COMMISSIONING RESULTS WITH MULTI-PASS ERL

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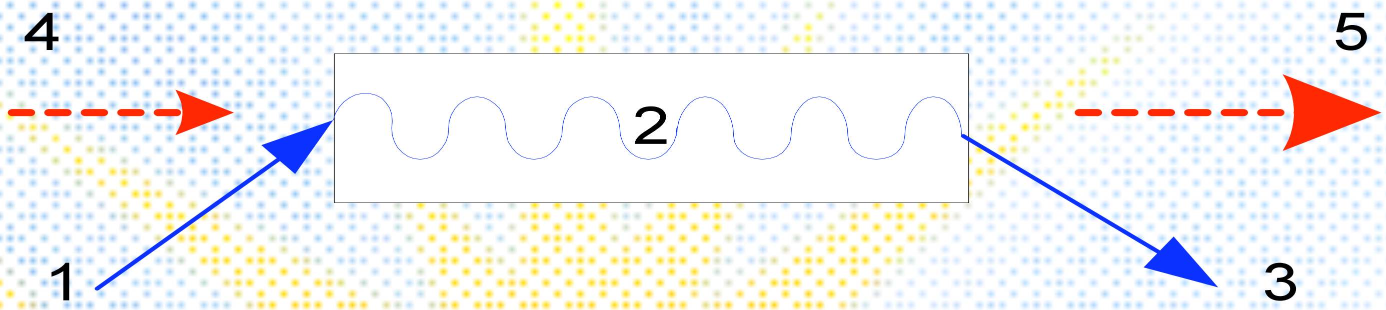
Free Electron Laser (FEL)



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

FEL advantages compared to other types of lasers:

- capability to provide radiation at 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).

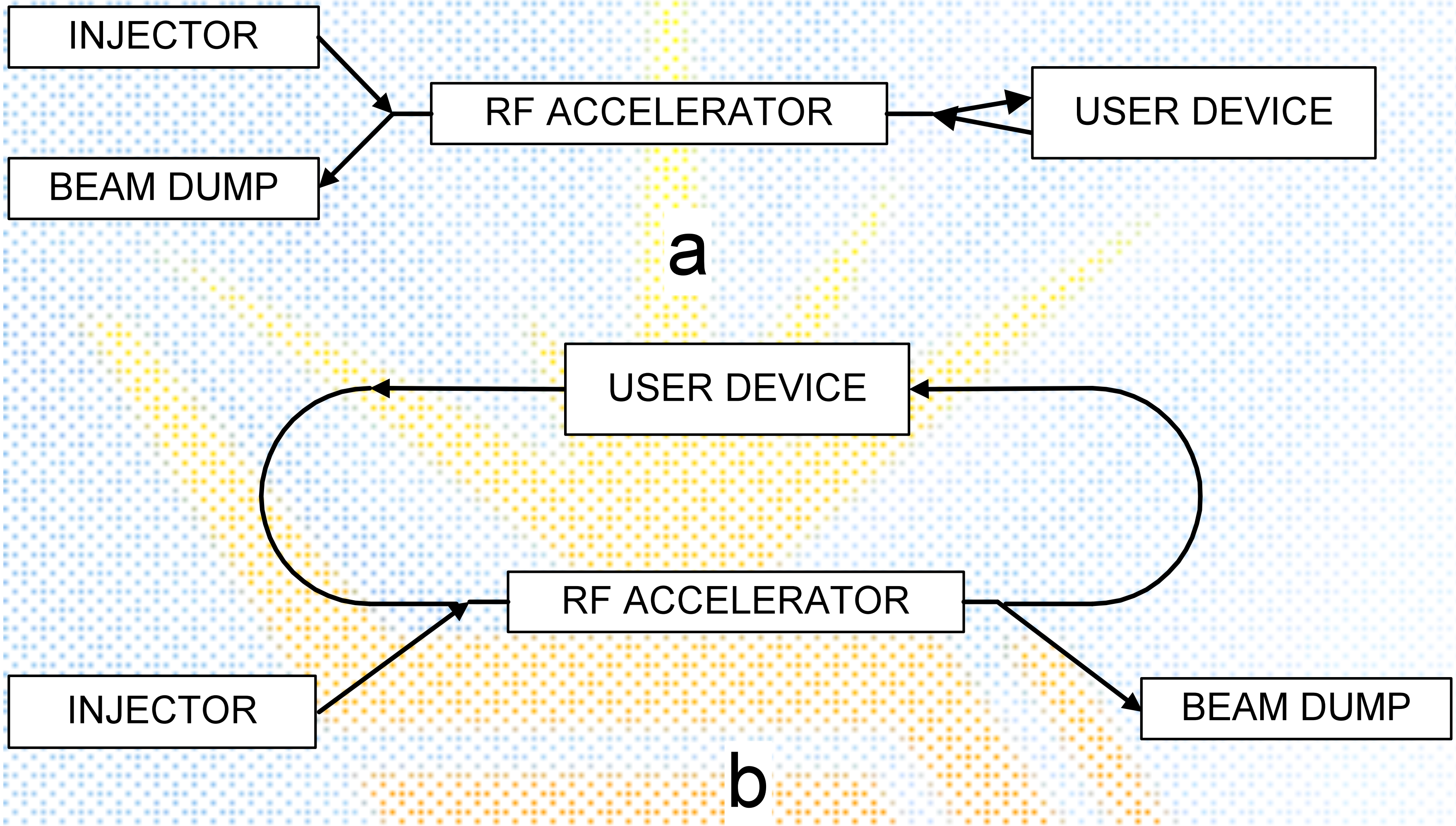
FEL disadvantages: size and cost.

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

Energy recovery

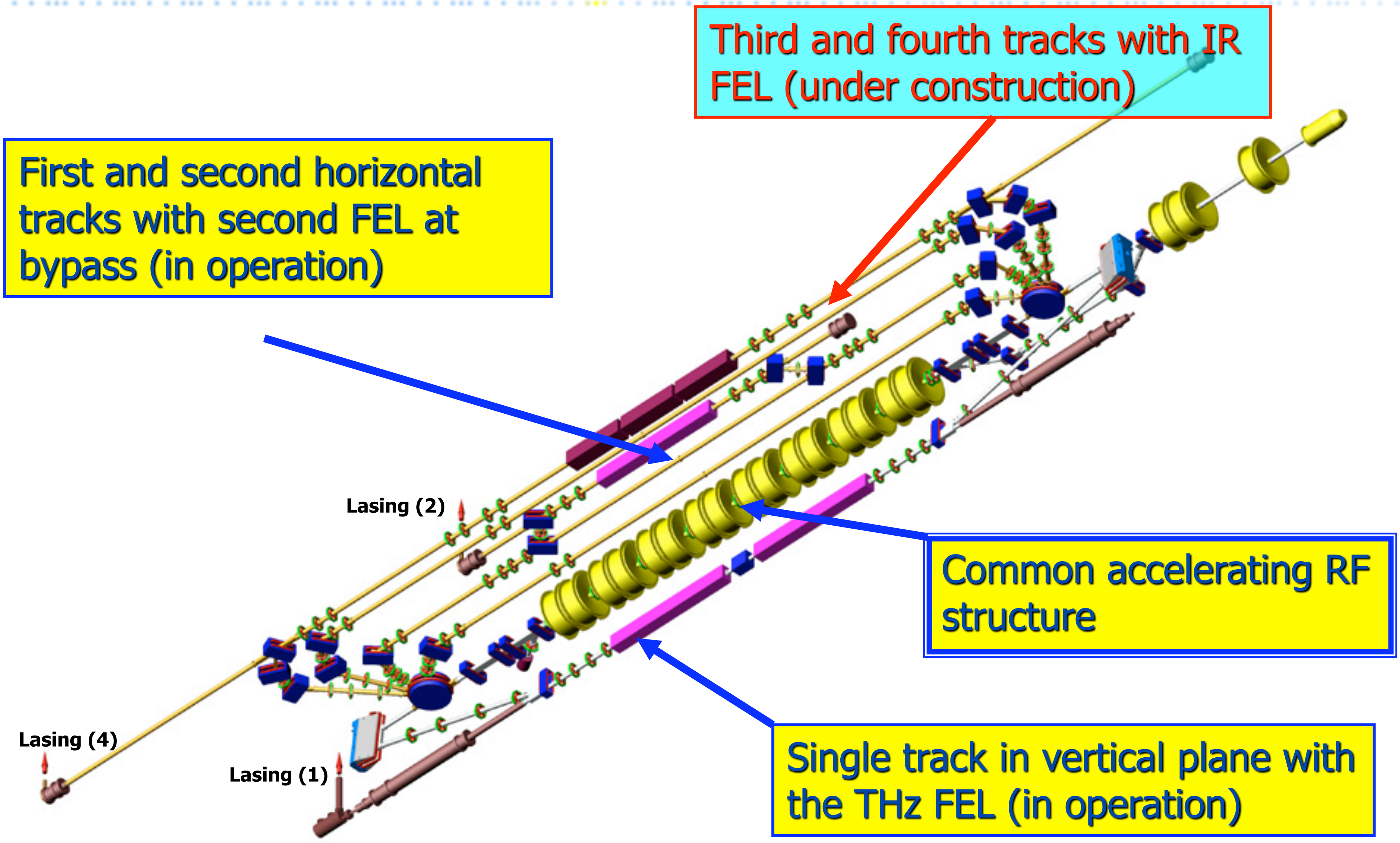
- **decreases radiation hazard and**
- **makes possible operation at high average current.**

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



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

Novosibirsk ERL with 3 FELs



Features of the 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

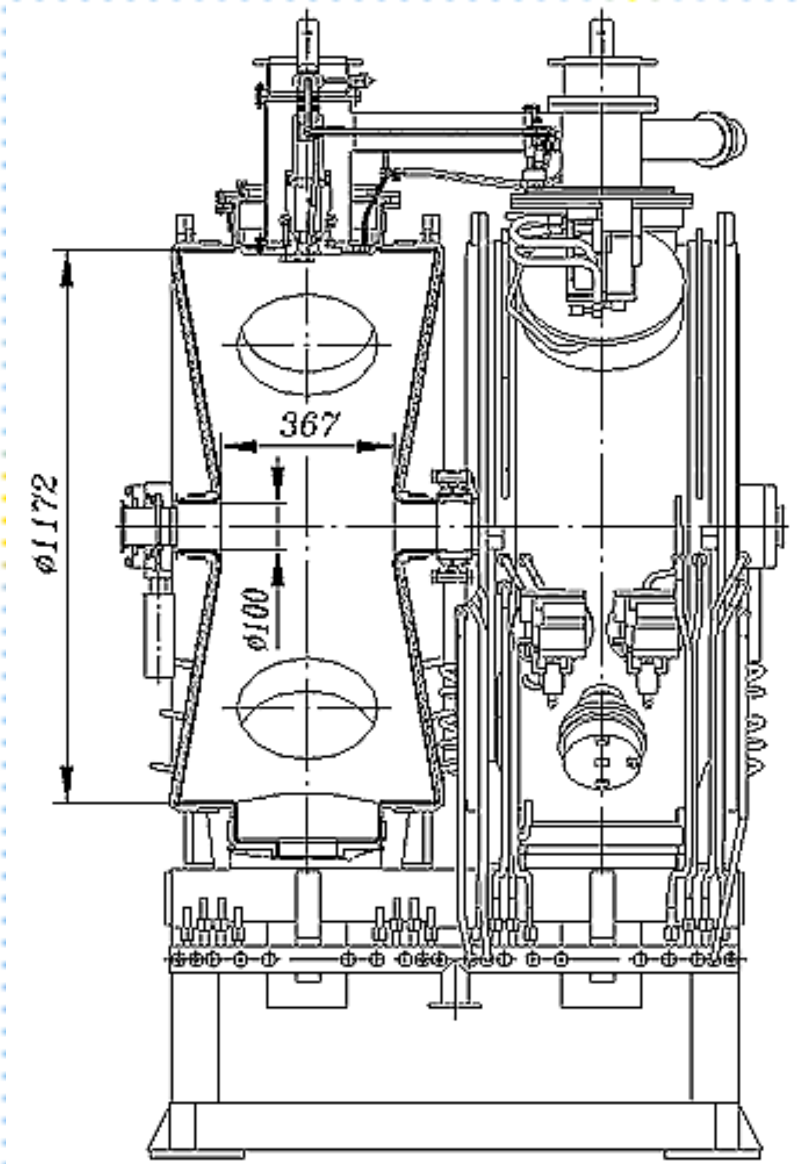
$$I < \frac{1}{-e\rho Q \sum_{n=1}^{2N} \sum_{k=1}^{n-1} \left[S_{nk} \sin(\varphi_k - \varphi_n) \right]}$$

