NOVOSIBIRSK FOUR-ORBIT ERL WITH THREE FELS

Presented by N. A. Vinokurov
Budker Institute of Nuclear Physics SB RAS
Novosibirsk, Russia

Authors

N.A. Vinokurov, V.S. Arbuzov, K.N. Chernov,
I.V. Davidyuk, O.I. Deichuly, E.N. Dementyev,
B.A. Dovzhenko, Ya.V. Getmanov, Ya.I. Gorbachev,
B.A. Knyazev, E.I. Kolobanov, A.A. Kondakov,
V.R. Kozak, E.V. Kozyrev, S.A. Krutikhin, V.V. Kubarev,
G.N. Kulipanov, E.A. Kuper, I.V. Kuptsov, G.Ya. Kurkin,
L.E. Medvedev, S.V. Motygin, V.K. Ovchar, V N. Osipov,
V.M. Petrov, A.M. Pilan, V.M. Popik, V.V. Repkov,
T.V. Salikova, M.A. Scheglov, I.K. Sedlyarov,
S.S. Serednyakov, O.A. Shevchenko, A.N. Skrinsky,
S.V. Tararyshkin, A.G. Tribendis, V.G. Tcheskidov,
P.D. Vobly, V.N. Volkov

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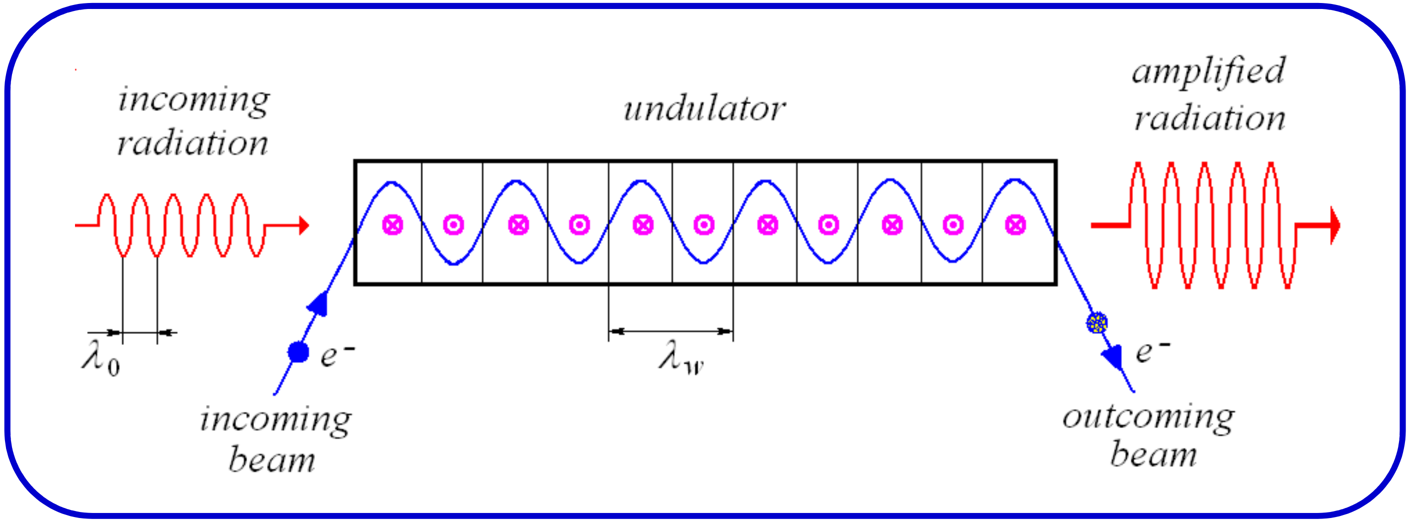
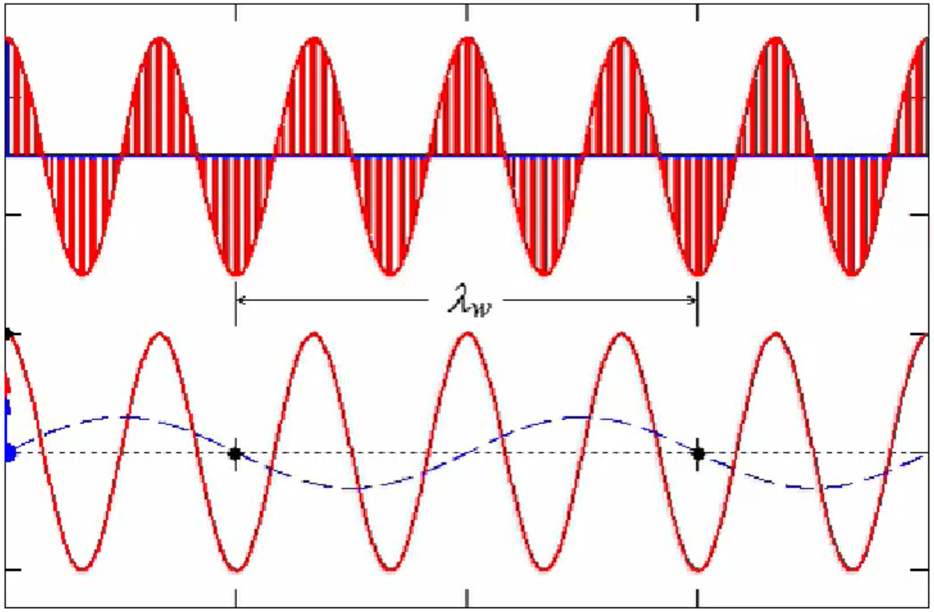
Outline

- Brief reminding on the FEL operation principle
- The NovoFEL accelerator design and operation
- NovoFEL as three FELs based source of radiation
- Nearest plans

FEL principle of operation





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

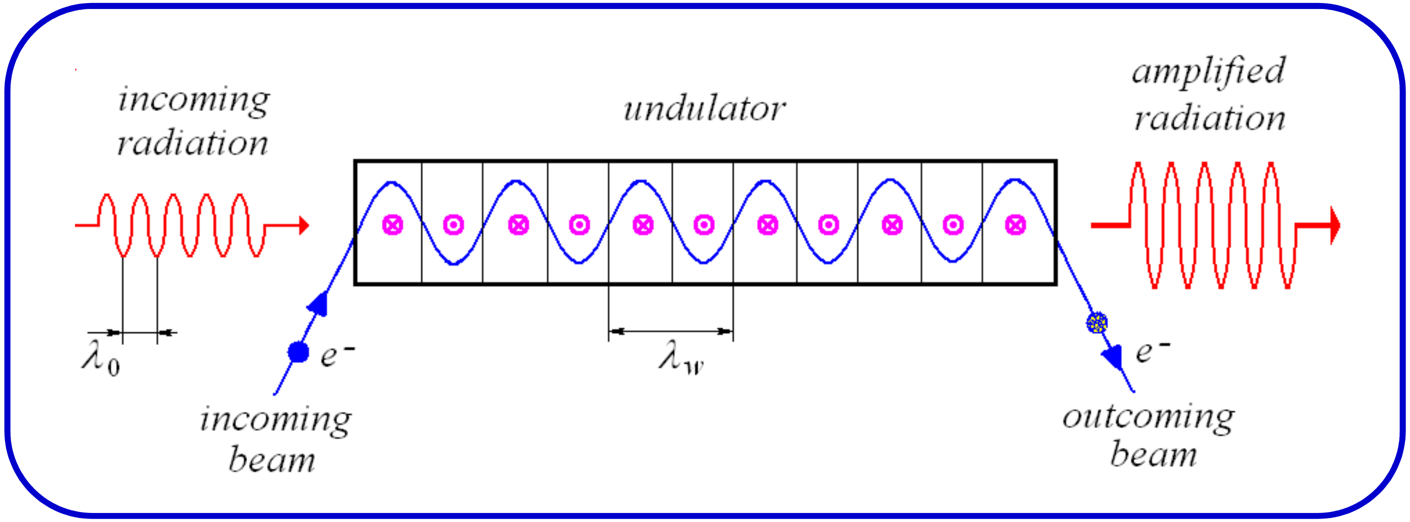
synchronisme condition

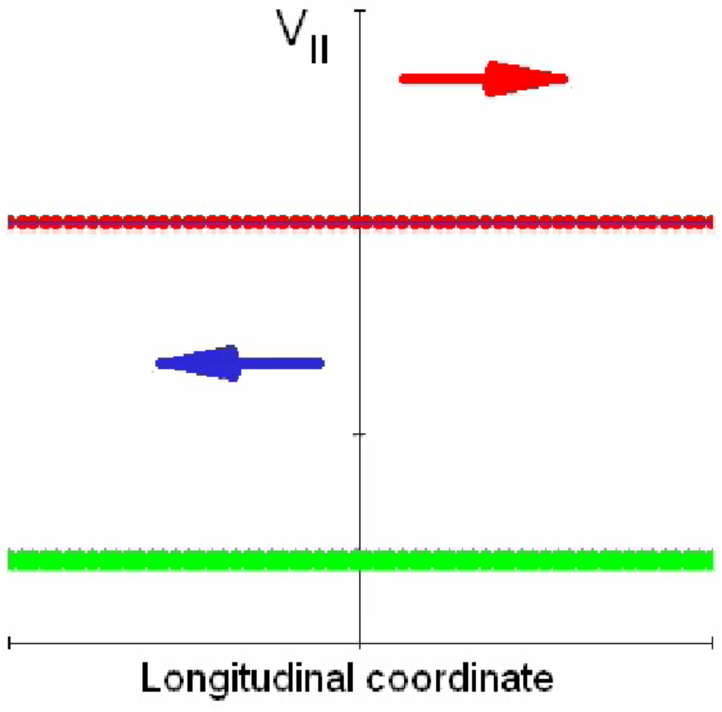
which is necessary for the

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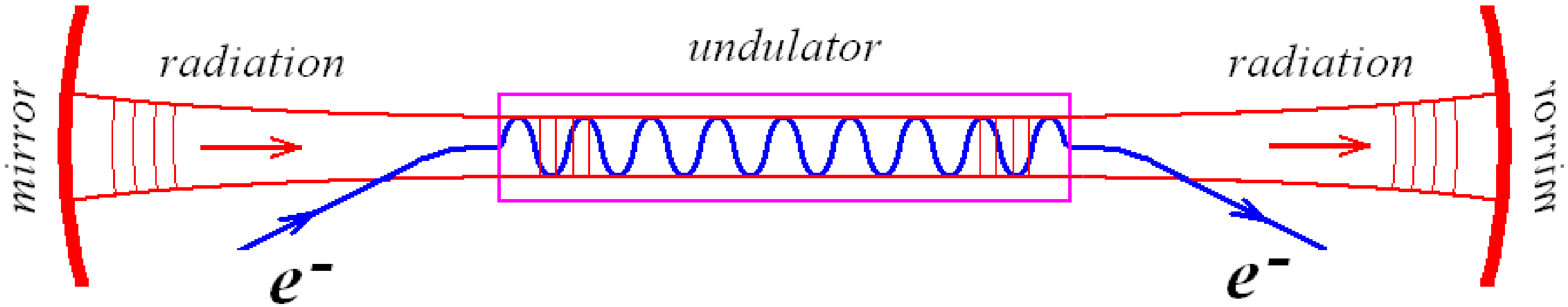
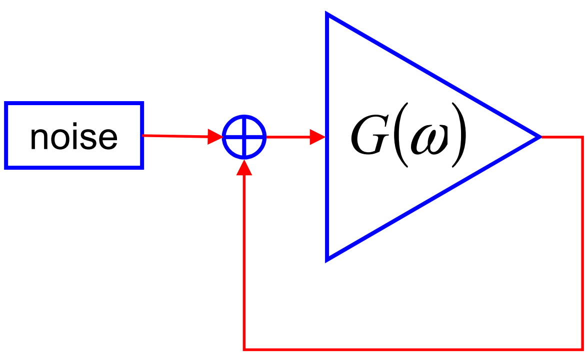
$$\left\langle \frac{d\gamma}{dz} \right\rangle = \frac{e}{mc^3}\left\langle \mathcal{E}_x V_x \right\rangle$$

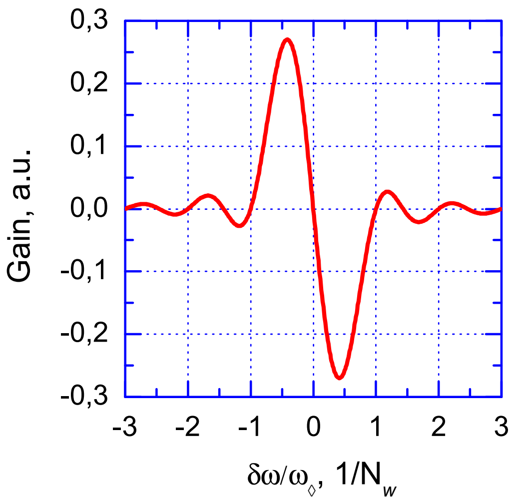
FEL principle of operation

FEL oscillator



Equivalent scheme





Energy recovery

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

- Energy recovery:

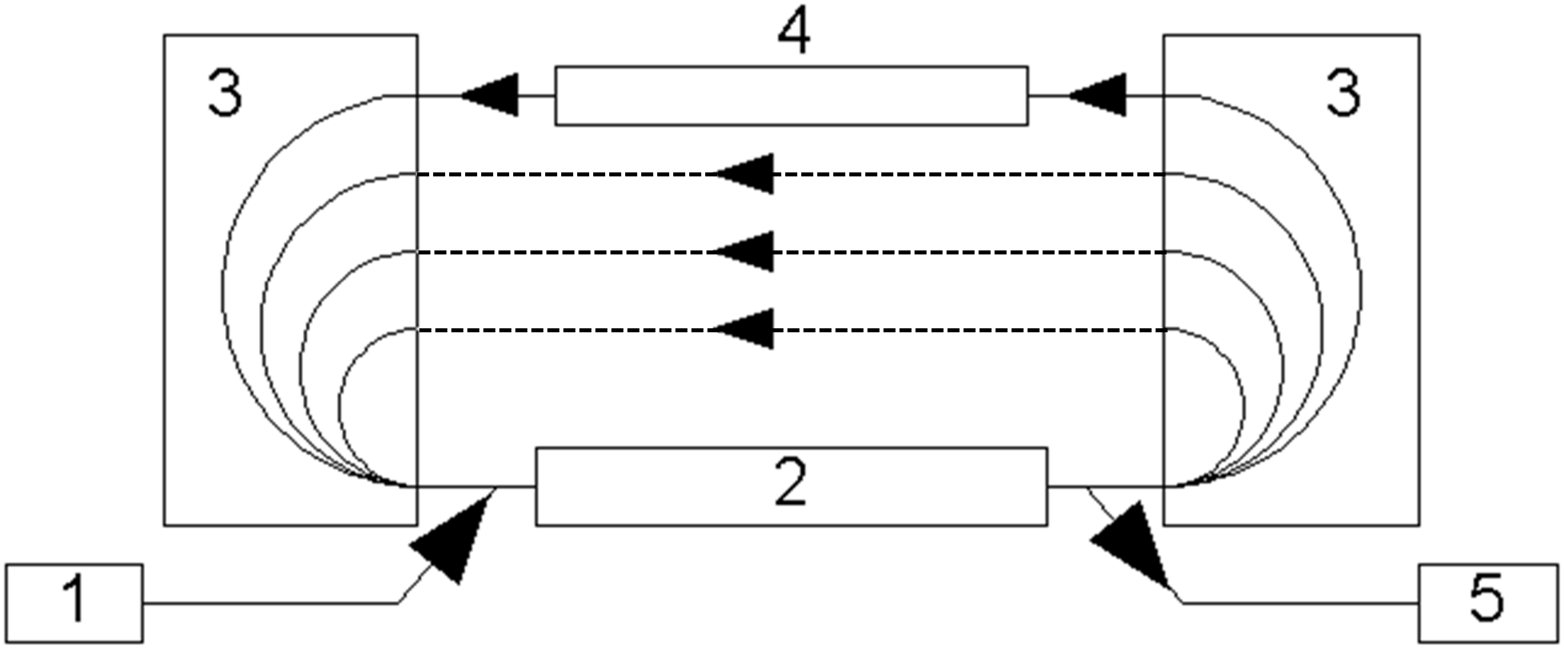
- decreases radiation hazard and

- makes possible operation at high average current.

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

NovoFEL Accelerator Design

Energy Recovery Linac



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

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.

Disadvantages:

low accelerating rate and high power consumption.

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

Advantage: high beam current.

Disadvantage: high RF power consumption.

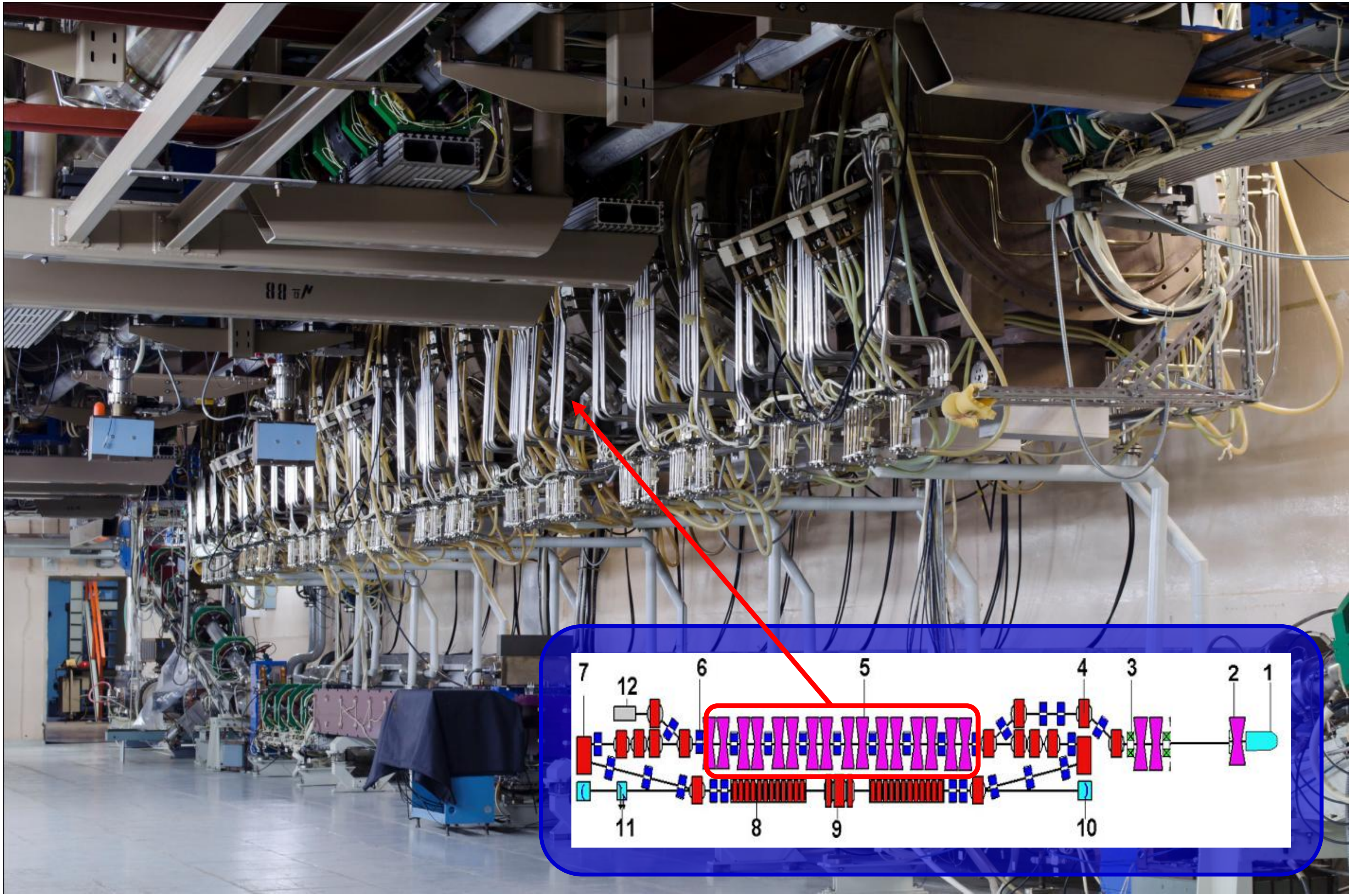
Indeed, the characteristic stability parameter is

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

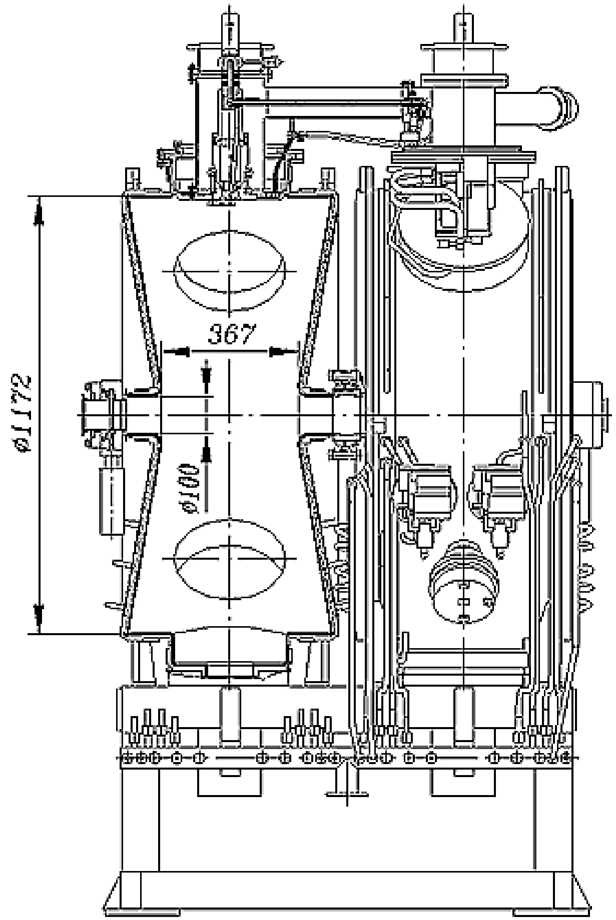
Therefore, the "critical" beam current is

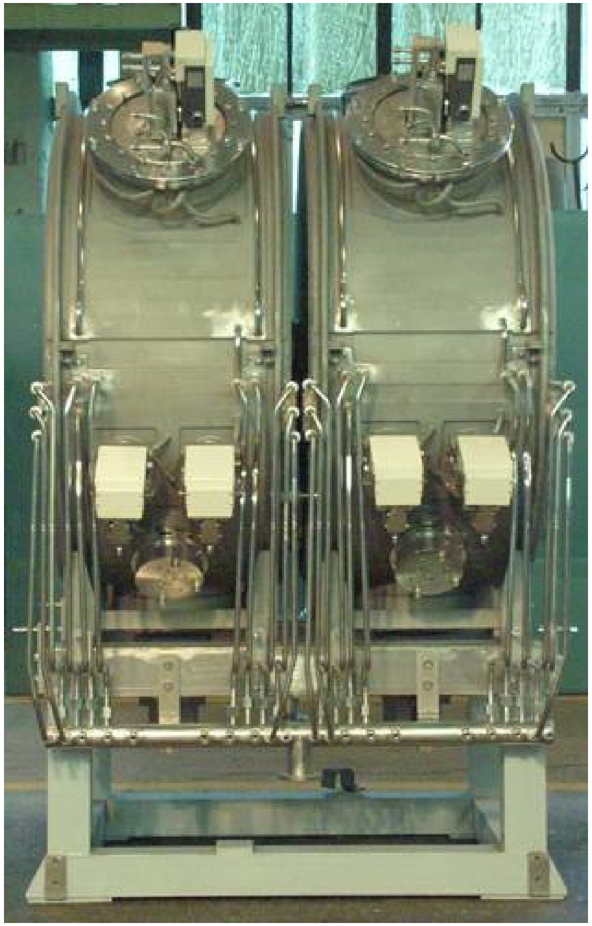
$$I_{beam\,cr} = \frac{U}{2R} = \frac{U}{2Q(R/Q)} \sim \frac{10\text{kA}}{Q}$$

