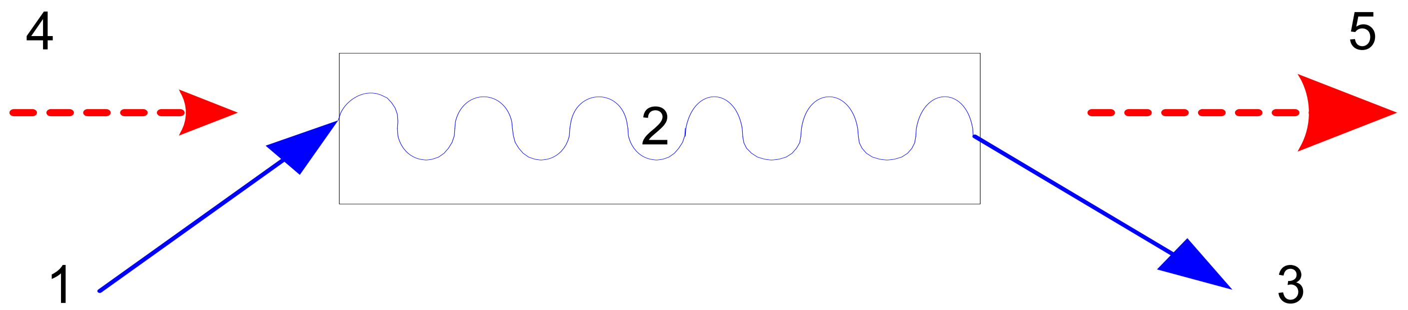
Novosibirsk Free Electron Laser: operation and second stage commissioning

N.A. Vinokurov, E.N. Dementyev, B.A. Dovzhenko, N.G. Gavrilov, B.A. Knyazev, E.I. Kolobanov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, V.K. Ovchar, V.M. Popik, T.V. Salikova, M.A. Scheglov, S.S. Serednyakov, O.A. Shevchenko, A.N. Skrinsky, V.G. Tcheskidov, Yu.F. Tokarev, and P.D. Vobly

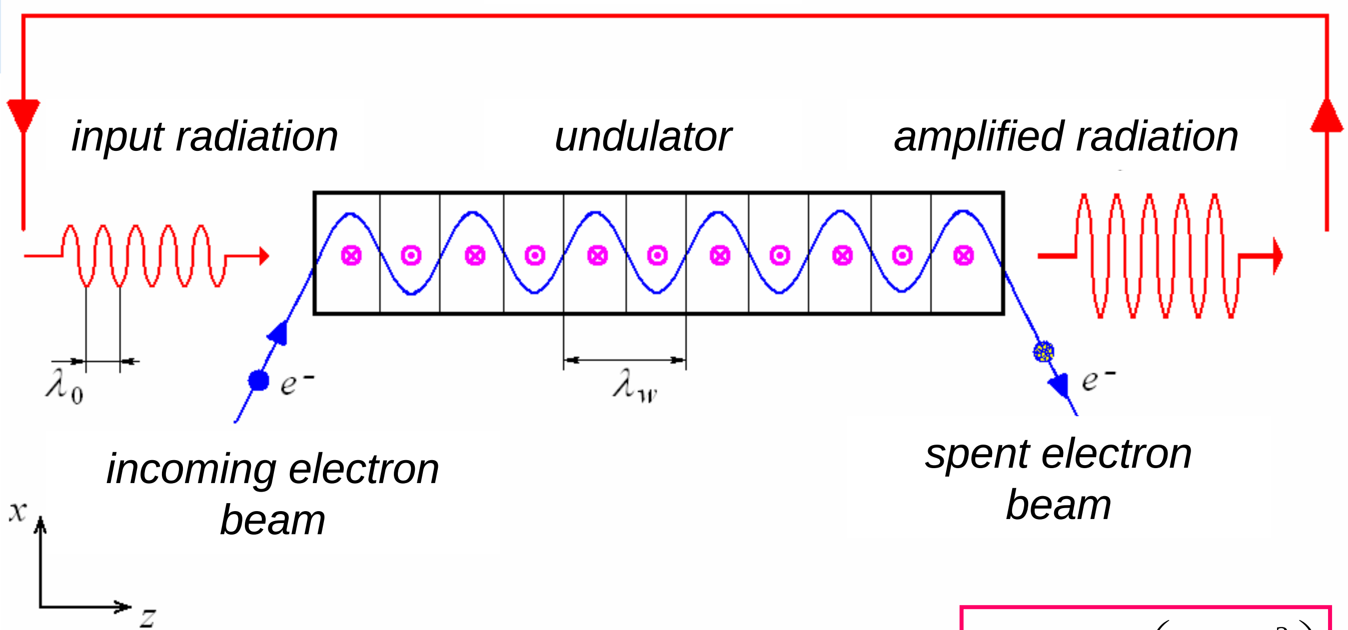
Budker INP, Novosibirsk, Russia

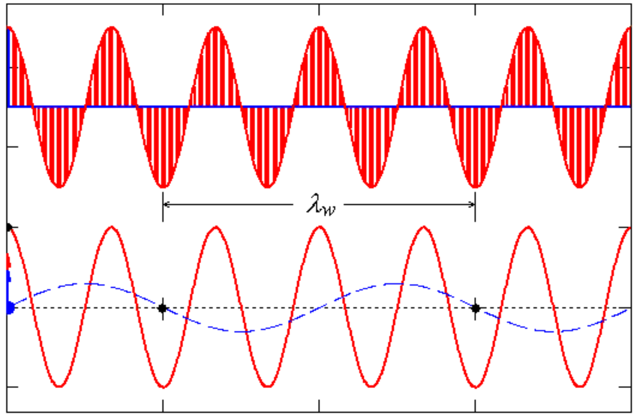
Free Electron Laser (FEL)



1 – incoming (“fresh”) electron beam, 2 – undulator,
3- spent electron beam, 4 – input electromagnetic radiation,
5 – amplified radiation.

FEL-oscillator





Electron velocity changes in synchronism with the wave electric field

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

synchronism condition

for maximum energy transfer

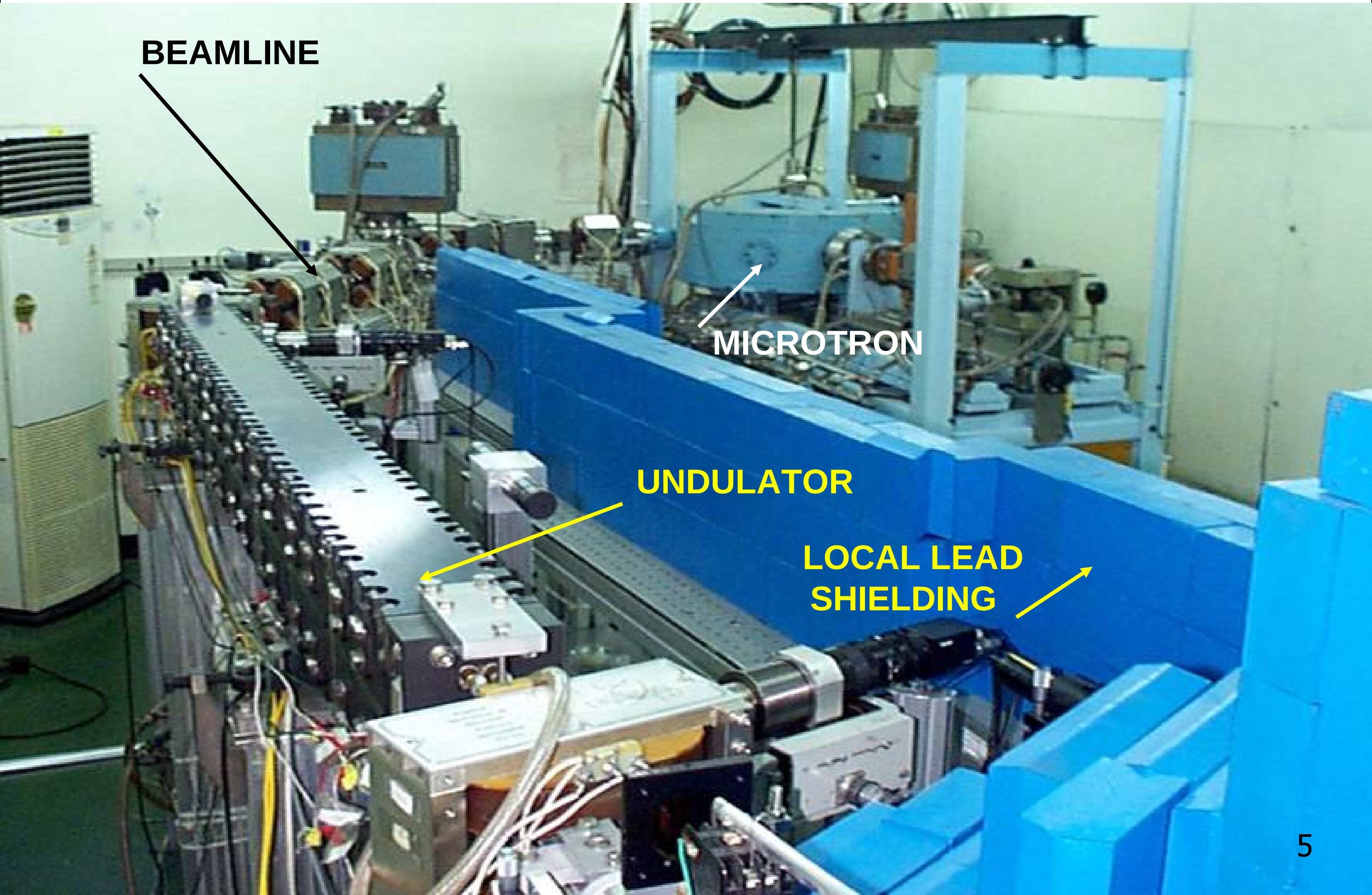
$$\left\langle \frac{d\gamma}{dz} \right\rangle = \frac{e}{mc^3}\left\langle \mathcal{E}_x V_x \right\rangle$$

FEL advantages compared to other types of lasers:

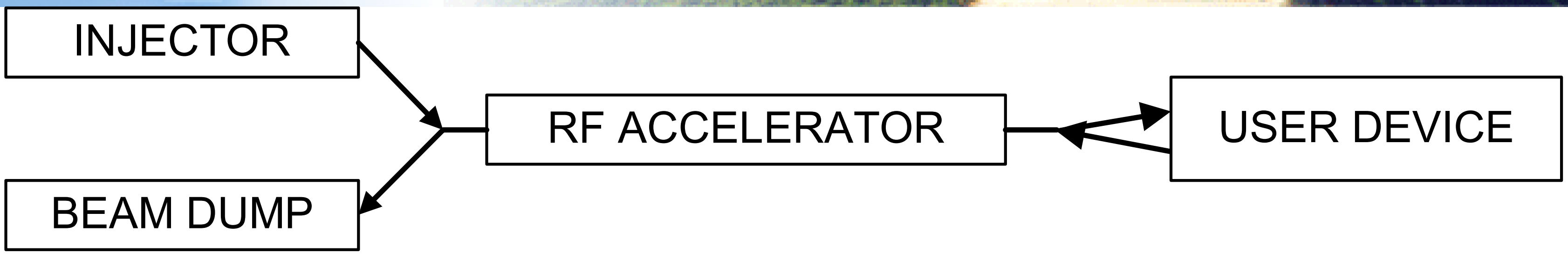
- capability to provide radiation with any given wavelength (from 1 Å to 1 mm);
- capability of tuning of the radiation wavelengths;
- high average power of radiation (up to 10^4 – 10^6 W).

FEL disadvantages: size and cost.

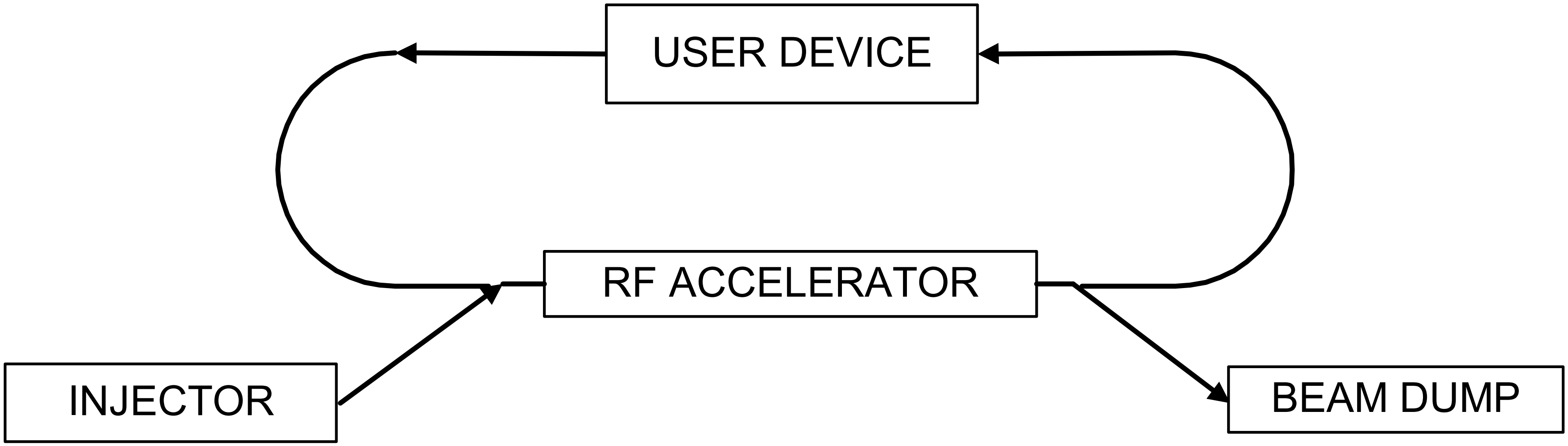
Compact microtron-based terahertz FEL (in operation since 1998 in KAERI, S. Korea)



Energy recovery linacs (ERLs) with the same cavity energy recovery



a



b

Problems: a – colliding beams, b – focusing of two beams with different energies in the RF accelerator.

