulator is the key part of an FEL. It provides effective energy exchange between electron and plane electromagnetic wave.



$$\lambda_0 \approx \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

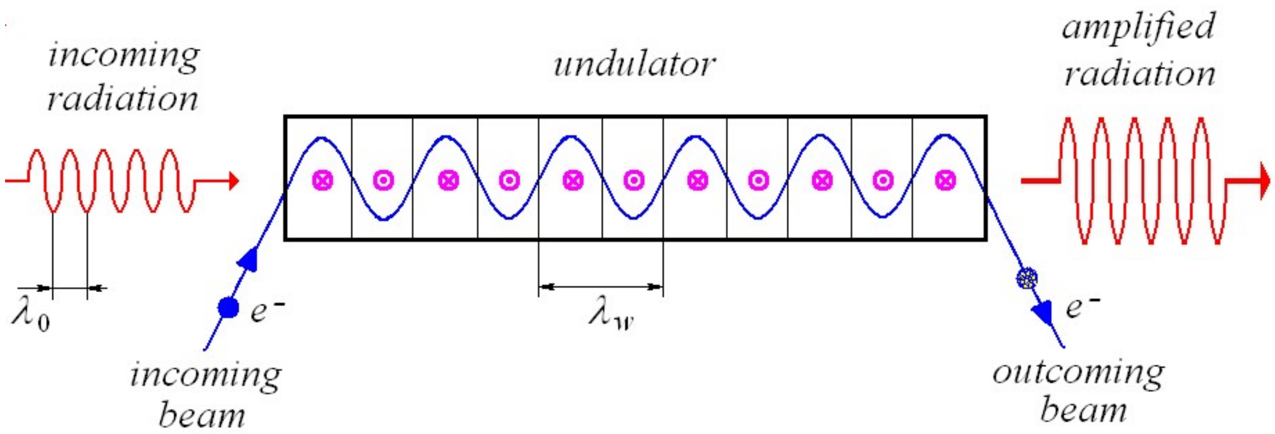
synchronism condition

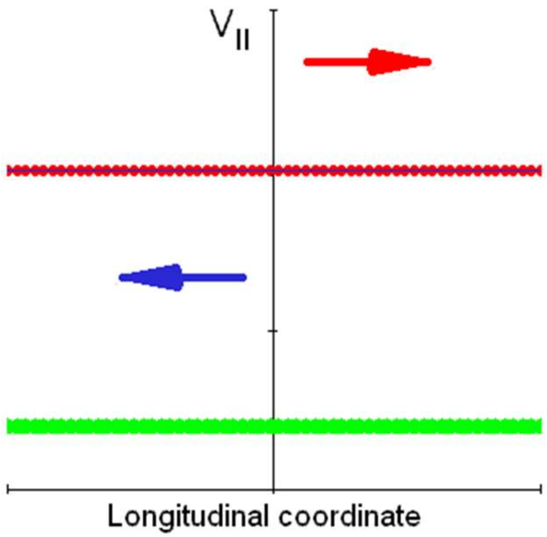
which is necessary for the

energy transfer

$$\left\langle \frac{d\gamma}{dz} \right\rangle = \frac{e}{mc^3}\left\langle \mathcal{E}_x V_x \right\rangle$$

FEL principle of operation





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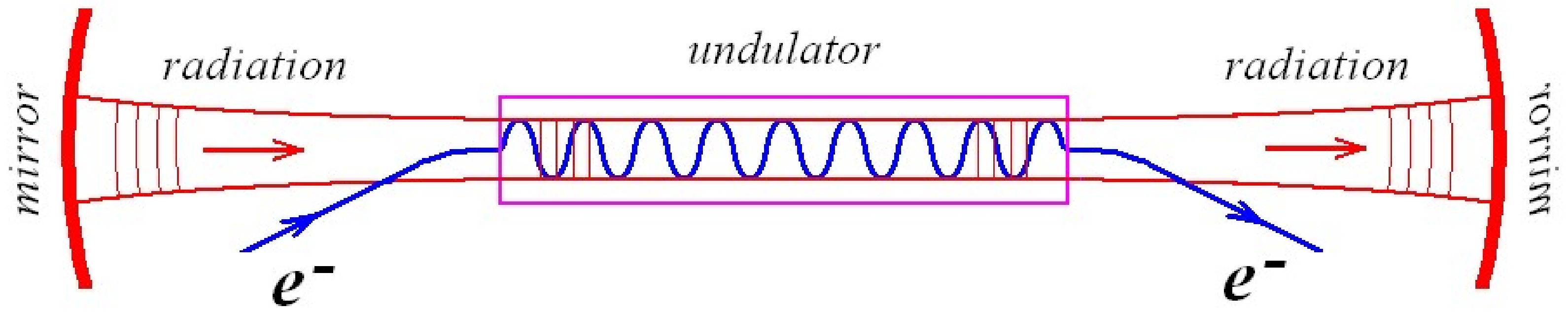
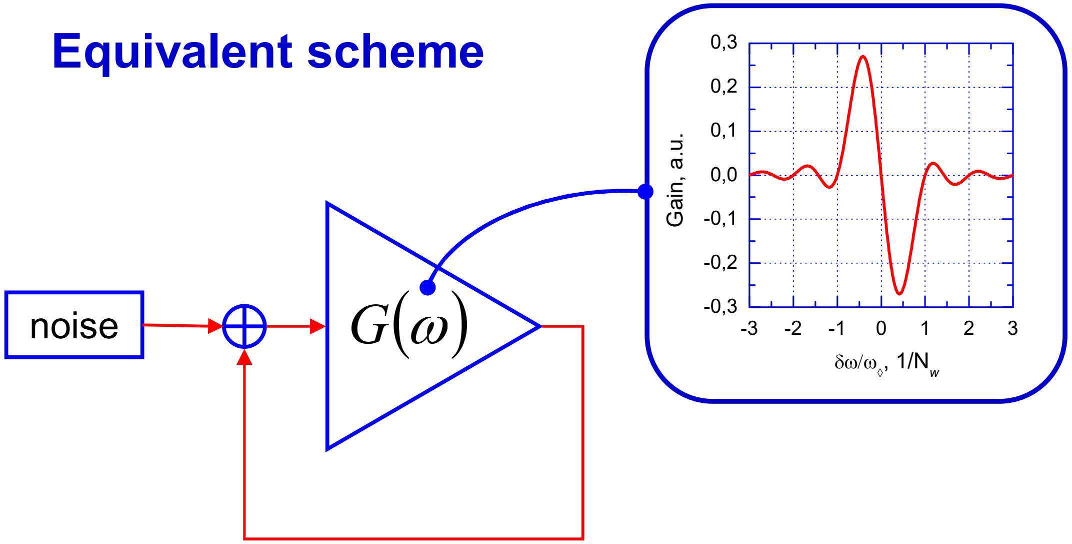
FEL principle of operation

FEL oscillator



Equivalent scheme



Narrow bandwidth amplifier
with feedback

To get lasing electron and radiation bunches have to come to undulator at the same time

High electron beam repetition rate is required!

Energy recovery

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

- Energy recovery:

  - decreases radiation hazard and heating load to dump

  - makes possible operation at high average current.

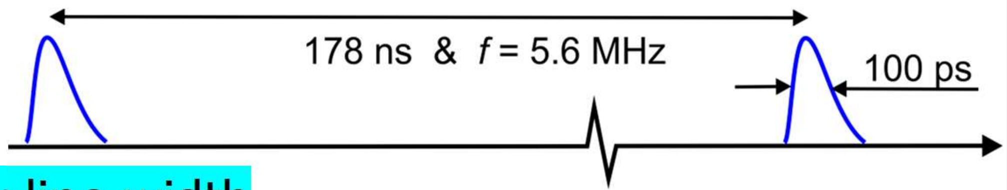
- Due to energy recovery, the cost of the building for FEL can be reduced.

Novosibirsk FELs

Radiation parameters of the Novosibirsk FEL facility (3 FELs)

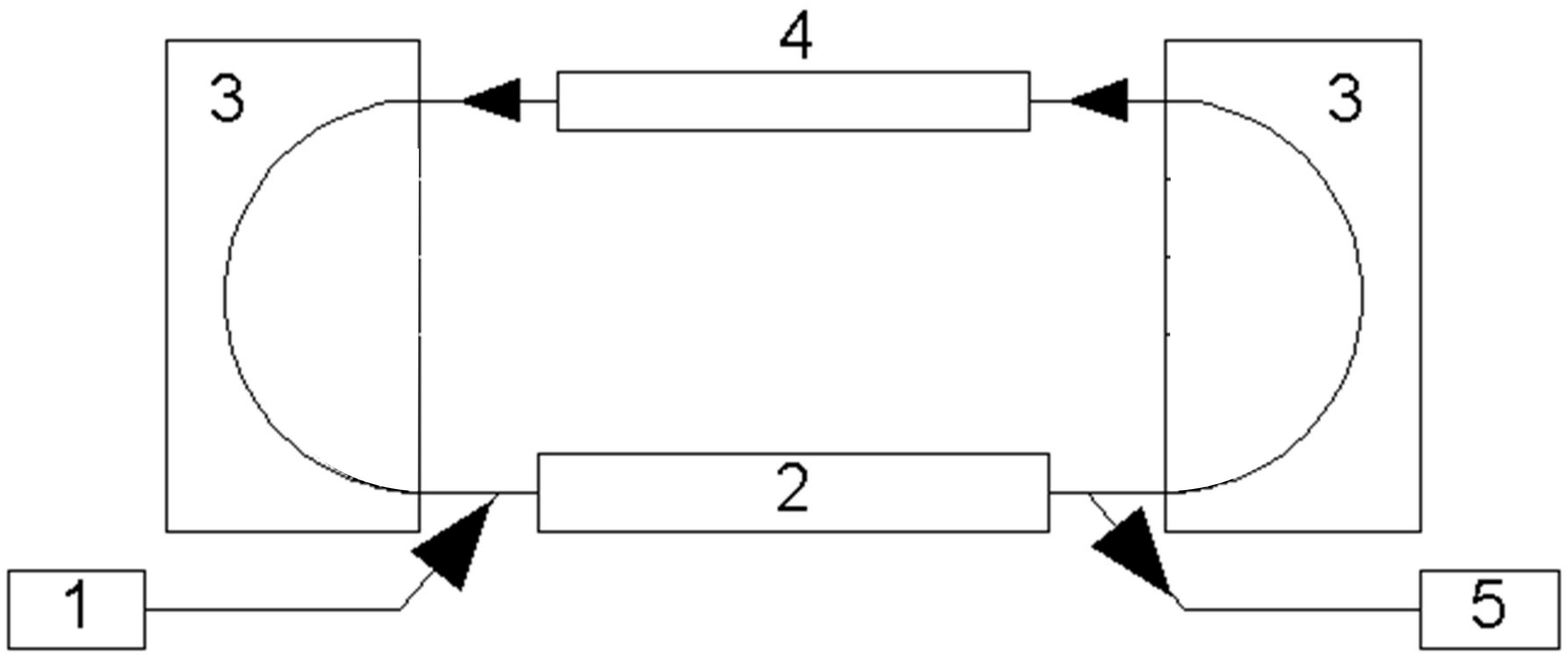
Laser	Terahertz	Far-Infrared	Infrared
Status	In operation since 2003	In operation since 2009	In operation since 2015
Wavelength, μm	90 – 340	37 – 80	8 – 11
Relative line width (FWHM), %	0.2 – 2.0	0.2 - 1	0.1 - 1
Maximum average power, kW	0.5	0.5	0.1
Maximum peak power, MW	0.5	2.0	10
Pulse duration, ps	30 - 120	20 - 40	10 - 20
Pulse repetition rate, MHz	2.8 - 5.6 - 11.2 - 22.4		
Linear polarization degree, %	> 99.6		

- Tunability
- High power
- Relatively narrow line width



NovoFEL Accelerator Design

Energy Recovery Linac

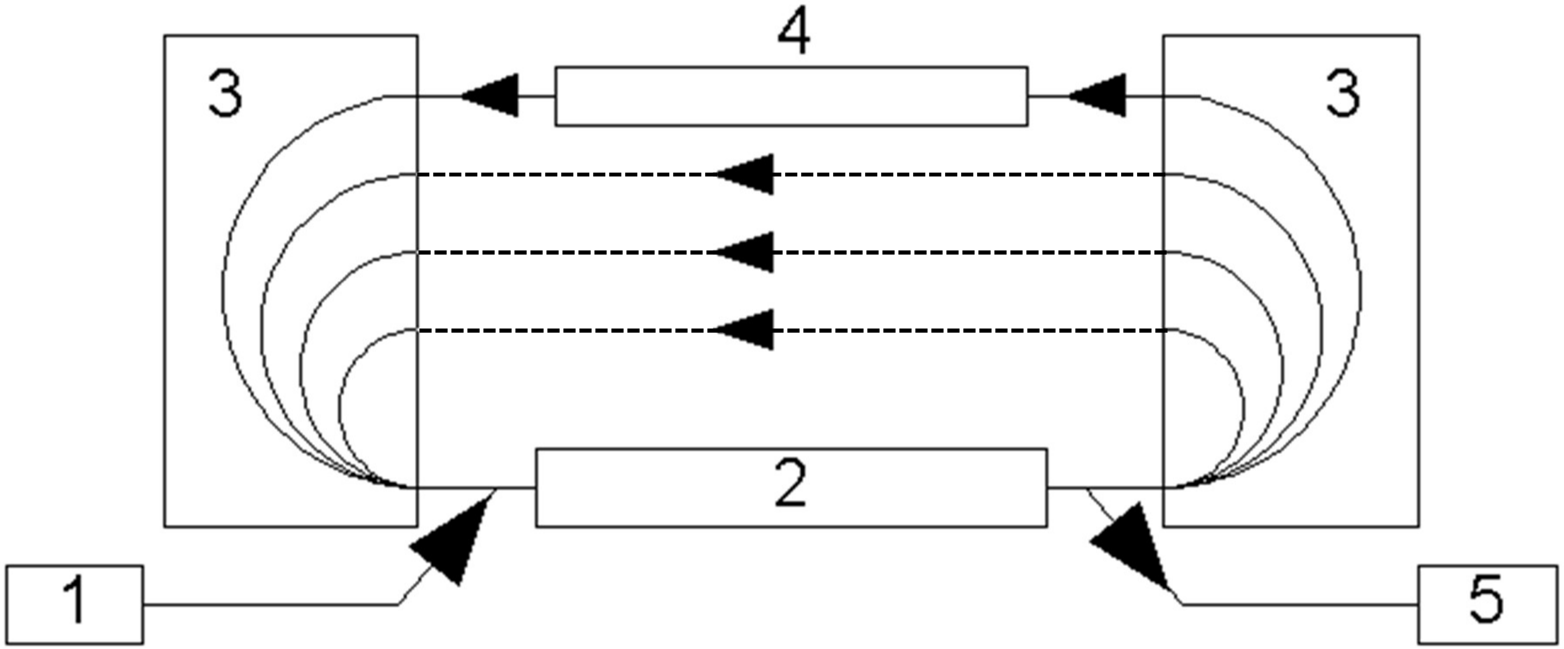


1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 –dump

Accelerator is the most important part of any **FEL**.
ERL is the best choice for **high power FEL**.

