Novosibirsk Free Electron Laser:

Terahertz and Infrared Coherent Radiation Source

Presented by Ya. V. Getmanov
Budker INP

Project participants

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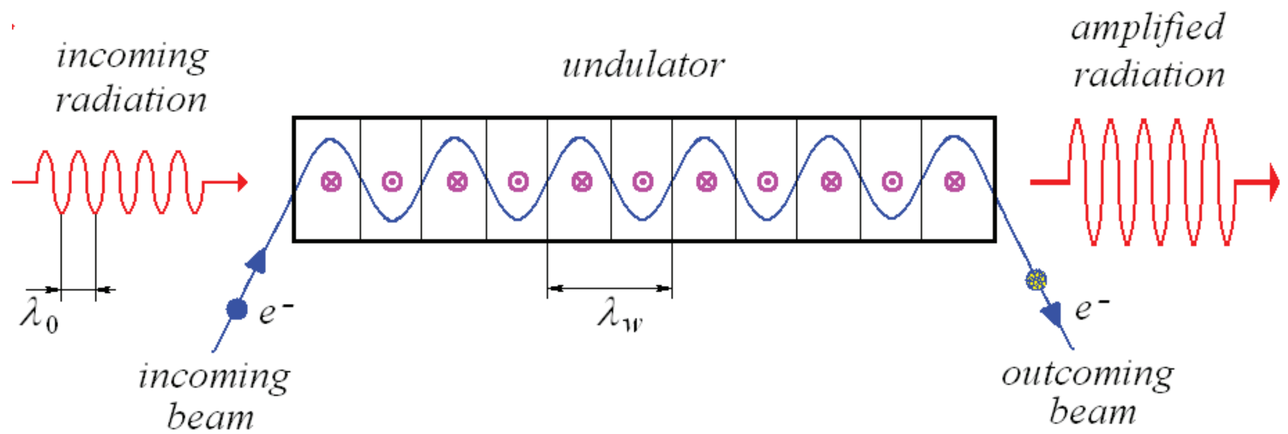
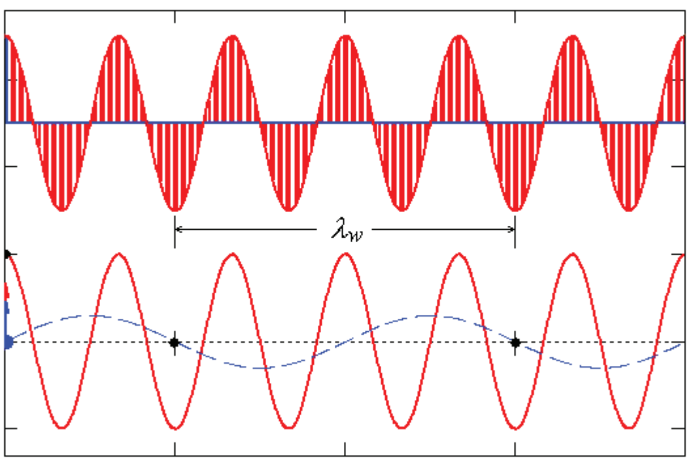
Outline

- Brief introduction to the FEL physics
- The NovoFEL accelerator design and operation
- NovoFEL as three FELs based source of radiation
- The third FEL commissioning and first experiments
- Nearest and far future plans for the conclusion

FEL principle of operation





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

↑

synchronisme condition

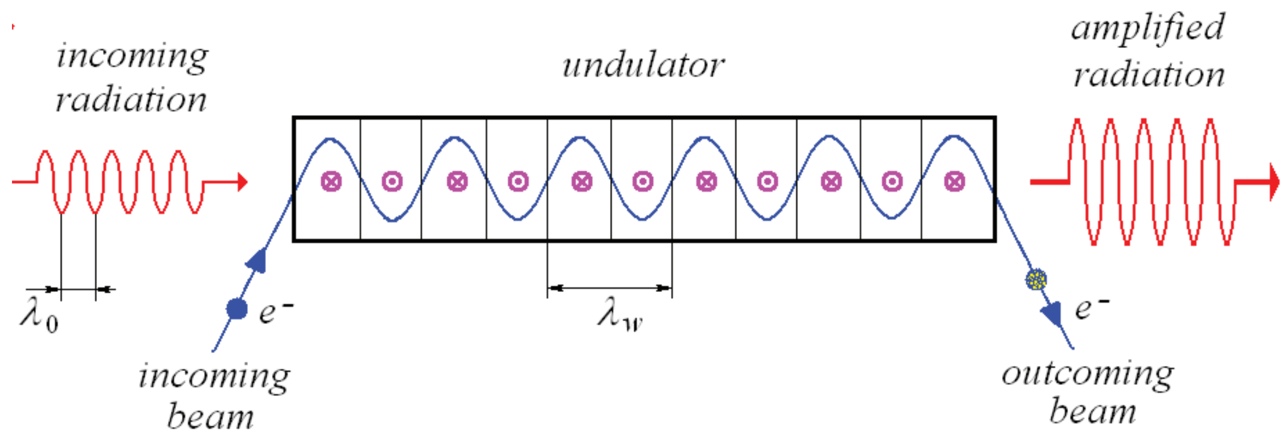
which is necessary for the

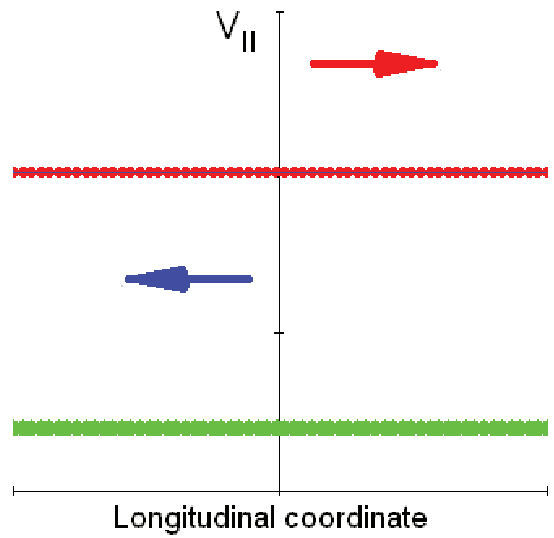
energy transfer

↓

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

FEL principle of operation





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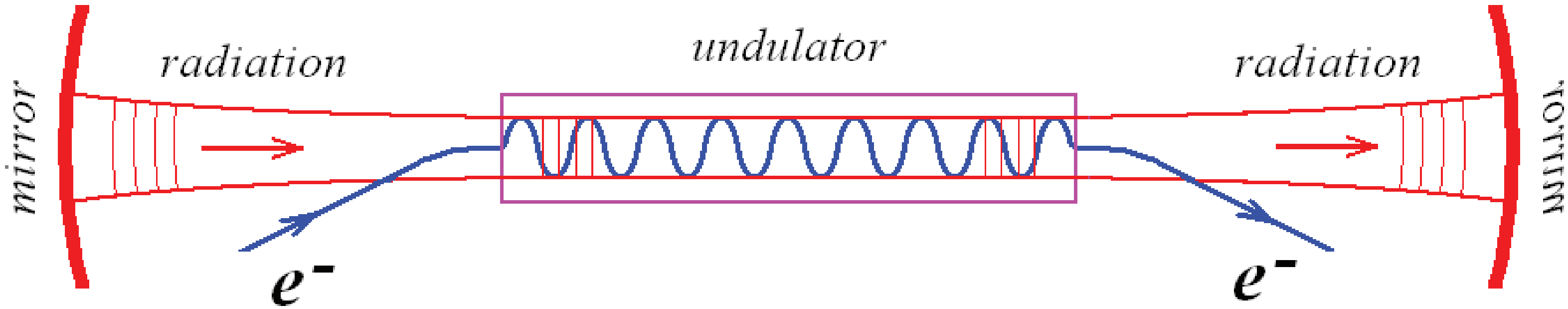
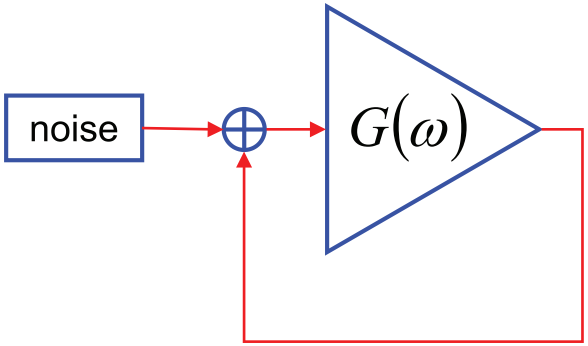
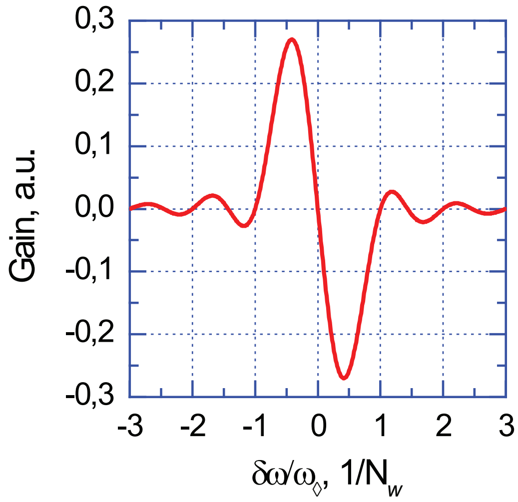
FEL principle of operation

FEL oscillator



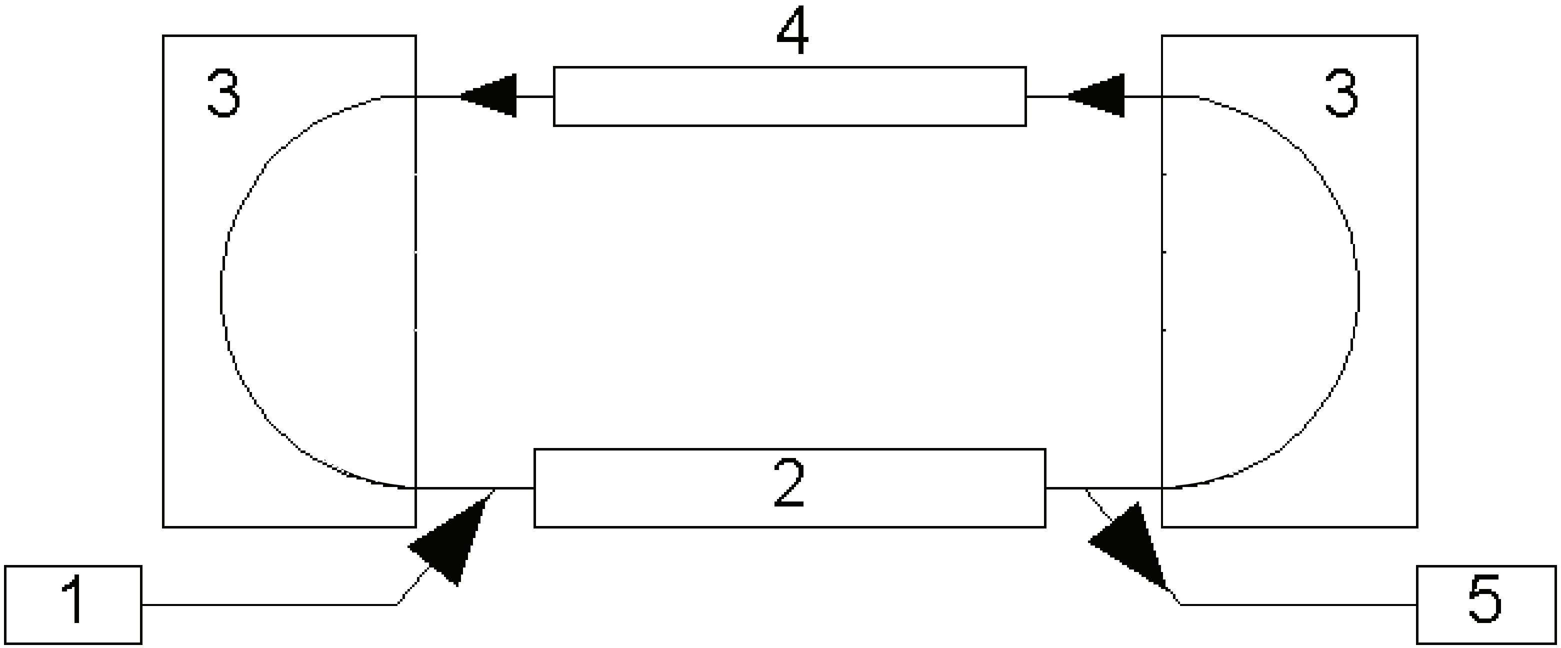
Equivalent scheme





NovoFEL Accelerator Design

Energy Recovery Linac

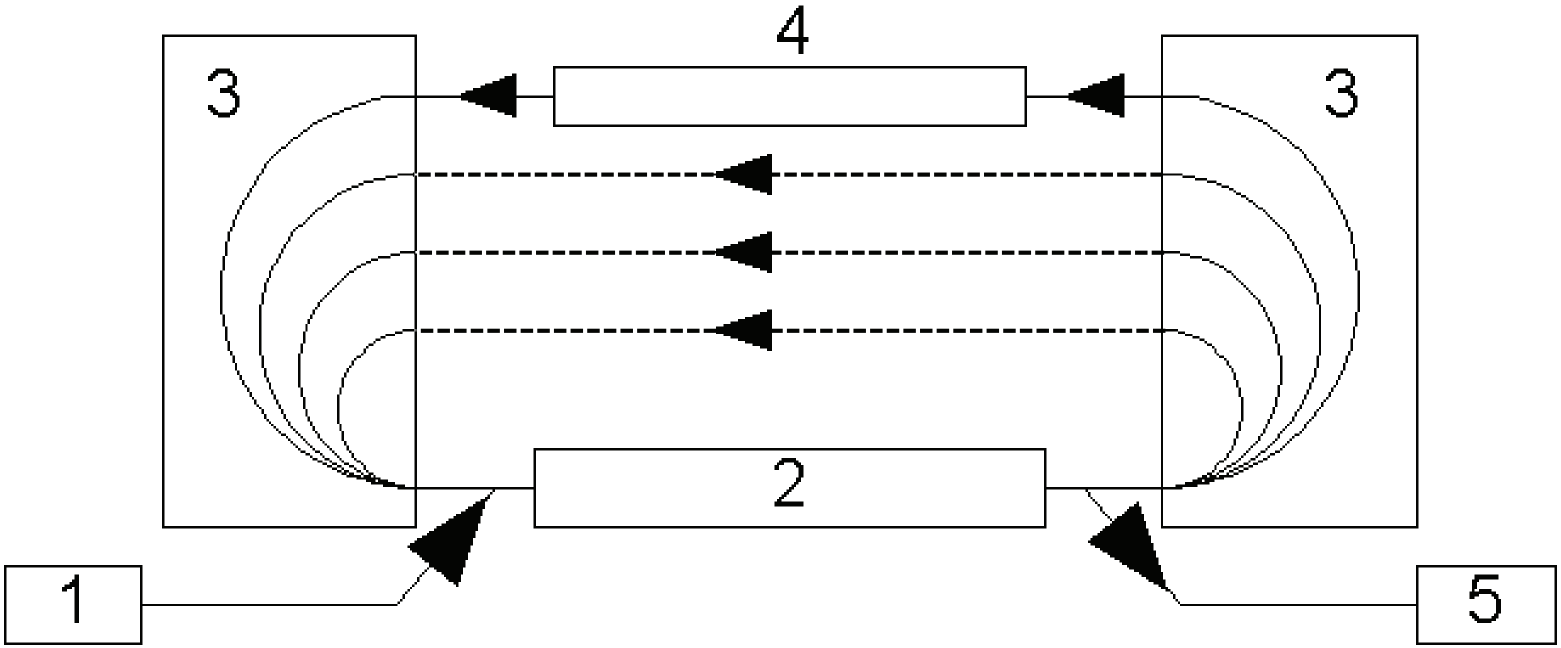


1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 –dump

Accelerator is the most important part of any **FEL**.
ERL is the best choice for **high power FEL**.

NovoFEL Accelerator Design

Energy Recovery Linac



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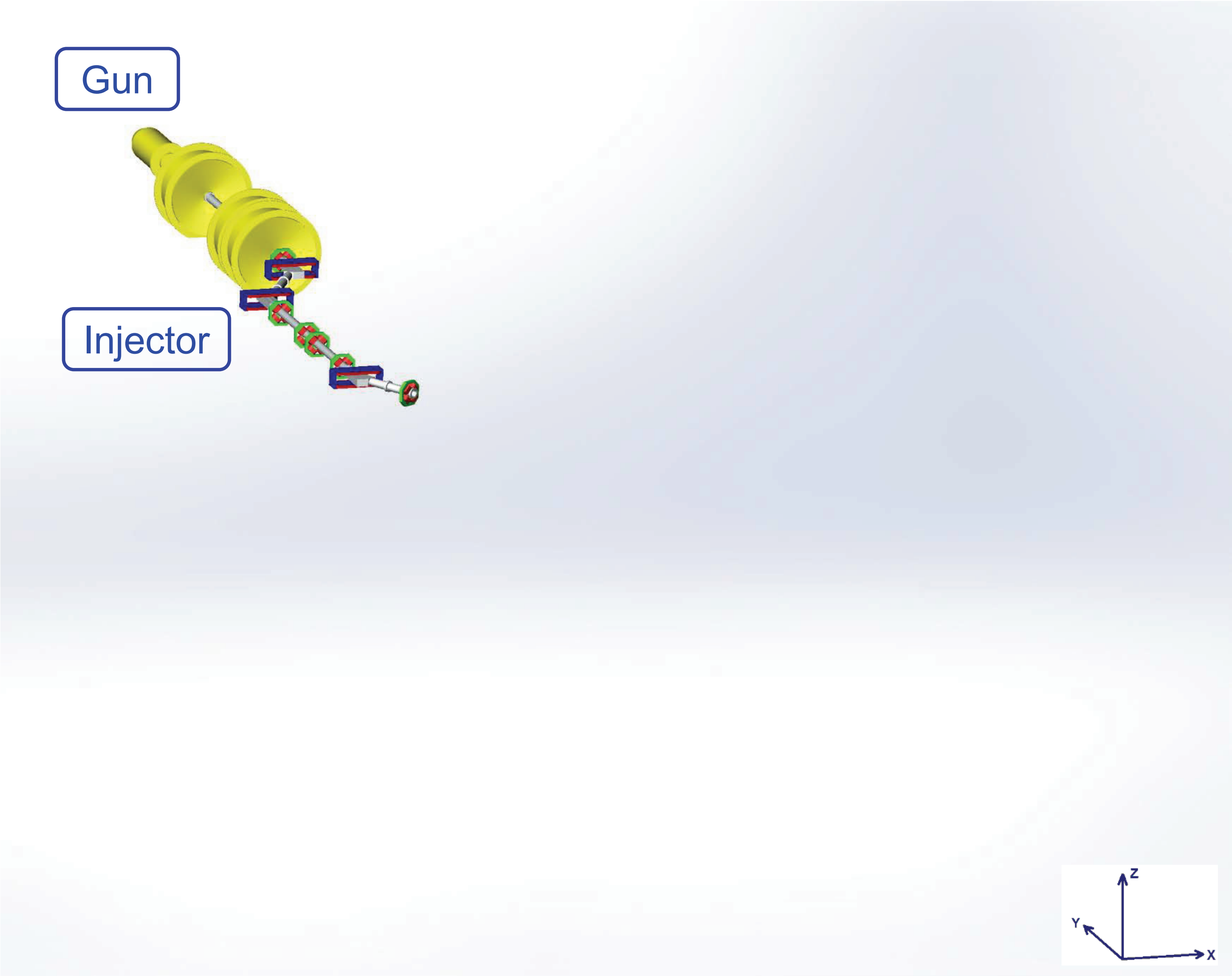

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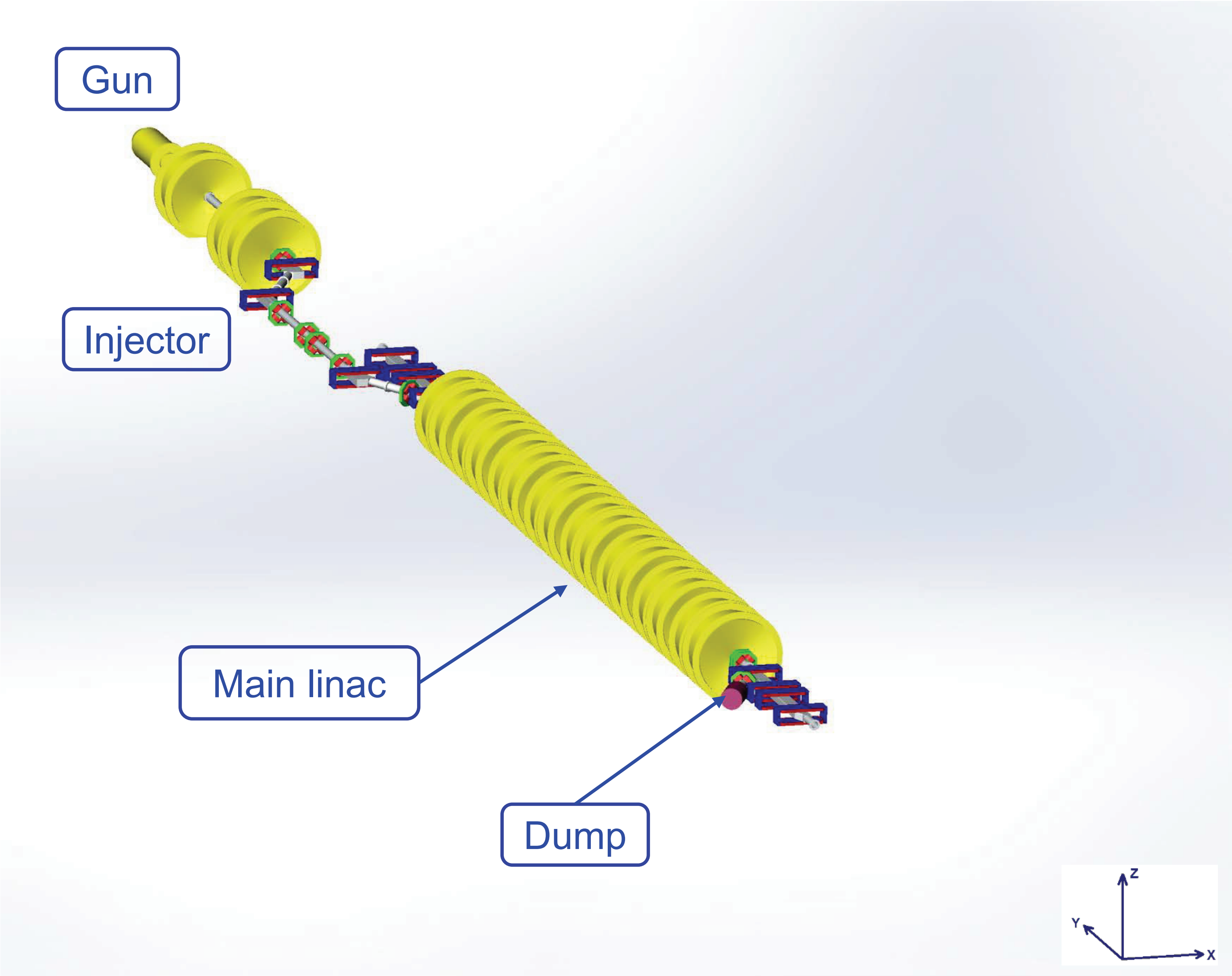

