Novosibirsk ERL facility

G.N. Kulipanov and NovoFEL team

Budker INP, Novosibirsk, Russia

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NovoFEL Team

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1. Introduction.
History of ERL activity in Novosibirsk

The Energy Recovery Linac concept for the FEL was proposed at Budker INP by N. Vinokurov and A. Skrinsky (Preprint BINP 78-88, Novosibirsk, 1978; Proceedings of the 6th Soviet Union Accelerator Conference, Dubna, 11-13 October 1978, V II, p.233-236).

The first project of the four-turn race-track microtron-recuperator for the free electron laser NovoFEL was proposed at FEL'90 Conference, which took place in Paris (September 1990).
Gavrilov N.G., Gorniker E.I., Kulipanov G.N., …, Vinokurov N.A., NIM A304 (1991), P.228-229

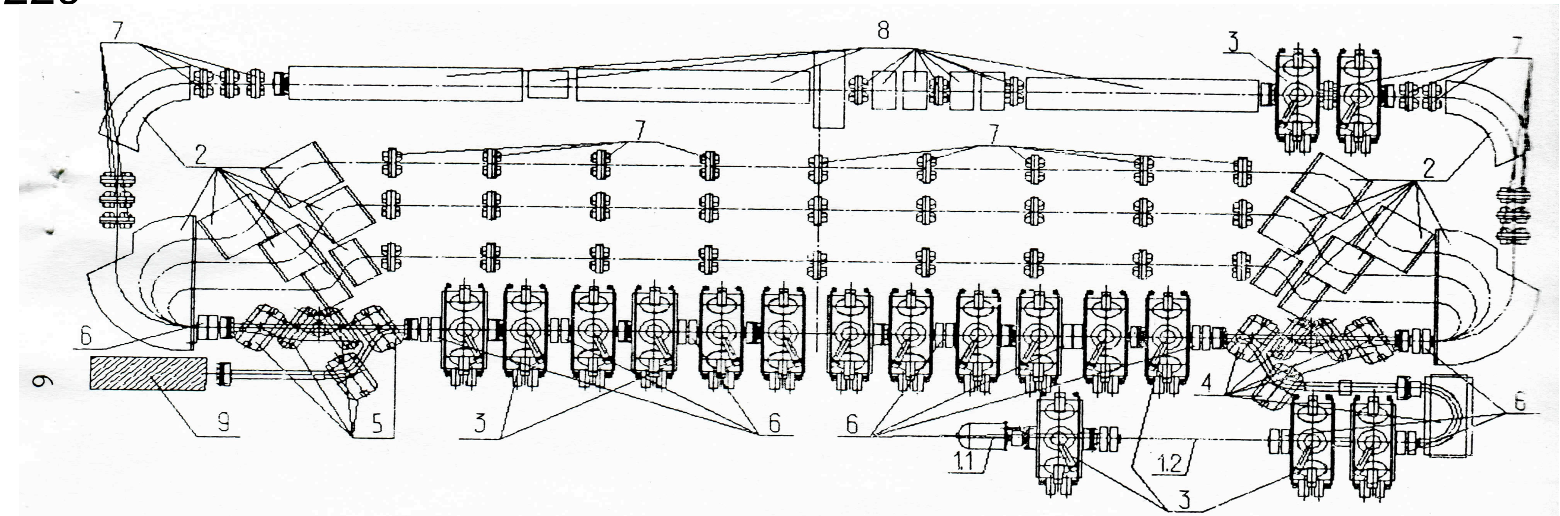


Fig. 1. The general layout of the race-track microtron-recuperator: 1 – injector; 1.1 – electron gun of the injector; 1.2 – bunching straight section; 2 – magnetic systems of the 180° bend; 3 – rf cavities; 4 – magnets of the injection system; 5 – magnets of the extraction system; 6 – solenoidal magnetic lenses; 7 – quadrupole magnetic lenses; 8 – magnetic system of the FEL; 9 – beam dump.

Later the project was modified, the base lines kept:

- A four-turn normal conductance linac with energy recovery;
- Low RF cavities (180 MHz)
- A grid-controlled DC gun with Q~ 1nC, t=1nsec, and f_{rep}=10kHz÷22.5 MHz;
- The ERL can operate in three modes, providing an electron beam for the three different FELs, from 5 μm up to 240 μm

Advantages of the low frequency (180 MHz) RF system

- High threshold currents for 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

- Low RF frequency (180 MHz) allows to use normal-conducting RF

Advantage: high beam current.

Disadvantage: high RF power consumption.

Indeed, the characteristic stability parameter is

$$\frac{P_{beam}}{P_{RF}} = \frac{I_{beam}U}{U^2/(2R)} = \frac{2I_{beam}R}{U} = \frac{QI_{beam}2(R/Q)}{U} \sim \frac{QI_{beam}}{10\mathrm{kA}}$$

Therefore, the “critical” beam current is

$$I_{beam\,cr} = \frac{U}{2R} = \frac{U}{2Q(R/Q)} \sim \frac{10\mathrm{kA}}{Q}$$

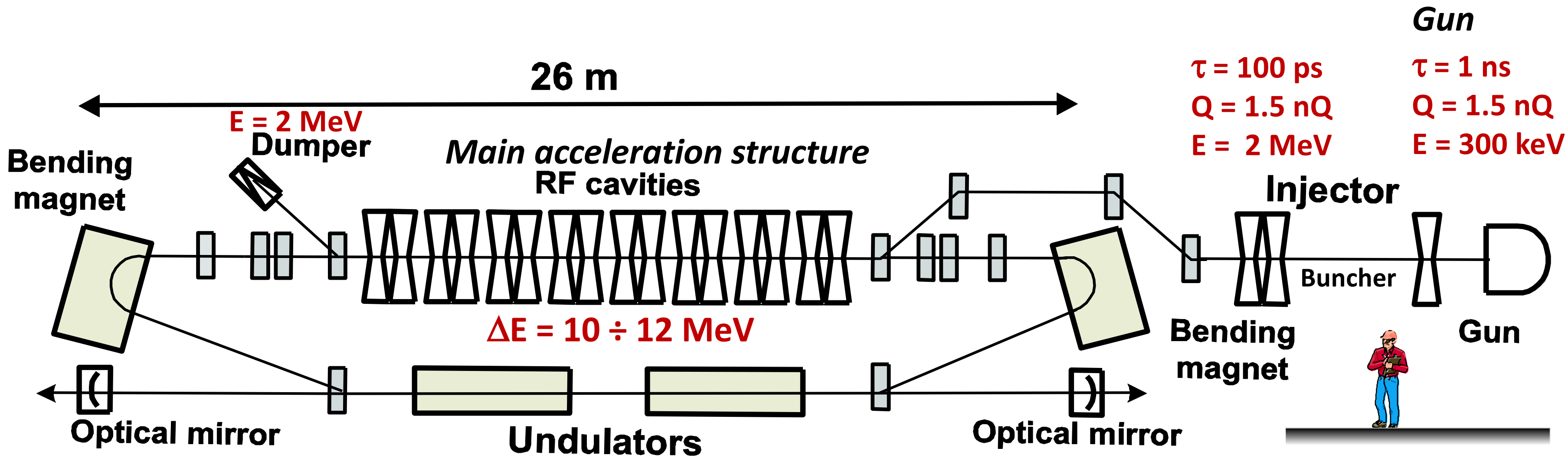
- Construction and commissioning four track ERL was divided on three stages;

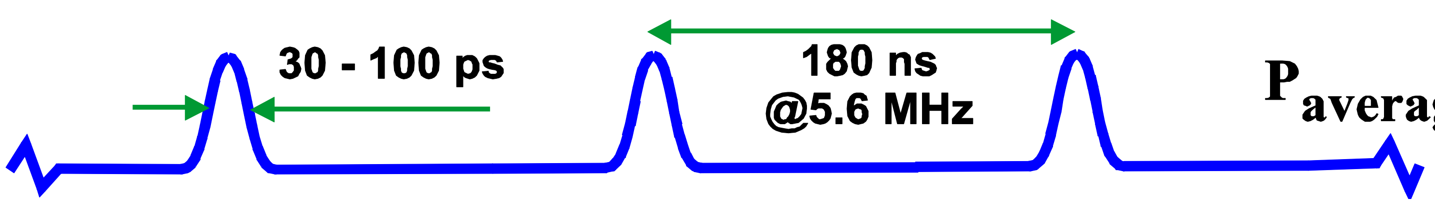
- The first stage of Novosibirsk high power free electron laser (NovoFEL) working in spectral range (90 ÷ 240) μm, based on one track energy recovery linac (ERL) with energy 12 MeV, was commissioned in 2003.

- The second stage of NovoFEL working in spectral range (35 ÷ 80) μm, based on two track energy recovery linac with energy 22 MeV, was commissioned in 2009.

- The third stage of NovoFEL working in spectral range (8 ÷ 15) μm, based on four track energy recovery linac with energy 42 MeV, was commissioned in 2015.

