Commissioning of Novosibirsk Multi-Pass Energy Recovery Linac

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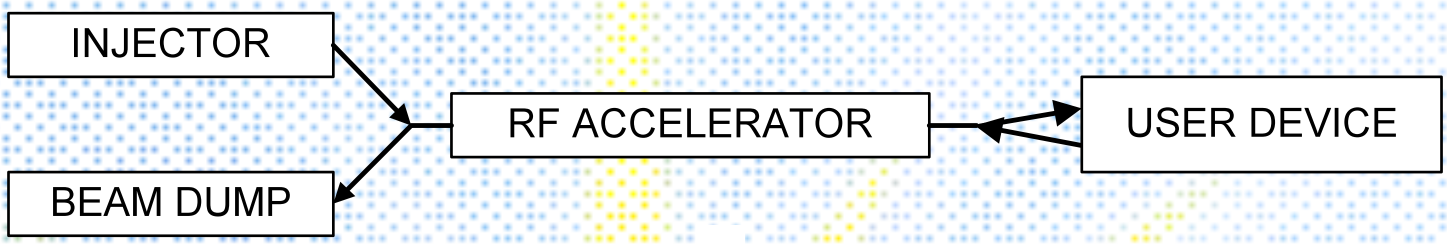
Outline

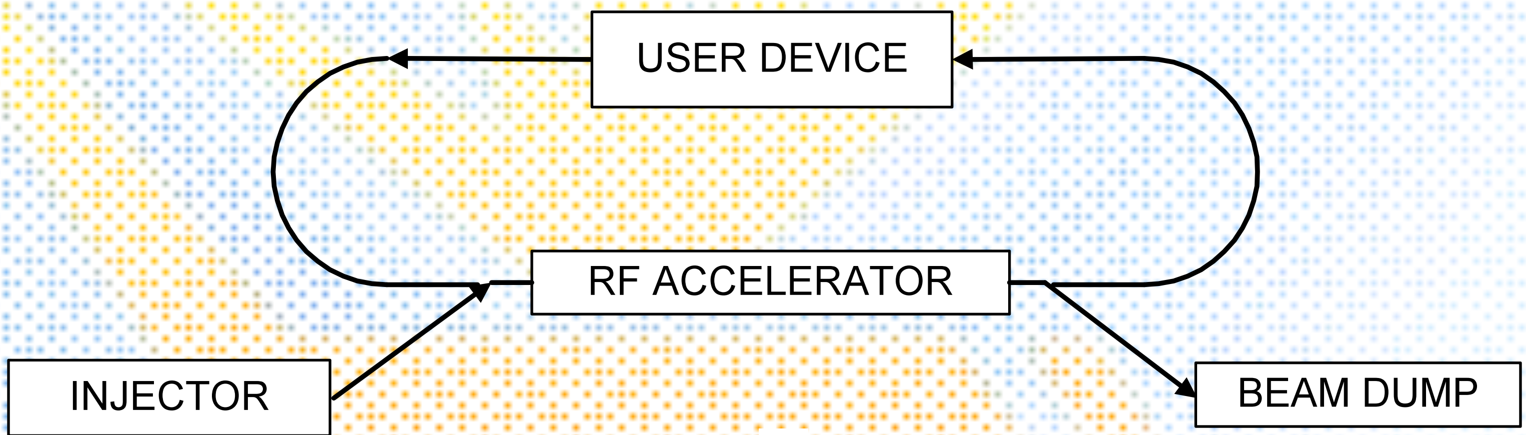
1. First stage ERL and FEL
   a. Accelerator design
   b. FEL parameters
   c. Status of operation
2. Second stage ERL commissioning
   a. Second stage layout
   b. Lattice simulations
   c. Status of commissioning
3. Future prospects

Energy recovery linacs (ERLs)

(with the same cavity energy recovery)



a

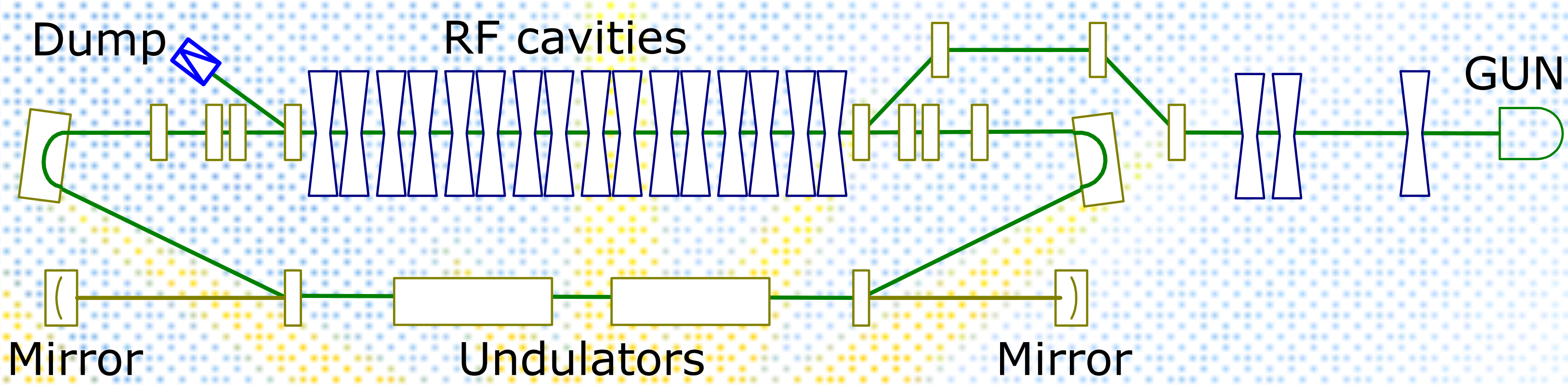


b

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

Novosibirsk ERL and FEL – 1st stage

Accelerator design



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

Accelerator room

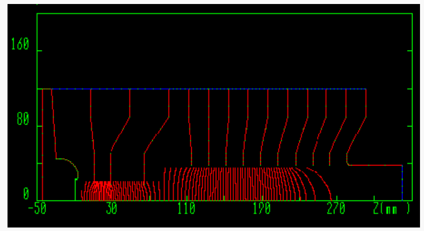
2 MeV Injector Parameters

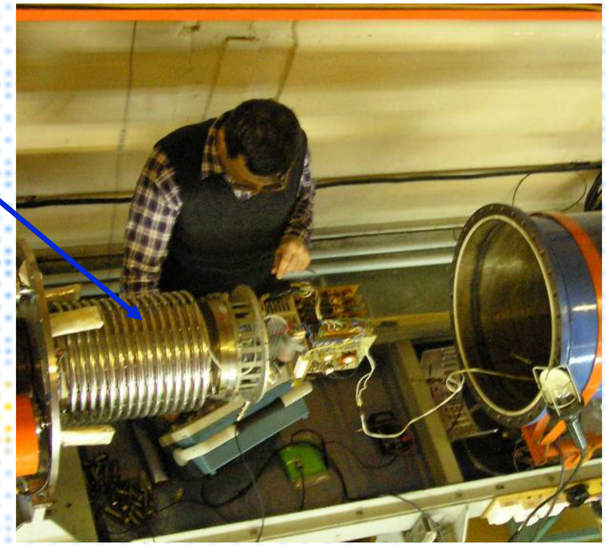
♦ DC electron gun voltage, kV	up to 300
♦ Bunch repetition rate, MHz	up to 22.5
♦ Charge per bunch, nC	up to 2
♦ Start bunch length, ns	1.0
♦ Final bunch length, ns	0.1
♦ Final energy, MeV	1.7

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

Electrostatic gun

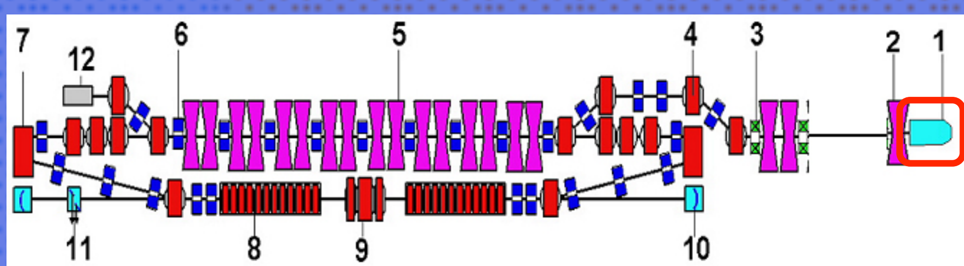


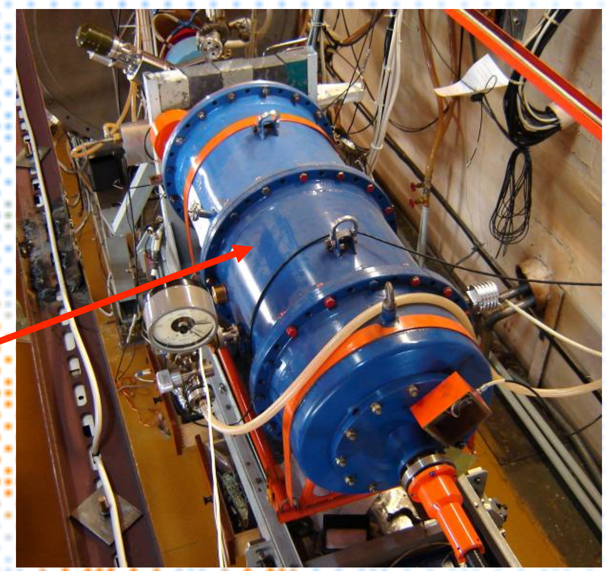


Power supply:

U_{max} = 300 kV

I_{max} = 50 mA

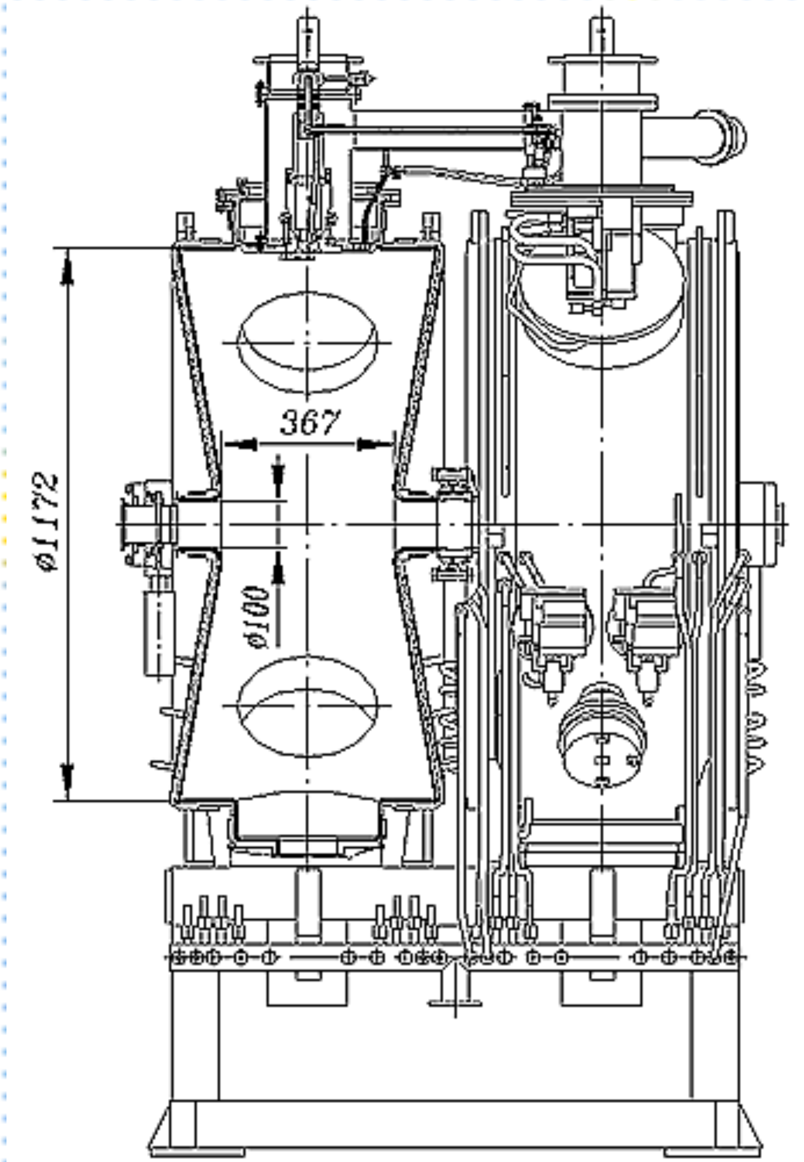


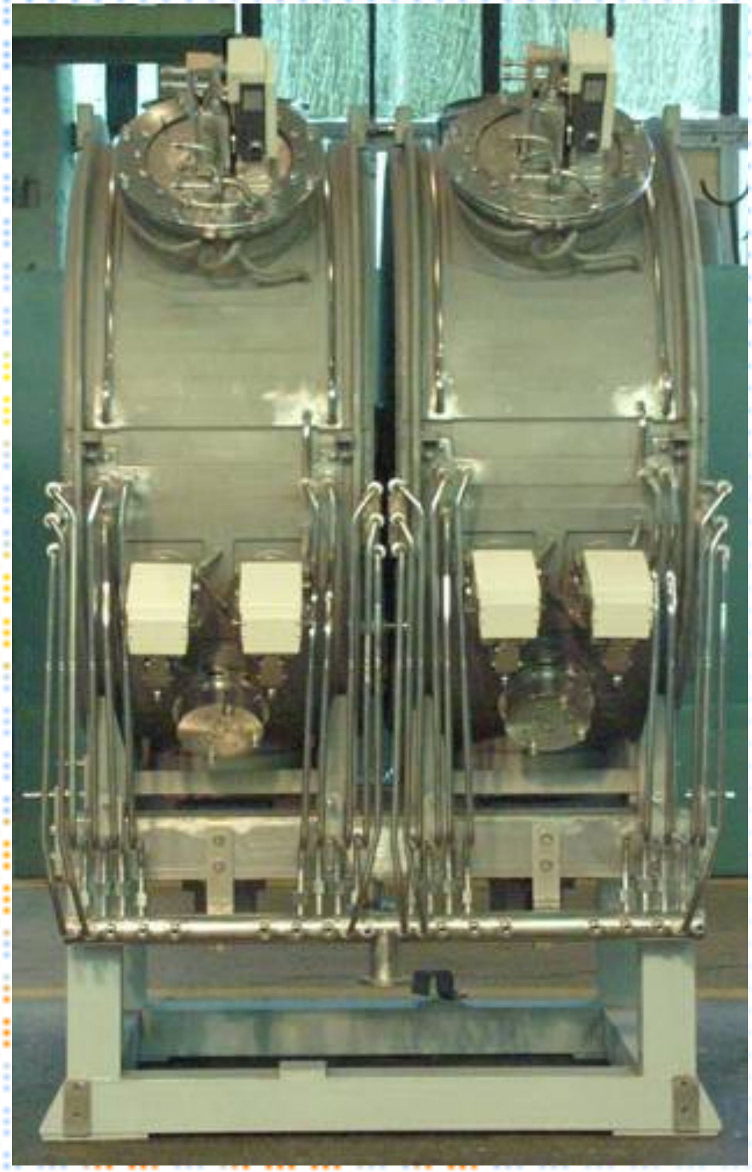


Features of RF system

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

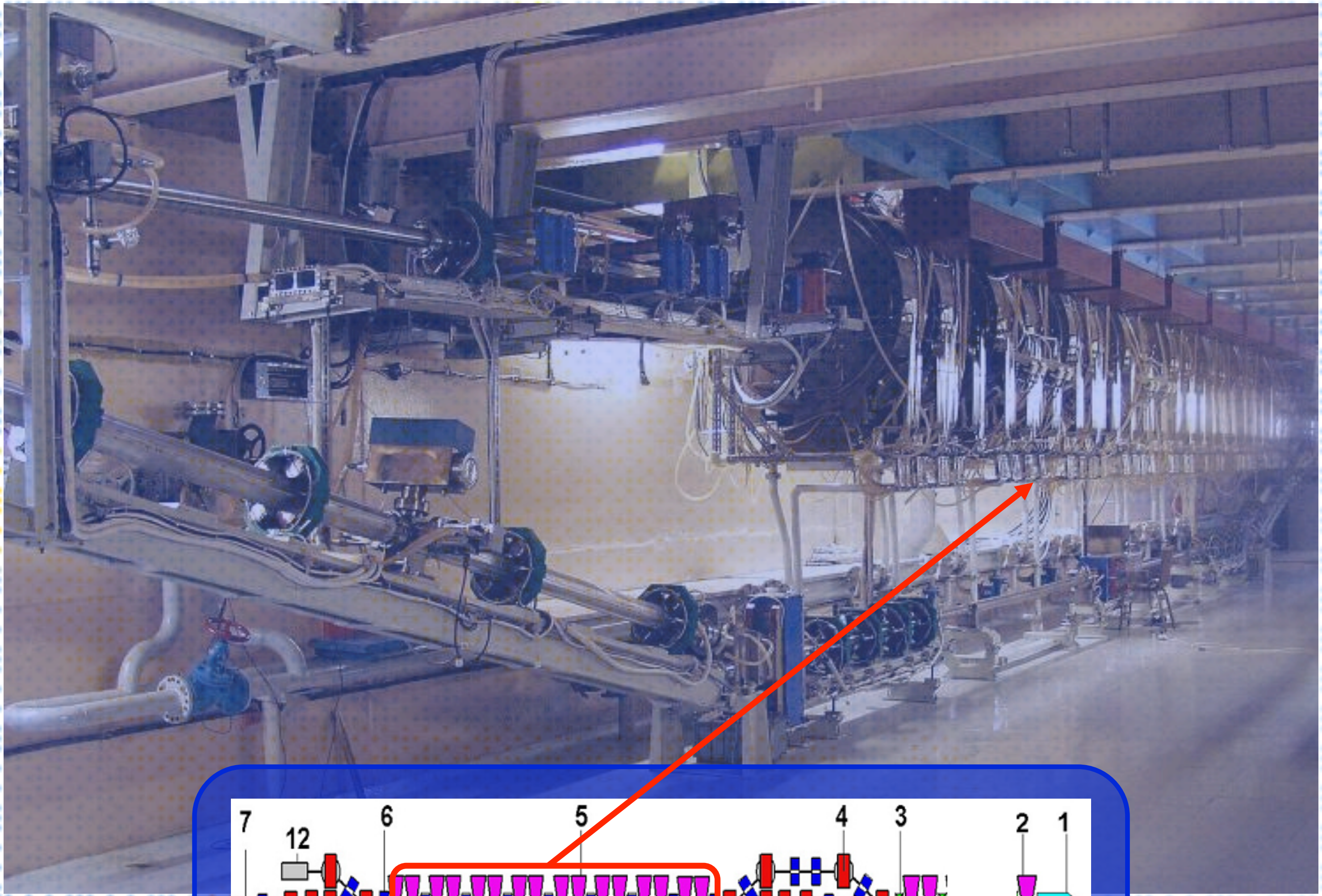
A pair of accelerating cavities on a support frame