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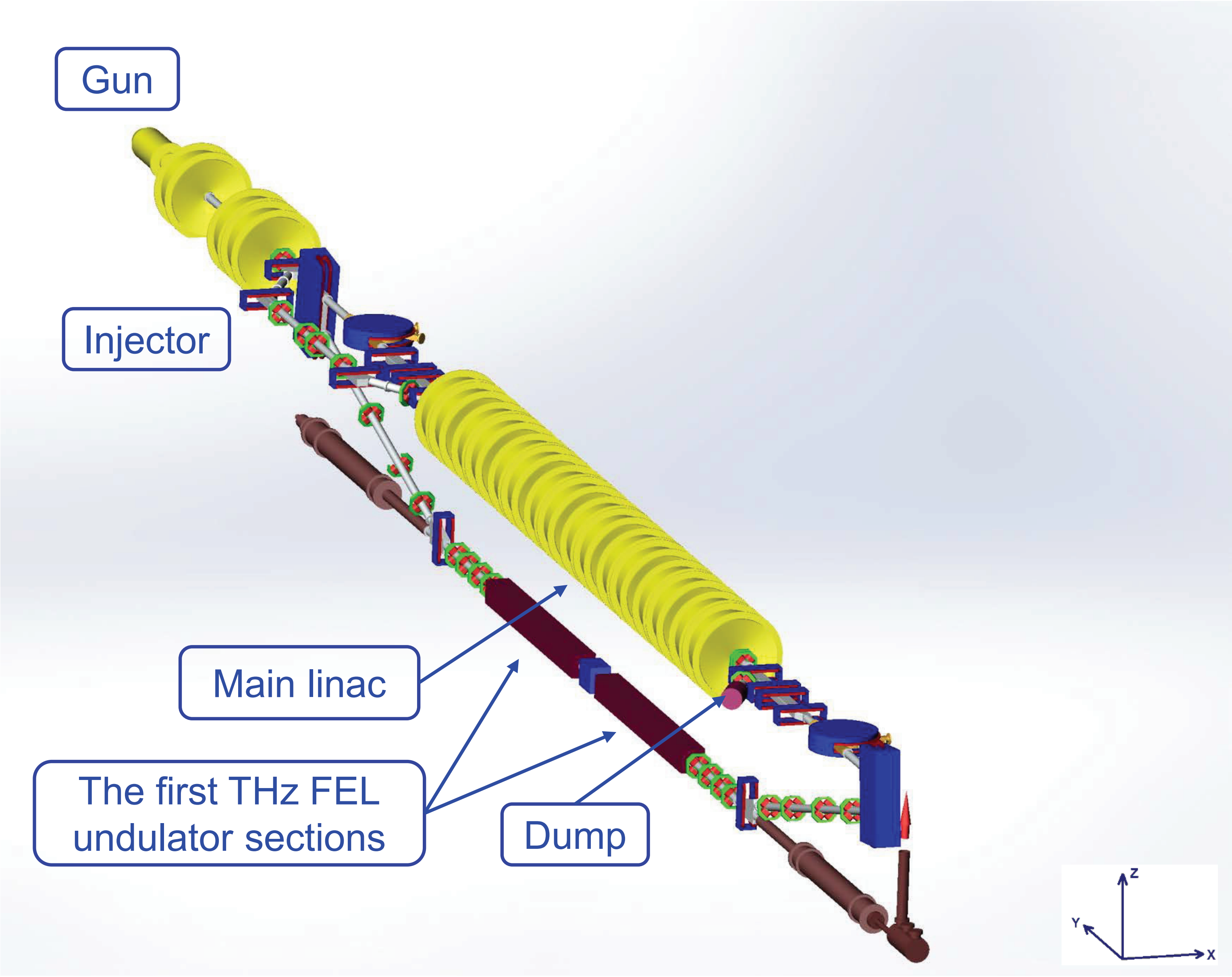

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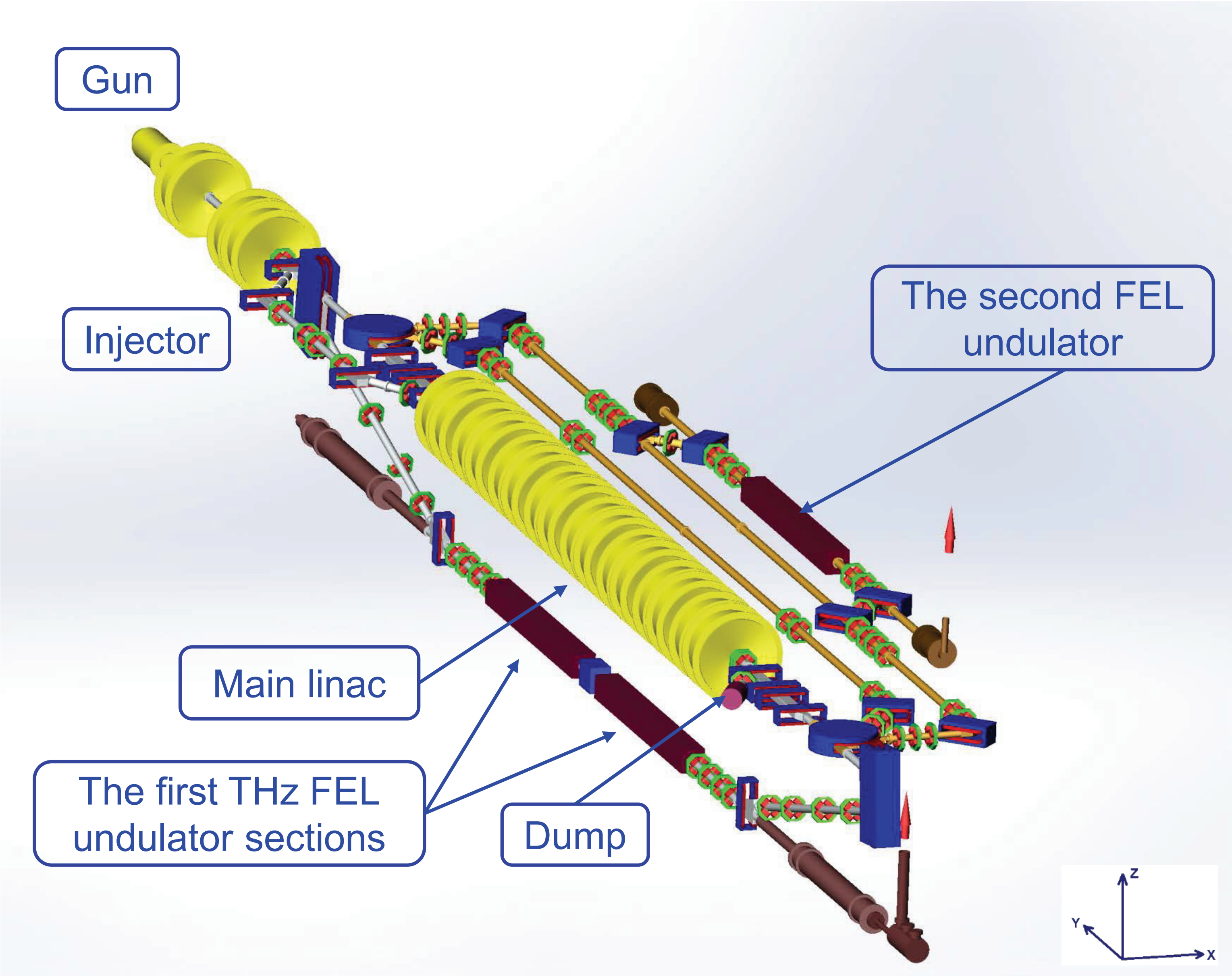

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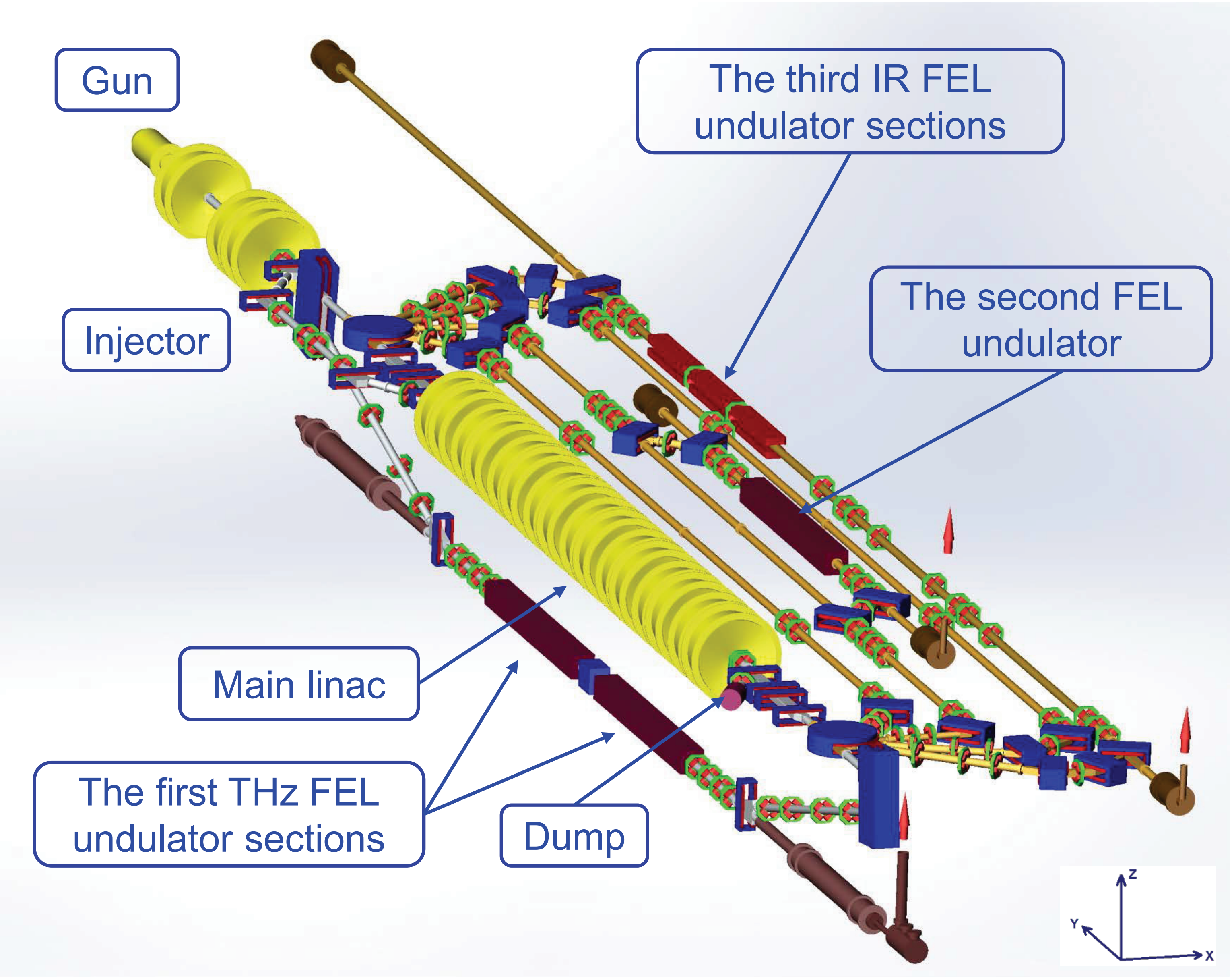
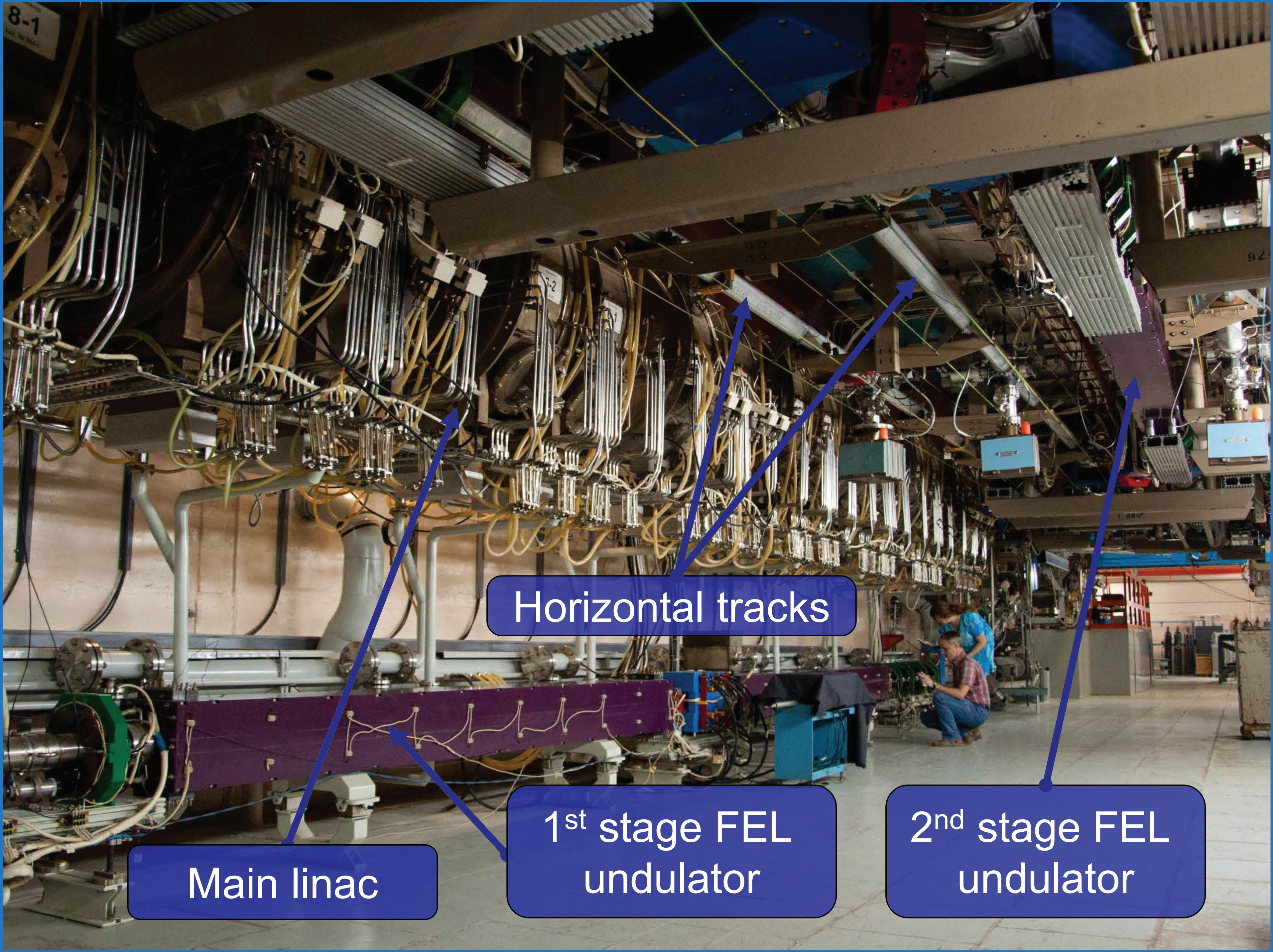
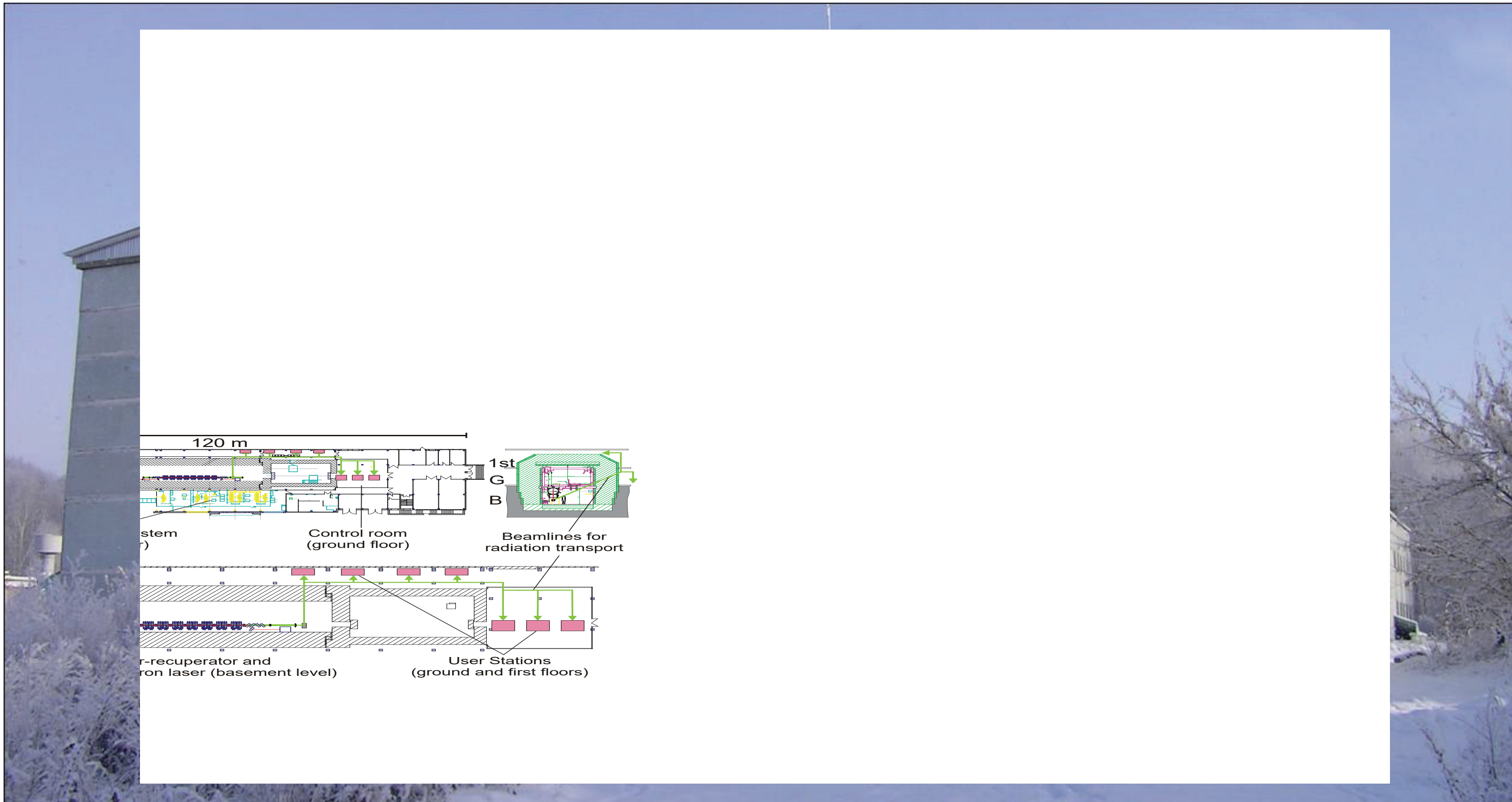



Horizontal tracks
Main linac
1st stage FEL undulator
2nd stage FEL undulator

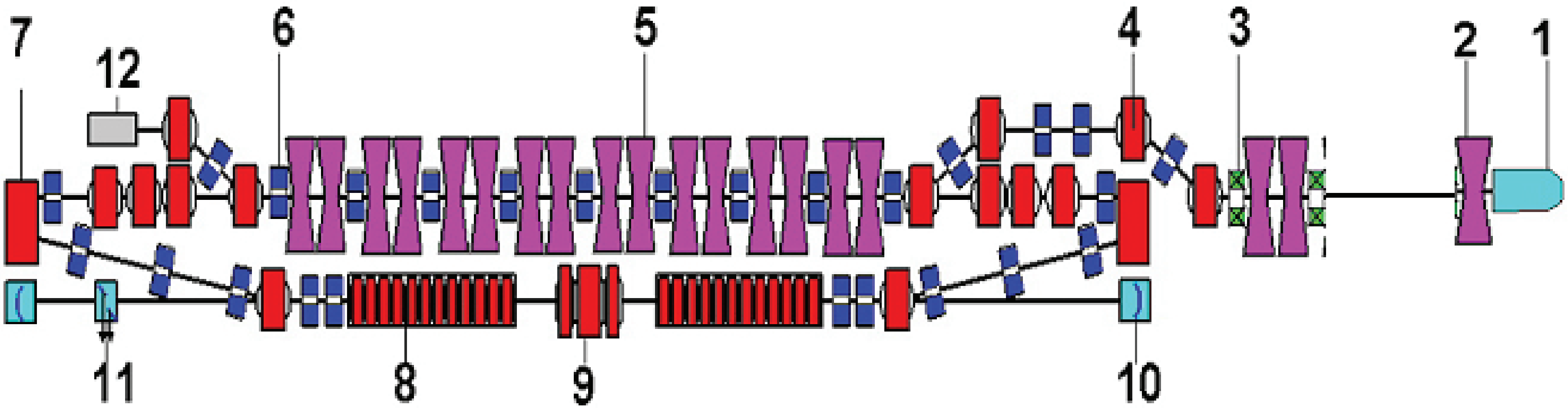

3rd stage FEL undulator

Siberian Center of Photochemical Research

Siberian Center of Photochemical Research



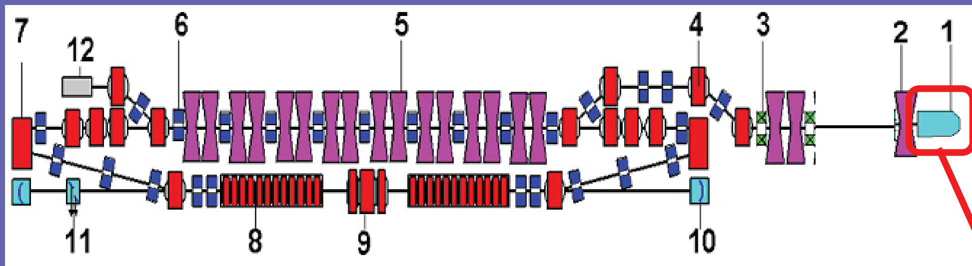
Layout of Injector, Main Linac and Vertical Beamline (the First ERL)

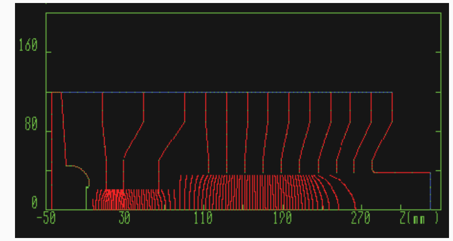


1 – electron gun
2 – bunching cavity
3 – focusing solenoids
4 – merger
5 – main linac
6 – focusing quadrupoles