2. Status of NovoFEL - First stage



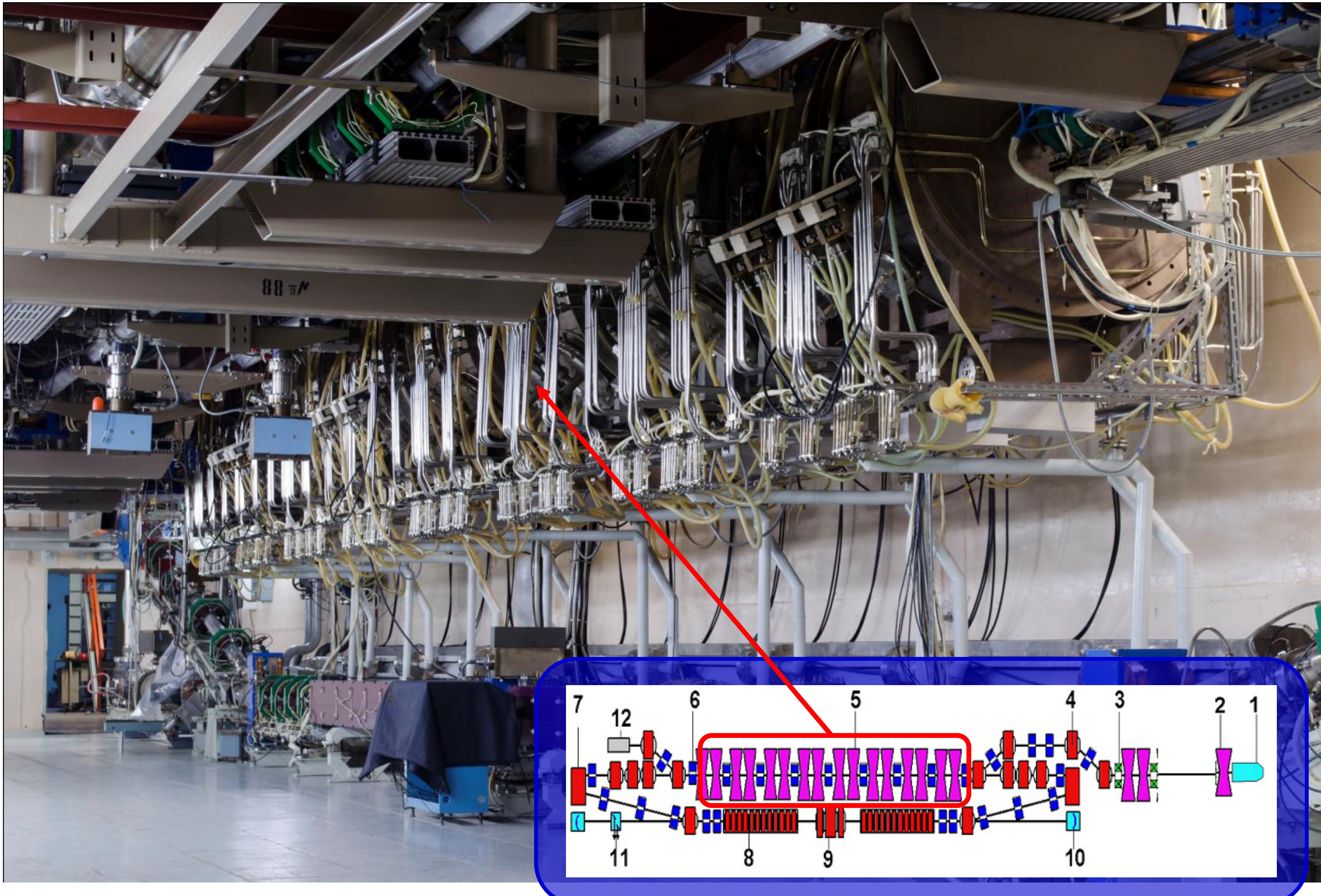


$P_{average} \leqq$ **0.5 kW**

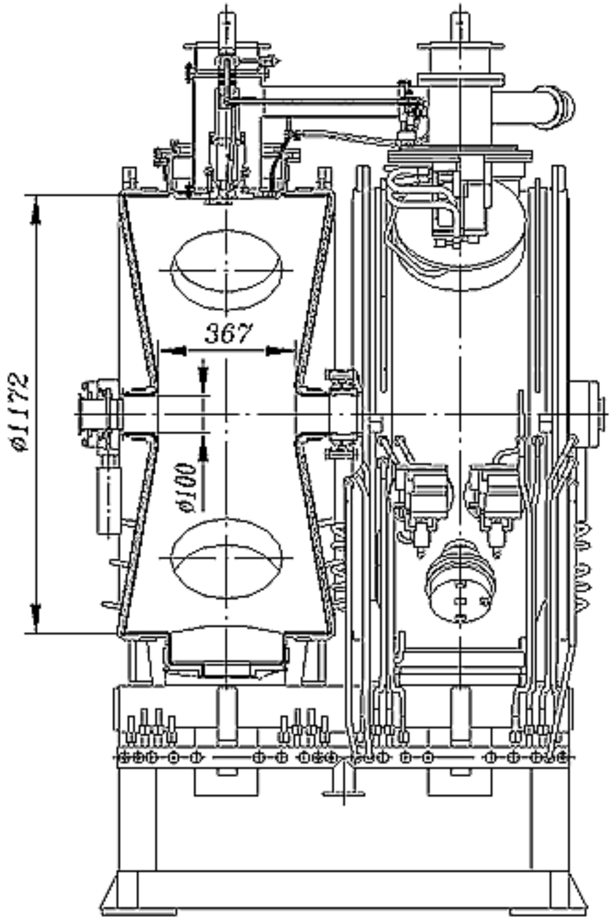
Electron beam from the gun passes through the buncher (a bunching RF cavity), drift section, 2 MeV accelerating cavities, the main accelerating structure and the undulator, where a fraction of its energy is converted to radiation.

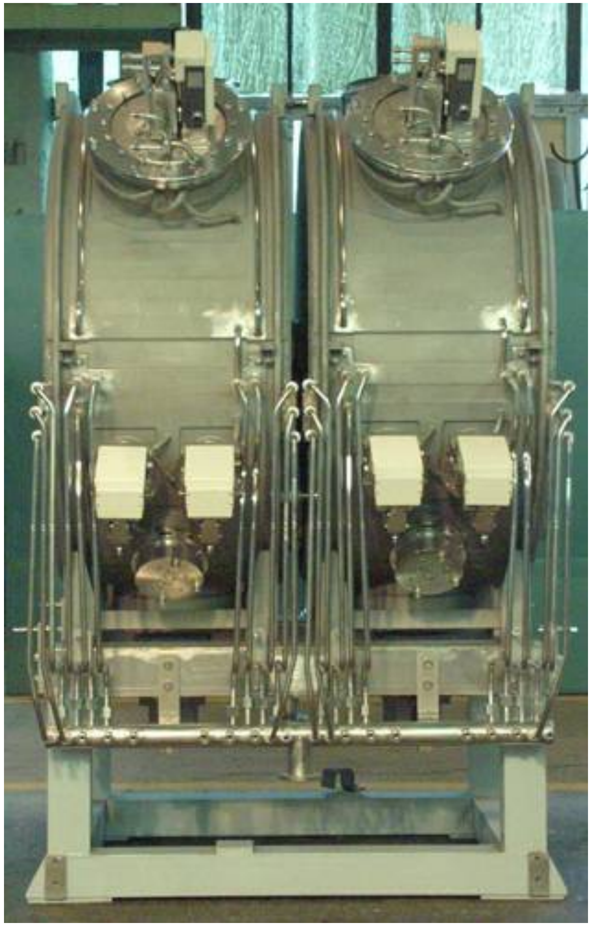
After that, the beam returns to the main accelerating structure in a decelerating RF phase, decreases its energy to its injection value (2 MeV) and is absorbed in the beam dump.