NovoFEL Accelerator Design

Energy Recovery Linac



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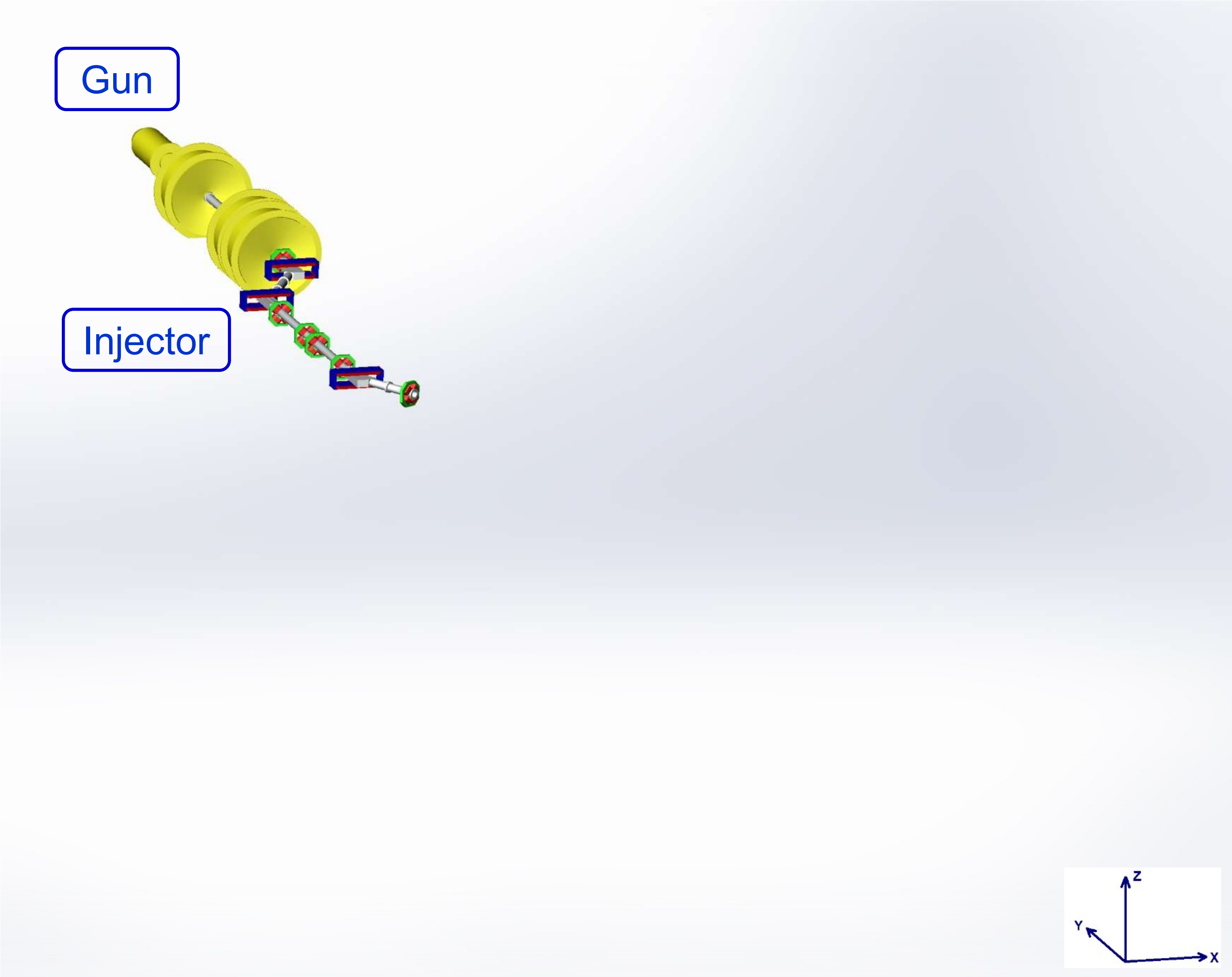
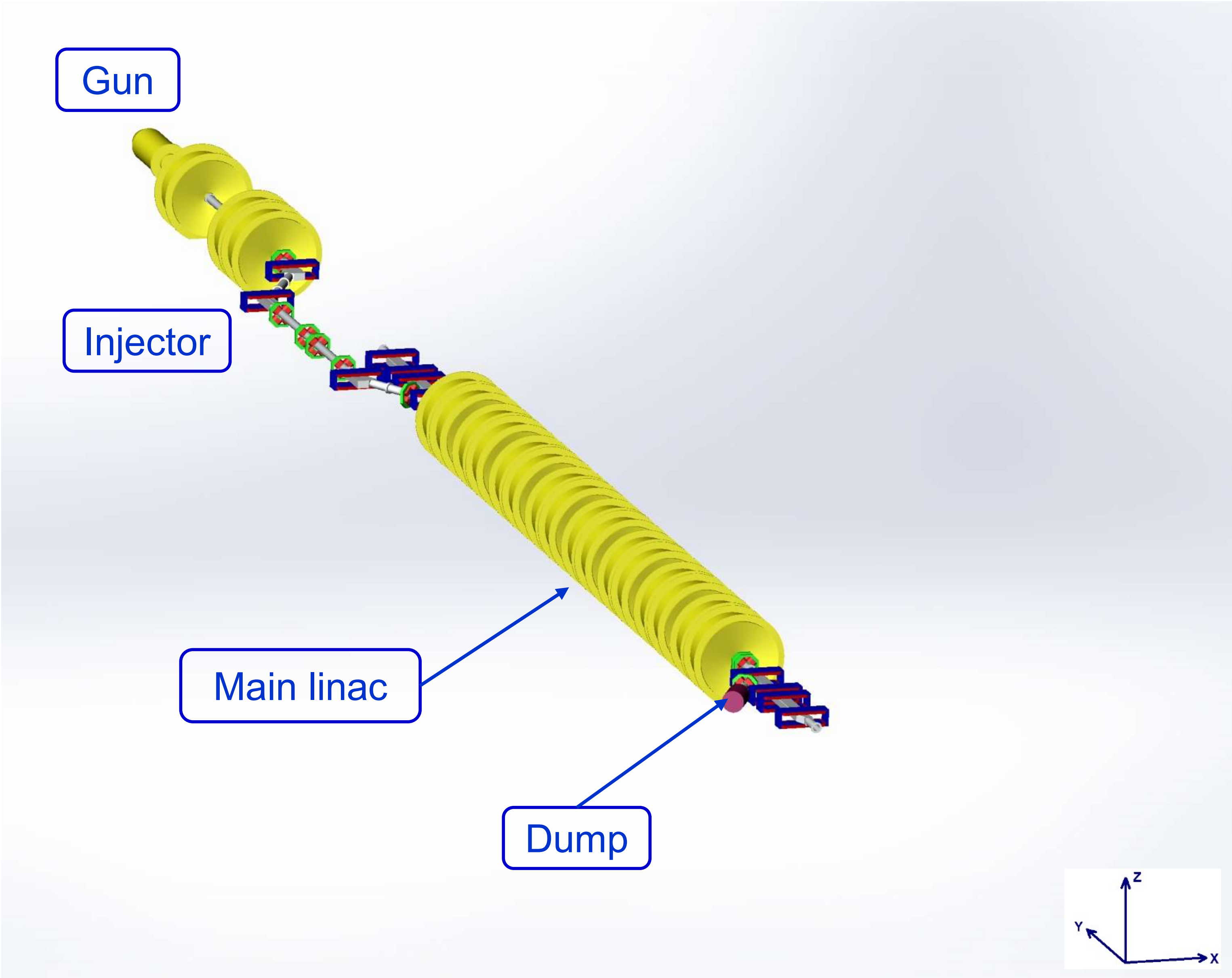


NovoFEL Accelerator Design



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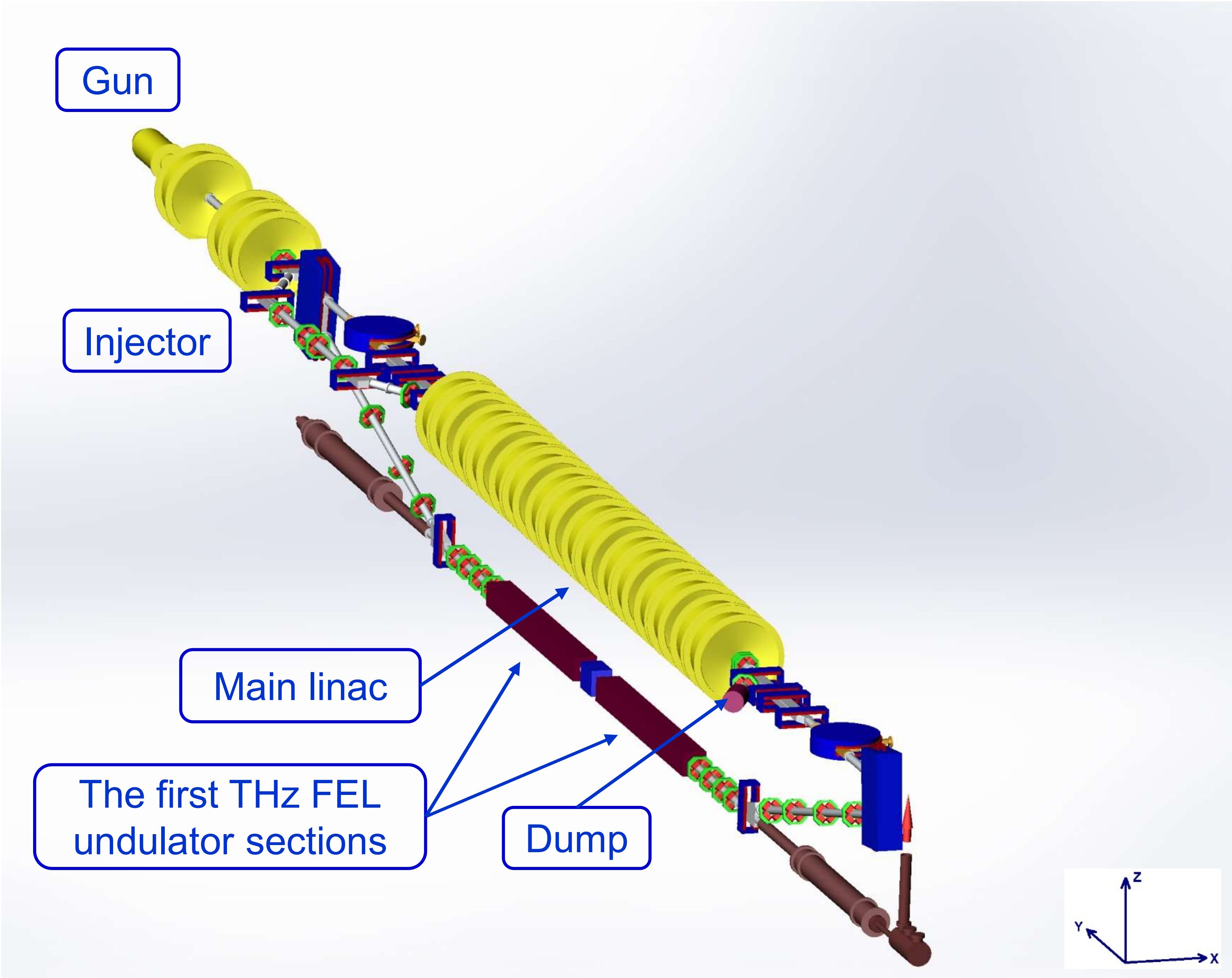

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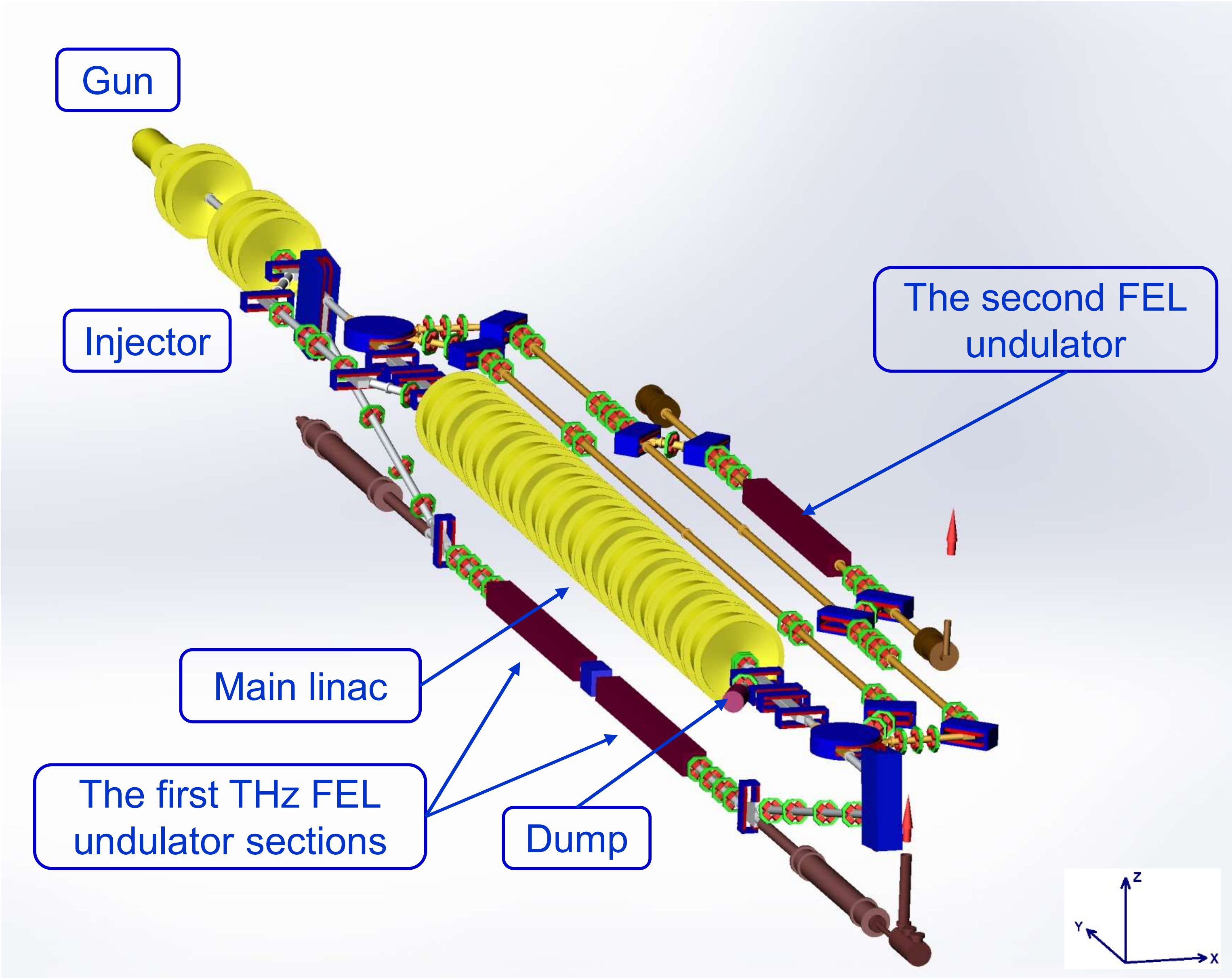
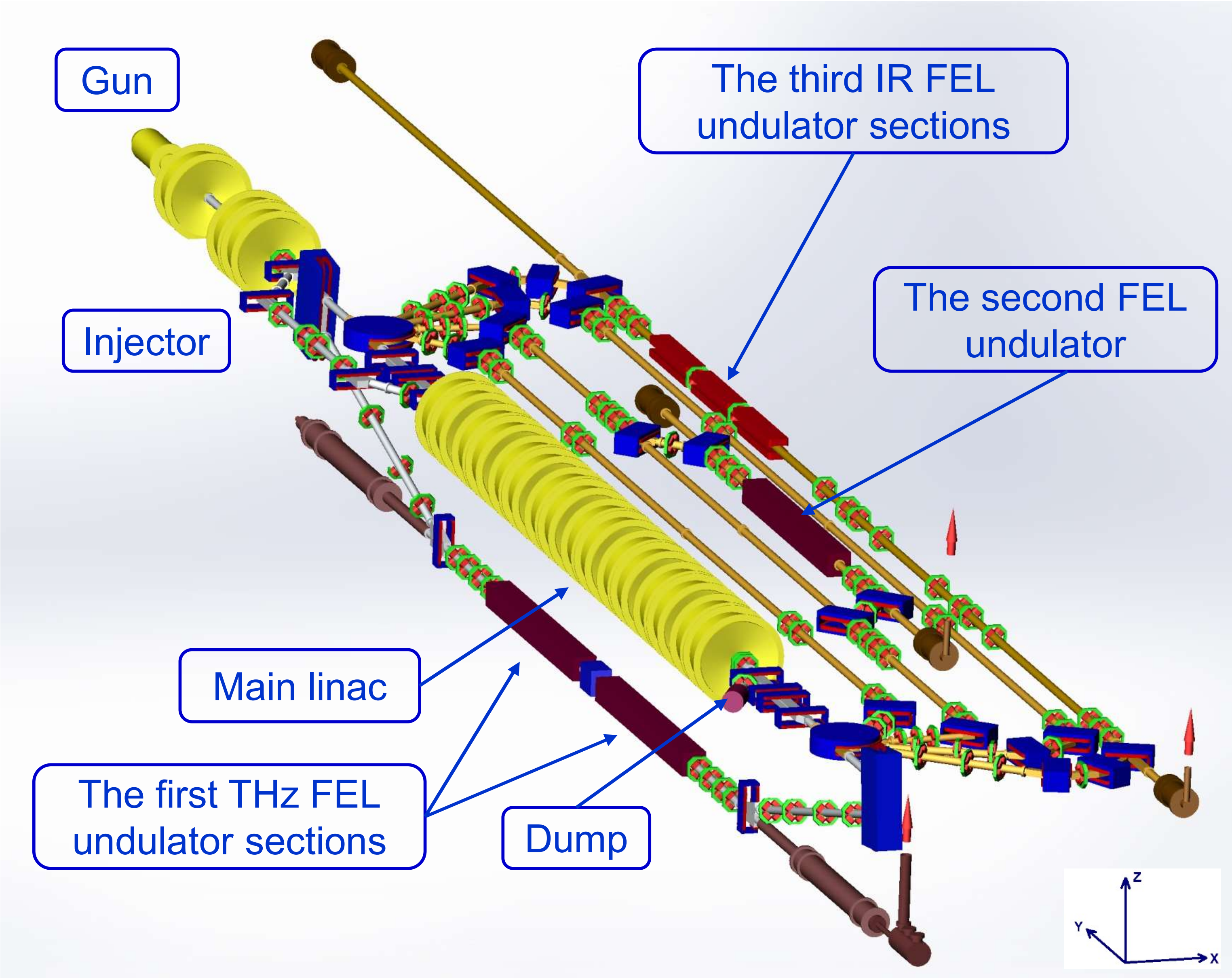
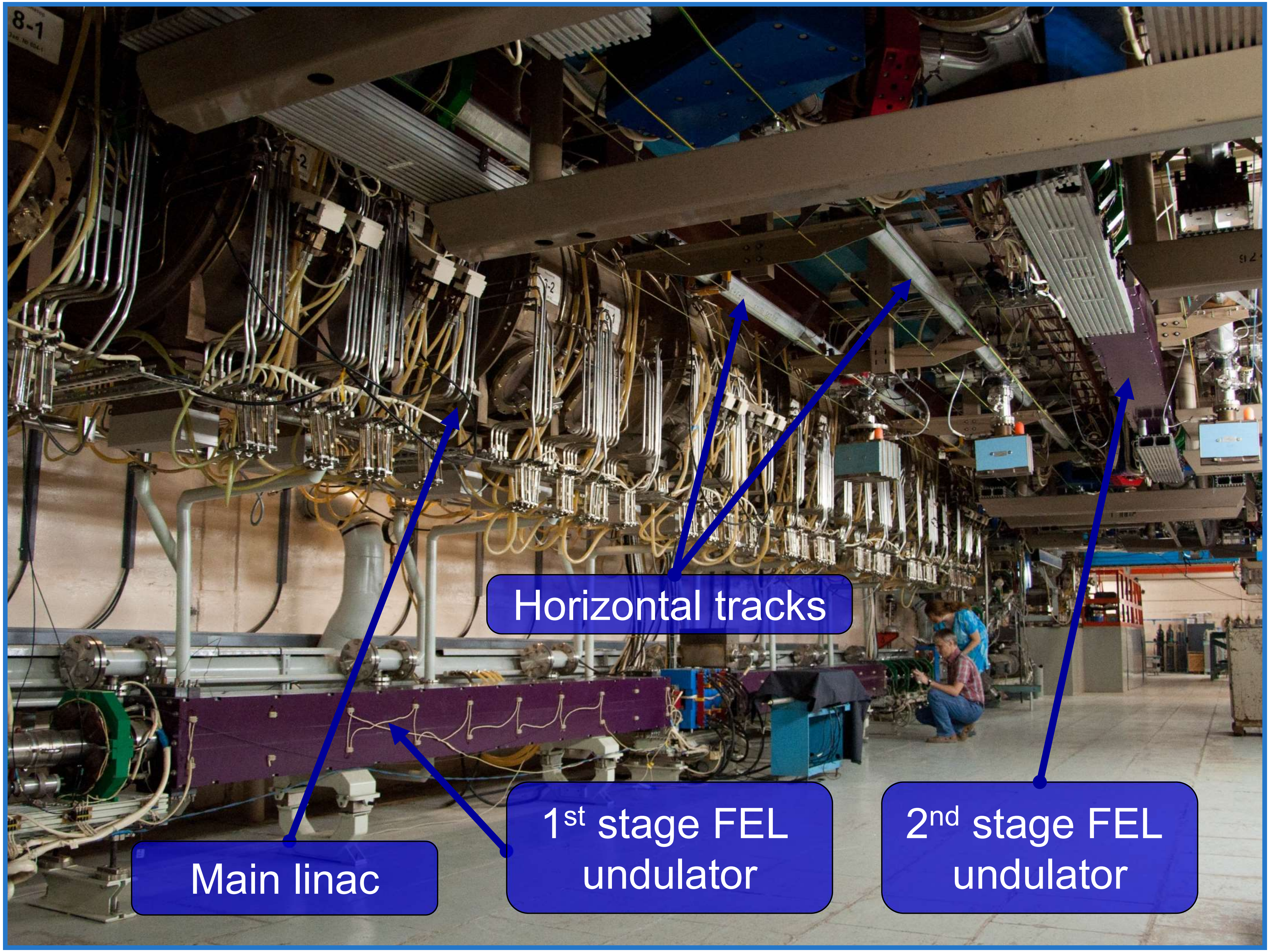