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

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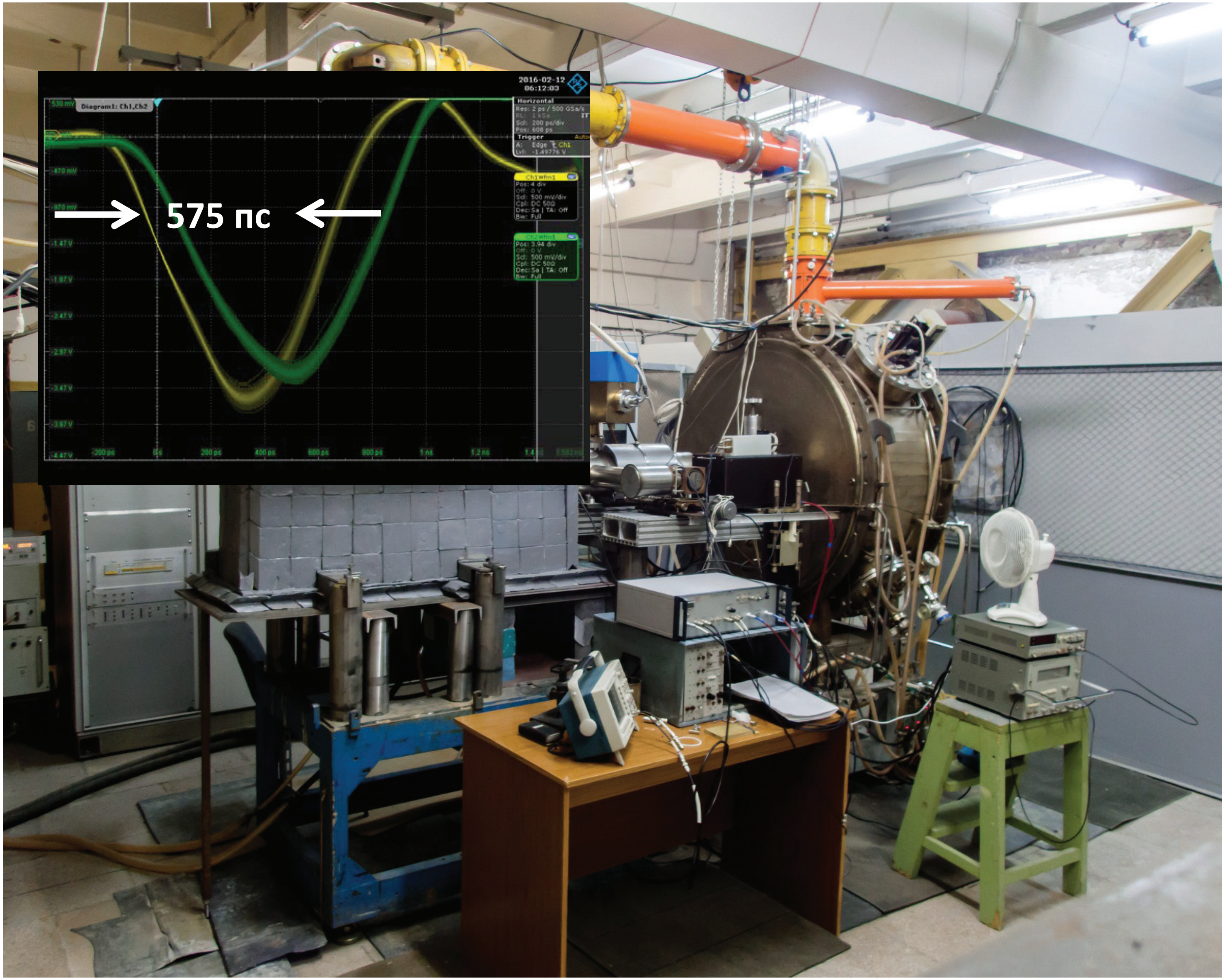
RF Gun Test Setup

RF Gun Test Setup



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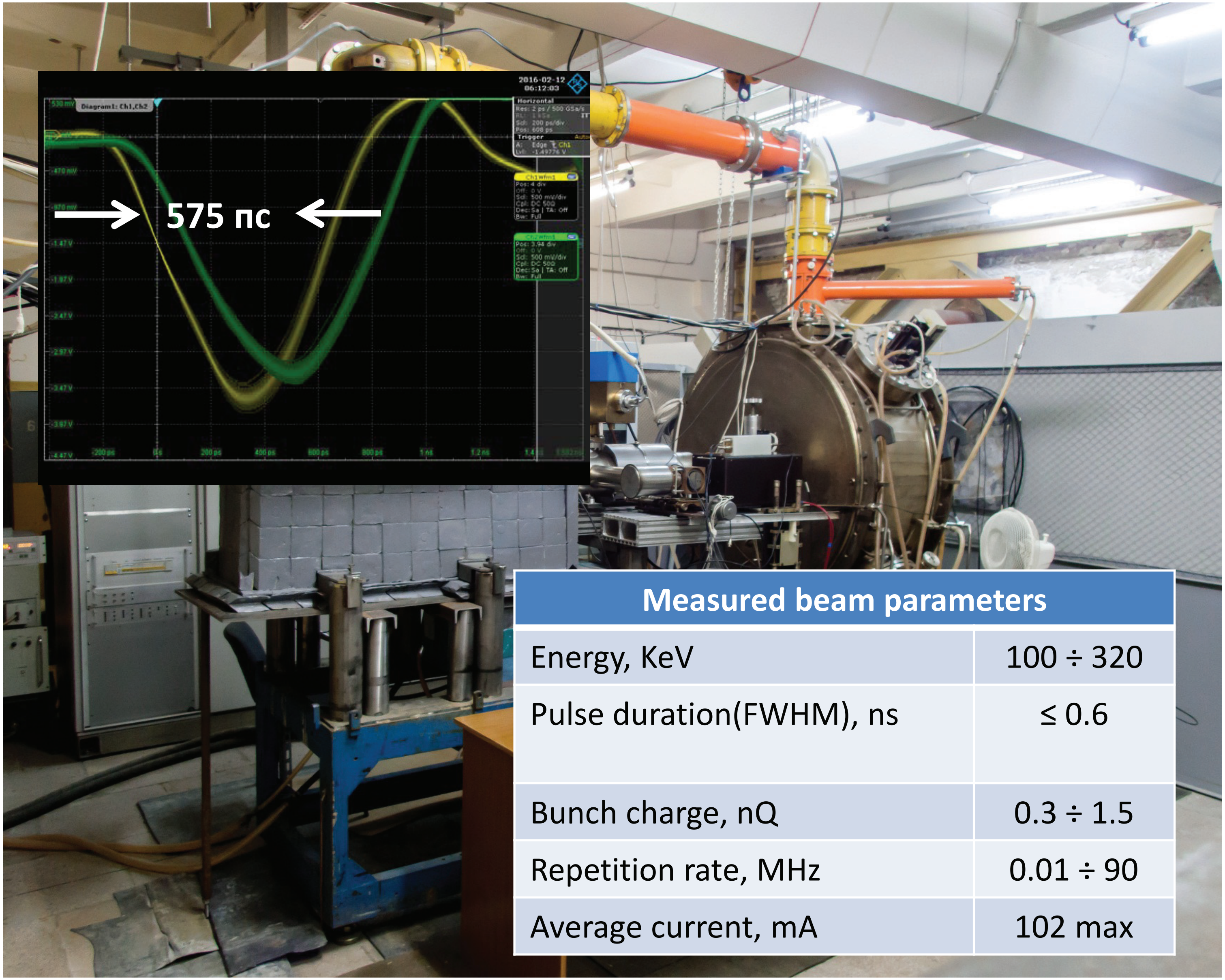
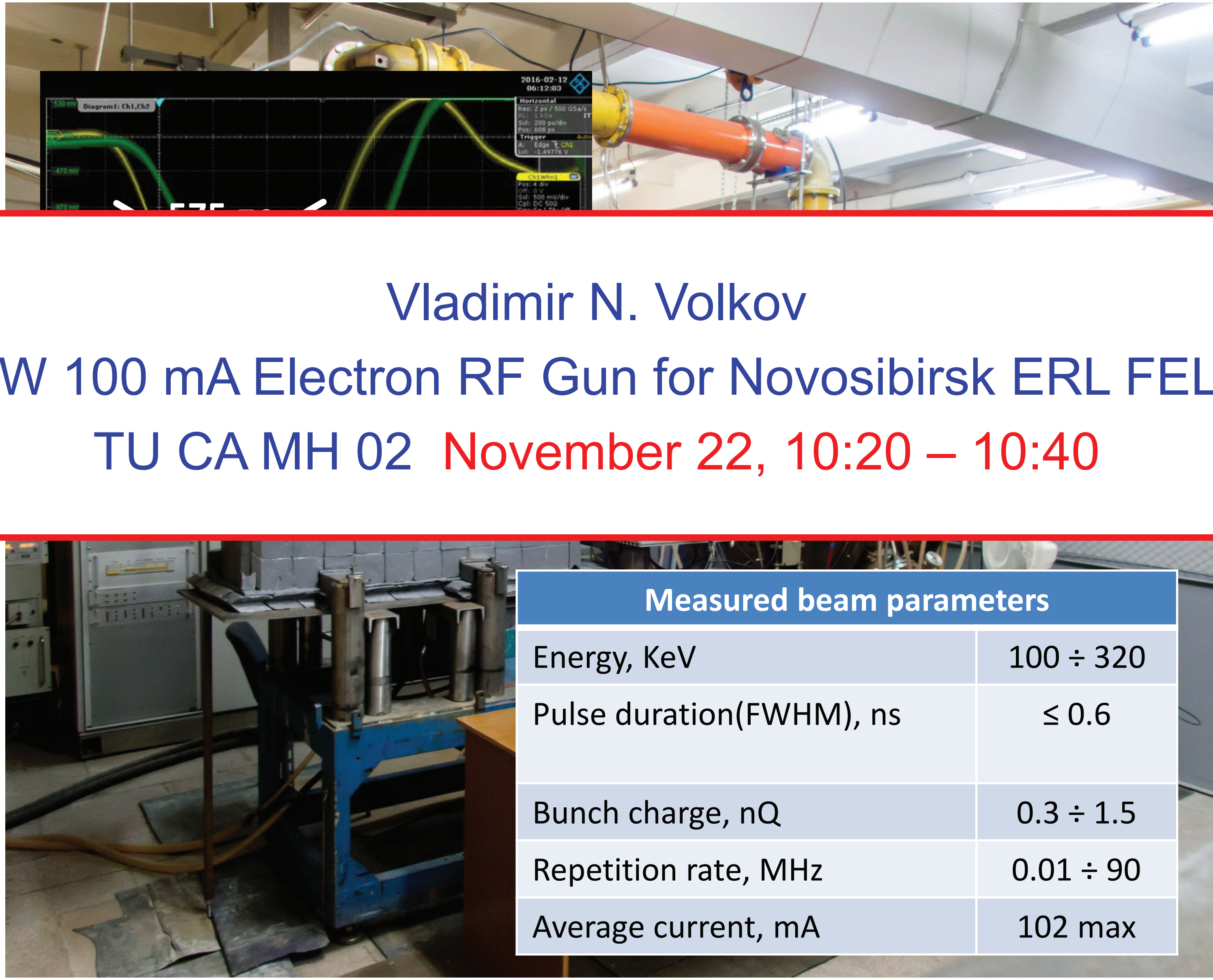


Measured beam parameters	
Energy, KeV	100 ÷ 320
Pulse duration(FWHM), ns	≤ 0.6
Bunch charge, nQ	0.3 ÷ 1.5
Repetition rate, MHz	0.01 ÷ 90
Average current, mA	102 max

RF Gun Test Setup



Vladimir N. Volkov

CW 100 mA Electron RF Gun for Novosibirsk ERL FEL

TU CA MH 02 November 22, 10:20 – 10:40

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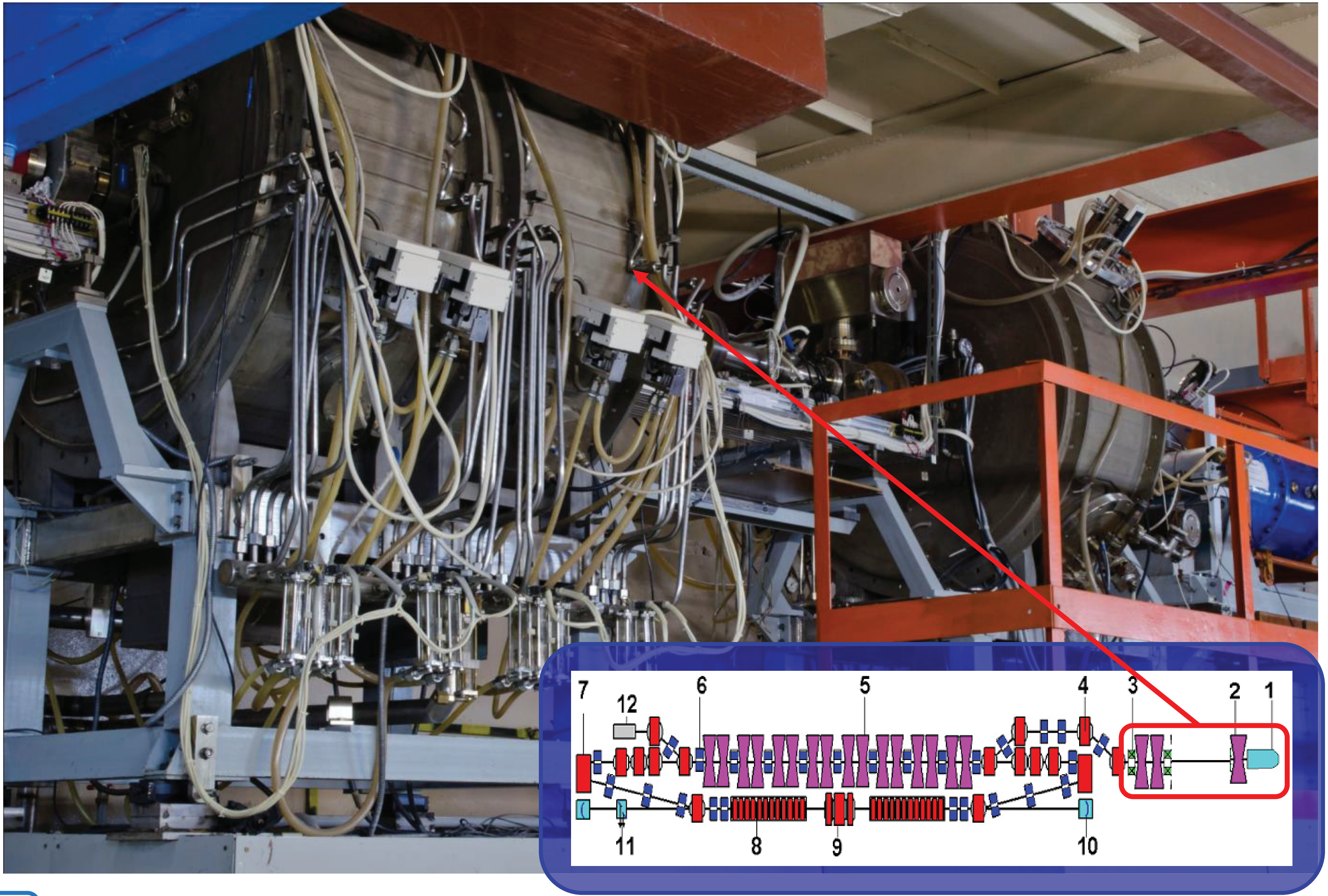
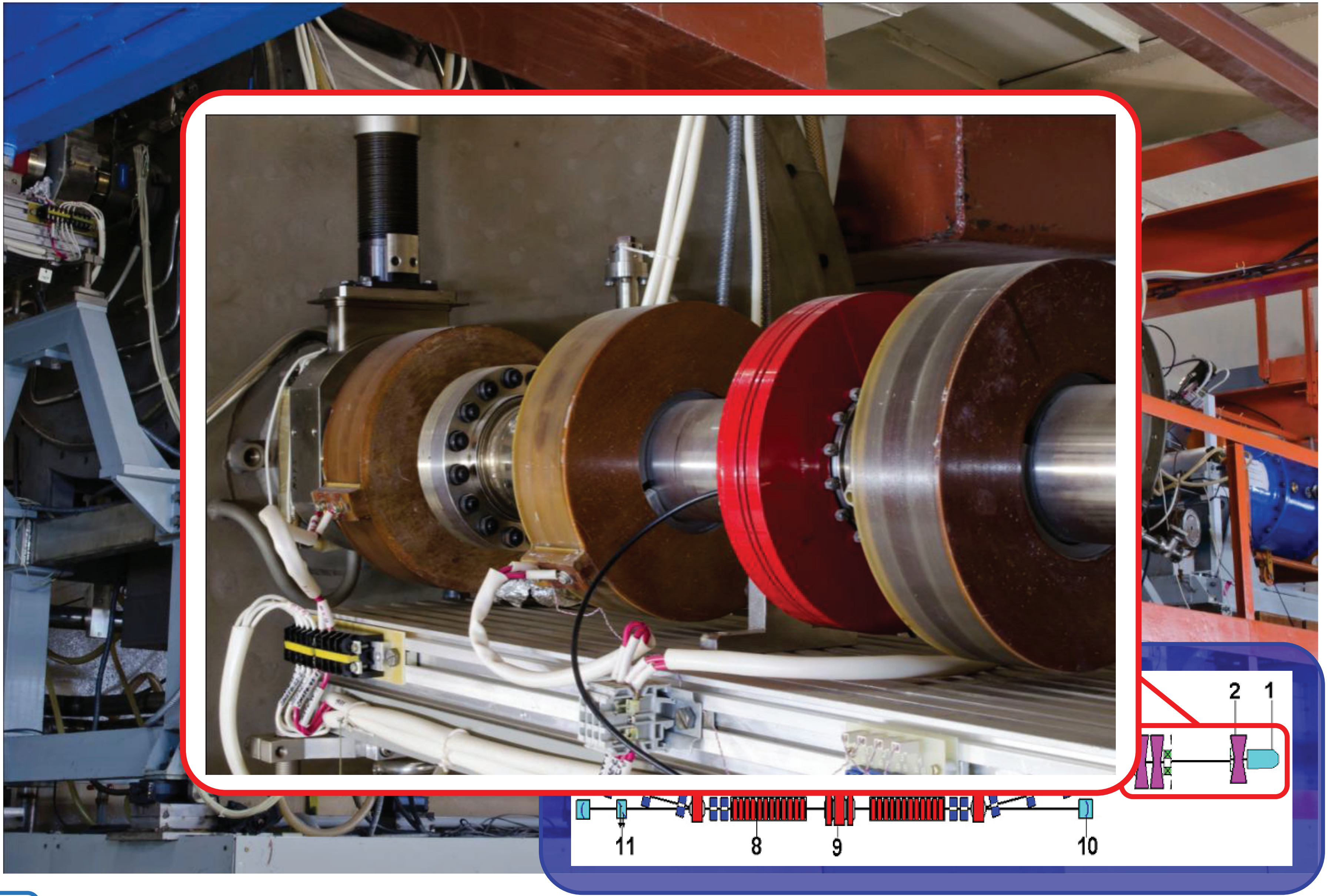
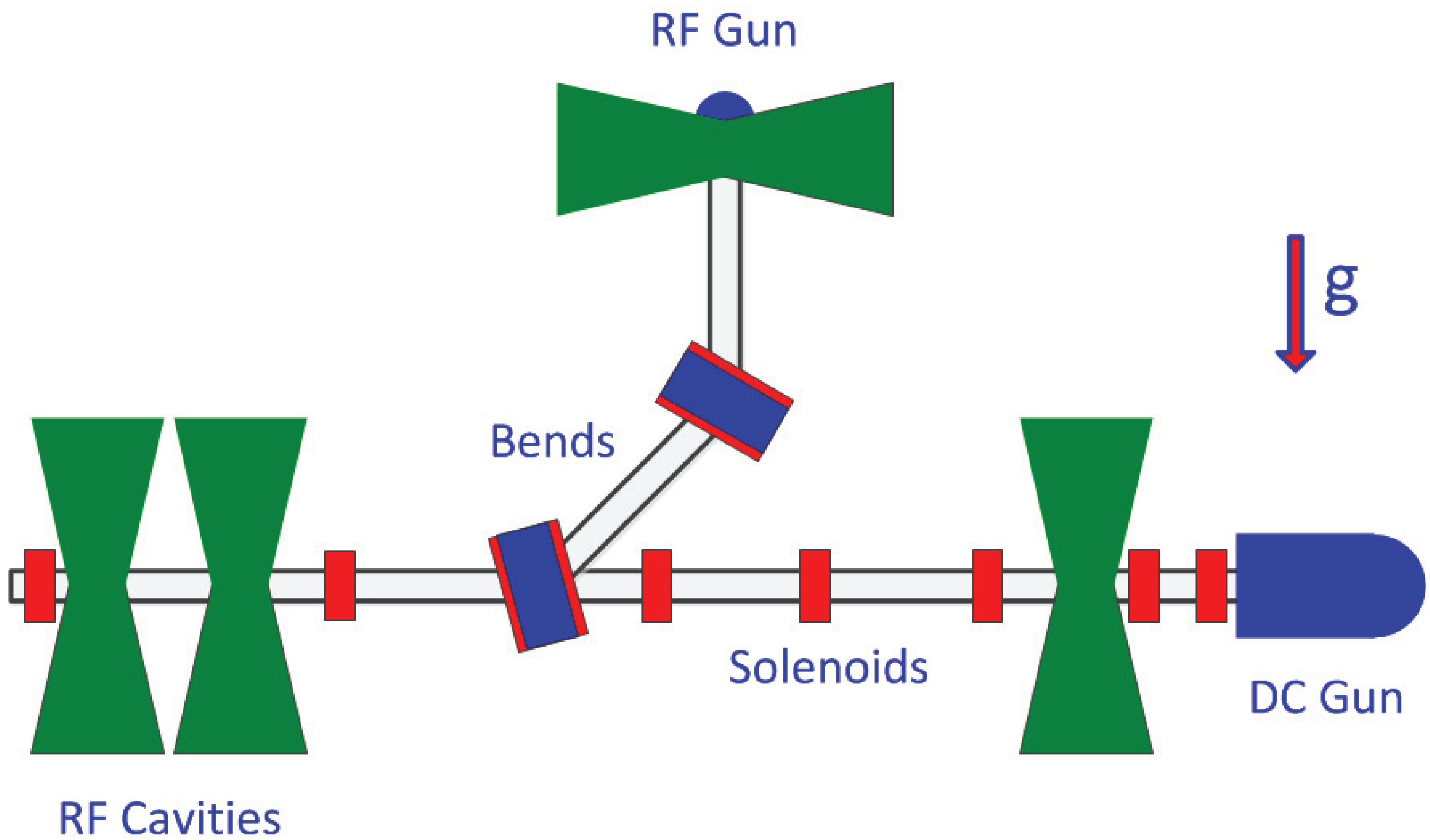
Injector