Main Linac

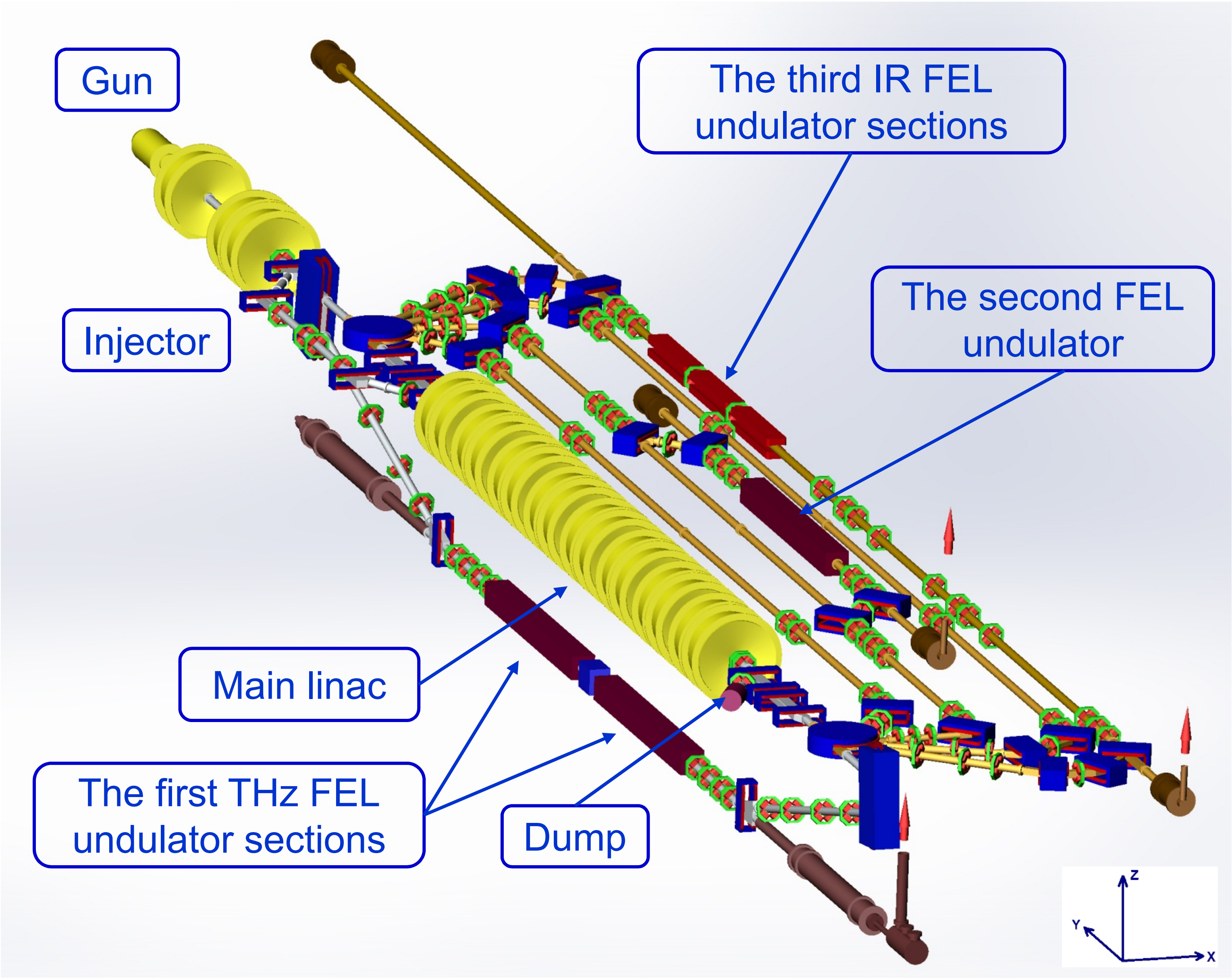


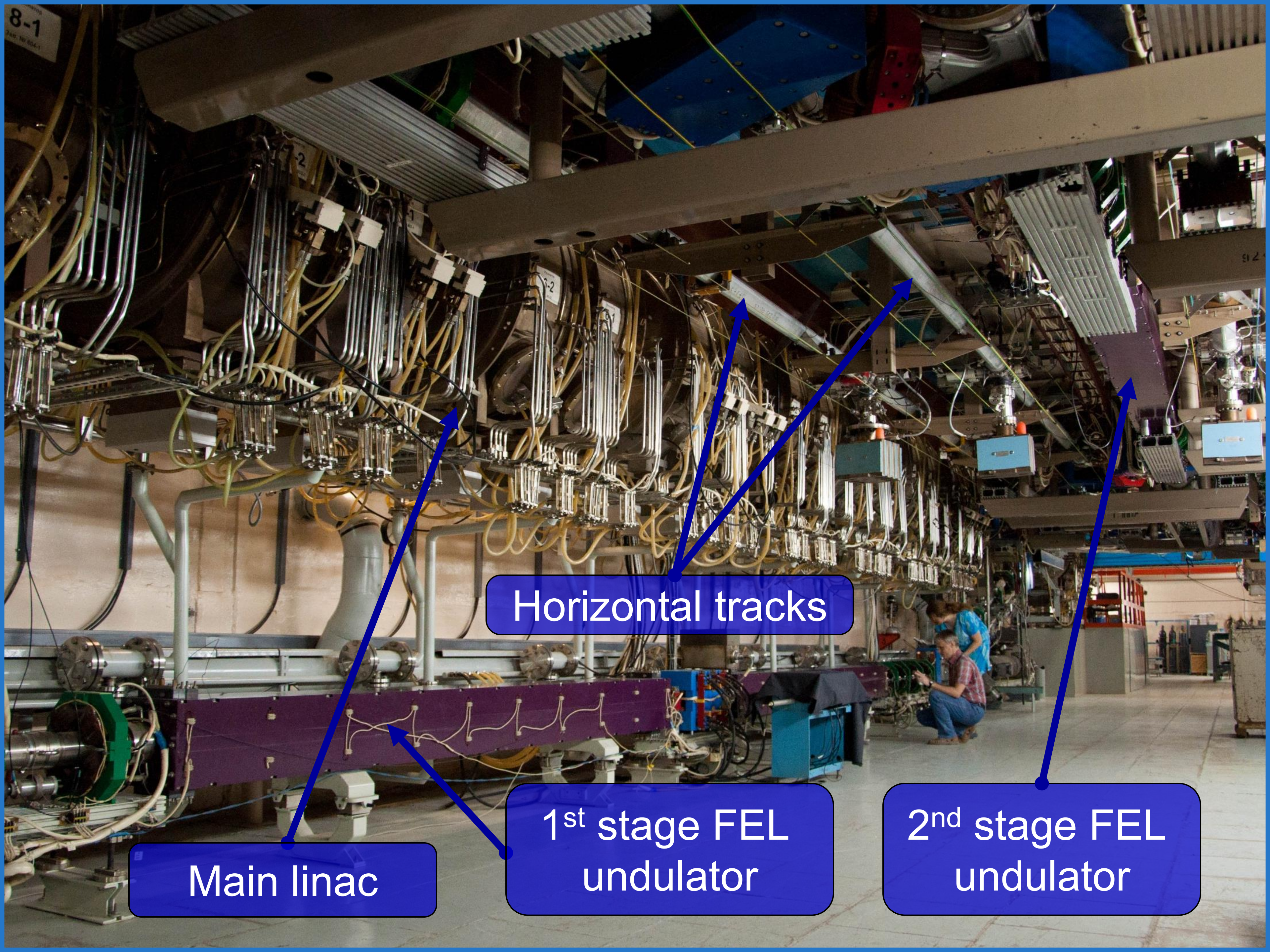
Main Linac





NovoFEL Accelerator Design



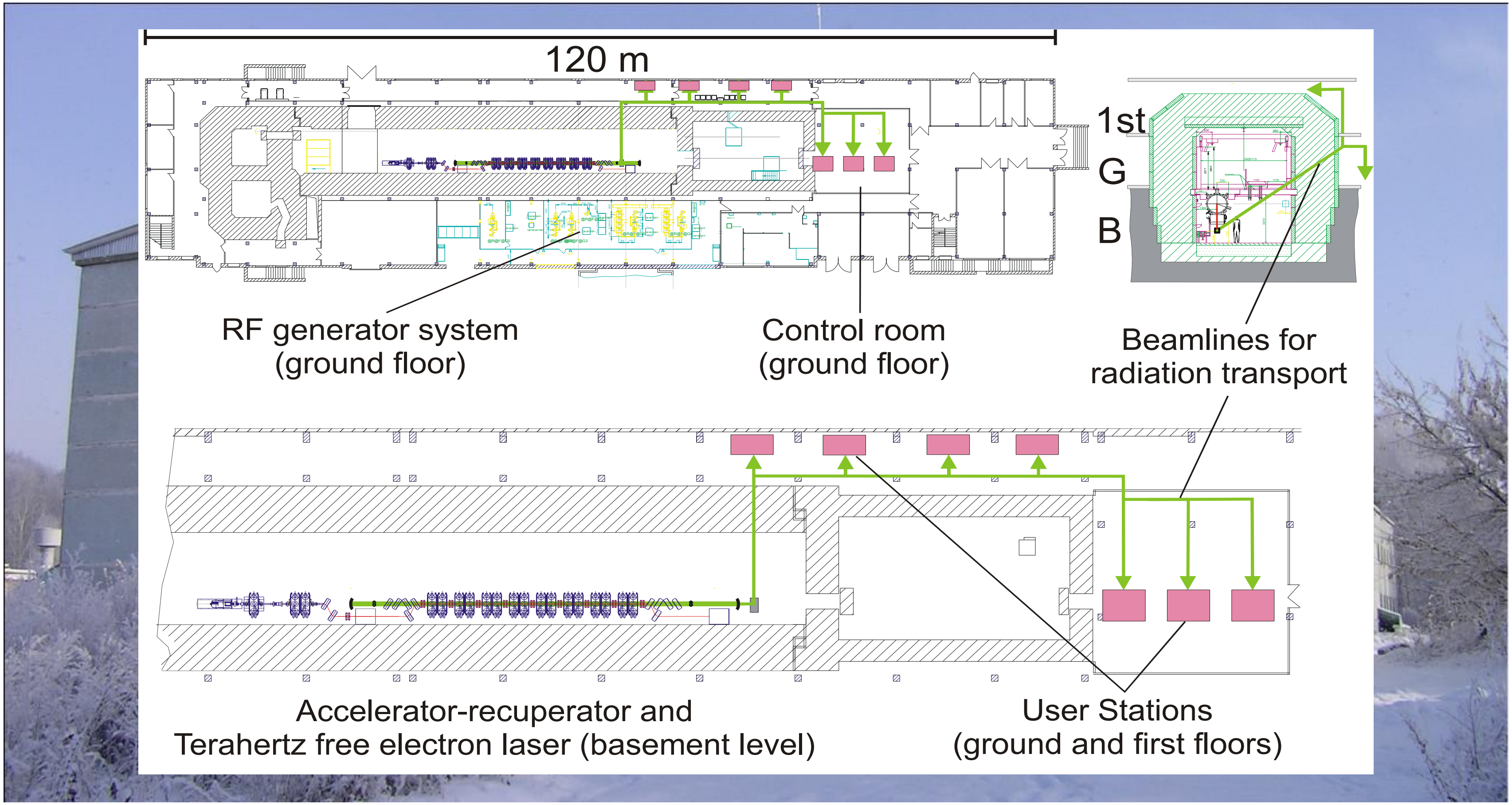


Horizontal tracks
1st stage FEL undulator
2nd stage FEL undulator
Main linac

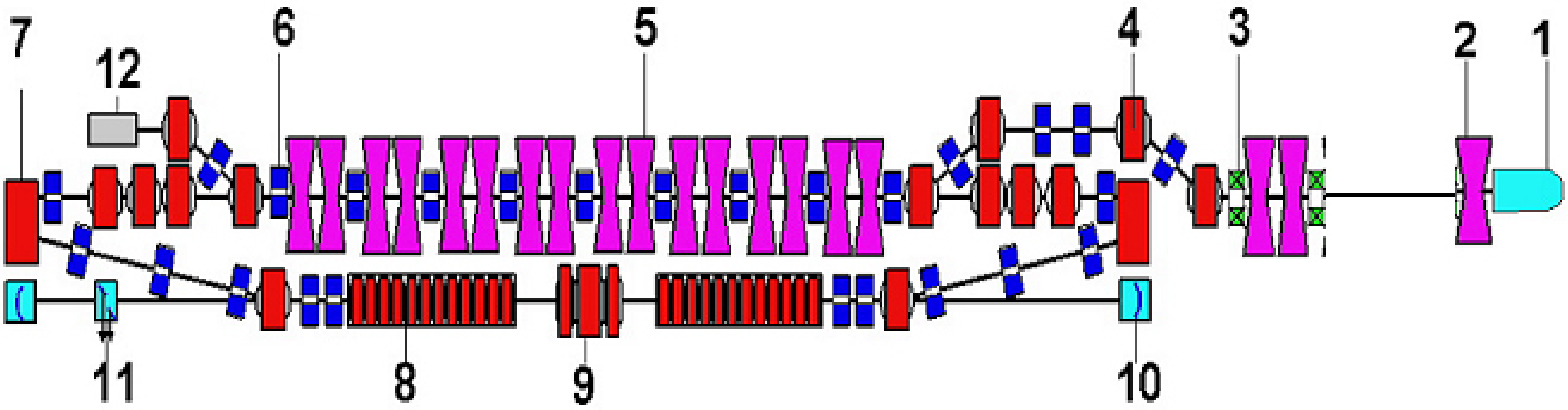

3rd stage FEL
undulator

Siberian Center of Photochemical Research

Siberian Center of Photochemical Research



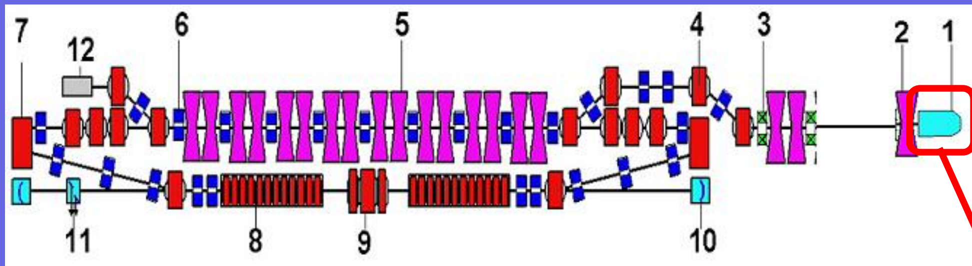
Layout of Injector, Main Linac and Vertical Beamline (the First ERL)

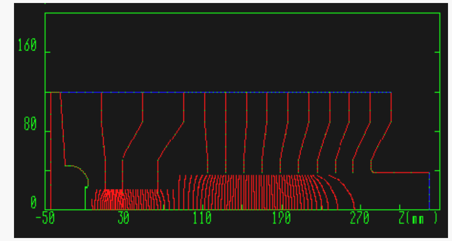


1 – electron gun
2 – bunching cavity
3 – focusing solenoids
4 – merger
5 – main linac
6 – focusing quadrupoles

7 – magnetic mirror
8 – undulator
9 – phase shifter
10 – optical cavity
11 – calorimeter
12 – beam dump

Electrostatic Gun



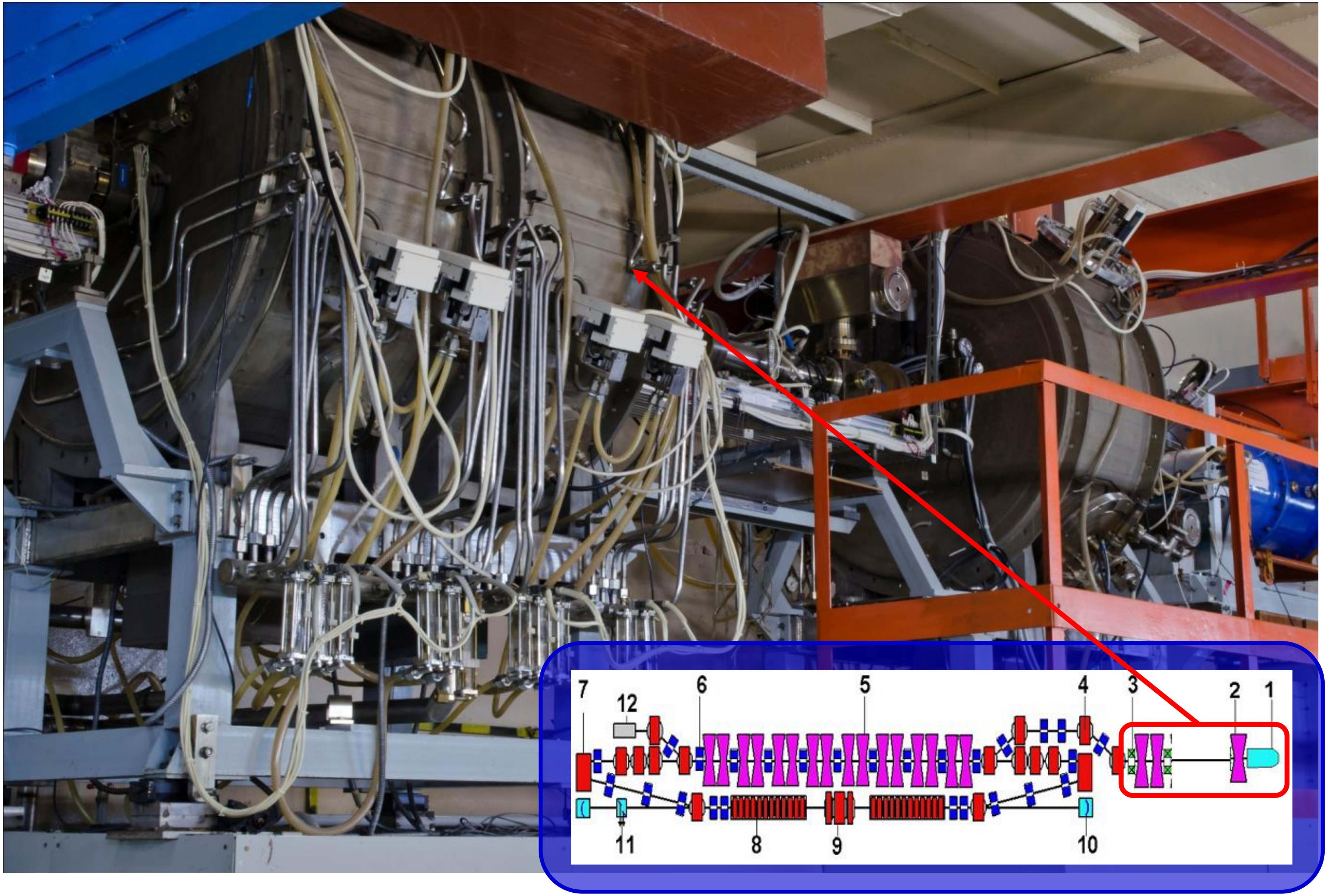


Power supply:

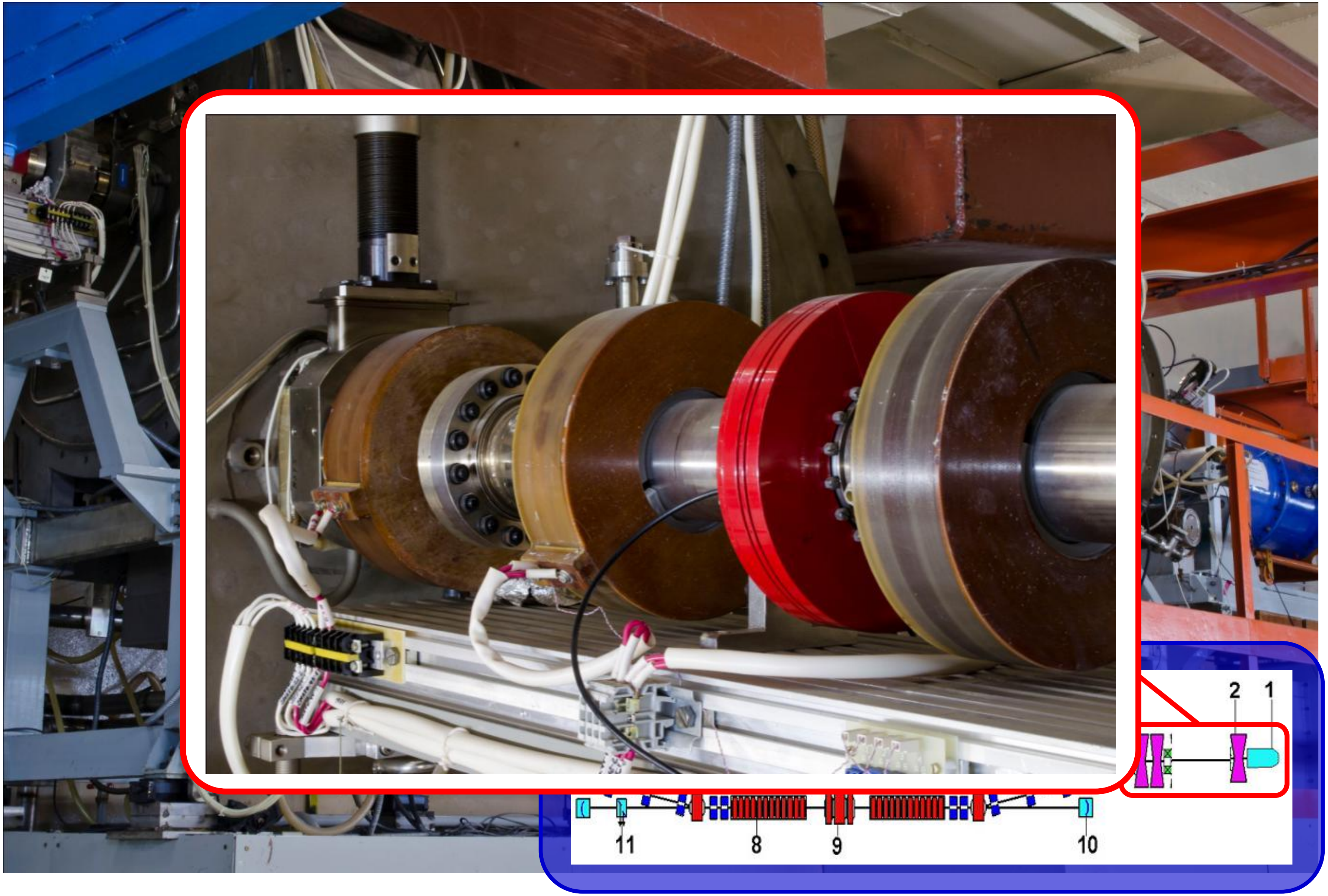
U_{max} = 300 kV

I_{max} = 50 mA

Injector

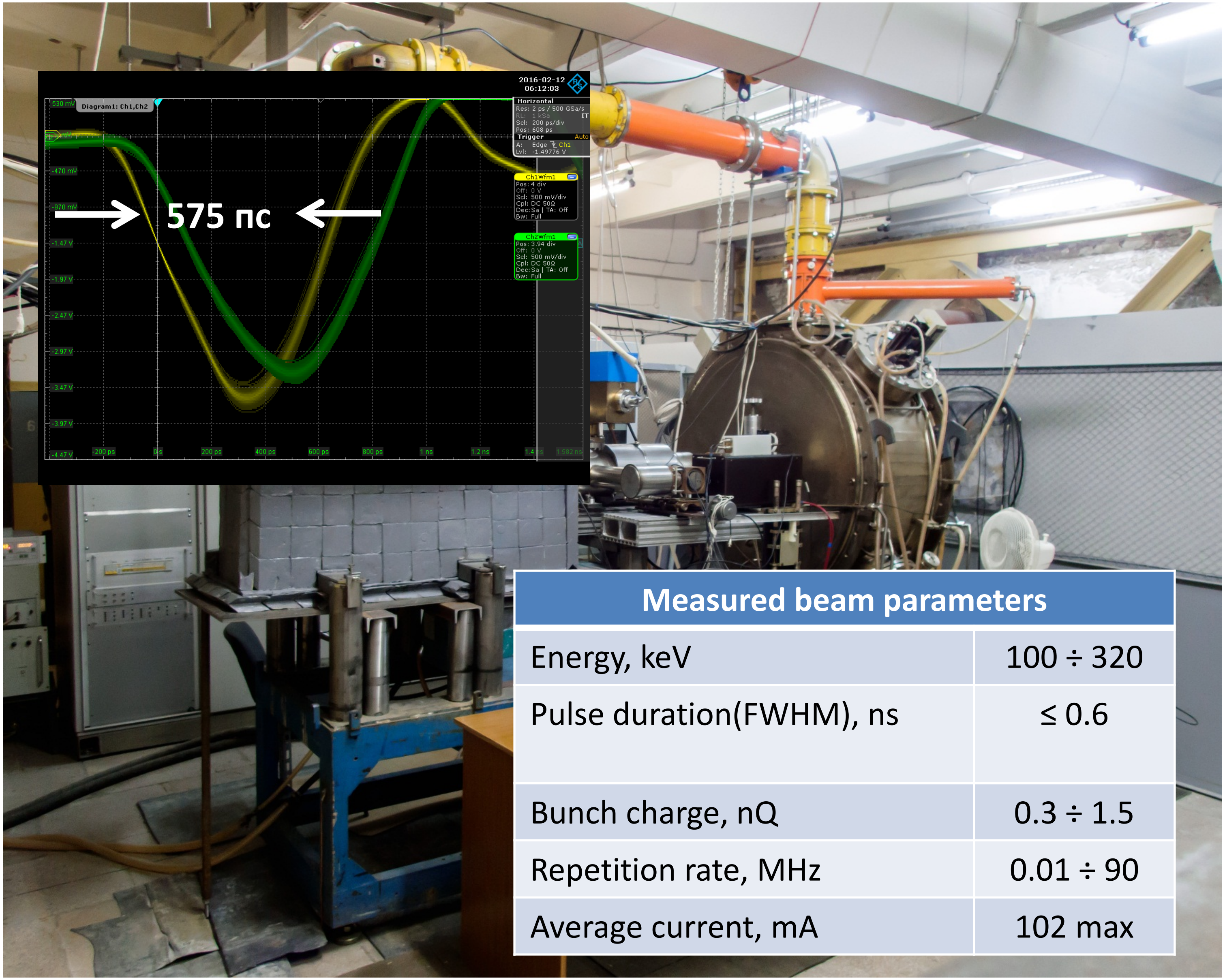


Injector



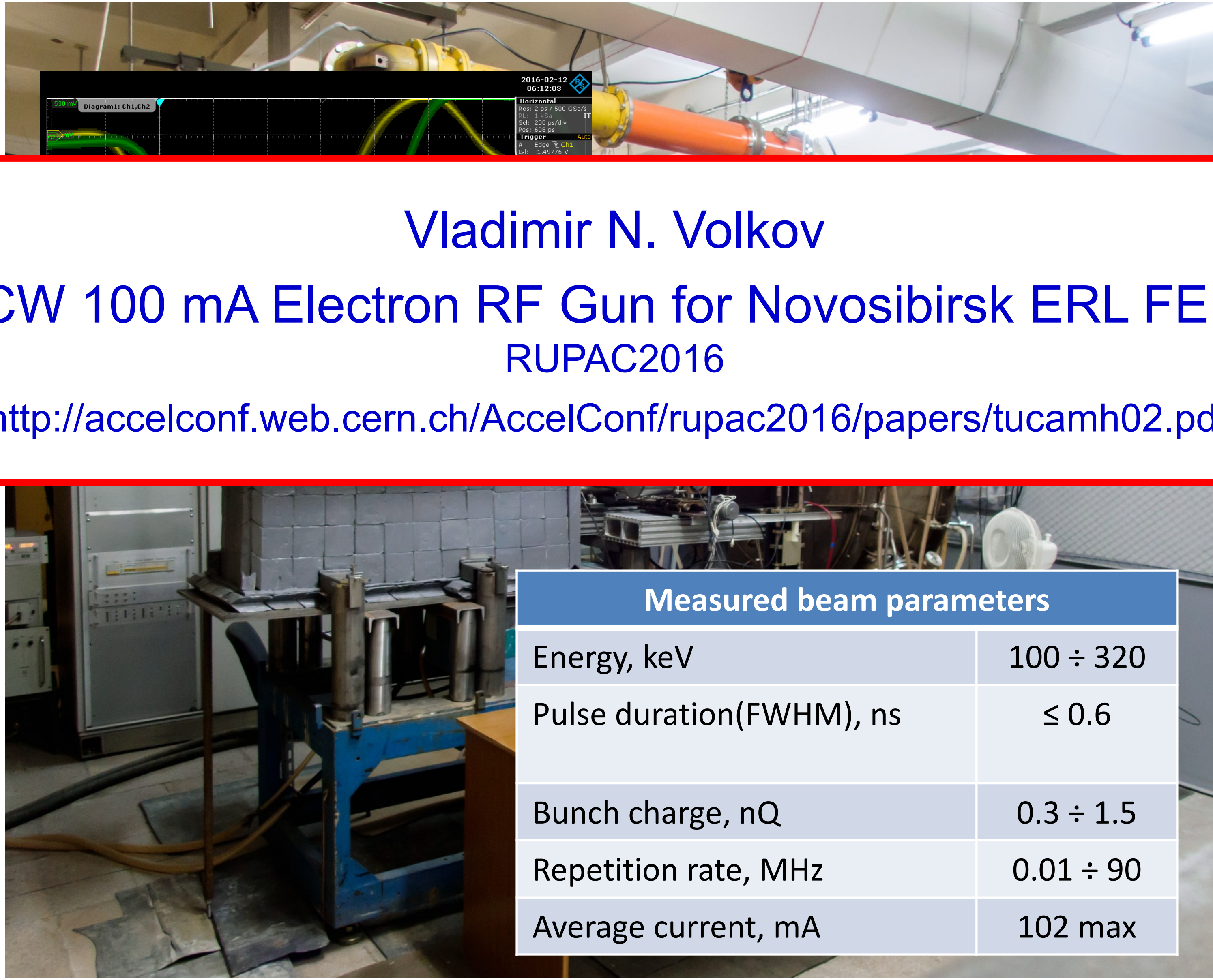
RF Gun Test Setup

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

RF Gun Test Setup



Vladimir N. Volkov

CW 100 mA Electron RF Gun for Novosibirsk ERL FEL

RUPAC2016

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

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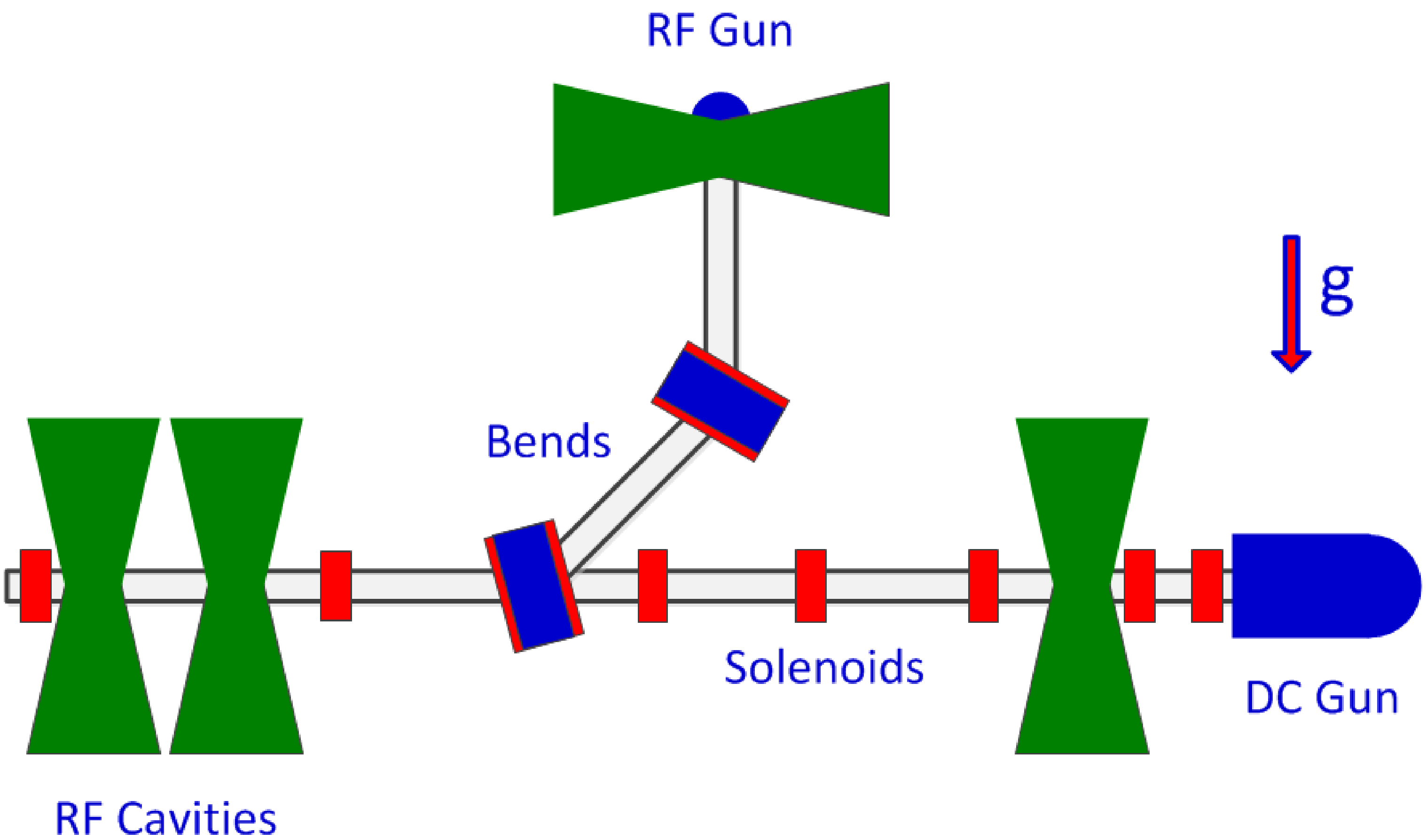
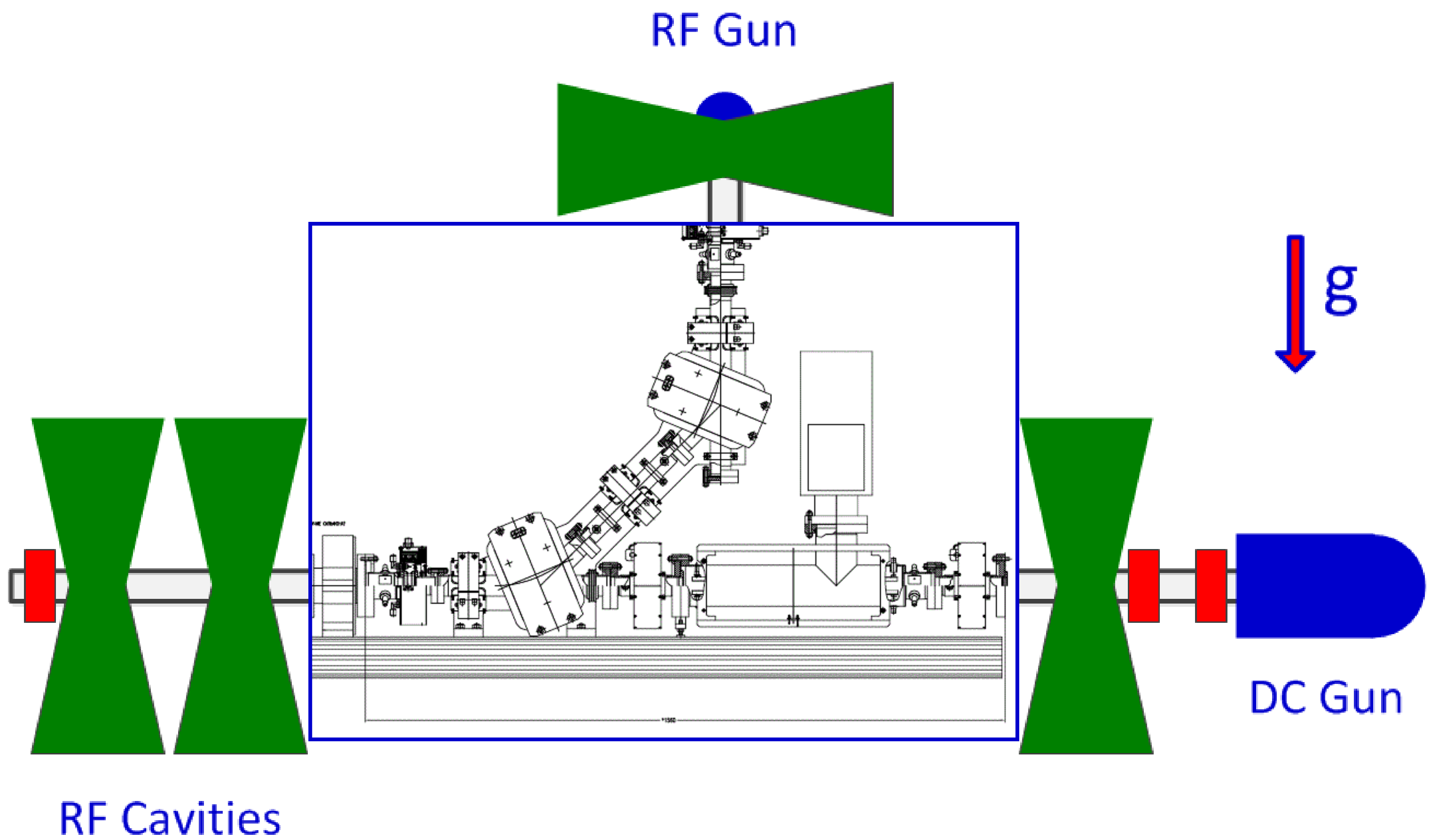
RF Gun Installation Layout

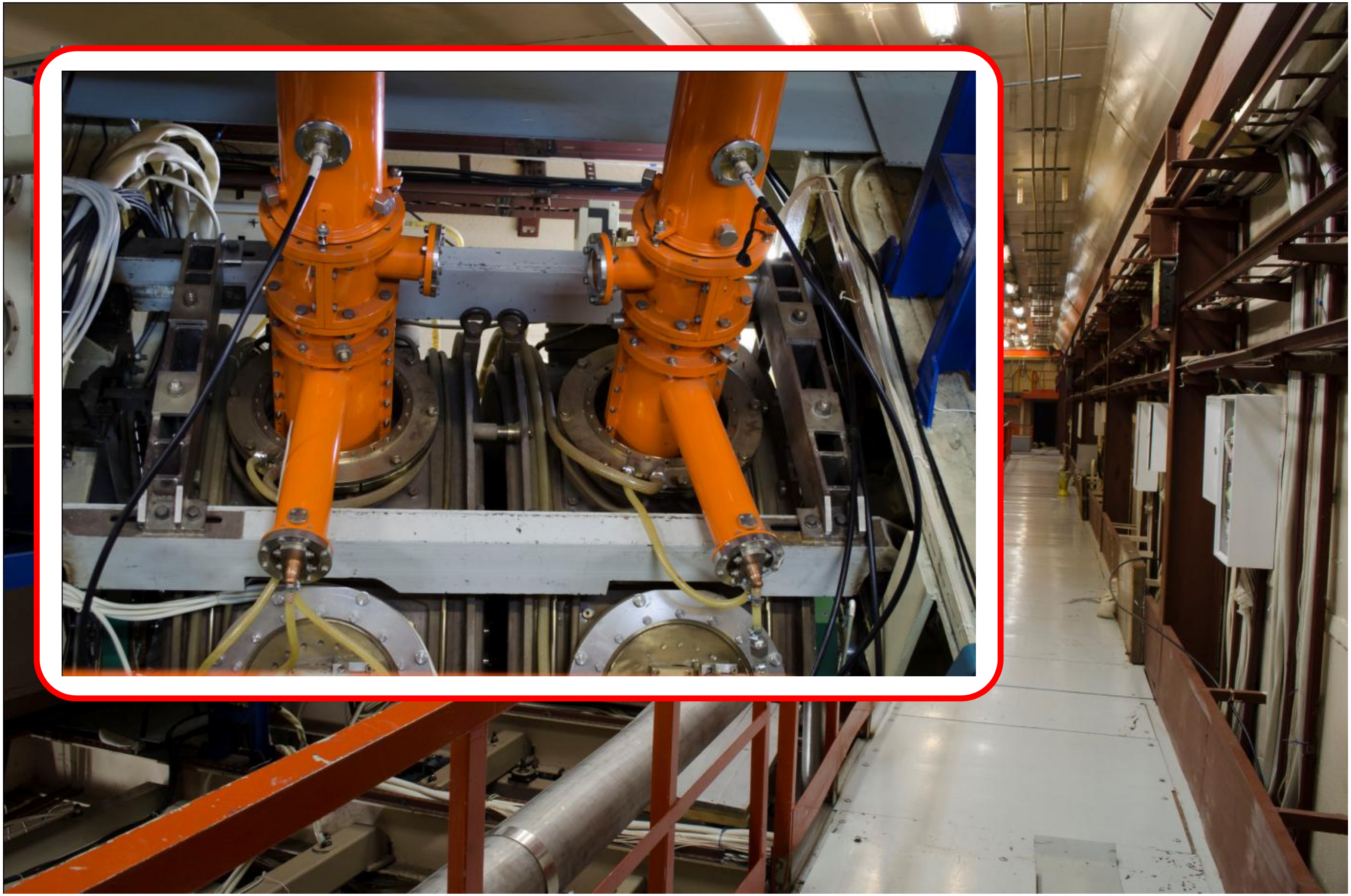


RF Gun Installation Layout



RF waveguides and feeders

RF waveguides and feeders

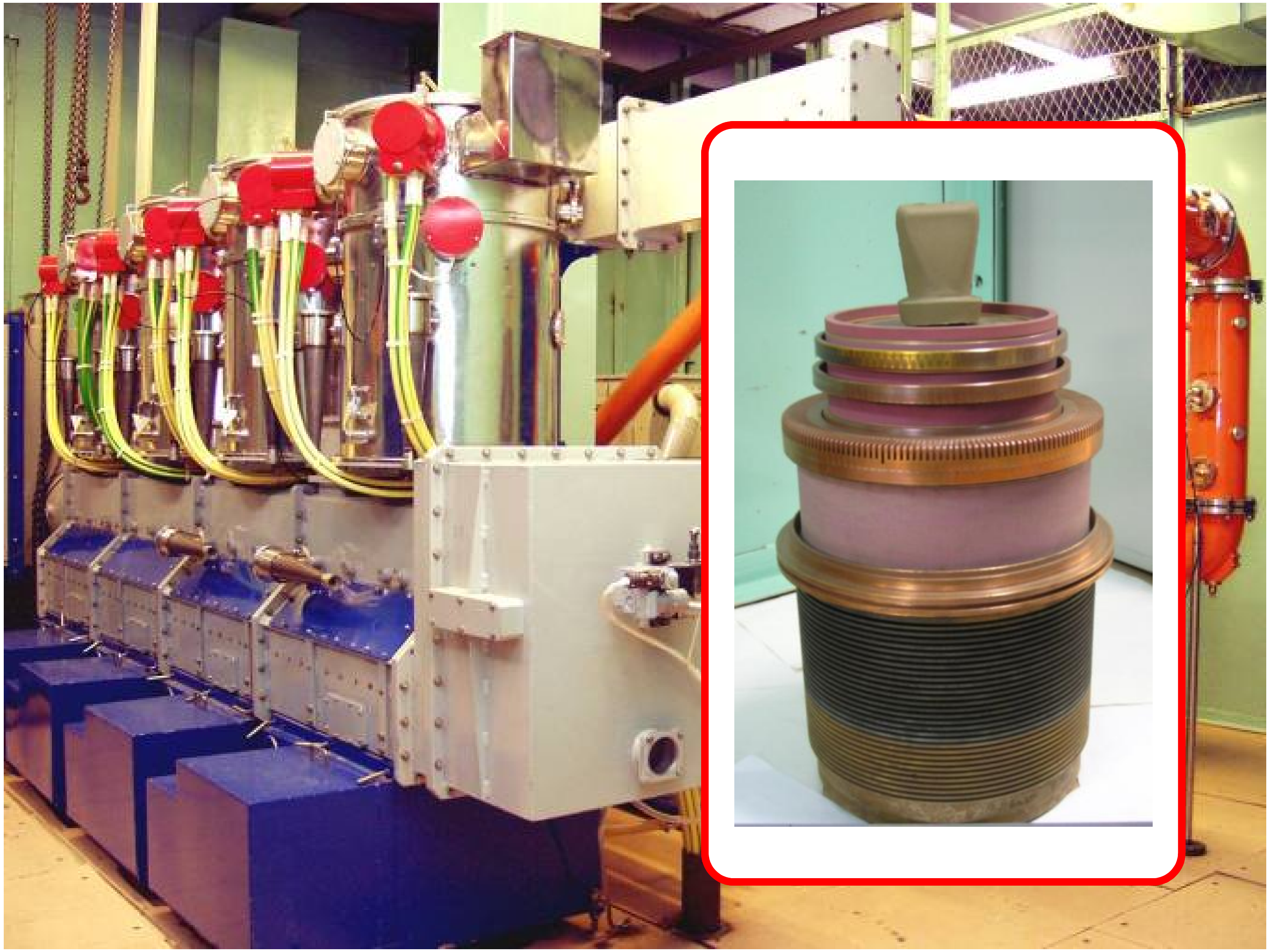


RF waveguides and feeders

RF Power Supply

Frequency, MHz	180.4
Power, MW	2 x 0.6

RF Power Supply



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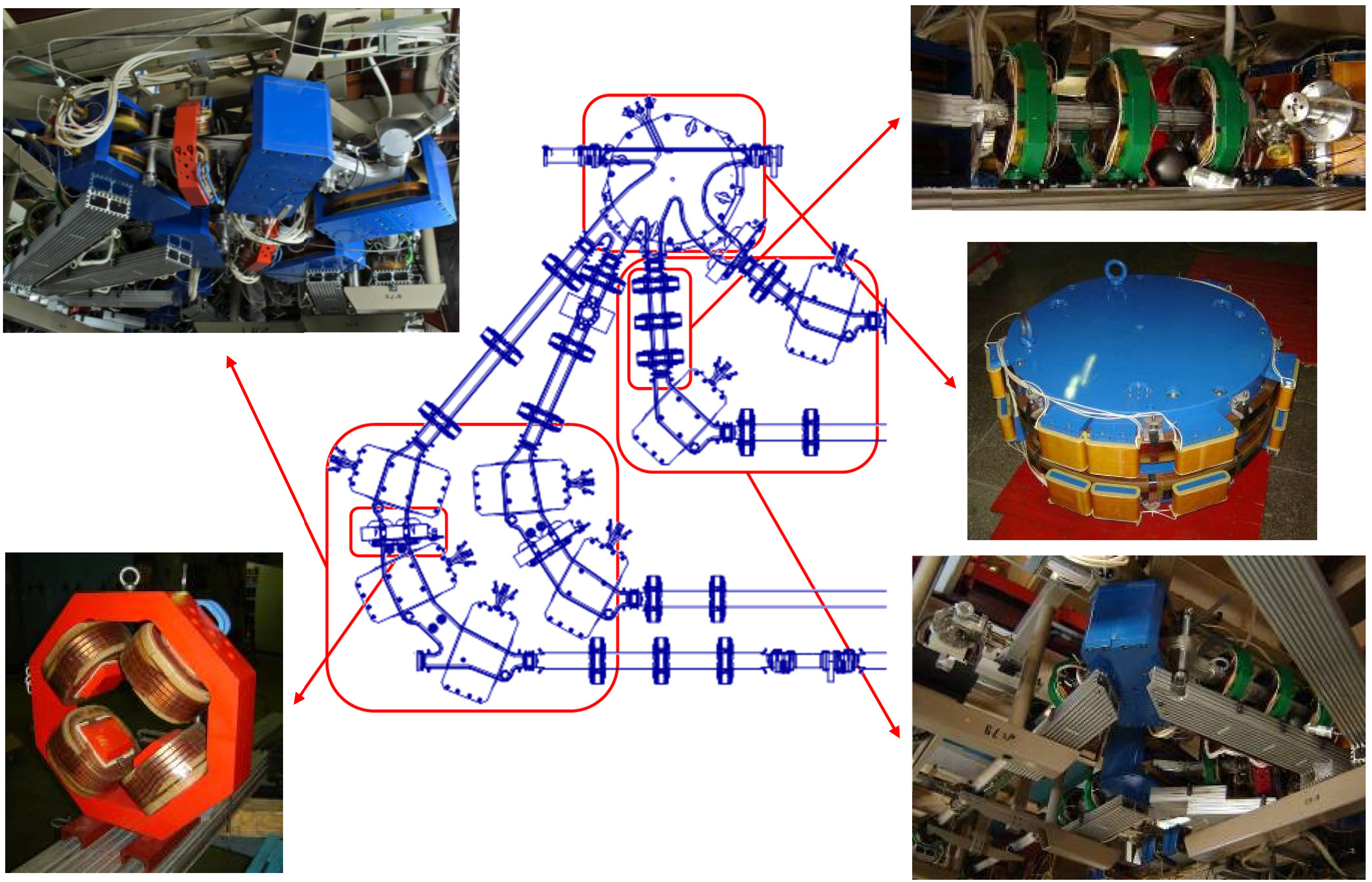
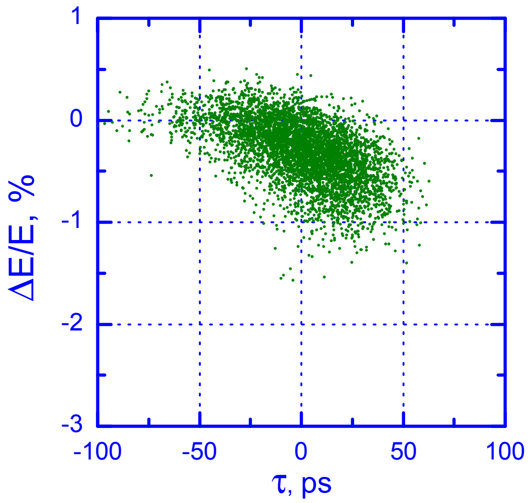
Magnets and Vacuum Chamber of Bends