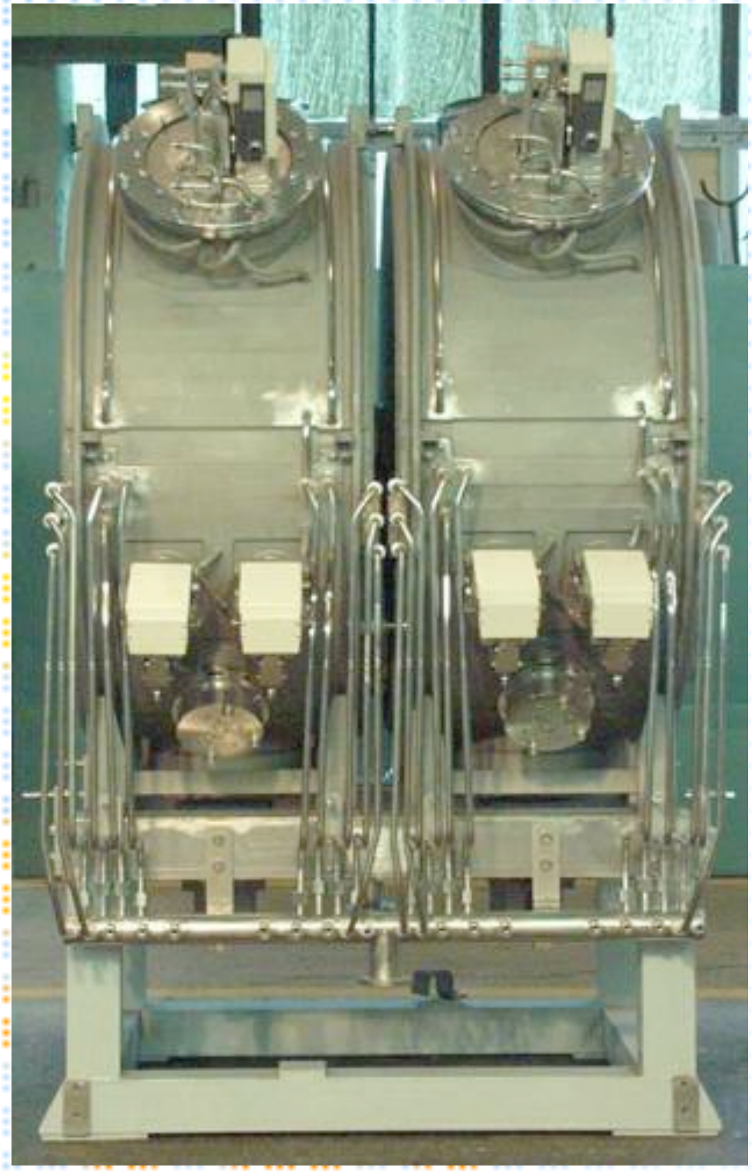
[1] E. Pozdeev et al., Multipass beam breakup in energy recovery linacs, NIM A 557, (2006), p.176-188.
[2] N. A. Vinokurov et al., Proc. of SPIE Vol. 2988, p. 221 (1997).

Advantages

- High threshold currents of instabilities
- Operation with long electron bunches
- 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





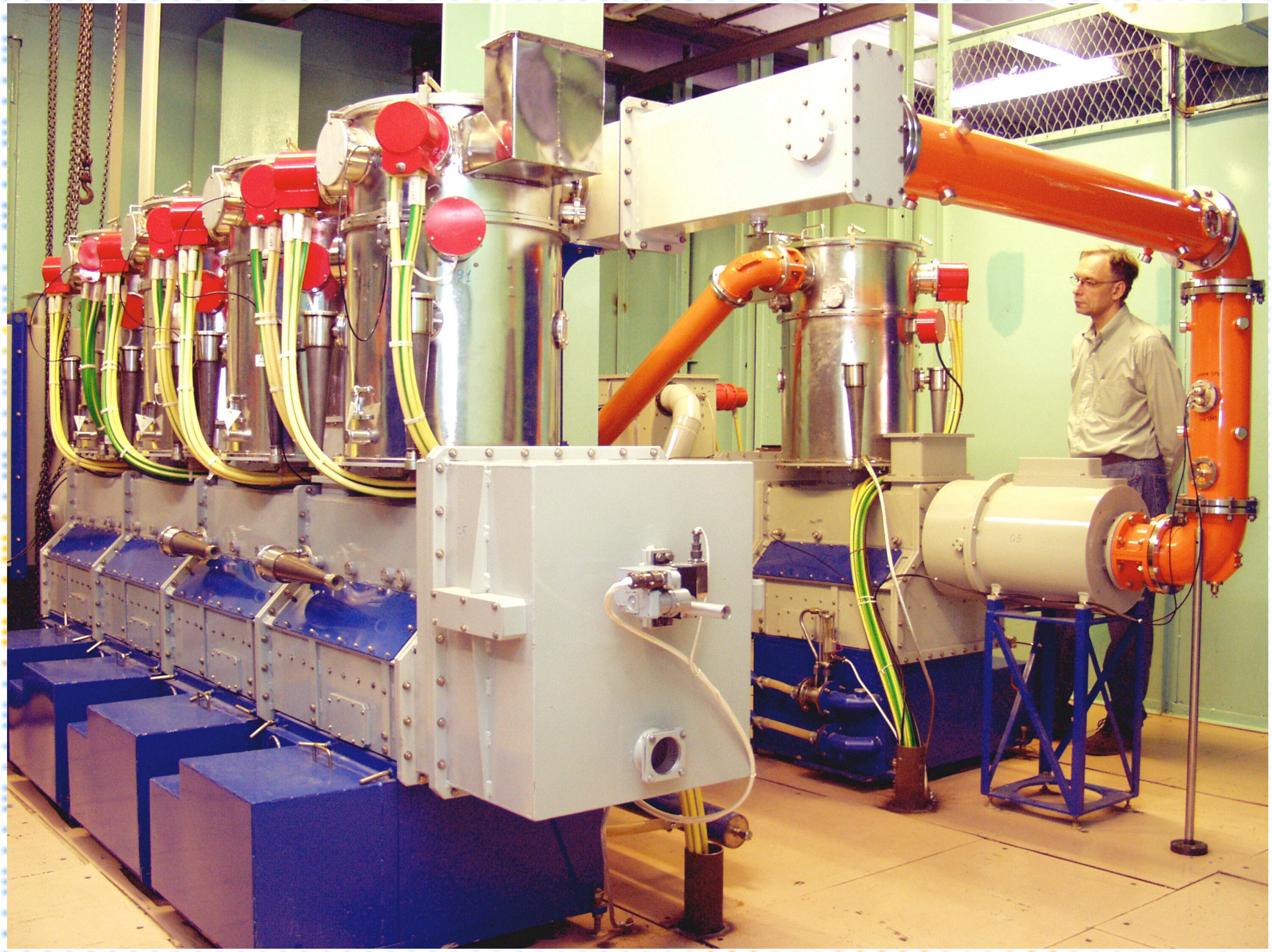
Bimetallic (copper and stainless steel) RF cavity tanks

Main parameters of the cavity

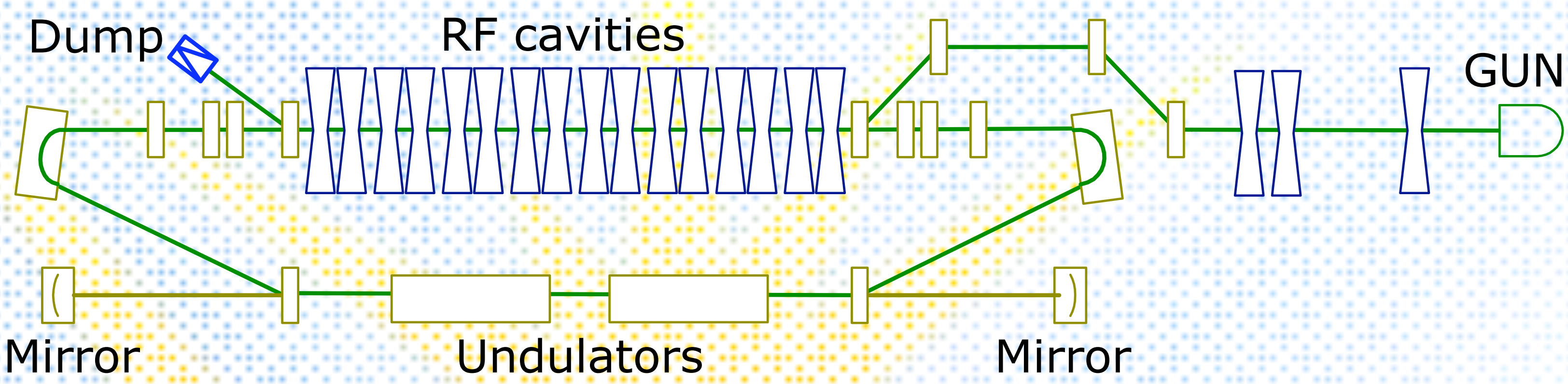
(for the fundamental TM_{010} mode)