Injector



RF Gun Installation Layout



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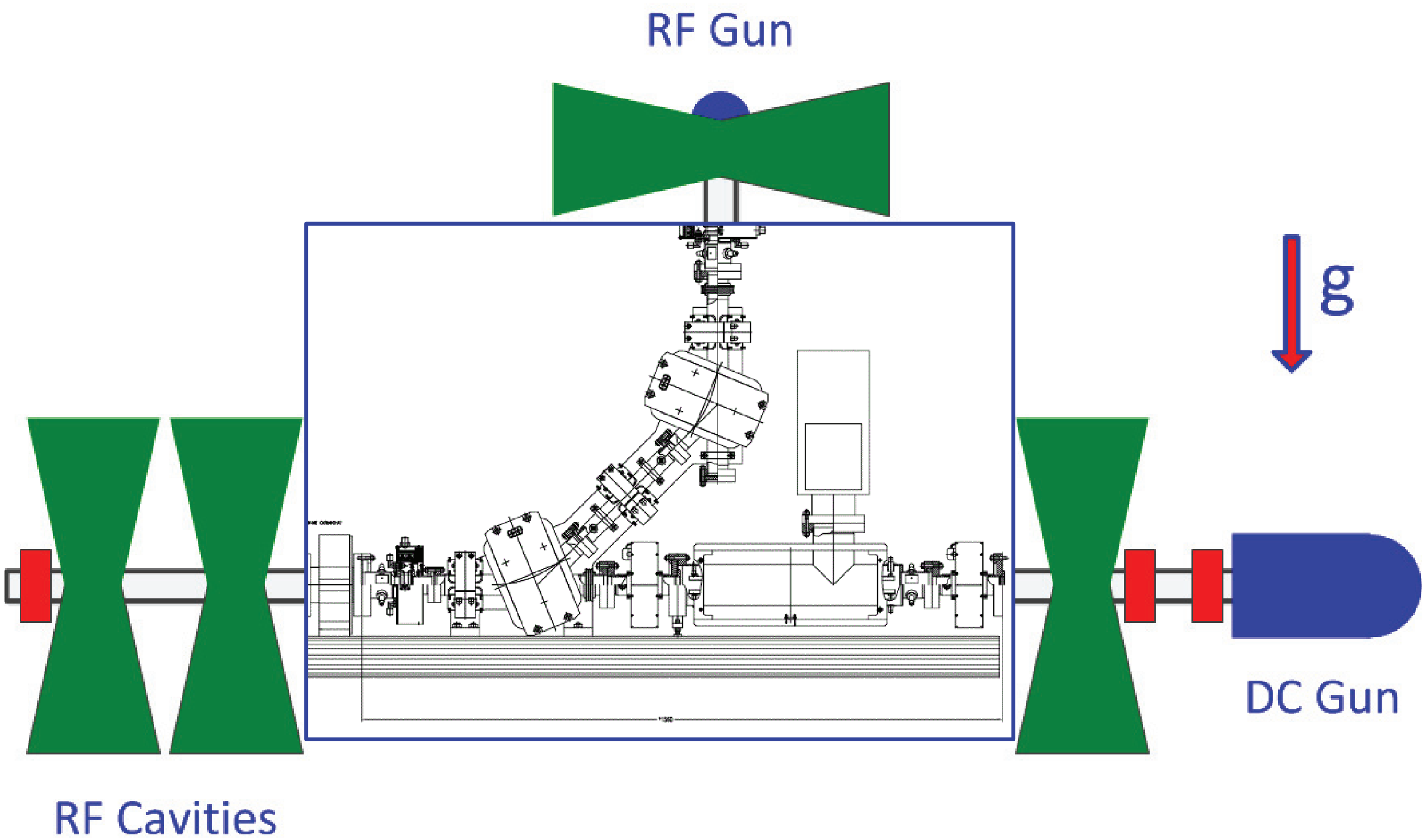
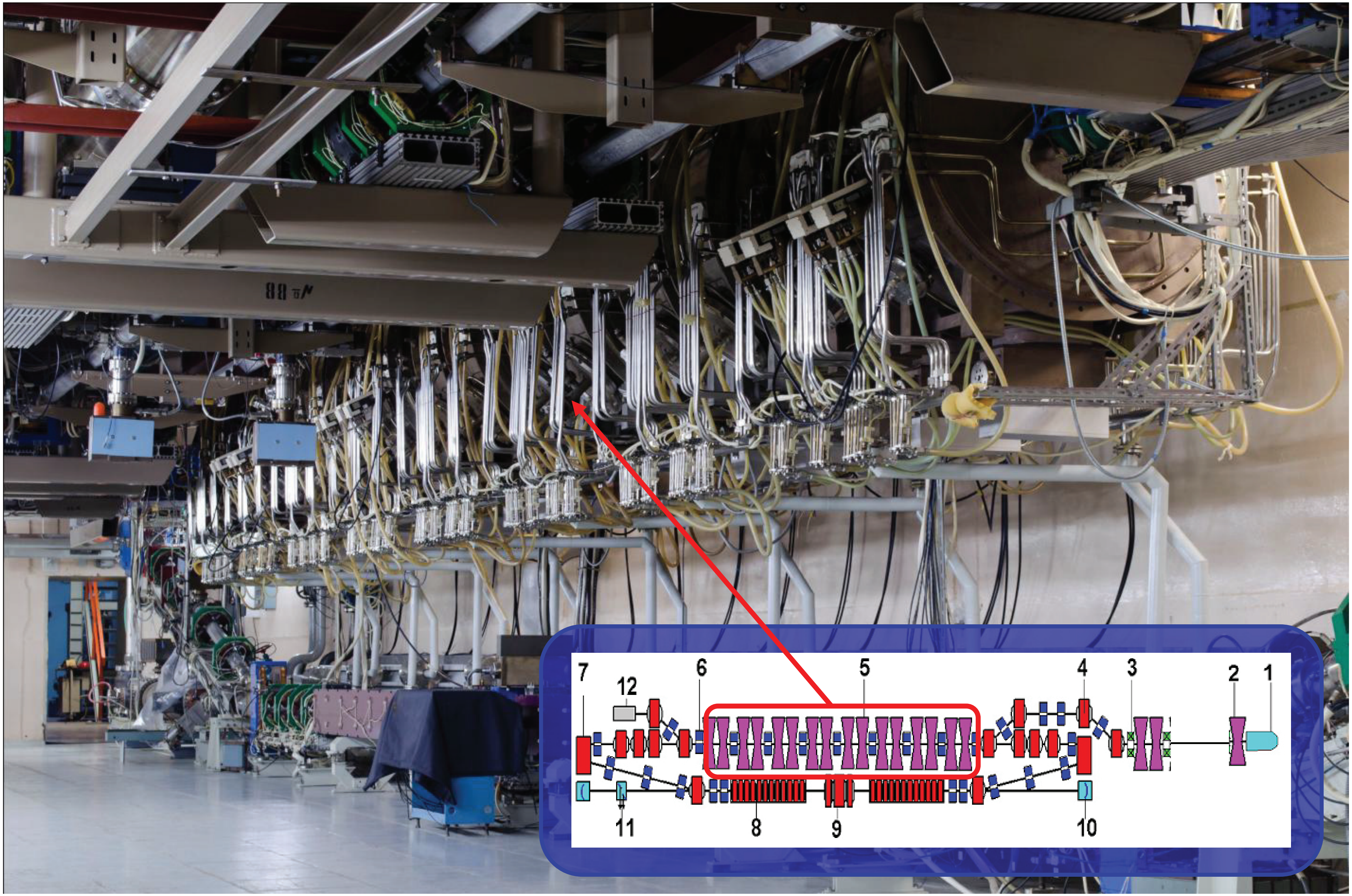


Main Linac



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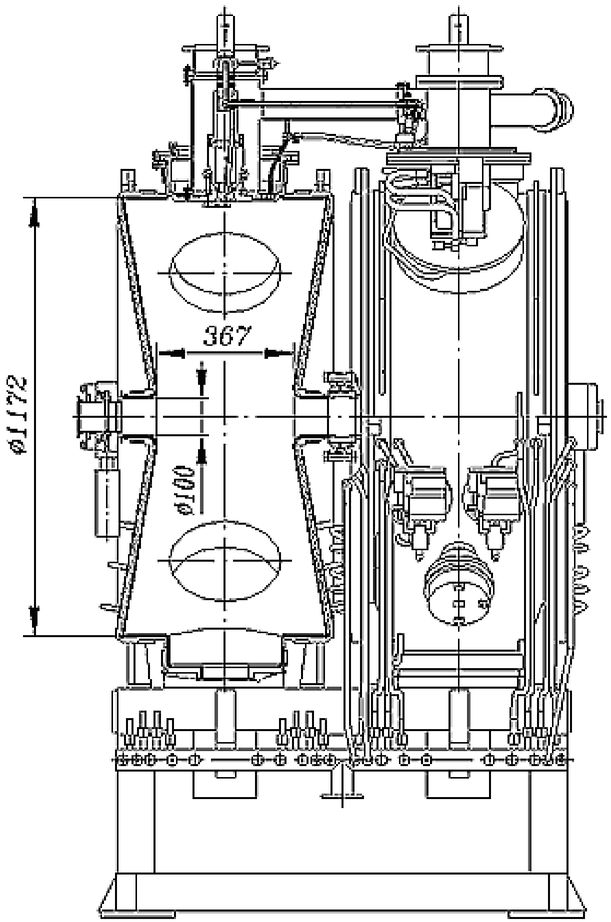

RF Power Supply

Frequency, MHz	180.4
Power, MW	2 x 0.6

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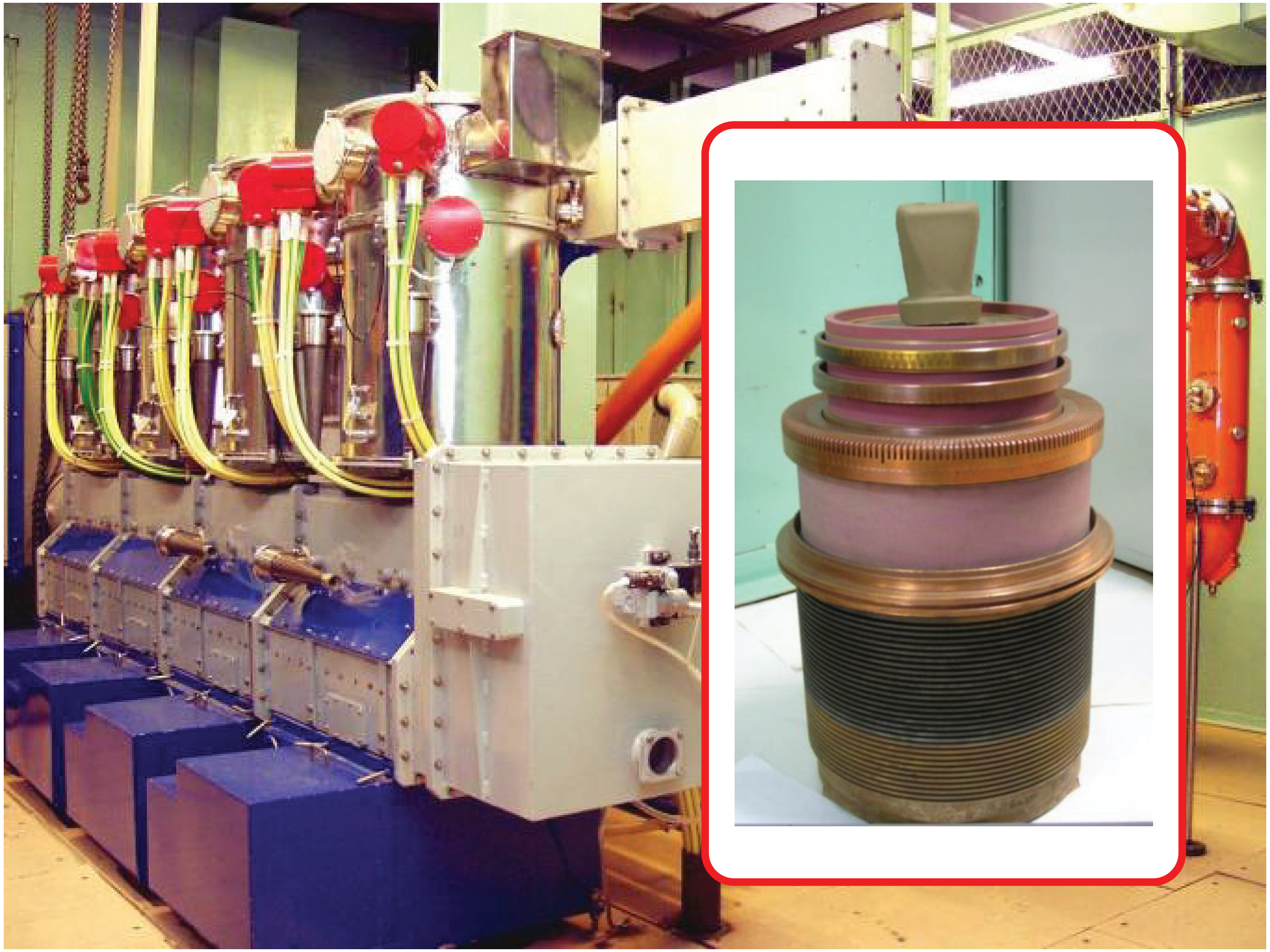

Frequency, MHz	180.4
Power, MW	2 x 0.6

New Amplifier for the Bunching Cavity

f = **180** MHz, efficiency = **52 %**

P_{IN} = **1** W, P_{OUT} = **5** kW

8 transistors NXP BLF188XR

water cooling

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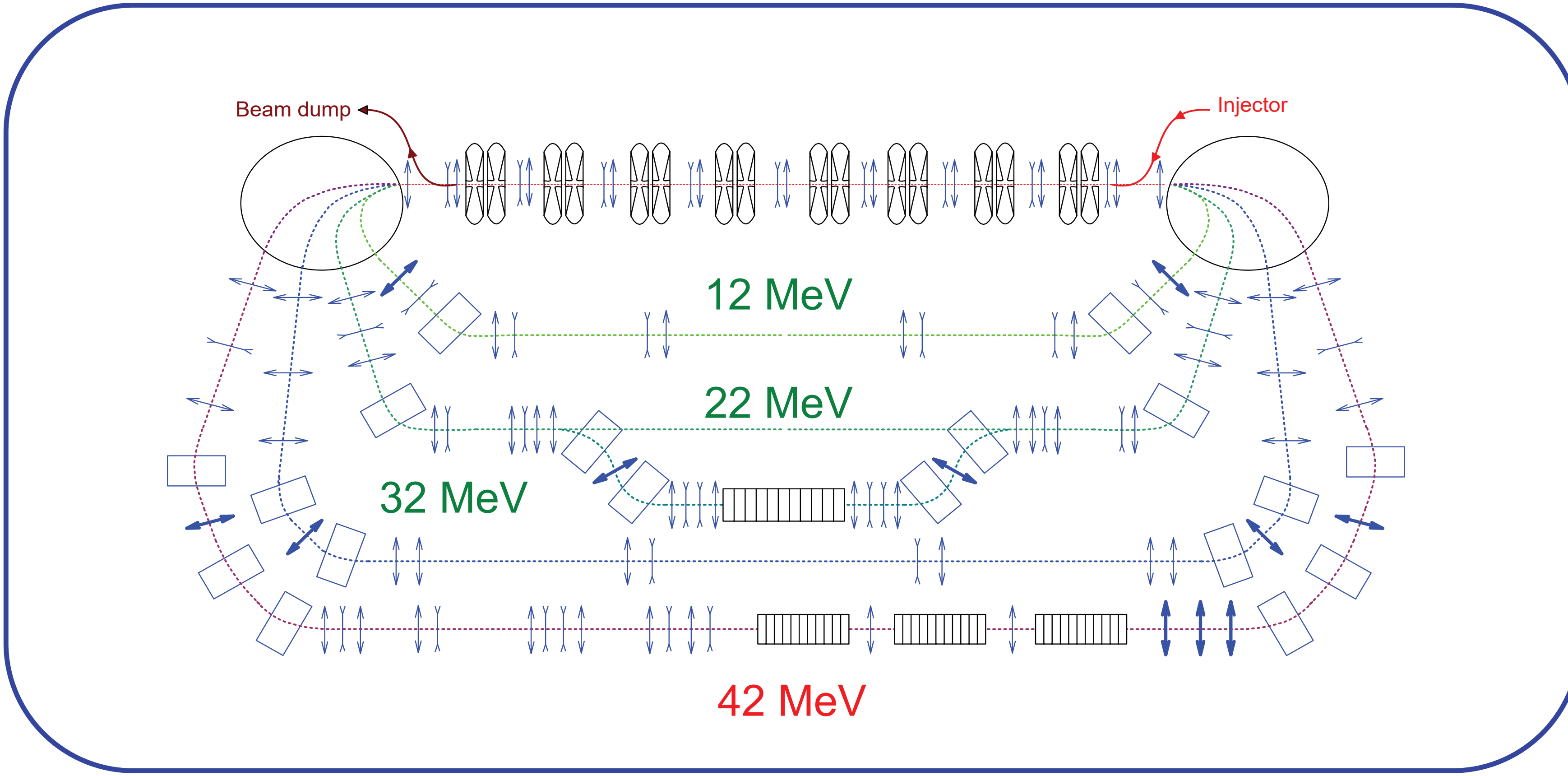
Layout of Horizontal Beamlines (the Second and the Third ERLs)



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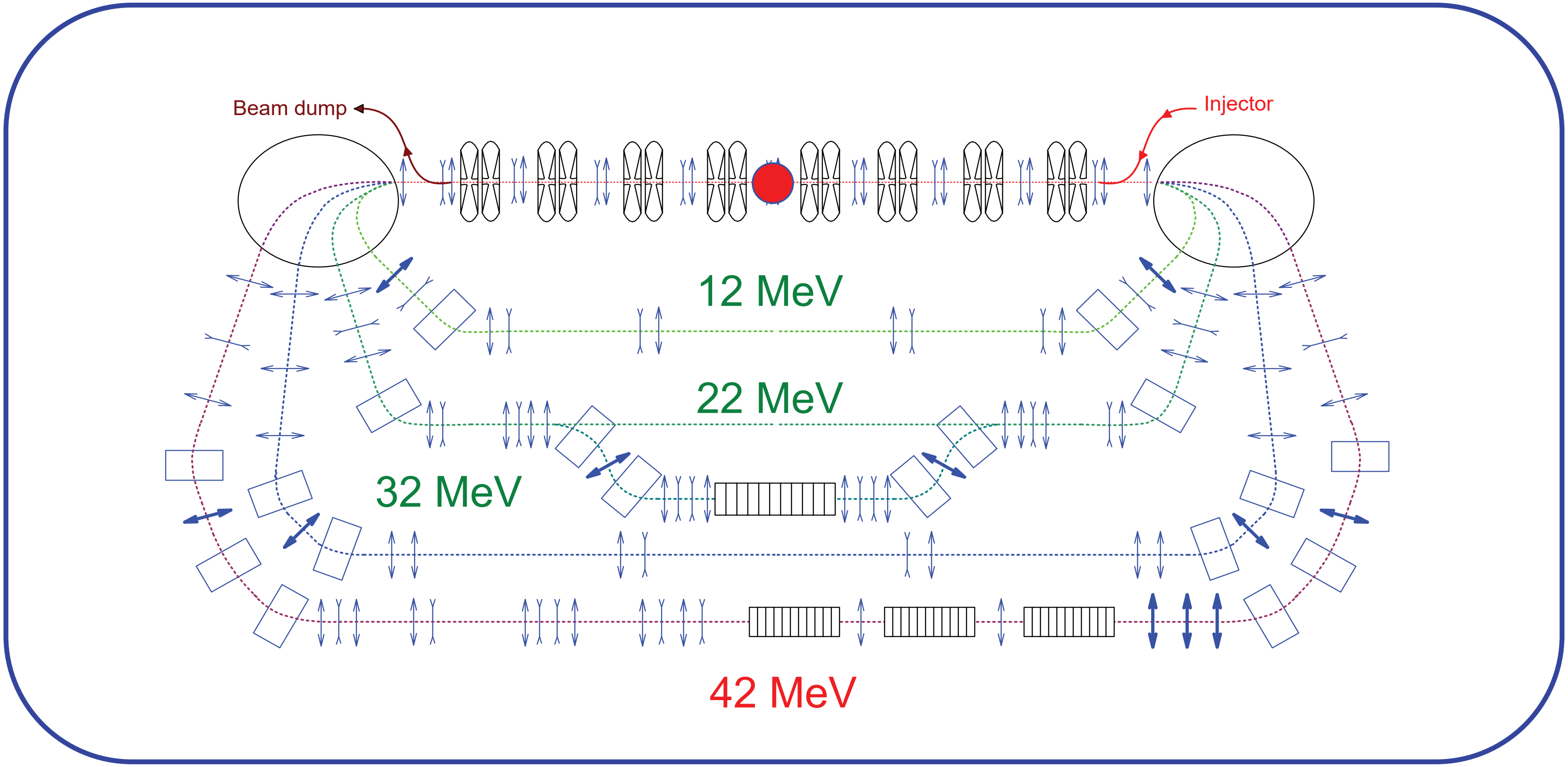

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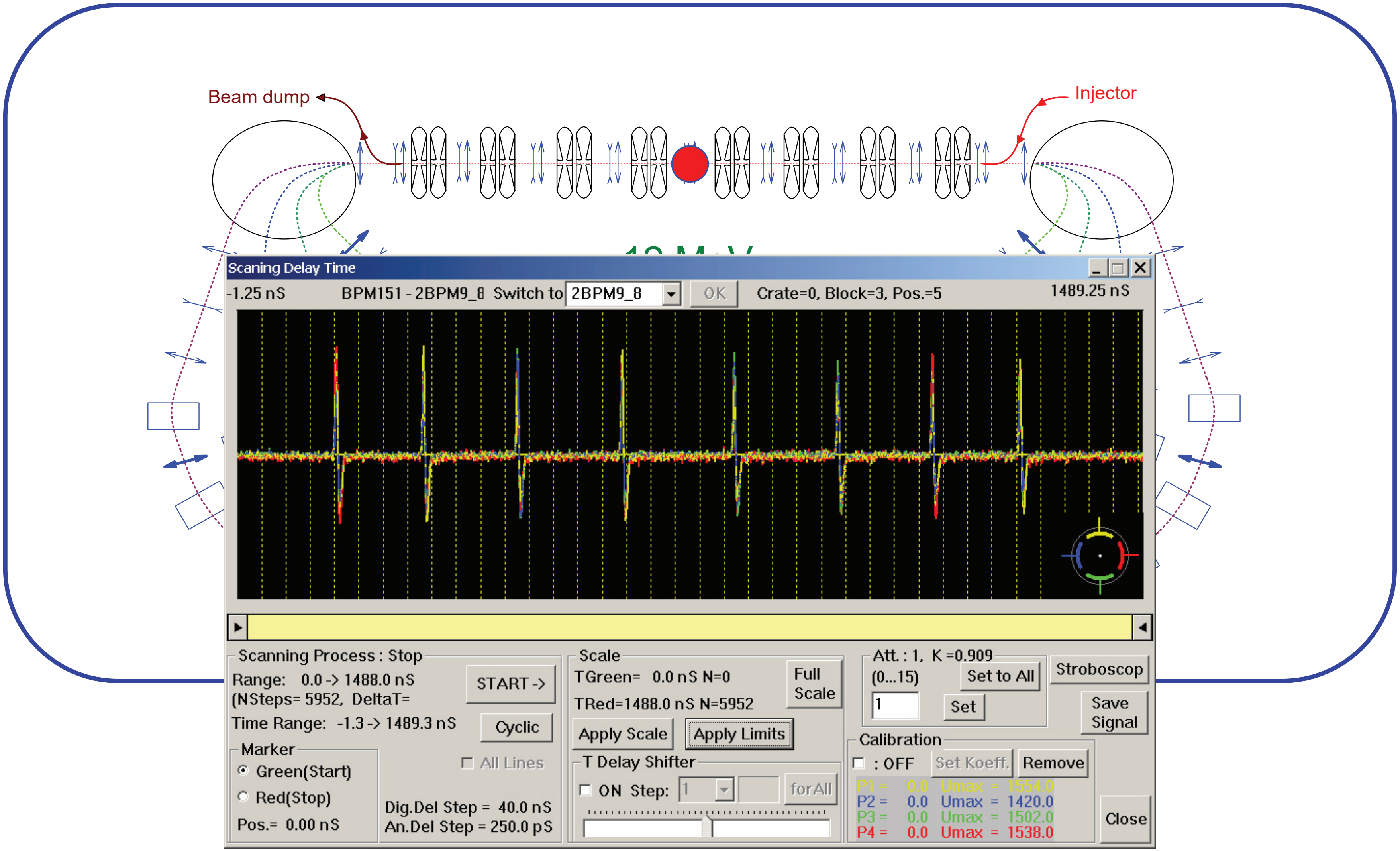