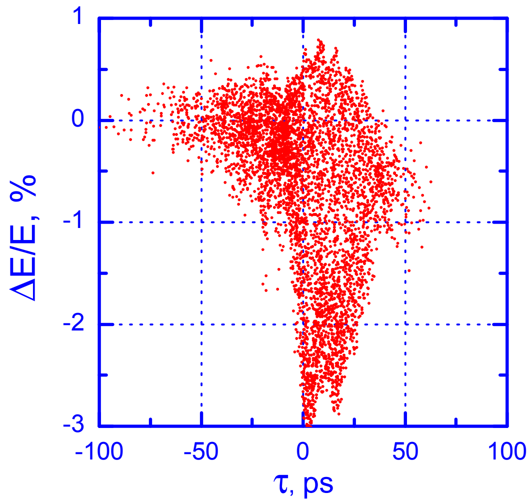


Optimization of the energy acceptance

Before FEL

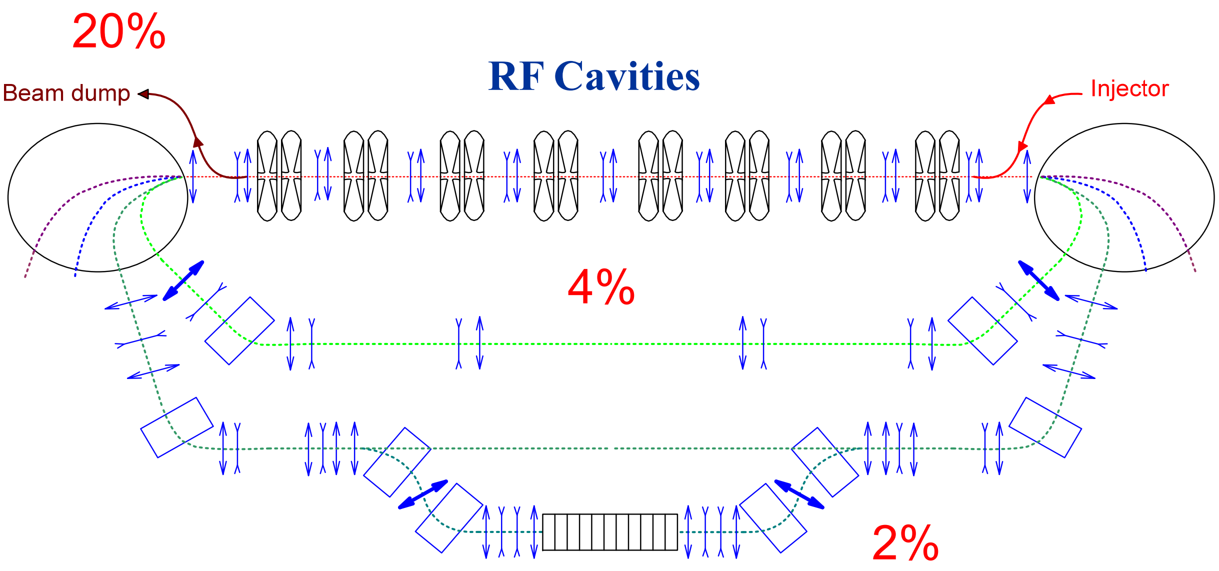


After FEL

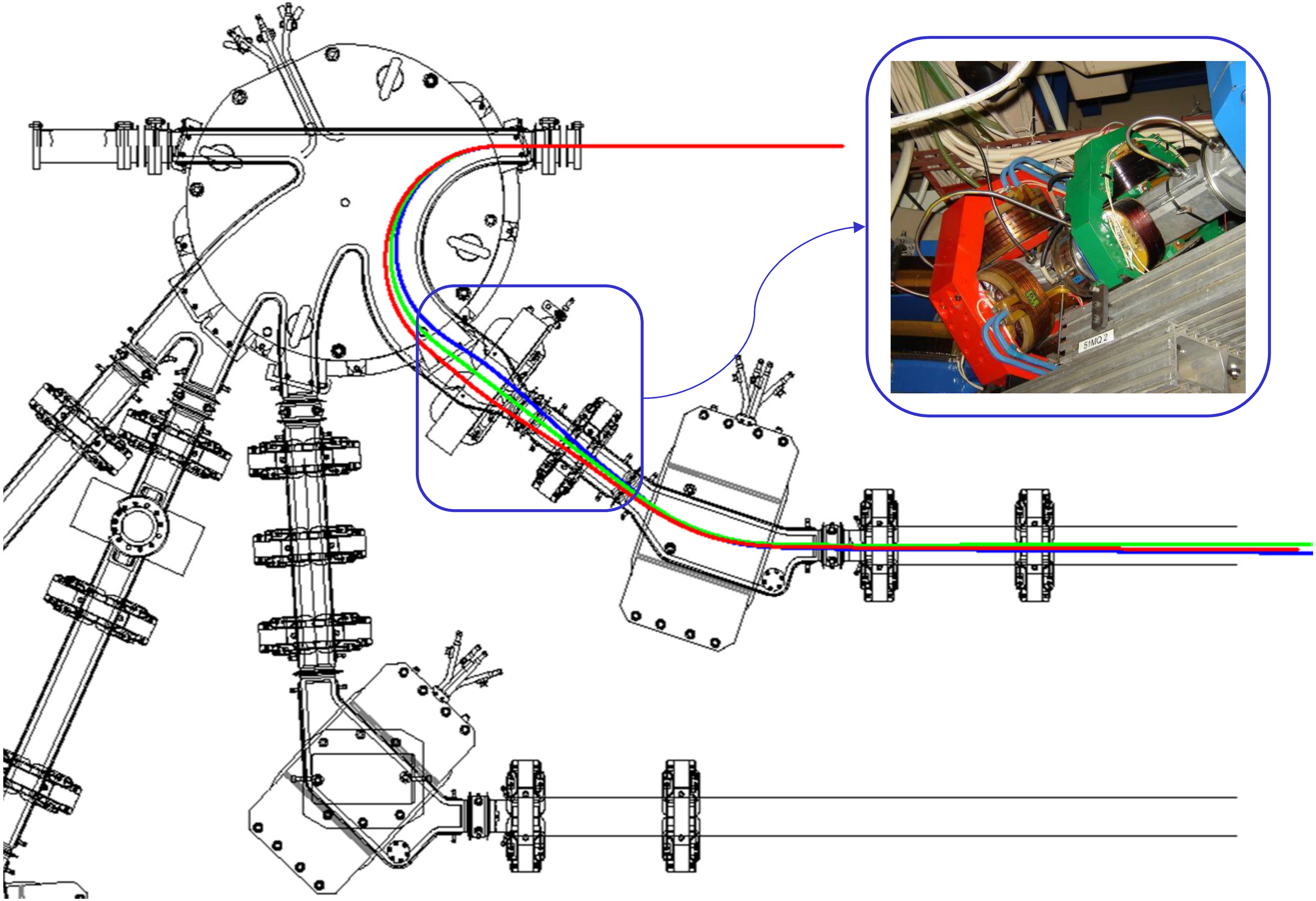


Interaction of electrons with radiation in FEL leads to large energy spread. Moreover the relative energy spread increases at deceleration. Therefore the longitudinal acceptance is very important parameter of ERLs which work for FELs

Optimization of the energy acceptance



1. Compensation of chromatic aberrations



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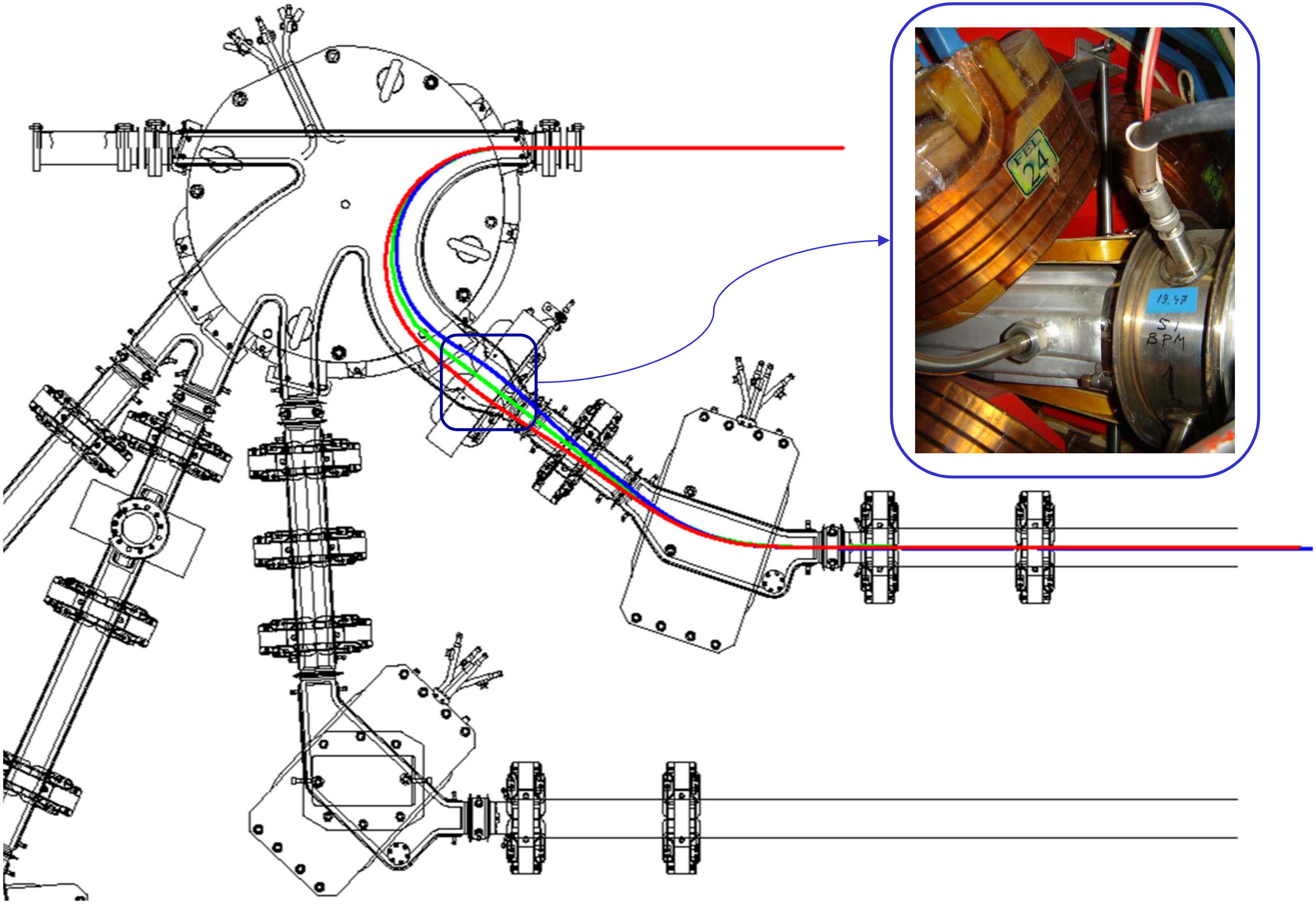

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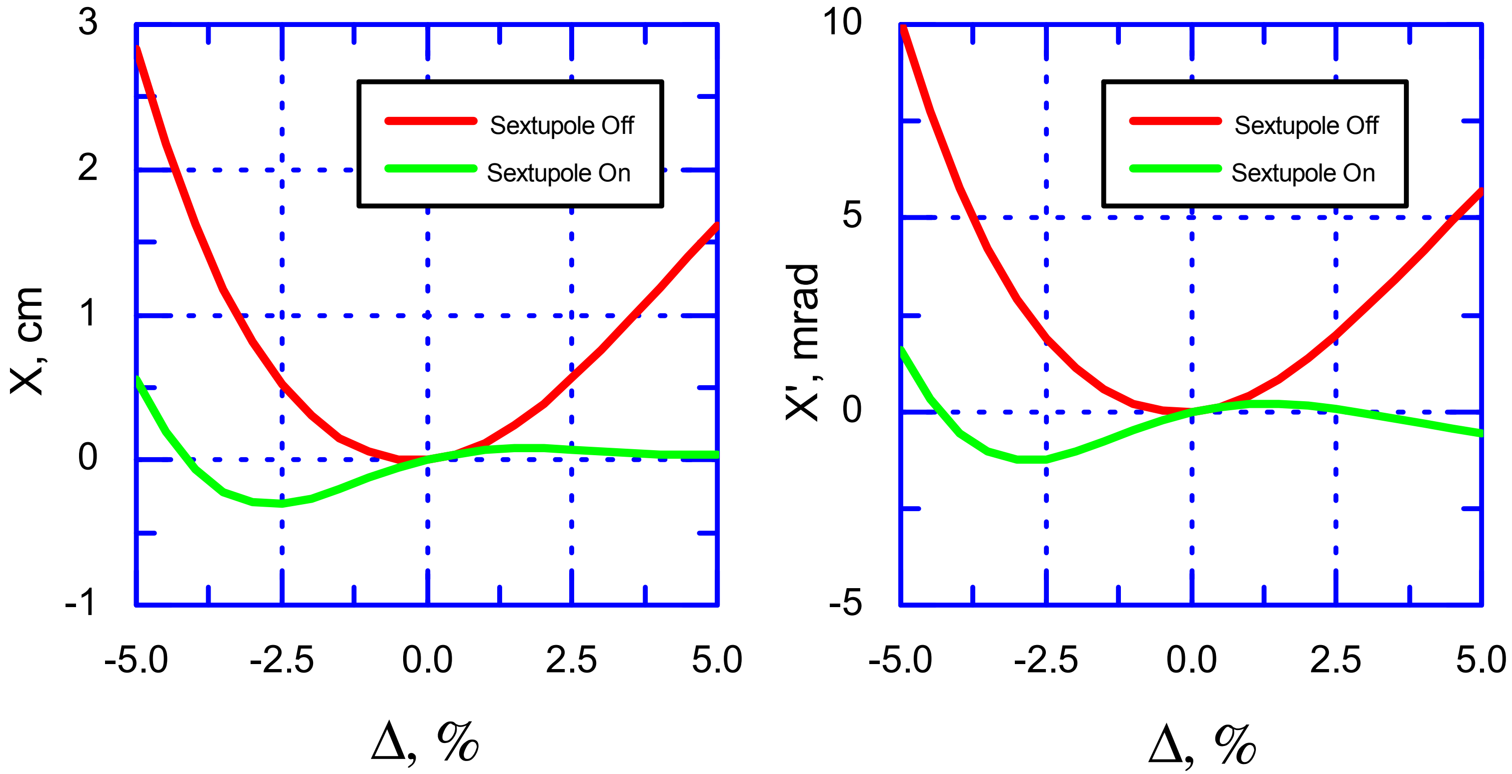
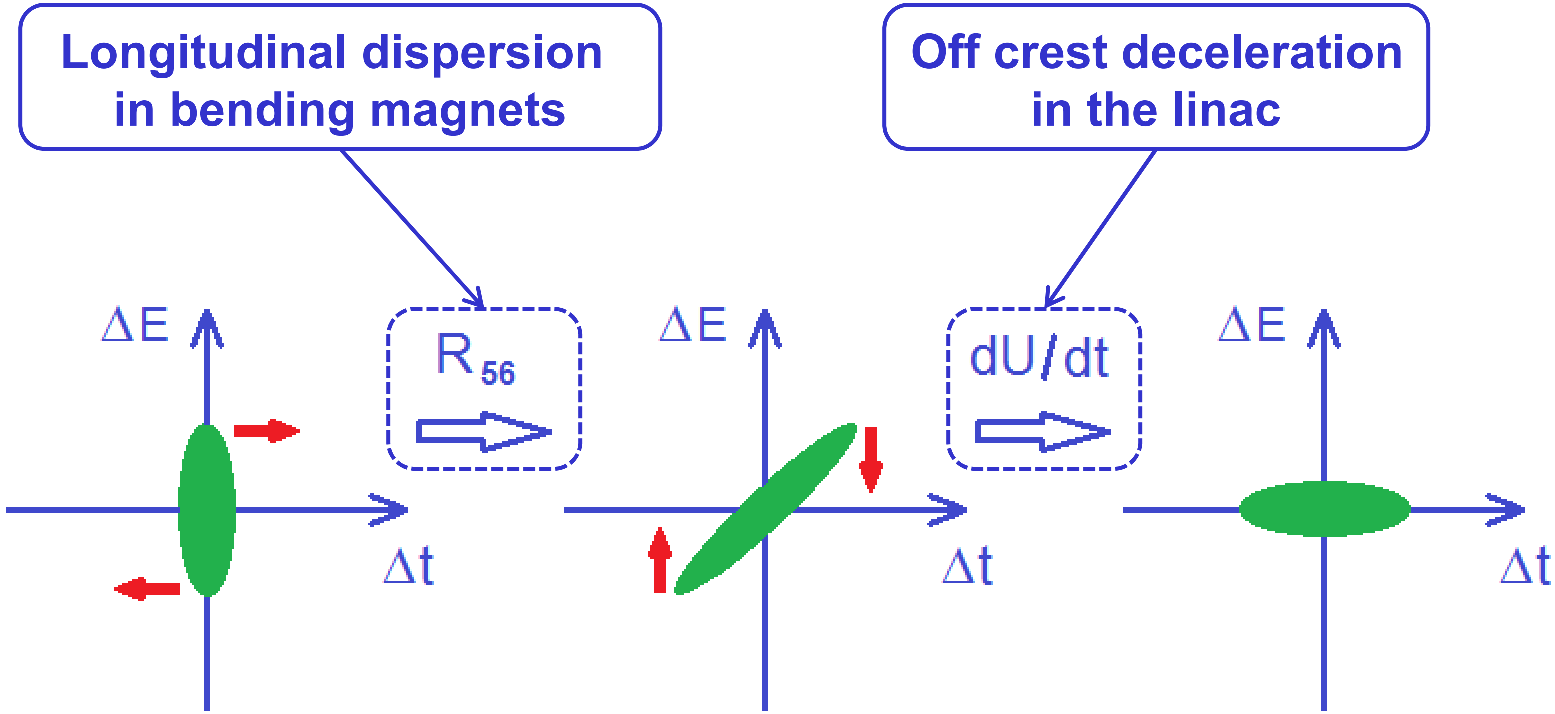


$$\delta\varepsilon = \frac{1}{2\varepsilon_0}\left(\beta_0\left\langle X'(\Delta)^2\right\rangle + 2\alpha_0\left\langle X'(\Delta)X(\Delta)\right\rangle + \gamma_0\left\langle X(\Delta)^2\right\rangle\right)$$