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 amplifiers



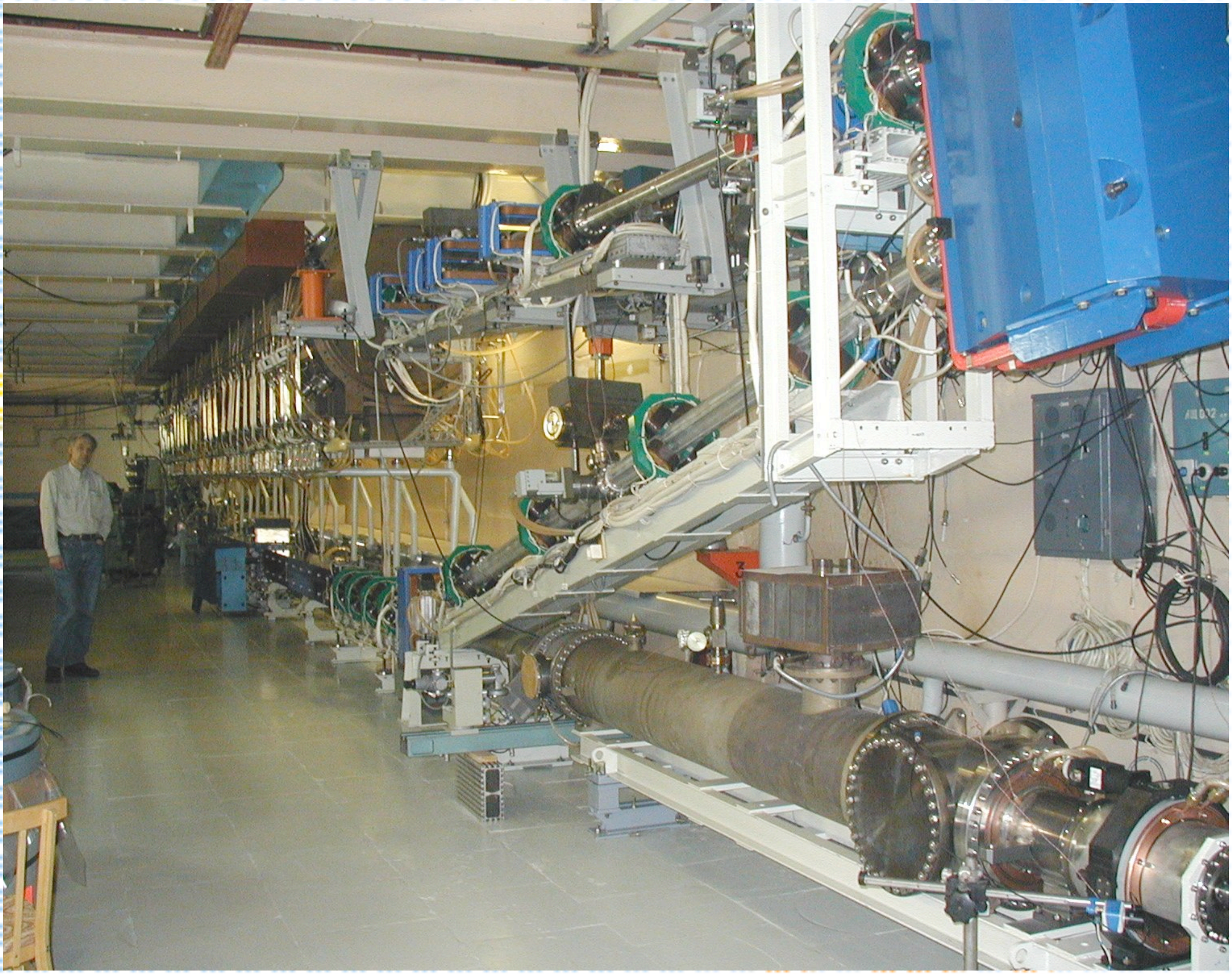
First stage: submillimeter (THz) FEL



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

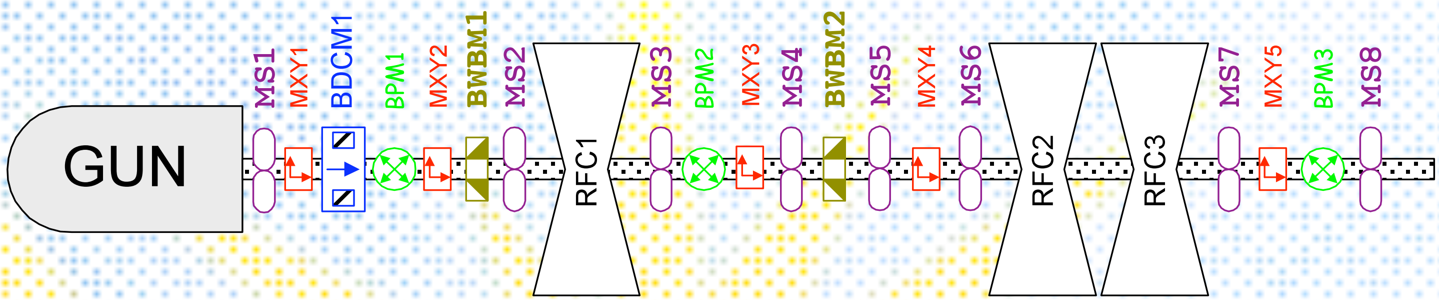
After that, the beam returns to the main accelerating structure in a decelerating RF phase, decreases its energy to its injection value (2 MeV) and is absorbed in the beam dump.

THz FEL (old)



Accelerator hall

2 MeV injector



MS: focusing solenoid

MXY: steering magnet

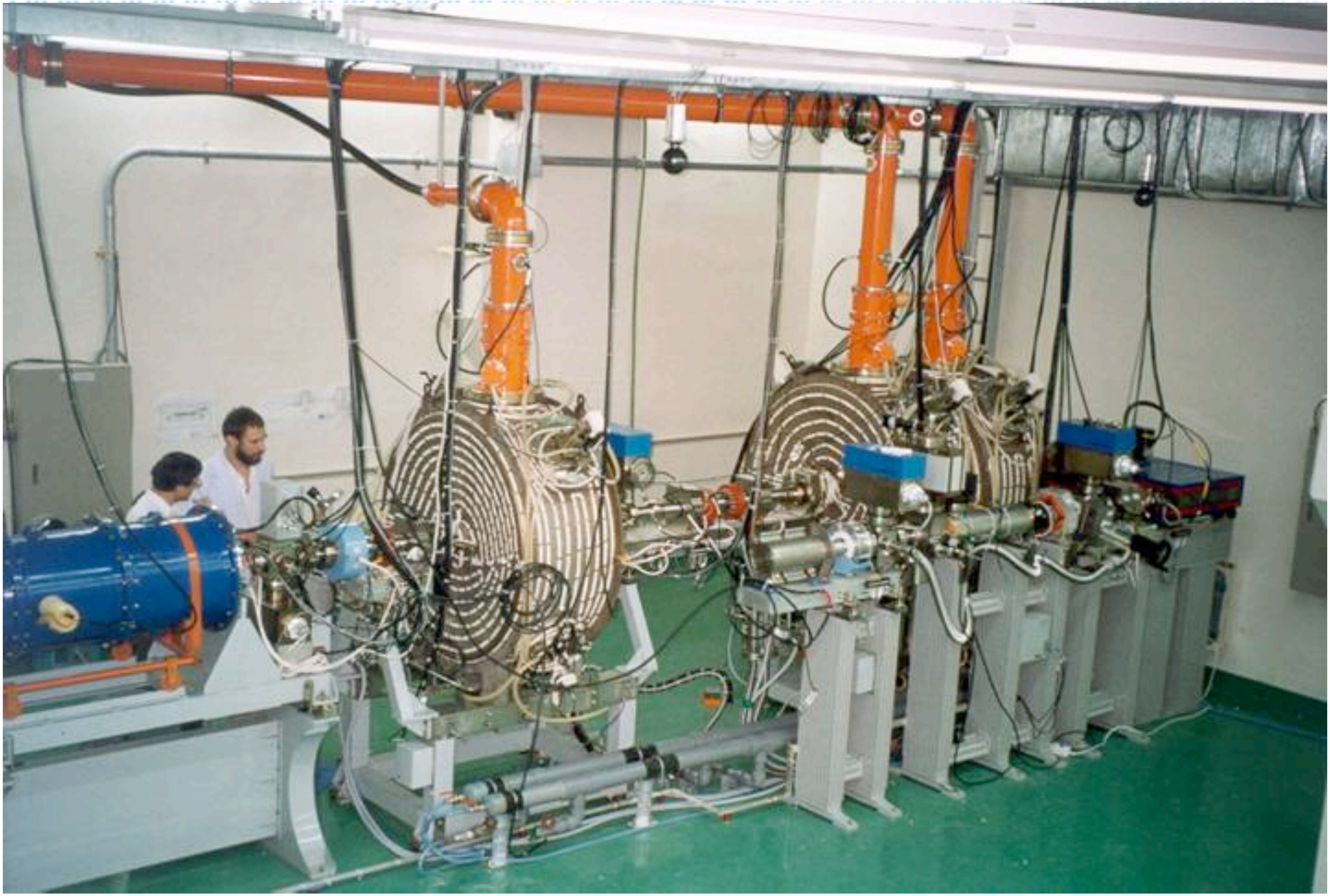
BDCM: beam current monitor

BPM: bean position monitor

BWBM: strip line monitor

RFC: RF cavity

The second 2-MeV injector built for KAERI



2 MeV Injector Parameters

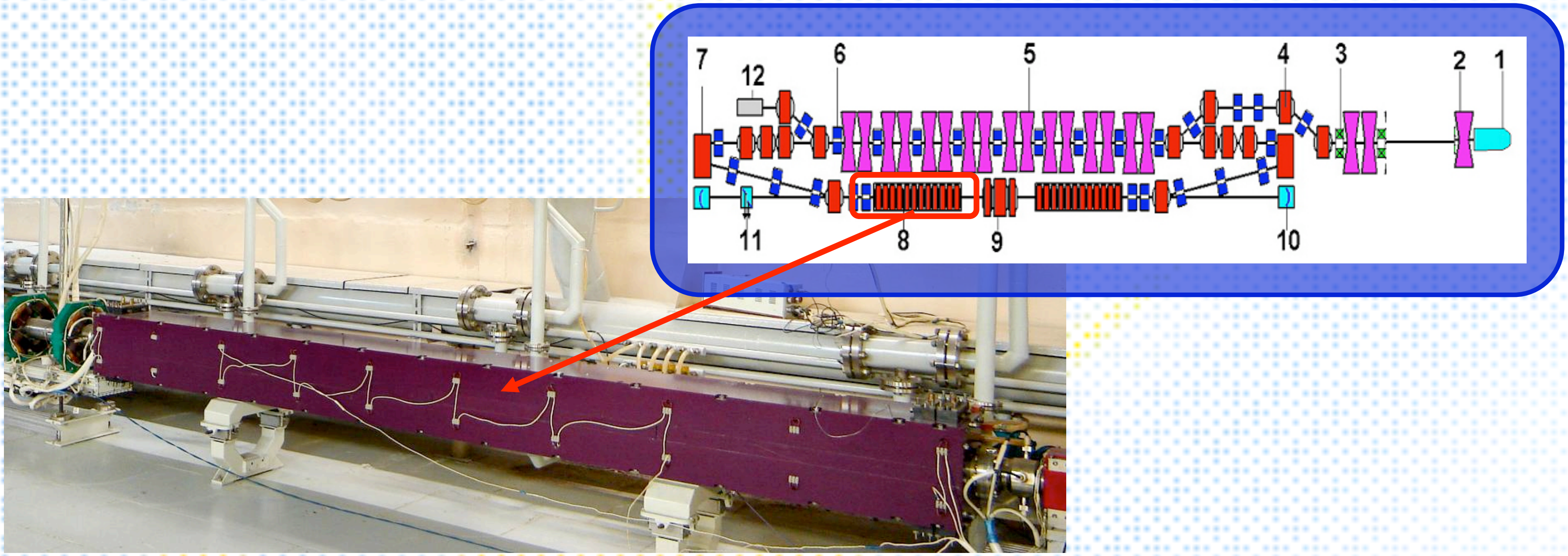
♦DC electron gun voltage, kV	up to 300
♦Bunch repetition rate, MHz	up to 22.5
♦Charge per bunch, nC	up to 2
♦Start bunch length, ns	1.0
♦Final bunch length, ns	0.1
♦Final energy, MeV	1.7