ERLs for FELs

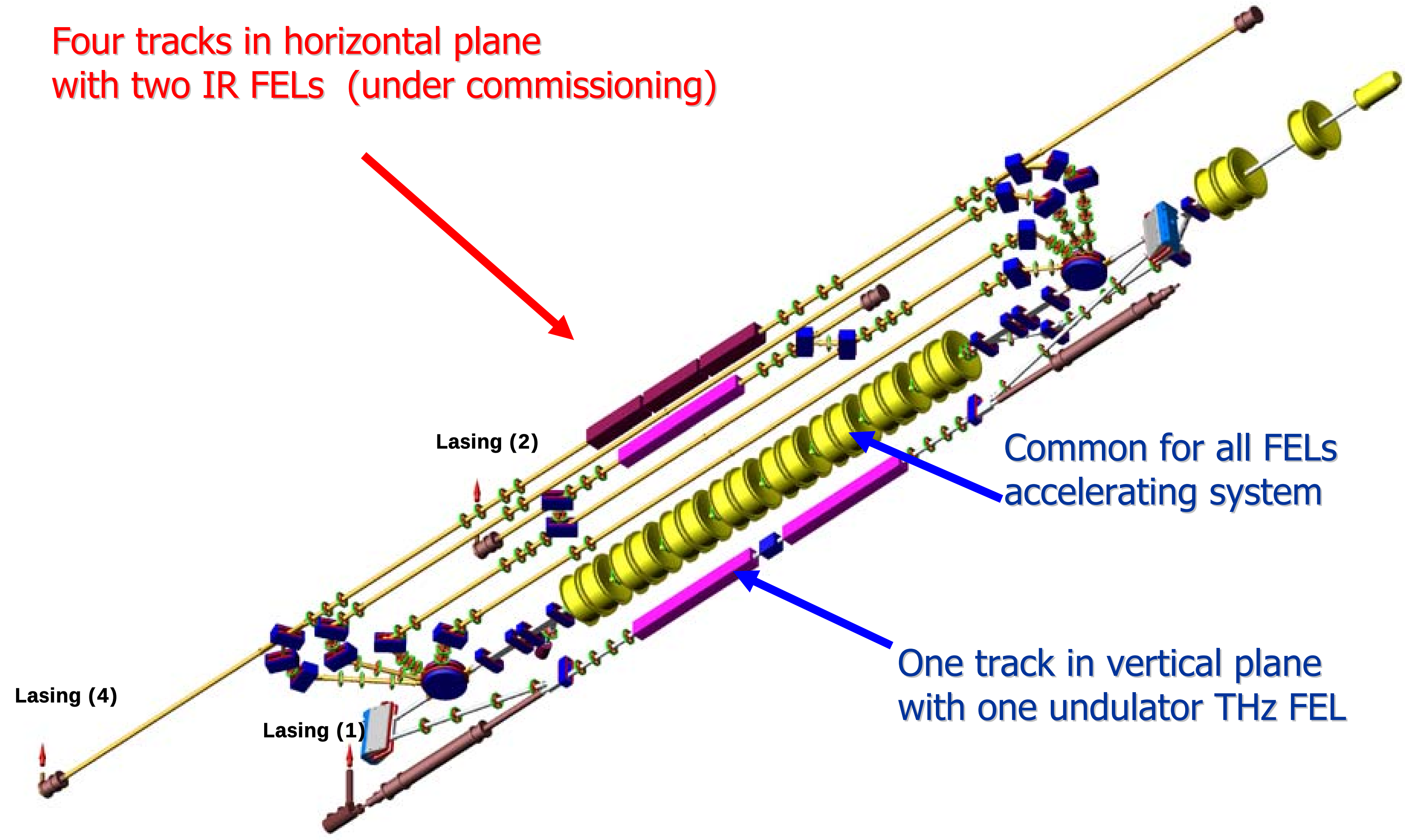
3 ERLs are in operation now. All they works for FEL.

Jefferson Lab. (USA) and JAERI (Japan) ERLs use superconducting RF.

Novosibirsk ERL uses normal-conducting RF. It is the only one with two orbits (two accelerations and two decelerations).

Novosibirsk ERL with 3 FELs

Four tracks in horizontal plane
with two IR FELs (under commissioning)



Common for all FELs
accelerating system

One track in vertical plane
with one undulator THz FEL

Features of RF system

- Low frequency (180 MHz)
- Normal-conducting uncoupled RF cavities
- CW operation

Threshold currents of some instabilities

Transverse beam breakup

$$I < I_0 \frac{\lambda\!\!\!^{-2}}{Q_a L_{eff} \sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}}$$

Longitudinal instability

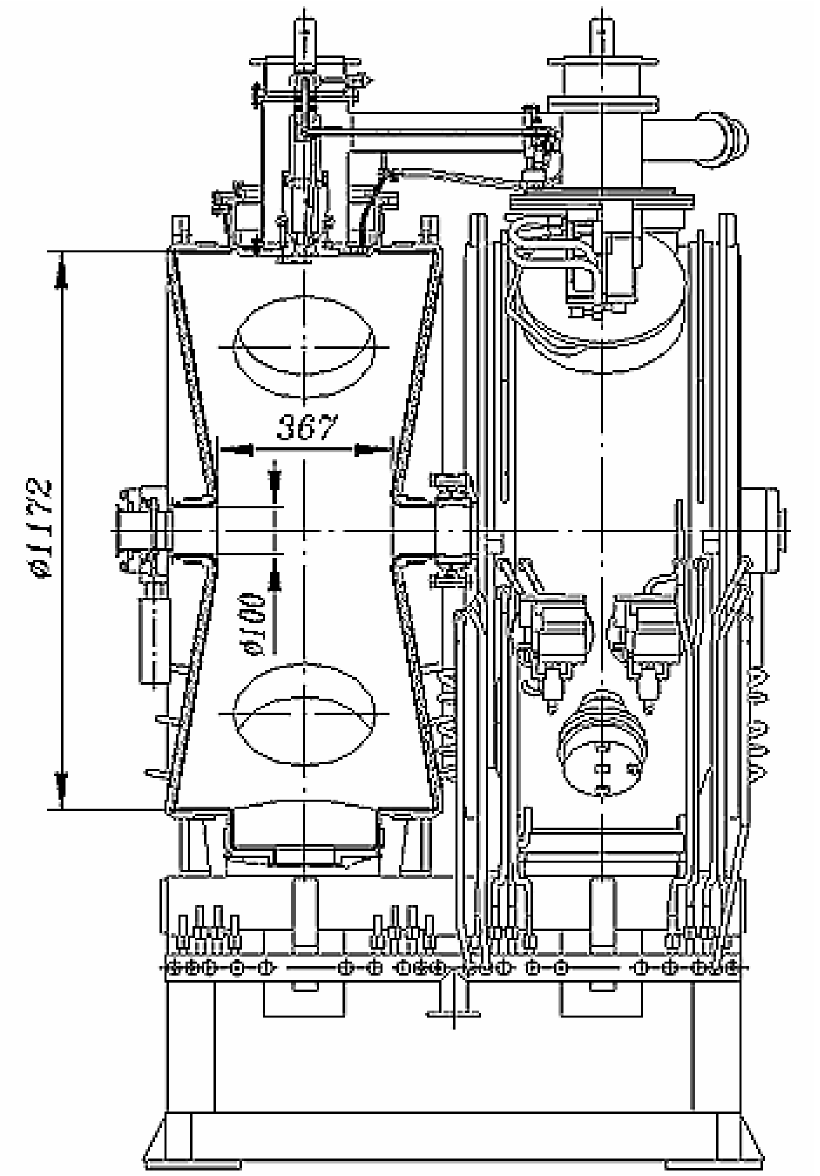
$$I < \frac{1}{-e\rho Q \sum_{n=1}^{2N} \sum_{k=1}^{n-1} [S_{nk} \sin(\varphi_k - \varphi_n)]}$$

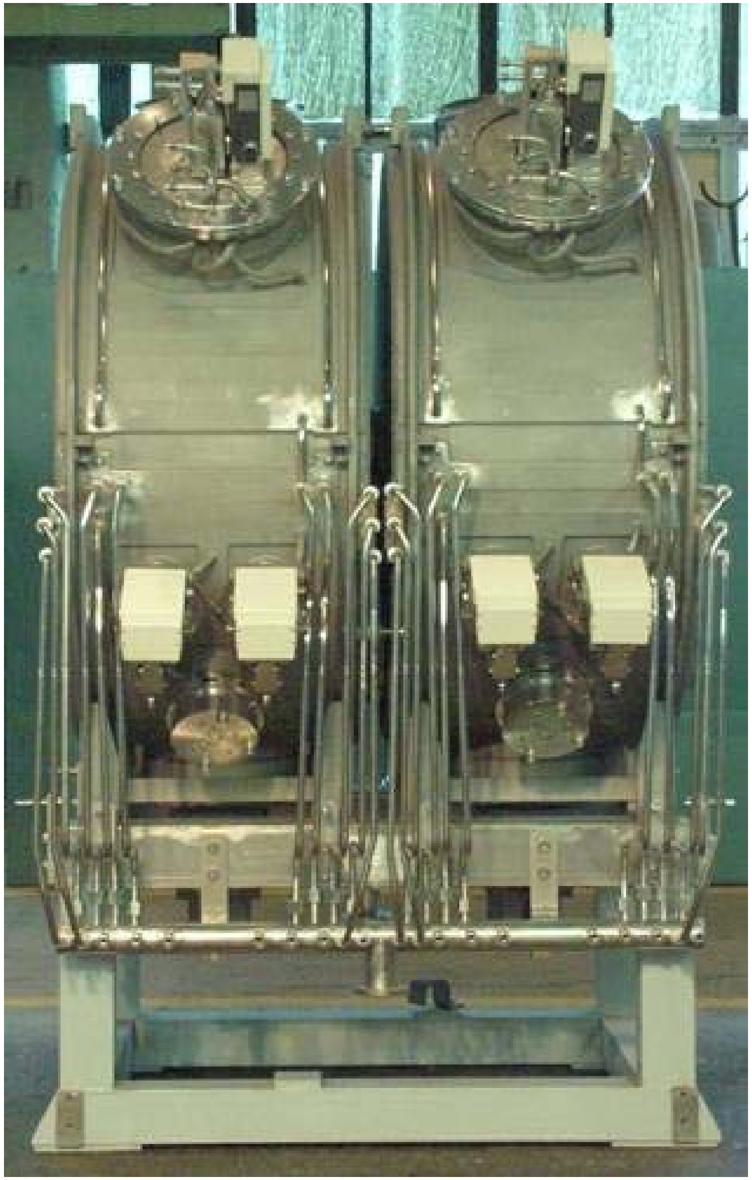
[1] E. Pozdeev et al., Multipass beam breakup in energy recovery linacs, NIM A 557, (2006), p.176-188.
[2] N. A. Vinokurov et al., Proc. of SPIE Vol. 2988, p. 221 (1997).