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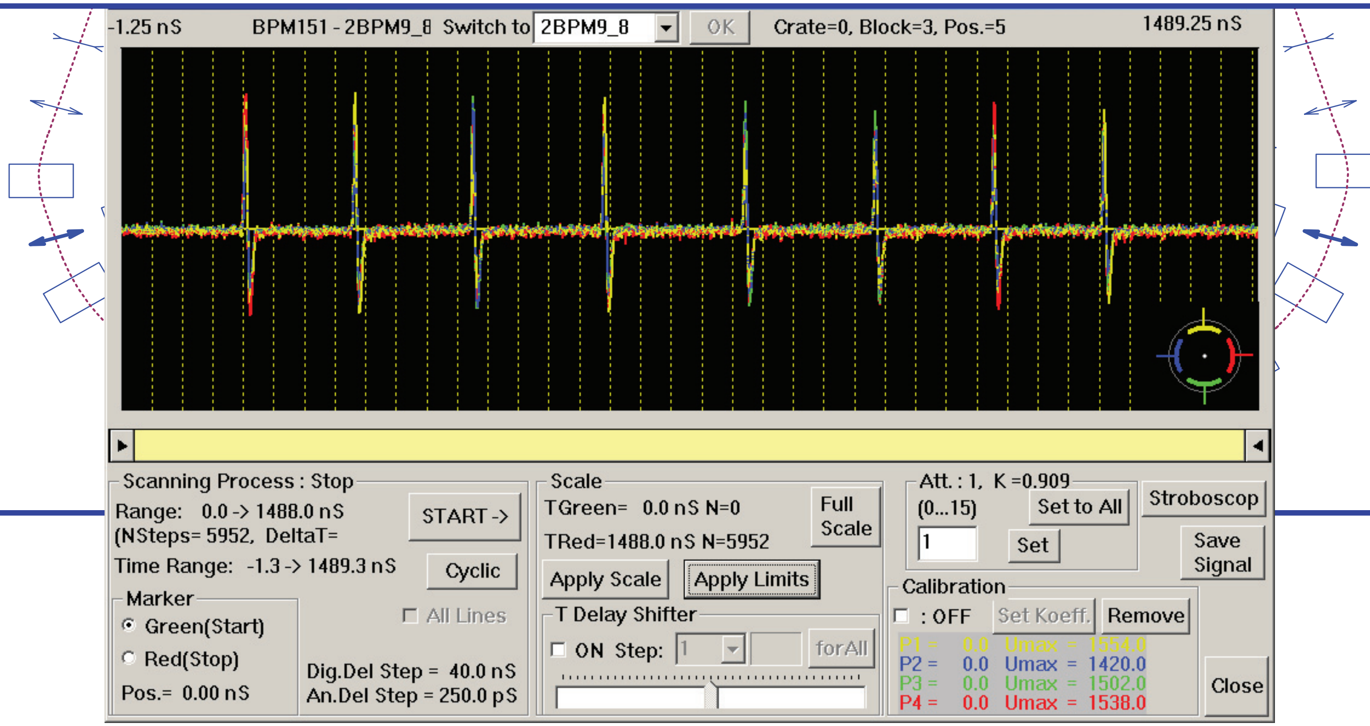
22 May 2012 – the first time the beam reached the dump after four accelerations and four decelerations



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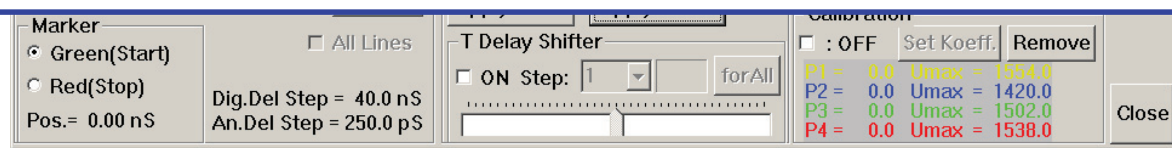
90% of beam current comes to the dump, the working repetition rate 3.75 MHz and average current 3.2 mA are obtained



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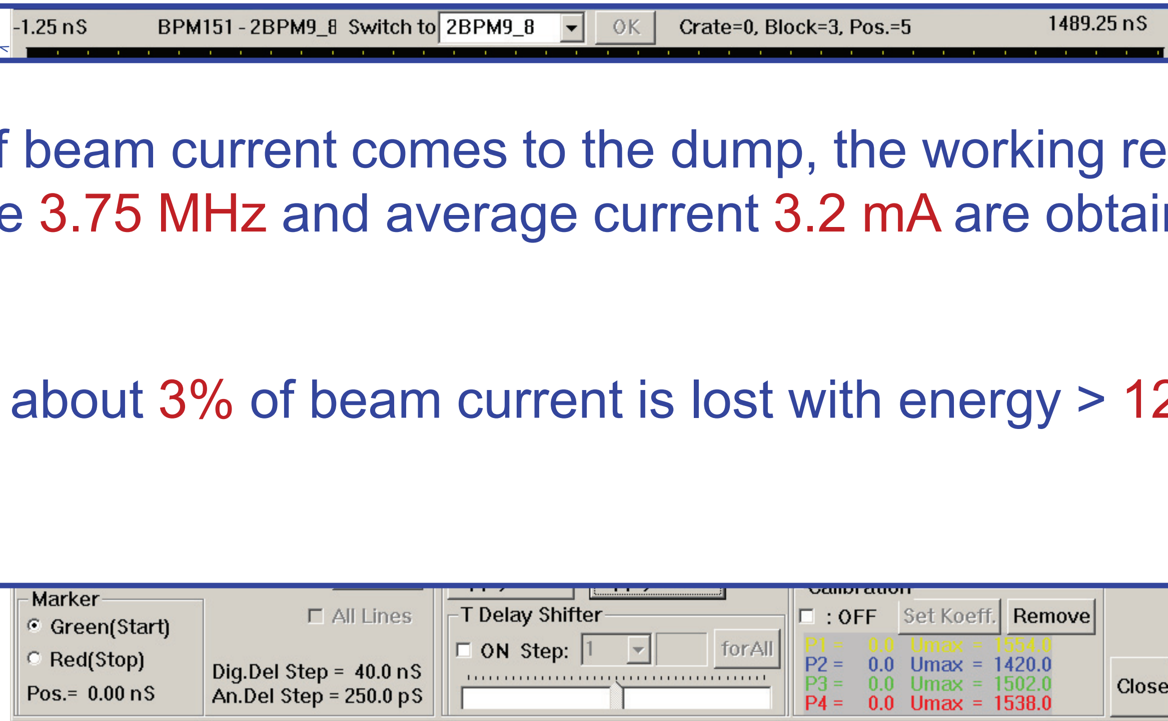
Only about 3% of beam current is lost with energy > 12 MeV



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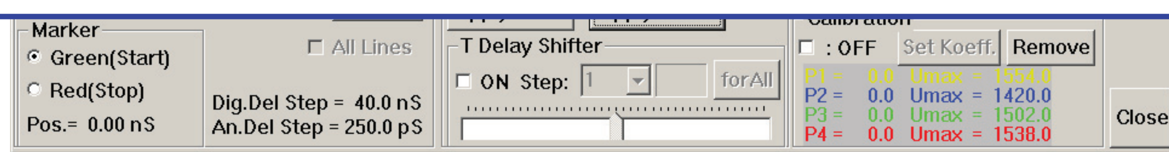
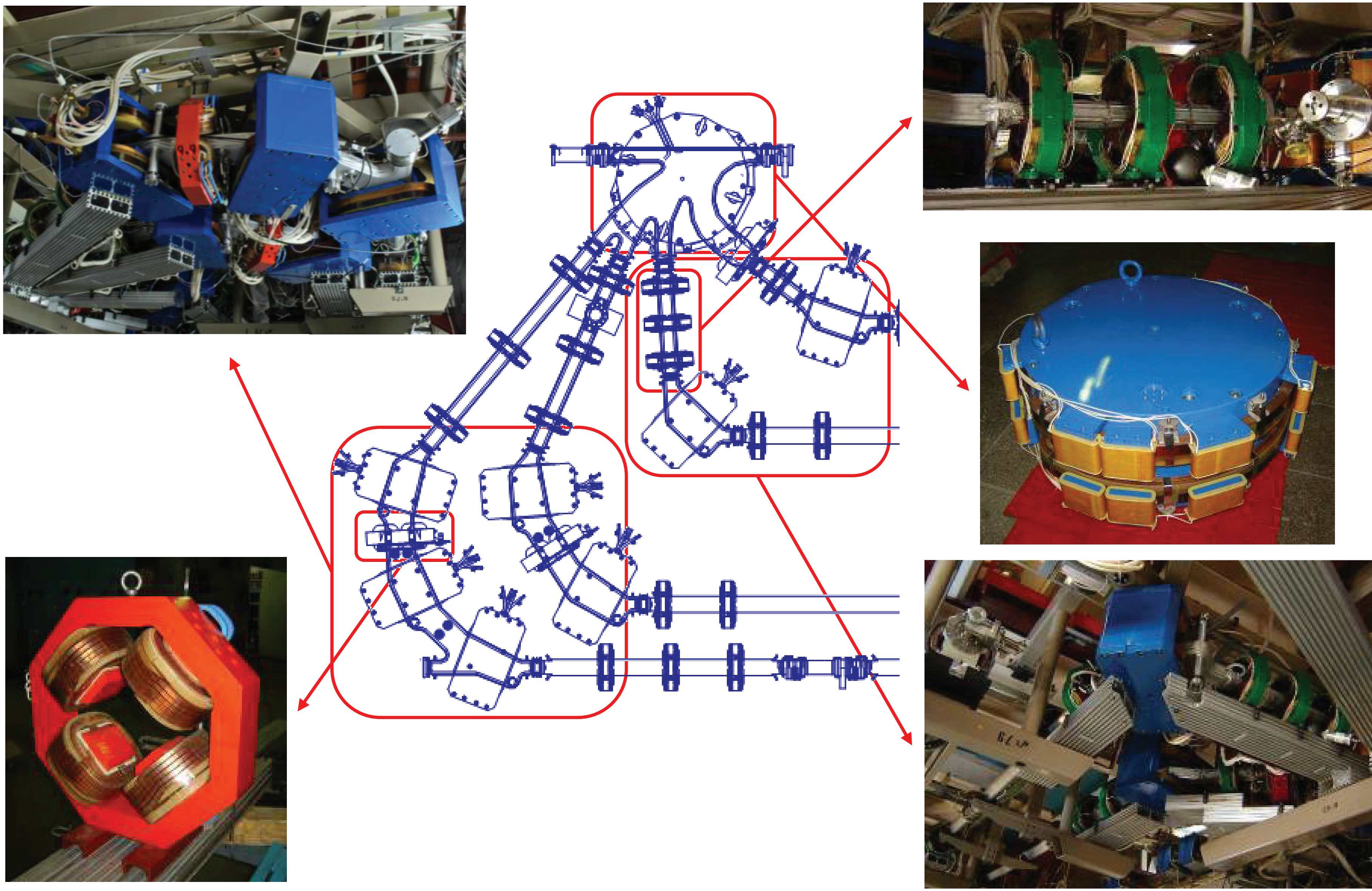
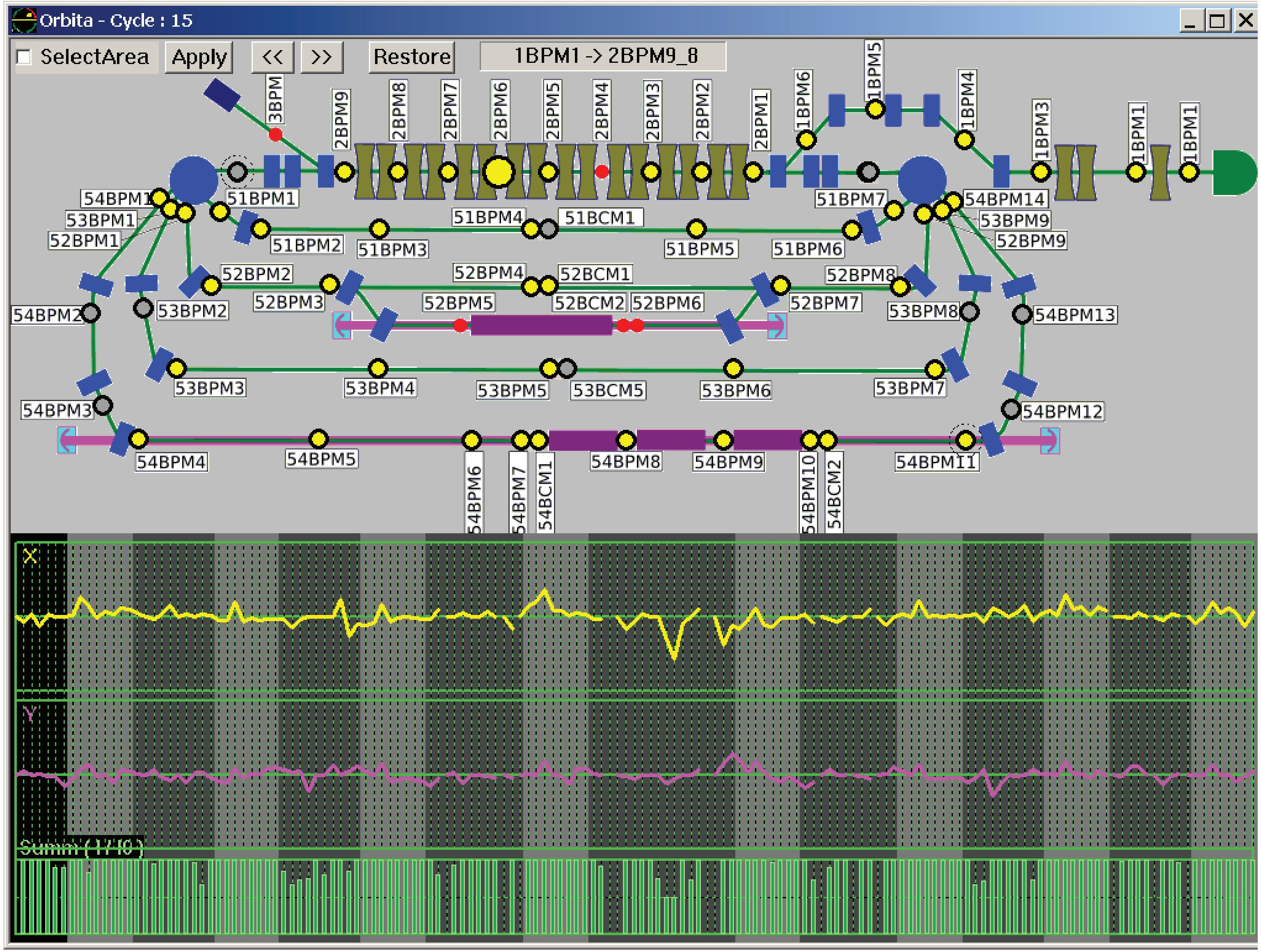
Less than 1% of beam current is lost at the last track



Magnets and Vacuum Chamber of Bends




Orbita - Cycle : 15
SelectArea
Apply
<<
>>
Restore
1BPM1 -> 2BPM9_8
3BPM
2BPM9
2BPM8
2BPM7
2BPM6
2BPM5
2BPM4
2BPM3
2BPM2
2BPM1
1BPM6
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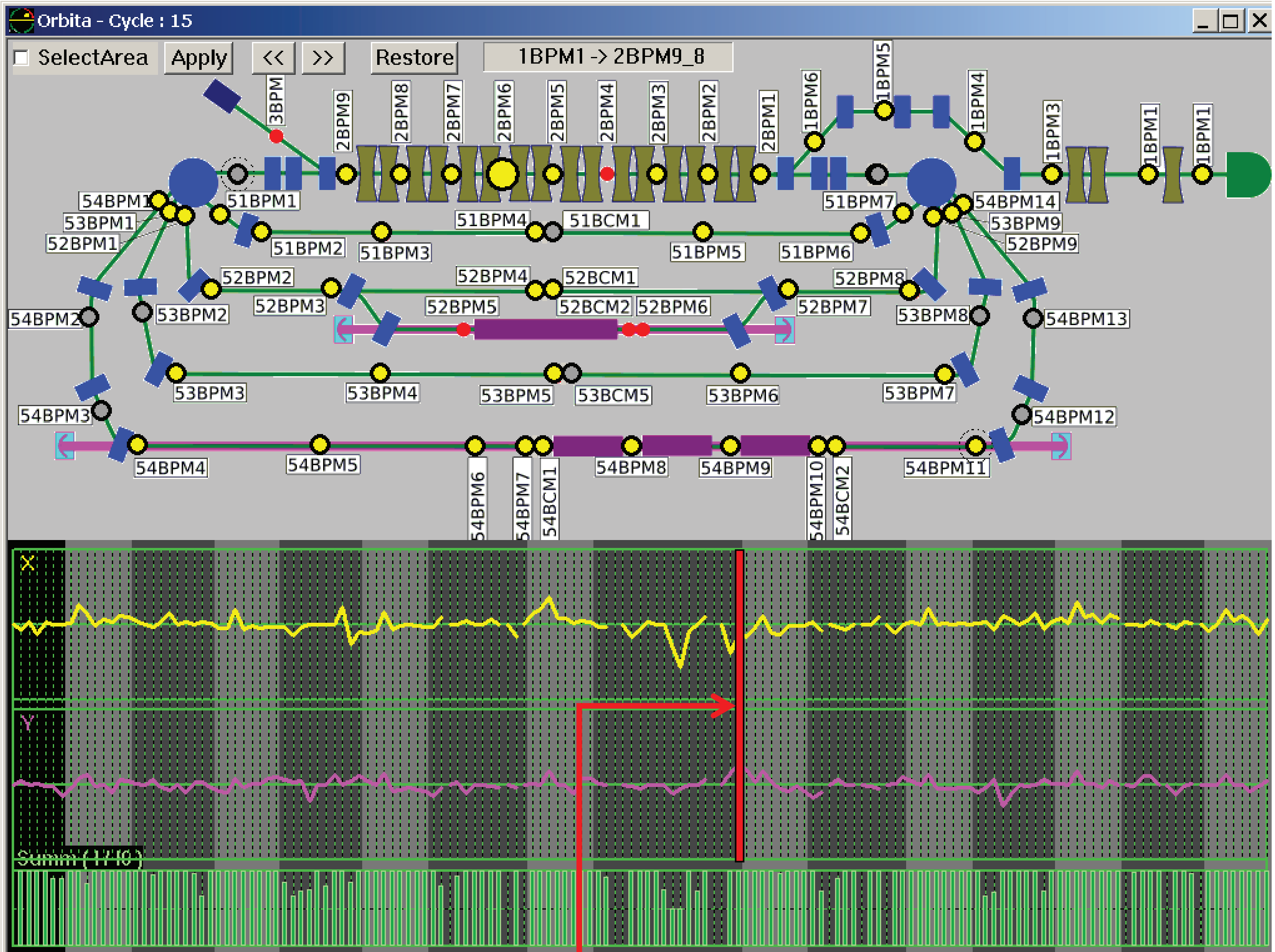
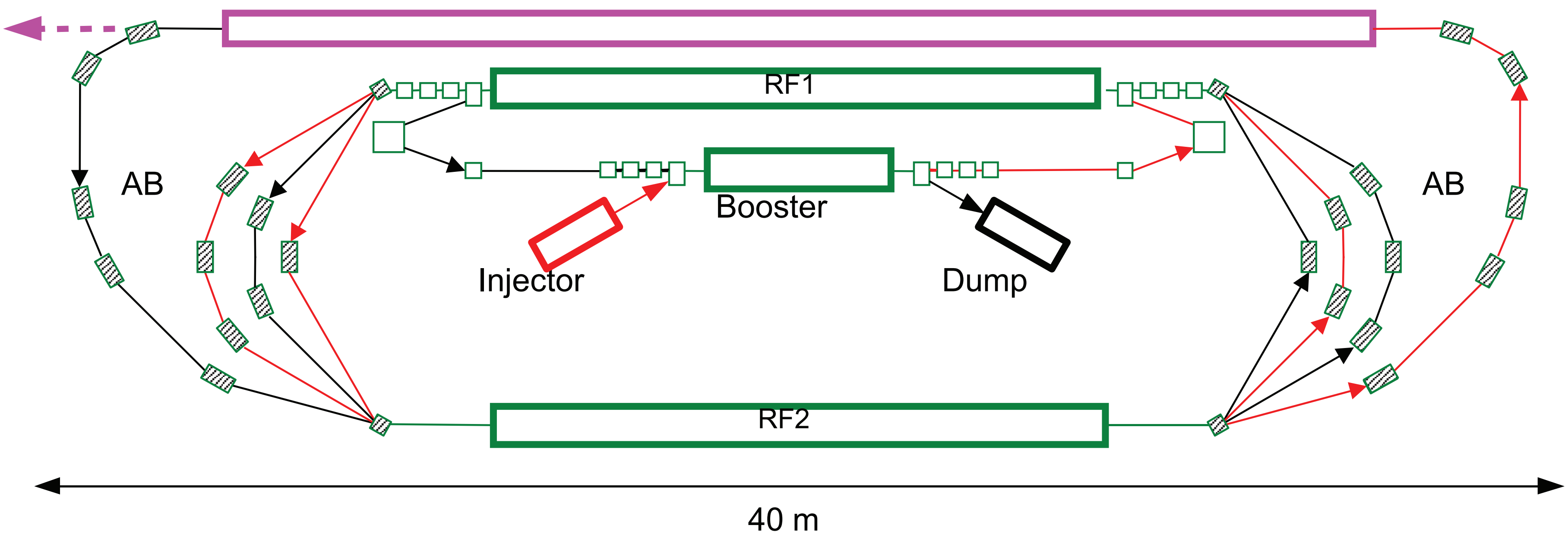
X
Y
Summ (1/10)



Beam trajectory can be adjusted only before this point

Compact 13.5-nm free-electron laser for extreme ultraviolet lithography

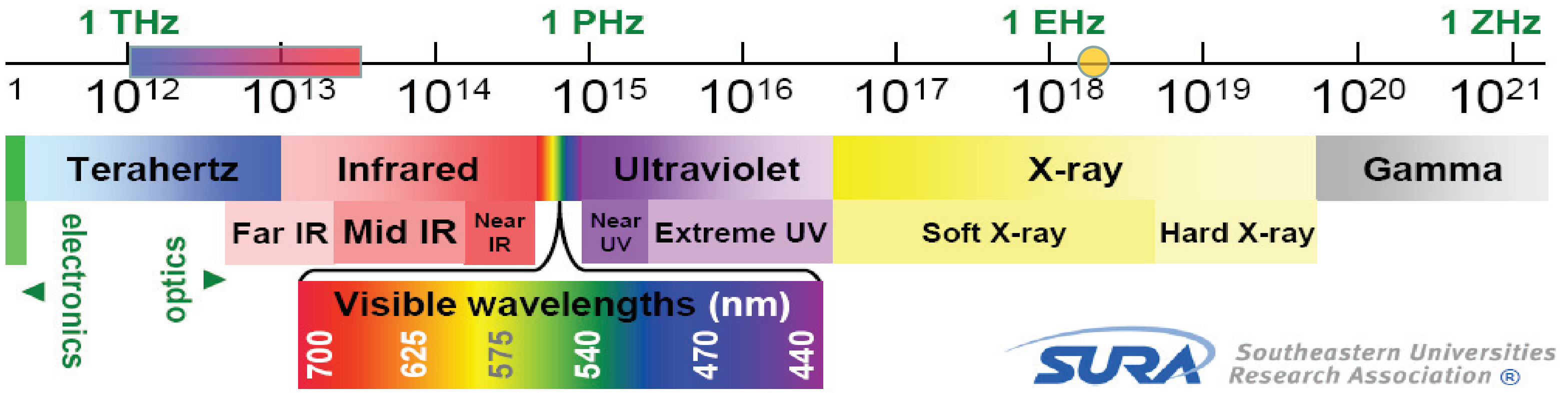
Y.Socol, G.N.Kulipanov, A.N.Matveenko, O.A.Shevchenko and N.A.Vinokurov, FEL10



With 10-T superconducting magnet it may be used to generate 20-fs periodic x-ray pulses, which are necessary for time-resolved experiments, which use femtoslicing technique at storage rings now. But, the number of useful photons is thousands times more.