Main linac



RF cavities of main linac





F_0 = 180 MHz, Δf_0 = 320 kHz, U_{max} = 950 kV,

U_{eff} = 850 kV, P_{dis} = 85 kW

RF power amplifier

Frequency, MHz	180.4
Power, MW	2 x 0.6

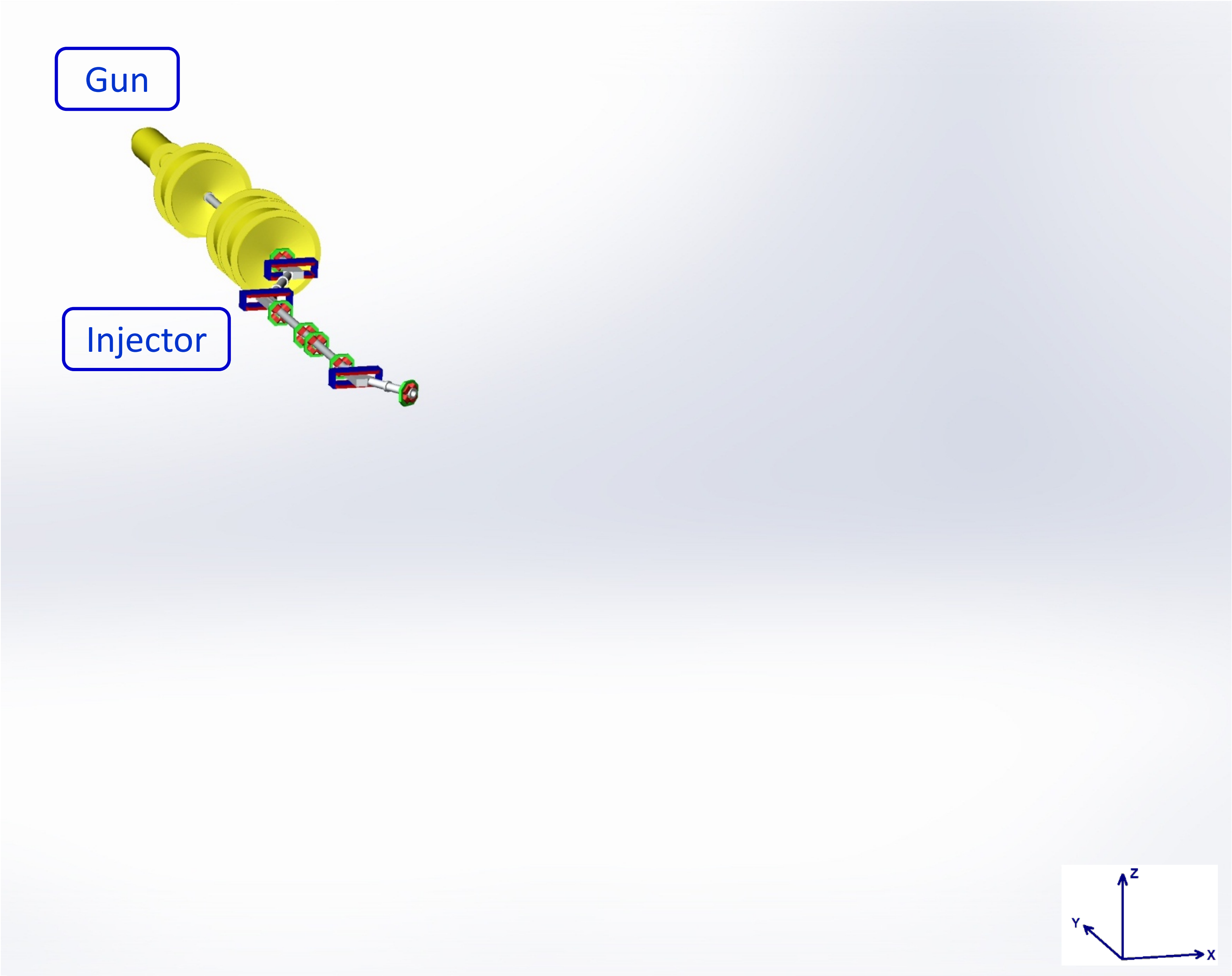
RF waveguides and feeders

3. Second and third stages of NovoFEL design and commissioning

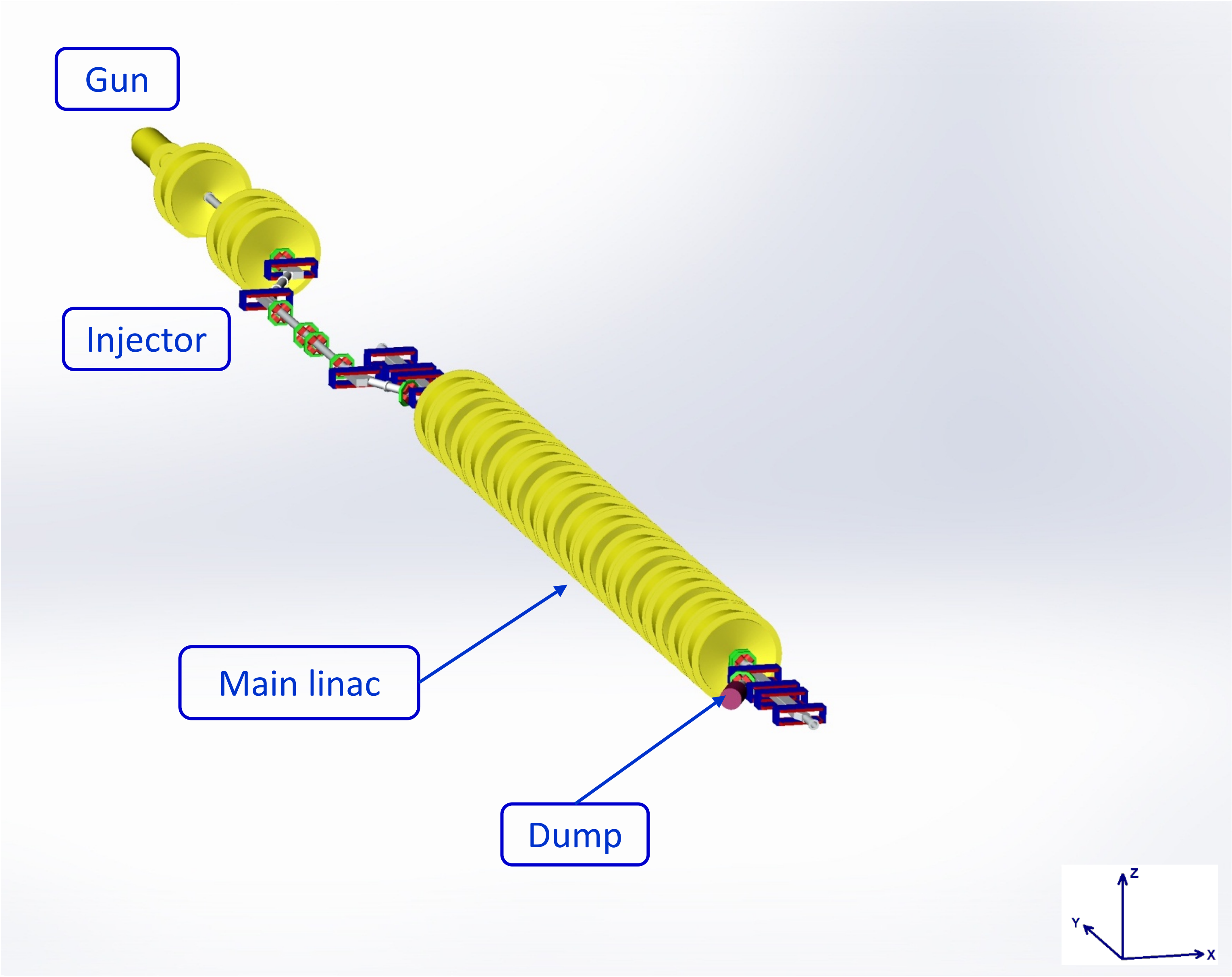
Novosibirsk energy recovery linac has rather complicated magnetic system. First stage of NovoFEL with 12-MeV electron energy lies in vertical plane.

Other four orbits lie in the horizontal plane.
The beam is directed to these orbits by switching on of two round magnets. In this case electrons pass four times through acceleration RF cavities, obtaining 43-MeV energy. Than, (at the fourth orbit) the beam is used in FEL and decelerated four times.