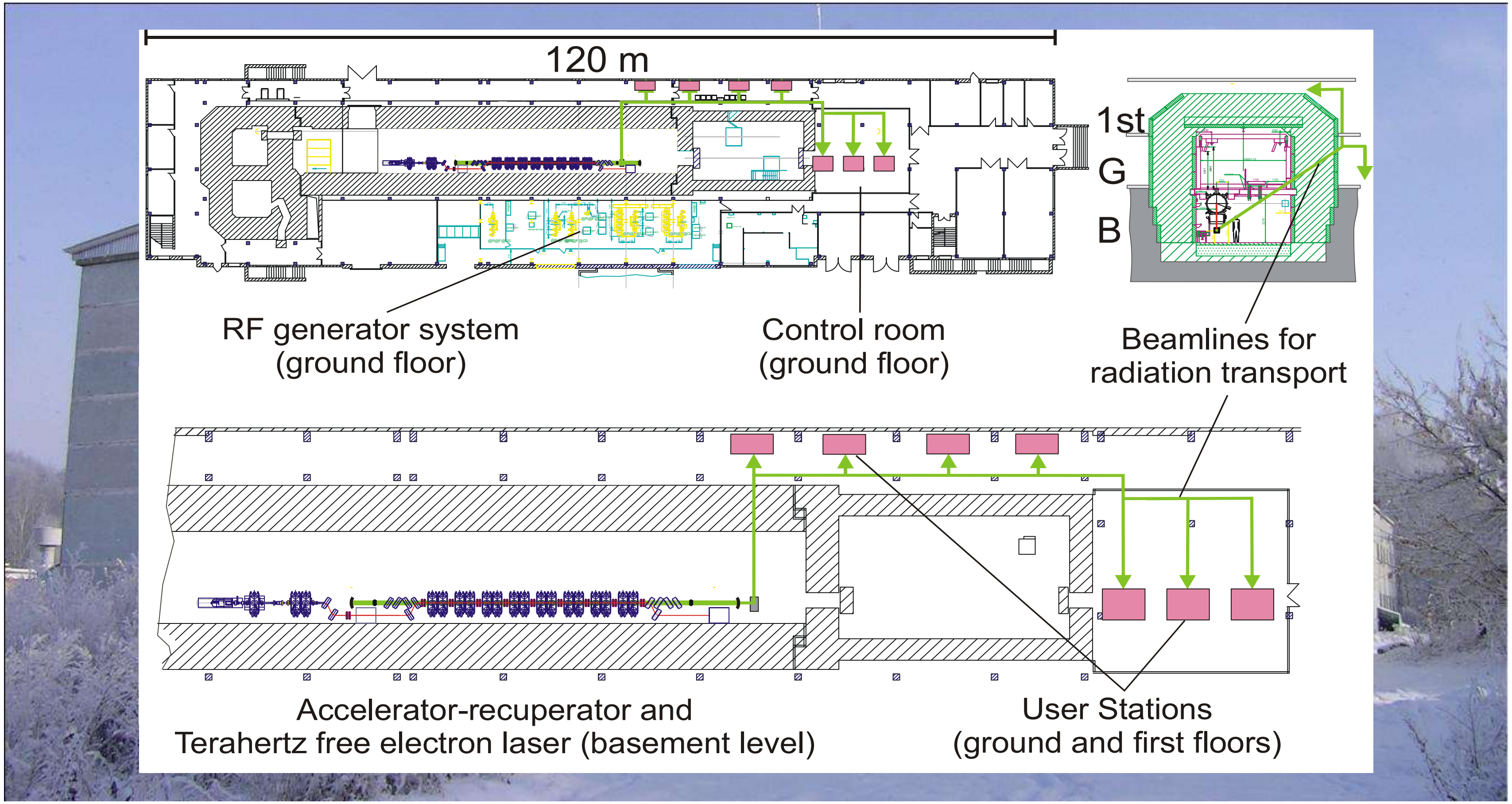
NovoFEL Accelerator Design



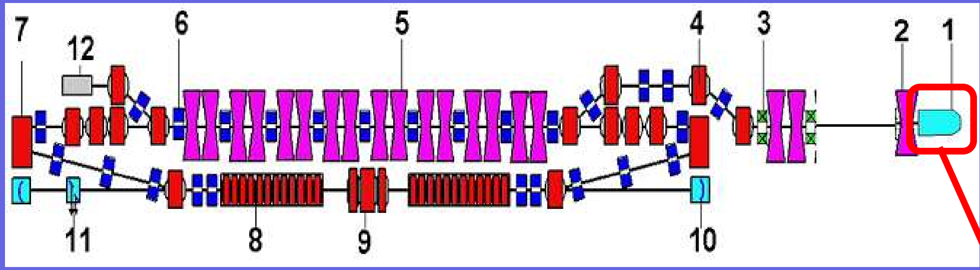

Horizontal tracks
Main linac
1st stage FEL undulator
2nd stage FEL undulator

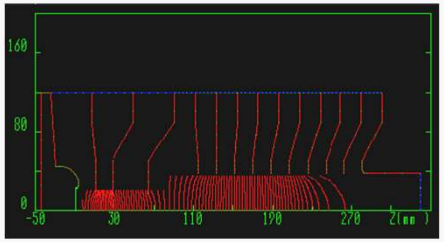

3d stage FEL
undulator

Siberian Center of Photochemical Research



Electrostatic Gun



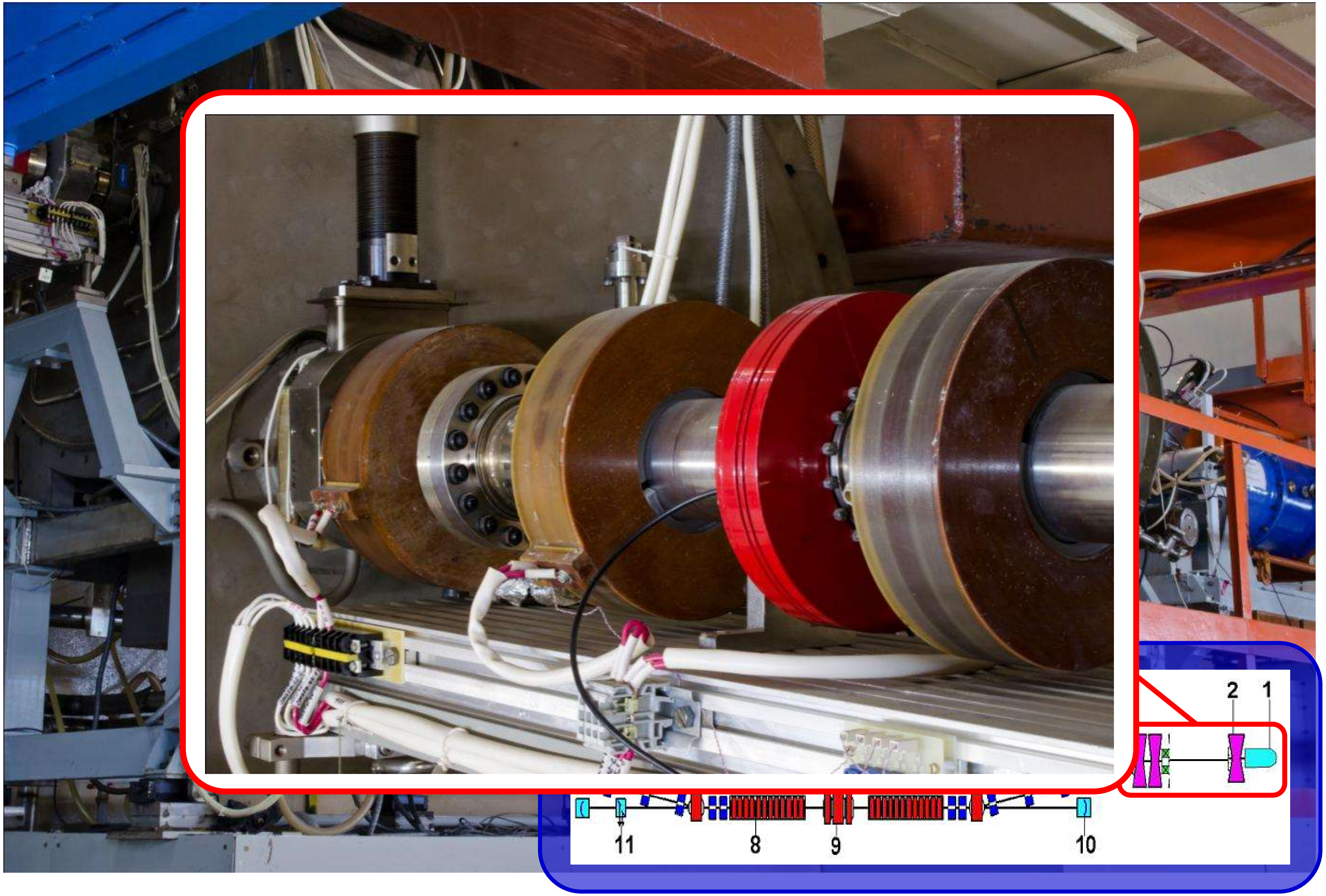


Power supply:

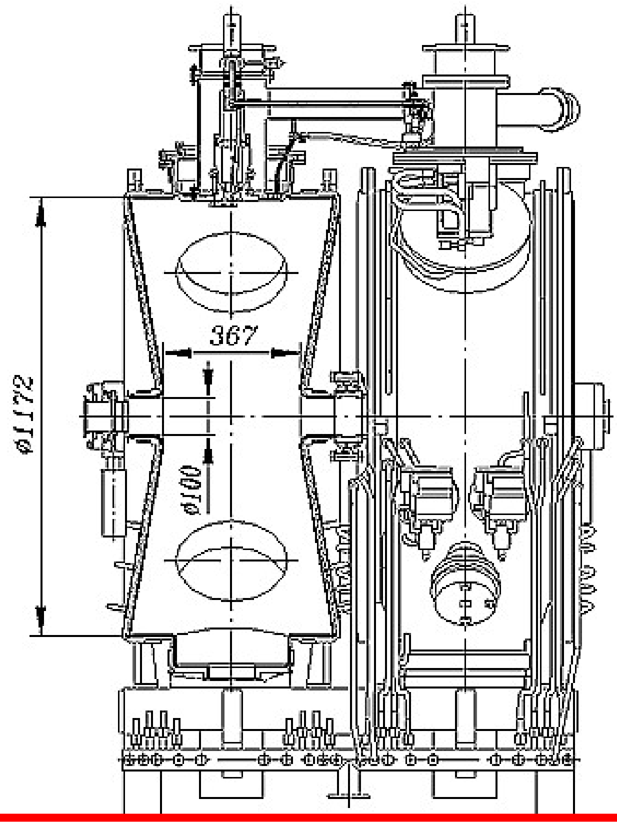
U_{max} = 300 kV

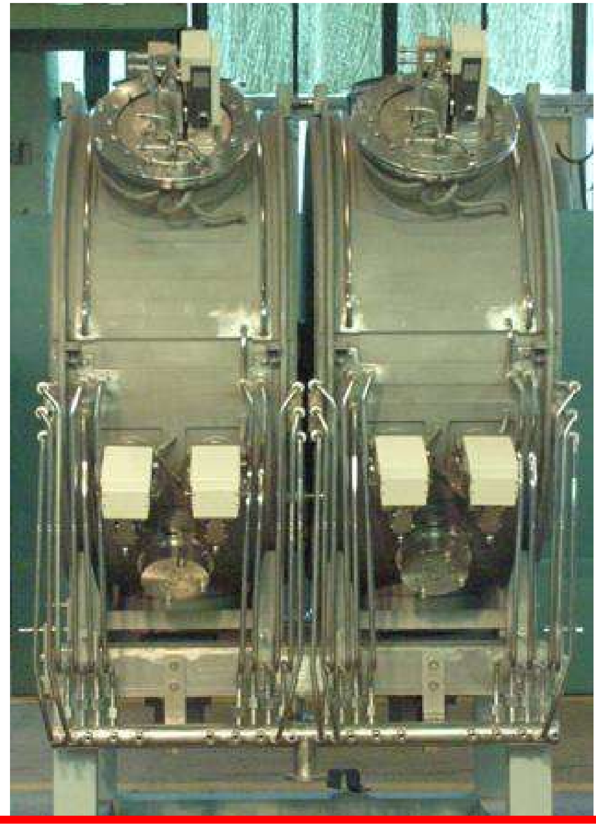
I_{max} = 50 mA

Injector



Main Linac

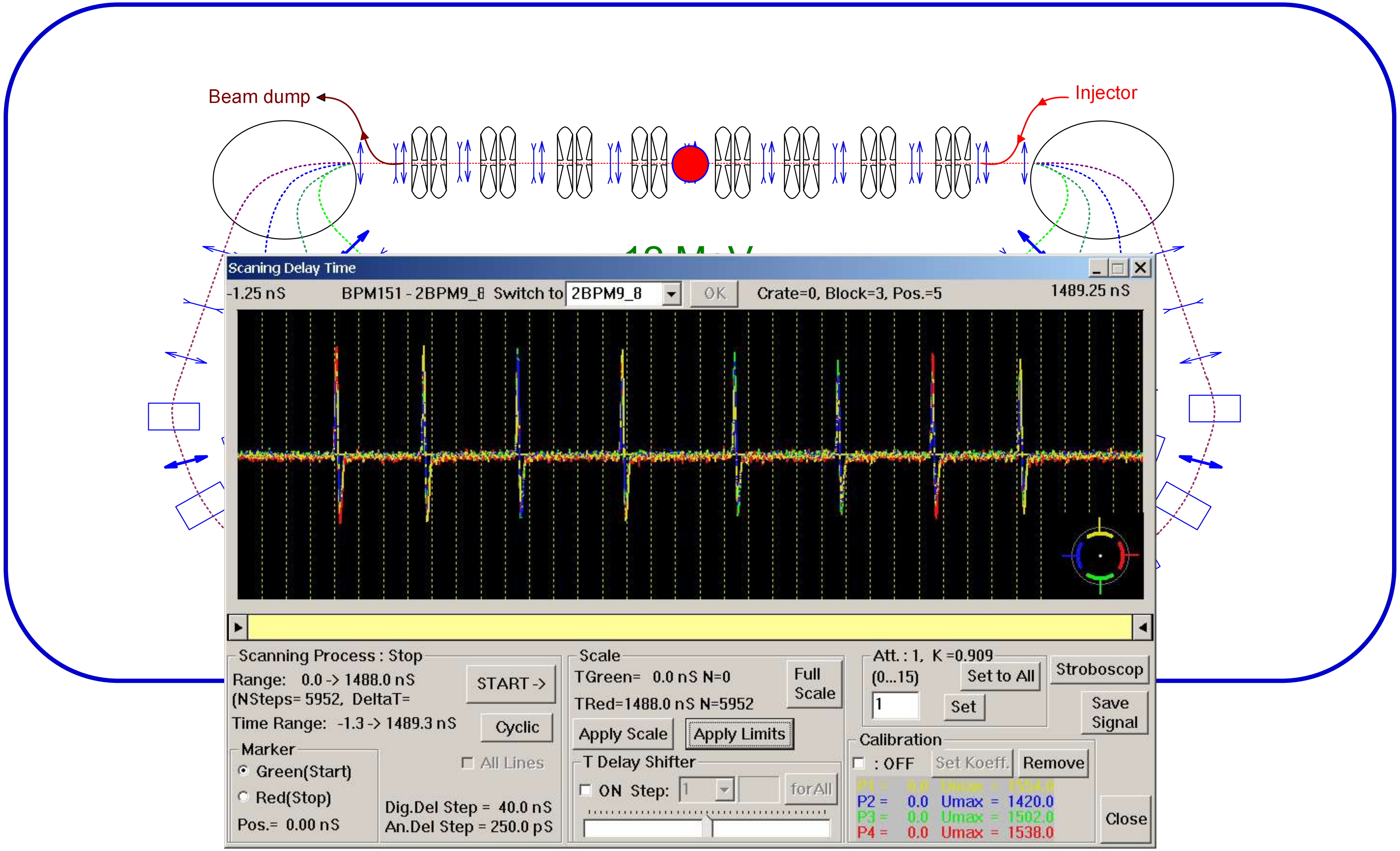




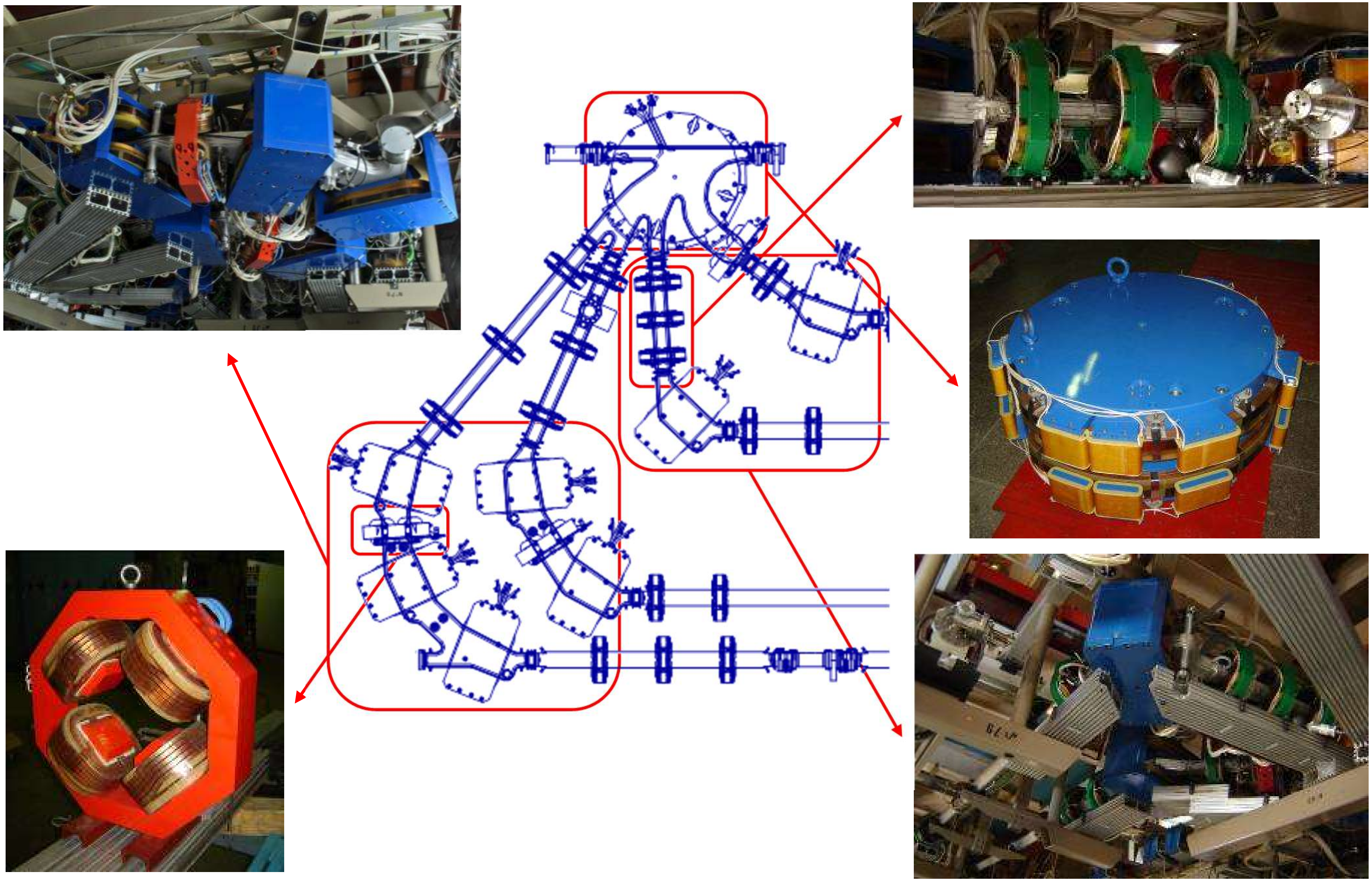
$$f_0 = 180\ \text{MHz},\quad \Delta f_0 = 320\ \text{kHz},\quad U_{max} = 950\ \text{kV},$$

$$U_{eff} = 850\ \text{kV},\quad P_{dis} = 85\ \text{kW}$$

Layout of Horizontal Beamlines (the Second and the Third ERLs)

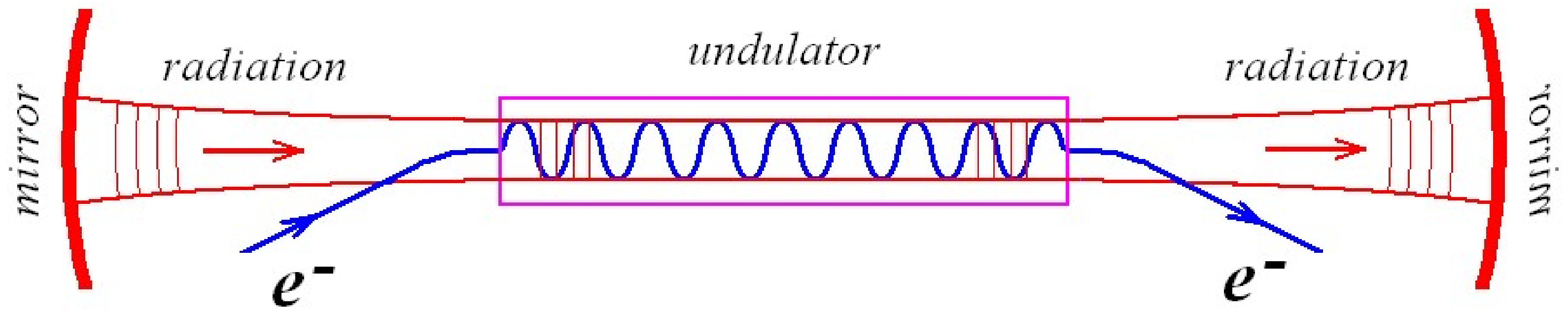


Magnets and Vacuum Chamber of Bends

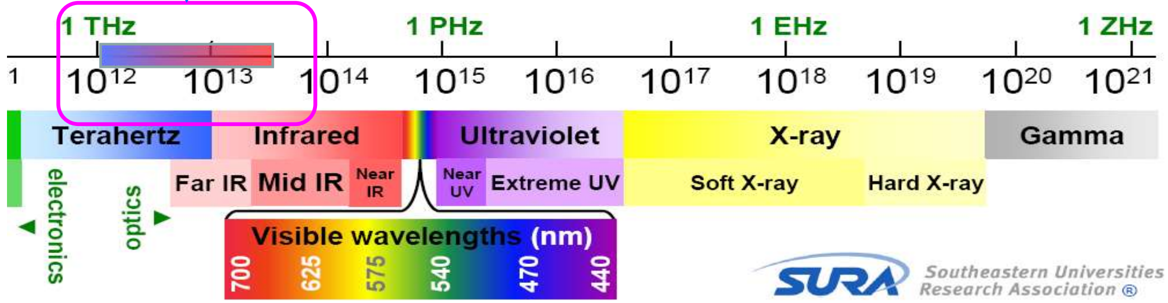


NovoFEL as Radiation Source

FEL oscillator



NovoFEL

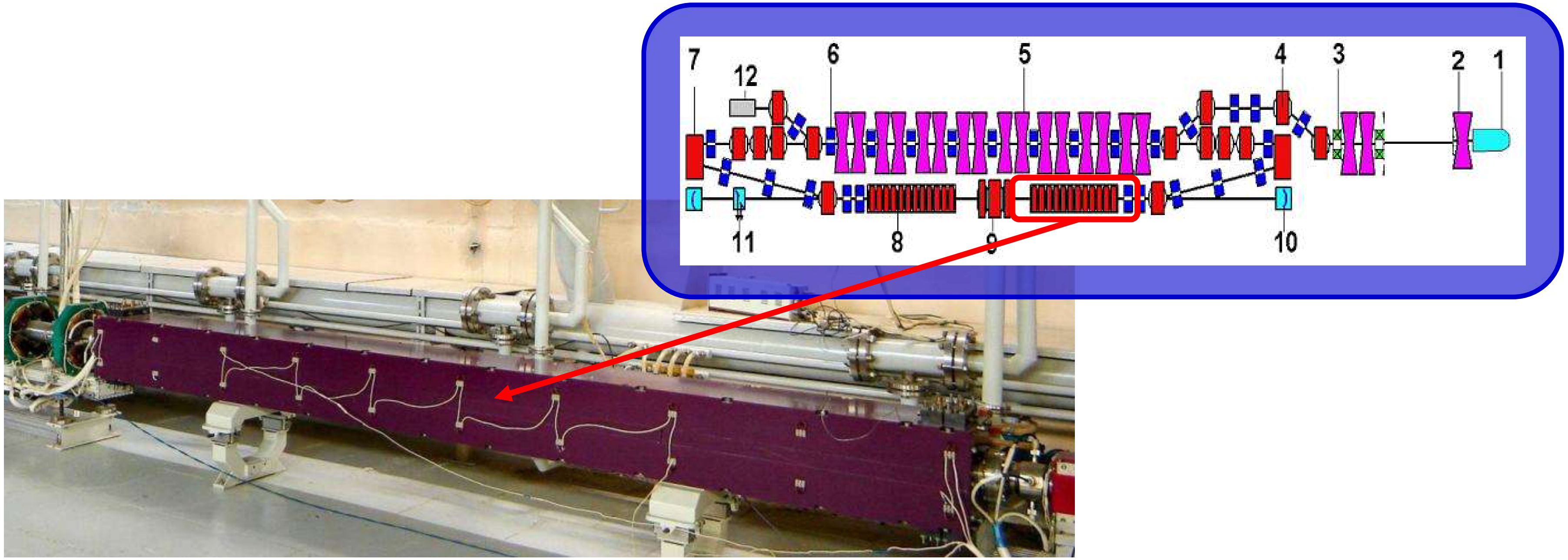


One of the main FEL advantages is the ability to adjust the wavelength

$$\lambda = \lambda_u \frac{1}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