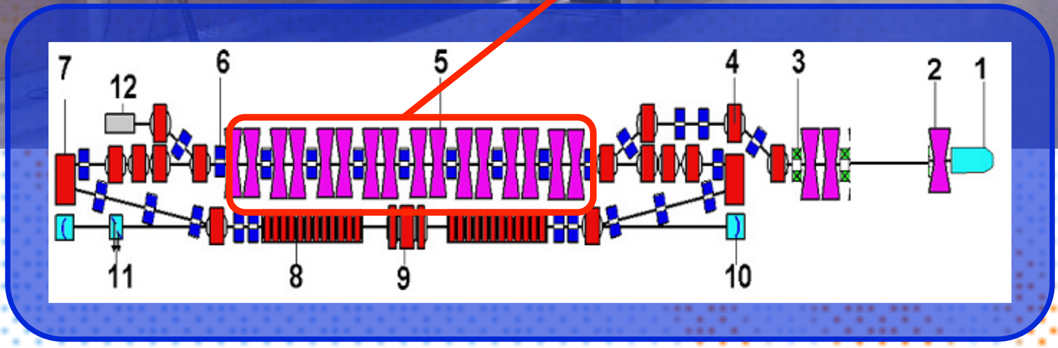




Bimetallic (copper and stainless steel) RF cavity tanks

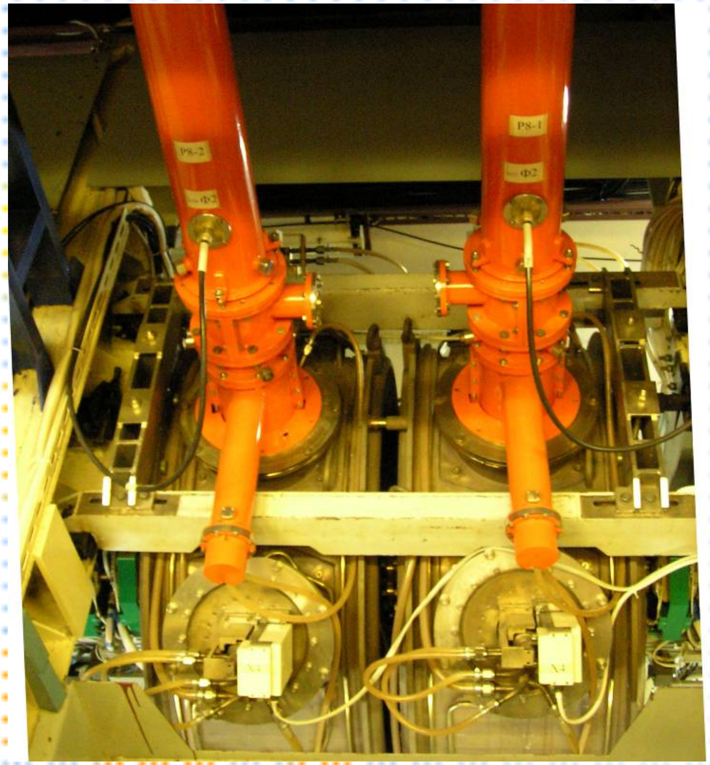
Main accelerating cavities





Tetrode-based output amplifier stages

Waveguides and feeders



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

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).

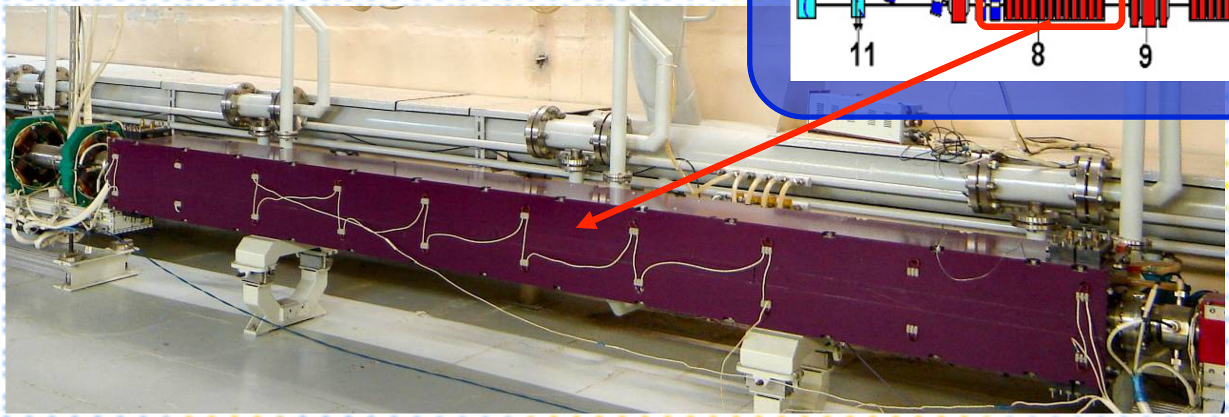
Advantages

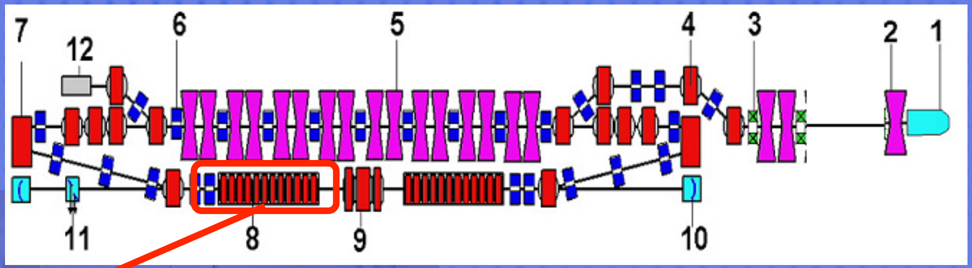
- *High threshold currents of instabilities*
- *Operation with long electron bunches (for narrow FEL linewidth)*
- *Large longitudinal acceptance (good for operation with large energy spread of used beam)*
- *Relaxed tolerances for orbit lengths and longitudinal dispersion*

FEL parameters and design

♦Wavelength, mm	0.12-0.24
♦Pulse duration, FWHM, ps	~70
♦Pulse energy, mJ	0.04
♦Repetition rate, MHz	11.2
♦Average power, kW	0.4
♦Minimum relative linewidth, FWHM	$3 \cdot 10^{-3}$