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

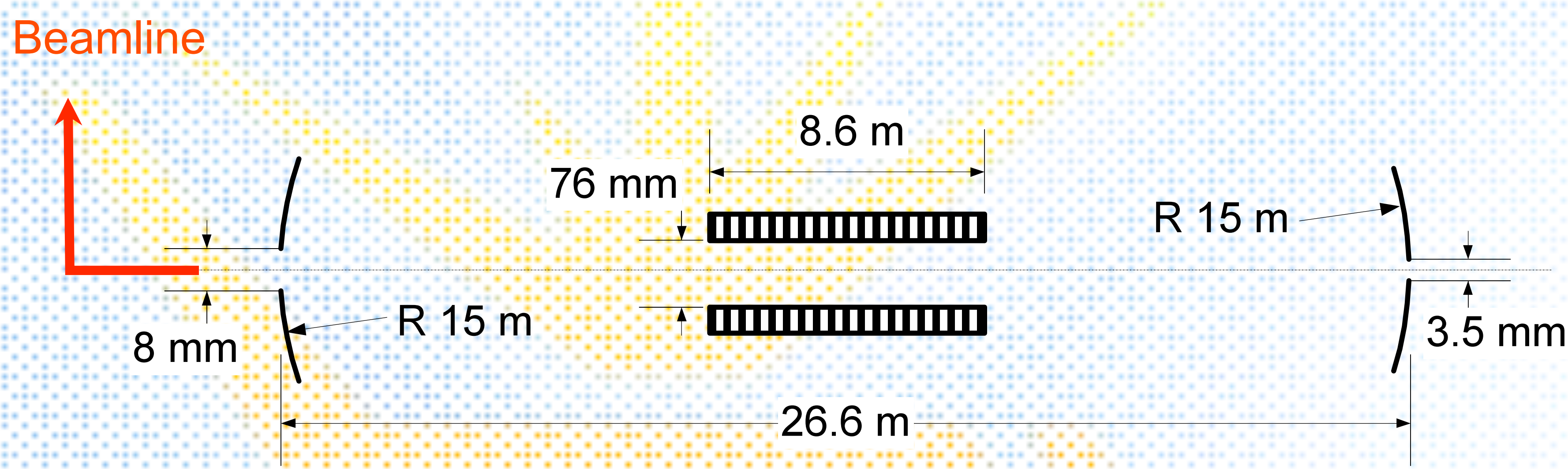
Undulators and accelerating RF cavities

Undulator



Period, cm	12
Maximum current, kA	2.4
Maximum K	1.25

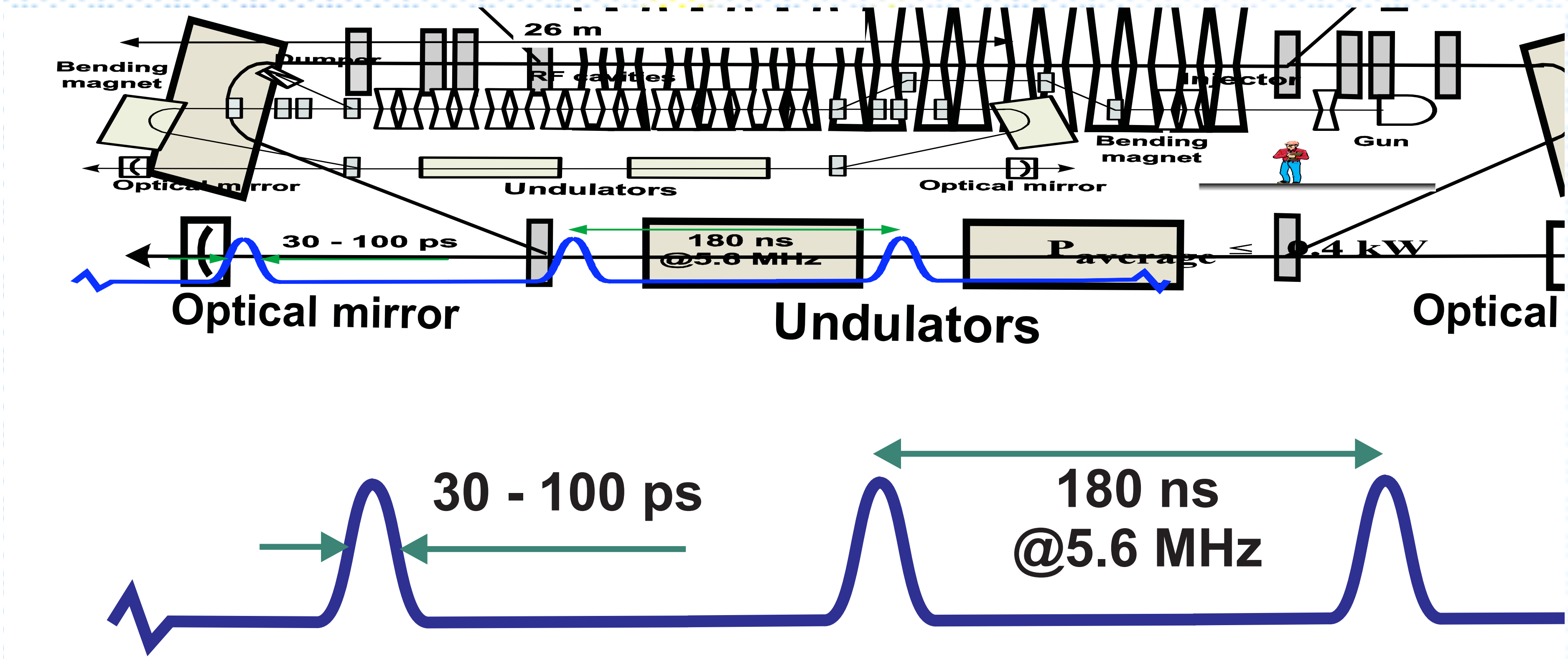
Layout of the optical resonator



Free Electron Laser Parameters

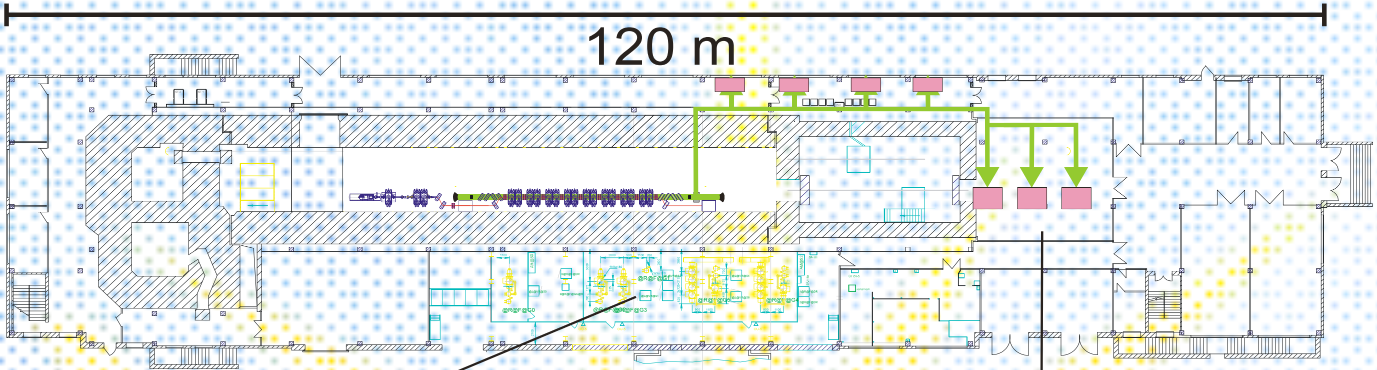
♦Wavelength, mm	0.12-0.24
♦Pulse duration, FWHM, ps	~70
♦Pulse energy, mJ	0.04
♦Repetition rate, MHz	11.2
♦Average power, kW	0.5
♦Minimum relative linewidth, FWHM	$3{\cdot}10^{-3}$

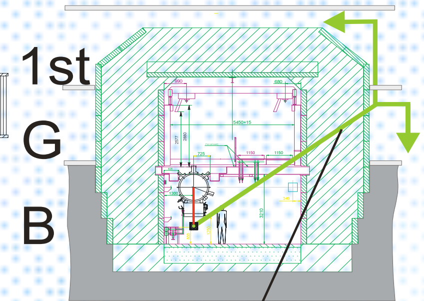
Novosibirsk FEL (1st stage) and radiation power time-dependence



Siberian center of photochemical research

Layout of terahertz FEL and user stations

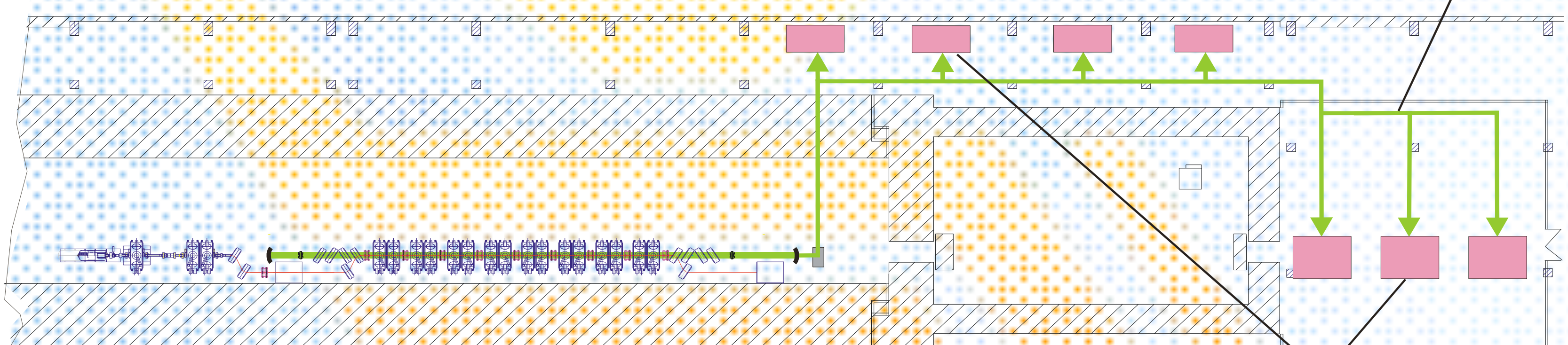




RF generator system (ground floor)

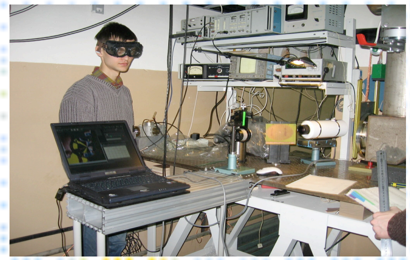
Control room (ground floor)