NovoFEL as Radiation Source

NovoFEL   X-ray FELs



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

$\lambda_u = 12\ cm$

Electromagnetic undulator

K ~ 0…1.5

$\lambda_u = 6\ cm$

Variable gap undulator

K ~ 0.4…2.5

Variation of beam energy

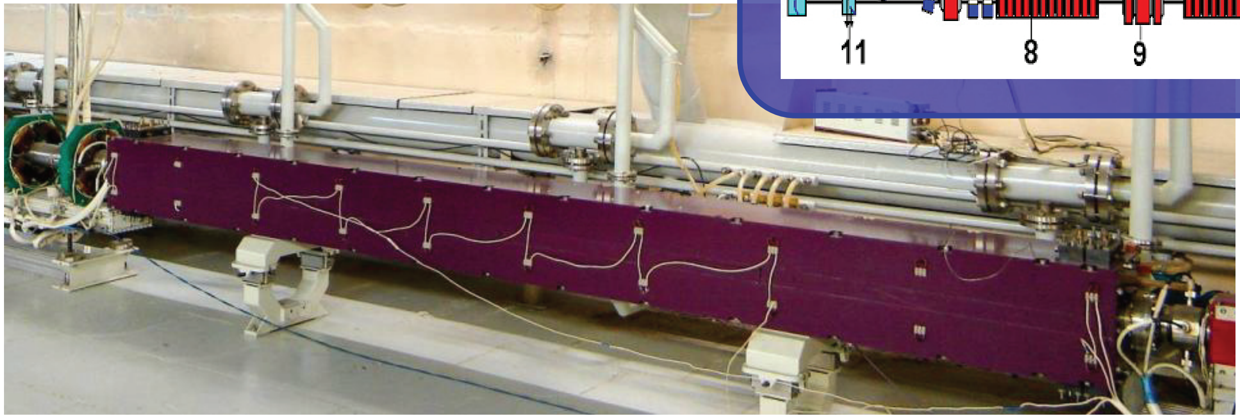
E1 ~ 10…13 MeV
E2 ~ 20…24 MeV
E3 ~ 40…46 MeV

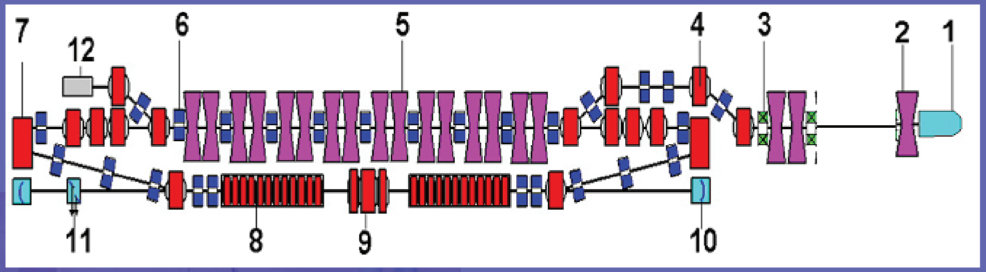
Variation of undulator period

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

Variable period undulator

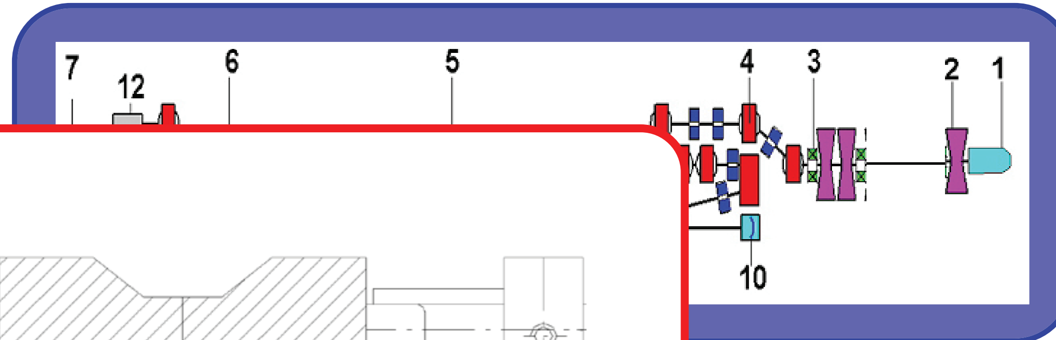
Electromagnetic Undulators

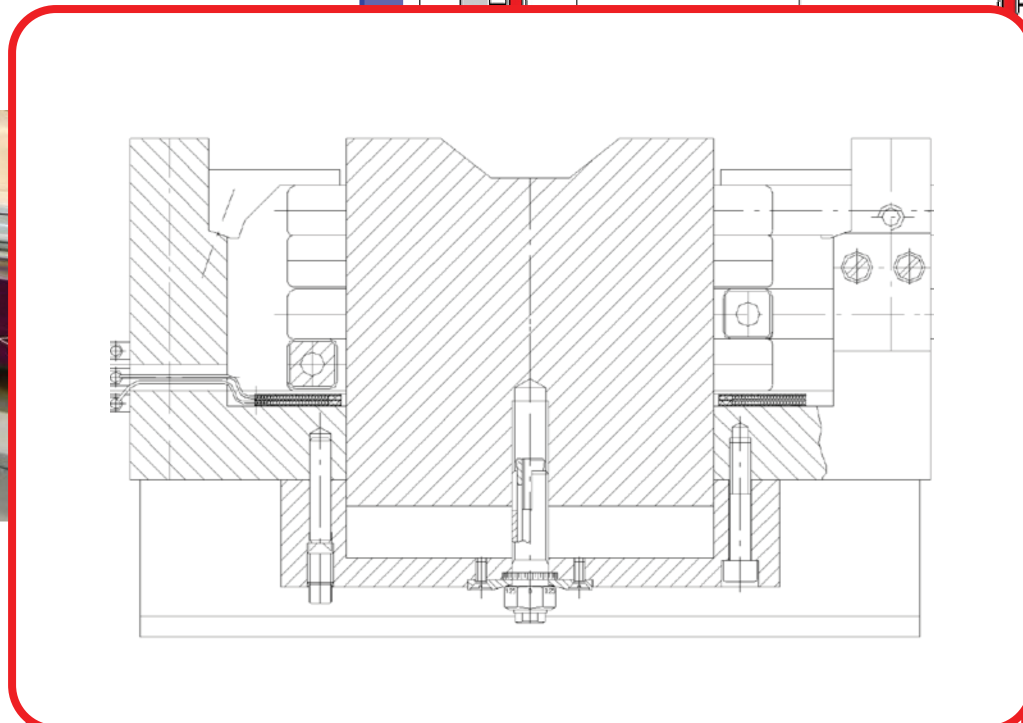




	1-st FEL	2-d FEL
Period, cm	12	12
Maximum current, кA	2.4	2.4
Maximum K	1.25	1.47

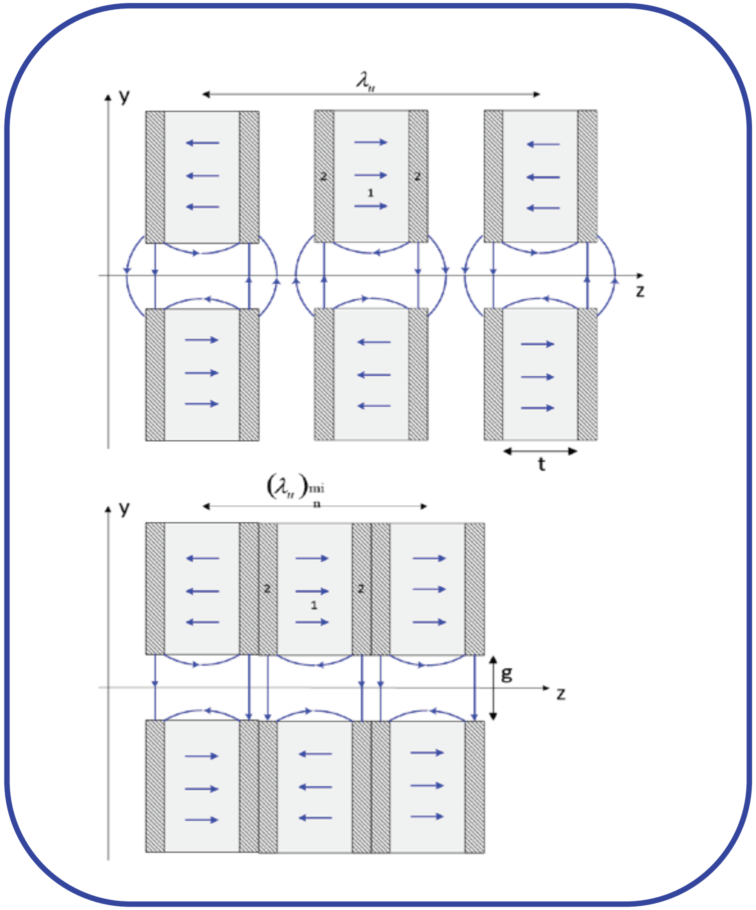
Electromagnetic Undulators

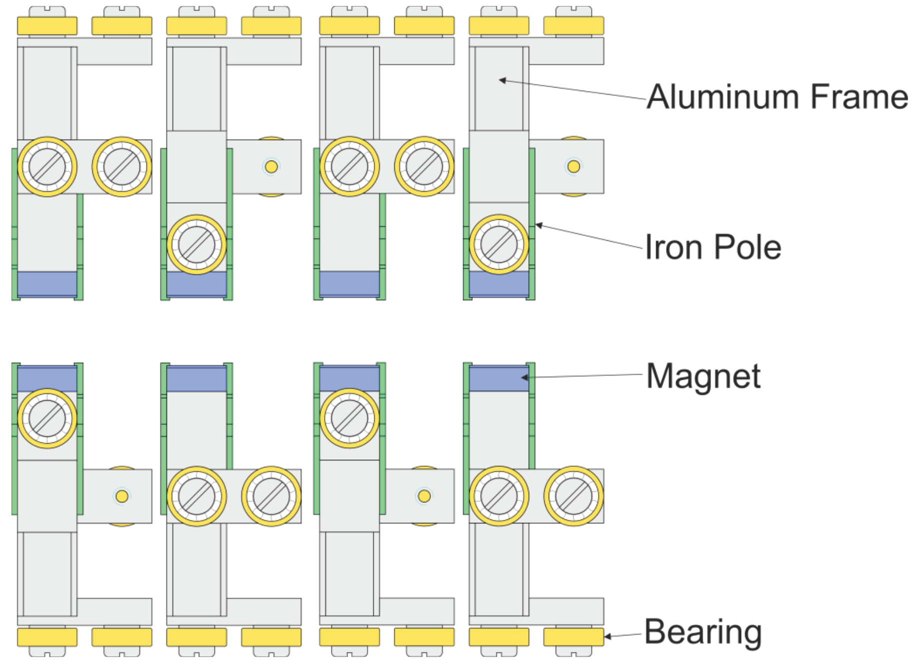




		FEL
Period, cm	12	12
Maximum current, кА	2.4	2.4
Maximum K	1.25	1.47

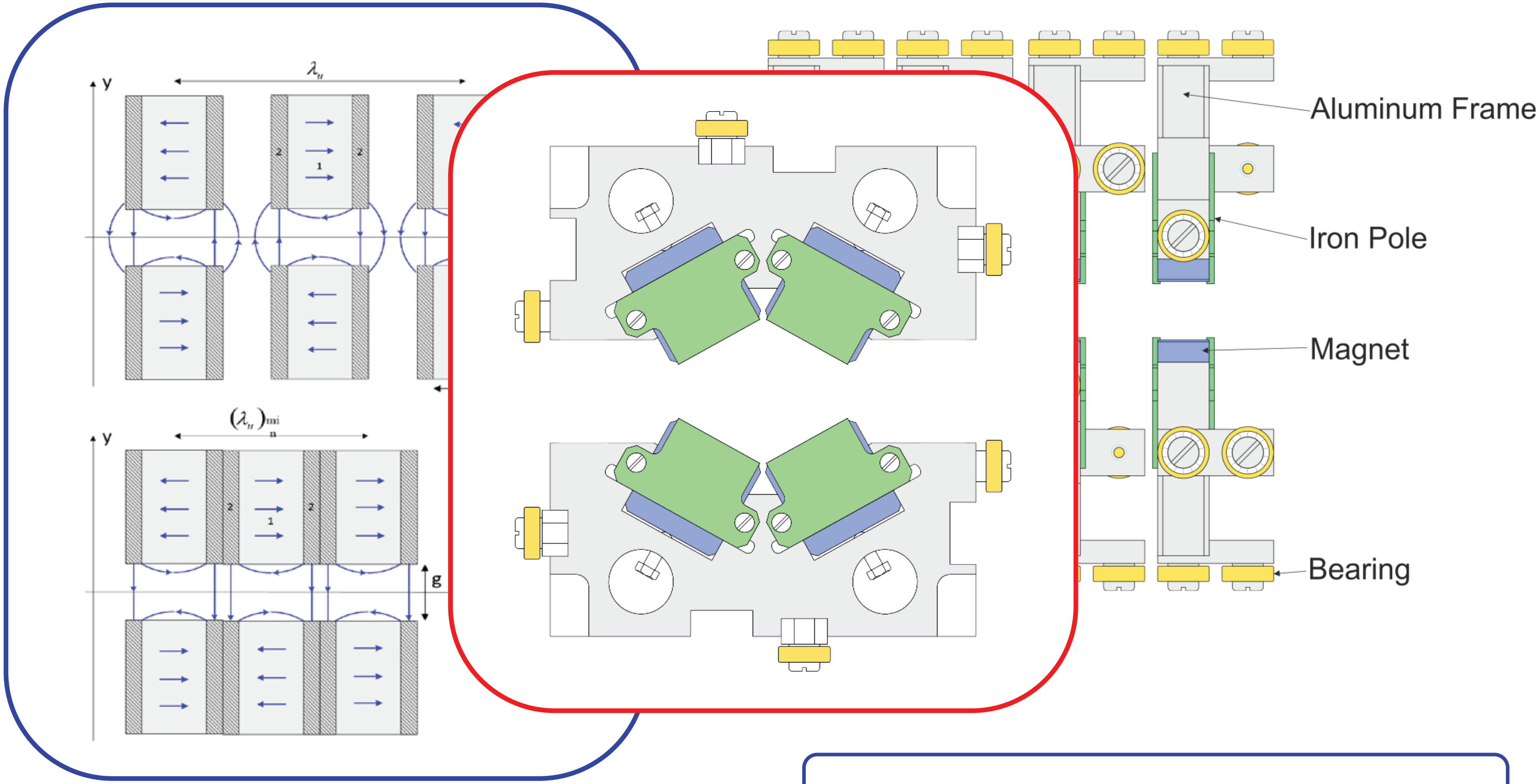
Variable Period Undulator (for the 2nd FEL)





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

Variable Period Undulator (for the 2nd FEL)



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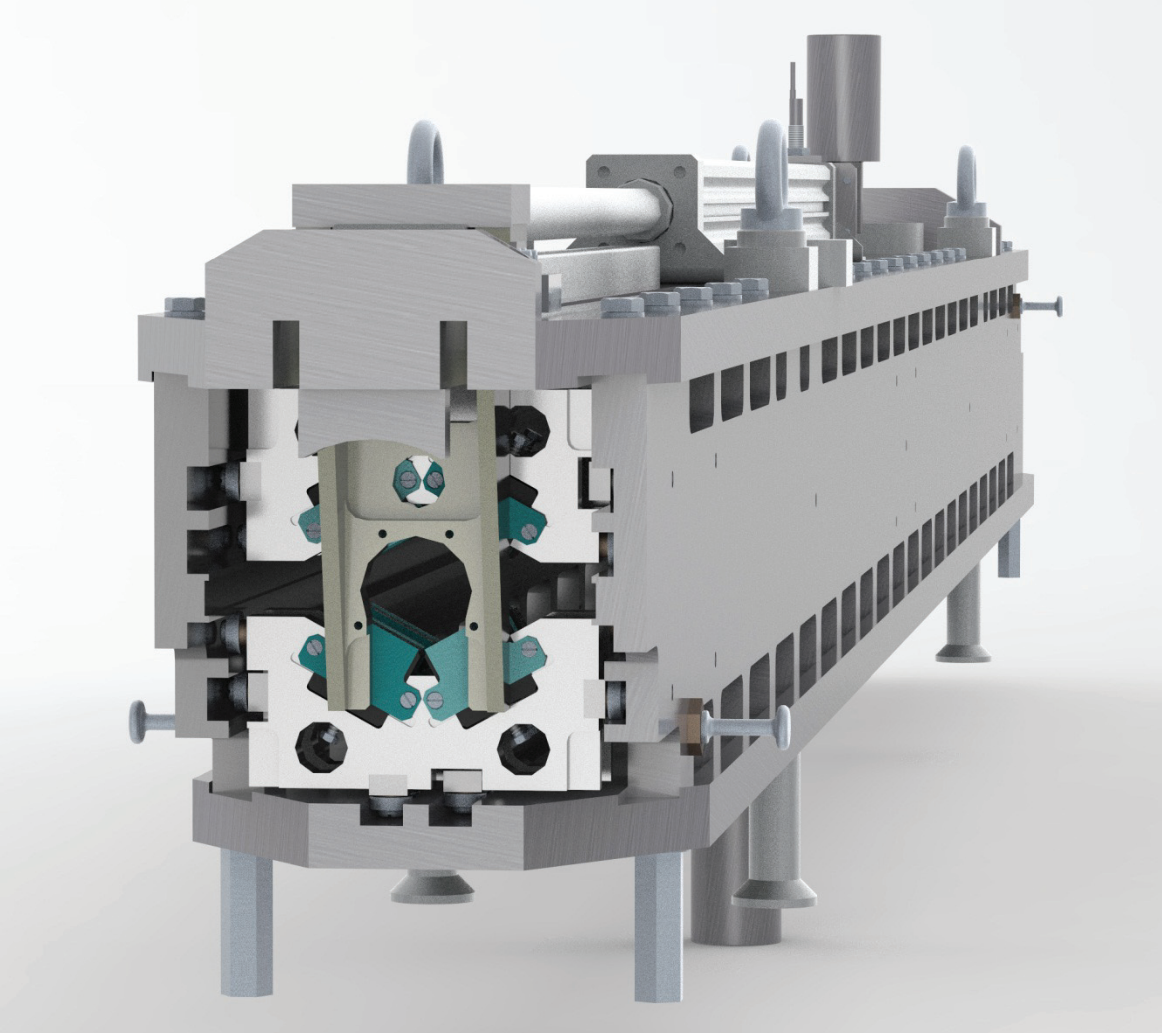

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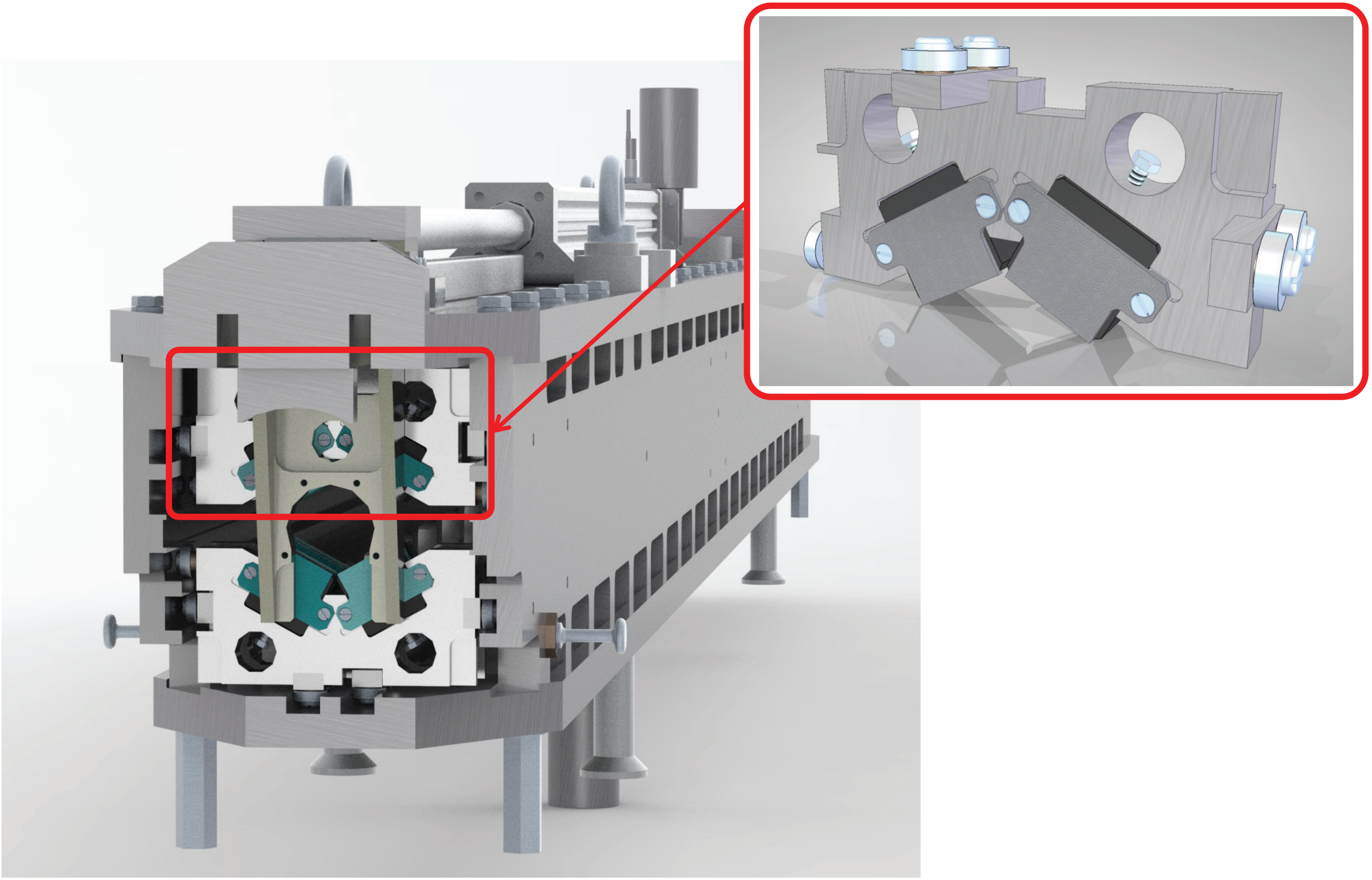
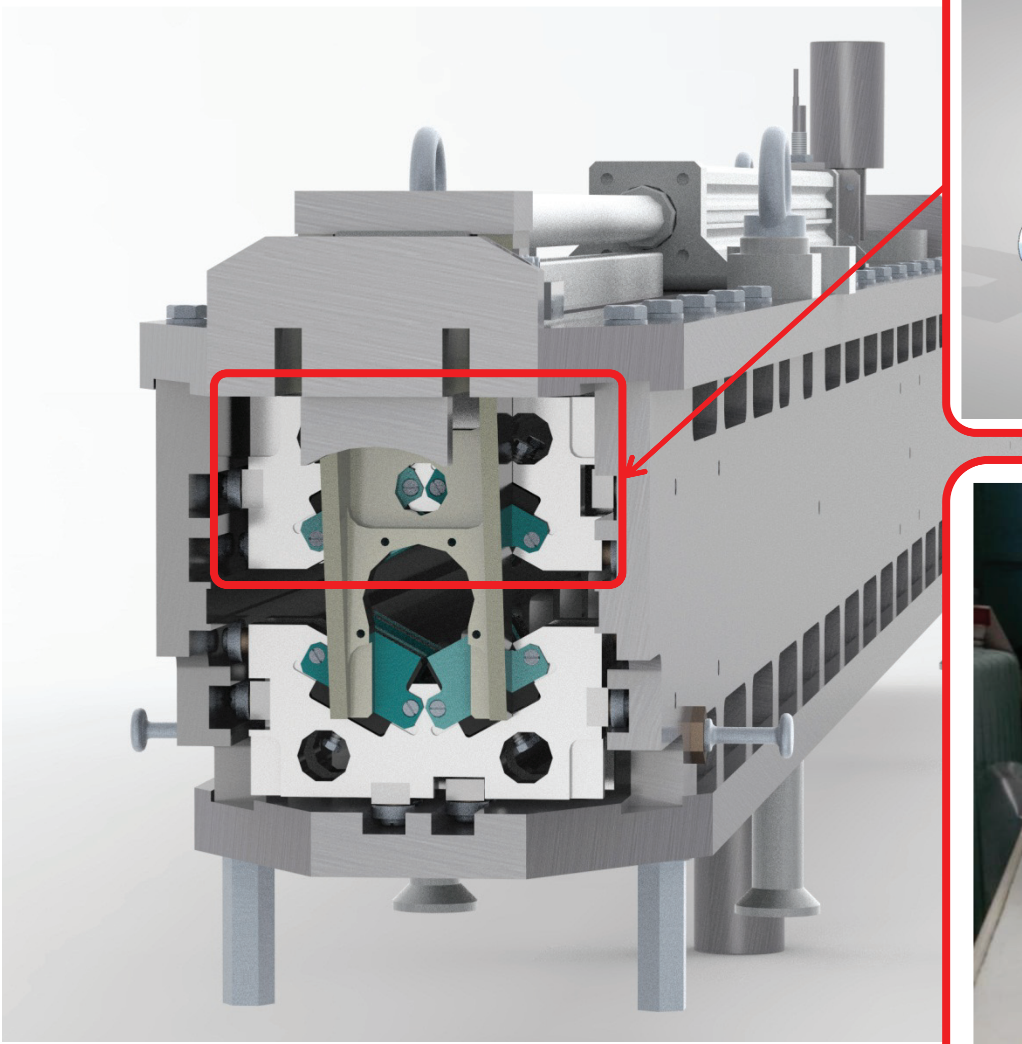
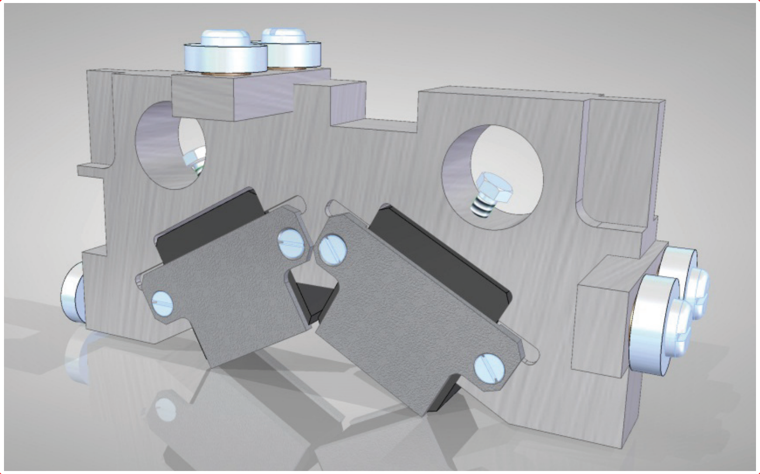
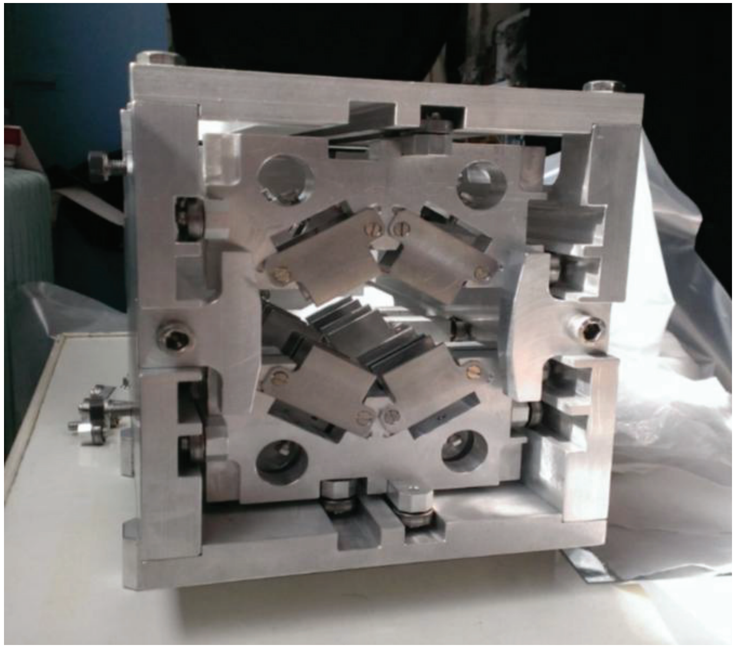