Advantages

- High threshold currents of instabilities
- Operation with long electron bunches (for narrow FEL linewidth)
- Large longitudinal acceptance (good for operation with large energy spread of used beam)
- Relaxed tolerances for orbit lengths and longitudinal dispersion

A pair of accelerating cavities on a support frame





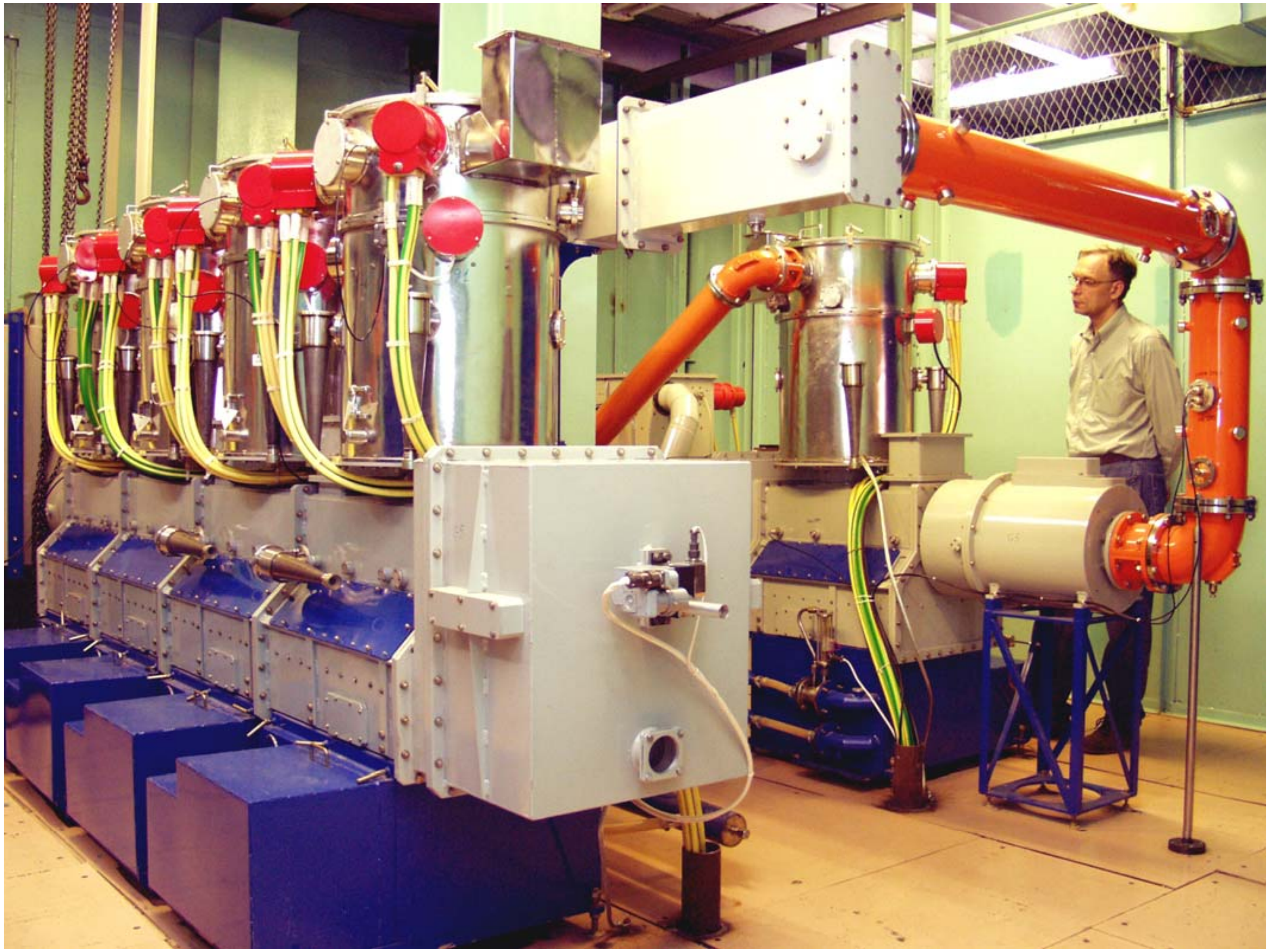
Bimetallic (copper and stainless steel) RF cavity tanks

Main parameters of the cavity

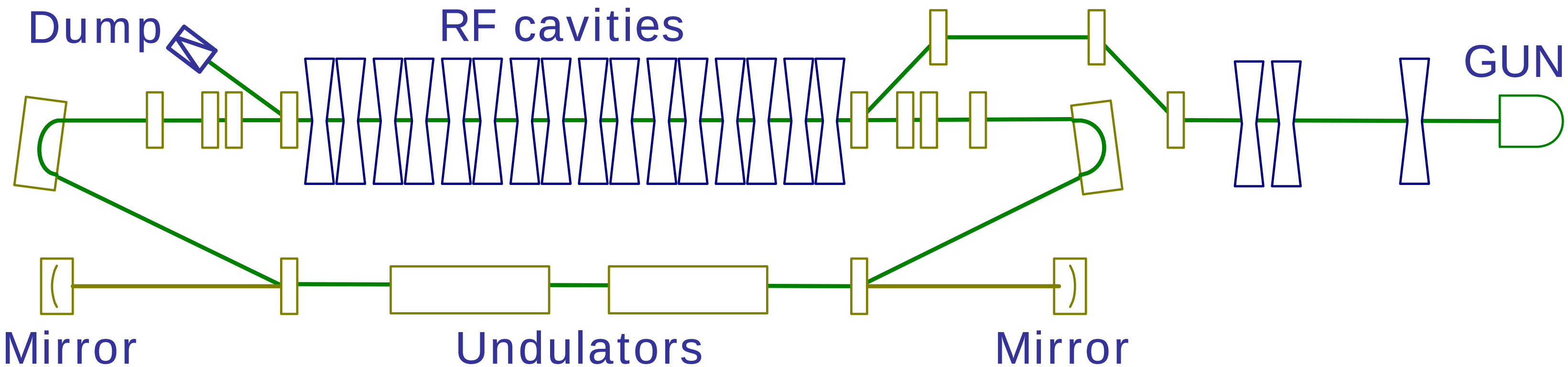
(for the fundamental TM_{010} mode)

Resonant frequency, MHz	f_0	180,4
Frequency tuning range, kHz	Δf_0	320
Quality factor	Q	40000
Shunt impedance, MOhm	R=U2/2P	5,3
Characteristic impedance, Ohm	ρ=R/Q	133,5
Operating gap voltage amplitude, MV	U	0-1.1
Power dissipation in the cavity, kW, at U=1100 kV	P	115
Input coupler power capability, kW (*tested, limited by available power*)	P_{in}	400

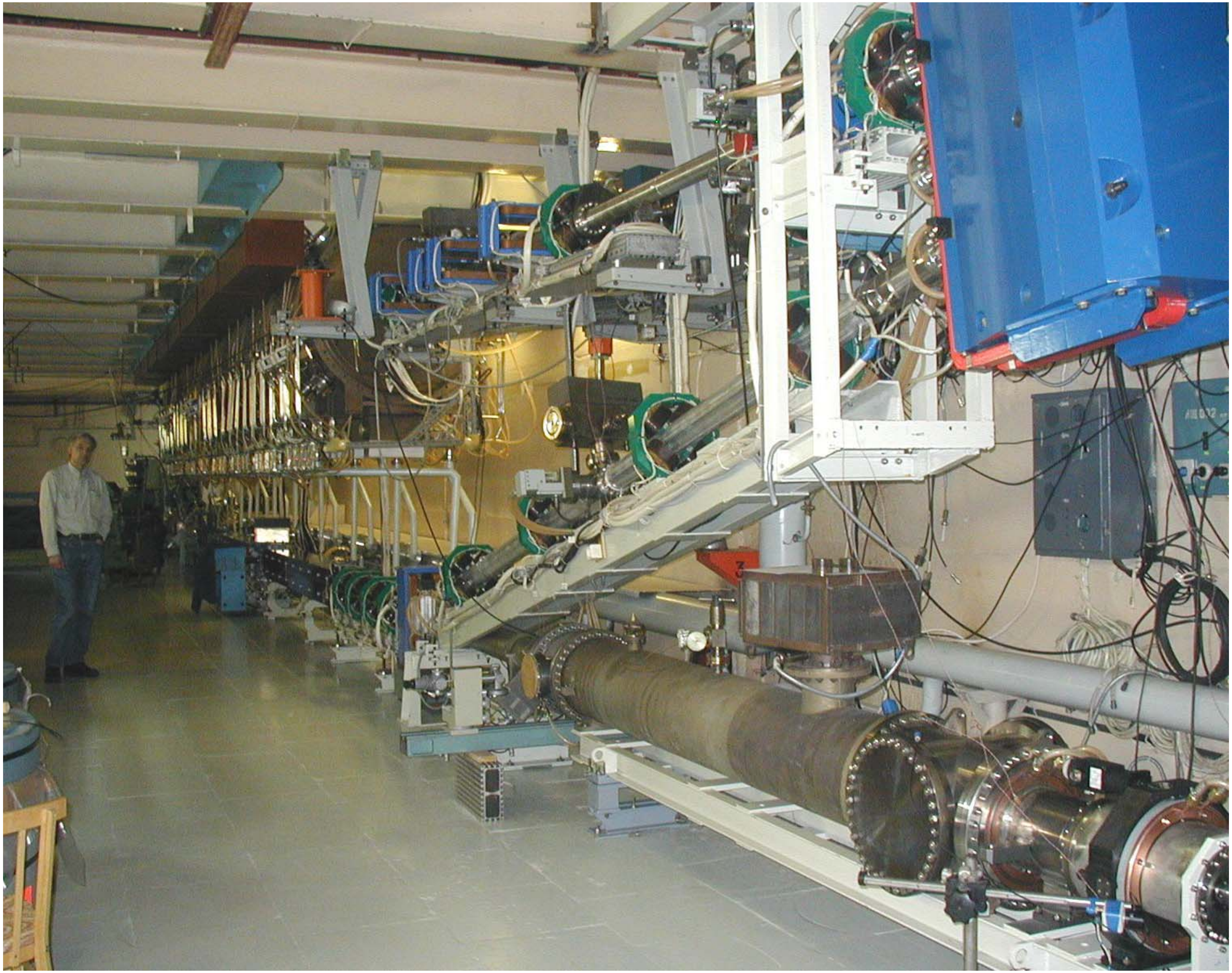
Tetrode-based output amplifier stages



First stage: submillimeter (THz) FEL



THz FEL (old)



2 MeV Injector Parameters

♦ DC electron gun voltage, kV	up to 300
♦ Bunch repetition rate, MHz	up to 22.5
♦ Charge per bunch, nC	up to 2
♦ Start bunch length, ns	1.0
♦ Final bunch length, ns	0.1
♦ Final energy, MeV	1.7

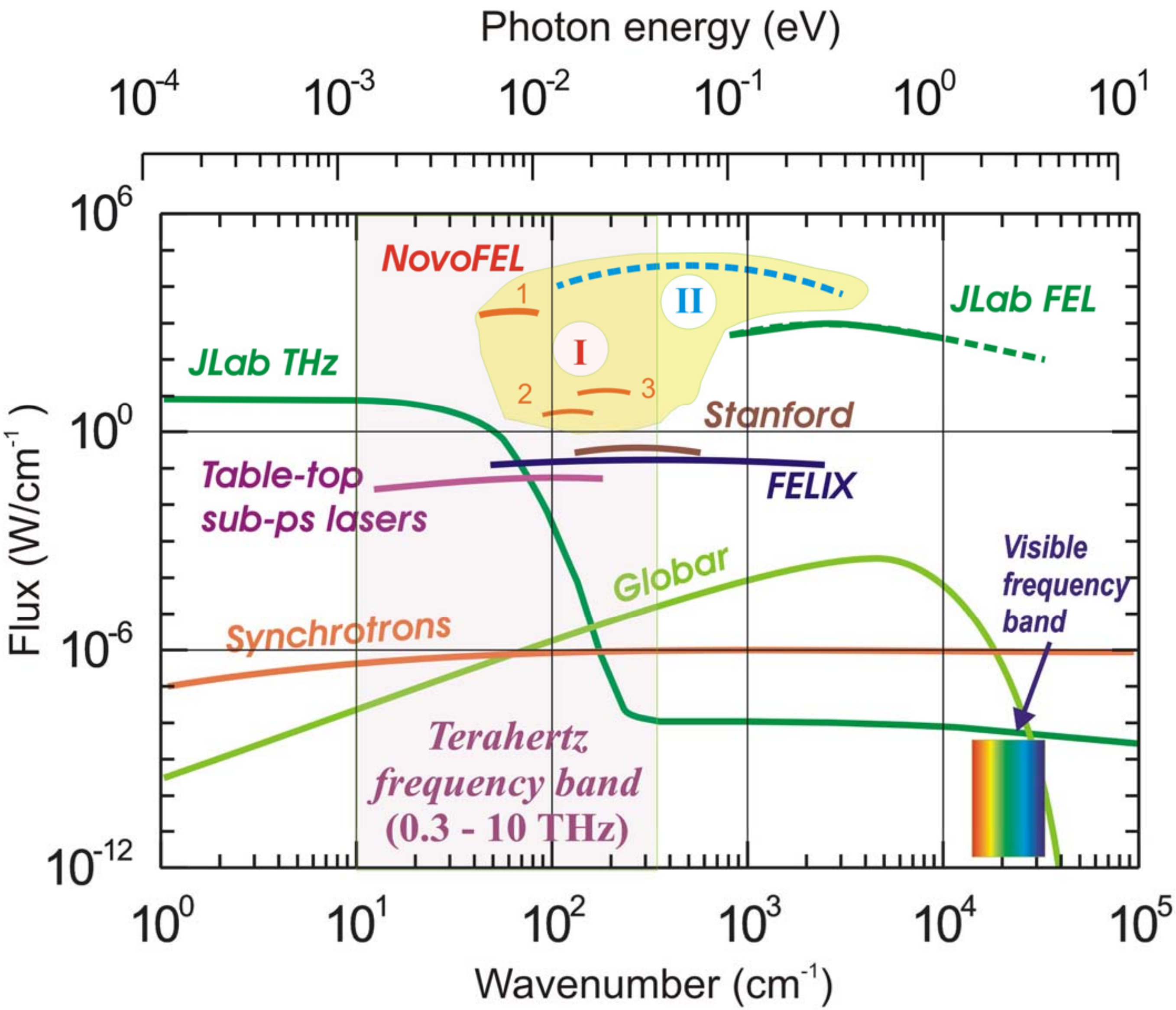
First Stage Accelerator-Recuperator Parameters