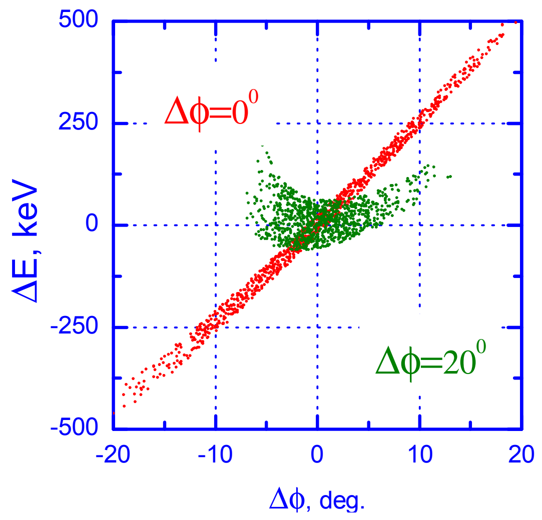
Emittance degradation

2. Optimization of the deceleration phase

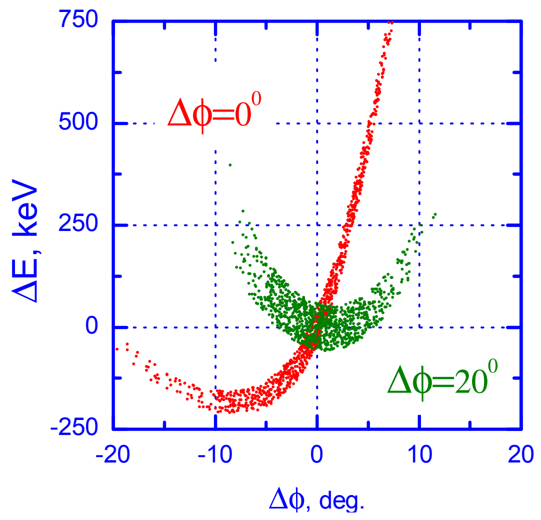


2. Optimization of the deceleration phase

The first track

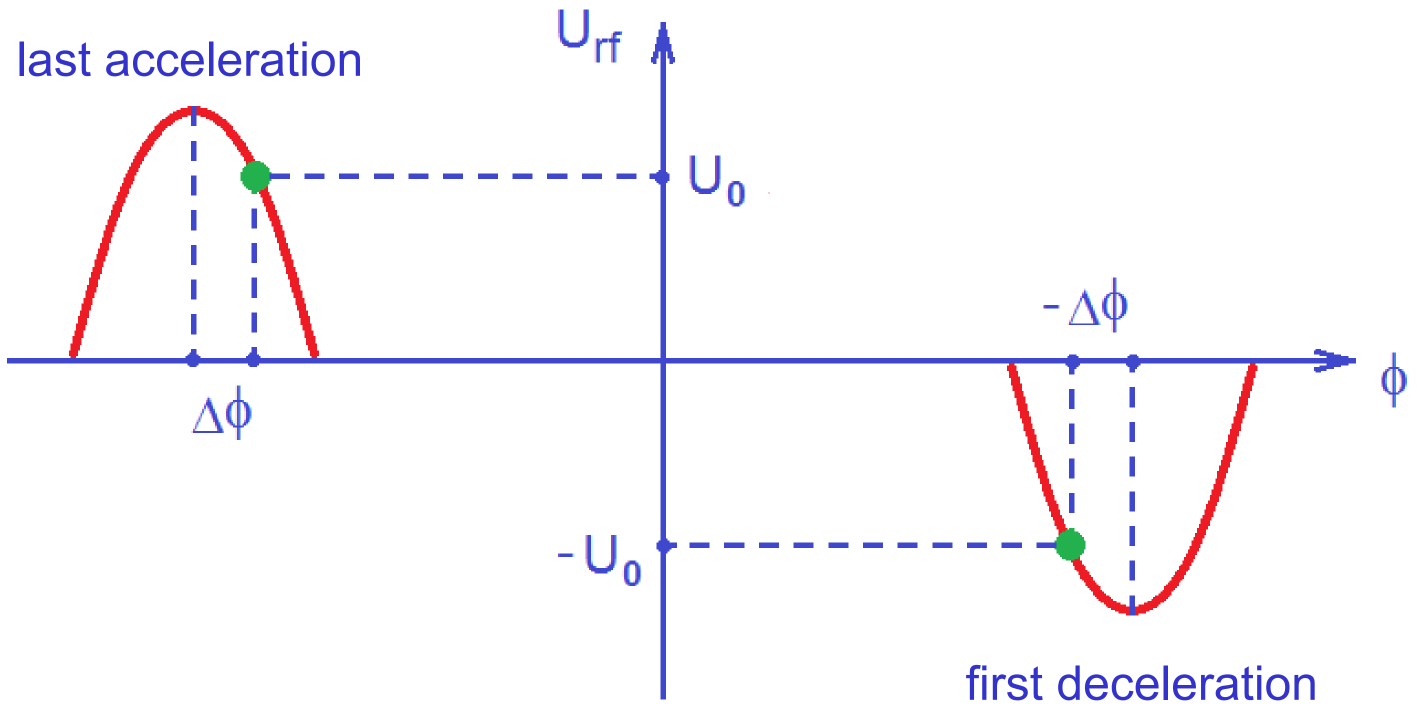


The dump



Beam longitudinal phase space for different deceleration phases

2. Optimization of the deceleration phase

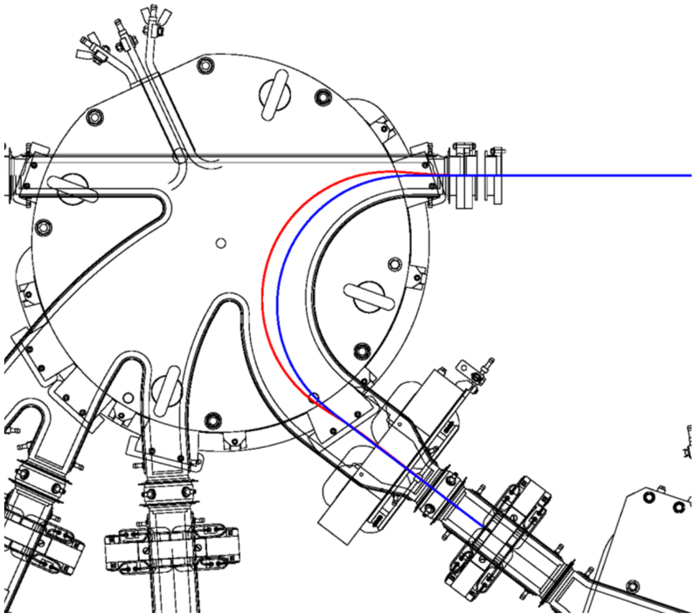


$$L = \lambda_{rf}\left(N + \frac{1}{2} - \frac{\Delta\varphi}{\pi}\right)$$

Length of the last track

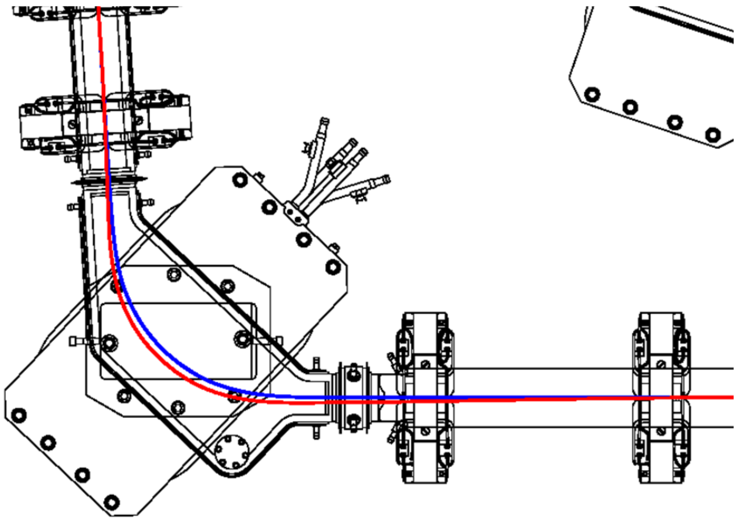
Adjustment of the orbit length

Common track round magnet



ΔL = 8 cm

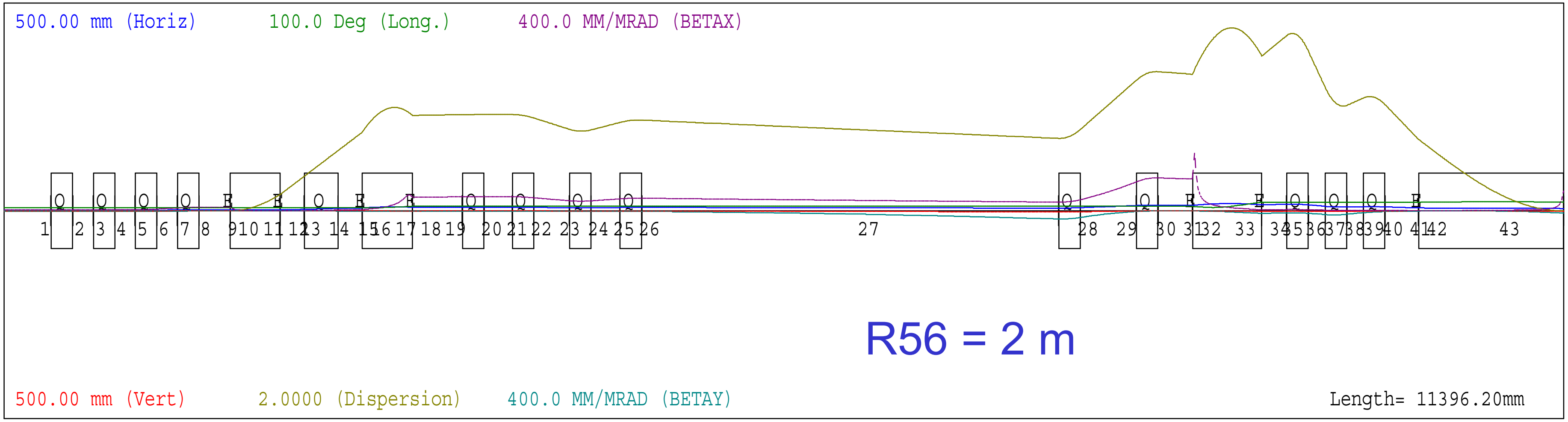
Second track bending magnet

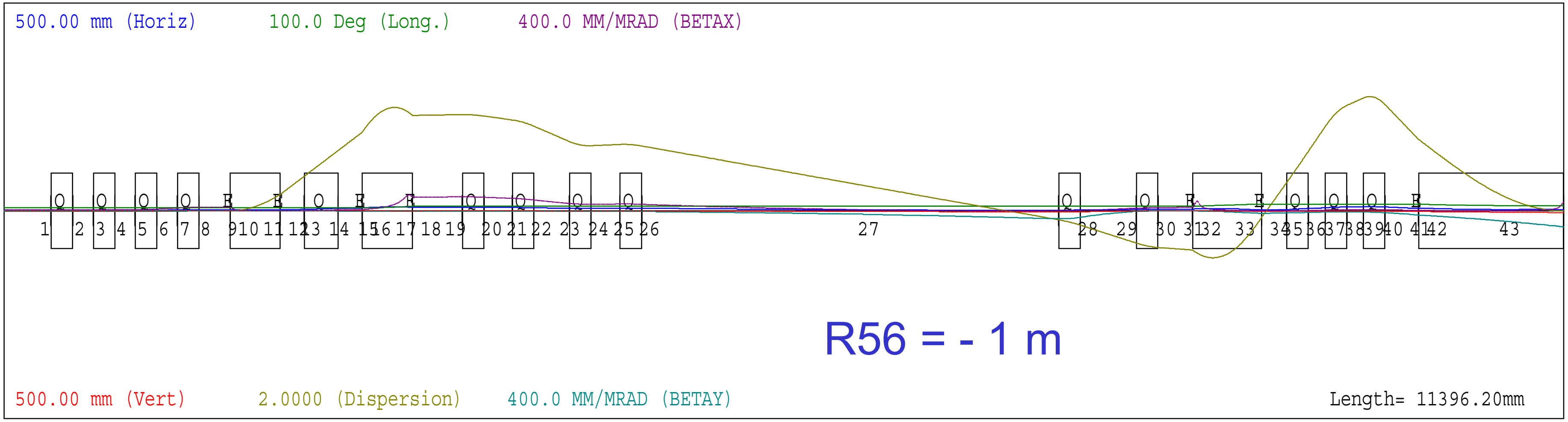


ΔL = 2 cm

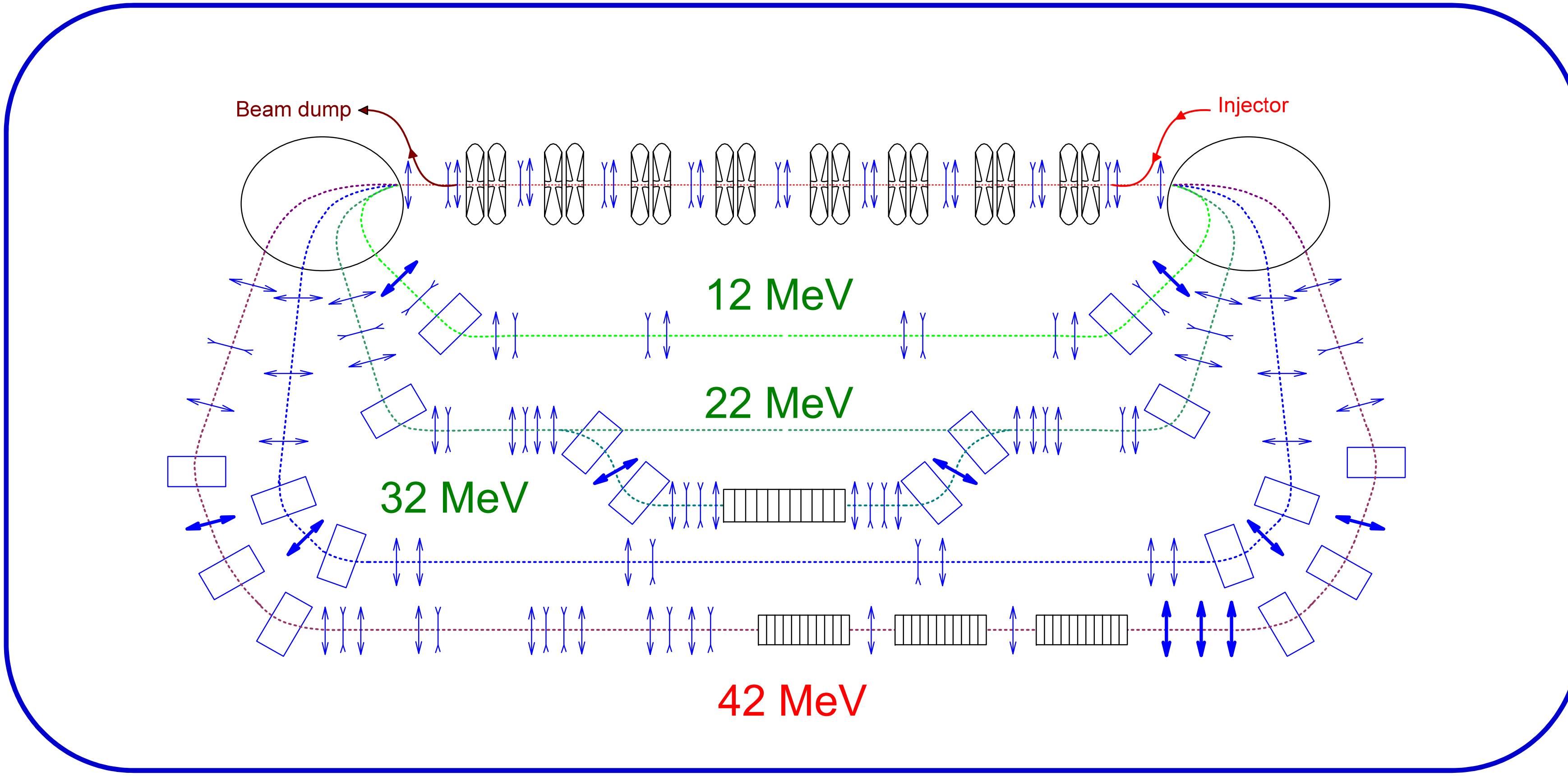
Adjustment of the longitudinal dispersion

(after bypass)





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



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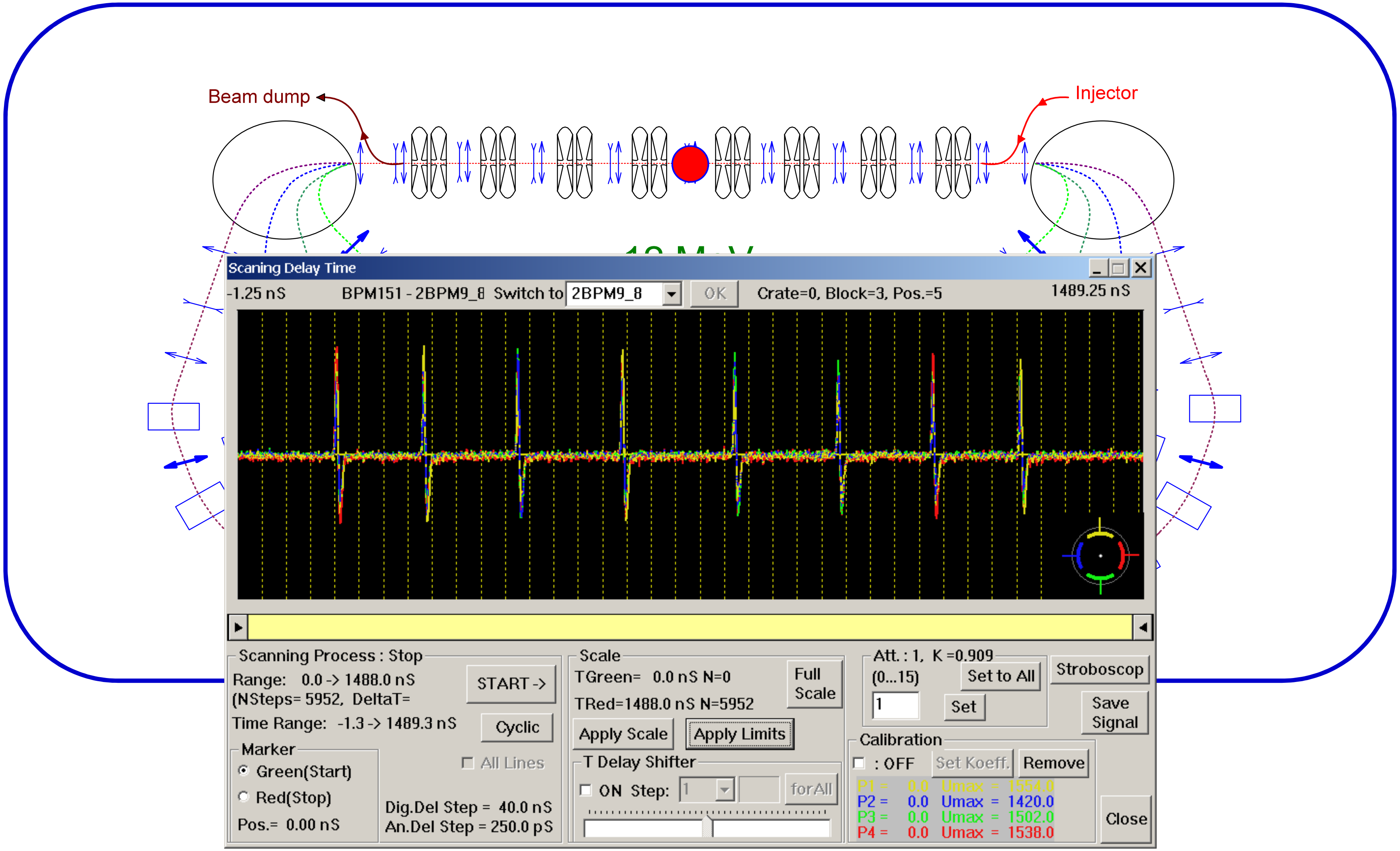
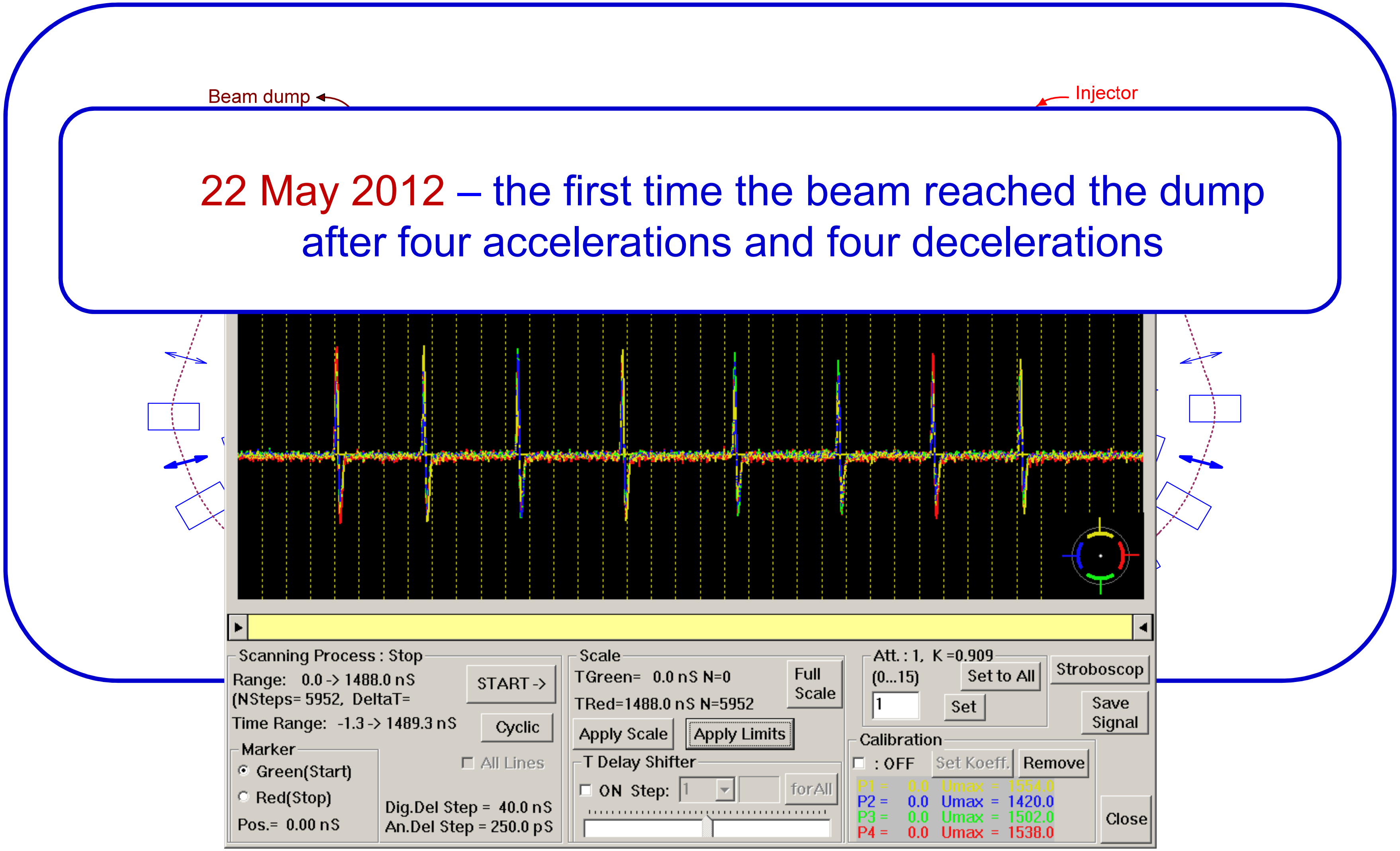
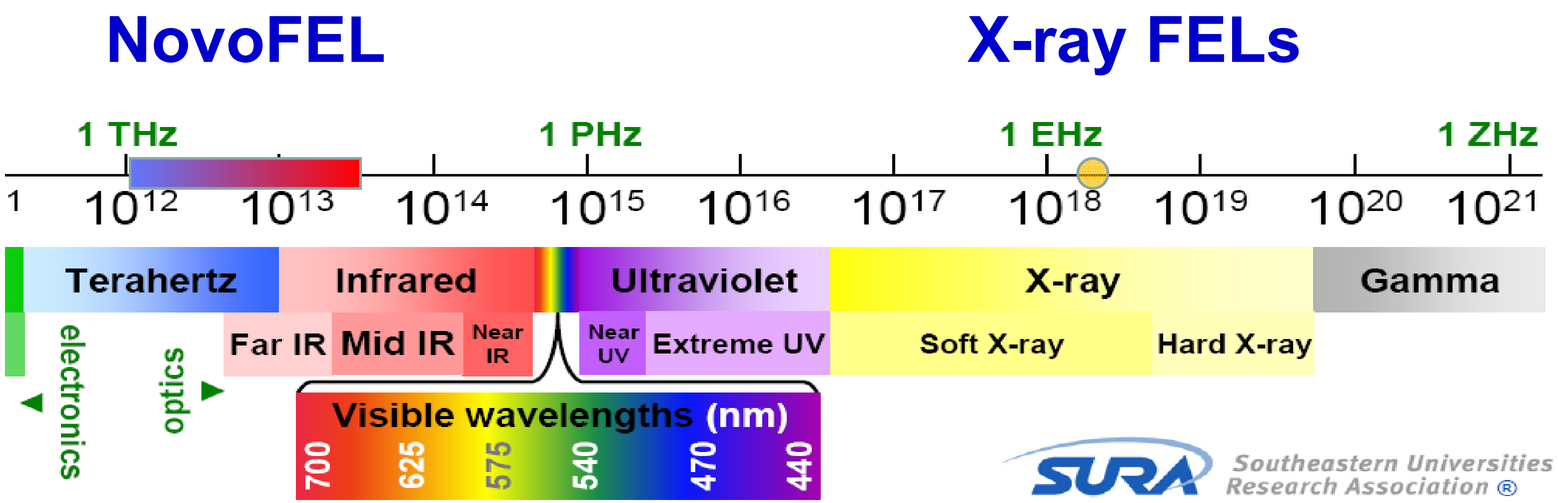


Layout of Horizontal Beamlines (the Second and the Third ERLs)

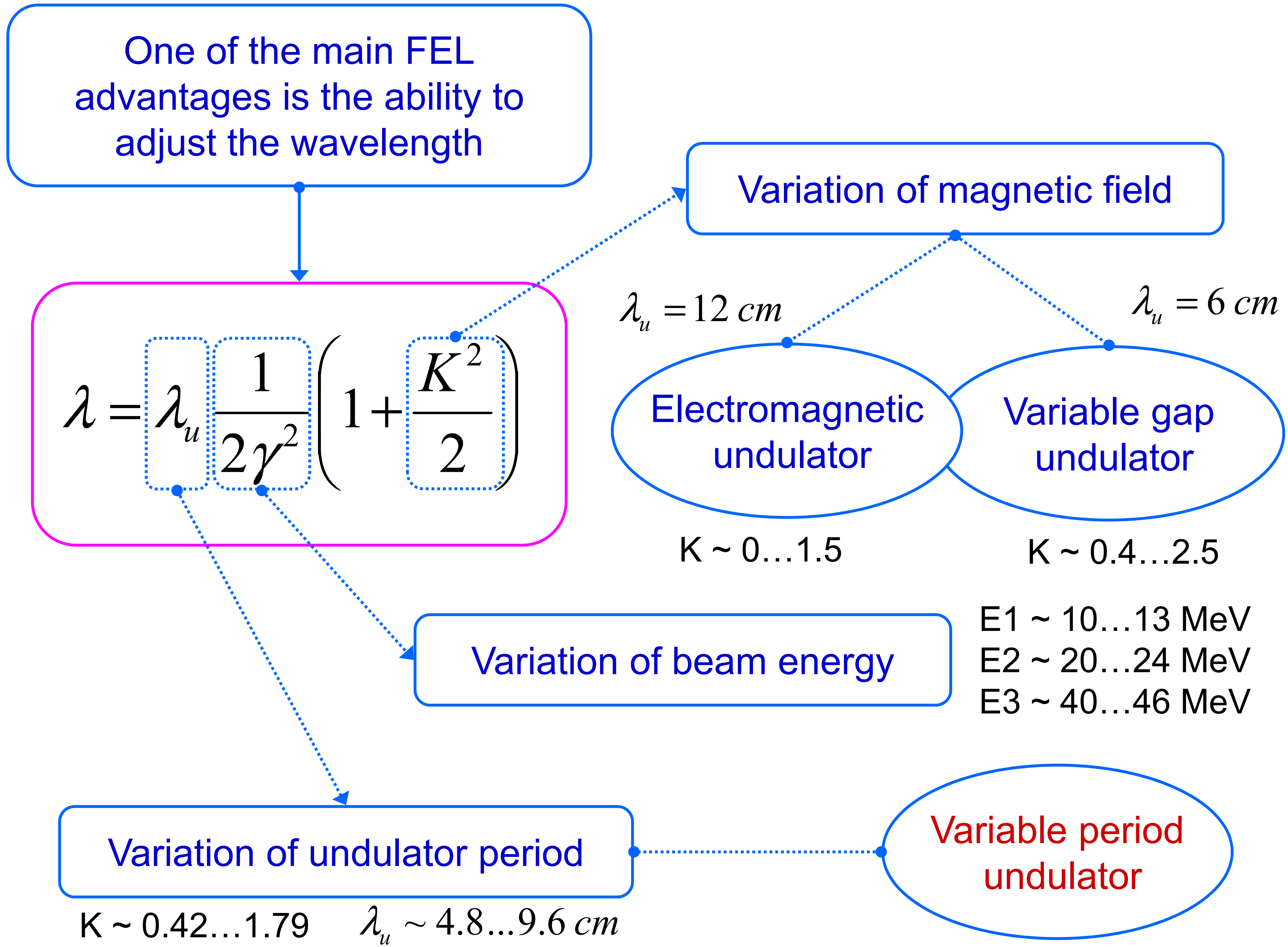
22 May 2012 – the first time the beam reached the dump after four accelerations and four decelerations



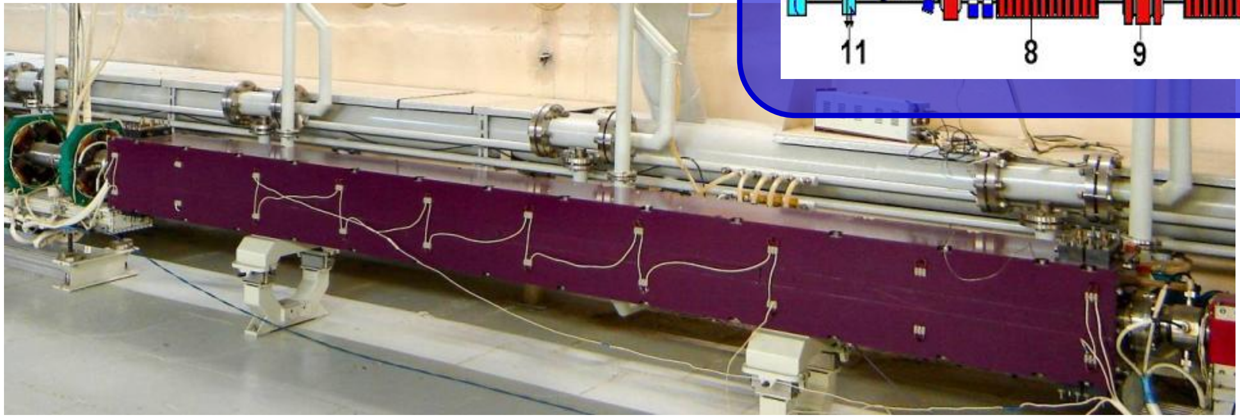
NovoFEL as Radiation Source

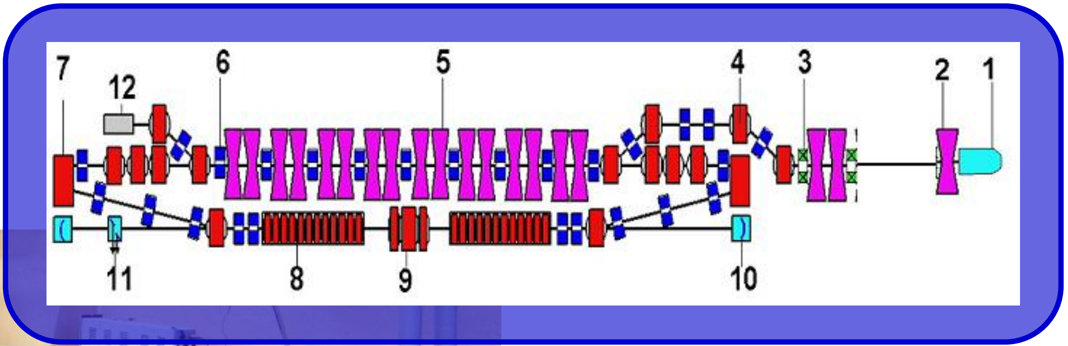


The most attractive ranges for FELs are at very short and at very long wavelength, where there are no other lasers


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
$\lambda_u = 12\ cm$
$\lambda_u = 6\ cm$
Electromagnetic undulator
Variable gap undulator
K ~ 0…1.5
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
Variable period undulator
K ~ 0.42…1.79
$\lambda_u \sim 4.8 \ldots 9.6\ cm$