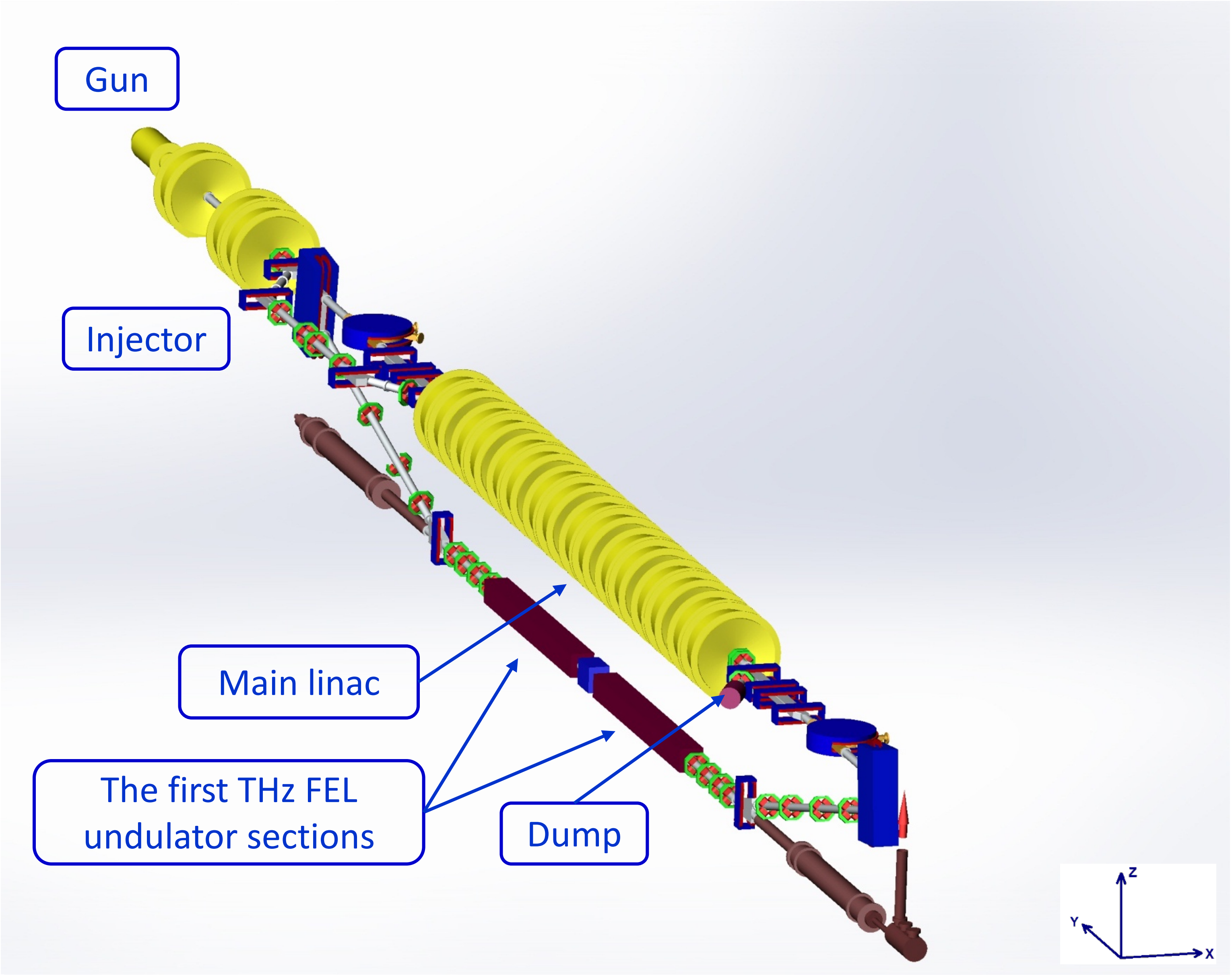
NovoFEL Accelerator Design and status



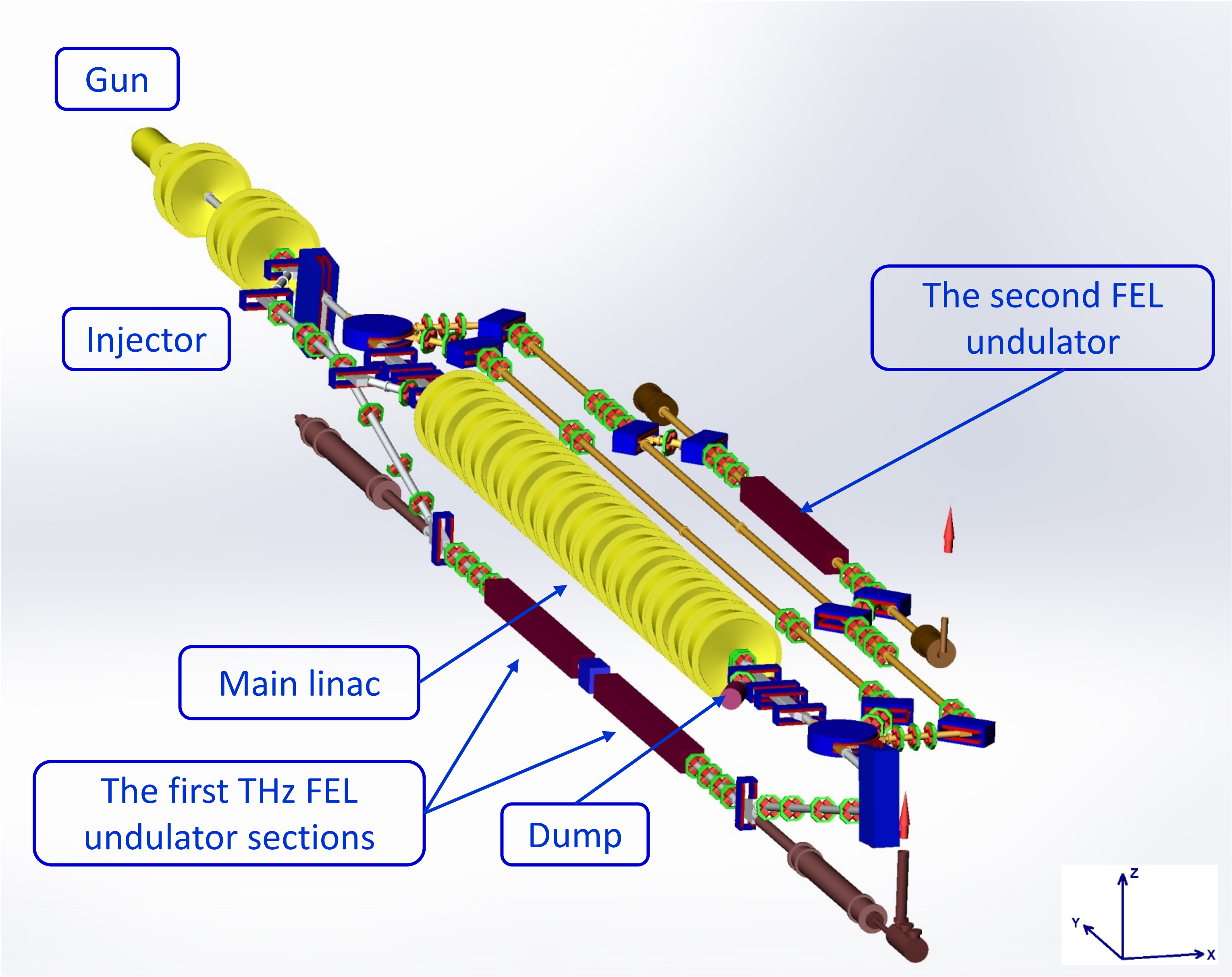
NovoFEL Accelerator Design and status



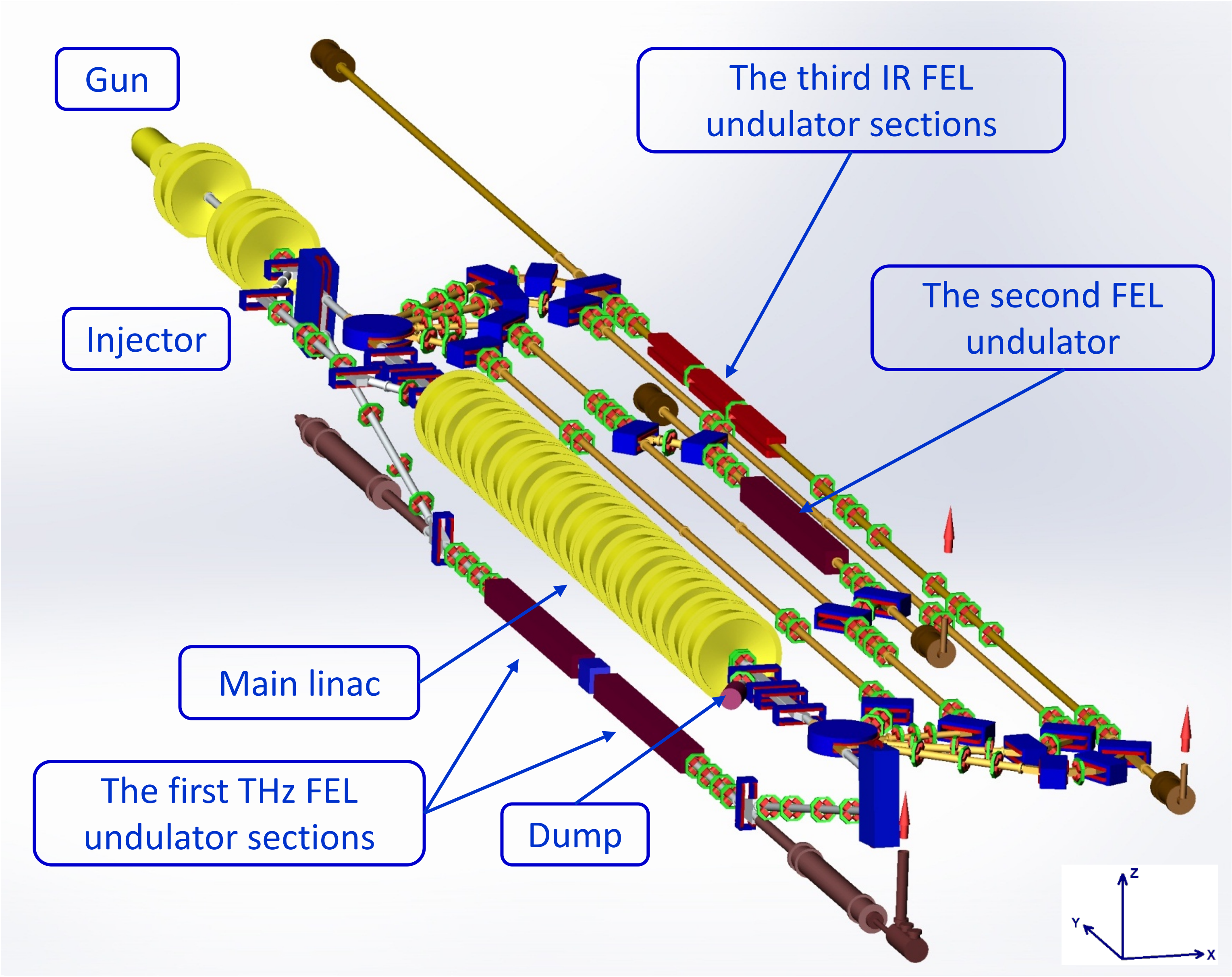
NovoFEL Accelerator Design and status



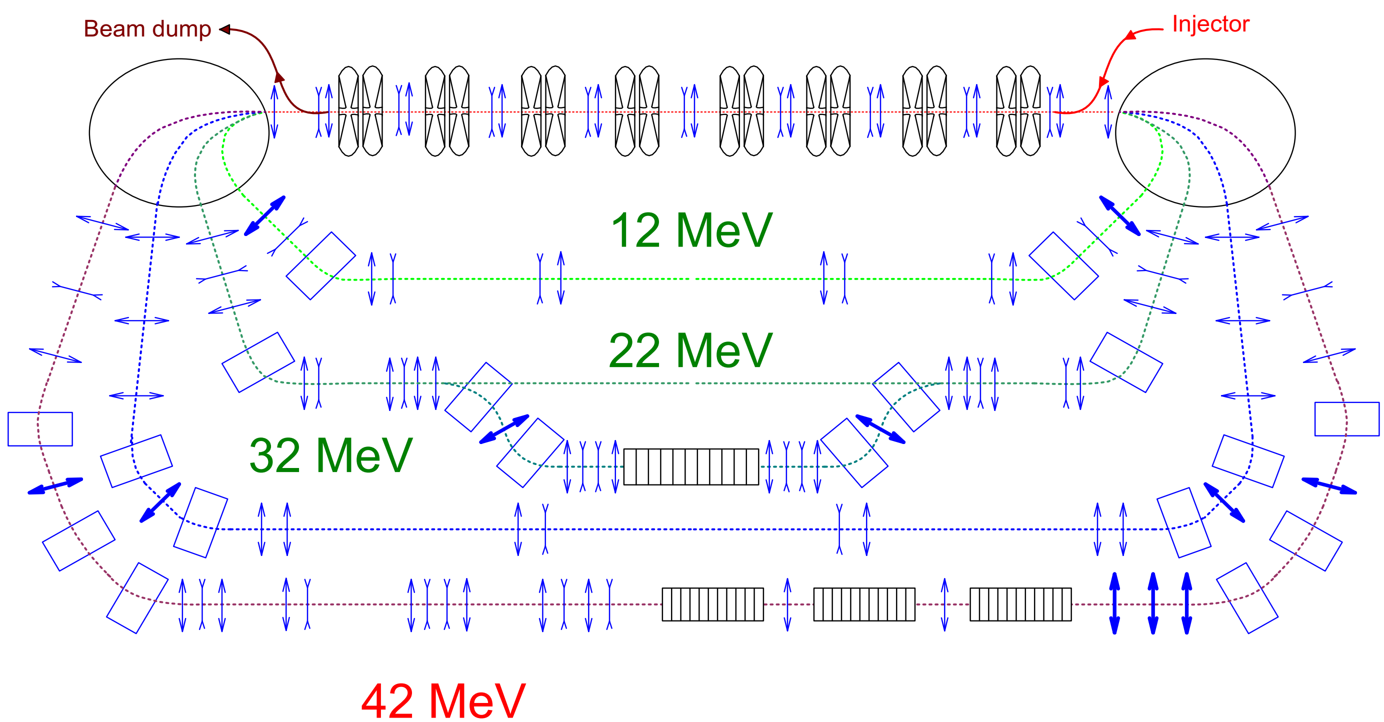
NovoFEL Accelerator Design and status



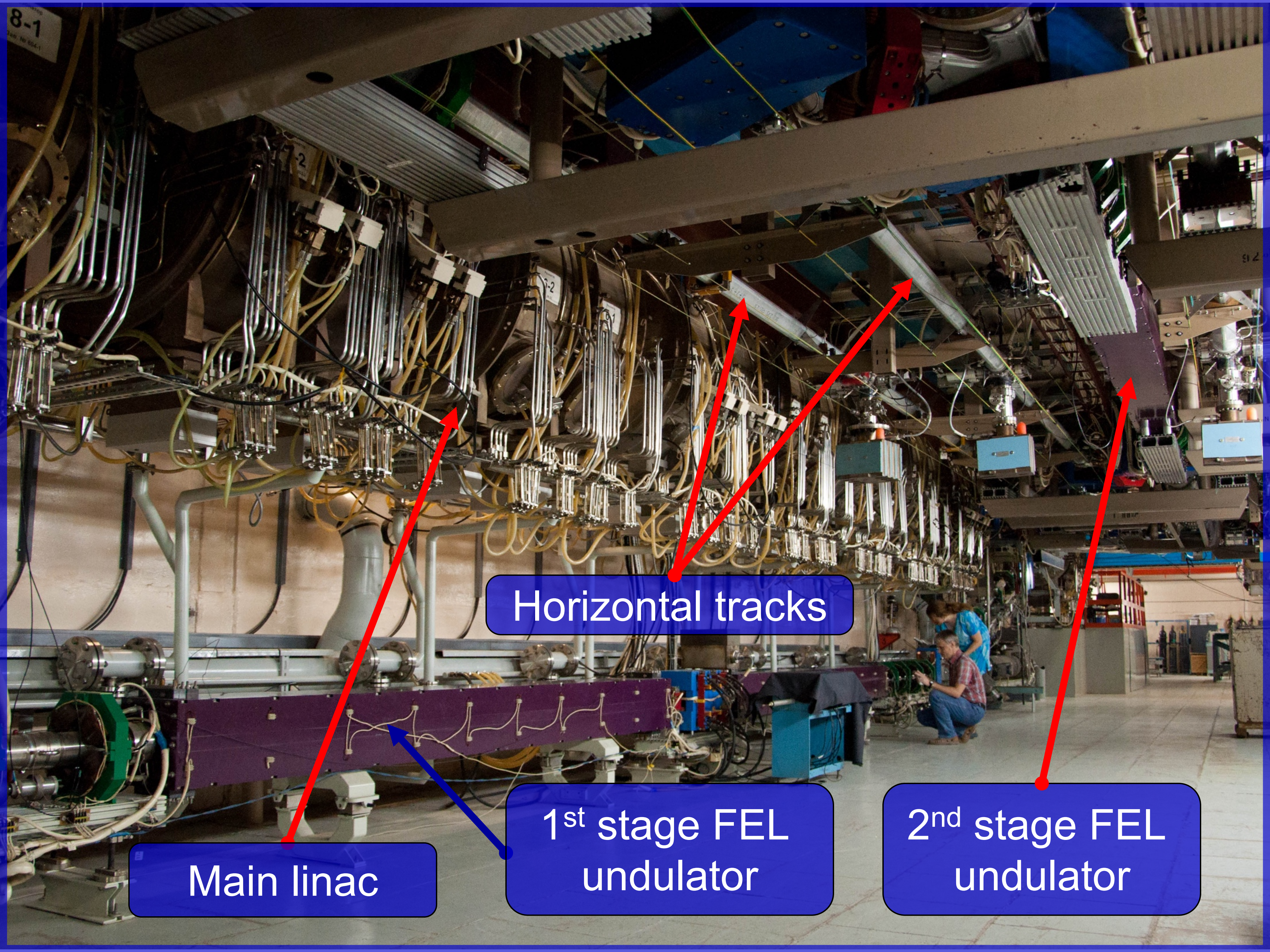
NovoFEL Accelerator Design and status



Second and third stages beamlines



(horizontal plane)


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


3rd stage FEL
undulator

Electron beam and radiation parameters (1)

	1^{st} E=12 MeV			2^{nd} E=22 MeV		3^{rd} E=42 MeV	
	lasing	working	max	lasing	max	lasing	max
Current, mA	5.5	11	30	7.0	7.5	3.0	5
Rep. rate, MHz	5.6	11.2	22.4	7.52	7.52	3.76	5.64