♦Bunch repetition rate, MHz	22.5
♦Average electron current, mA	30
♦Maximum energy, MeV	12
♦Bunch length, ps	100
♦Normalized emittance, mm*mrad	30

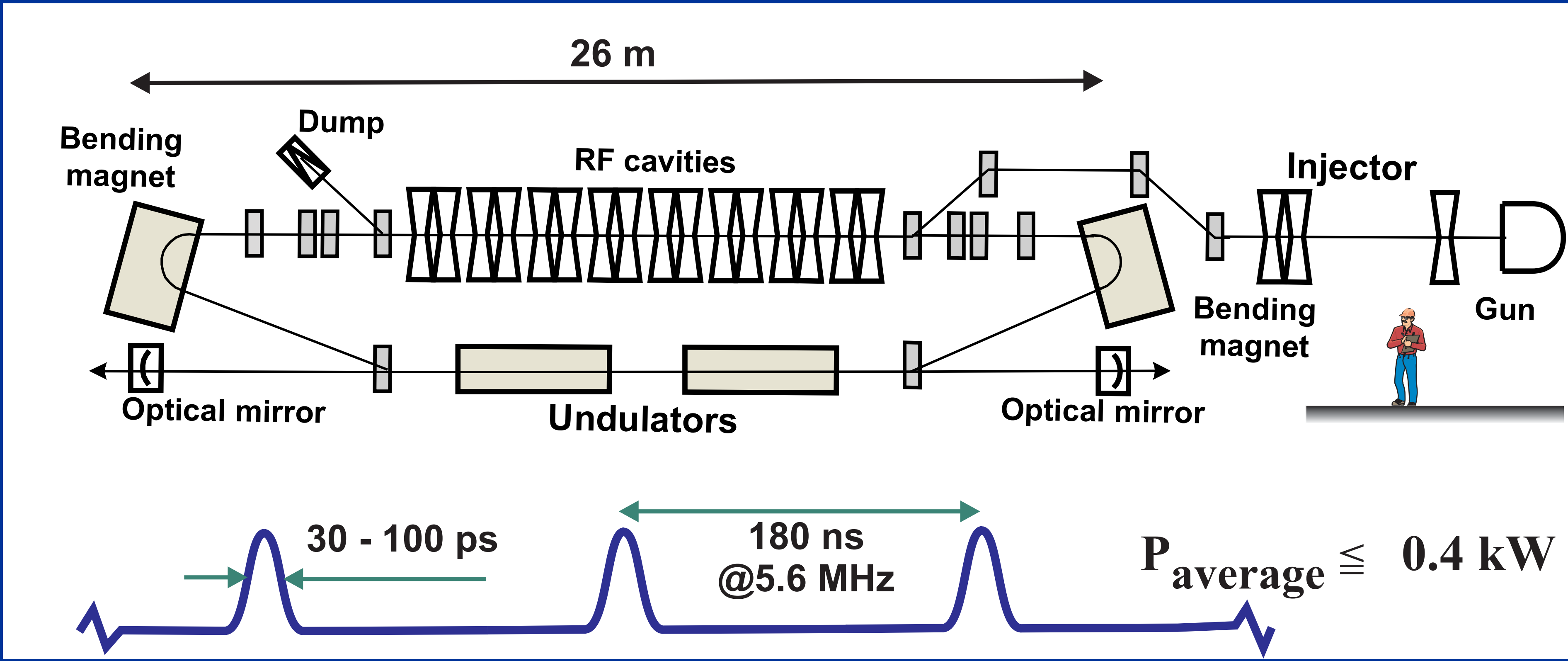
Free Electron Laser Parameters

♦ Wavelength, mm	0.12-0.24
♦ Pulse duration, FWHM, ps	~70
♦ Pulse energy, mJ	0.04
♦ Repetition rate, MHz	11.2
♦ Average power, kW	0.5
♦ Minimum relative linewidth, FWHM	$3 \cdot 10^{-3}$

Average spectral power density of the light sources



Layout of the Novosibirsk FEL (1st stage)

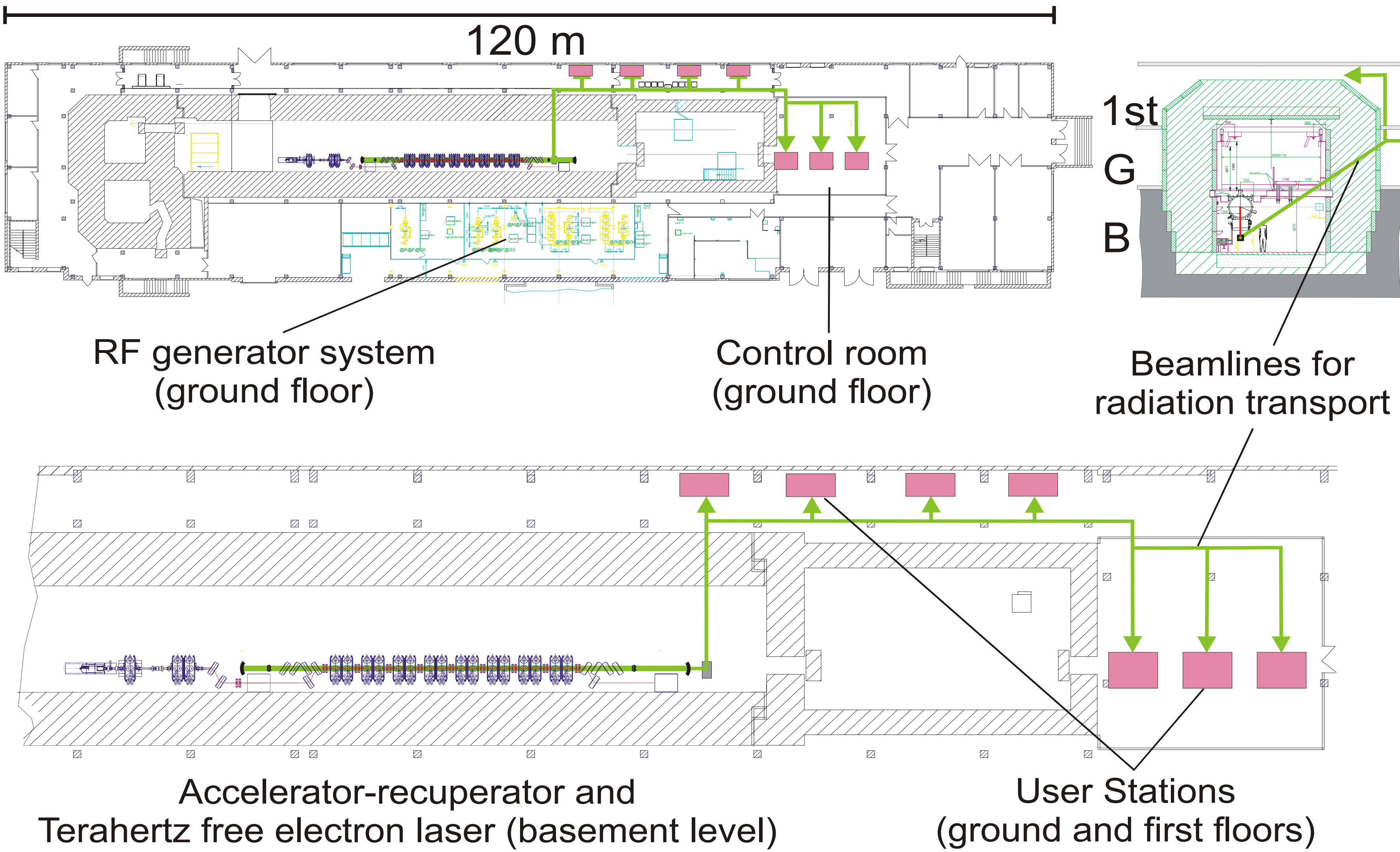


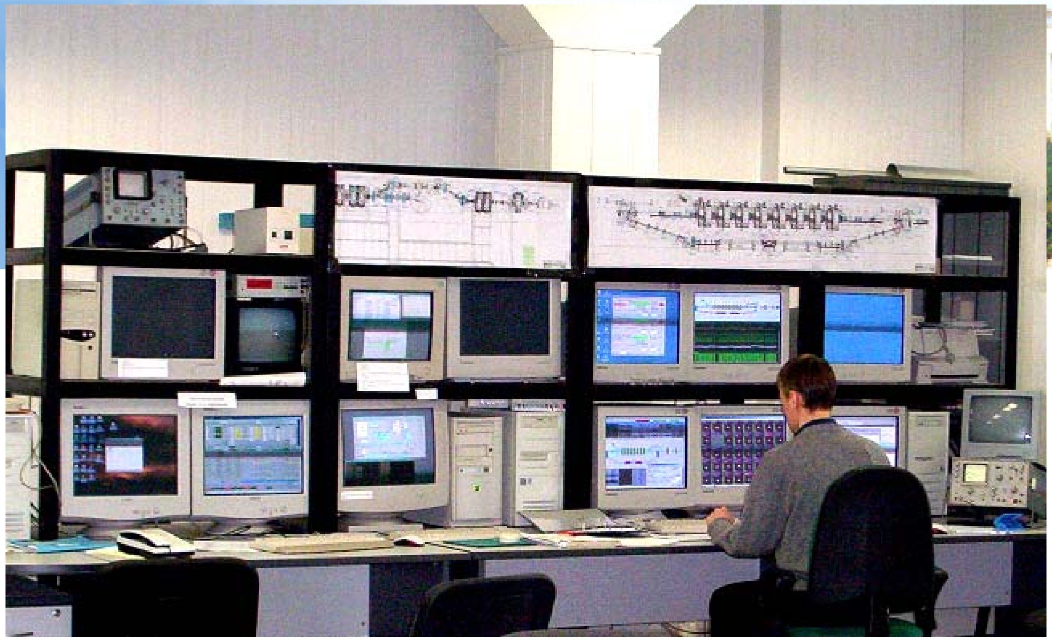
Electron beam from the gun passes through the buncher (a bunching RF cavity), drift section, 2 MeV accelerating cavities and the main accelerating structure and the undulator, where a fraction of its energy is converted to radiation.

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.