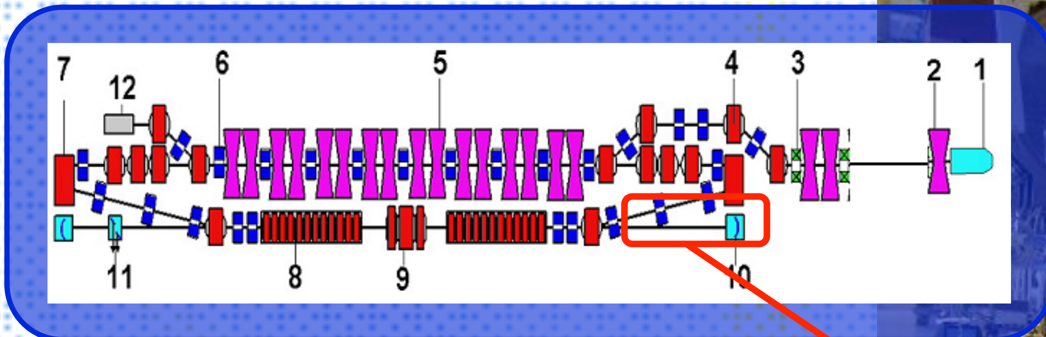
Undulator

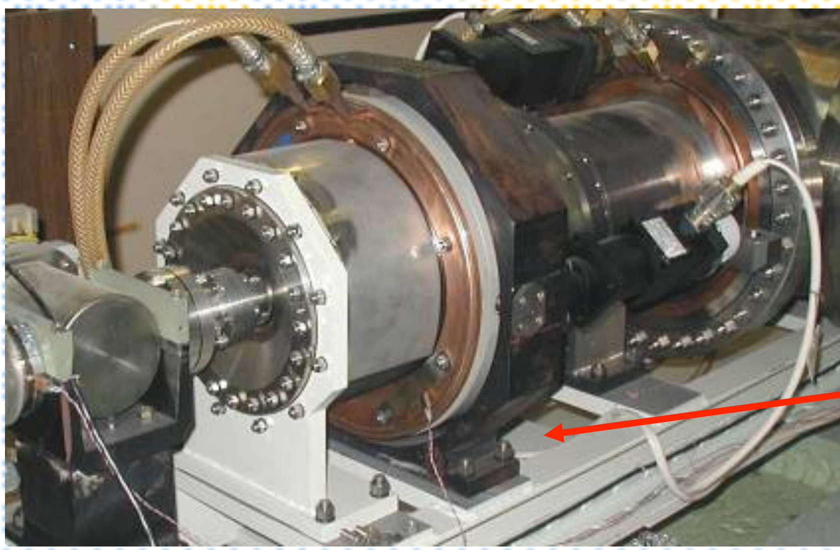


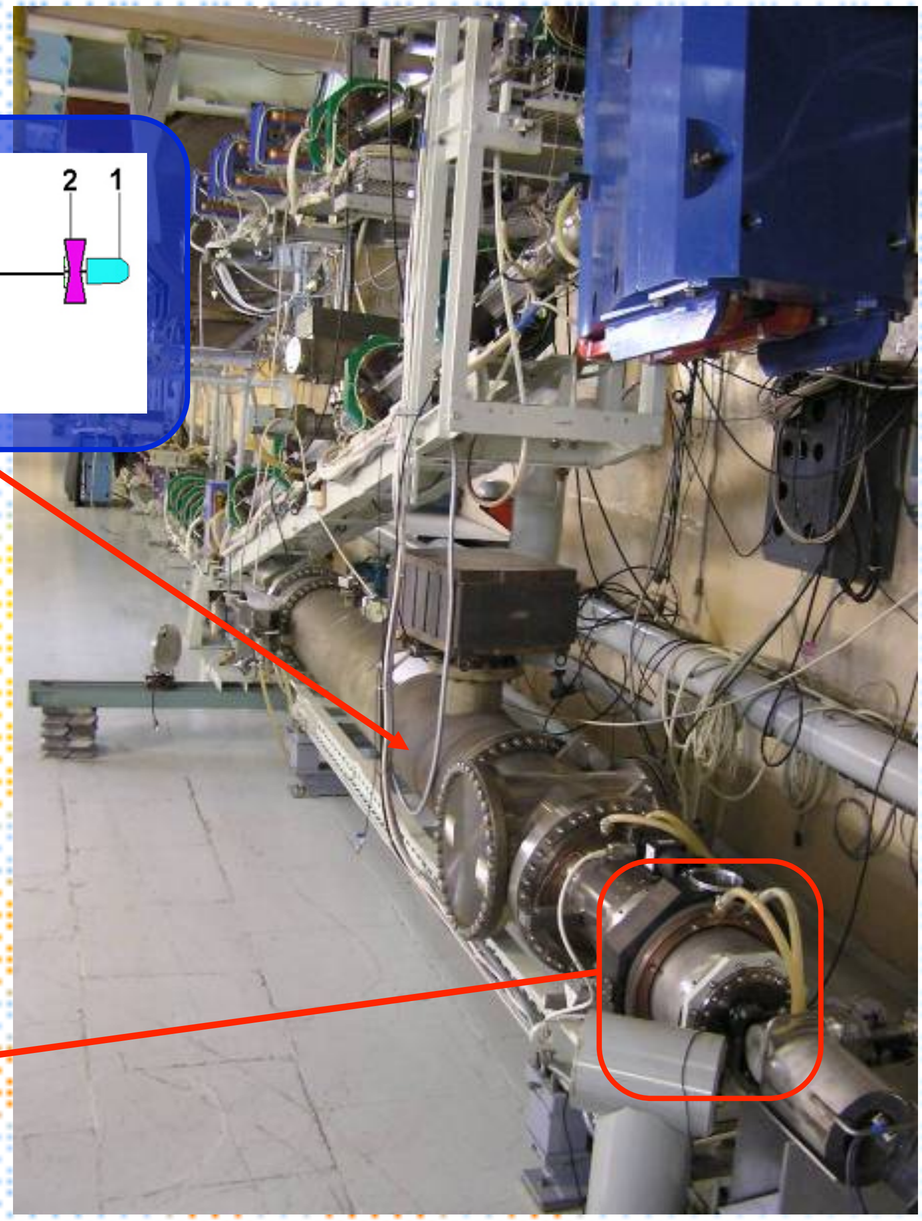


Period, cm	12
Maximum current, kA	2.4
Maximum K	1.25

Optical cavity












2005

2006

First stage ERL and FEL 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.

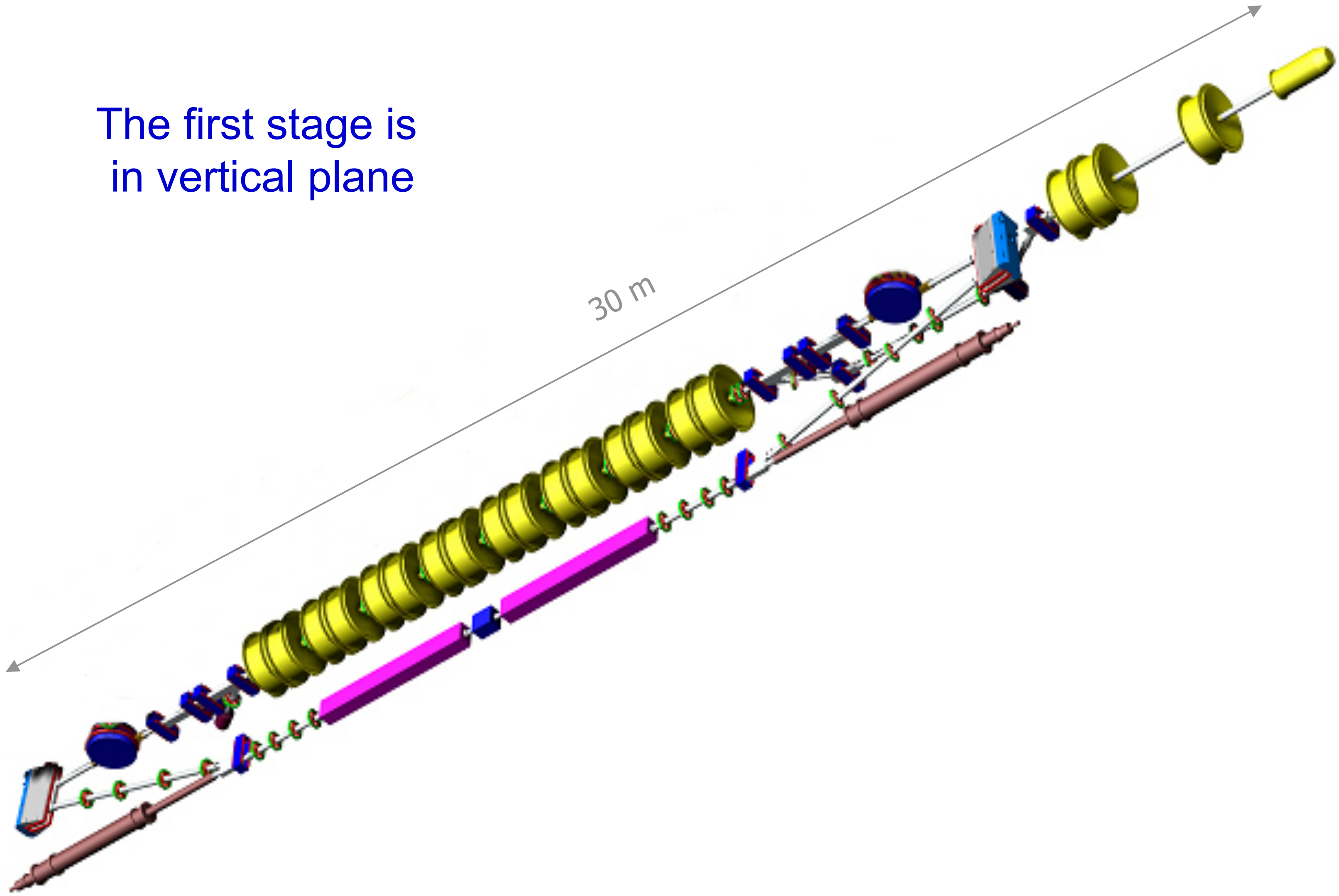
- Most of the user stations are in operation.

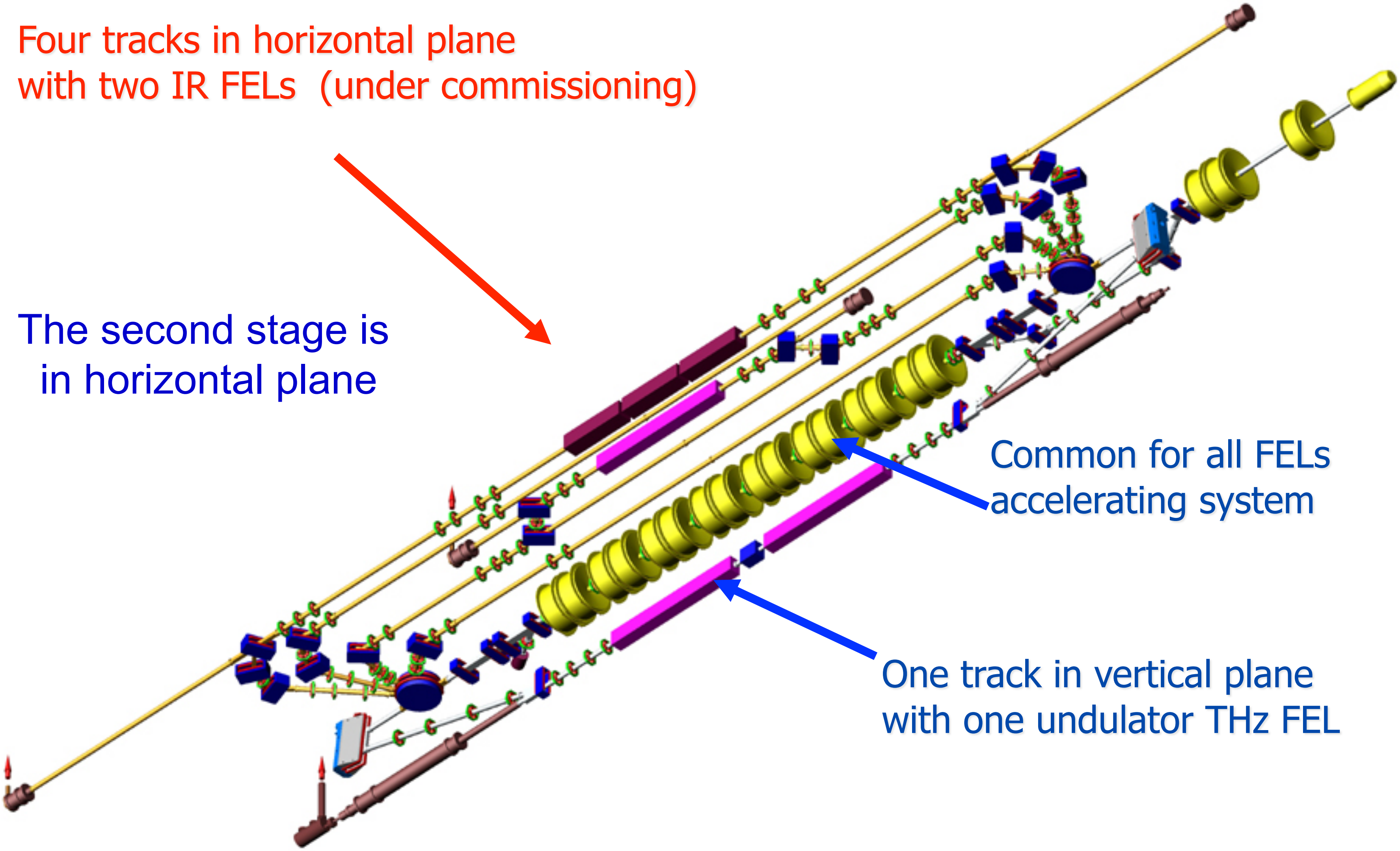
Second stage of Novosibirsk FEL

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 achieved by switching of bending magnets.