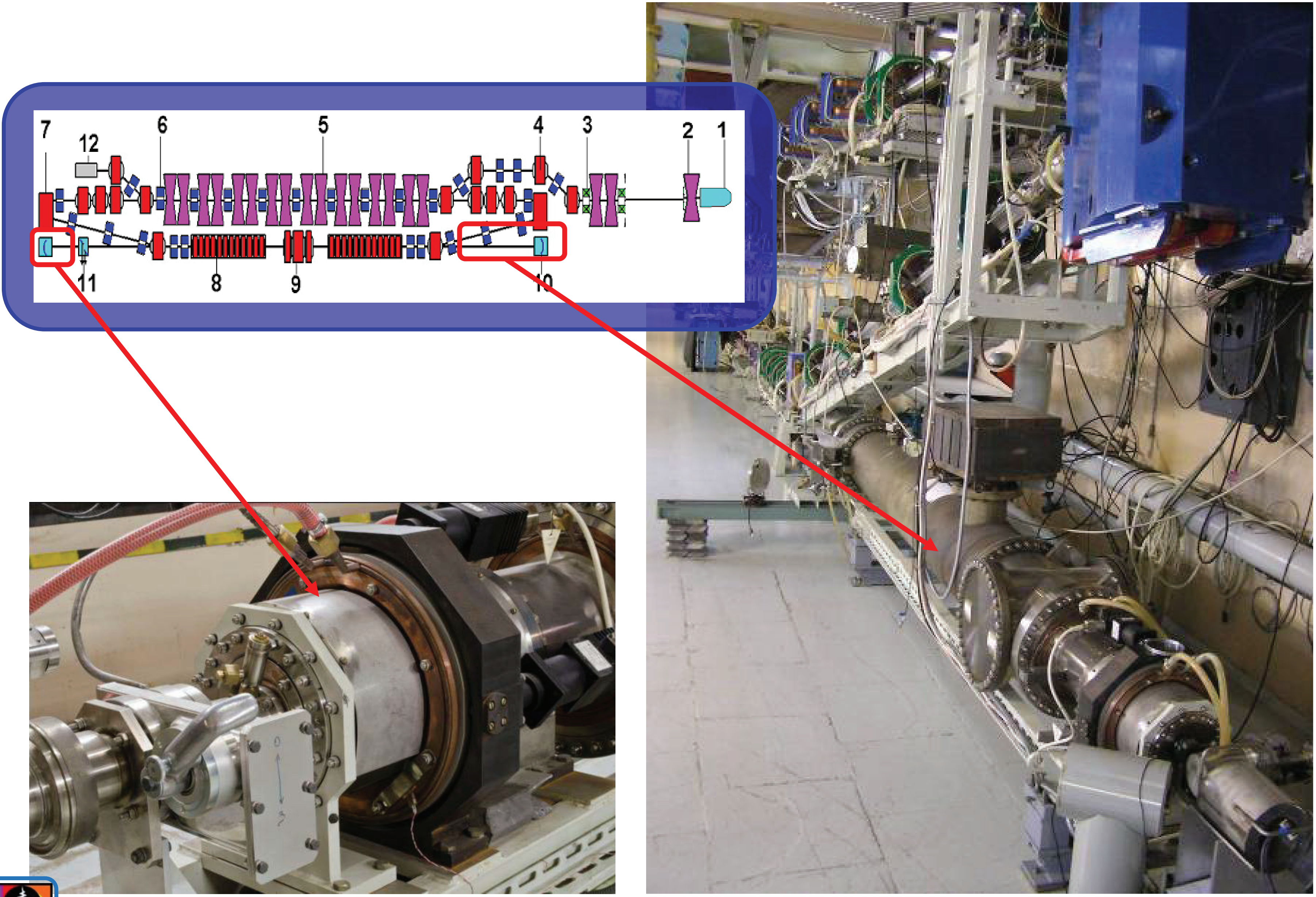
Variable Period Undulator (for the 2nd FEL)



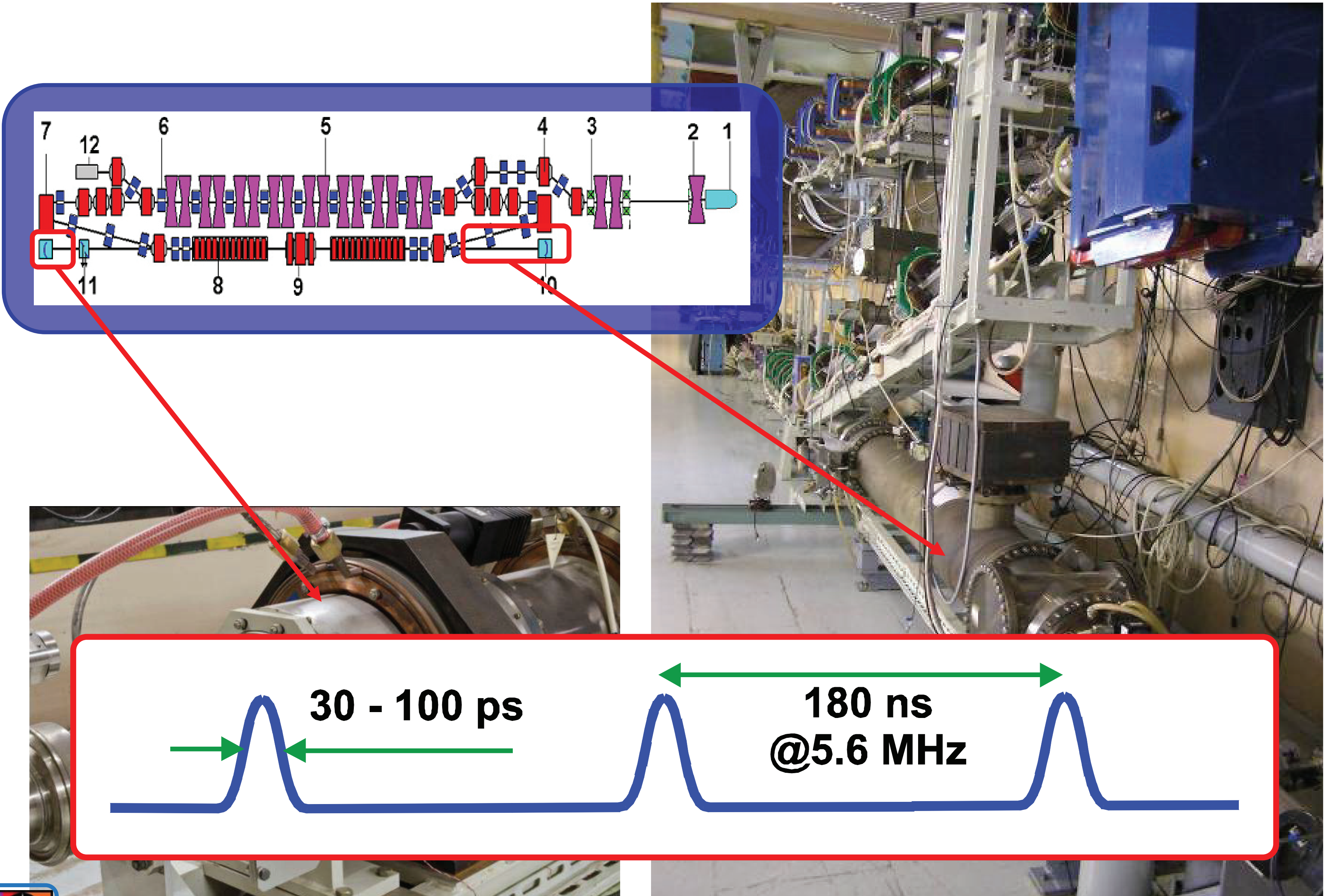




FEL Optical Cavities



FEL Optical Cavities



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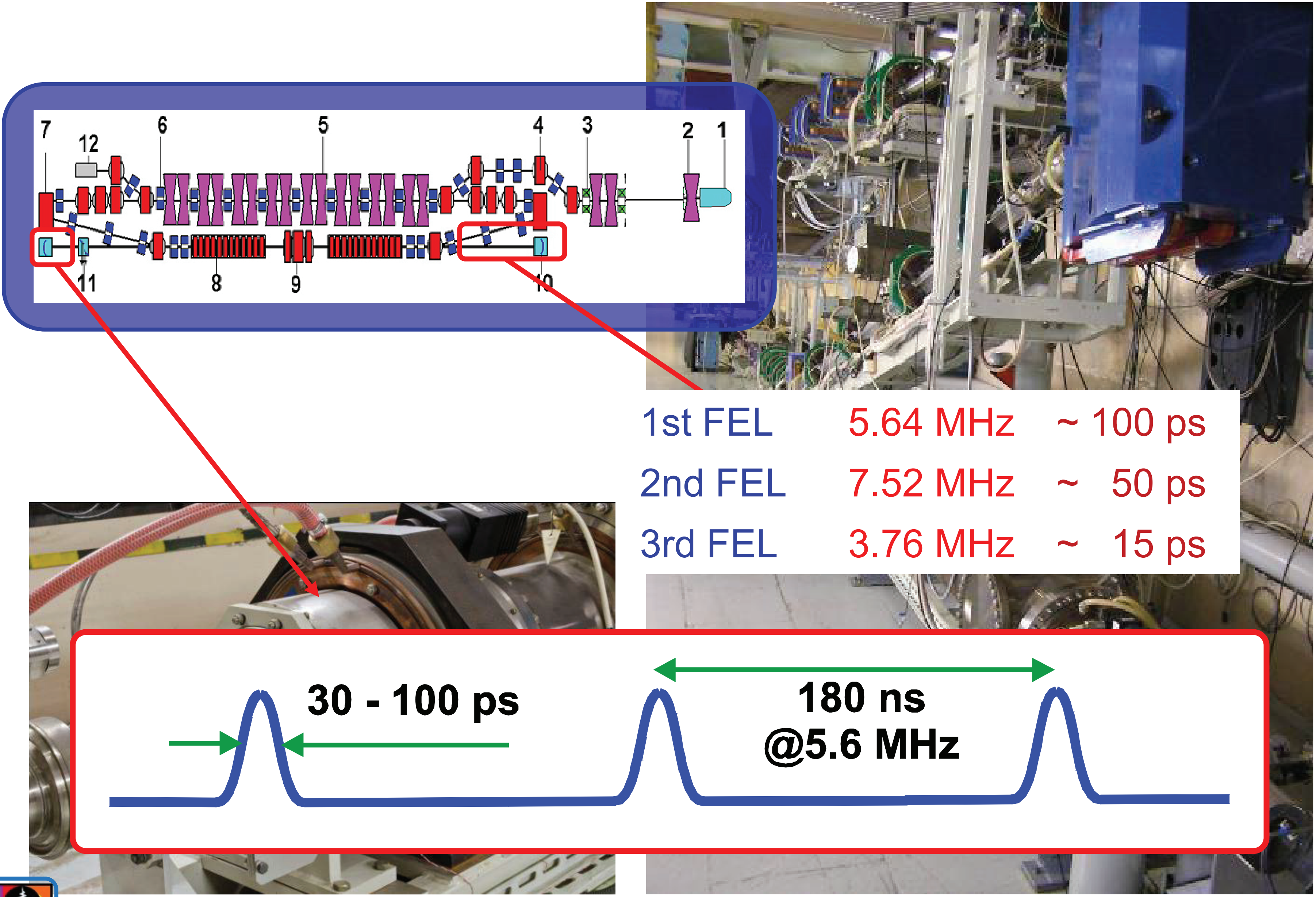
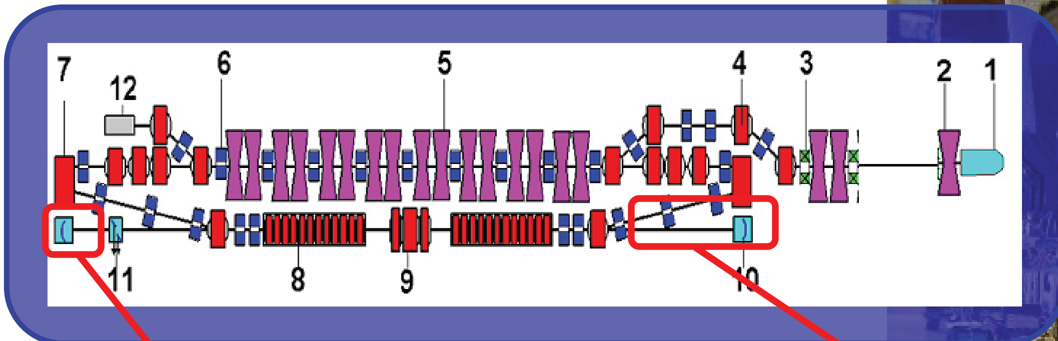
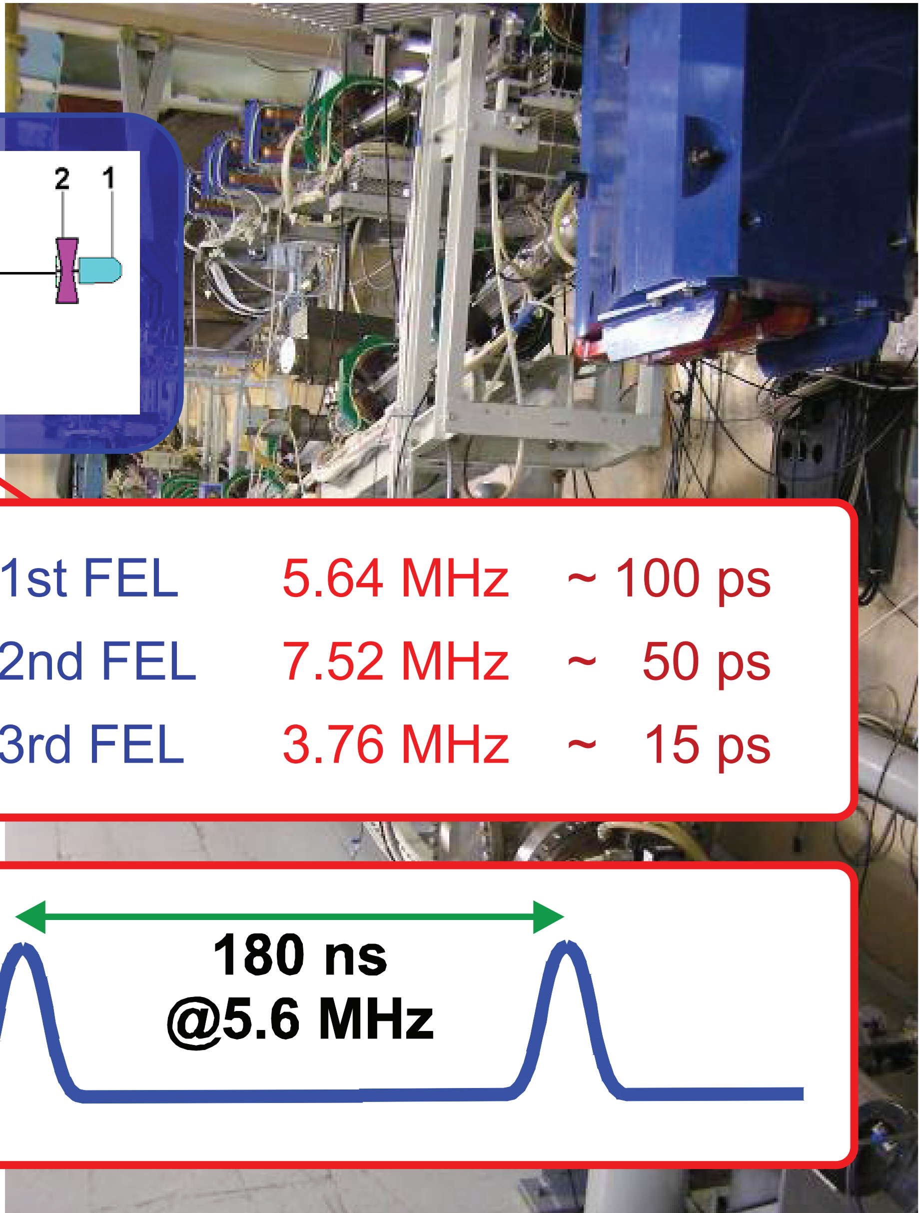
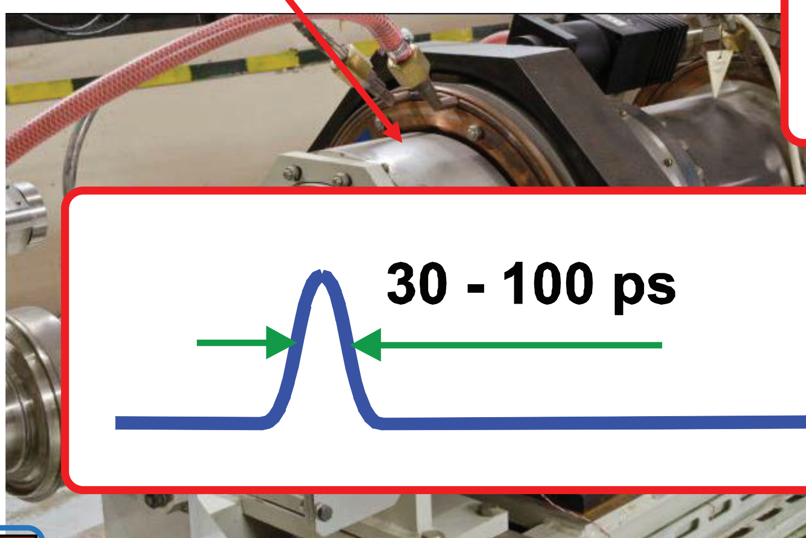
FEL Optical Cavities



FEL Optical Cavities





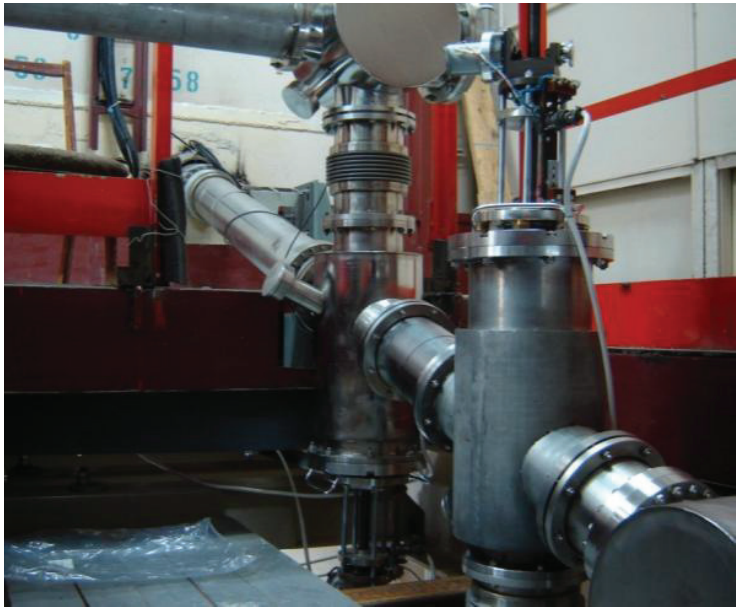


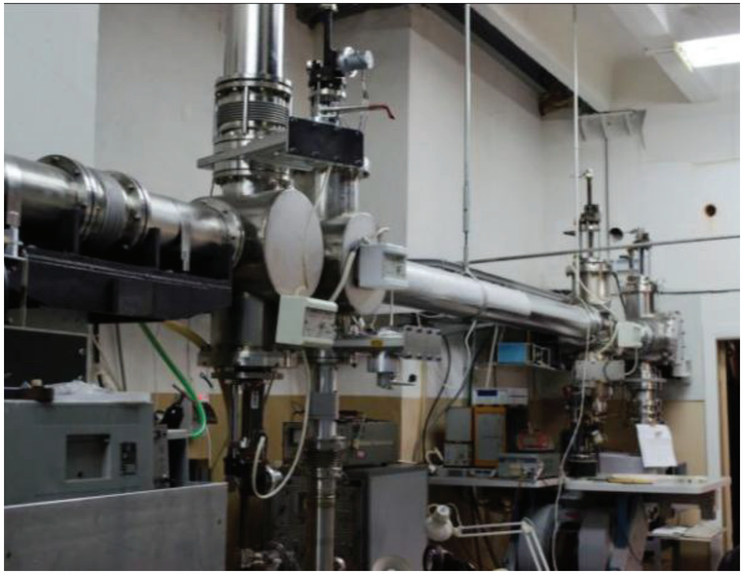
1st FEL	5.64 MHz	~ 100 ps
2nd FEL	7.52 MHz	~ 50 ps
3rd FEL	3.76 MHz	~ 15 ps

30 - 100 ps

180 ns
@5.6 MHz

Optical beamlines and user stations





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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.