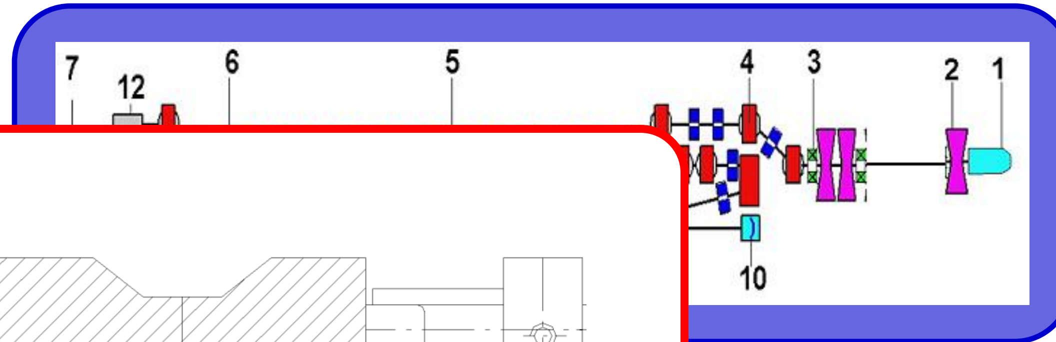
Electromagnetic Undulators

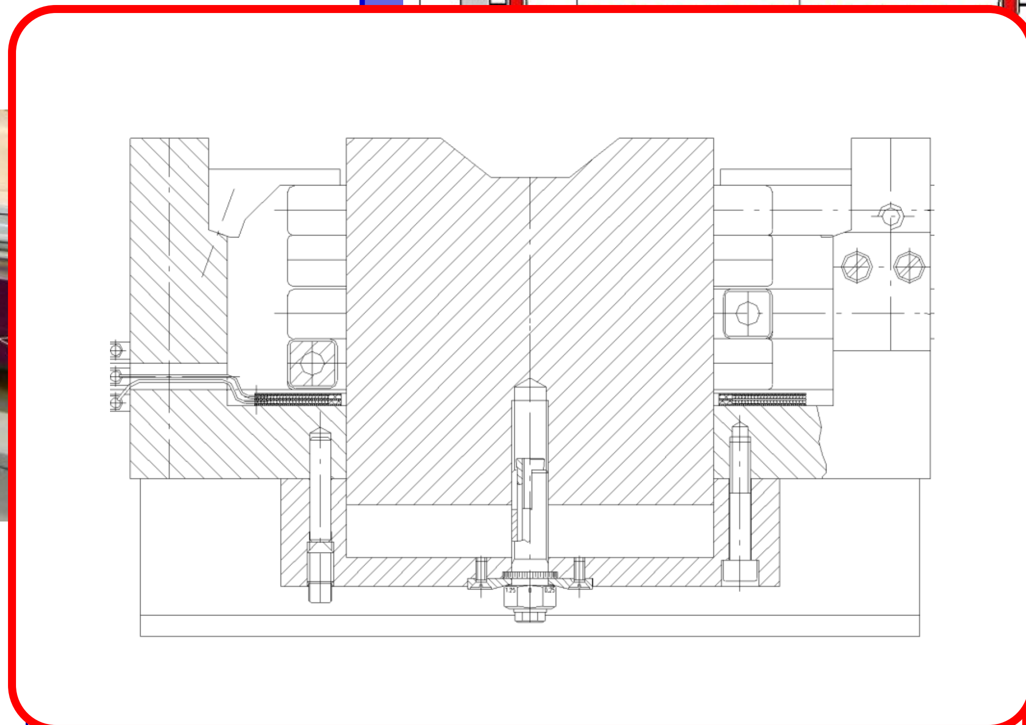




	1-st FEL	2-d FEL
Period, cm	12	12
Maximum current, кA	2.4	2.4
Maximum K	1.25	1.47

Electromagnetic Undulators





		FEL
Period, cm	12	12
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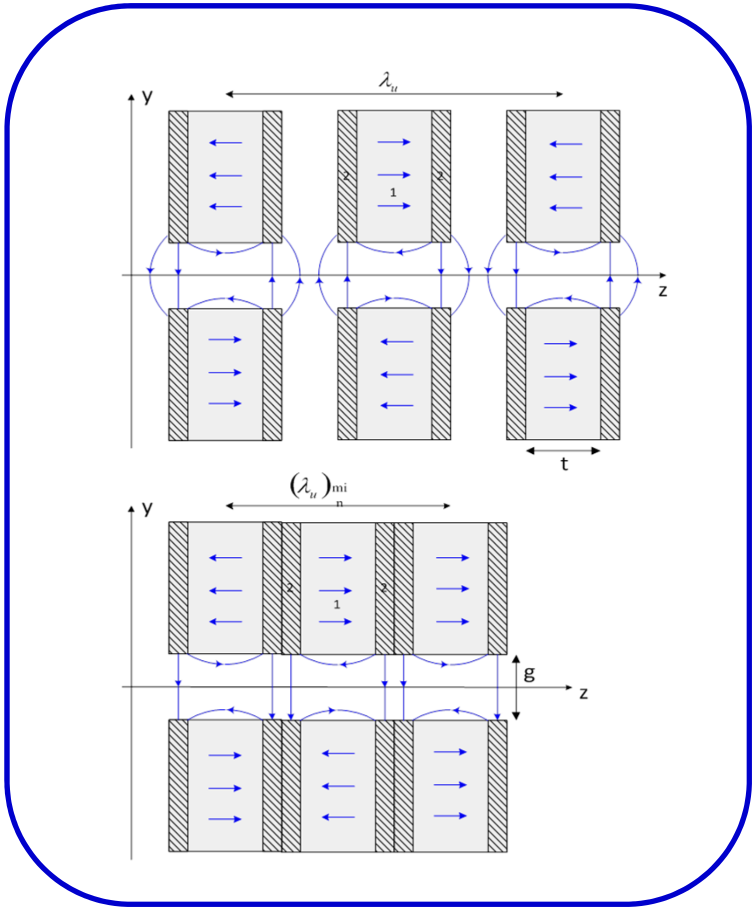
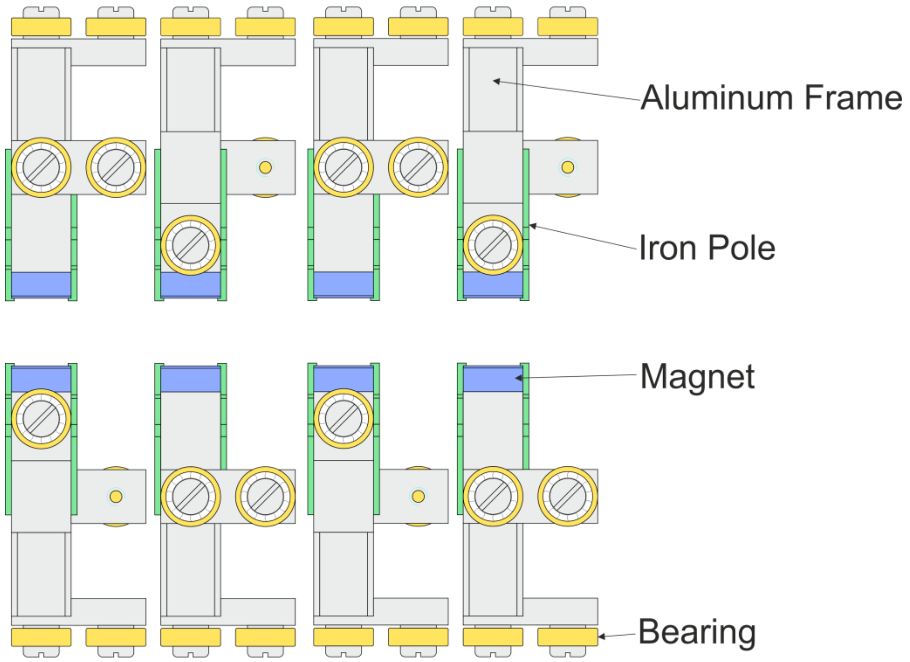
Maximum K	1.25	1.47

Variable Period Undulator (for the 2nd FEL)
(Vinokurov N.A., Shevchenko O.A., Tcheskidov V.G. Variable-period permanent magnet undulators, PRST AB, 2011,14, No 4, 040701)





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

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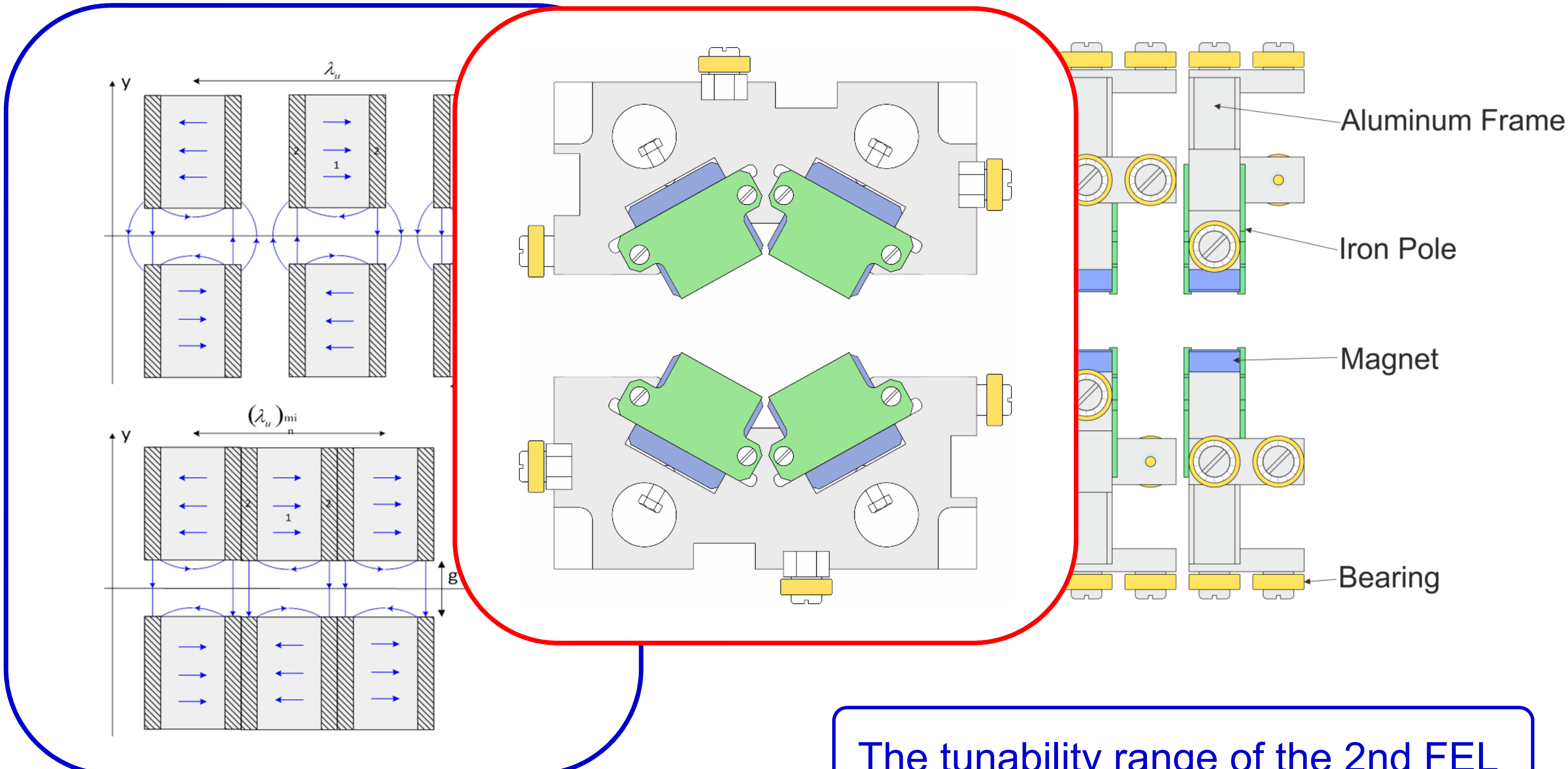

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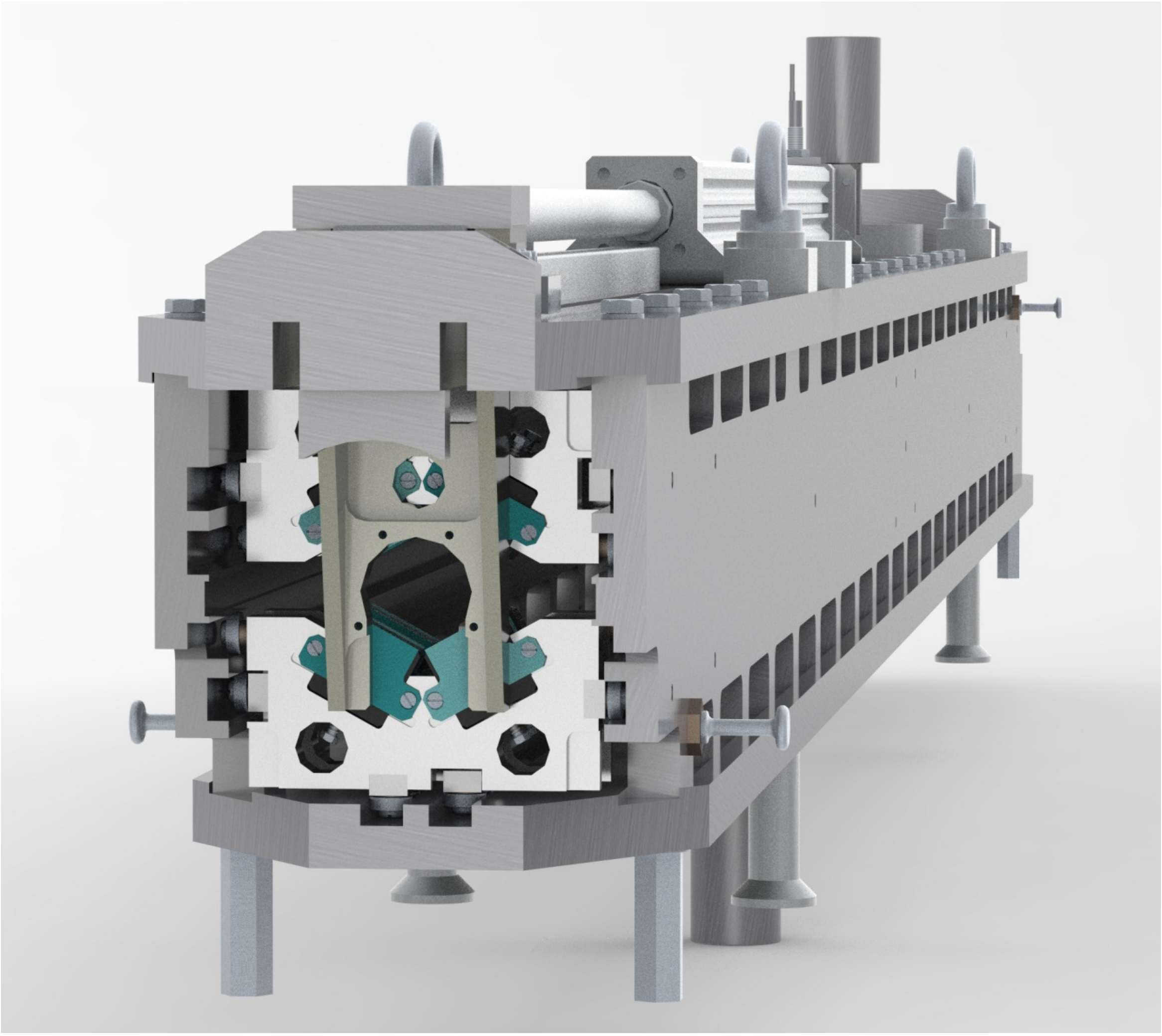
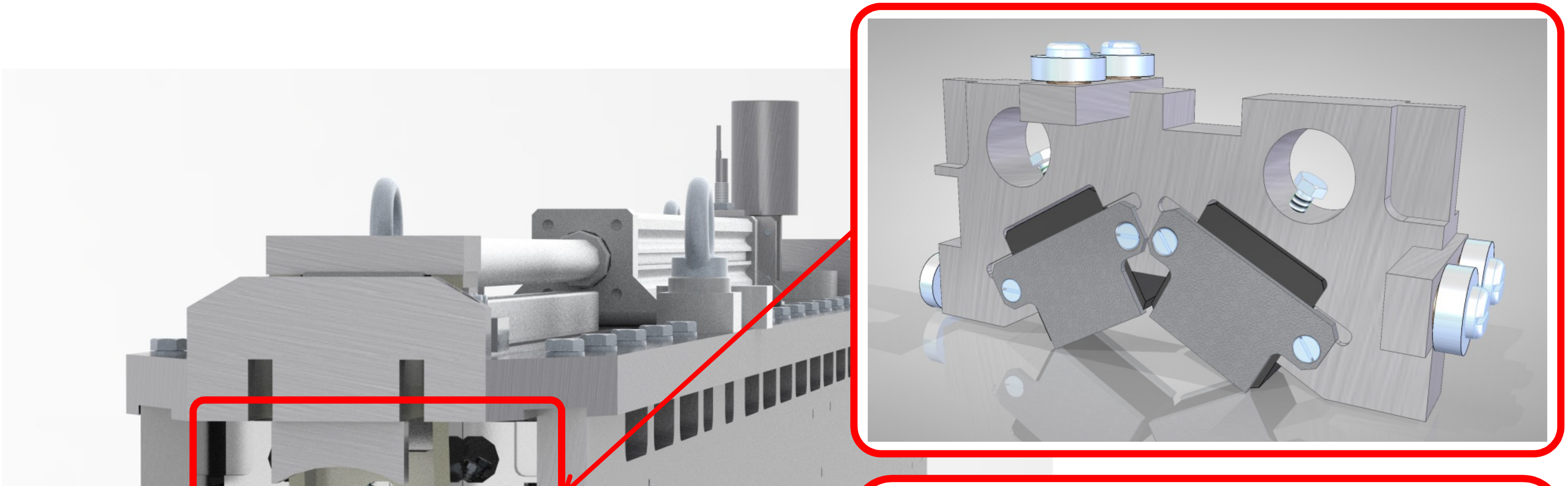
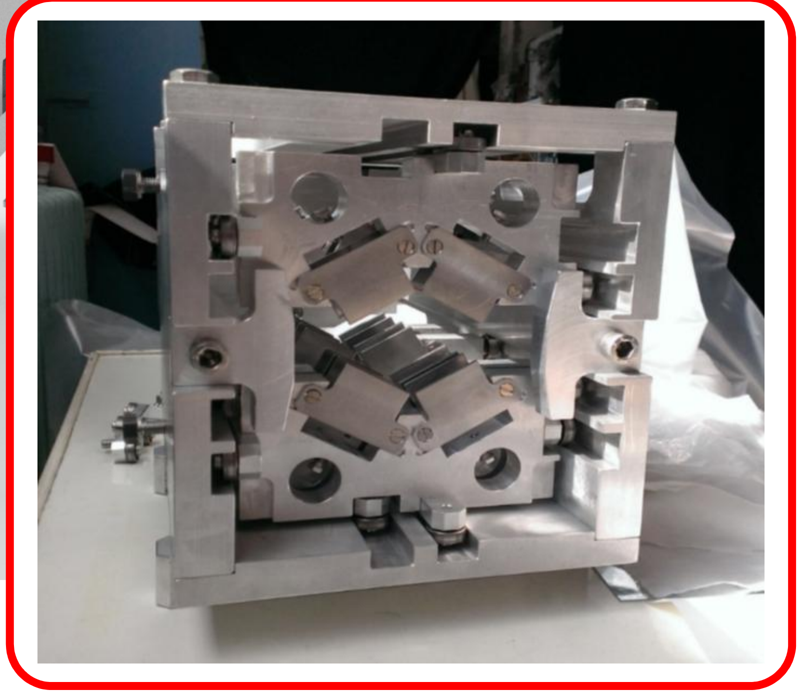
Variable Period Undulator (for the 2nd FEL)



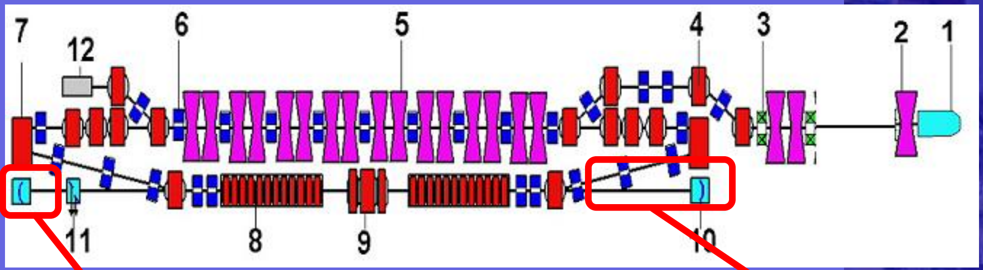
Variable Period Undulator (for the 2nd FEL)