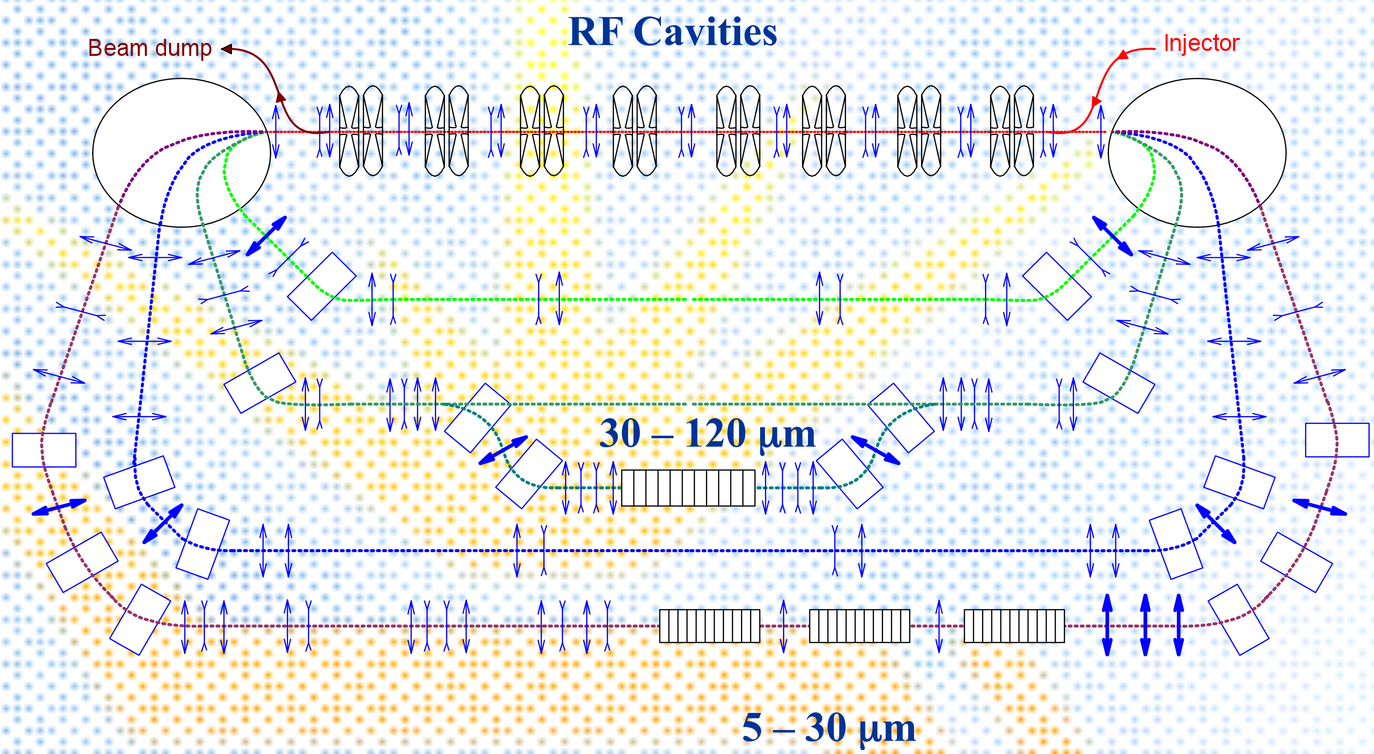
The first stage is
in vertical plane



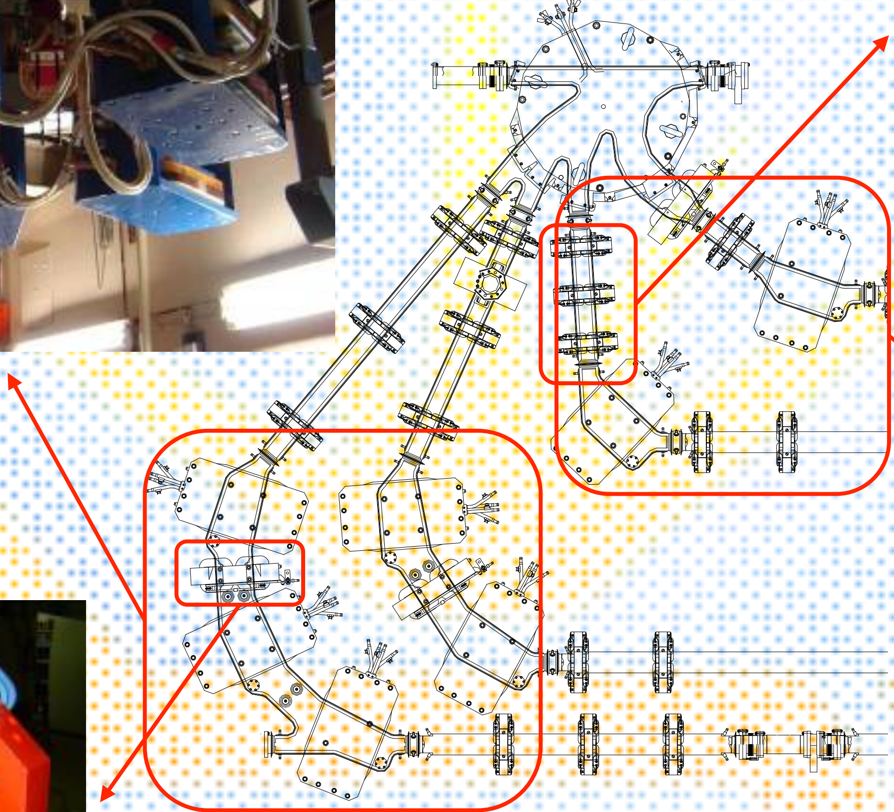

Four tracks in horizontal plane
with two IR FELs (under commissioning)
The second stage is
in horizontal plane
Common for all FELs
accelerating system
One track in vertical plane
with one undulator THz FEL

2-nd stage Novosibirsk FEL layout

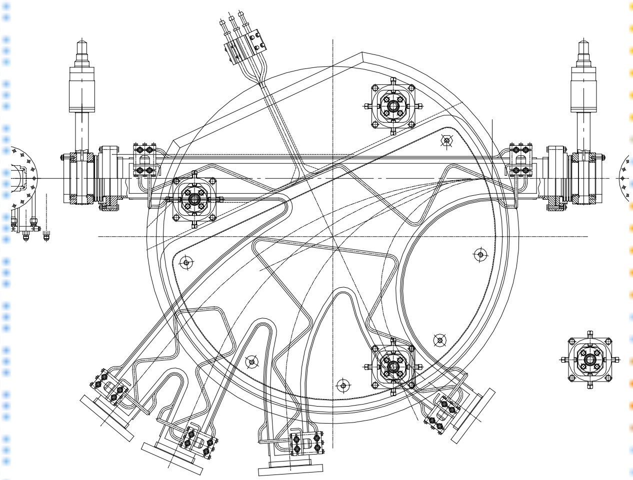
(horizontal plane)