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

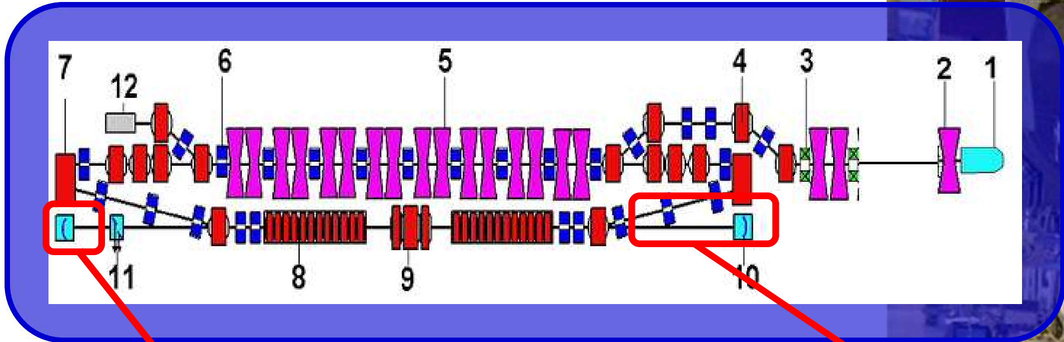
Electromagnetic Undulators

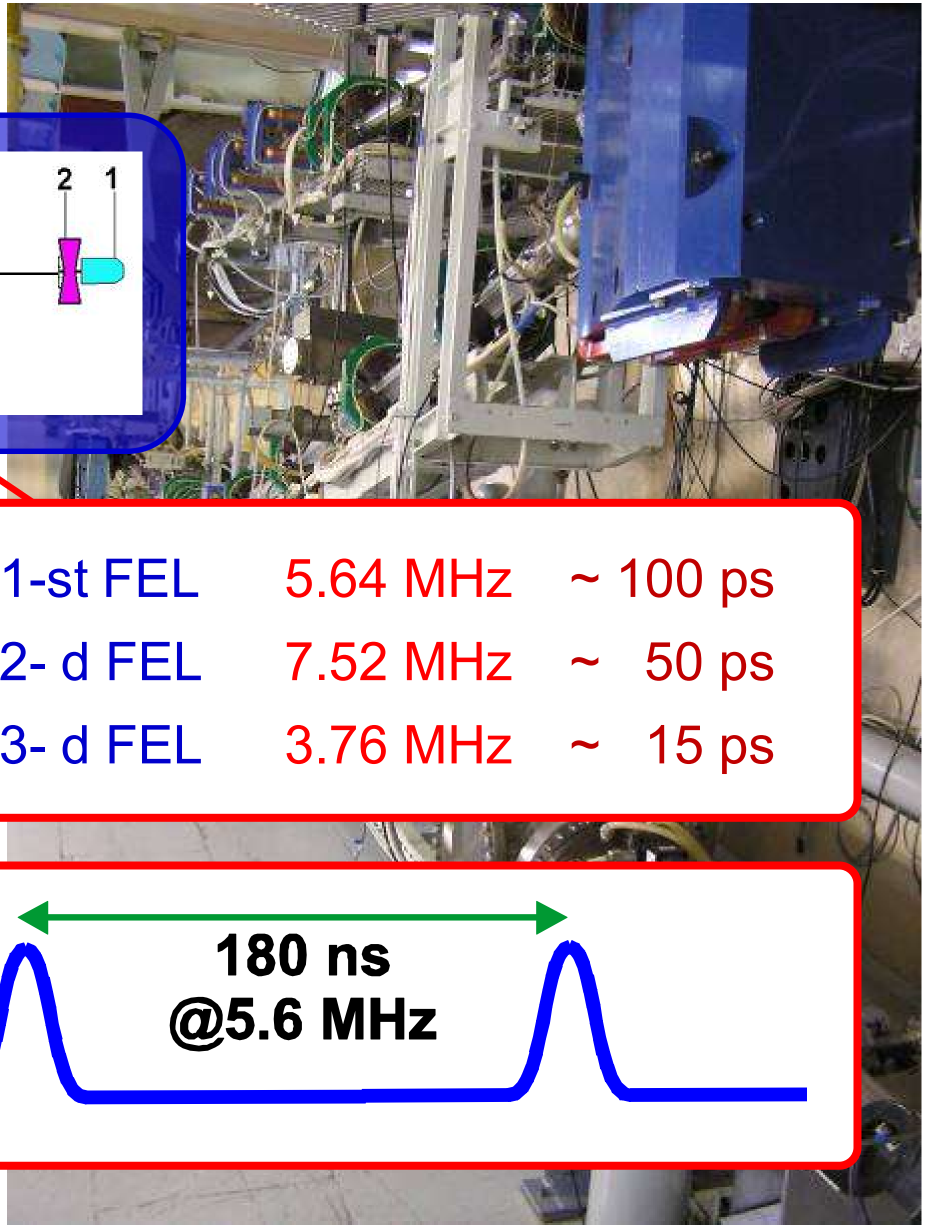


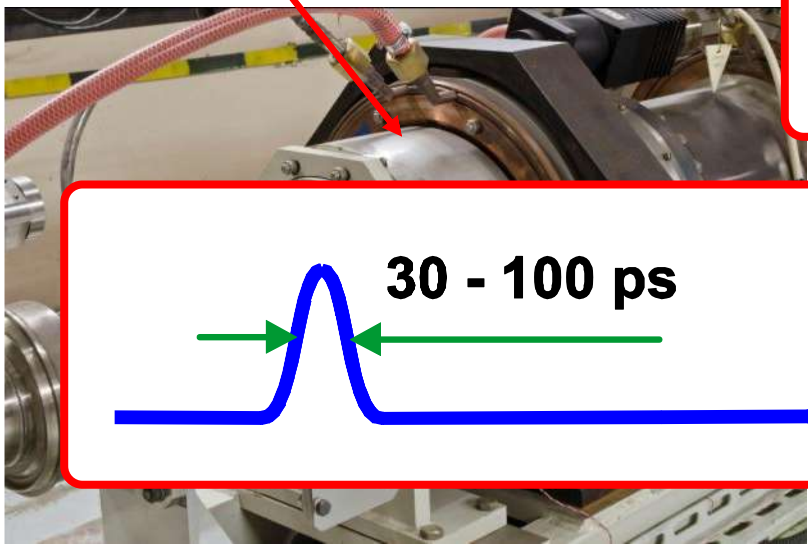
	1-st FEL	2-d FEL
Period, cm	12	12
Maximum current, кA	2.4	2.4
Maximum K	1.25	1.47

The third FEL undulator

FEL Optical Cavities





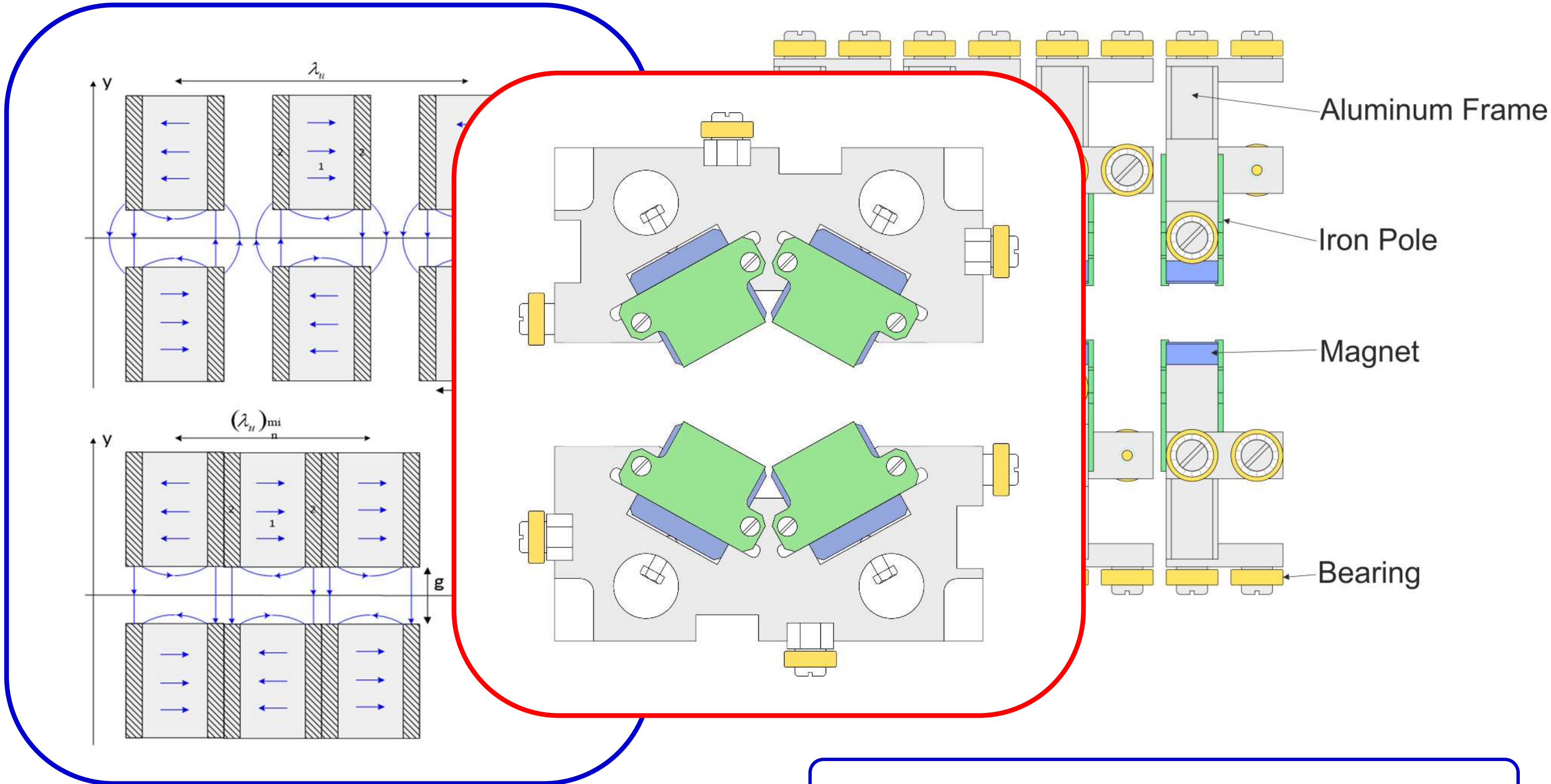


1-st FEL	5.64 MHz	~ 100 ps
2- d FEL	7.52 MHz	~ 50 ps
3- d FEL	3.76 MHz	~ 15 ps

30 - 100 ps

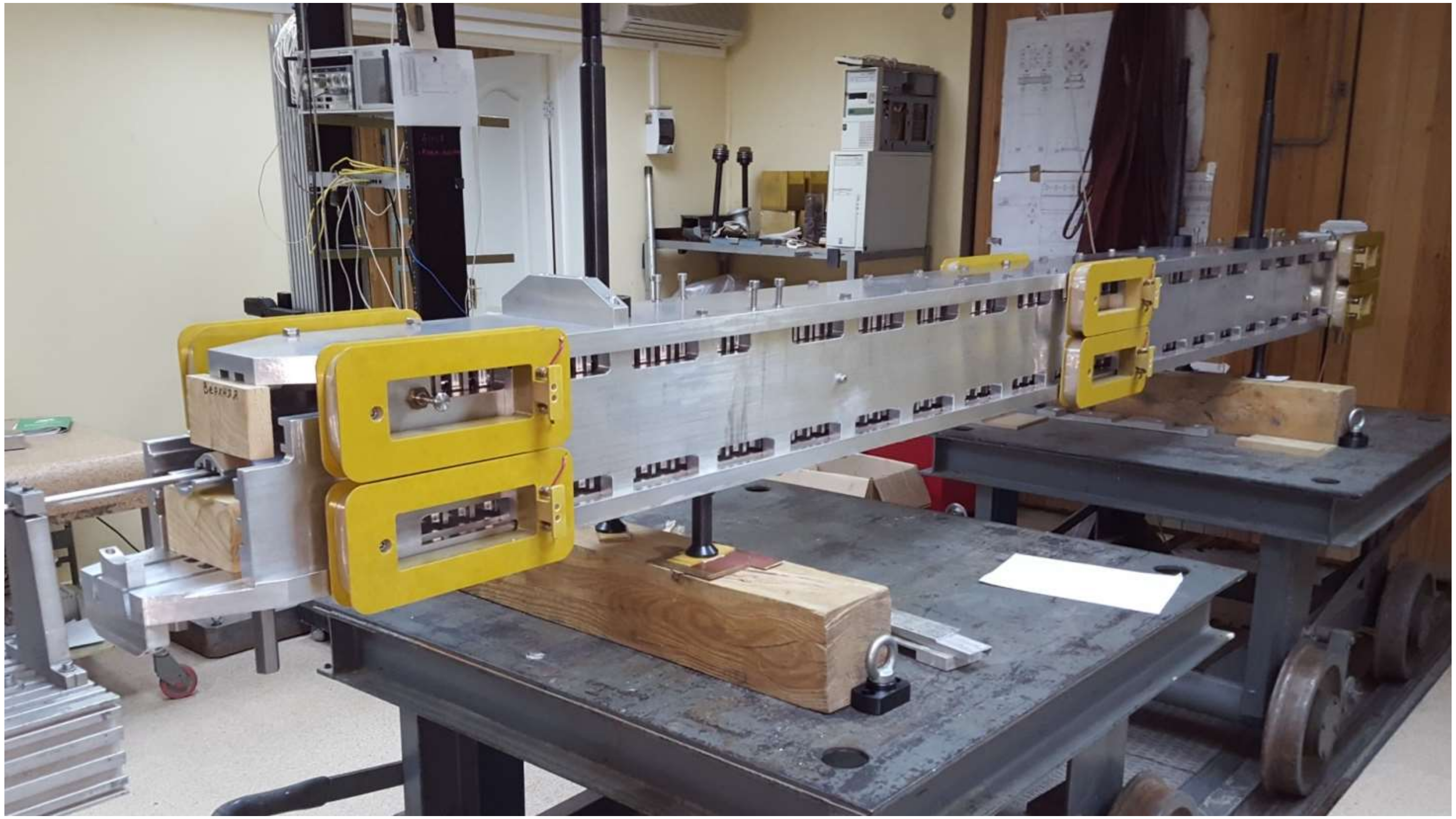
180 ns
@5.6 MHz

Variable Period Undulator (for the 2-d FEL)



The tunability range of the 2-d FEL will be increased from **37 - 80** to **15 - 80** microns