Q nQ	1	1	1.4	0.9		0.8	
P, W	300	500	1000	500		100	

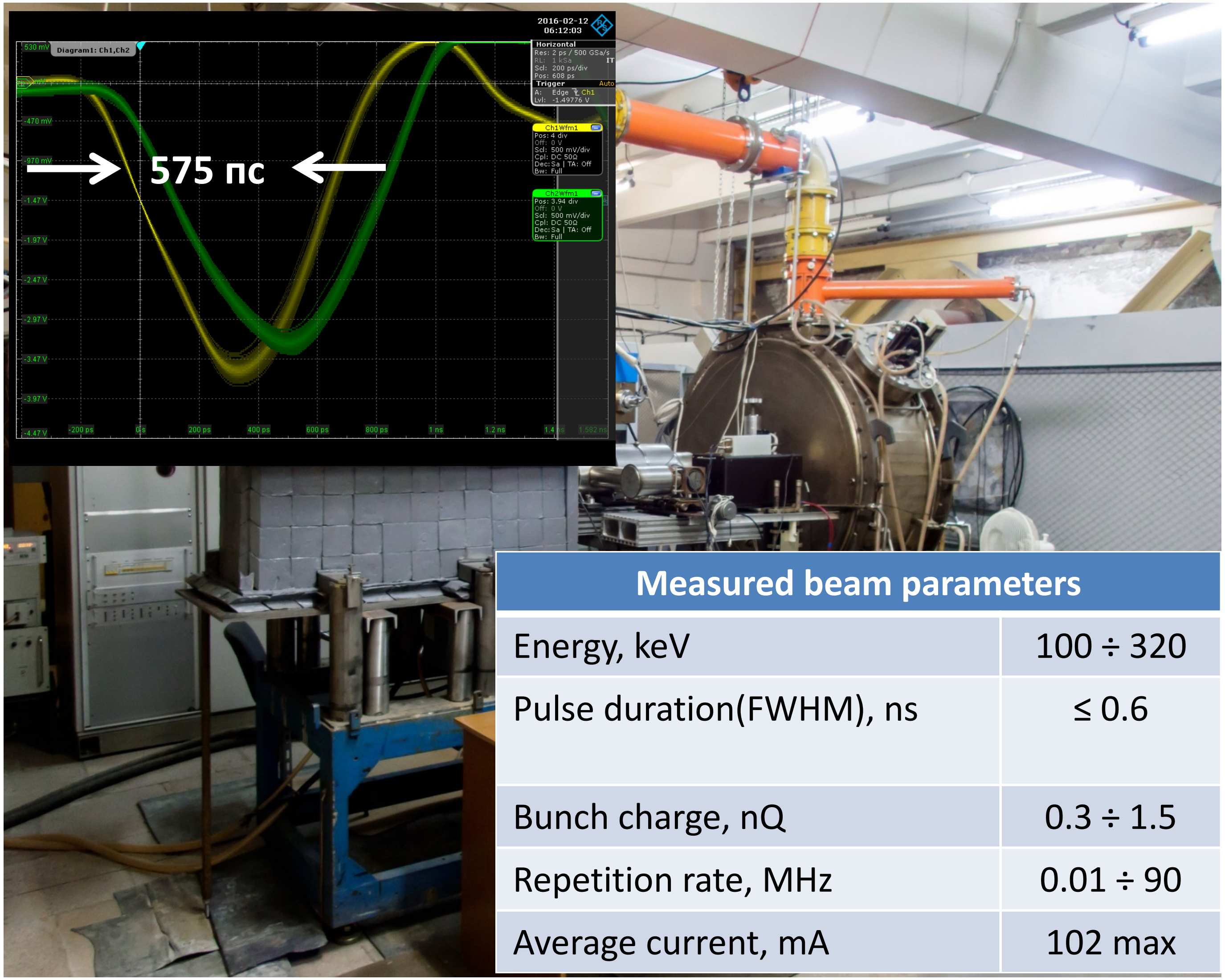
Electron beam and radiation parameters (2)

	1st	2nd	**3rd**	
Energy, MeV	12	22	**42**	46
Current, mA	30	7.5	**5**	50
Wavelength, μm	90-240	40-90	**8-11**	5-20
Radiation power, kW	0.5	0.5	**0.1**	5
Electron efficiency, %	0.6	0.3	**0.2**	0.5

4. Nearest and far future plans

- Install optical (SR) diagnostics of electron beam parameters
- Install undulator with variation of period
- Install RF gun
- Improve x-ray and neutron radiation shielding

RF Gun Test Setup

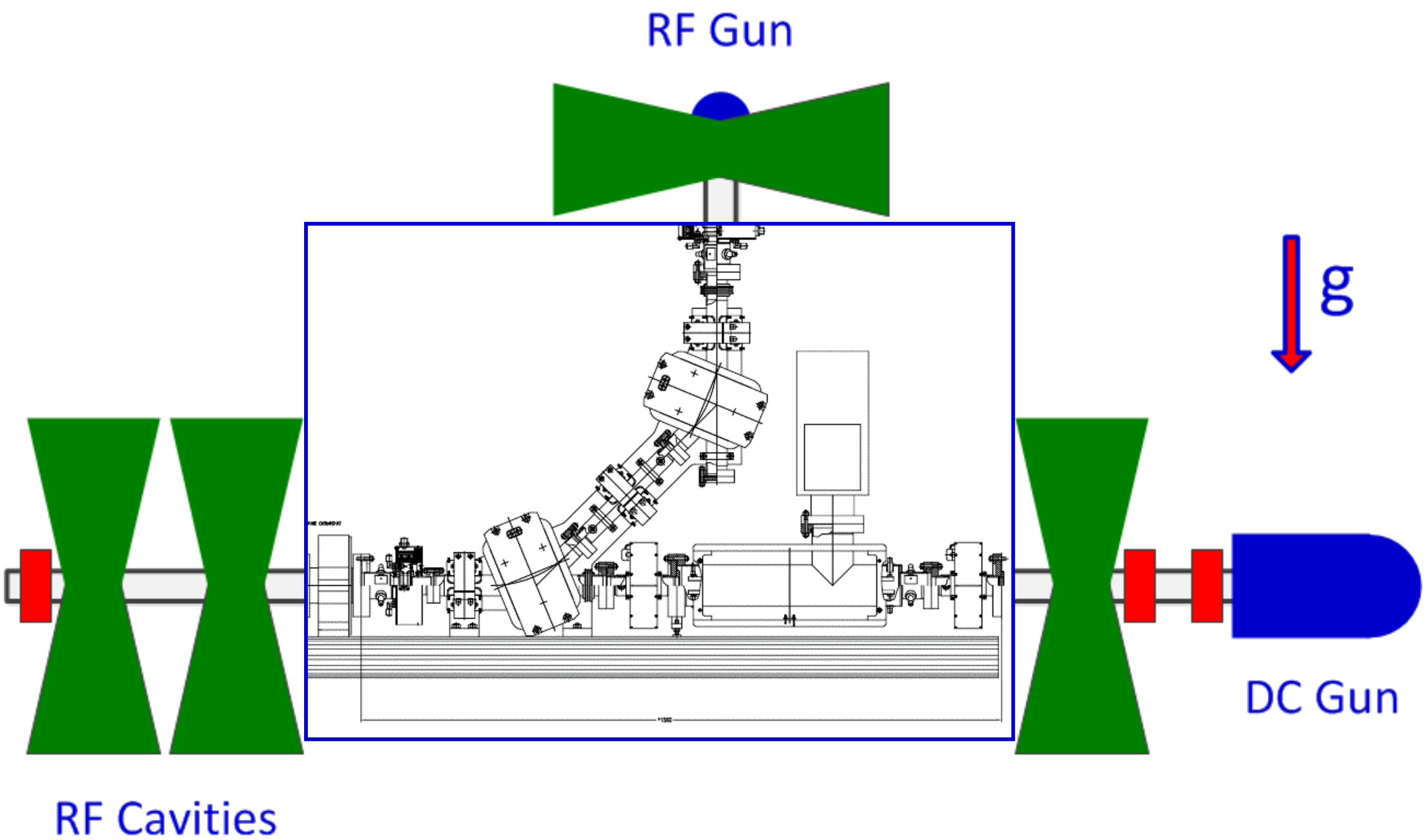


Measured beam parameters	
Energy, keV	100 ÷ 320
Pulse duration(FWHM), ns	≤ 0.6
Bunch charge, nQ	0.3 ÷ 1.5
Repetition rate, MHz	0.01 ÷ 90
Average current, mA	102 max