Siberian center of photochemical research

Layout of terahertz FEL and user stations

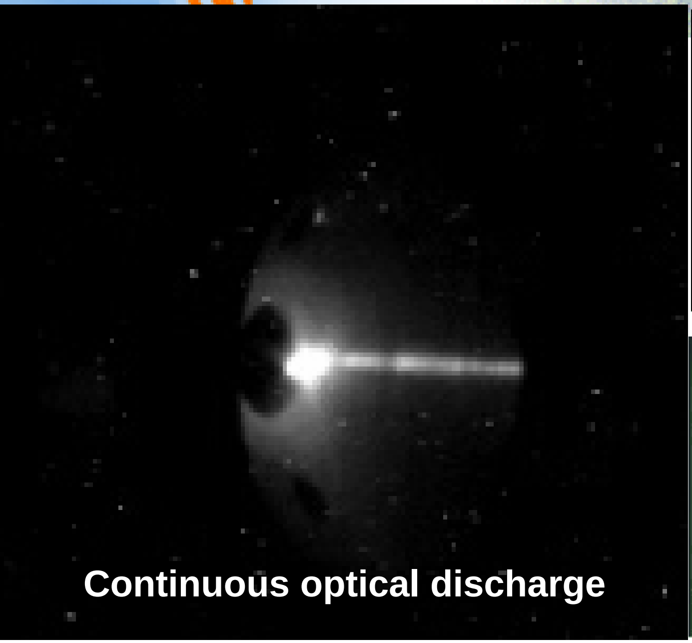


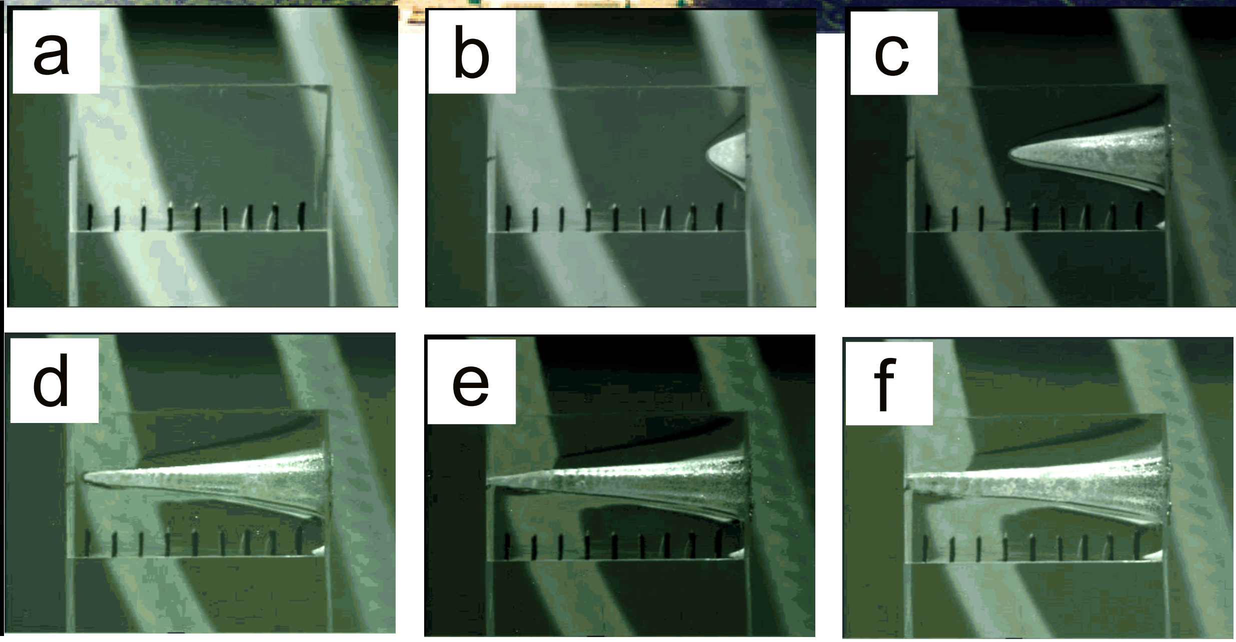



2005


2006

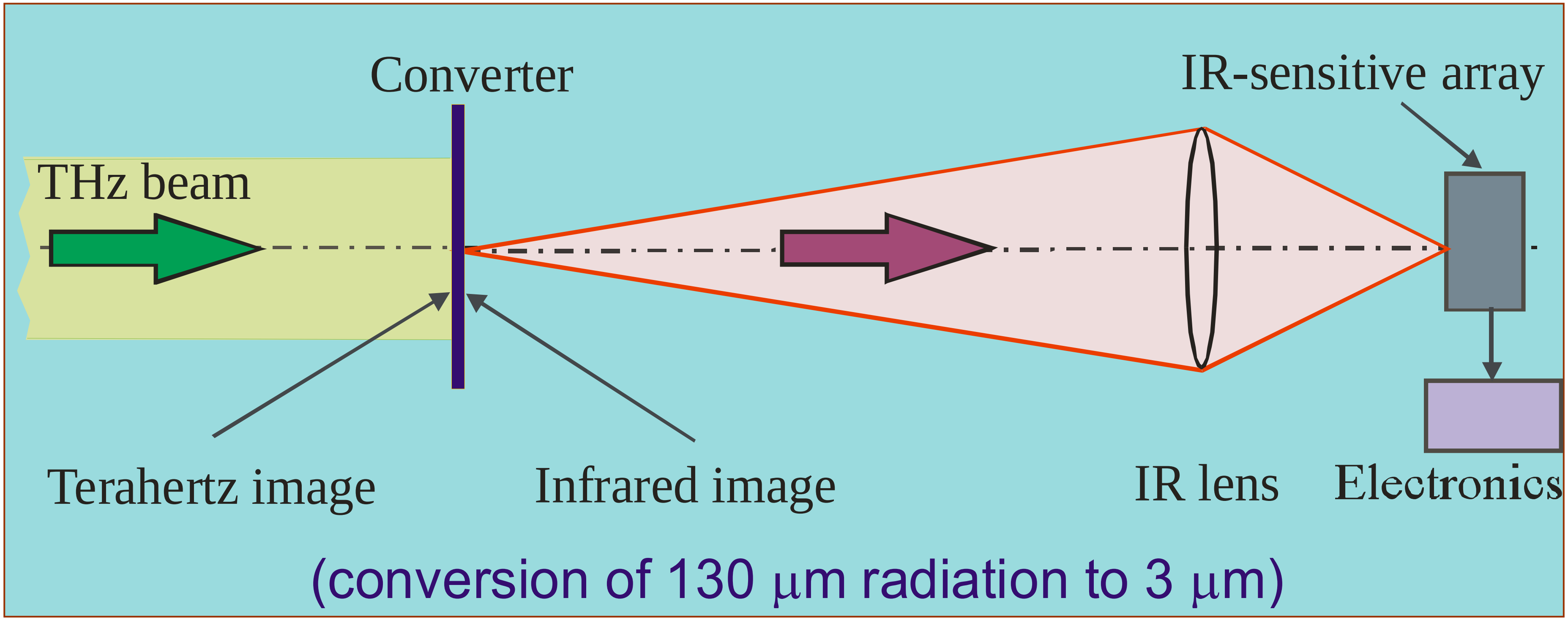
High average power of radiation (up to 400 W) in combination with high peak power (up to 0.6 MW) enables performing high power density experiments





- 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…)

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

Keys in an opaque paper envelope

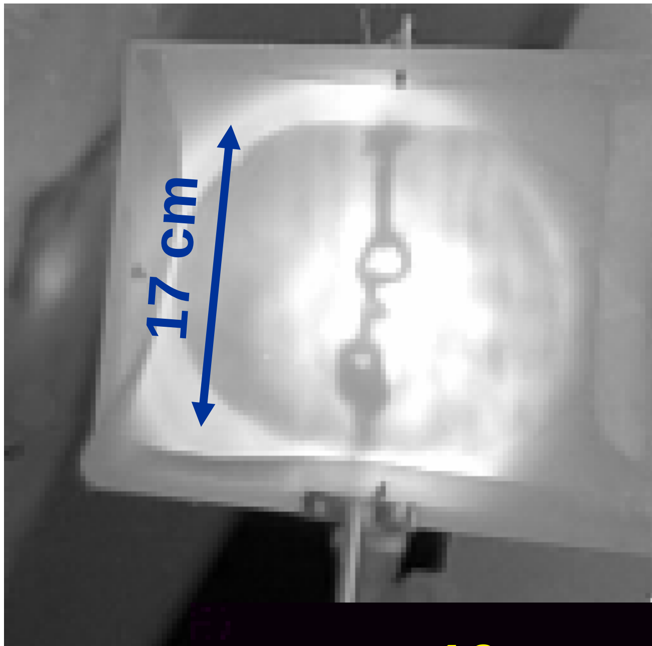
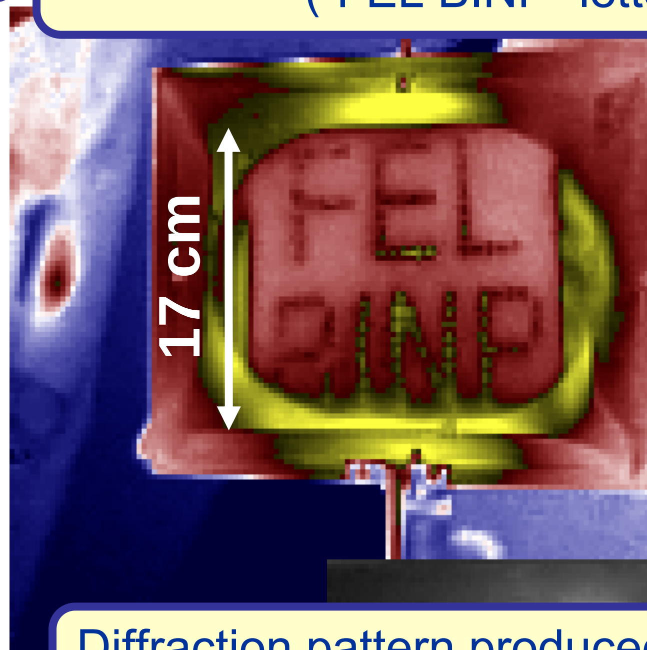
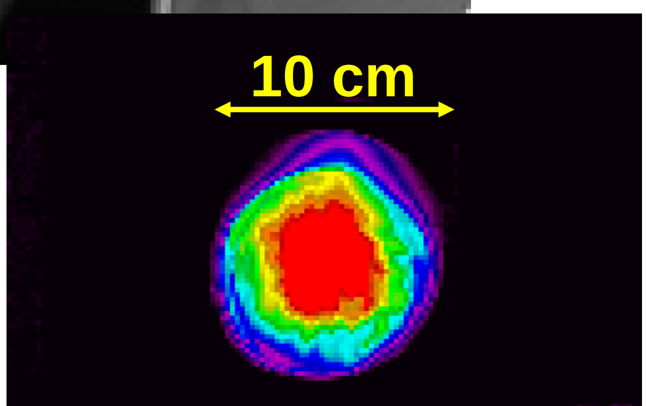


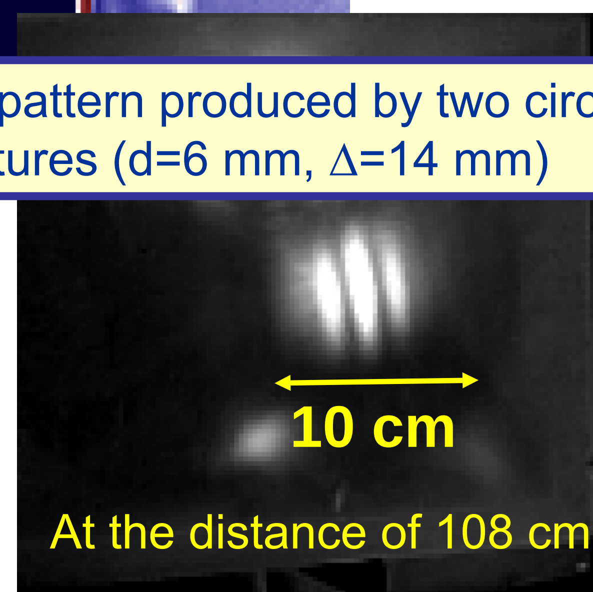
Image of 6-mm holes drilled in a metal plate ("FEL BINP" letters)





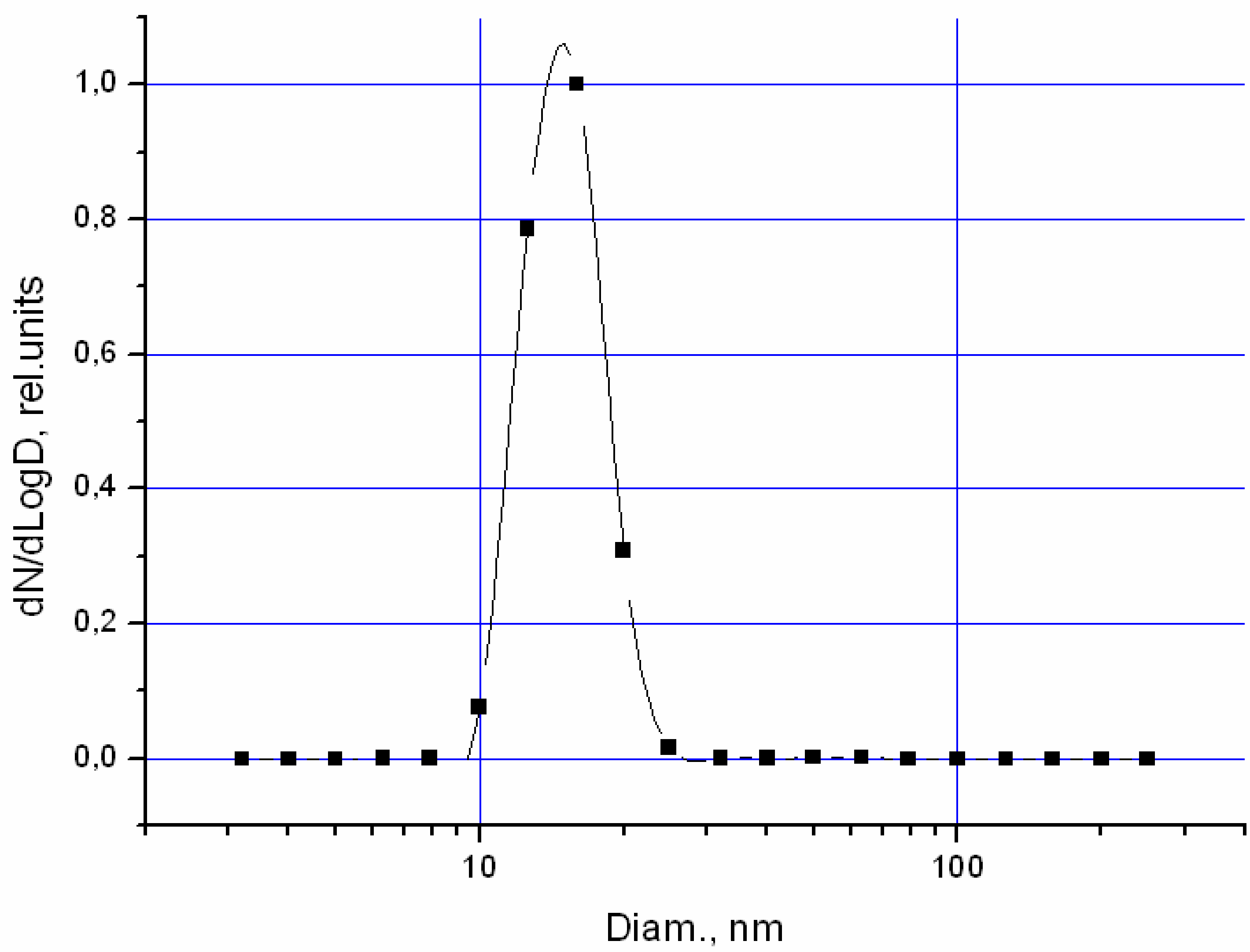
THz laser beam cross-section at the beamline output (13 meters from the laser)

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



Result of Treatment of Marble by THz Radiation

Ablation of crystal minerals (marble)



Status

• ERL works at 12 MeV and up to 30 mA average current (world record for ERLs).