Undulator Magnetic Field Measurement



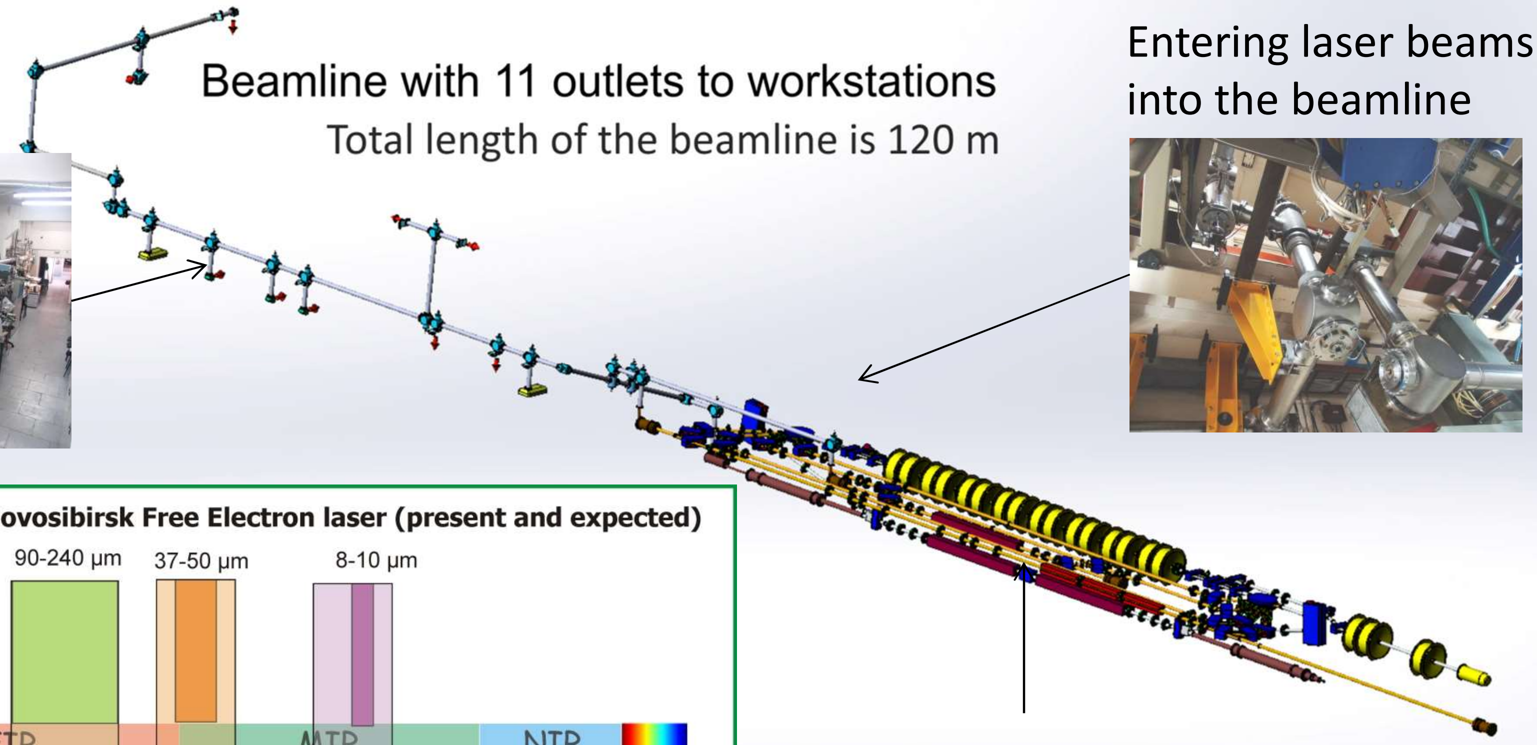
Optical beamlines and user stations

Novosibirsk FEL user facility

Section of the beamline

Beamline with 11 outlets to workstations

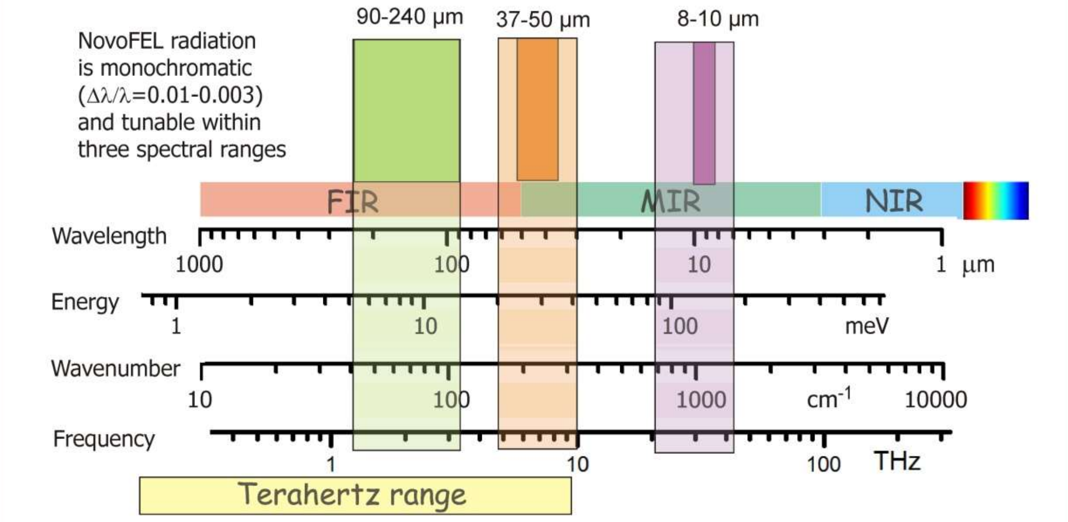
Total length of the beamline is 120 m



Entering laser beams into the beamline

Multiturn energy recovery linac with three individual laser systems

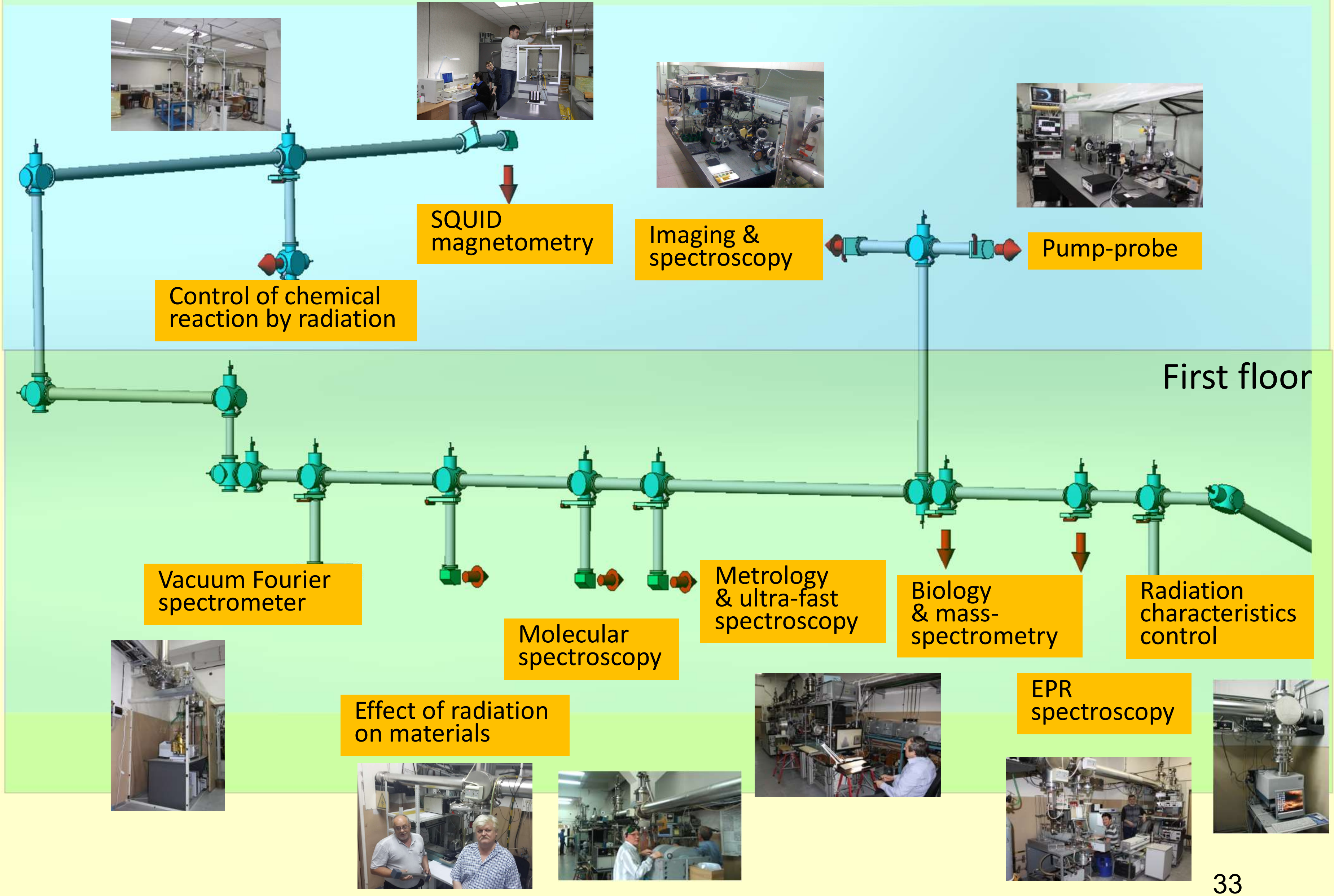
Generation ranges of Novosibirsk Free Electron laser (present and expected)



The classification of spectral ranges is given in accordance with the recommendations of International Organization for Standardization: ISO 20473:2007 Optics and photonics - Spectral bands

NovoFEL workstations

Second floor



Examples of experiments

NovoFEL beam transformation

TPX lens exposed to THz laser beam

Focusing of high-power terahertz beams

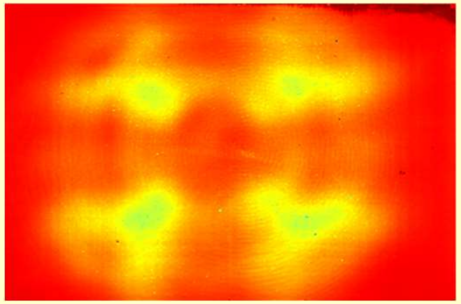
Tasks:

- Focusing beams into predetermined areas and volumes;
- Mode transformation

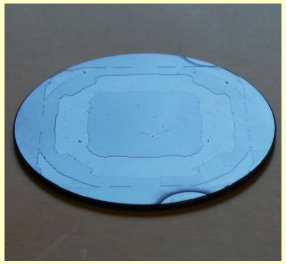
Solutions:

- Diffractive optical elements;
- Free form elements

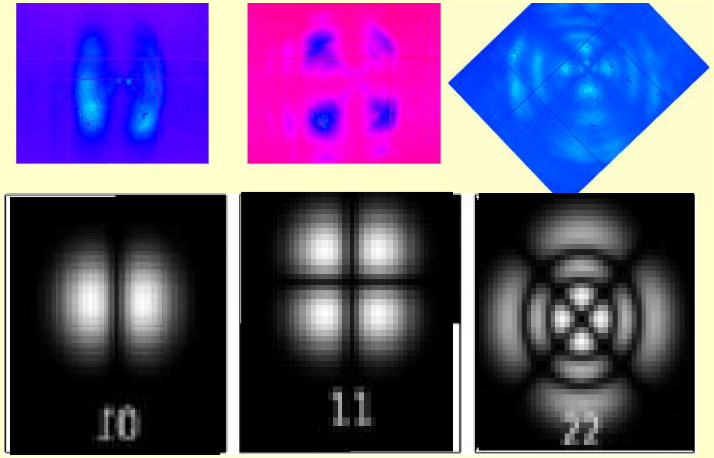
Scanning from 298 to 411 mm



Shaper in a "square"



HG (1,0) HG (1,1) LG (2,2)



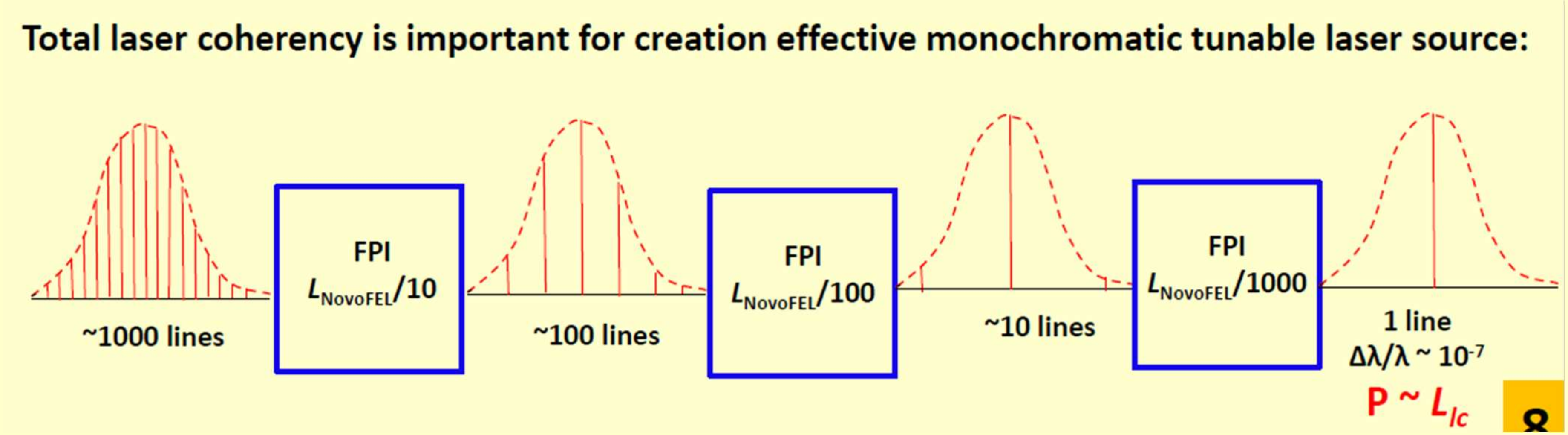
Silicon DOE: High radiation resistance

Large refractive index (Fresnel reflection);

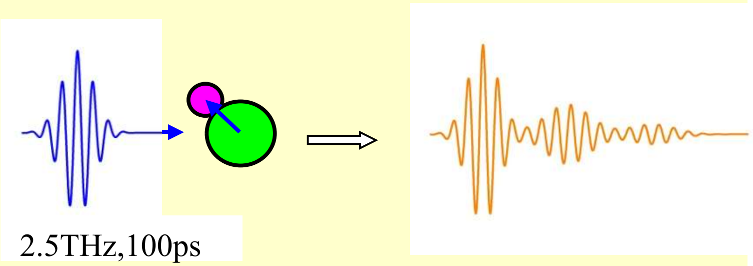
Parylene C - antireflection coating

How to employ the beam coherence

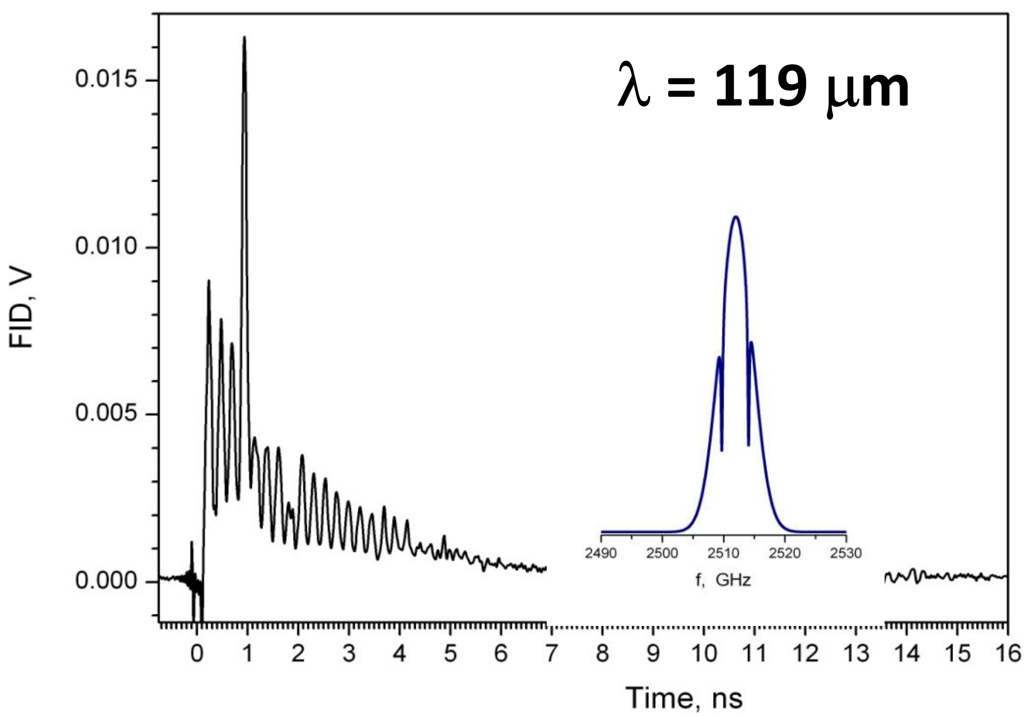
(courtesy of Dr. V. Kubarev)



The first experimental observation of signals of optical free induction decay in OH free radicals



Previously, free induction signals were recorded only for stable molecules. OH radicals were generated in the chemical reaction of excited oxygen atoms with water molecules initiated by a pulse of UV radiation.
The radiation of free induction was recorded in real time using ultrafast detectors of terahertz radiation.

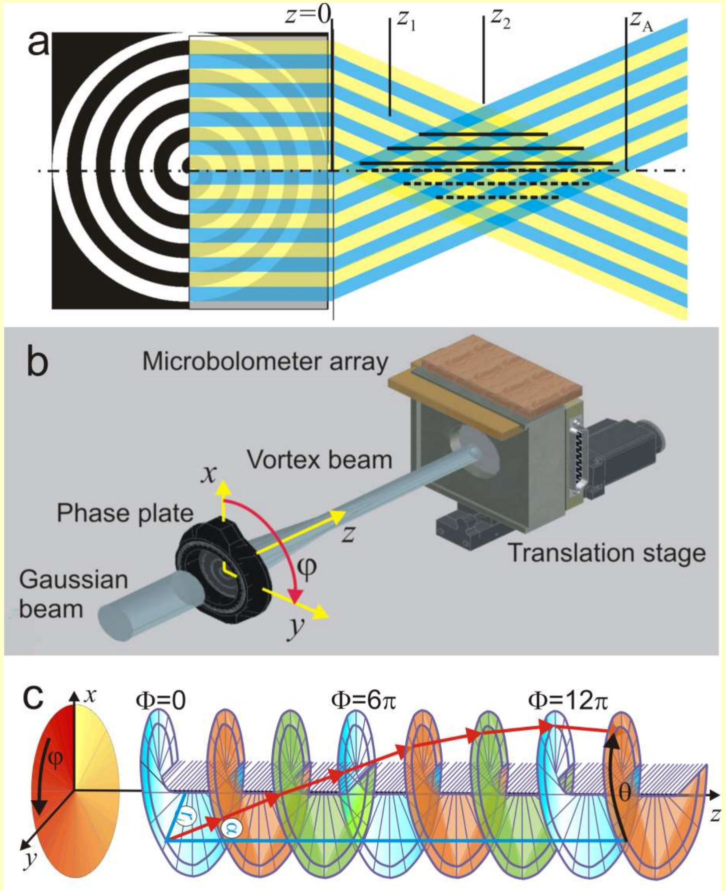


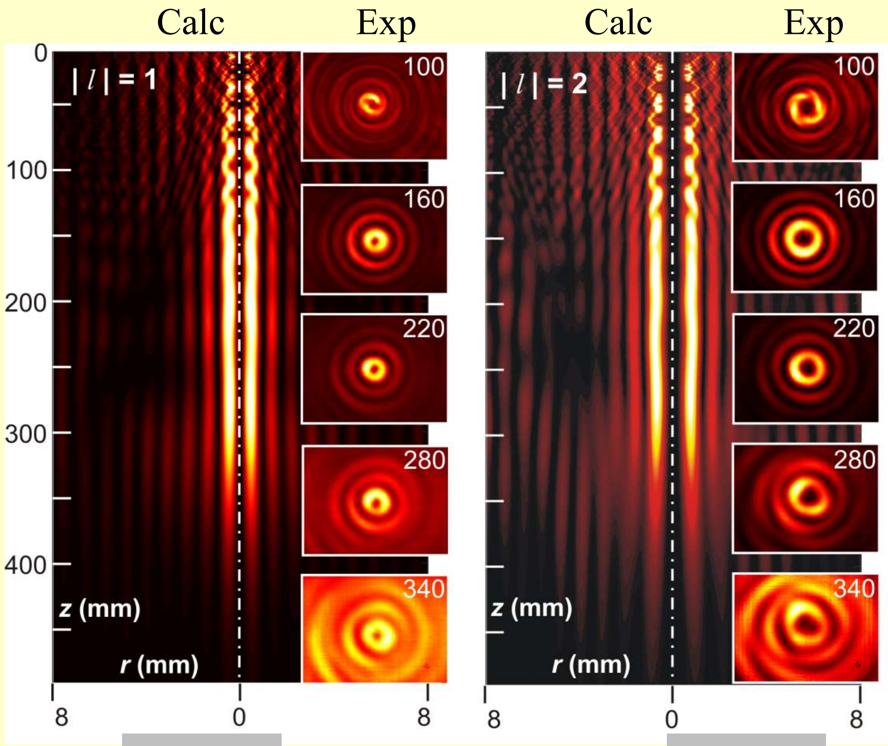
(courtesy of Dr. E. Chesnokov)