Vladimir N. Volkov CW 100 mA Electron RF Gun for Novosibirsk ERL FEL (RUPAC2016)

http://accelconf.web.cern.ch/AccelConf/rupac2016/papers/tucamh02.pdf

RF Gun Installation Layout



Undulator with variation of period

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

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

Variation of magnetic field

$\lambda_u = 12\ cm$

Electromagnetic undulator

K ~ 0…1.5

$\lambda_u = 6\ cm$

Variable gap undulator

K ~ 0.4…2.5

Variation of beam energy

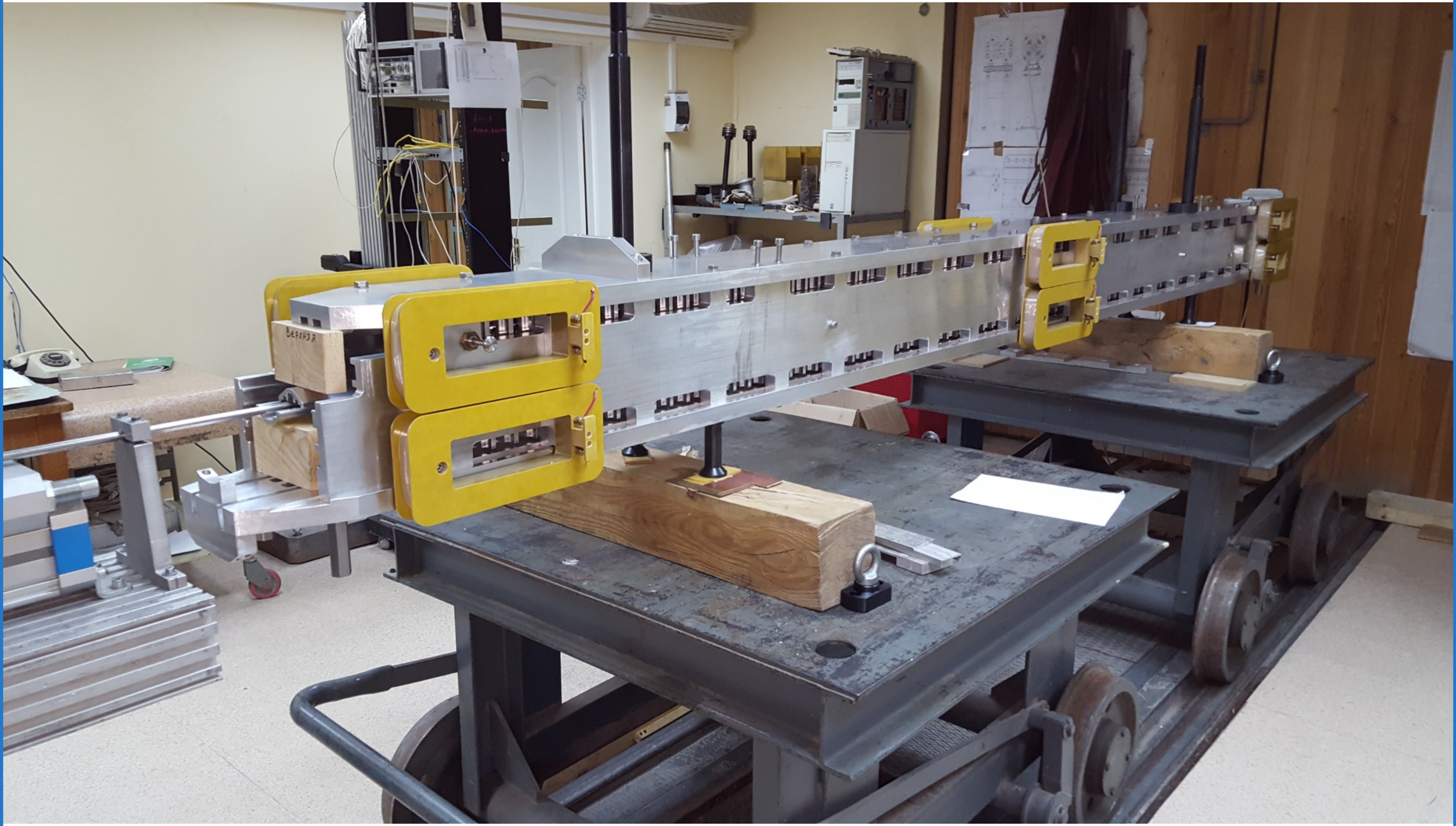
E1 ~ 10…13 MeV
E2 ~ 20…24 MeV
E3 ~ 40…46 MeV

Variation of undulator period (N. Vinokurov)

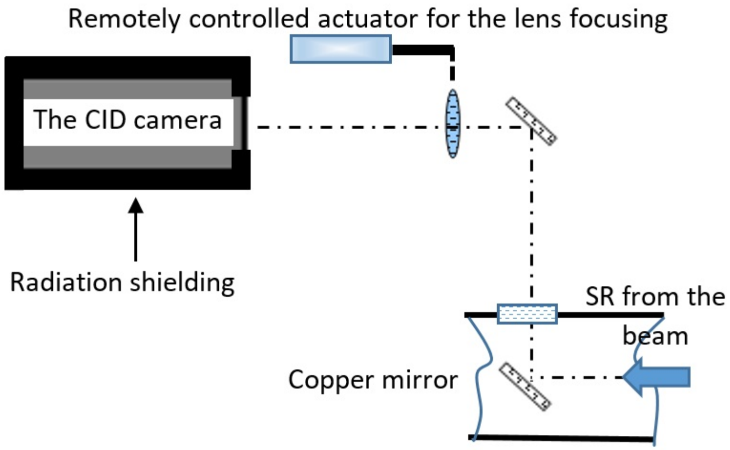
K ~ 0.42…1.79 $\qquad \lambda_u \sim 4.8 \ldots 9.6\ cm$

Variable period undulator

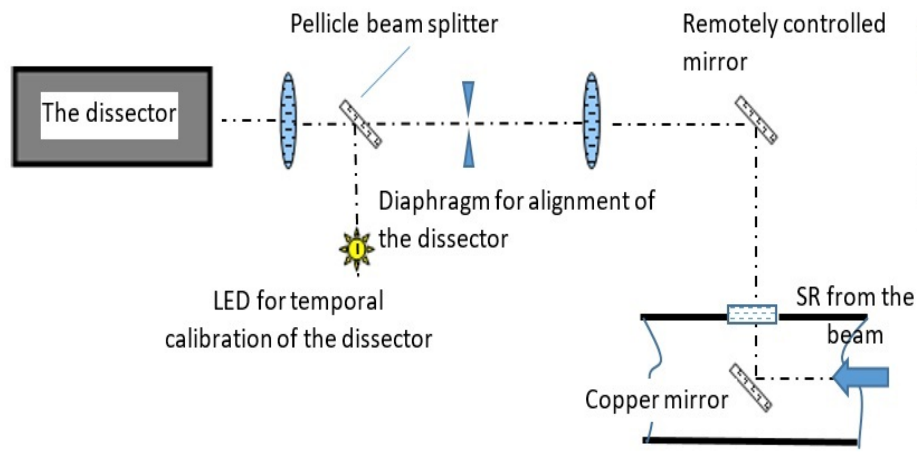
Variable period undulator at magnetic measurements



Optical diagnostic of electron beam parameters

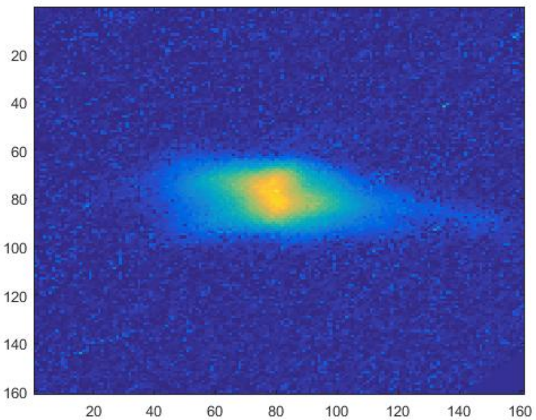


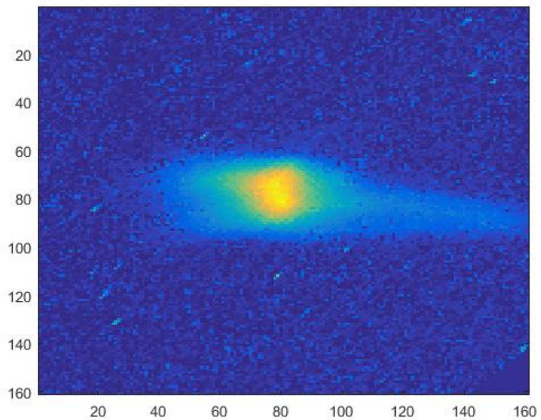
Layout of the diagnostics for acquisition of the transverse profile of the beam

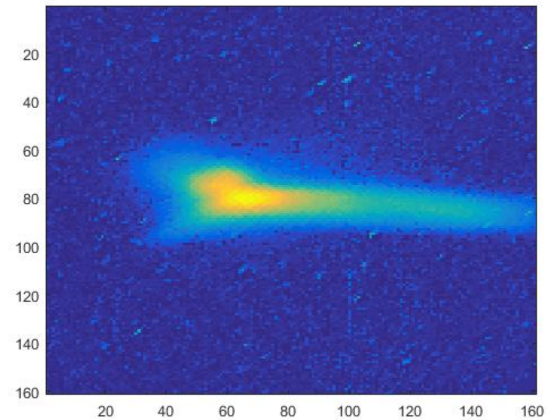


Layout of the diagnostics for acquisition of the longitudinal profile of the beam

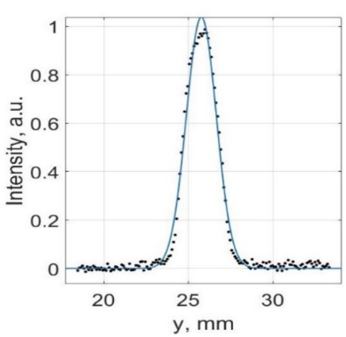
Optical diagnostic of electron beam parameters