• Up to 500 W of average power at 110 – 240 micron wavelength range is delivered to users. Linewidth is less than 1%, maximum peak power is about 1 MW.

• First user stations are in operation.

• Second stage of ERL is under commissioning.

Second stage of Novosibirsk FEL

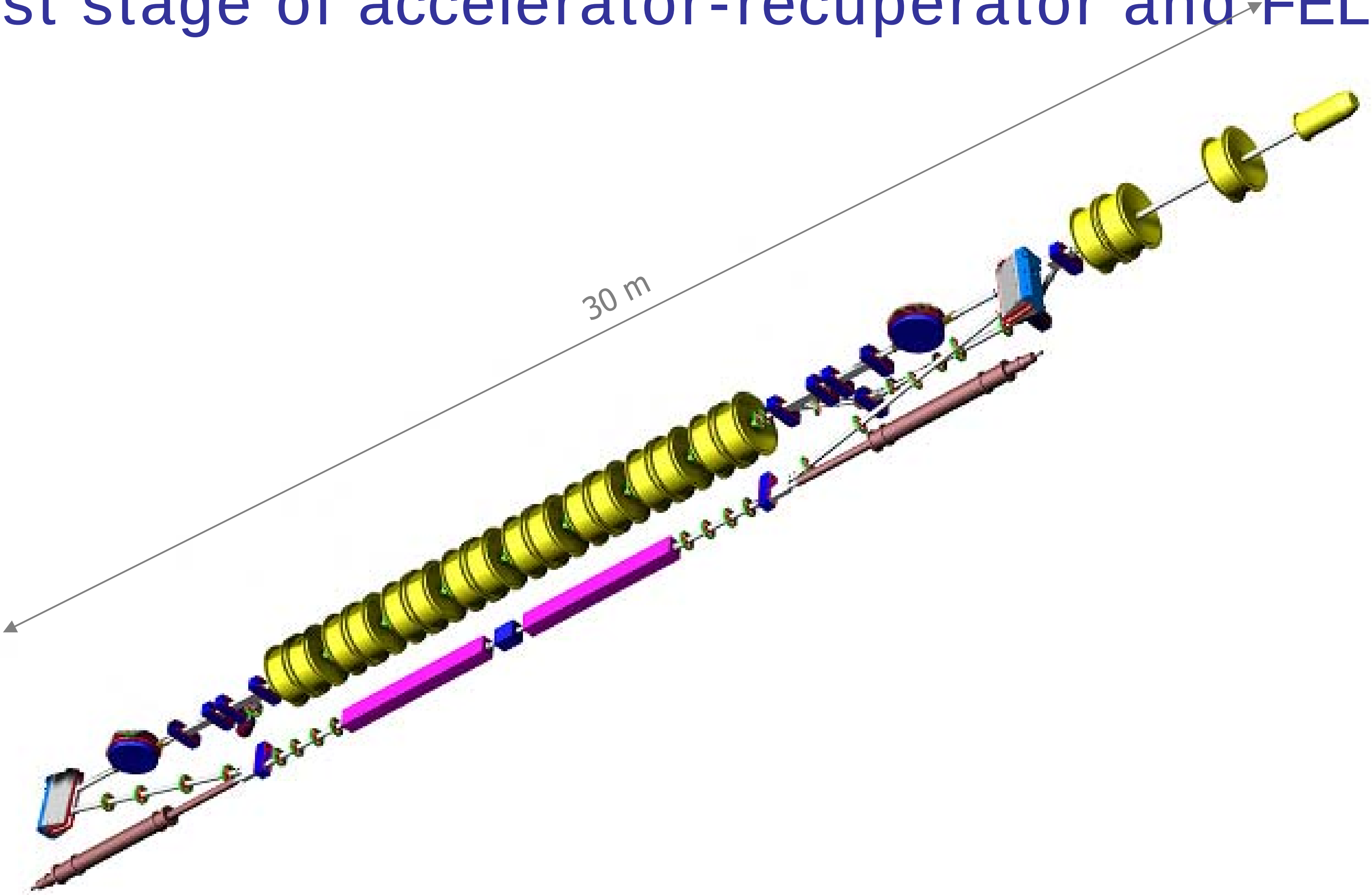
A full-scale 4-orbit ERL uses the same accelerating structure as the ERL of the 1st stage, but, in contrast to the latter, it is placed in the horizontal plane. Thus, the vertical orbit with the terahertz FEL is saved.

The choice of operation mode (one of three FELs) will be achived by switching of bending magnets.

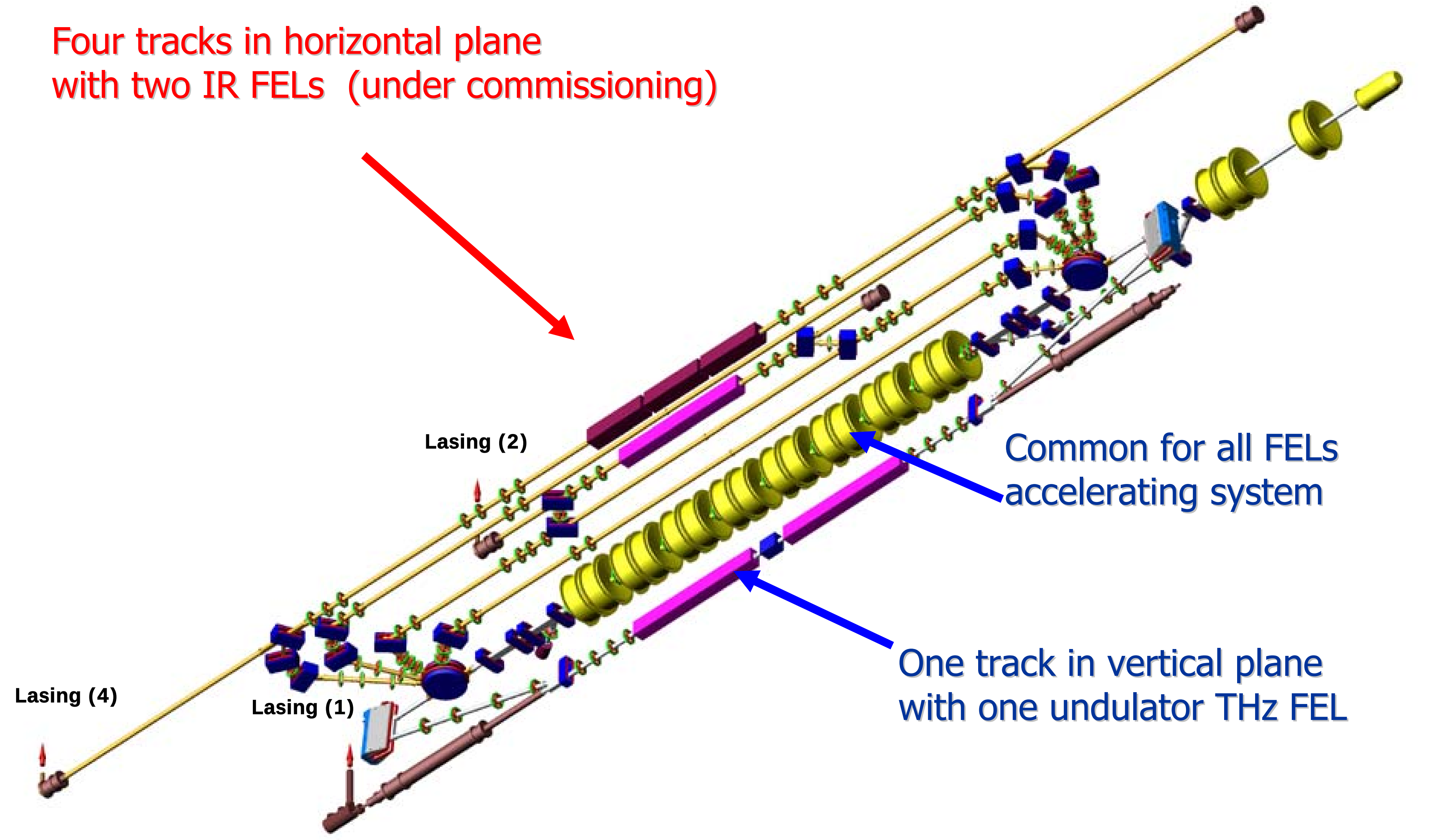
Second stage ERL and FEL parameters

Electron beam energy, MeV	40
Number of orbits	4
Maximum bunch repetition frequency, MHz	90
Beam average current, mA	100
Wavelength range, micron	5-240
Maximum output power, kW	10

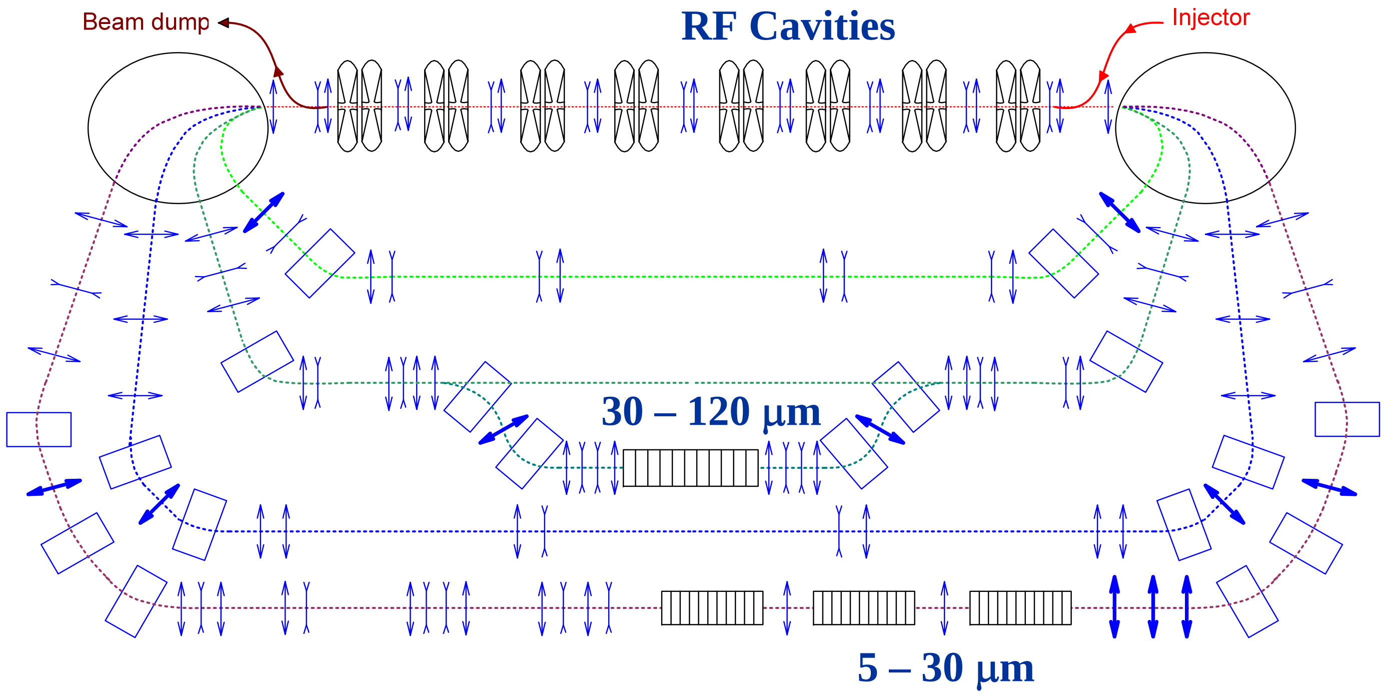
First stage of accelerator-recuperator and FEL



Novosibirsk ERL with 3 FELs

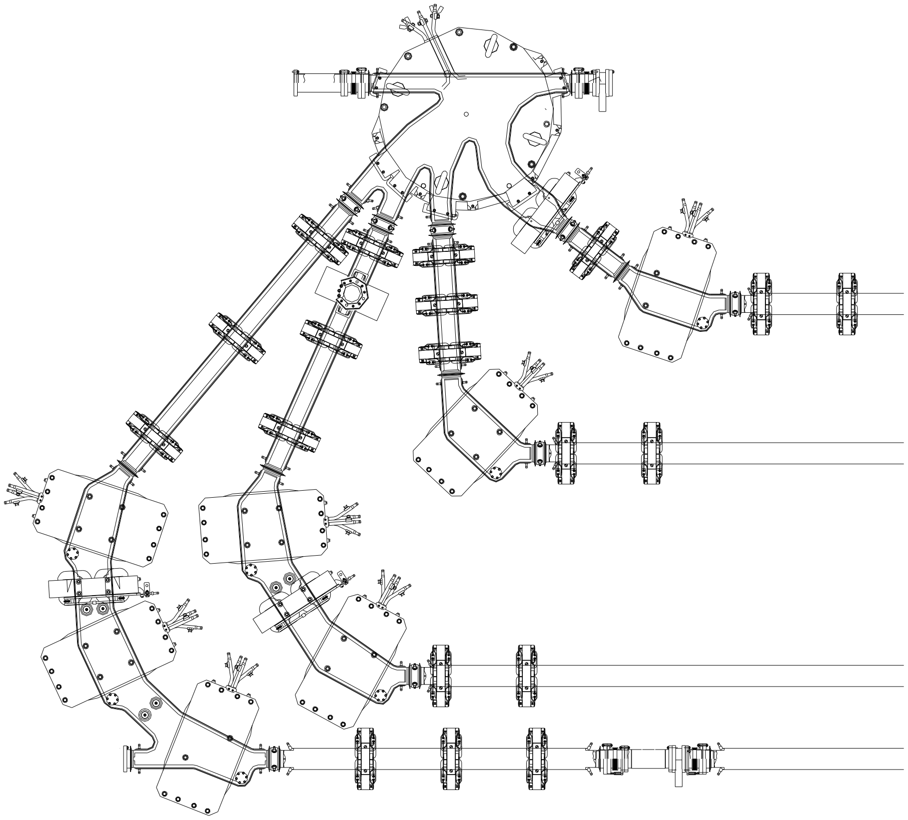


2-nd stage Novosibirsk FEL (in horizontal plane)