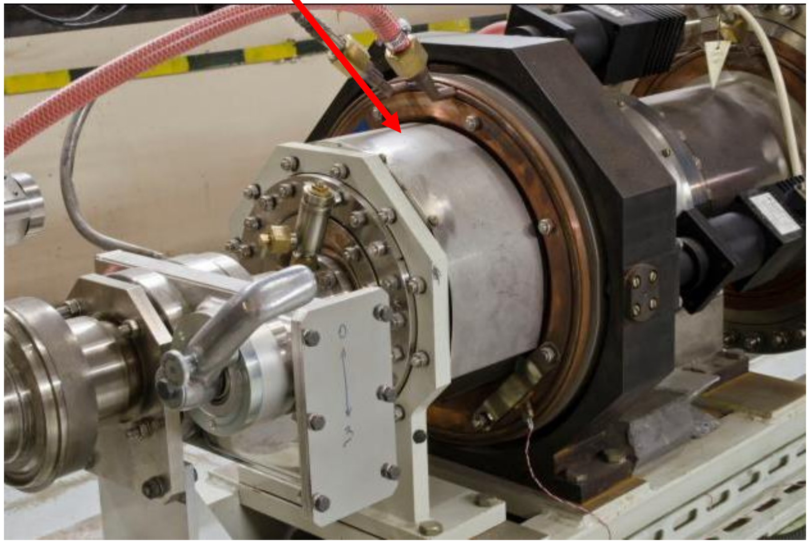


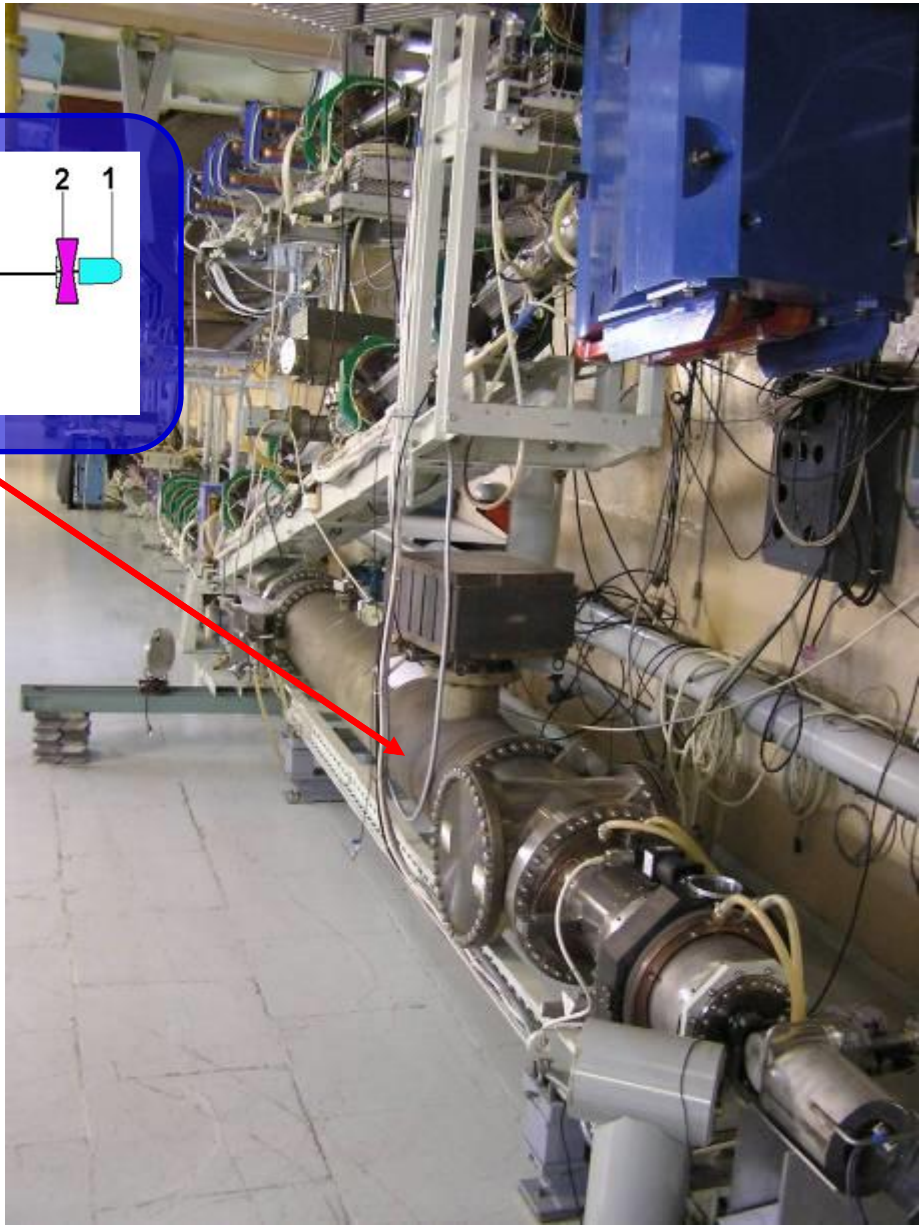


Variable period undulator at magnetic measurements

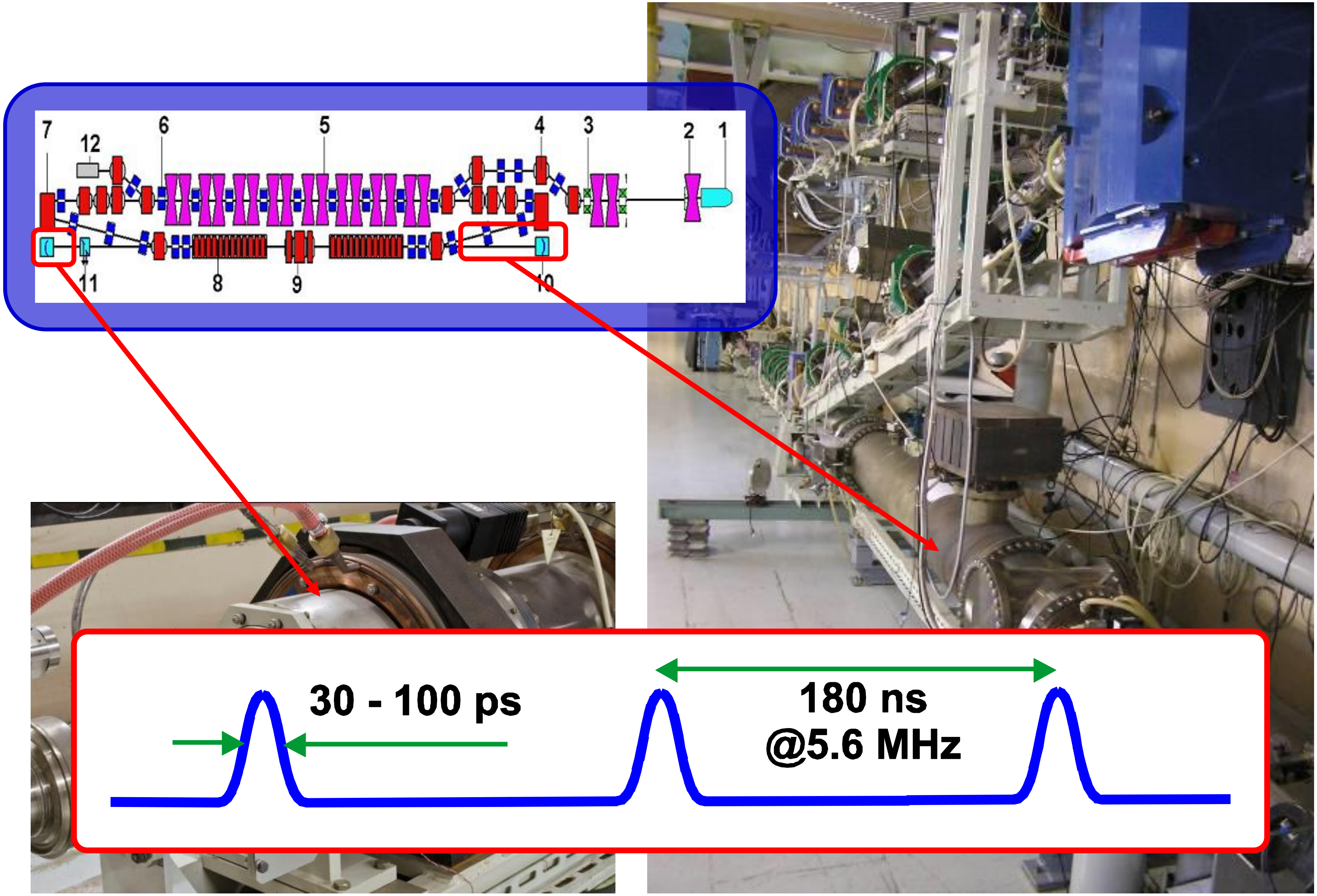
FEL Optical Cavities



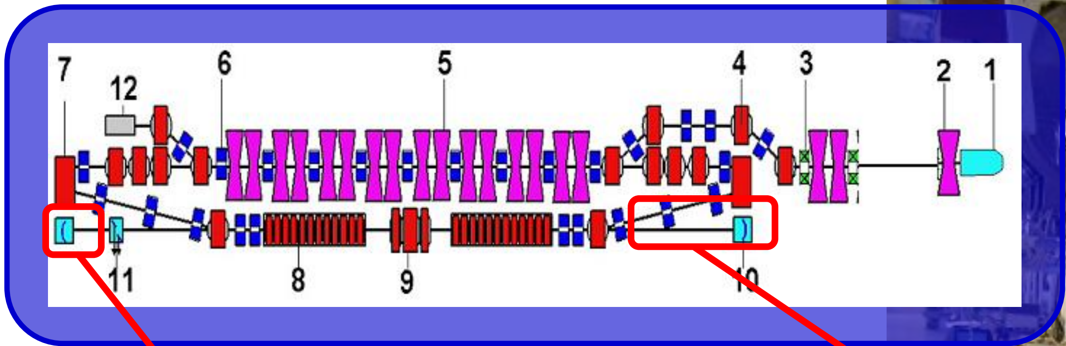




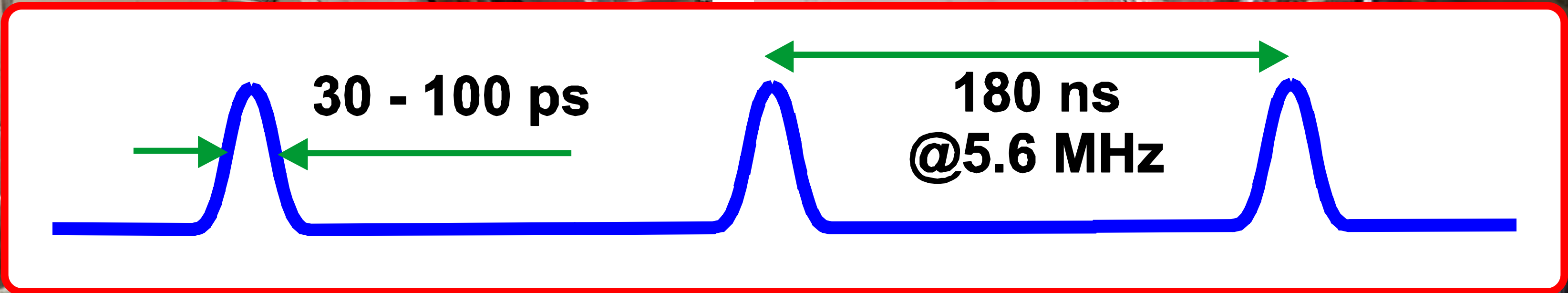
FEL Optical Cavities



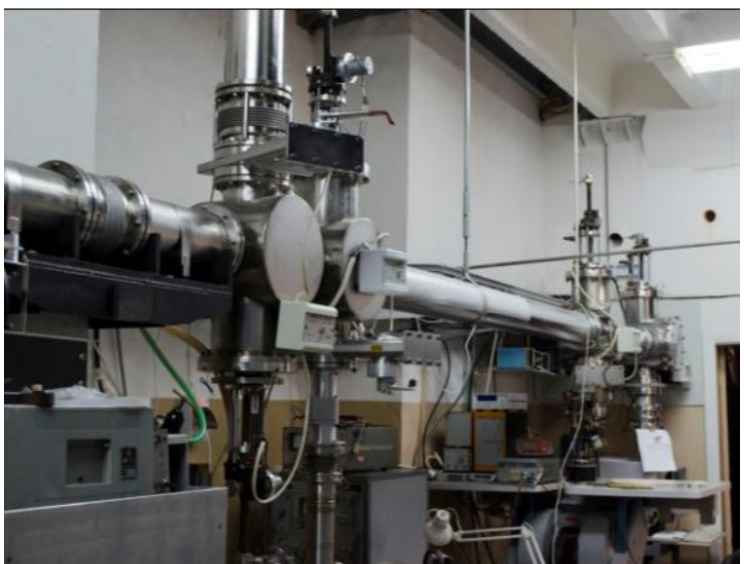
FEL Optical Cavities



1st FEL	5.64 MHz	~ 100 ps
2nd FEL	7.52 MHz	~ 50 ps
3rd FEL	3.76 MHz	~ 15 ps



Optical beamlines and user stations



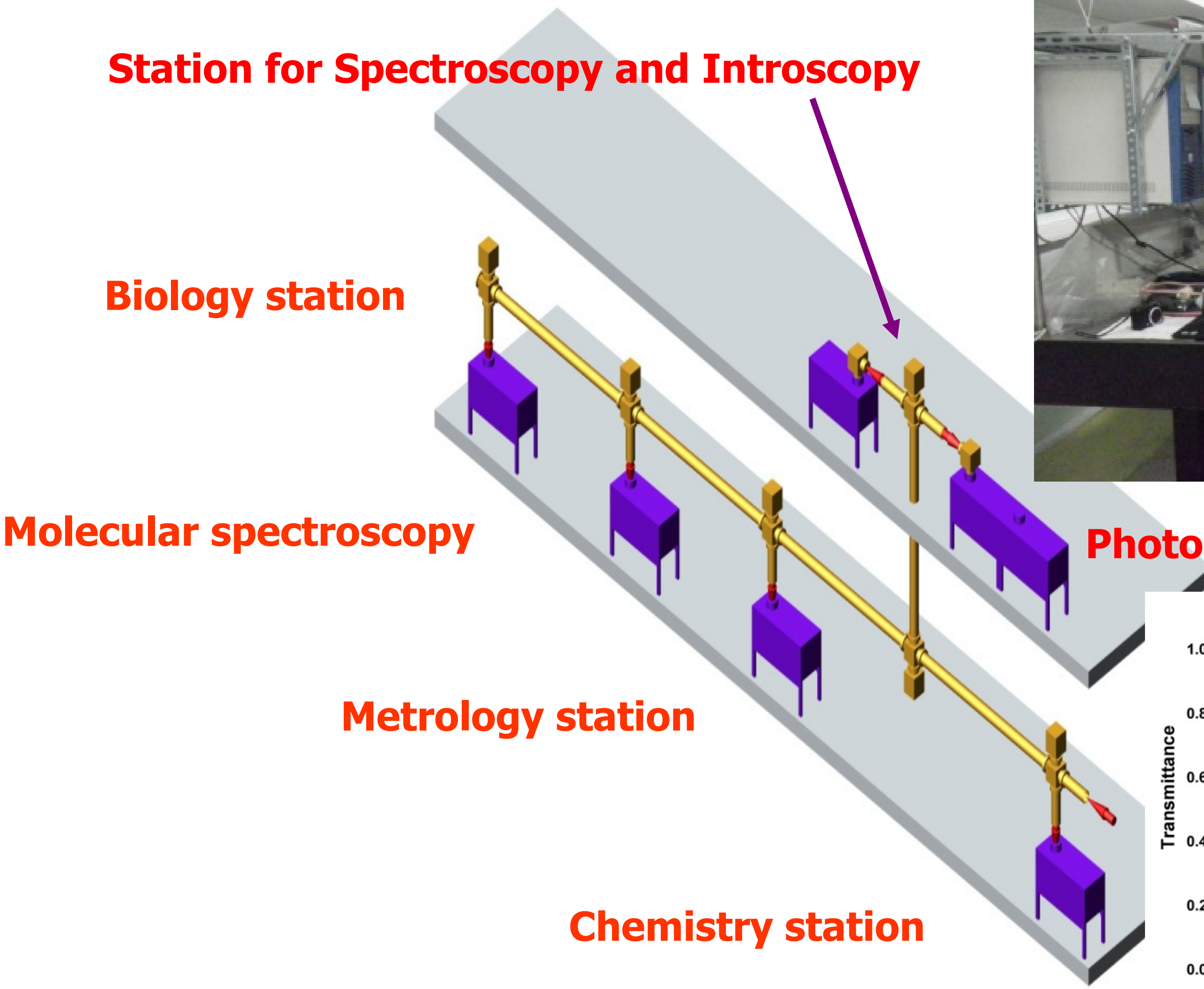
The 1st stage FEL radiation parameters

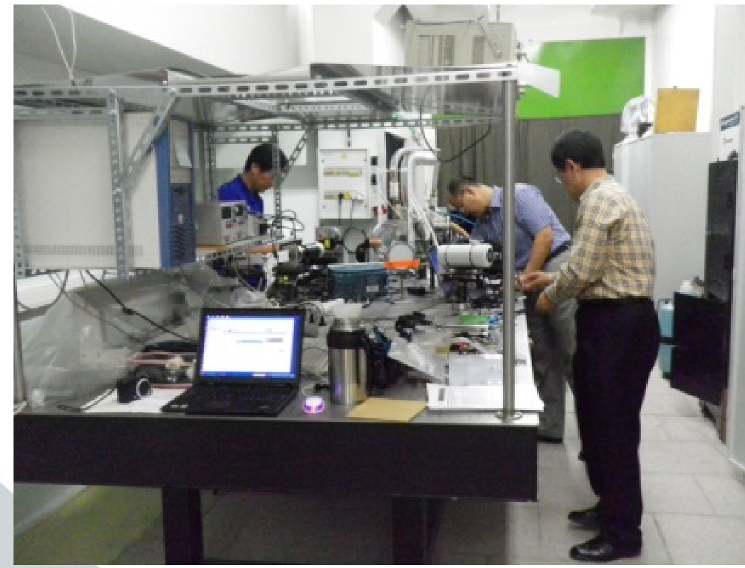
• Radiation wavelength, microns	90 - 240
• Minimum pulse duration, ps	70
• Repetition rate , MHz	5.6 / 11.2 / 22.4
• Maximum average power, kW	0.5
• Minimum relative linewidth (FWHM)	$3{\cdot}10^{-3}$
• Maximum peak power, MW	1

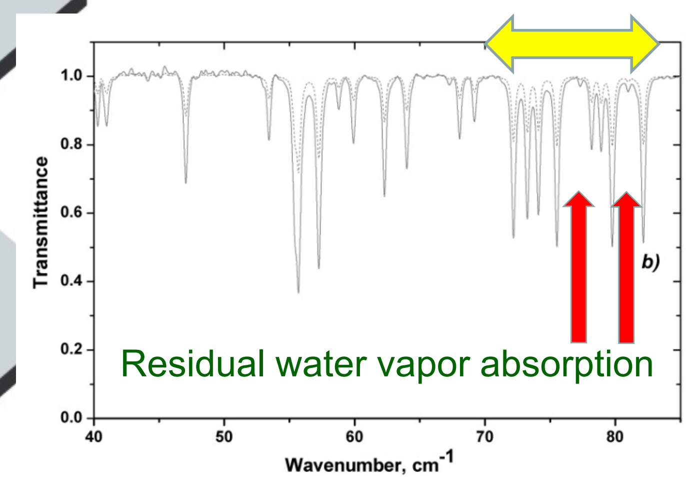
The obtained radiation parameters are still the world record in terahertz region.

Six user station are available for users

(more than 20 participating institutions)