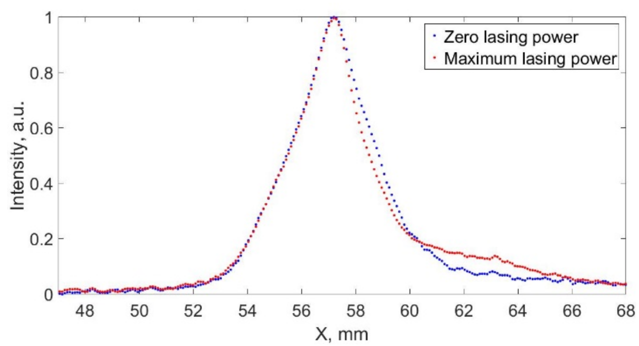




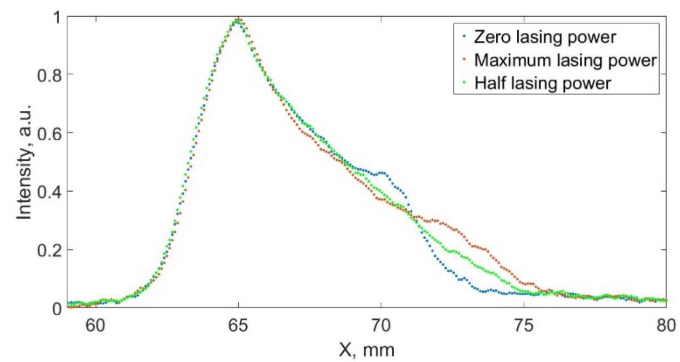
Examples of acquired transverse beam profiles



Vertical beam profile



Horizontal profiles acquired during the 2nd run



Horizontal profiles acquired during the 1st run

5. Perspective of ERL with SC cavities at Budker INP

5.1 MARS –Multiturn Accelerator Recuperator Source

- At SRI-97 conference for realization of a fully spatially coherent X-ray source was proposed by Kulipanov G., Skrinsky A., Vinokurov N. using of accelerators-recirculators with energy recuperation (SRI-97)

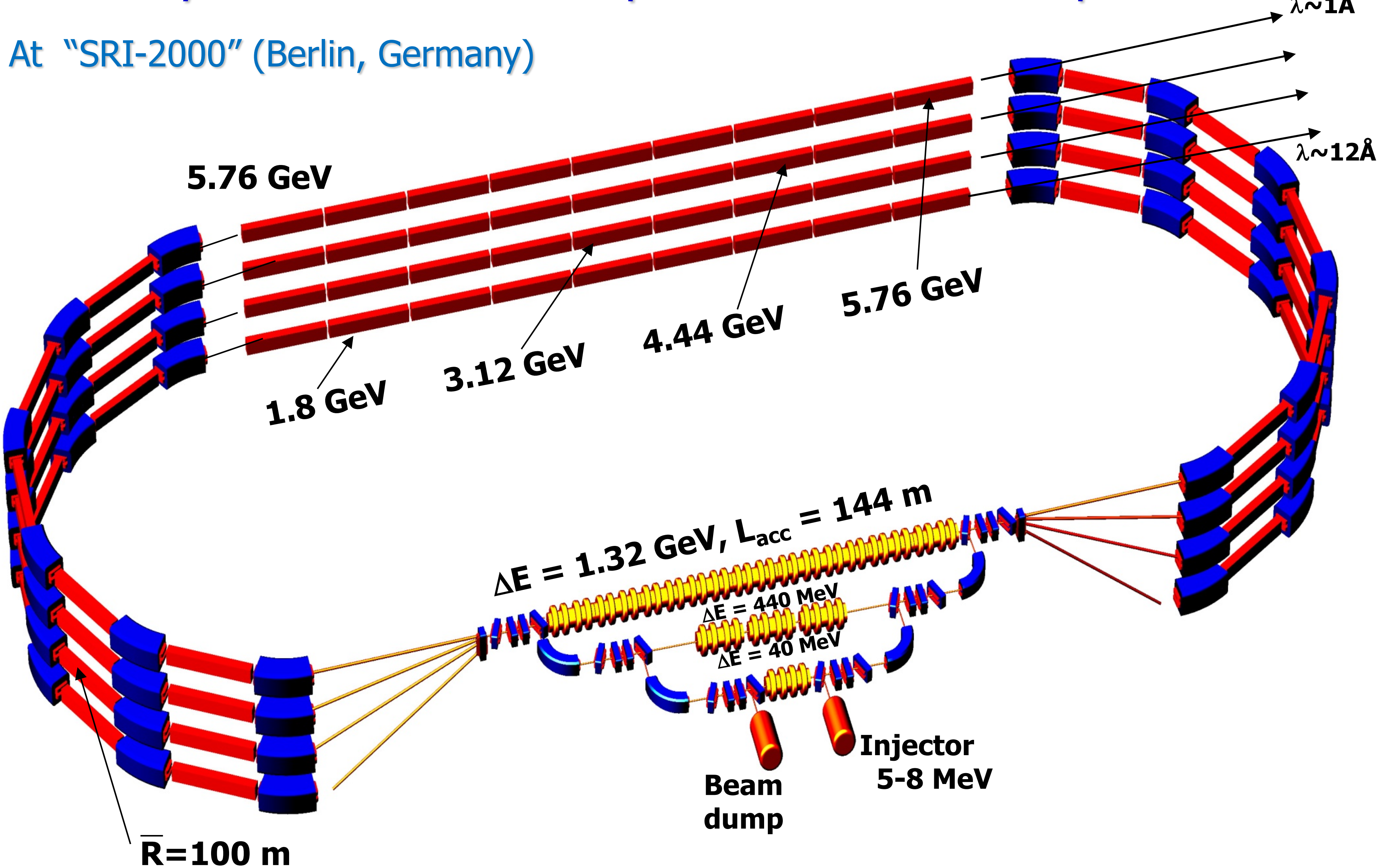
See: [1] *MARS - recirculator-based diffraction limited X-ray source. // Budker INP preprint No 97-103 (1997);*

[2] *Kulipanov G., Skrinsky A., Vinokurov N. Synchorton light sources and recent development of accelerator technology. // J. of Synchrotron Radiation –1998 V.5 pt.3 P.176*).

- After SRI-2000, the idea of using the accelerators-recuperators for creation of 4th generation of SR sources has been actively discussed at Jefferson Lab, Cornell Uni., KEK, BNL, LBL, Erlangen Uni., Daresbury Lab.

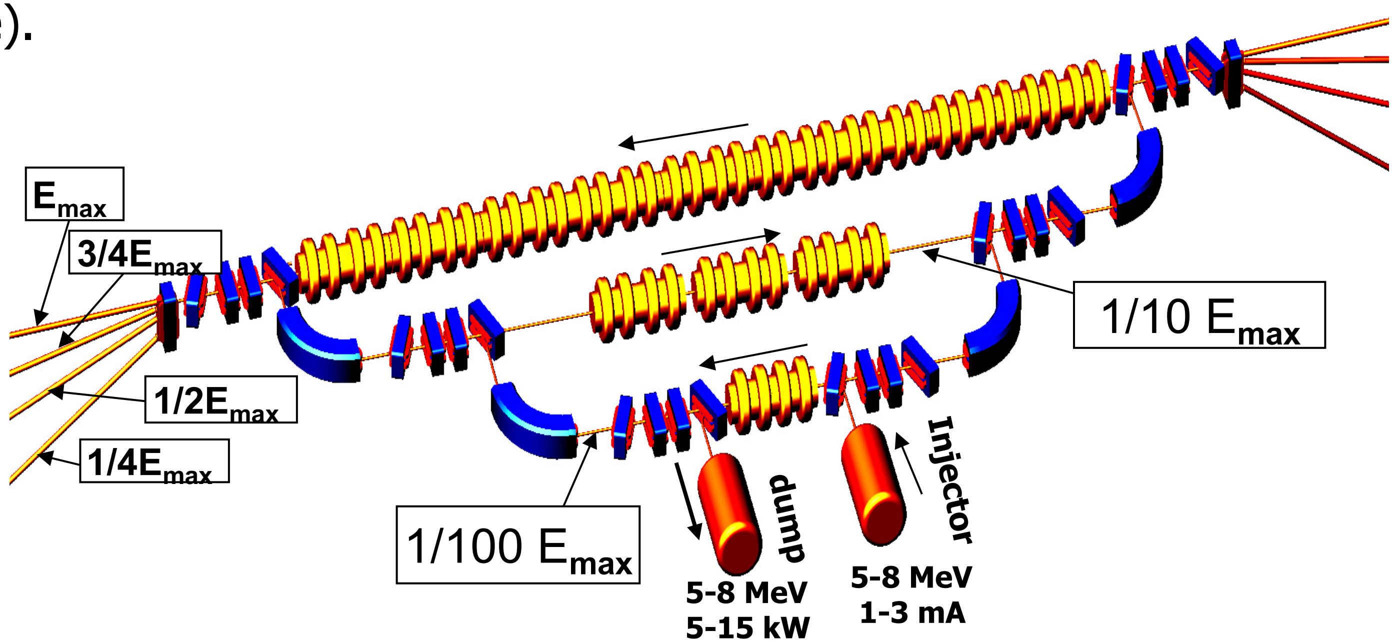
Layout of 5.7 GeV four-pass accelerator-recuperator

At "SRI-2000" (Berlin, Germany)



Cascade injection – effective solution of important problems of ERL

- Decrease in radiation hazard and limitation of induced radioactivity due to low energy of electrons at dump (5-8 MeV).
- Reduction in the cost of construction and RF power system for the injector
- Simplification the problem of focusing particles of different energies travelling simultaneously in the accelerating structure, because the cascade scheme enables injection of electrons into all accelerating structures with energies of no less than Emax/10 (Emax is the maximum energy of electrons traveling in the accelerating structure).