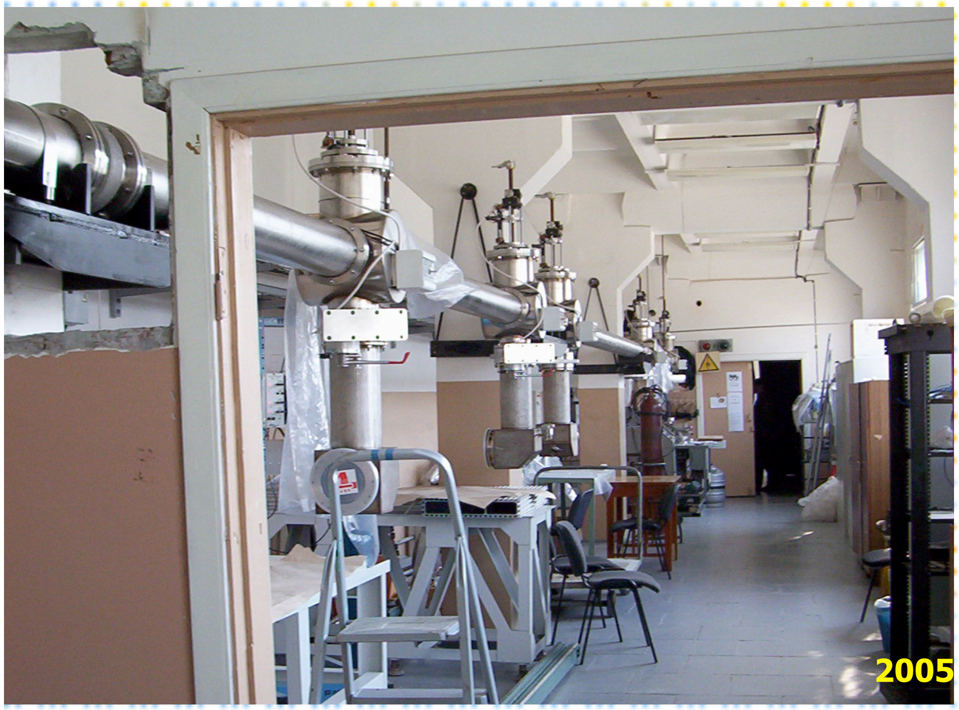
Beamlines for radiation transport



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

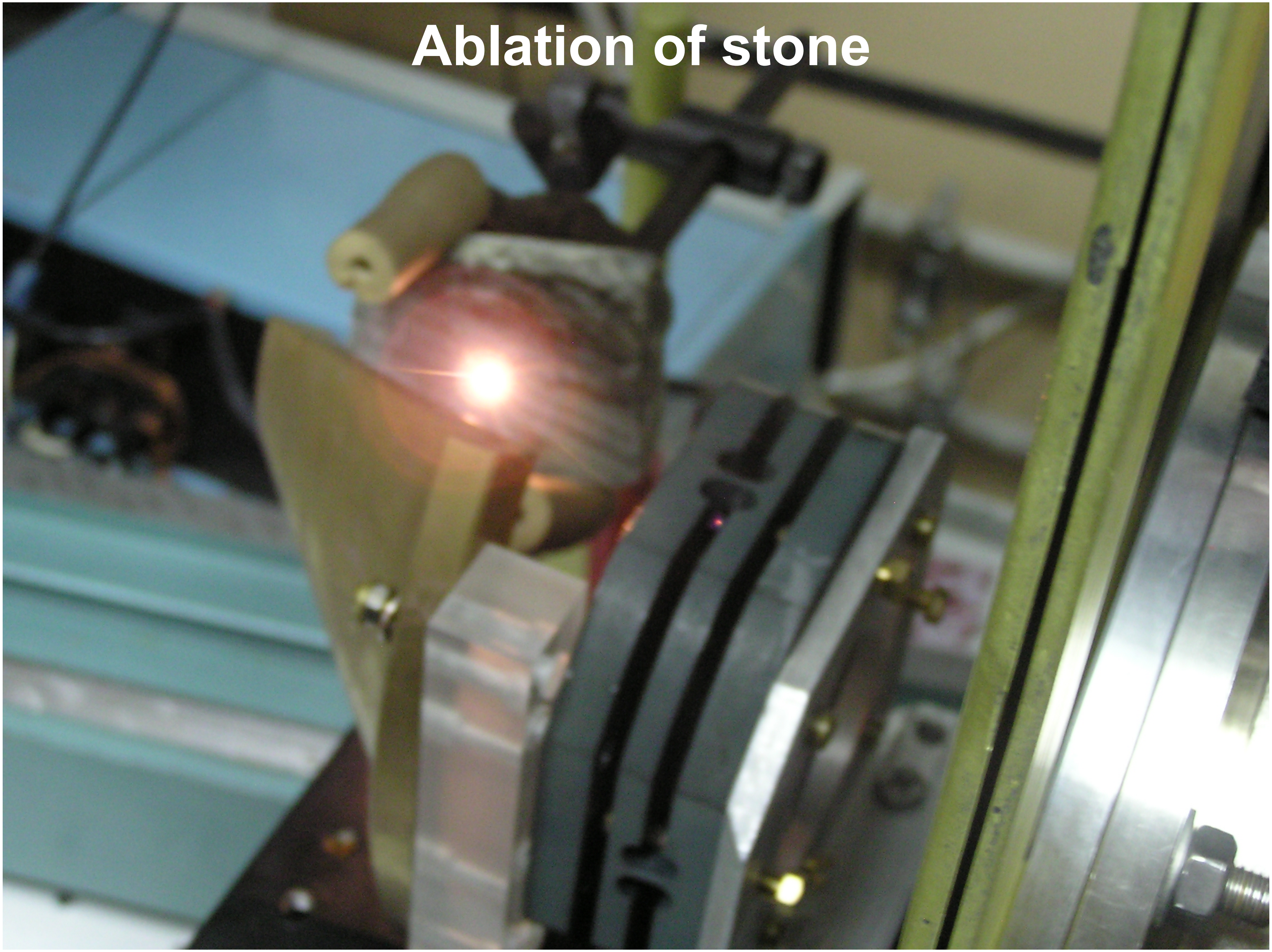
User Stations (ground and first floors)




2005


2006

Ablation of stone



Status of Novosibirsk ERL and FELs

- 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.
- Five user stations are in operation.
- Second stage of ERL and FEL was commissioned.

Second stage of Novosibirsk FEL

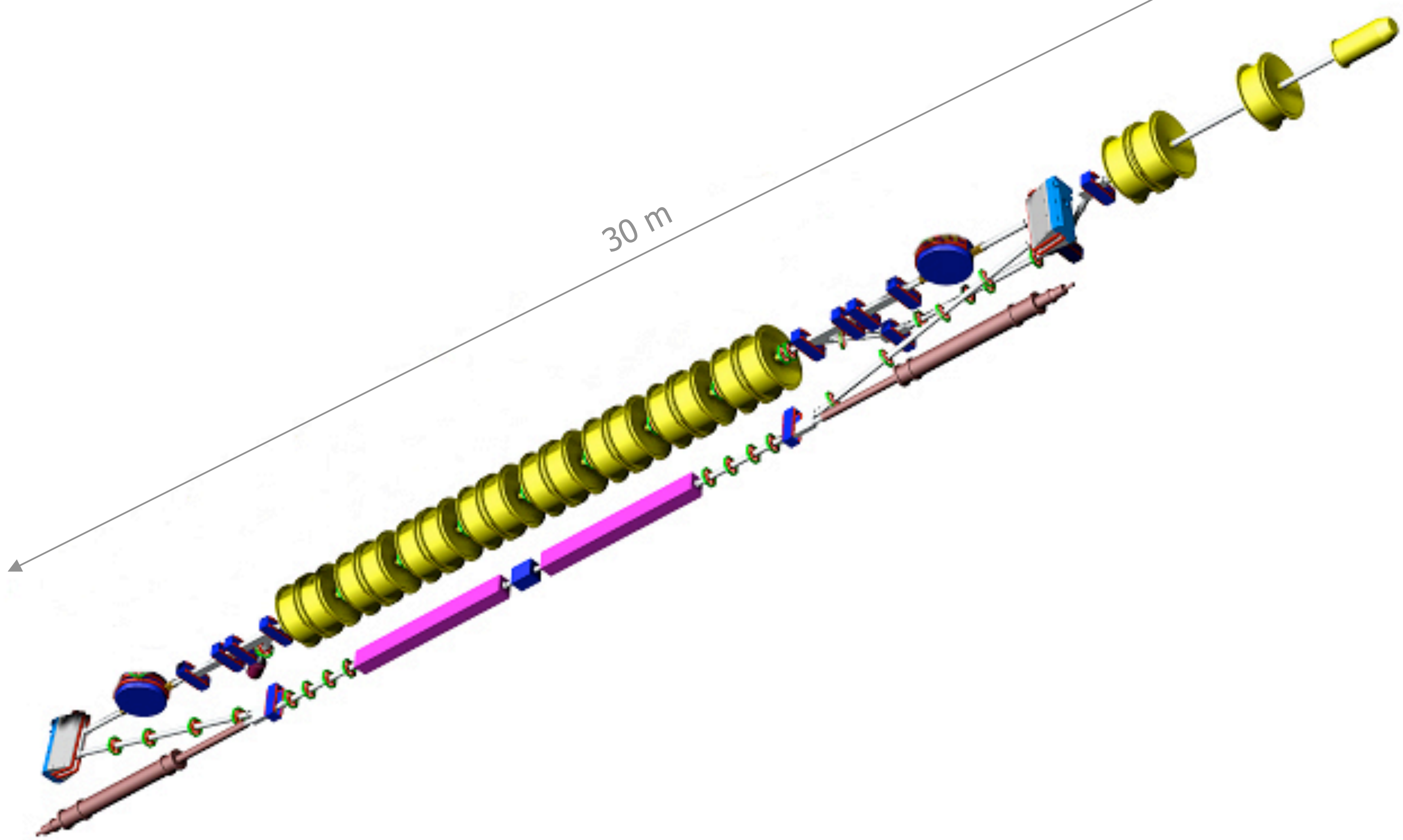
A full-scale 4-orbit ERL uses the same accelerating structure as the ERL of the 1st stage, but, in contrast to the latter, it is placed in the horizontal plane. Thus, the vertical orbit with the terahertz FEL is saved.

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

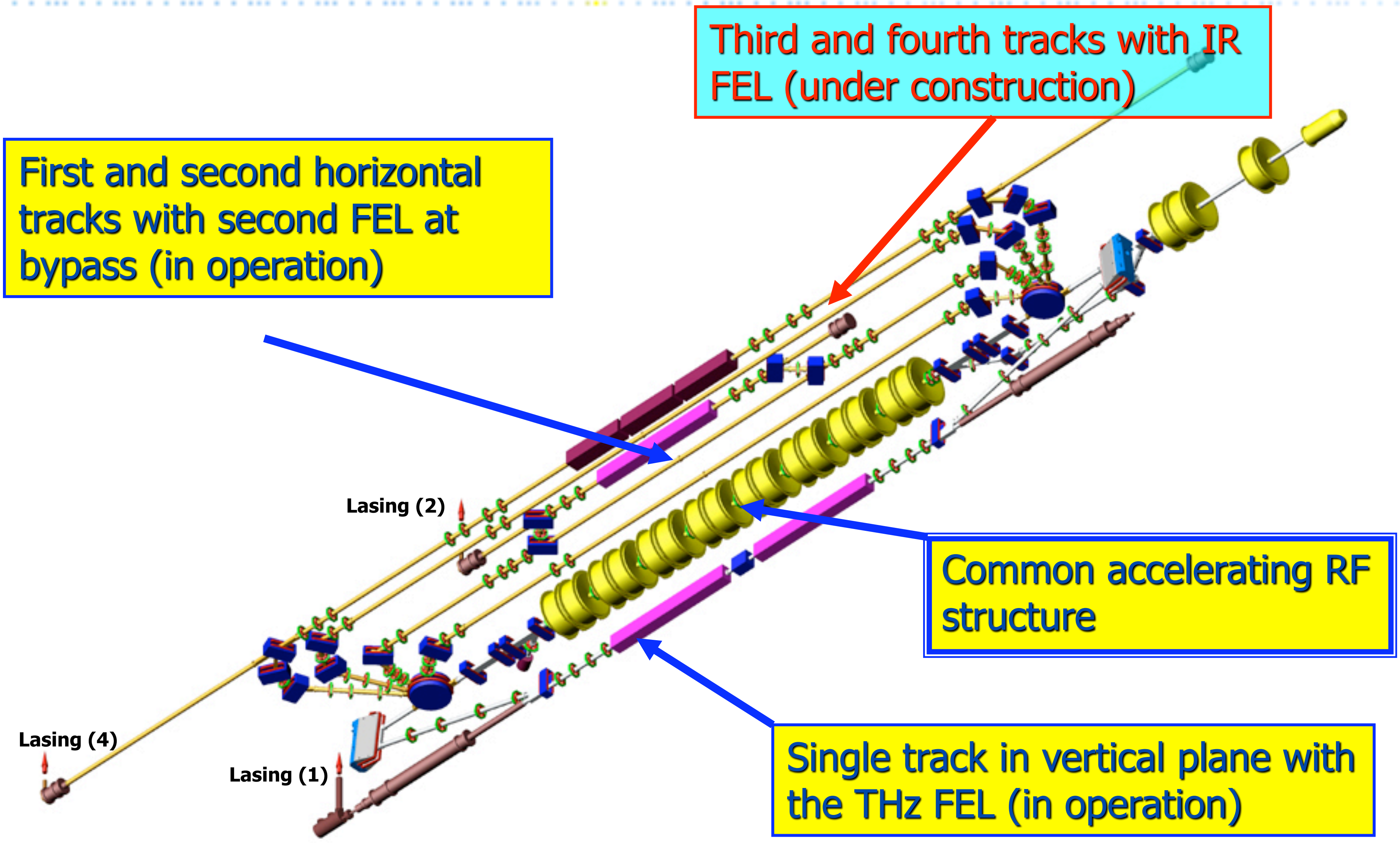
Project final parameters of ERL and FELs