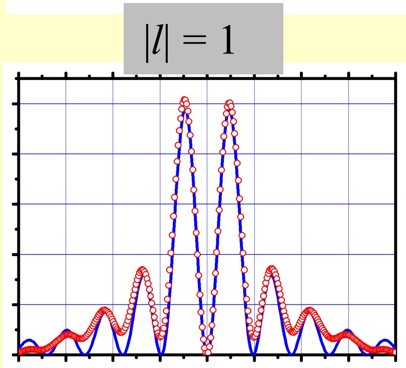
Generation of vortex beams

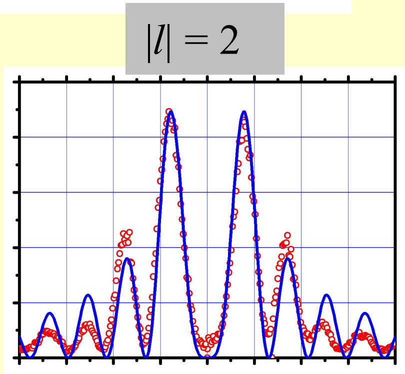
Transformation Gauss-to-Bessel

$$I(r,\varphi) = J_{\ell}(\kappa r)\exp(i\ell\varphi)$$



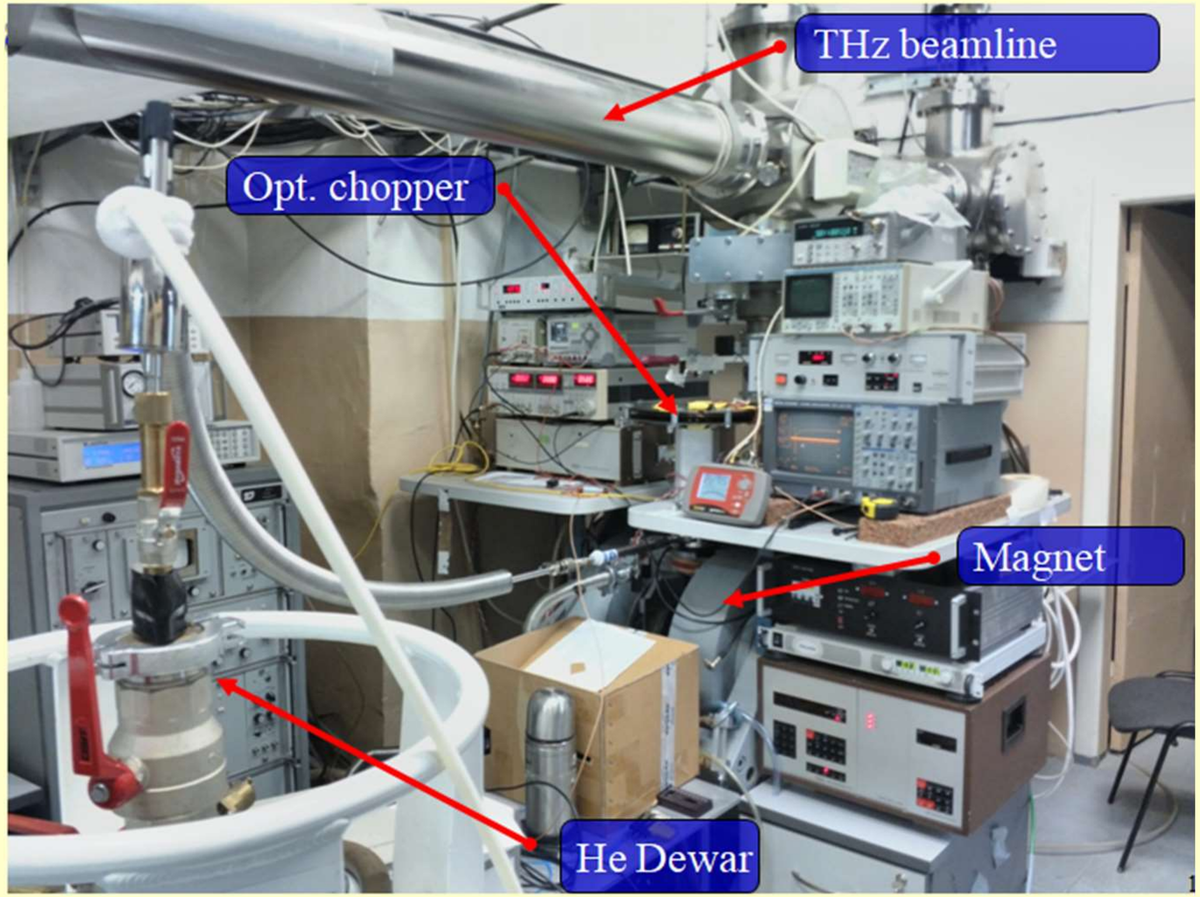






Phys. Rev. A **96**, 023846 (2017)
Physics Procedia **84**, 175-183 (2016)
Успехи физических наук **188**, 509 (2018)

Time-Resolved Electron Paramagnetic Resonance spectroscopy station

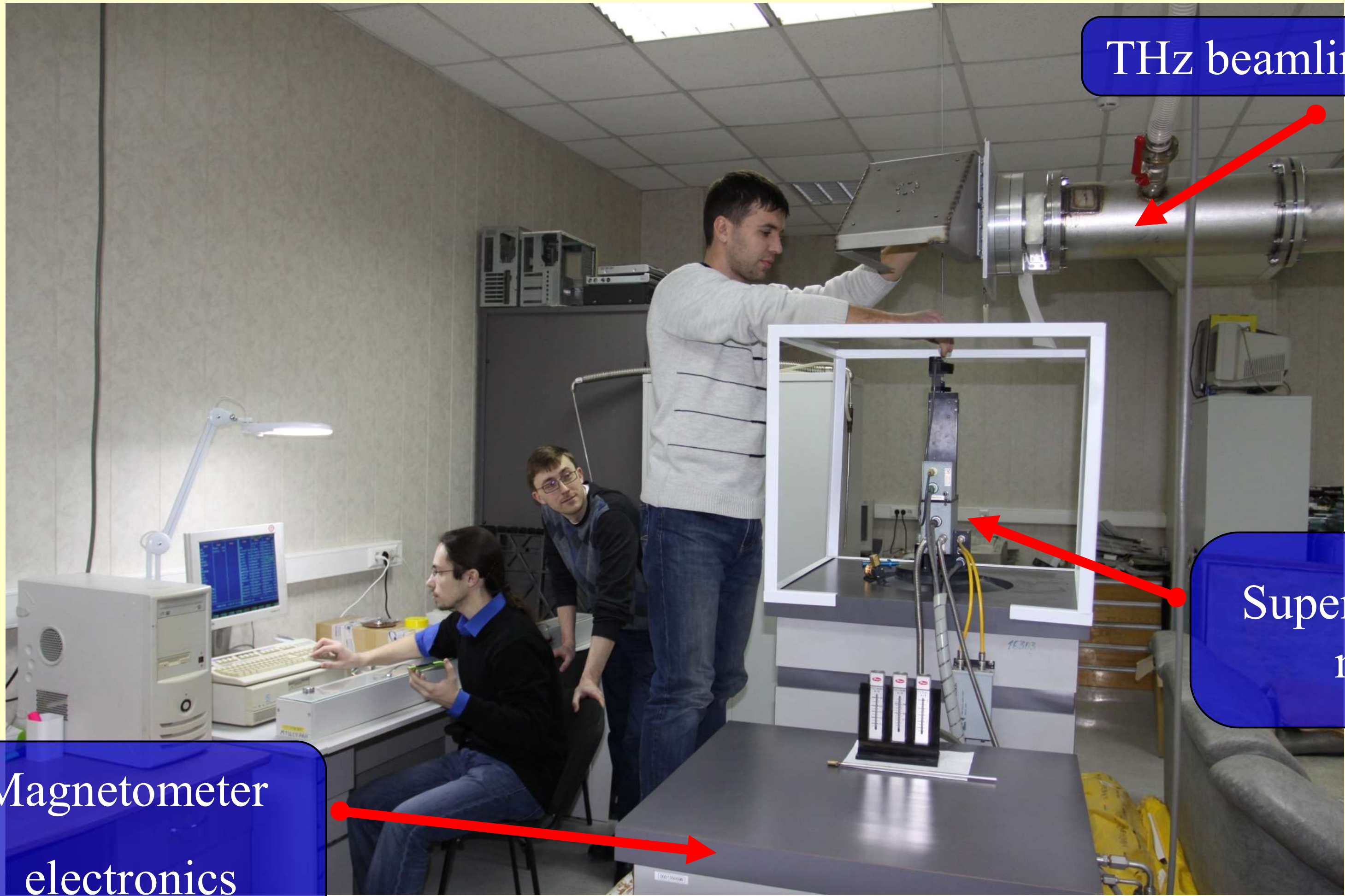


This station allows to study the influence of high-power THz light to the paramagnetic species:
The setup consists of electromagnet, microwave bridge, EPR resonator (between the magnet poles), cryostat and thermo controllers to change the temperature of the sample, and the PC to control the experiment.

The station is constructing by the International Tomography Center

SQUID-magnetometer station (under development)

Experiments with real objects (molecular magnets) are to be started soon



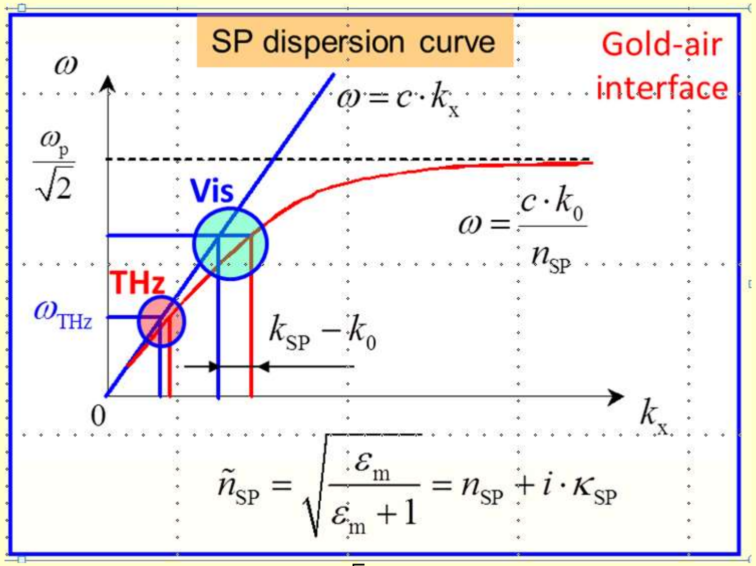
THz beamline

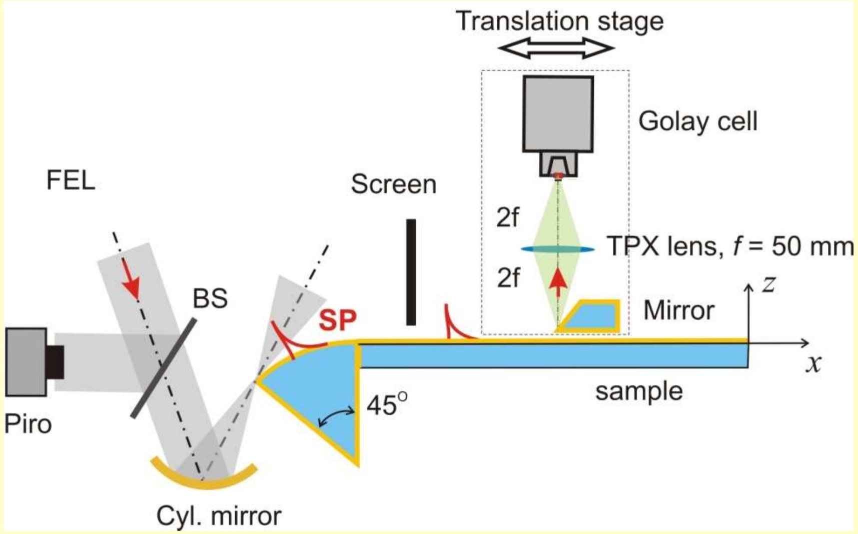
Superconductive magnet

Magnetometer electronics

The station is constructing by the International Tomography Center

Surface plasmon-polaritons in THz range

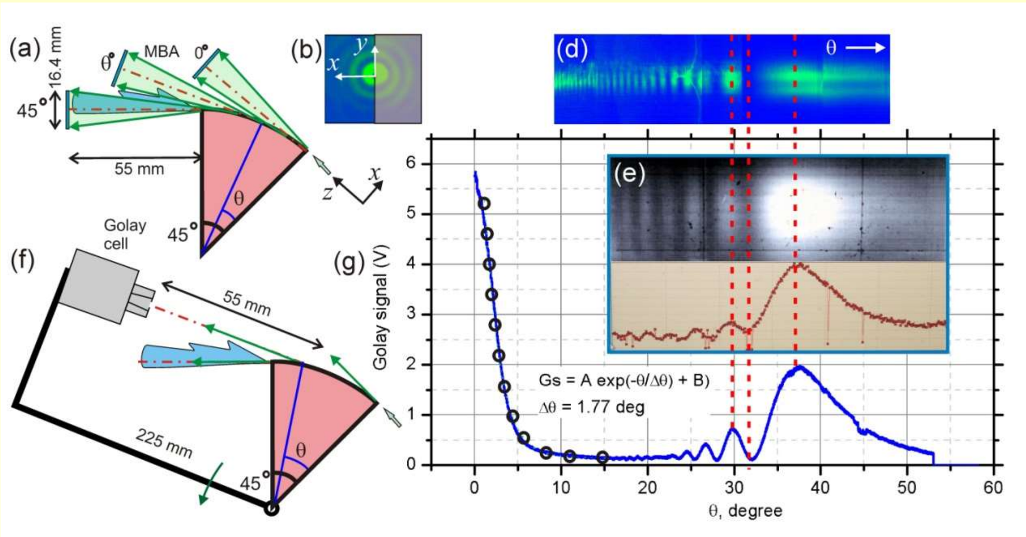


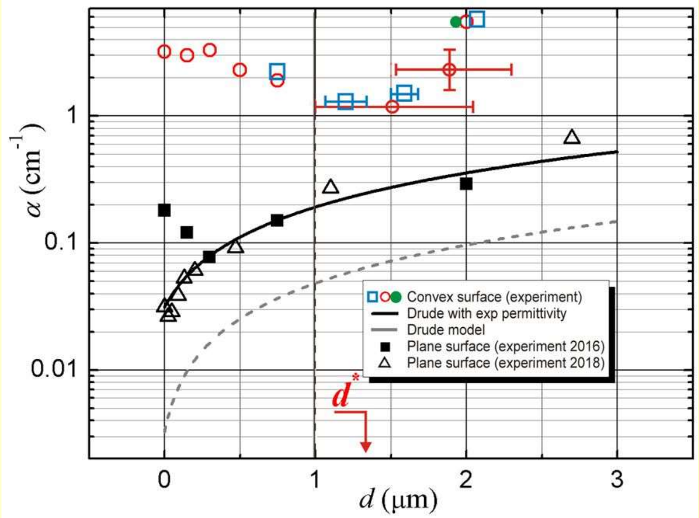


$$\alpha = 2\,\mathrm{Im}(k_s) \quad k_s = \frac{2\pi}{\lambda}\left[1+\frac{1}{2}\left(\frac{1}{\sqrt{-\varepsilon_2}}+\frac{\varepsilon_d-1}{\varepsilon_d}\cdot\frac{2\pi}{\lambda}d\right)^2\right]$$