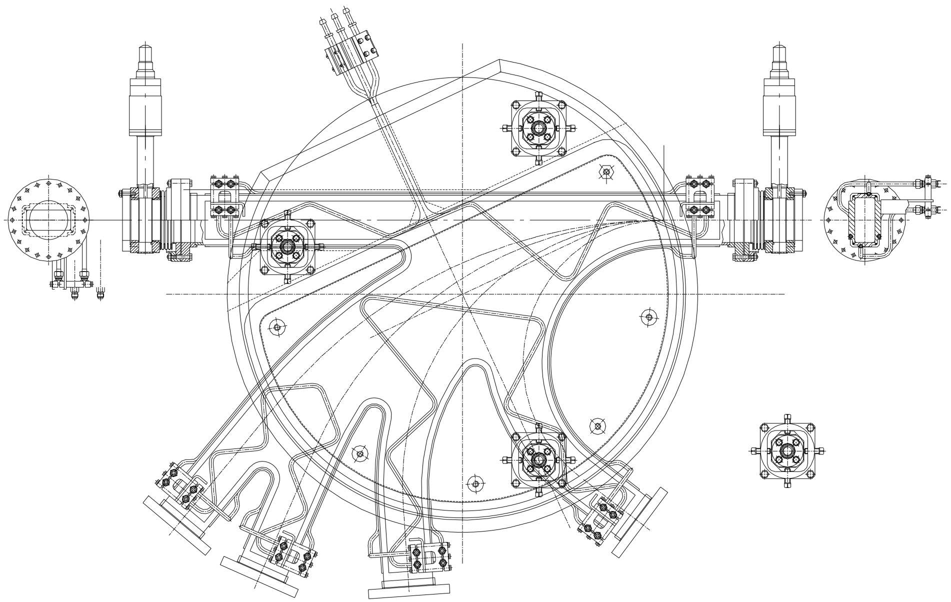


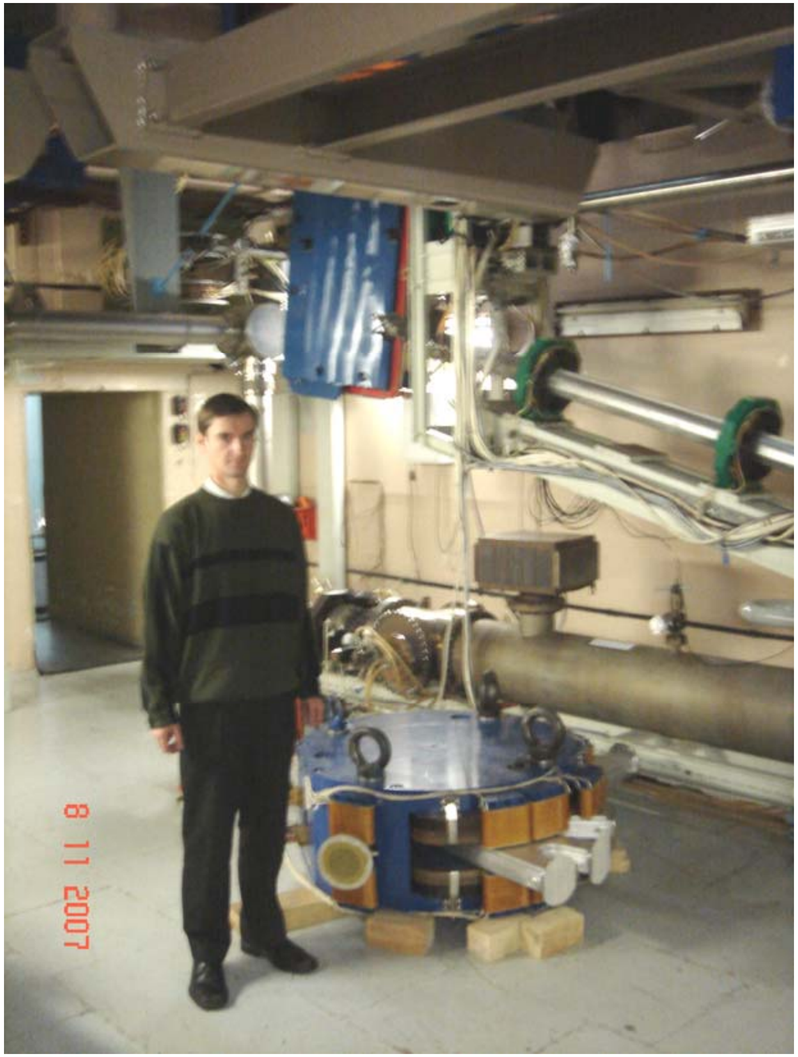
Radiation wavelength	**5 – 240 μm**
Average power	**Up to 10 kW**
E-beam energy	**up to 40 MeV**
Maximum repetition rate	**90 MHz**
Maximum mean current	**150 mA**

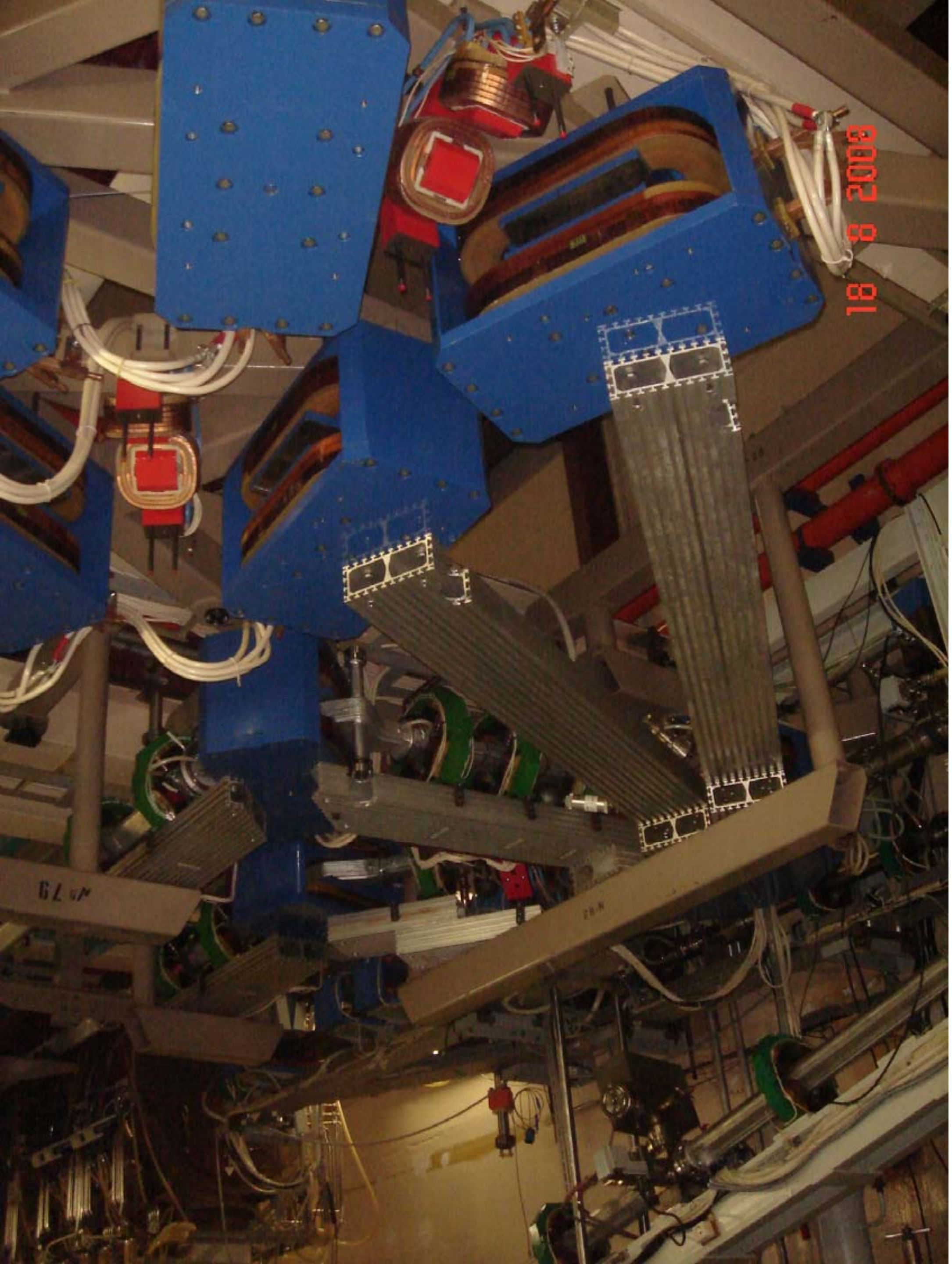
Magnets and vacuum chamber of bends



Round magnet







Small bending magnets of third and fourth tracks. Vacuum chambers are not installed yet. Top halves of quadrupoles between bending magnets are seen.