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



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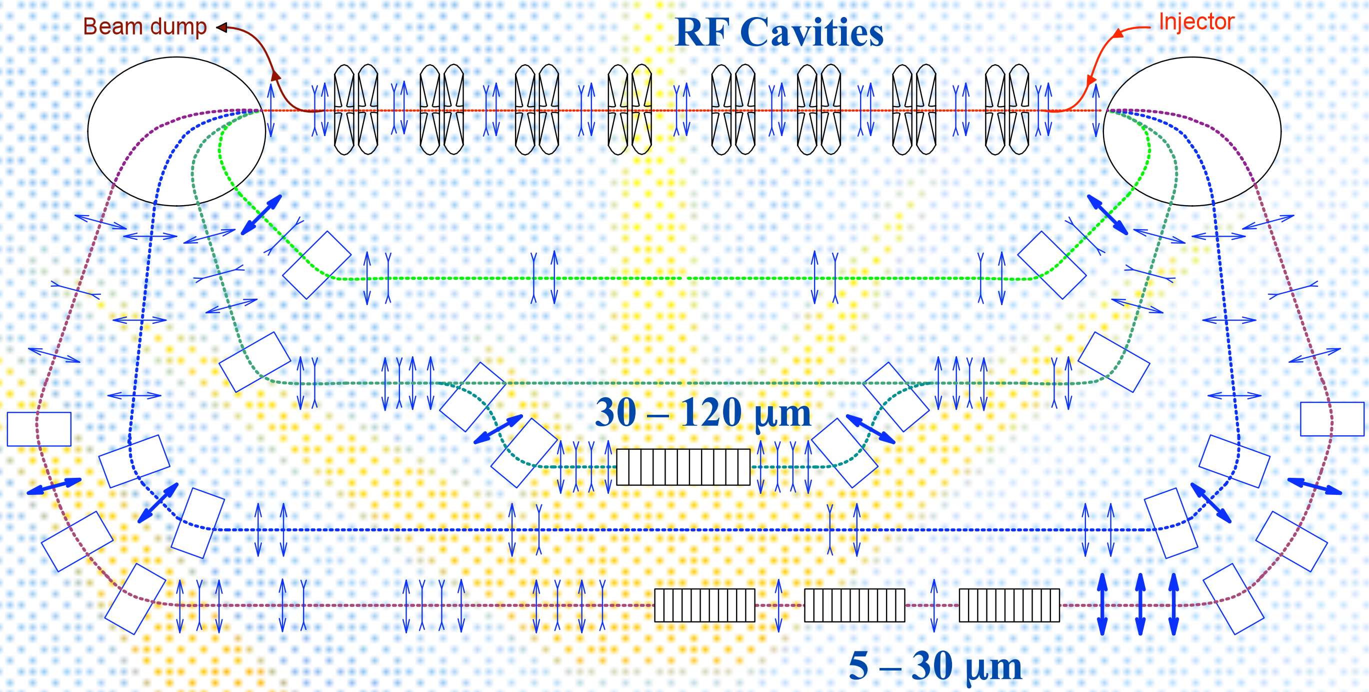
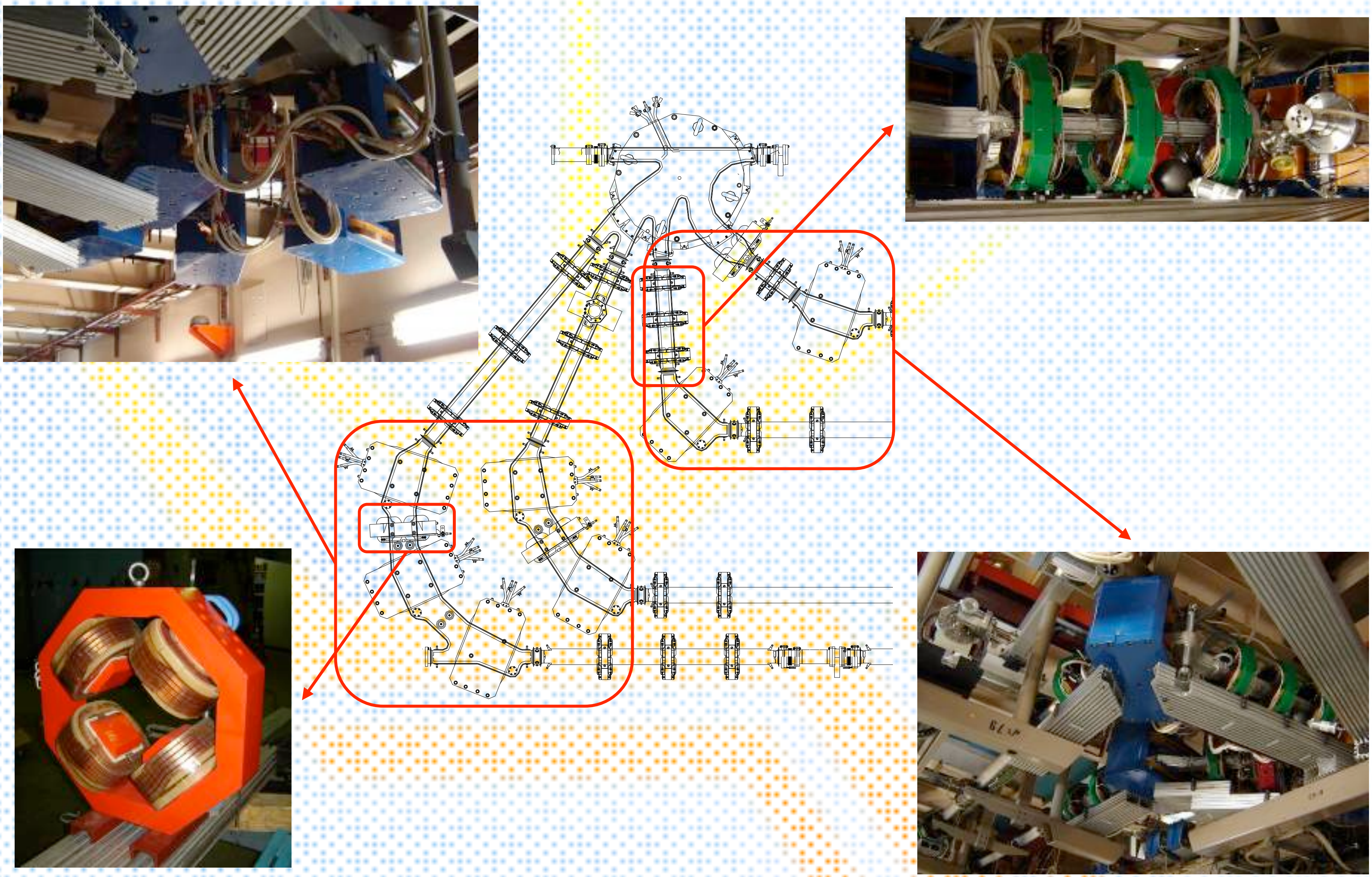
2-nd stage Novosibirsk FEL (in horizontal plane)

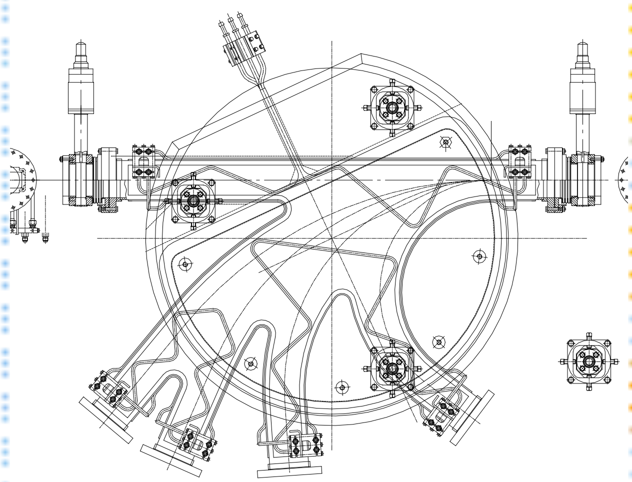


Radiation wavelength	**5 – 240 μm**
Average power	**Up to 10 kW**
E-beam energy	**up to 40 MeV**
Maximum repetition rate	**90 MHz**
Maximum mean current	**100 mA**