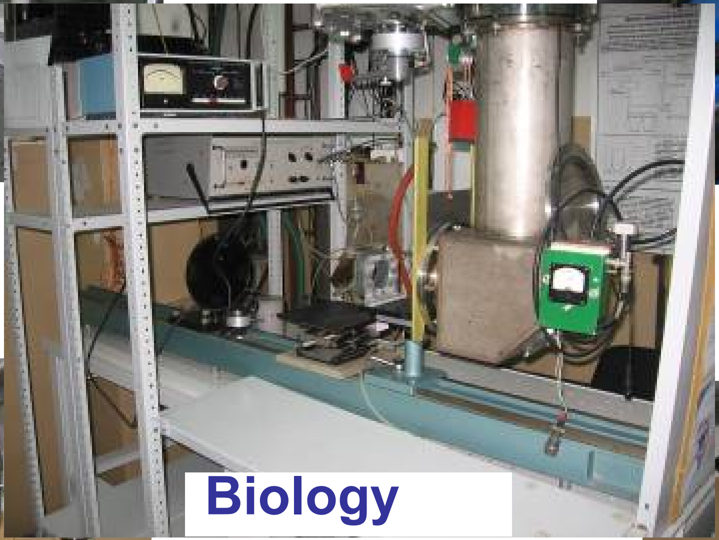
User stations at Novosibirsk FEL

Gas dynamics

Introscopy and Spectroscopy

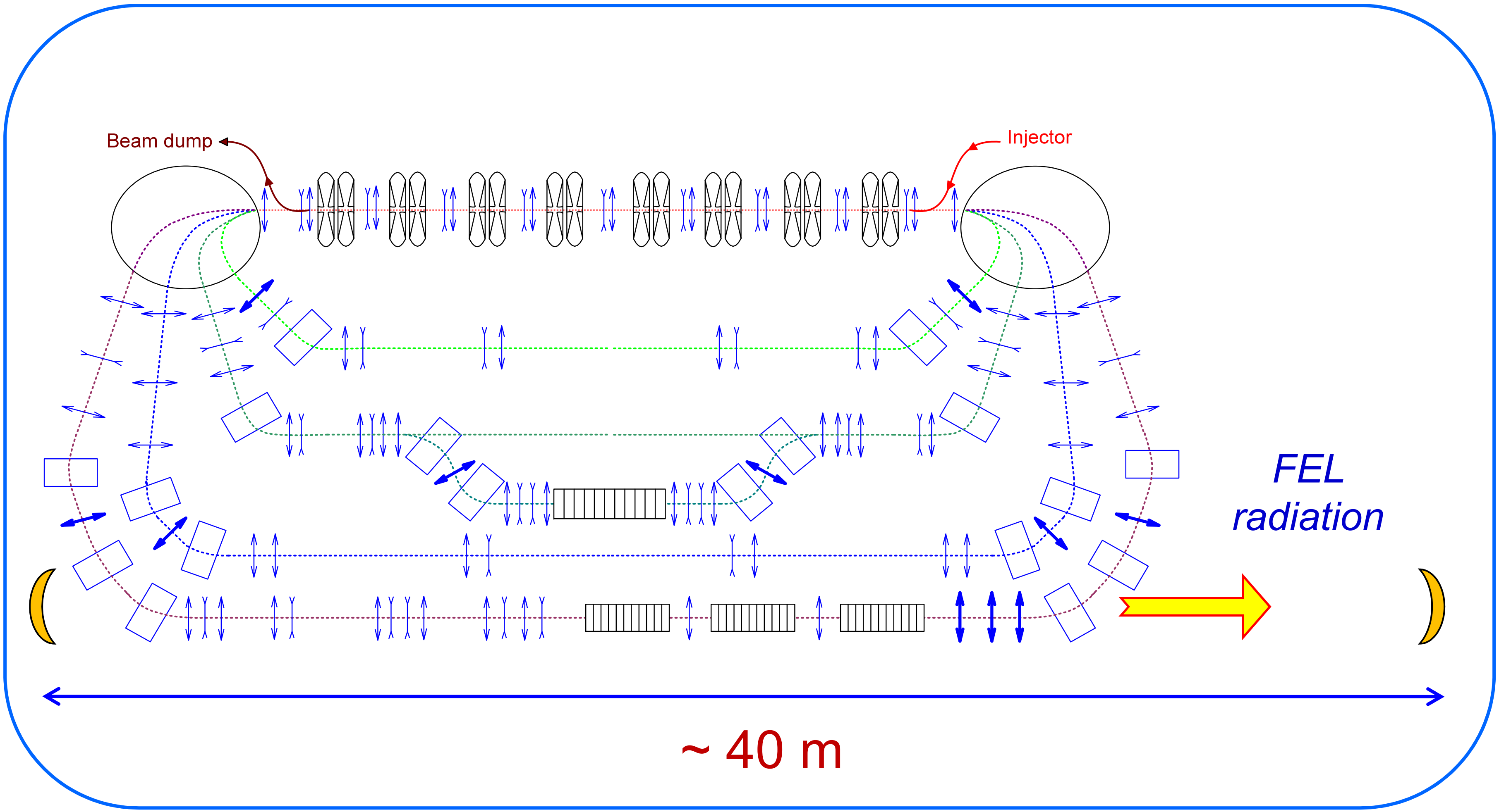
Molecular spectroscopy

Biology

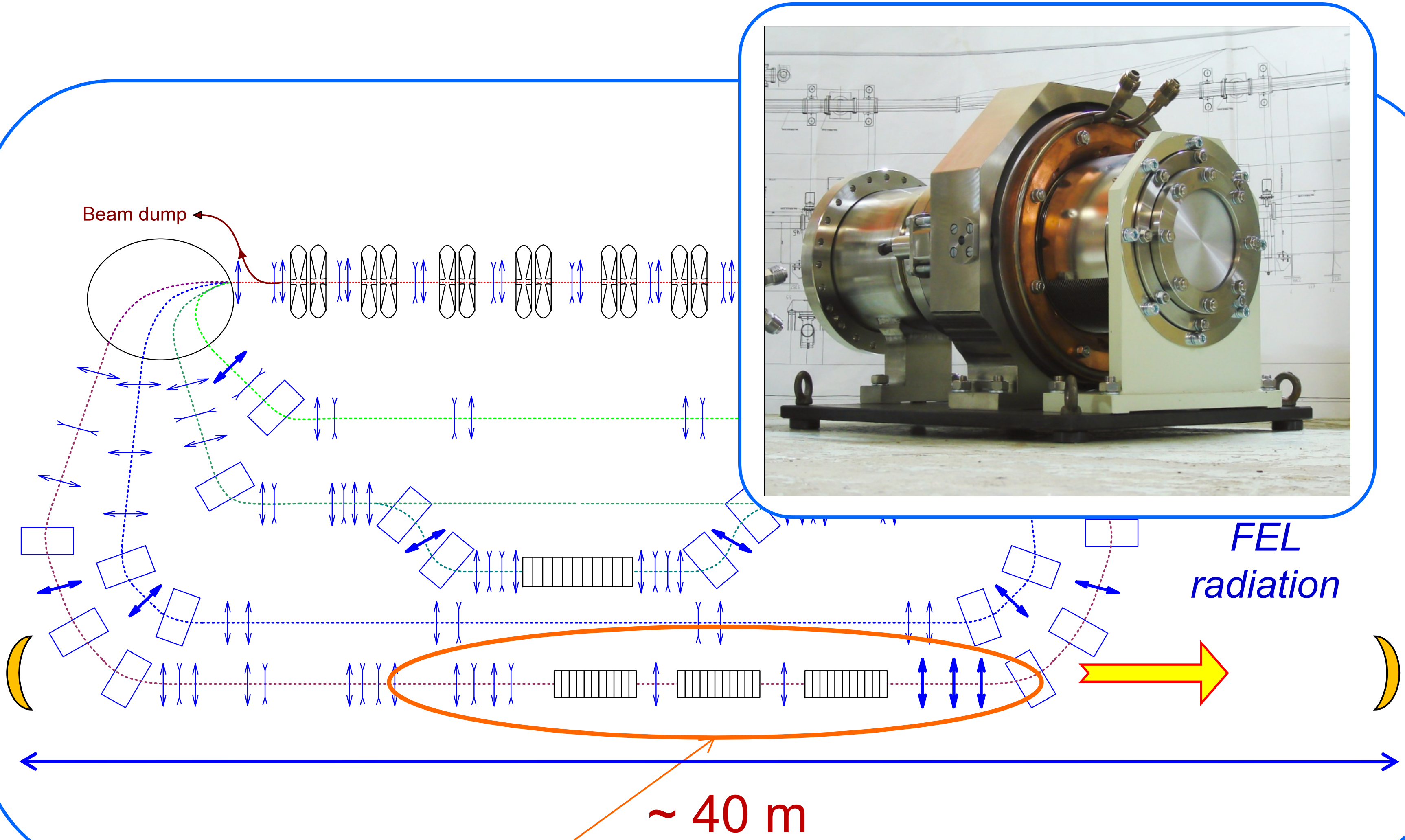


Metrology

The Third FEL

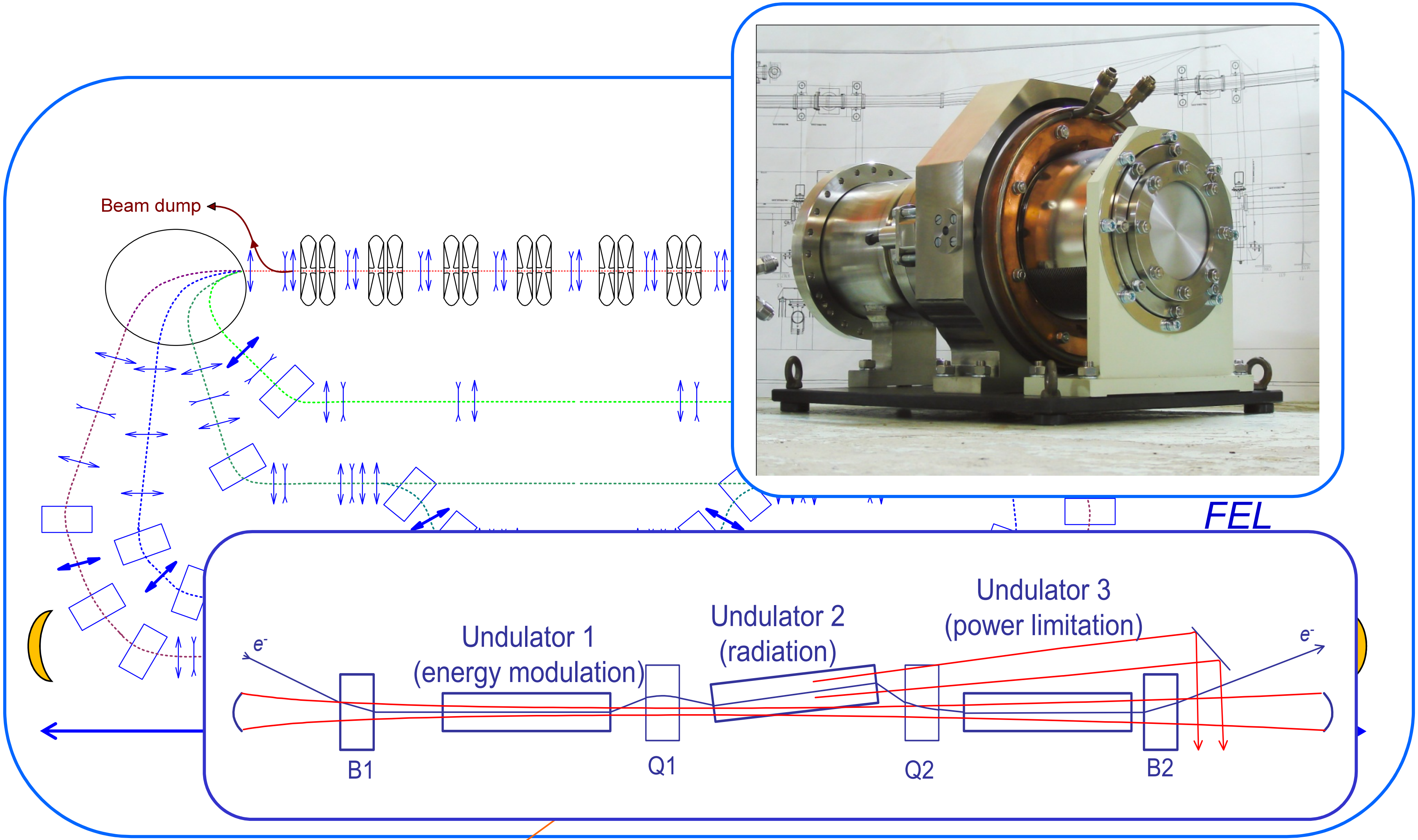


The Third FEL



Electron outcoupling scheme will be tested here

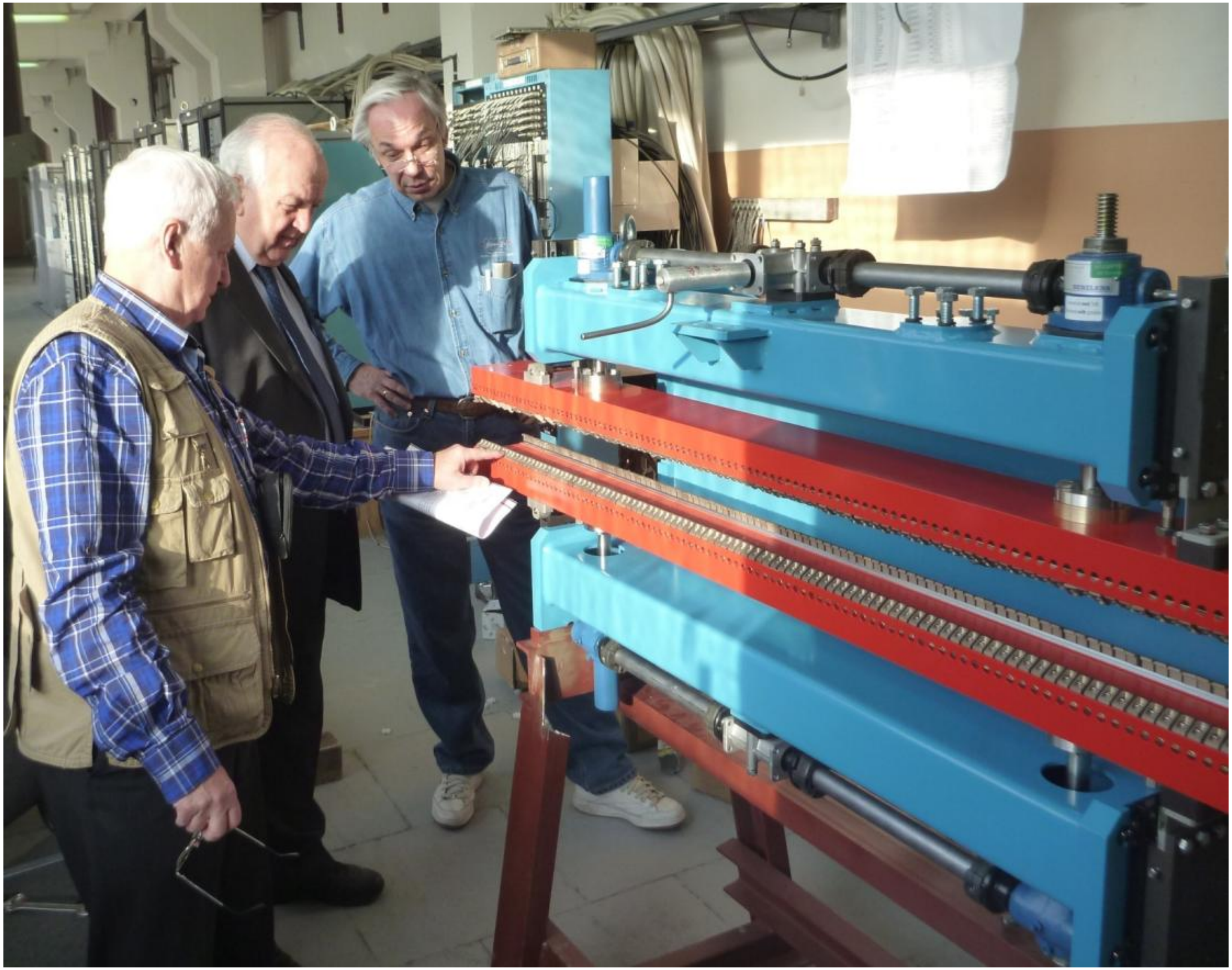
The Third FEL



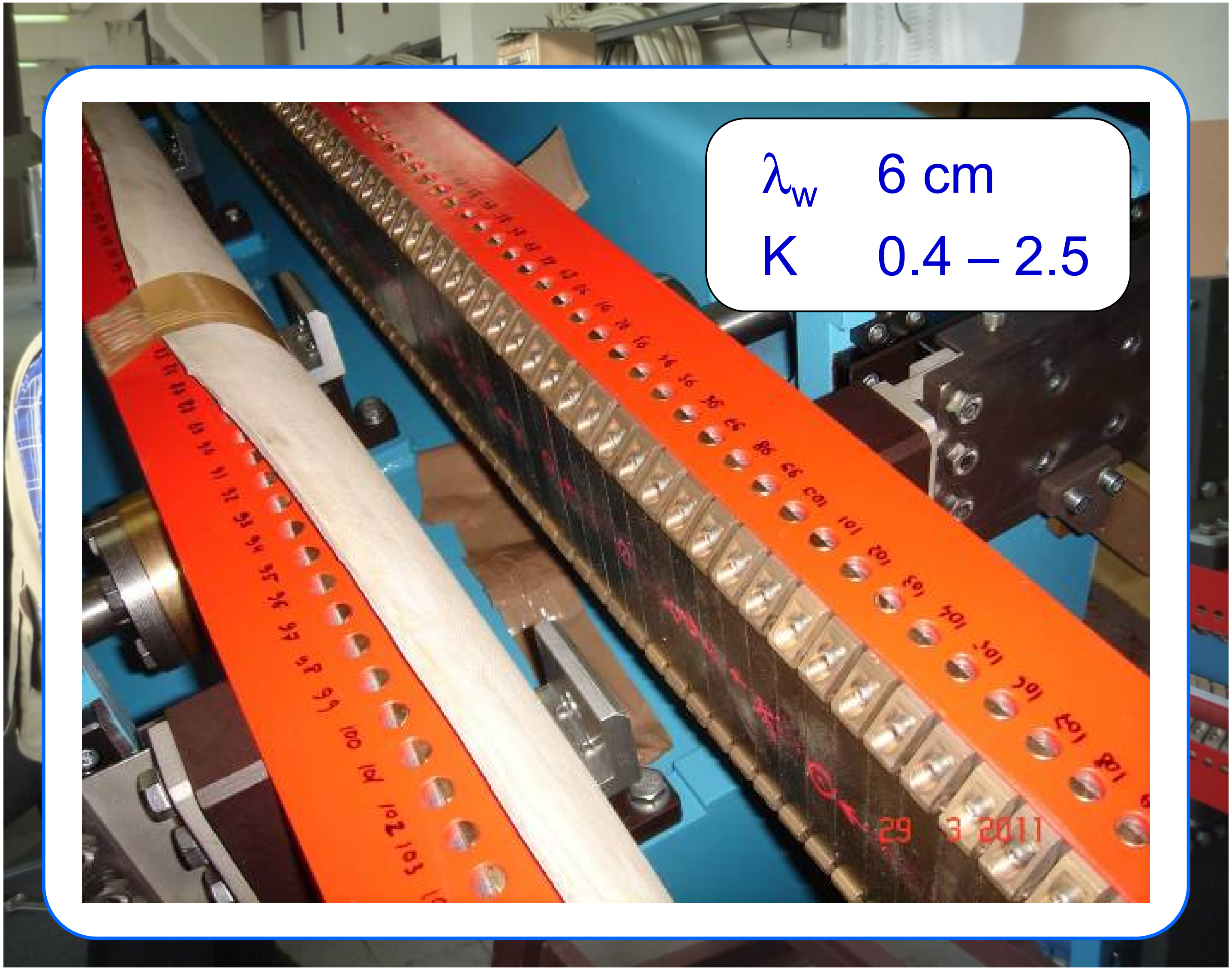
Electron outcoupling scheme will be tested here

The third FEL undulator

The third stage FEL undulator



The third stage FEL undulator

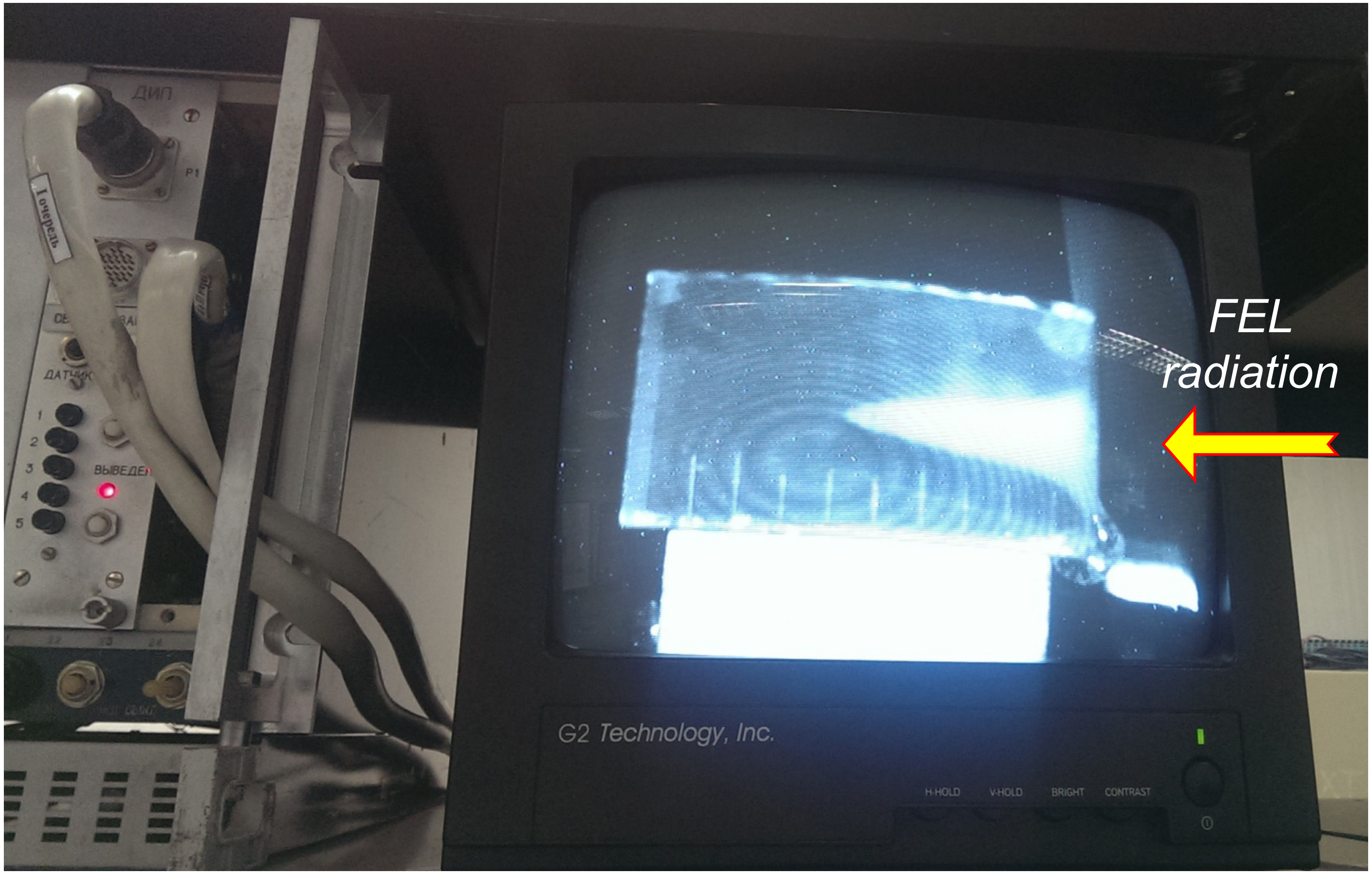


6 July 2015 – the first lasing of the 3rd FEL

Dr. Oleg Shevchenko commissioning the 3rd FEL

“First experiments” with 3rd stage FEL

Drilling holes in plexiglass

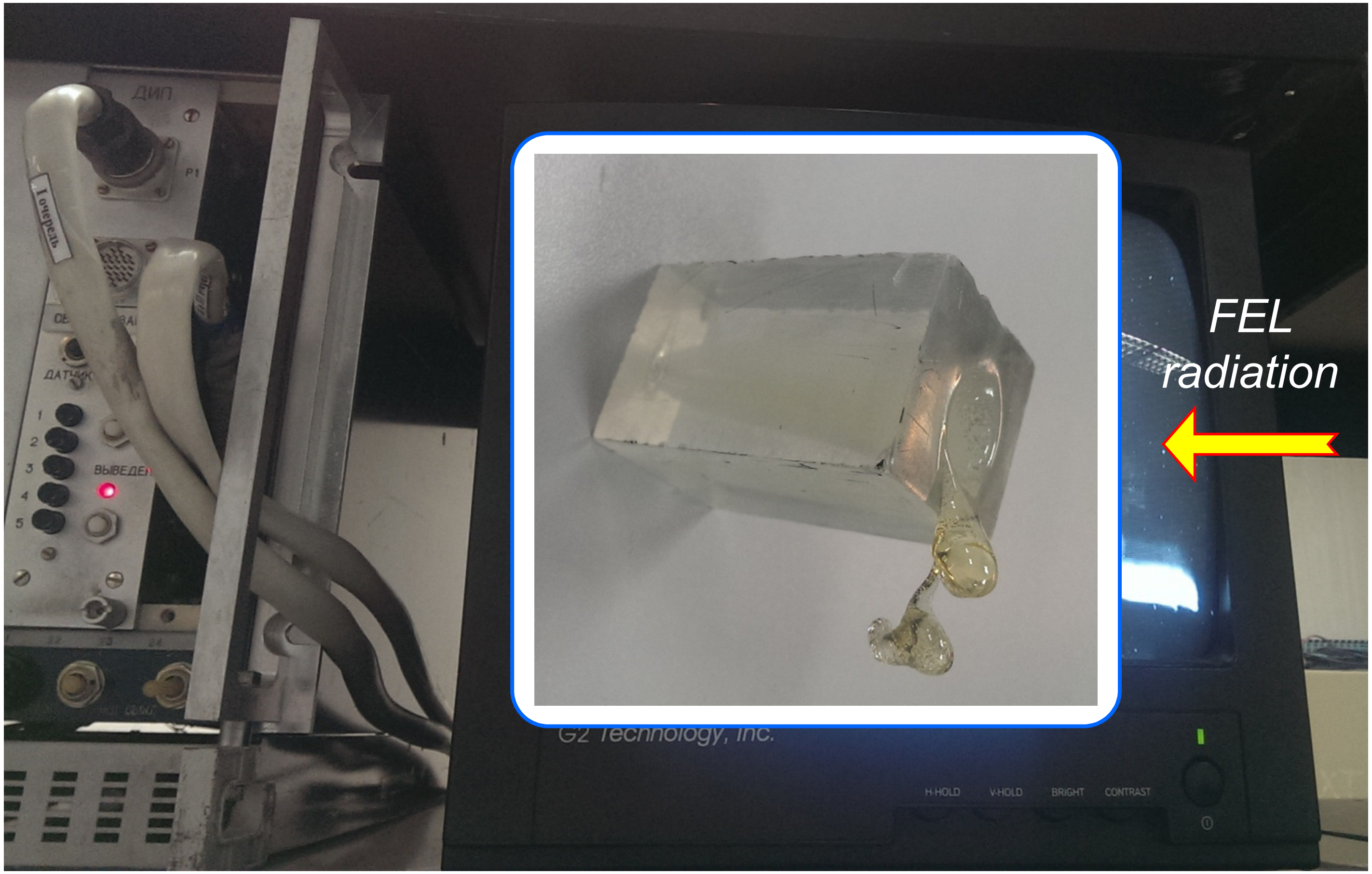


Radiation power was about 30 watts

Wavelength 8.96 μm

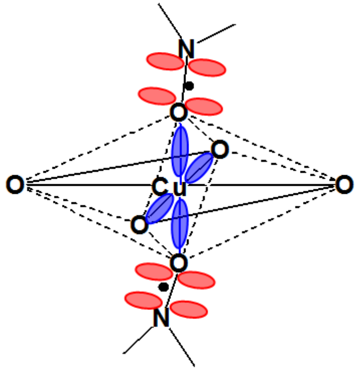
“First experiments” with 3rd stage FEL

Drilling holes in plexiglass

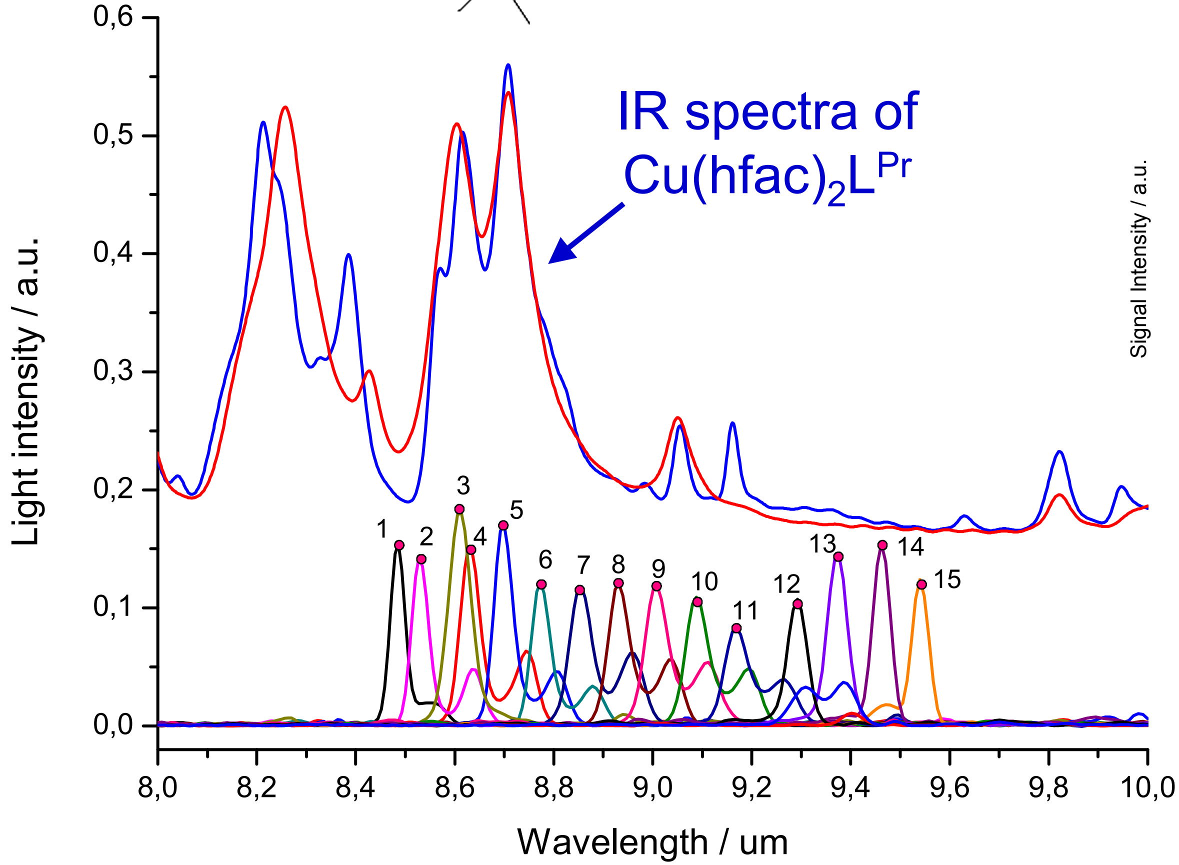


Radiation power was about 30 watts
Wavelength 8.96 μm

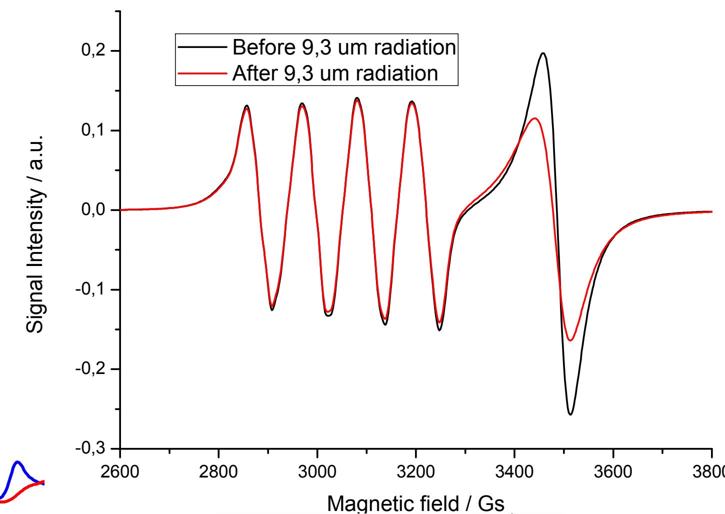
International Tomography Center SB RAS – the first user of the third FEL

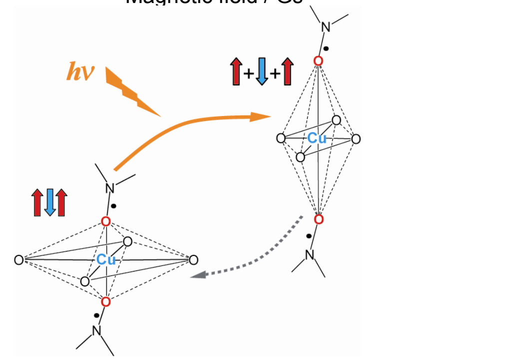


Influence of IR-light to the spin state of photoswitchable copper(II)-nitroxide magnetoactive compound $Cu(hfac)_2L^{Pr}$



EPR spectra of $Cu(hfac)_2L^{Pr}$

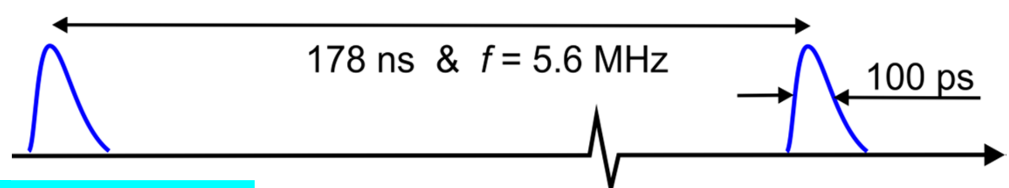




NovoFEL radiation parameters

Laser	Terahertz	Far-Infrared	Infrared
Status	In operation since 2003	In operation since 2009	In operation since 2015
Wavelength, μm	90 – 240	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



Nearest plans

- Replacement of the electromagnetic undulator of the 2nd FEL by the variable-period undulator
- Demonstration of electron outcoupling
- Installation of the RF gun
- Further halo and “dark” current suppression
- Continue work for users

Thank you for your attention.