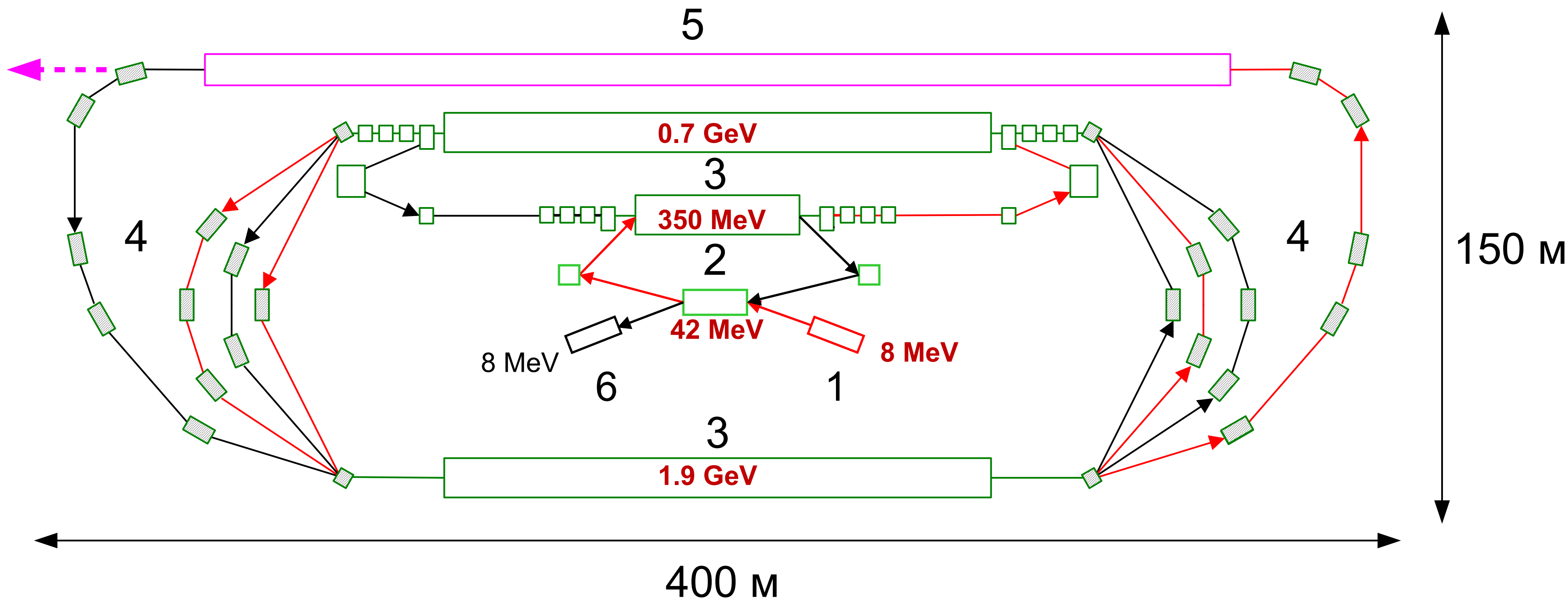


First linac has 5-8 MeV energy and does not use energy recovery.
For booster linacs (30 MeV and 330 MeV energy gain) energy recovery is used.

5.2. ERL with separated tracks for accelerated and decelerated beams

It was suggested at ERL-2011 (G. Kulipanov, Ya. Getmanov, O. Shevchenko, A. Skrinsky, A. Tribendis, N. Vinokurov, V. Volkov, “Multiturn ERL X-ray Source(MARS) Feasibility study,” ERL-2011, October 2011, KEK) to turn to an accelerator-recuperator scheme with two acceleration sections, similar to the scheme of the US accelerator CEBAF. Such schemes are considered below.

The simplest scheme of ERL (for understanding) with separated tracks



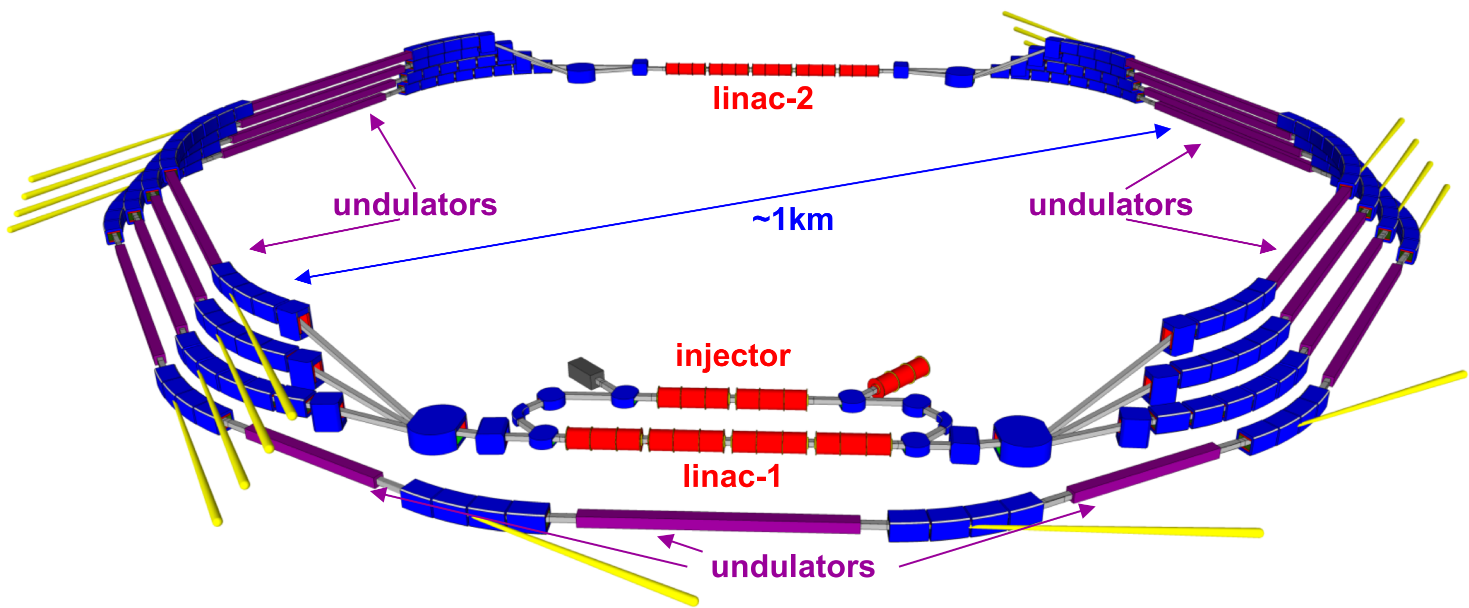
1 – injector, 2 – preliminary accelerating system, 3 – main accelerating RF structure, 4 – magnets, 5 – undulator, 6 – dump.

red arrows – accelerating bunch

black arrows – used decelerating bunch

Full Spatial Coherent multiturn ERL X-Ray Source MARS

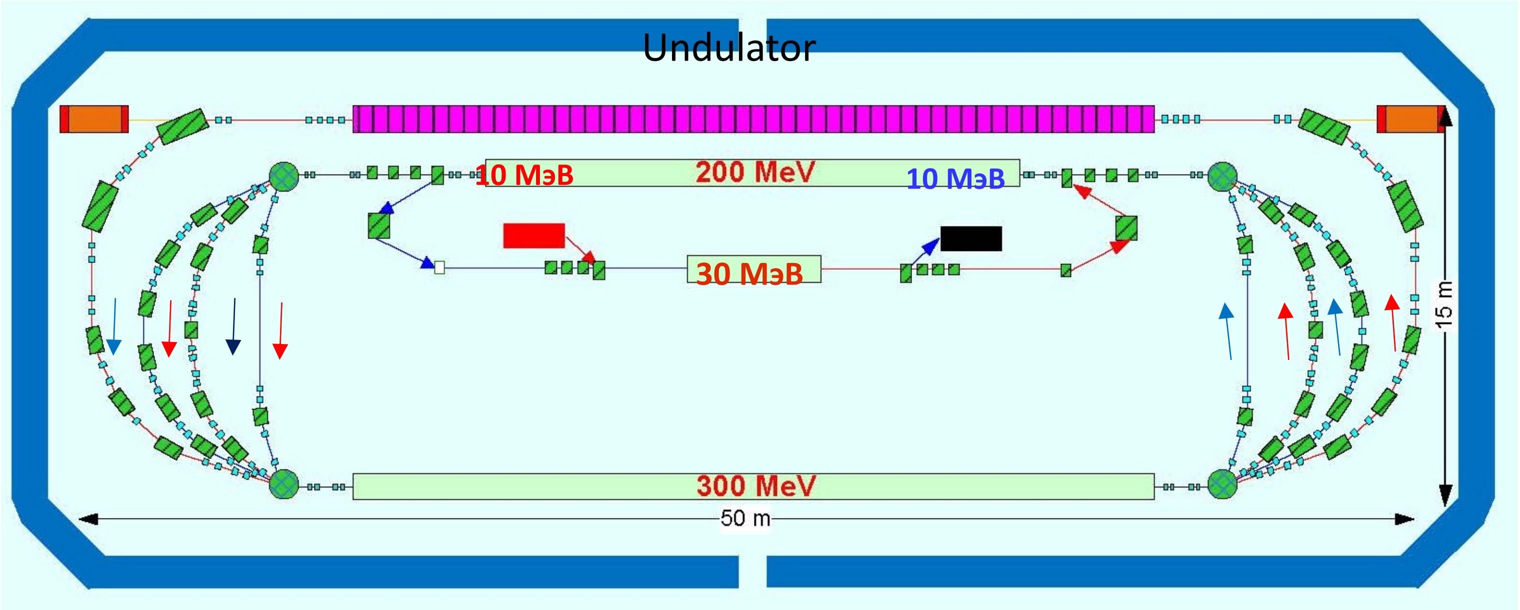
MULTIPASS ACCELERATOR-RECUPERATORS SOURCE



♦Energy range	5.6, 3.8, 3, 1.2 GeV	♦Bunch length	0.1 – 1 ps
♦Average current	10 mA	♦7 undulators for	5.6 GeV
♦Peak current	10 A	♦4 undulators for	3.8 GeV
♦Normalized Emittance	10^{-7} m·rad	♦4 undulators for	3 GeV
♦Bunch charge	10^{-11} Cl	♦4 undulators for	1.2 GeV

Project of FEL for EUV Lithography

(compact 13.5-nm free-electron laser for extreme ultraviolet lithography,
Y. Socol, G.N. Kulipanov, A.N. Matveenko, O.A. Shevchenko, and N.A. Vinokurov,
Phys. Rev. ST AB, Vol. 14, No 4. – 040702-1 – 040702-7, 2011).



λ	13.5 nm
E_e	1 GeV
P_{av}	10 kW
I	10-20 mA
λ_u	3 cm

accelerated beam

decelerated beam

Thank you for your attention!