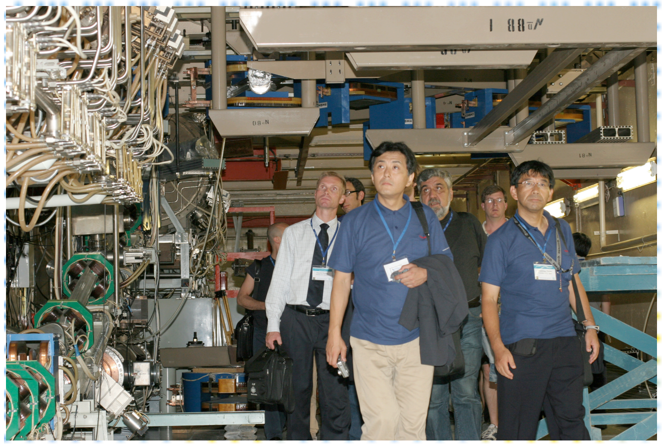
Magnets and vacuum chamber of bends



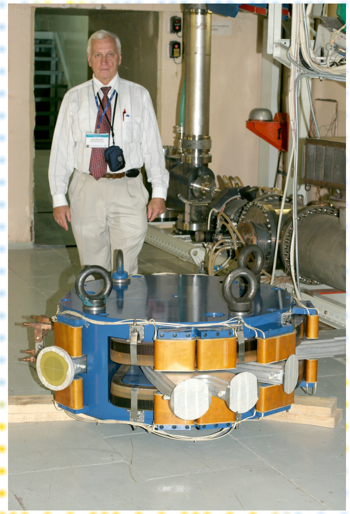
Round magnet

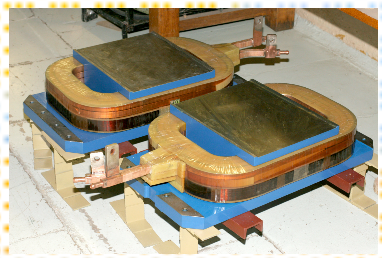


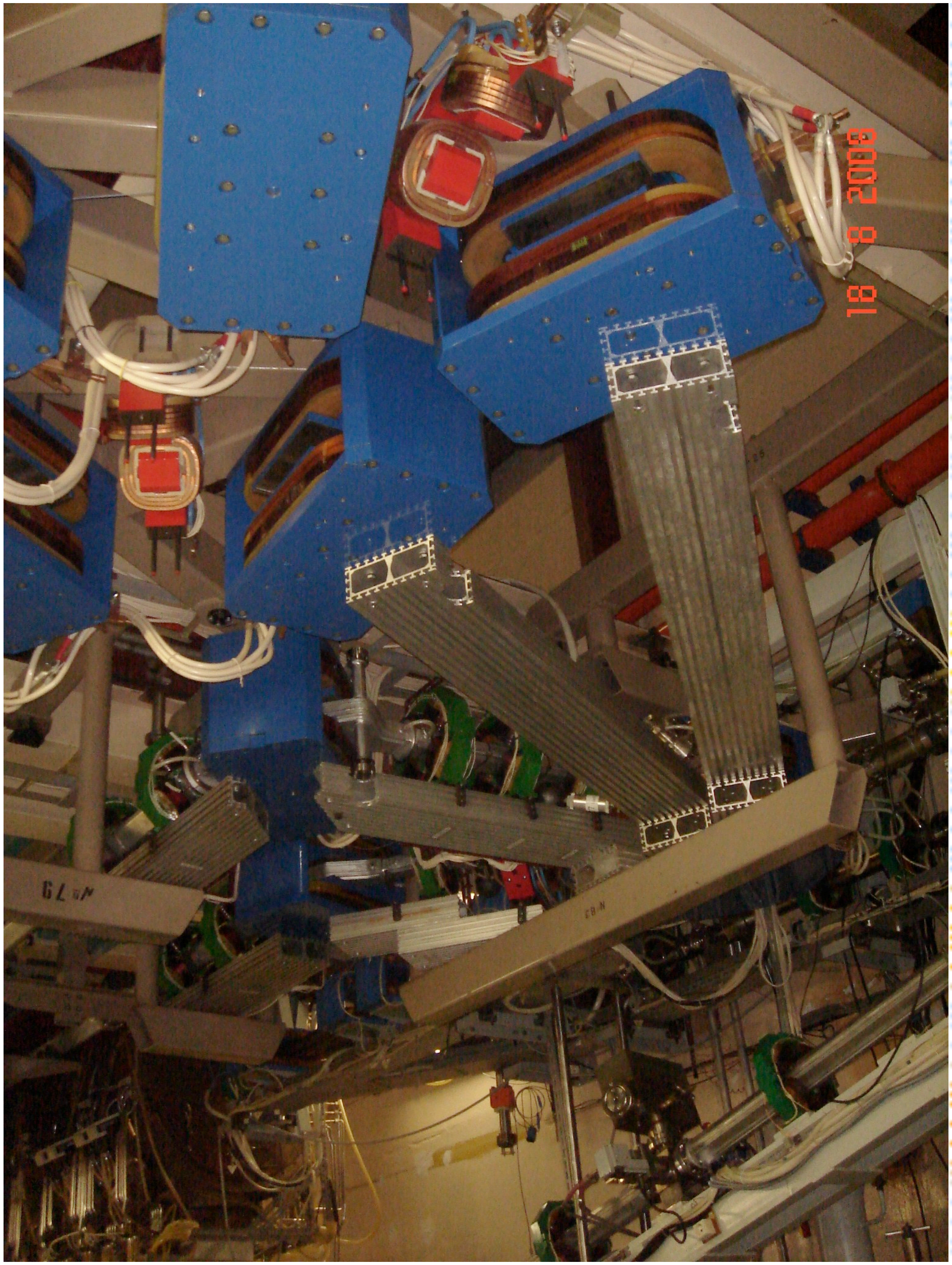
Assembly of four tracks is in progress



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







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

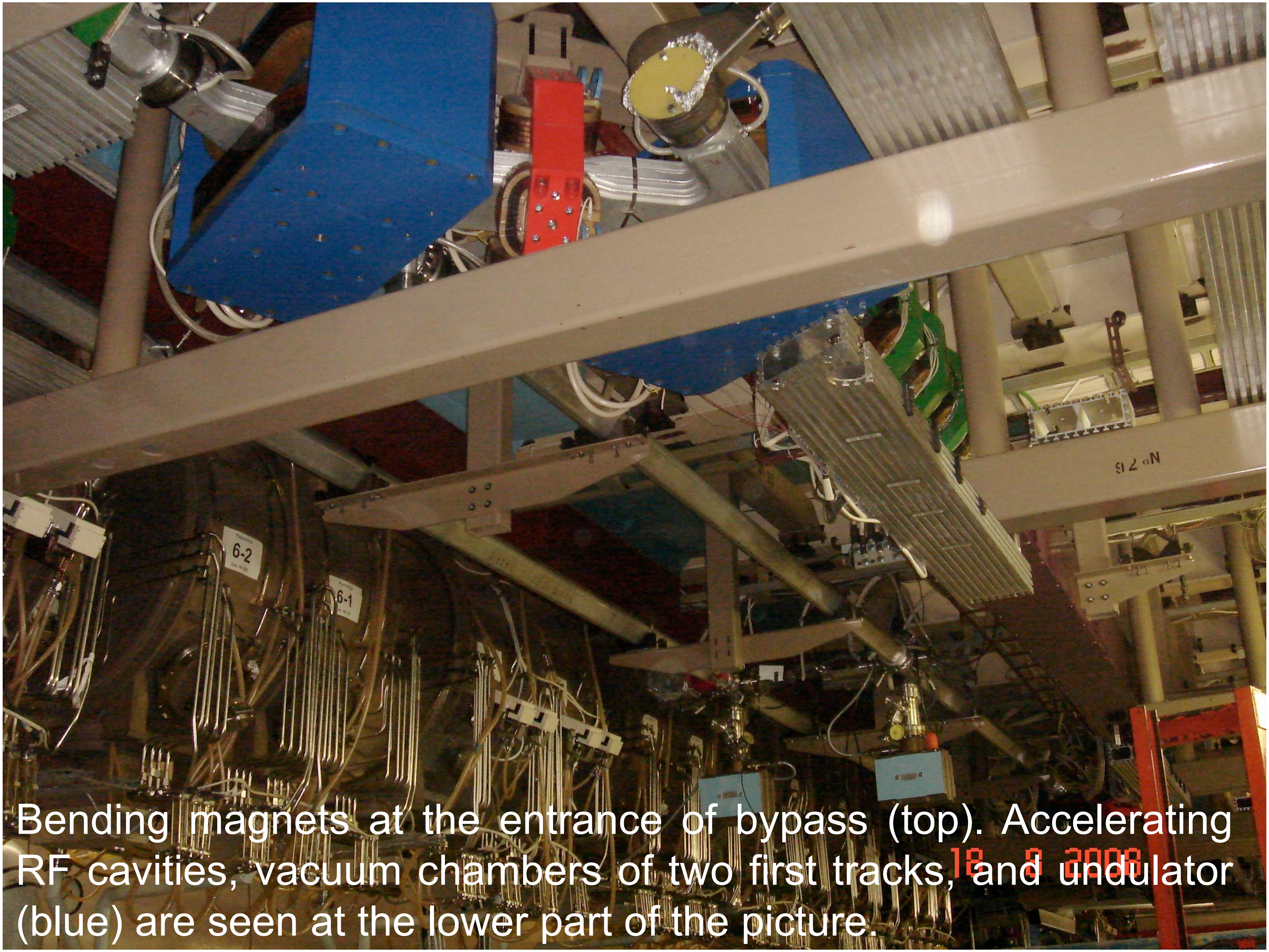
Second stage assembly


M6
18 8 2008

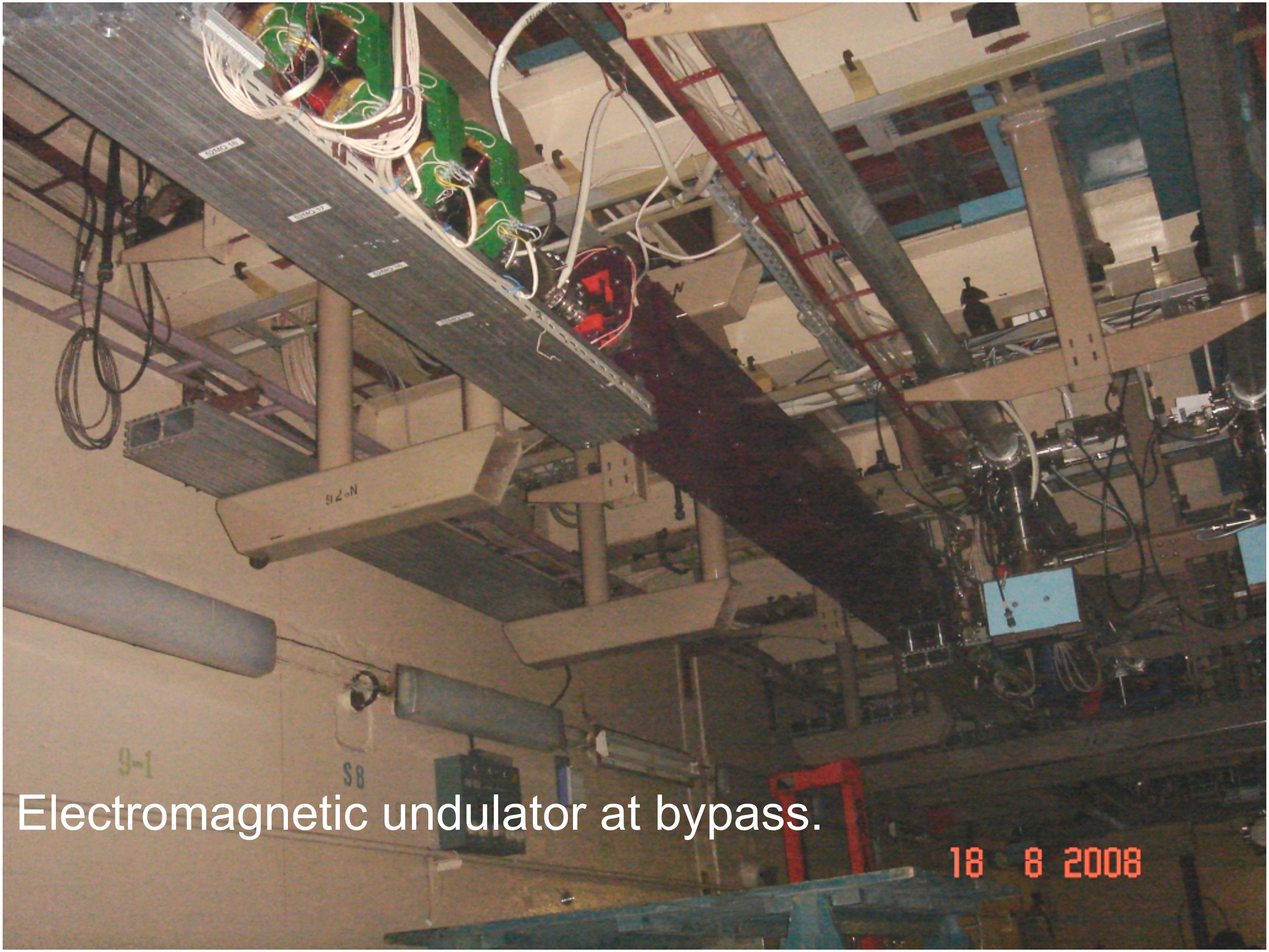
The bends are hanged on the ceiling.

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

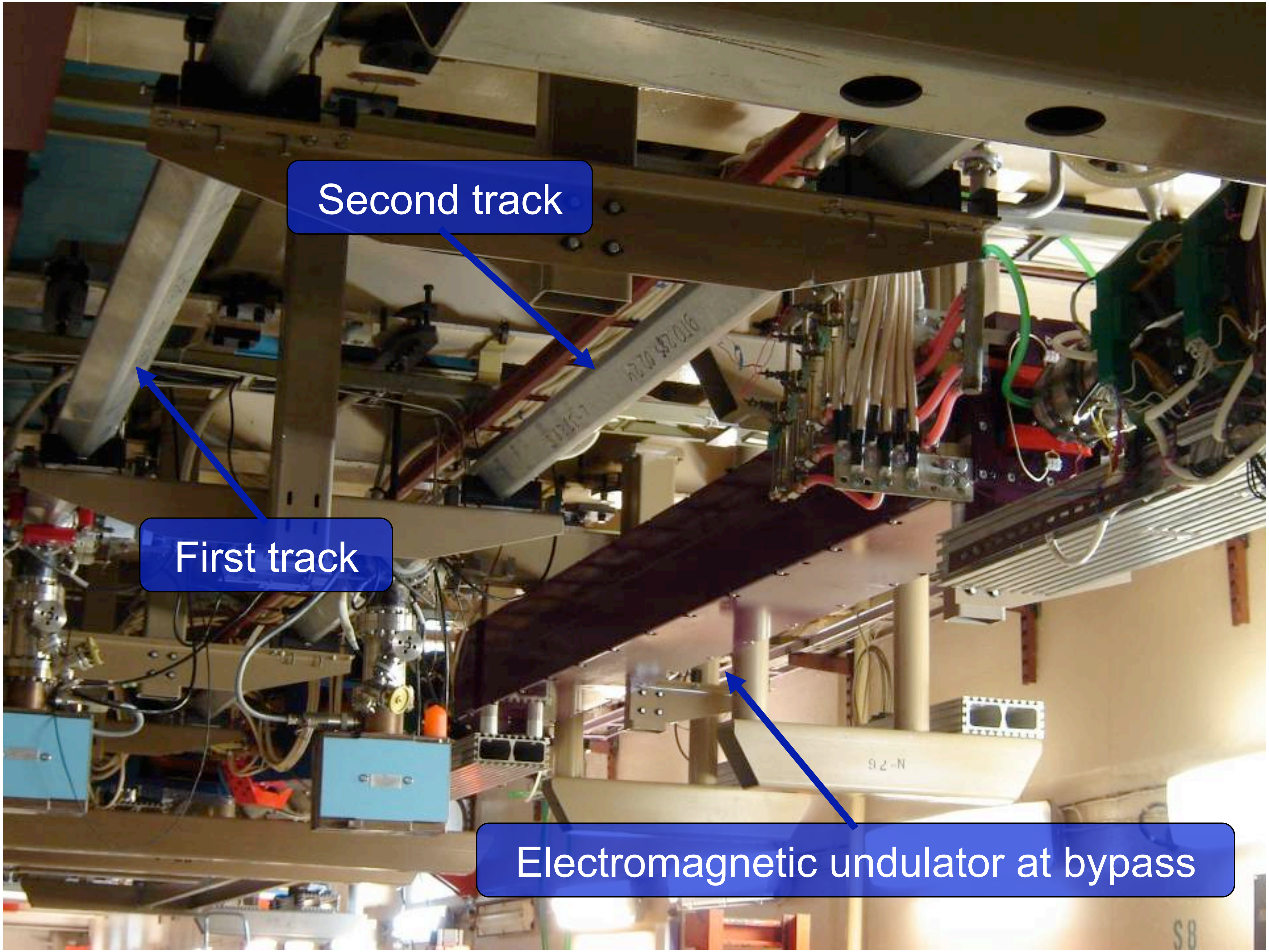
Elements of the optical resonator for the second-turn FEL are yet at the floor (down-right corner).