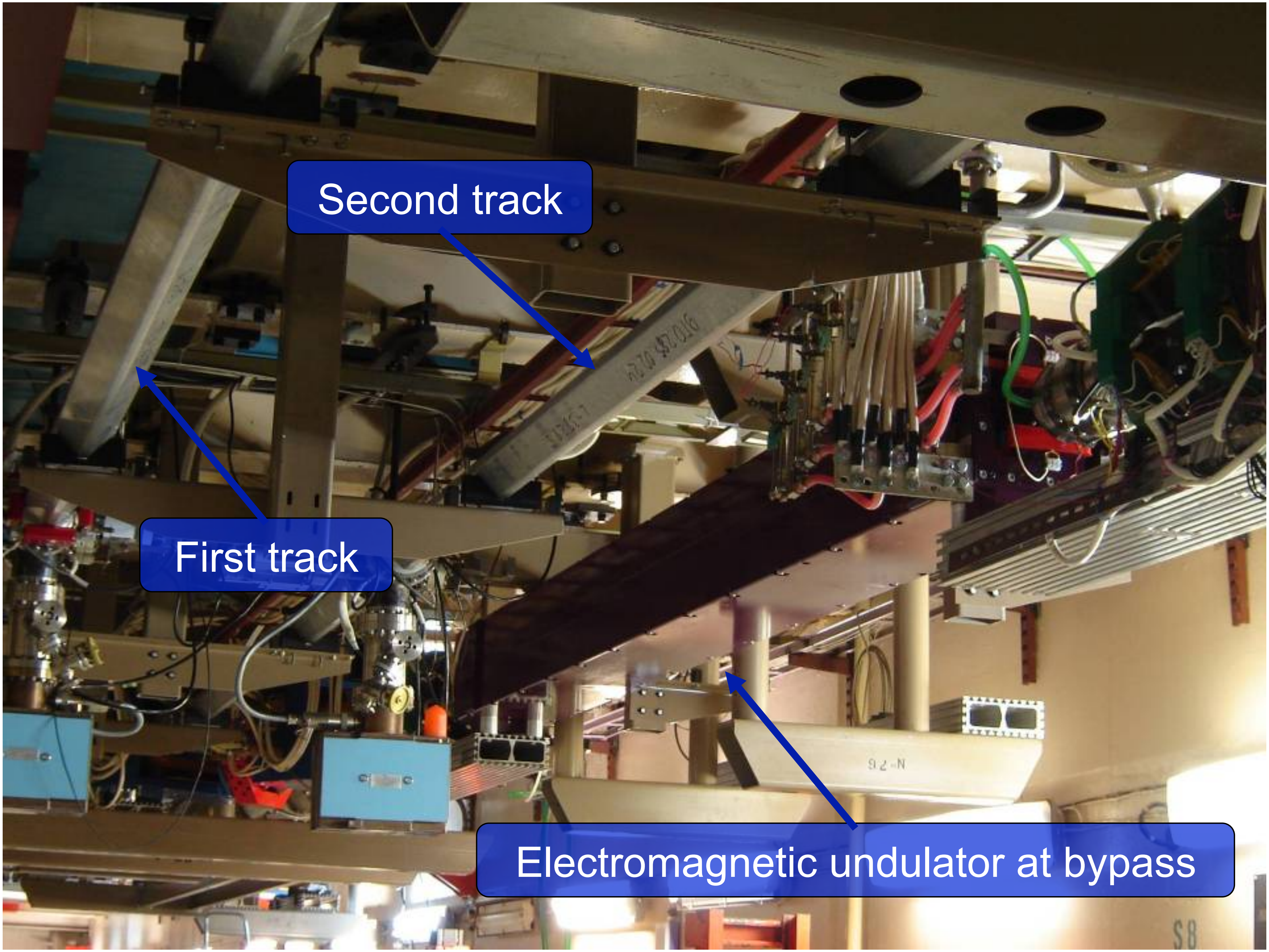


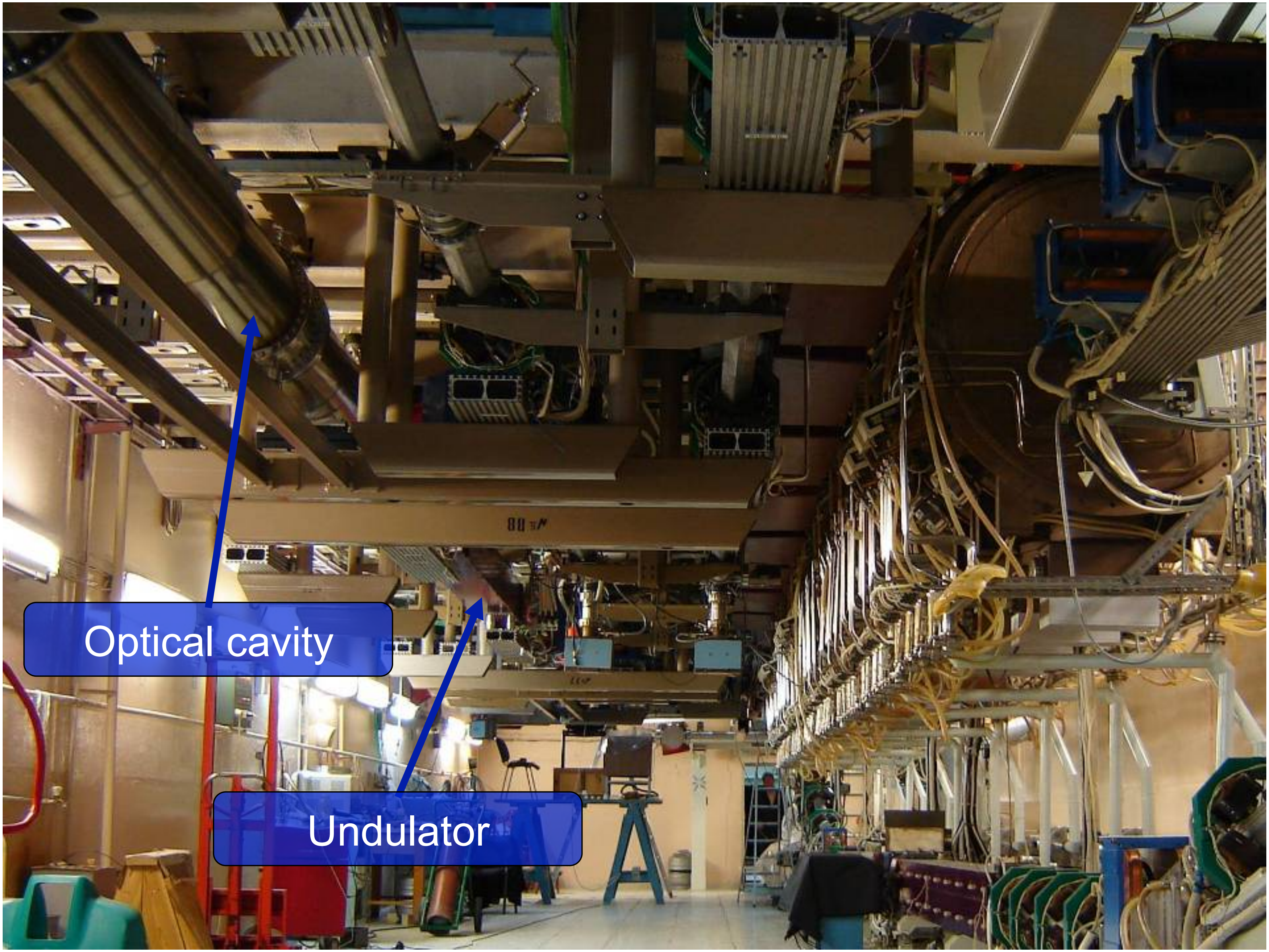
Magnets and vacuum chamber of bends



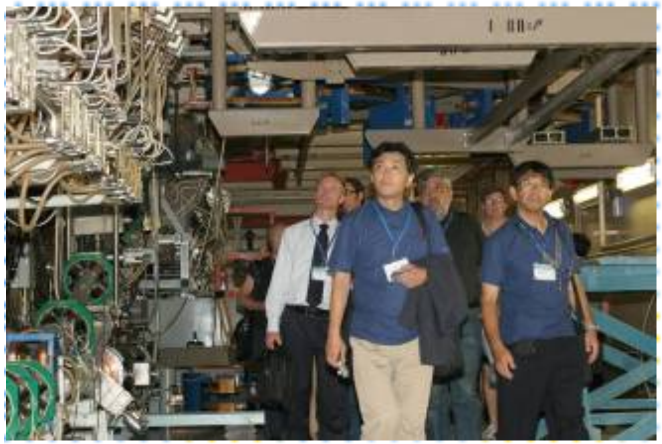
Round magnet




Second track
First track
Electromagnetic undulator at bypass


Optical cavity
Undulator

Assembly of four tracks is in progress



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

Second stage ERL and FEL parameters

Electron beam energy, MeV	20/40
Number of orbits	2/4
Maximum bunch repetition frequency, MHz	22 (90)
Beam average current, mA	30 (100)
Wavelength range, micron	5-120
Maximum output power, kW	10

Beam dynamics simulation

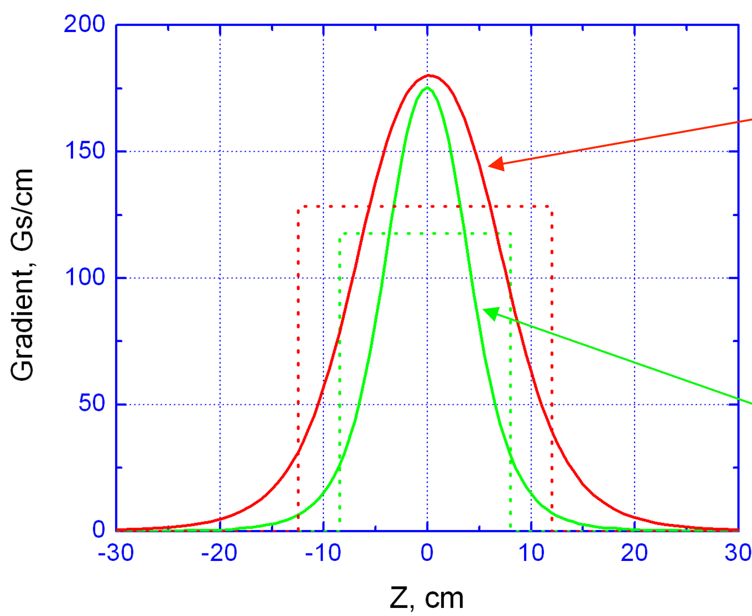
Problems:

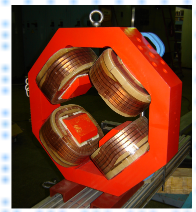
1. There are no reliable codes for time-dependant simulations of DC guns – One has to guess beam initial conditions.

2. Space charge plays important role at low energy.

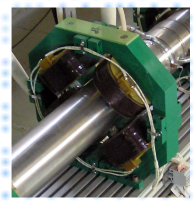
3. Standard beam propagation codes usually have only ideal magnetic elements.