Assembly of four tracks is in progress

FEL-2007 Conference excursion,
Novosibirsk, August 29, 2007

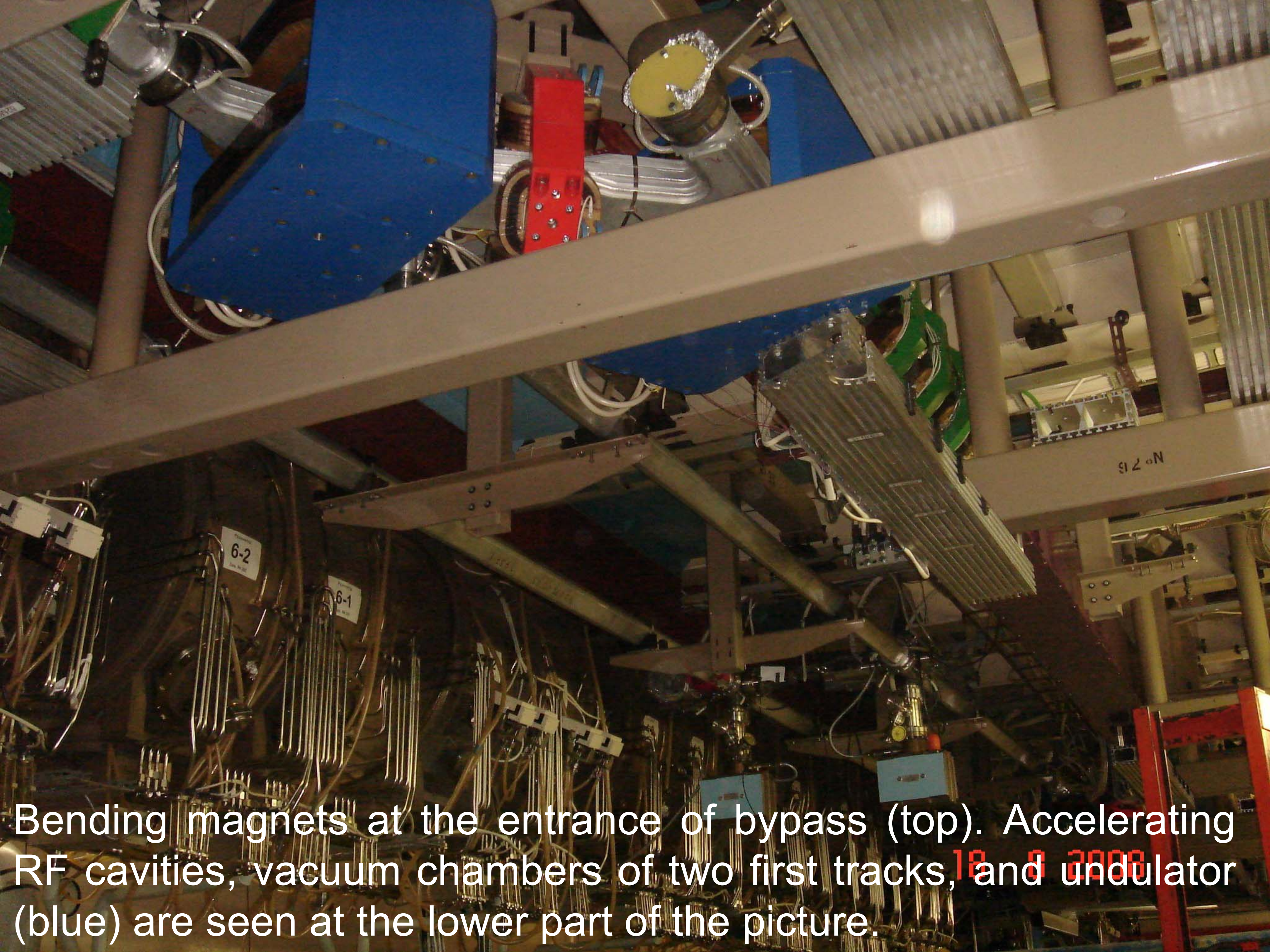
Second stage assembly


16
18 8 2008

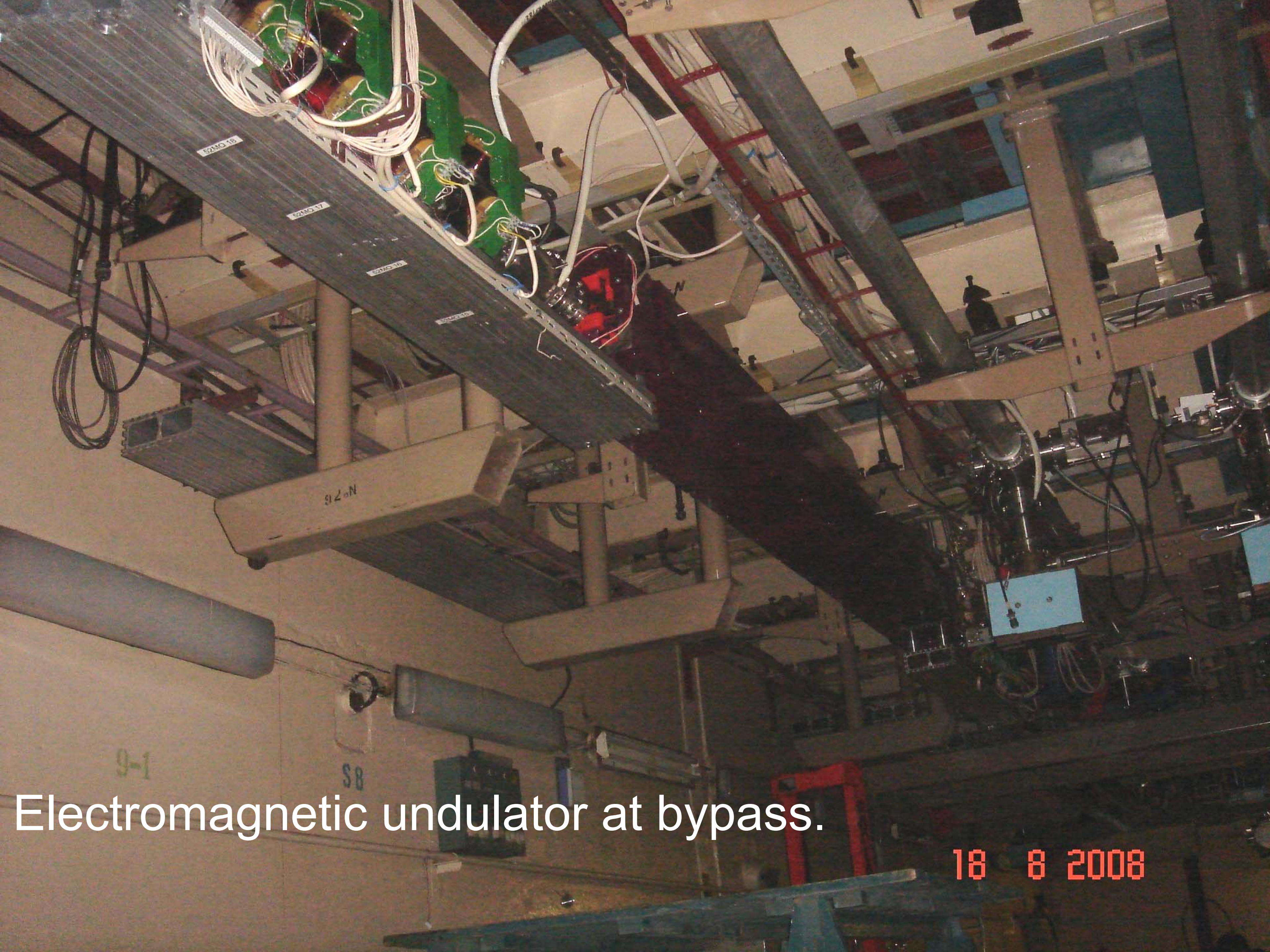
The bends are hanged on the ceiling.

Round magnet is at the top left corner, the old THz FEL magnetic system is at down-left.

Elements of the optical resonator for the second-turn FEL are yet at the floor (down-right corner).

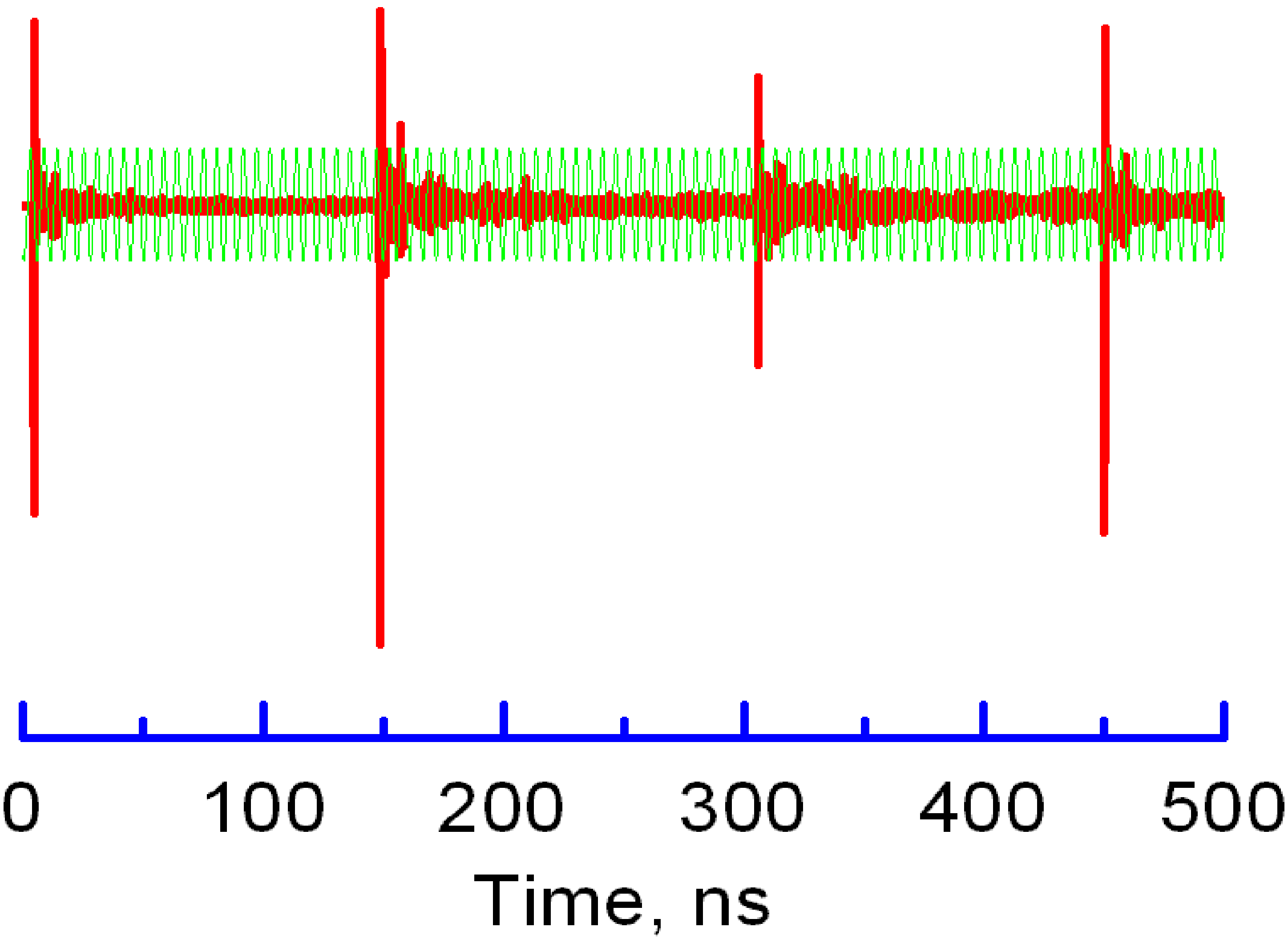


Bending magnets at the entrance of bypass (top). Accelerating RF cavities, vacuum chambers of two first tracks, and undulator (blue) are seen at the lower part of the picture.



Electromagnetic undulator at bypass.

BPM signal of single electron bunch. The sinusoidal RF signal (green) makes possible direct measurement of the orbit lengths.



Status of commissioning

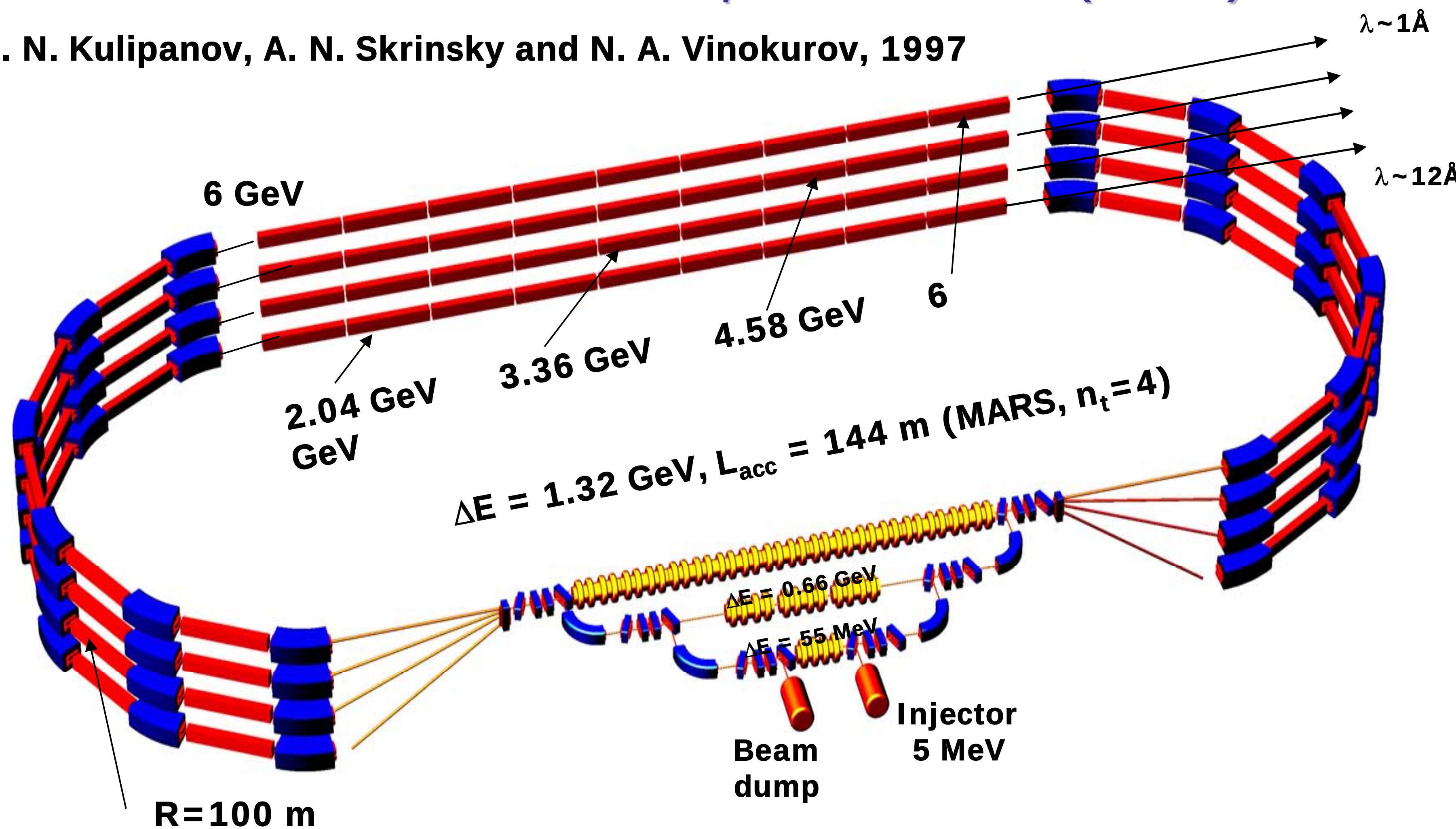
Electron beam passes twice trough the accelerating structure (acceleration to 20 MeV), then through the undulator, after that twice through the accelerating structure (deceleration to 2 MeV), then fly to the beam dump. Average current 9 mA was achieved.

First in the world multi-turn ERL is in operation now.

This is the way to MARS.

Multiturn Accelerator-Recuperator Source (MARS)

G. N. Kulipanov, A. N. Skrinsky and N. A. Vinokurov, 1997



Thank you