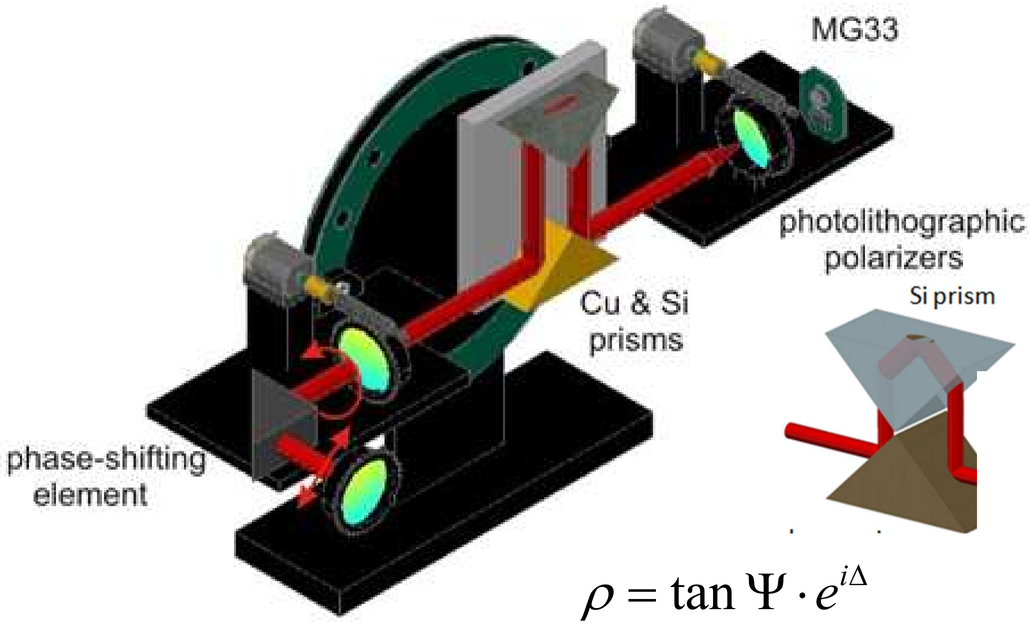
$$\delta = 1/2\,\mathrm{Re}(\kappa_1) \qquad \kappa_1 = \frac{2\pi}{\lambda}\sqrt{\frac{-\varepsilon_1^2}{\varepsilon_1+\varepsilon_2}}$$

$$\varepsilon_2 \approx 102000 - i\cdot 284000 \qquad \varepsilon_2^* \approx 7990 - i\cdot 10040$$

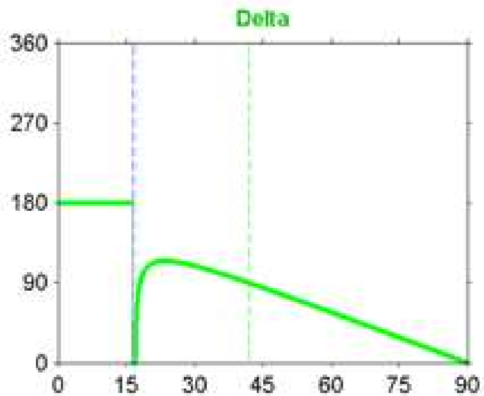


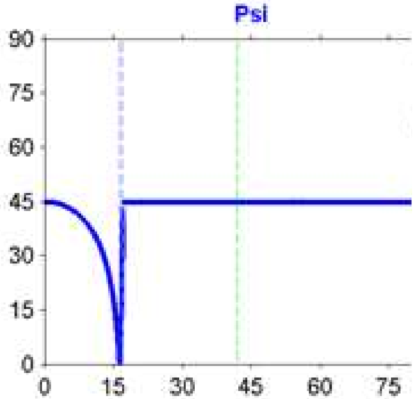


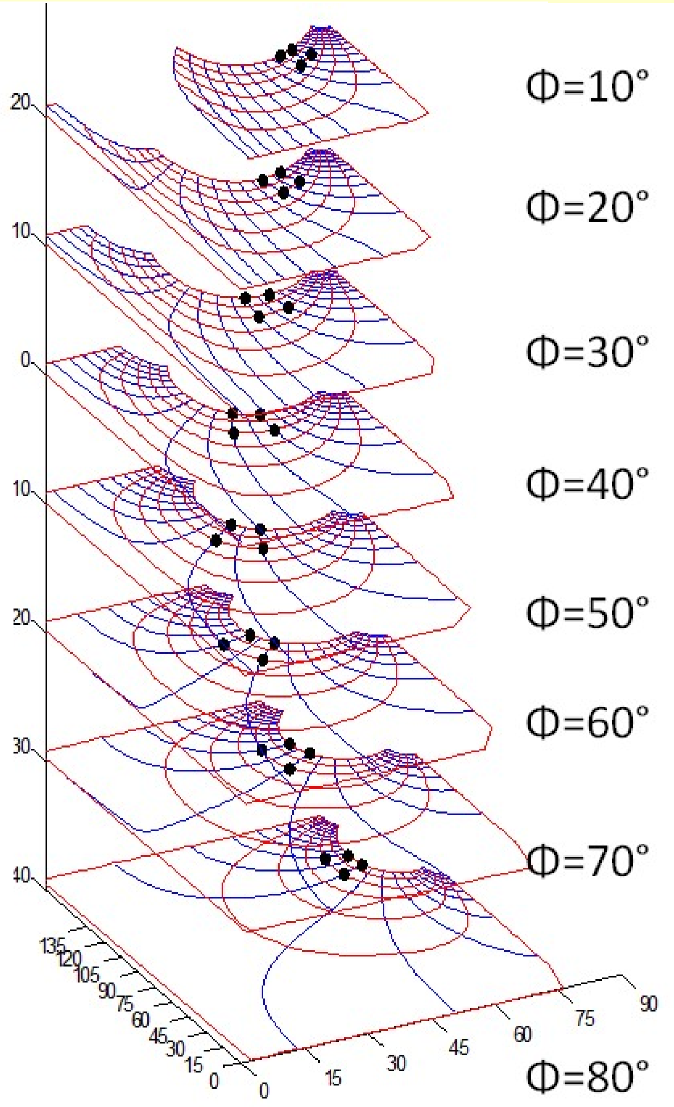
Attenuated total reflection ellipsometry



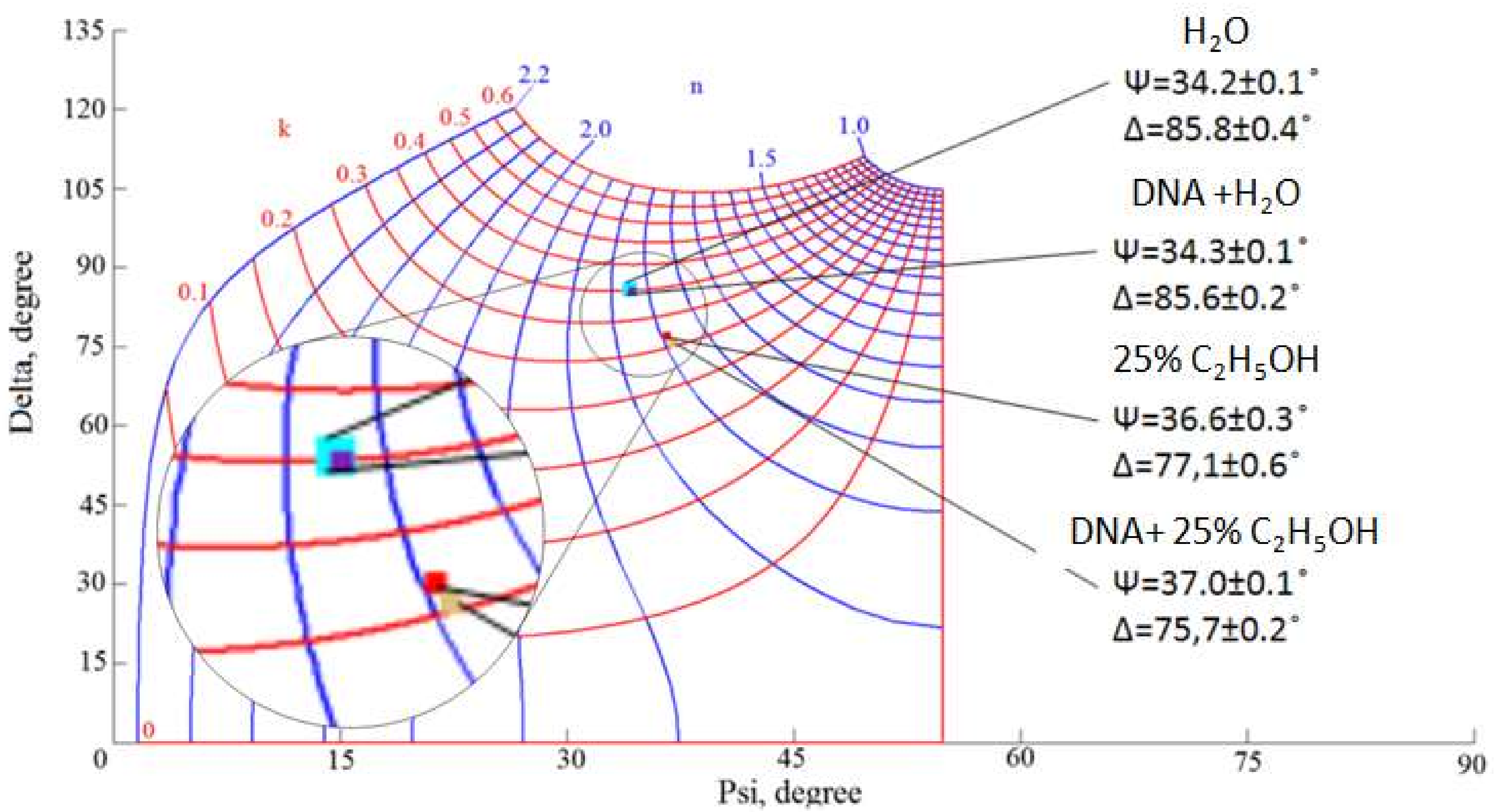
$$\rho = \tan\Psi \cdot e^{i\Delta}$$

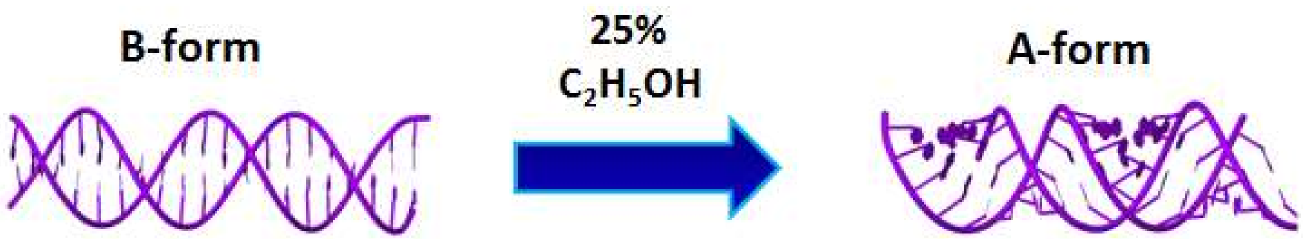




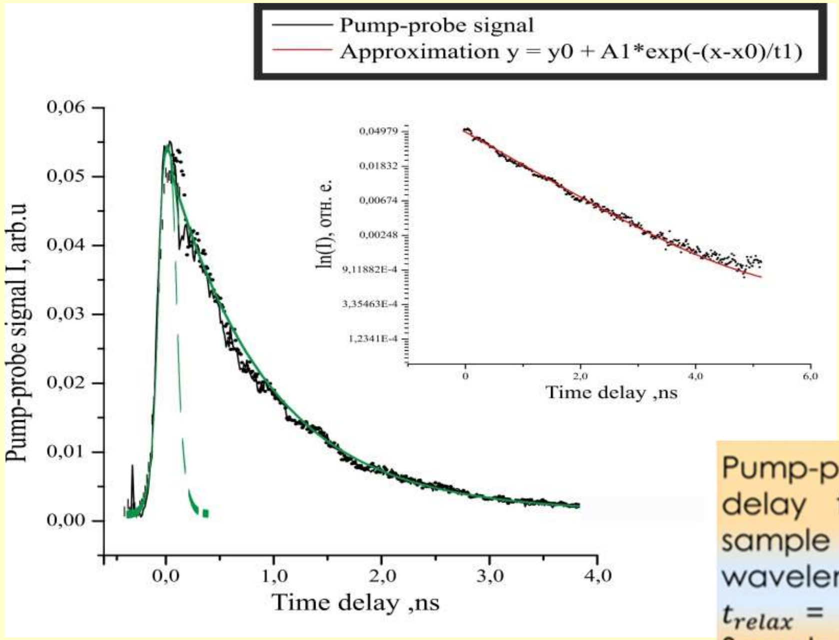


DNA conformation measurement



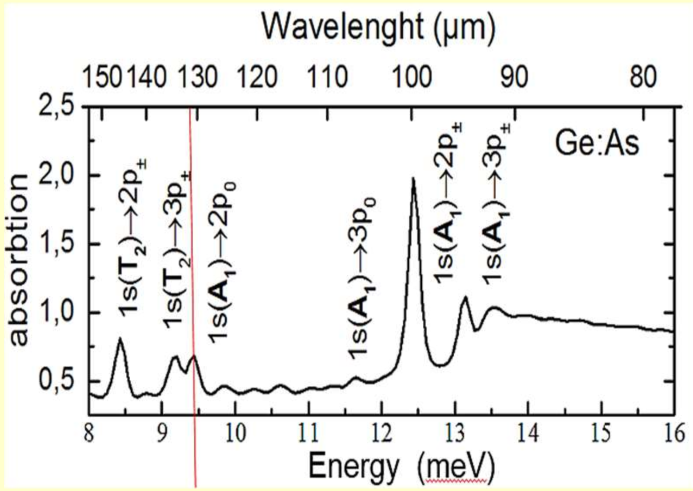


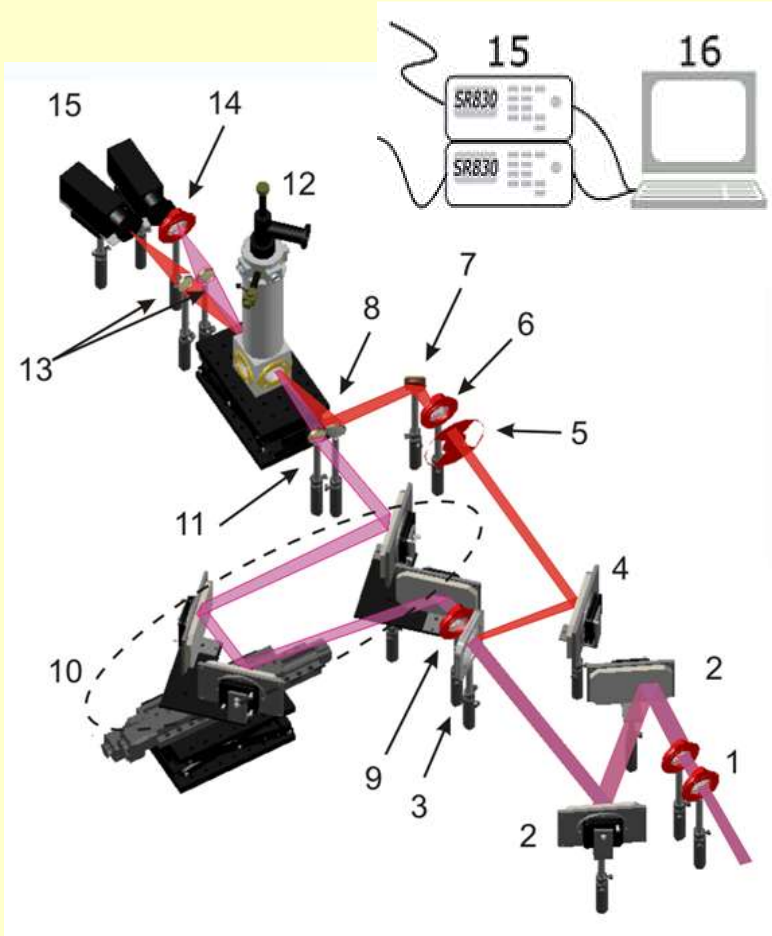
Pump-probe station



Pump-probe signal vs. delay time for Ge:As sample at 131,2 μm wavelength,
t_{relax} = 1,035 ± 0,012 ns.
Sample temperature: 4,2 K.

Inset: exponential part in the logarithmic scale.





Schematic of single-color pump-probe setup at NovoFEL facility.
Red line – pump beam, purple line – probe beam.
1 – grid polarizers, 2 – flat aluminum mirrors, 3 – Si beam splitter, 4 – flat aluminum mirror, 5 – chopper at 15 Hz frequency, 6 – photolithographic polarizer, 7 – copper parabolic mirror *f* = 250 mm, 8 – small flat aluminum mirror, 9 – photolithographic polarizer, 10 – optical delay line, 11 – TPX lens *f* = 150 mm, 12 – liquid-He flow cryostat, 13 – TPX lens *f* = 150 mm at 2*f* distance, 14 – photolithographic polarizer, 15 – Golay cells.

Summary

- **All three laser systems of the NovoFEL facility are now in operation (λ = 8-10, 37-50, 90-340 μm)**
- **11 workstations are in operation and more two are under construction**
- **The workstations are well equipped with instrumentation which is available to users**
- **We invite researchers to apply for beam time to perform experiments at the NovoFEL**

- The facility is open to all interested potential users without regard to nationality or institutional affiliation
- User fees are not charged for work if the user intends to publish the research results in the open literature
- The facility provides resources sufficient for users to conduct work safely and efficiently

Thank you for attention.