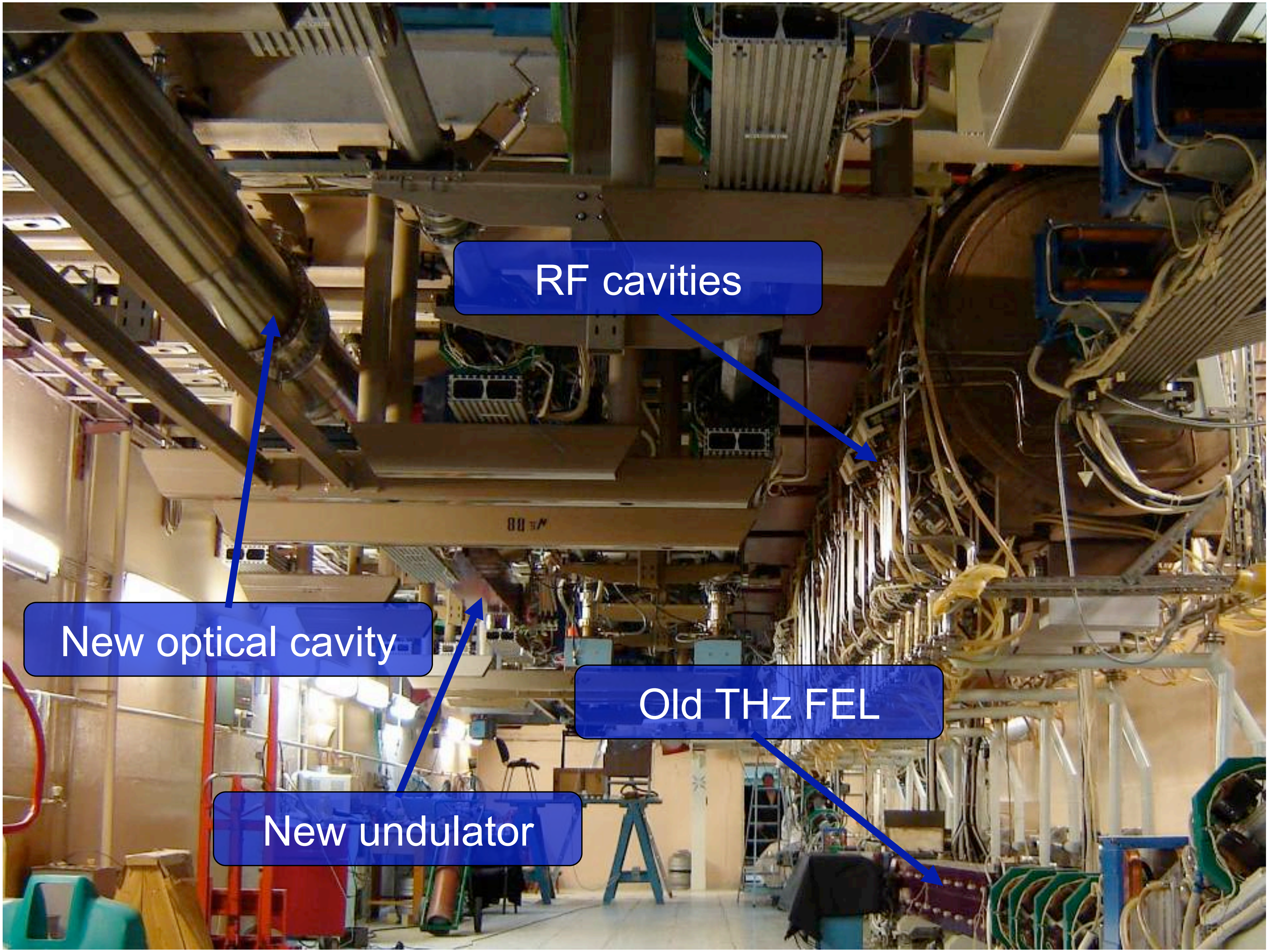


Bending magnets at the entrance of bypass (top). Accelerating RF cavities, vacuum chambers of two first tracks, and undulator (blue) are seen at the lower part of the picture.

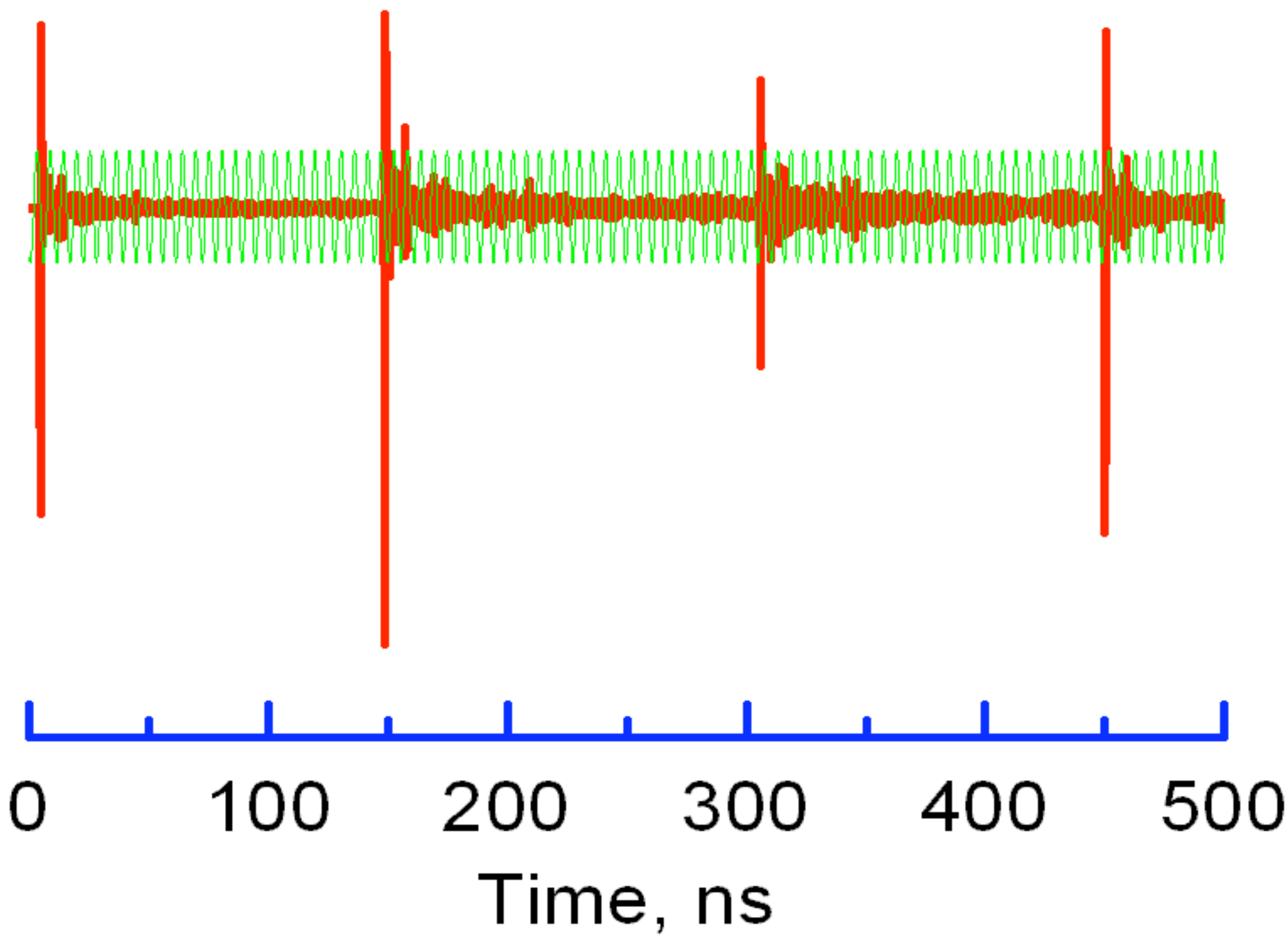


Electromagnetic undulator at bypass.


Second track
First track
Electromagnetic undulator at bypass


RF cavities
New optical cavity
Old THz FEL
New undulator

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



Status of the second stage ERL and FEL commissioning

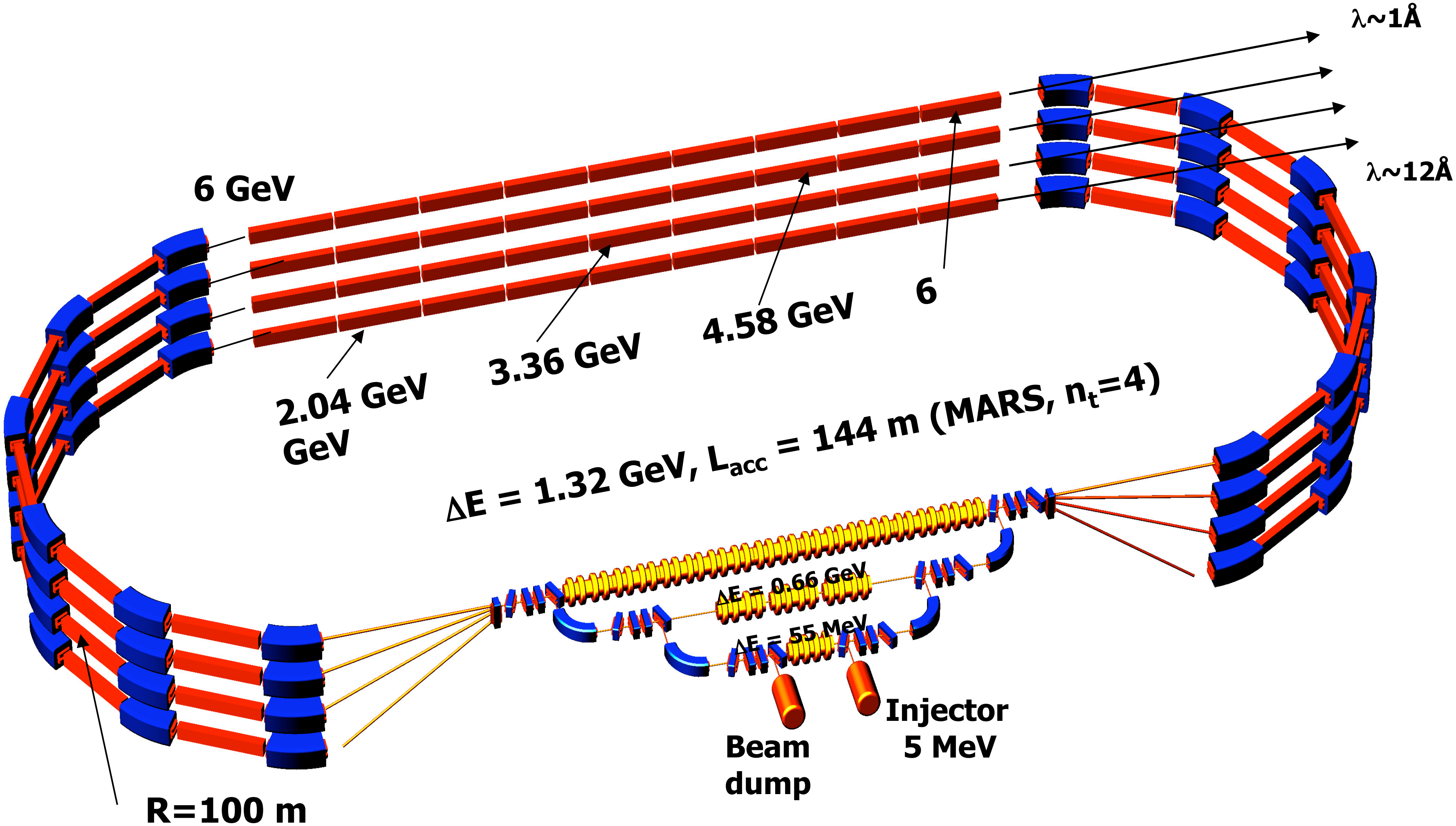
Electron beam passes twice trough the accelerating structure (acceleration to 20 MeV), then through the undulator, after that twice through the accelerating structure (deceleration to 2 MeV), then fly to the beam dump. Average current 9 mA was achieved.

First in the world multi-turn ERL is in operation now. This is the way to MARS.

First lasing took place on Fefruary 2 at the 50 micron wavelength. Maximum gain is more than 40%.

Multiturn Accelerator-Recuperator Source (MARS) – the high average brightness x-ray source

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



Thank you