Representation of real quadrupole with ideal one





I = 250 A



I = 10 A

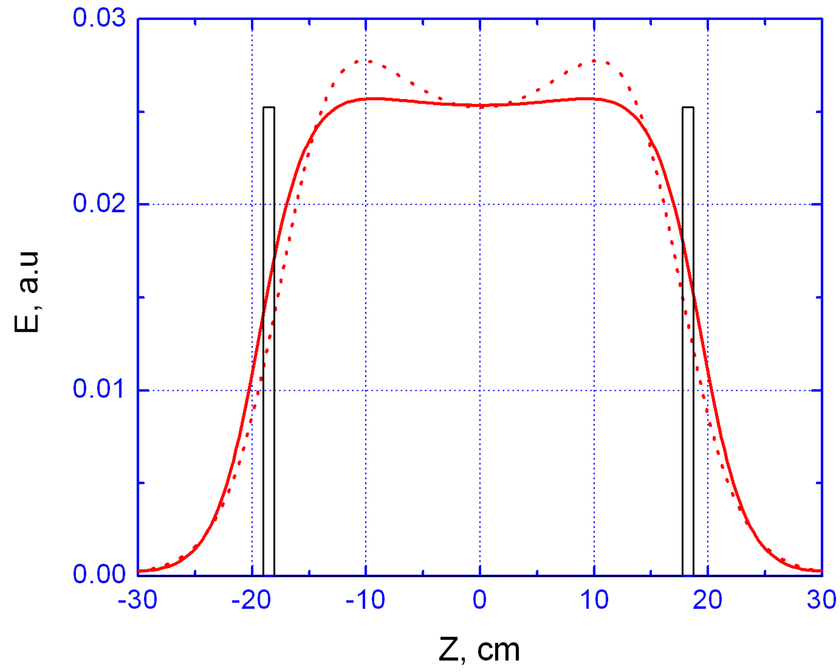
$$x'' + g(z)x = 0$$

$$I_0 = \int_{-\infty}^{\infty} g(z)dz$$

$$L_{eff} = \frac{6}{I_0^2}\int_{-\infty}^{\infty}\left(\int_{-\infty}^{z} g(z')dz' \cdot \left(I_0 - \int_{-\infty}^{z} g(z')dz'\right)\right)dz$$

$$g_{eff} = \frac{I_0}{L_{eff}}$$

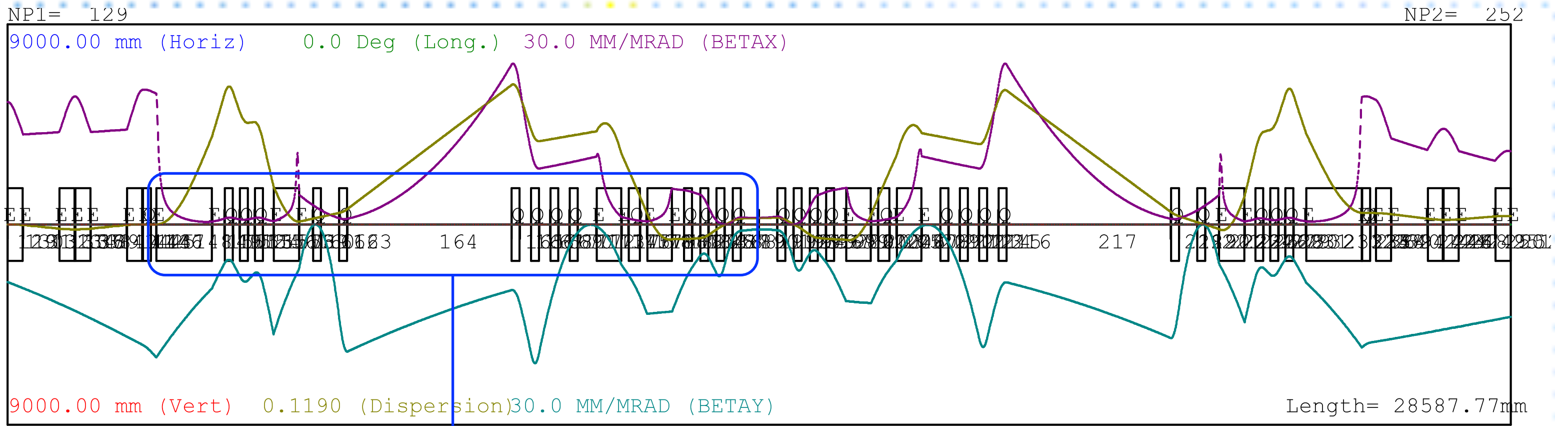
Representation of real RF cavity field in Trace-3D

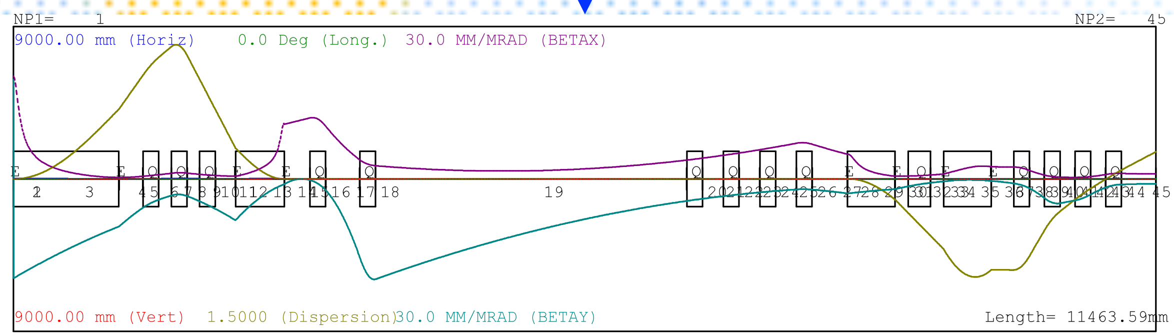


Solid red line – real field distribution, dotted red line – Trace-3D cavity field distribution with L_{eff} = 70 cm, black boxes – cavity boundary position.

Lattice of the 2d track (including bypass)

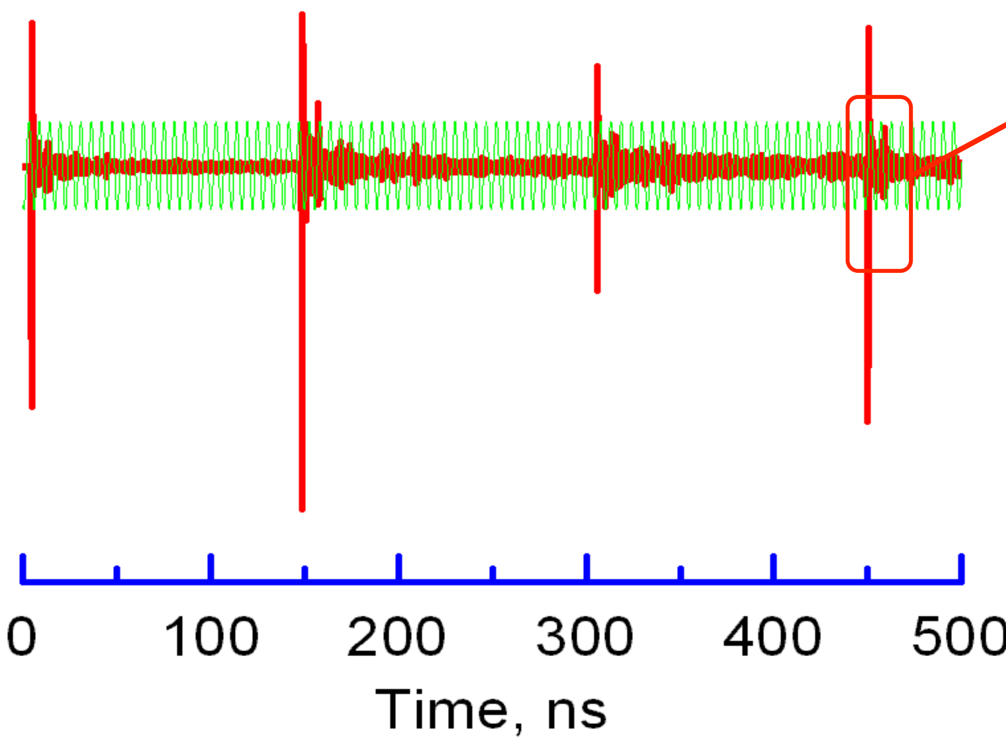
(Trace-3D simulation results)

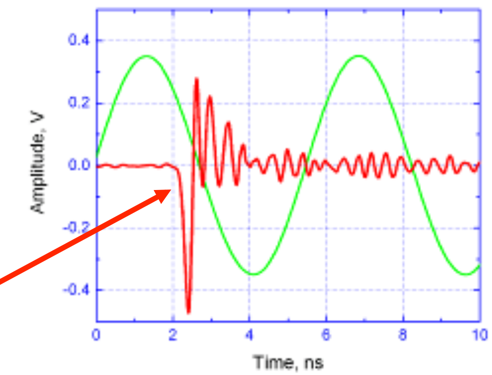




“Soft” regime with nonzero dispersion in undulator

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



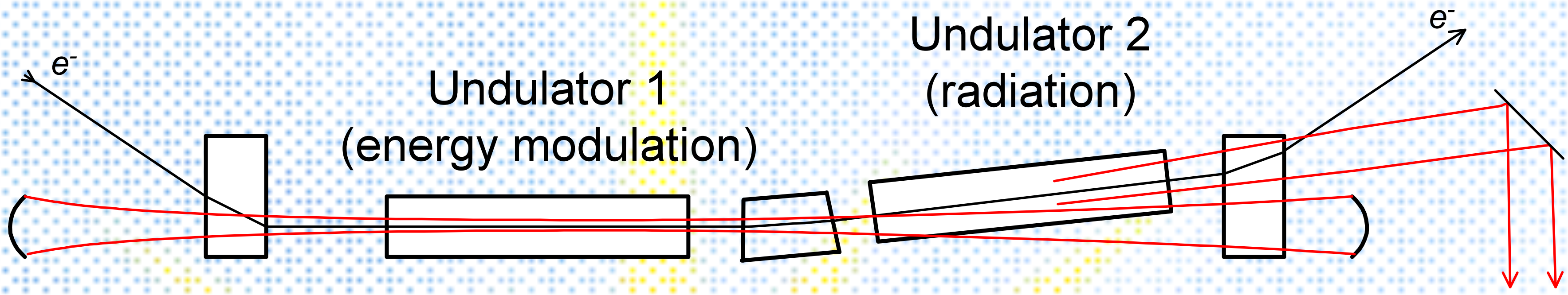


Status of commissioning

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.

Schematic diagram of electron outcoupling

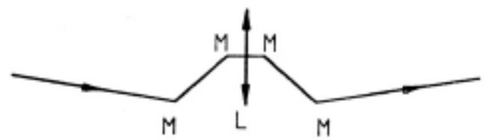


Why electron outcoupling?

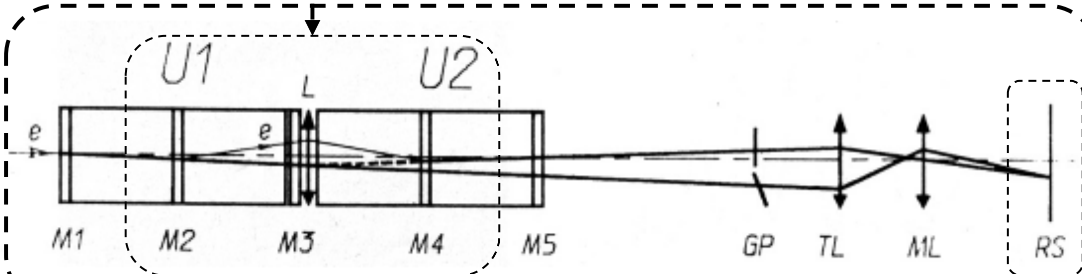
- lower load on optical cavity mirrors
- wavelength tunability (high power partially transparent mirrors have narrow band)

Experimental observation of the coherency of radiation from two undulators

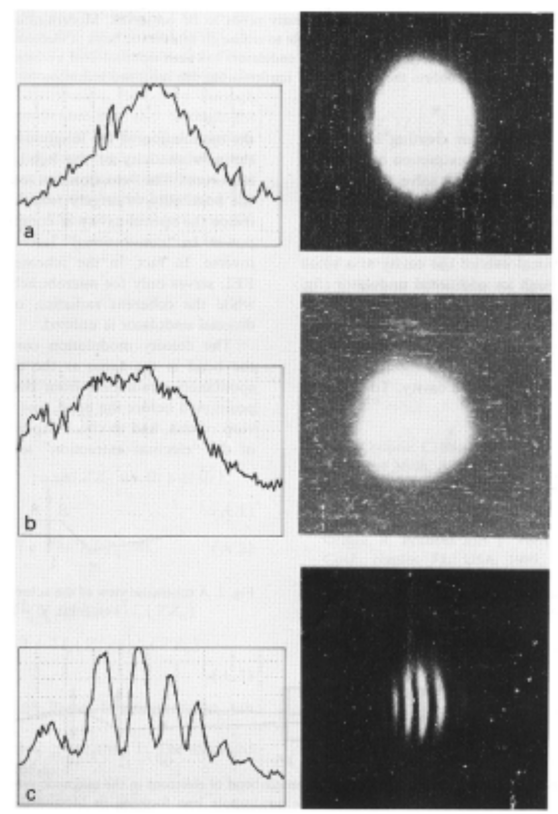
A schematic view of the achromatic bend: M – bending magnets, L -lens



$R_{5,1}$ and $R_{5,2} = 0$

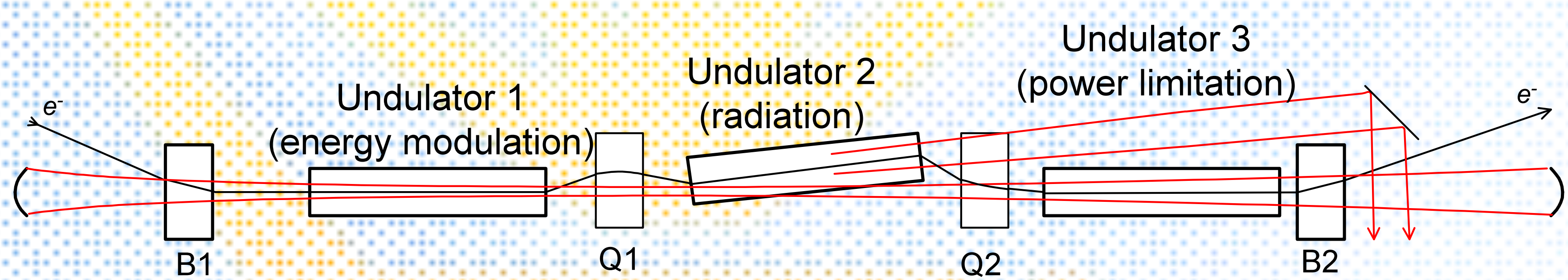


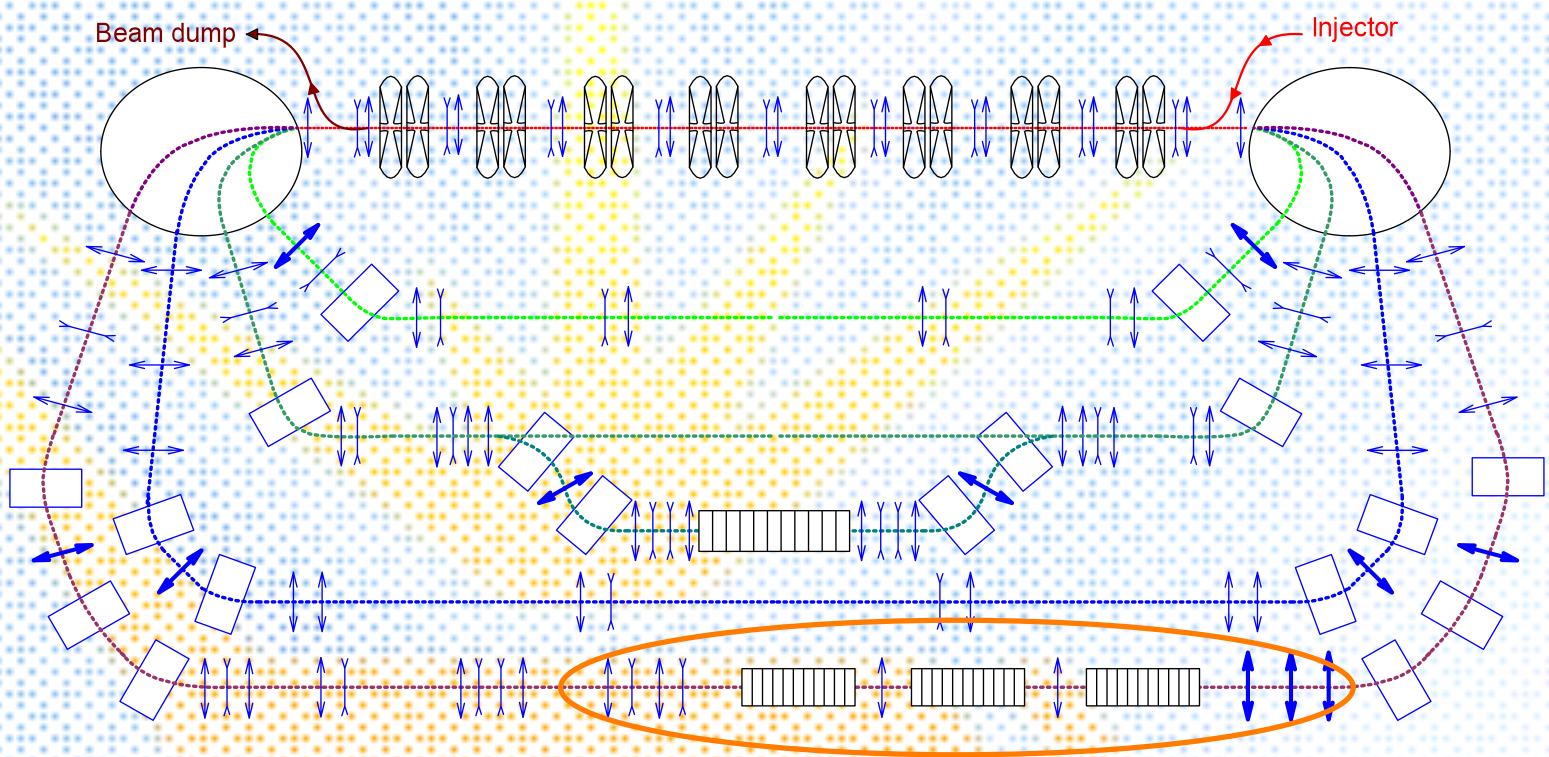
The scheme to observe radiation coherency at the achromatic bend of electrons in the magnetic system of the optical klystron on VEPP-3: M1-M5 –horizontal bending correctors; L – quadrupole lens focusing in horizontal direction; U1 and U2 undulators; TL and ML – optical telescope lens and imaging lens respectively; RS – registering screen



Interference pictures observed at a conventional (nonachromatic) bend (a), at an achromatic bend without the delay compensation (b) and with the delay compensation (c)

Electron outcoupling scheme of Novosibirsk FEL





Electron outcoupling scheme is used here

Thank you