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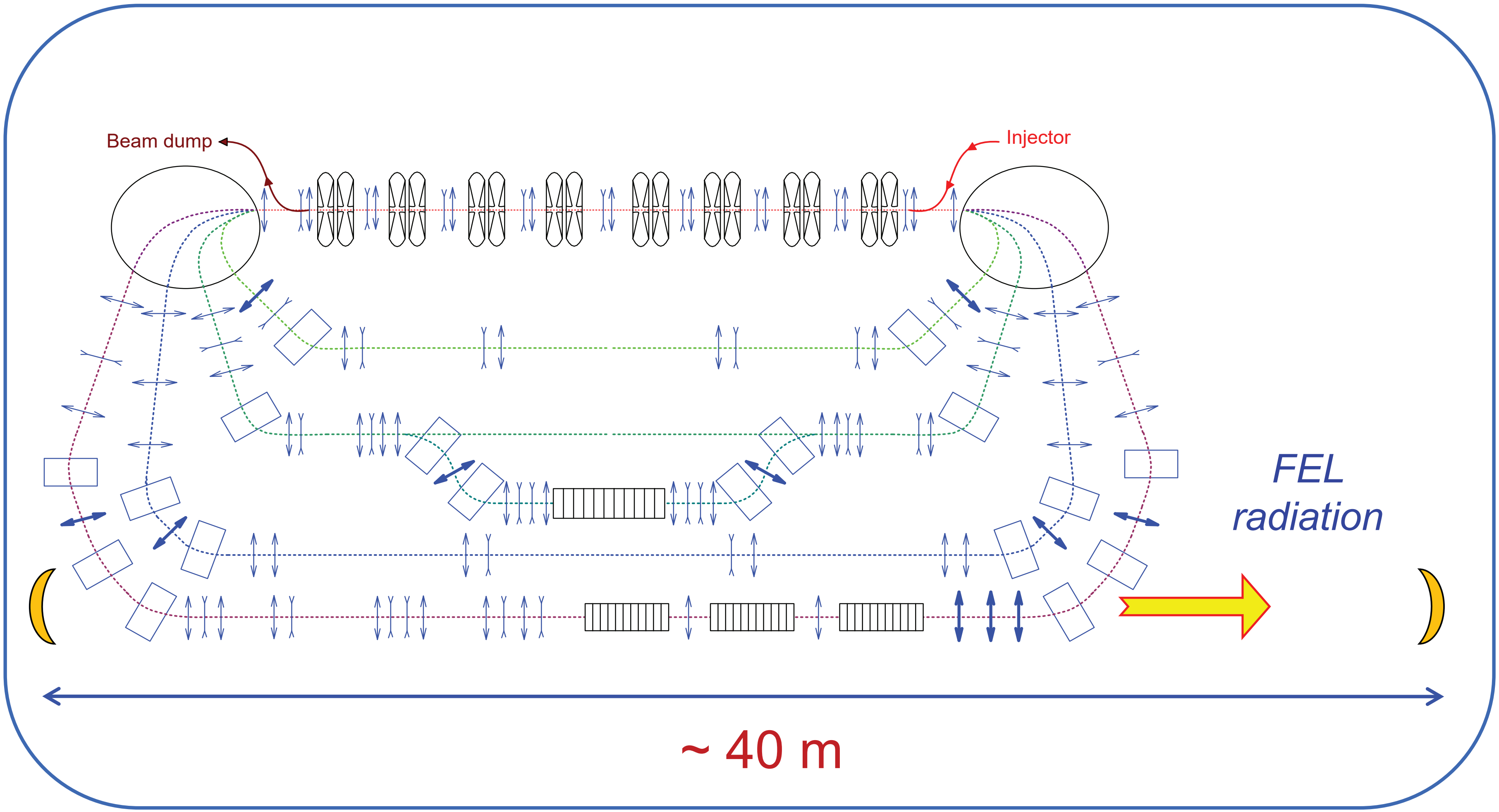
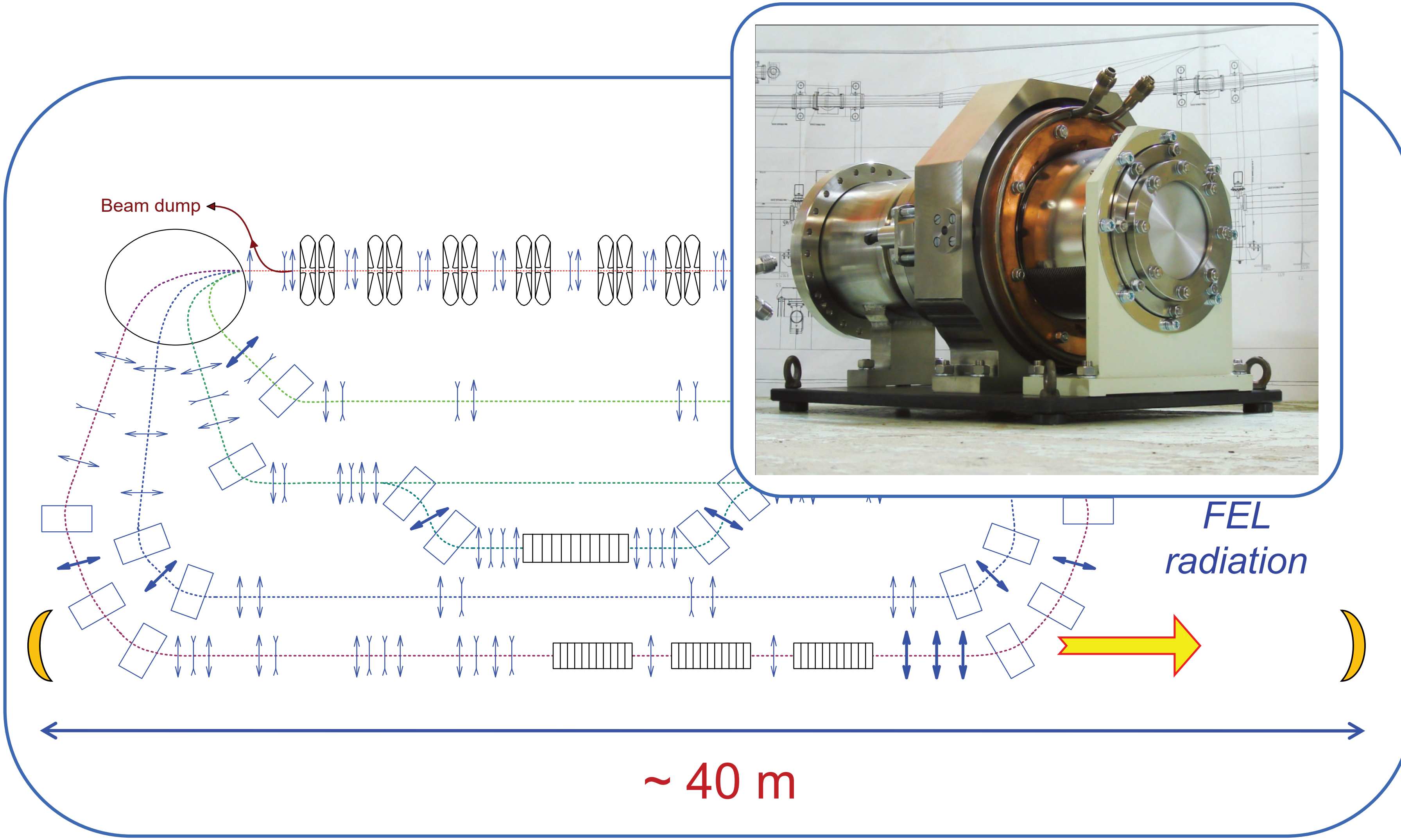
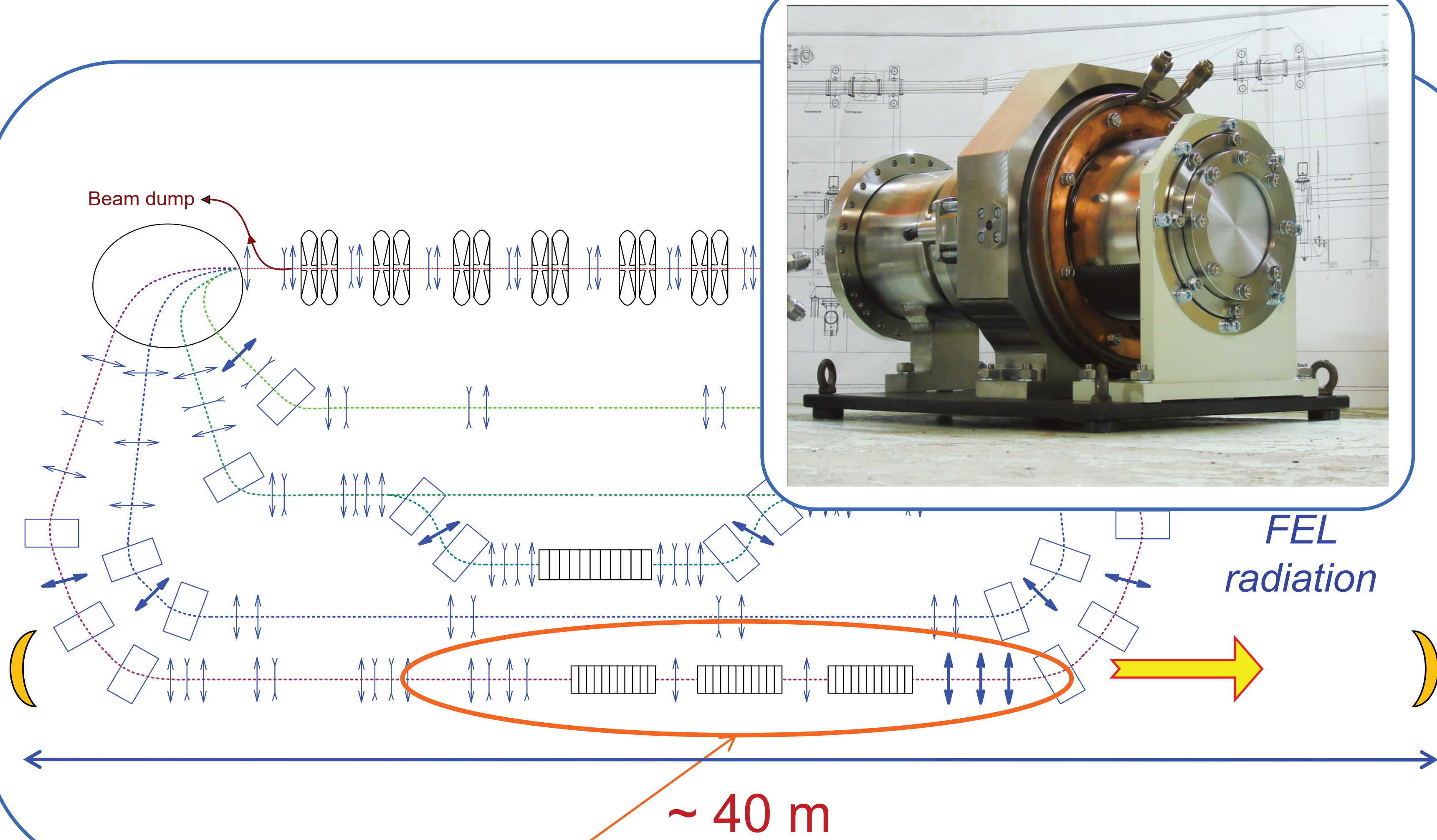
The Third FEL Design and Commissioning



The Third FEL Design and Commissioning

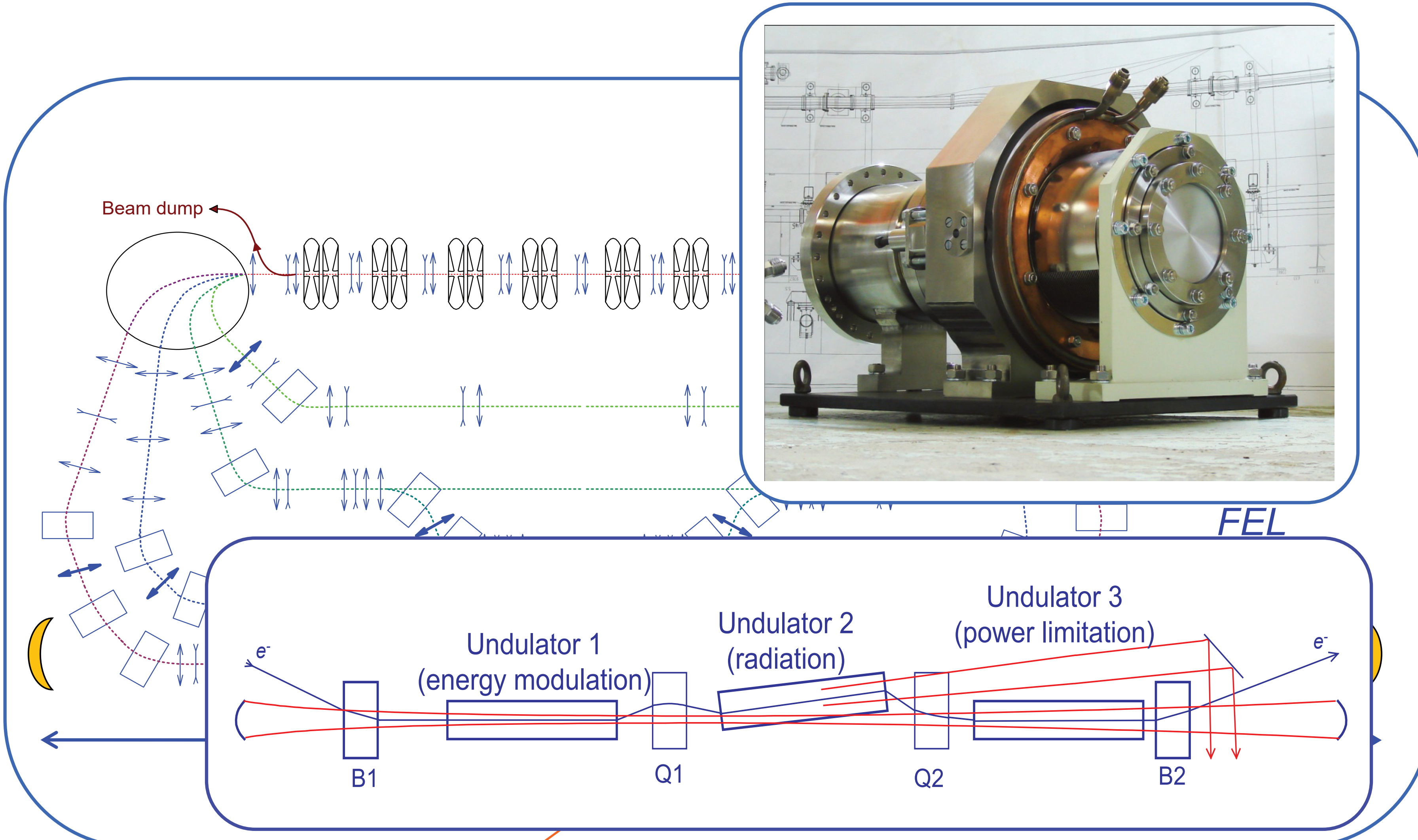


The Third FEL Design and Commissioning



Electron outcoupling scheme may be used here

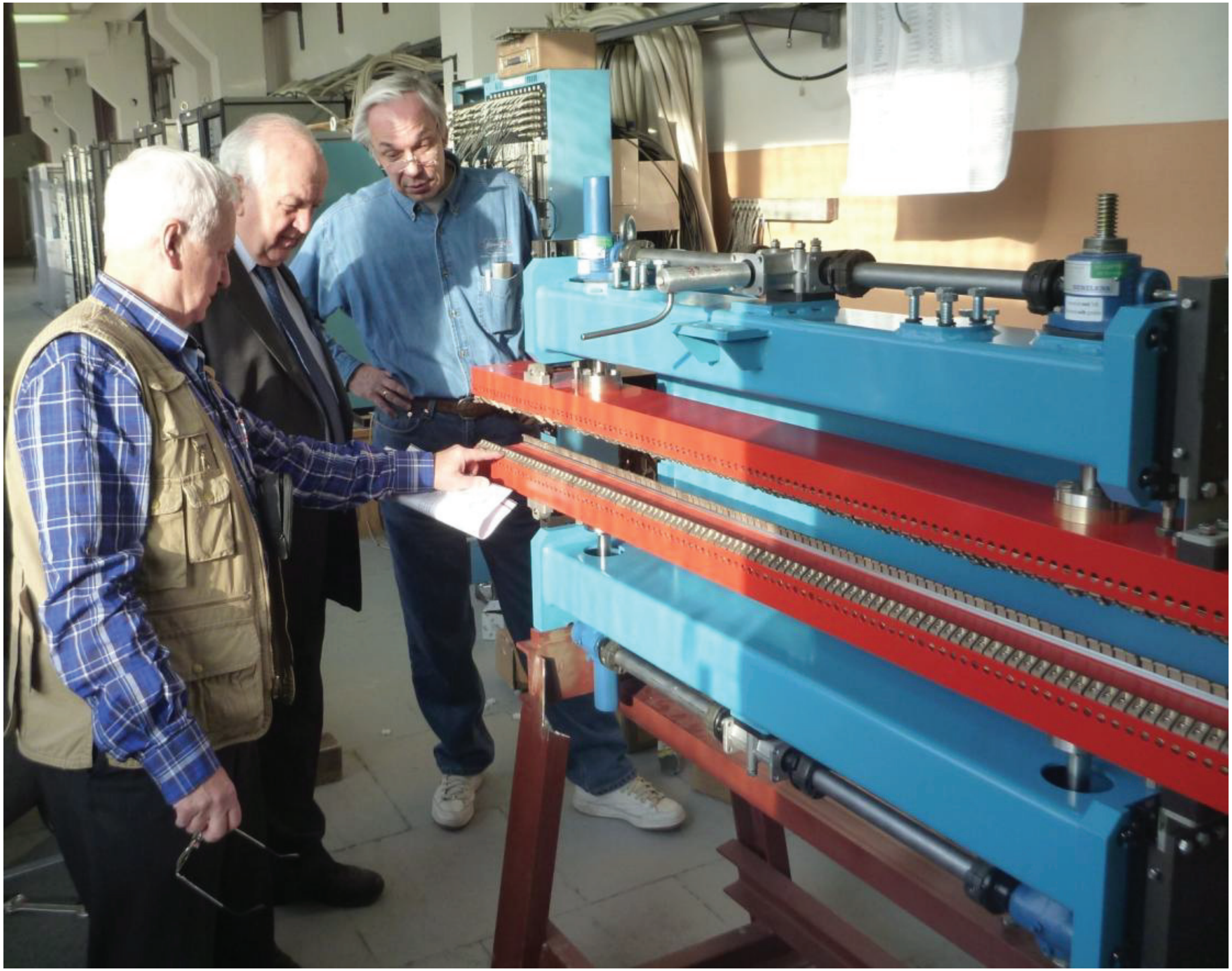
The Third FEL Design and Commissioning



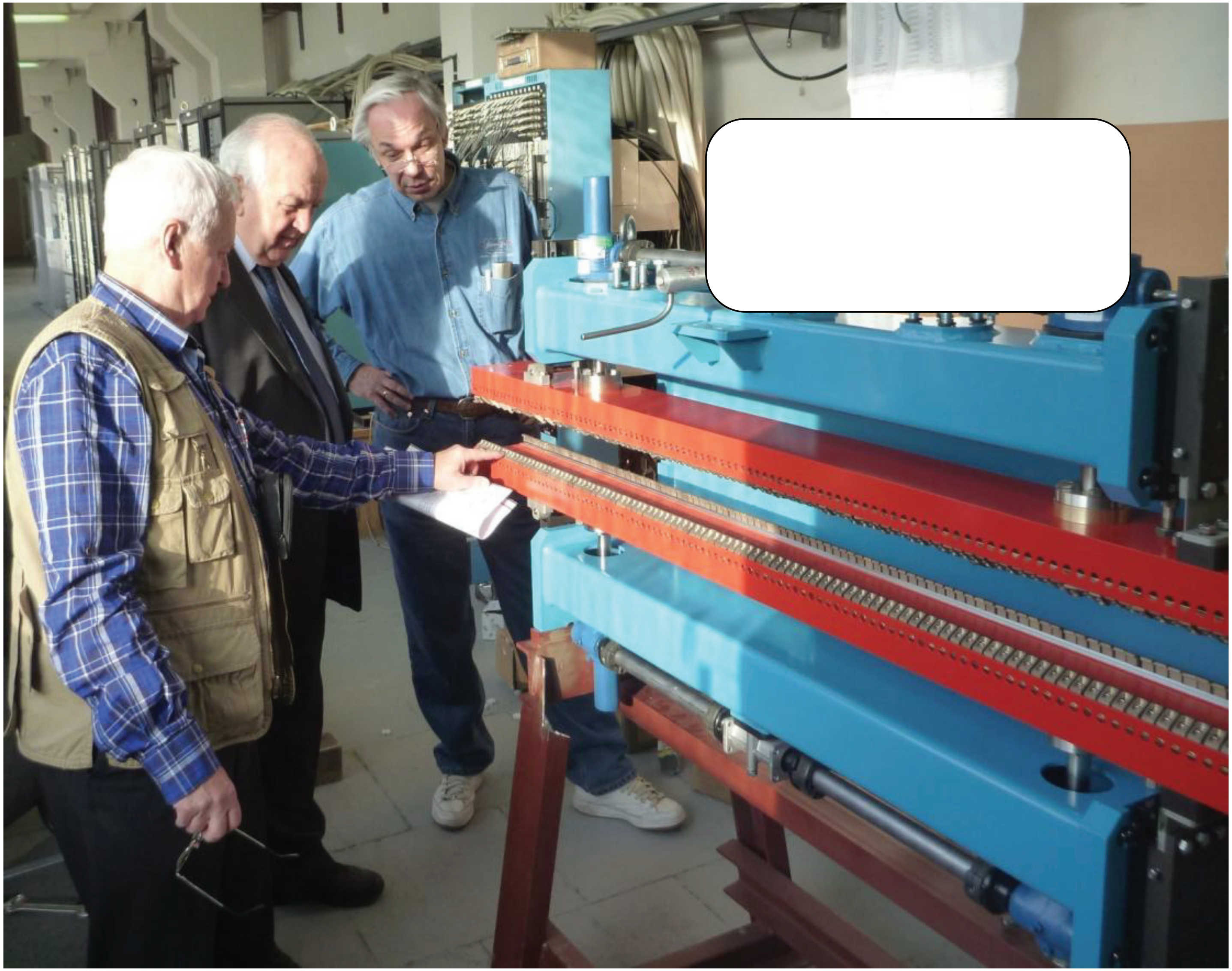
Electron outcoupling scheme may be used here

The third FEL undulator

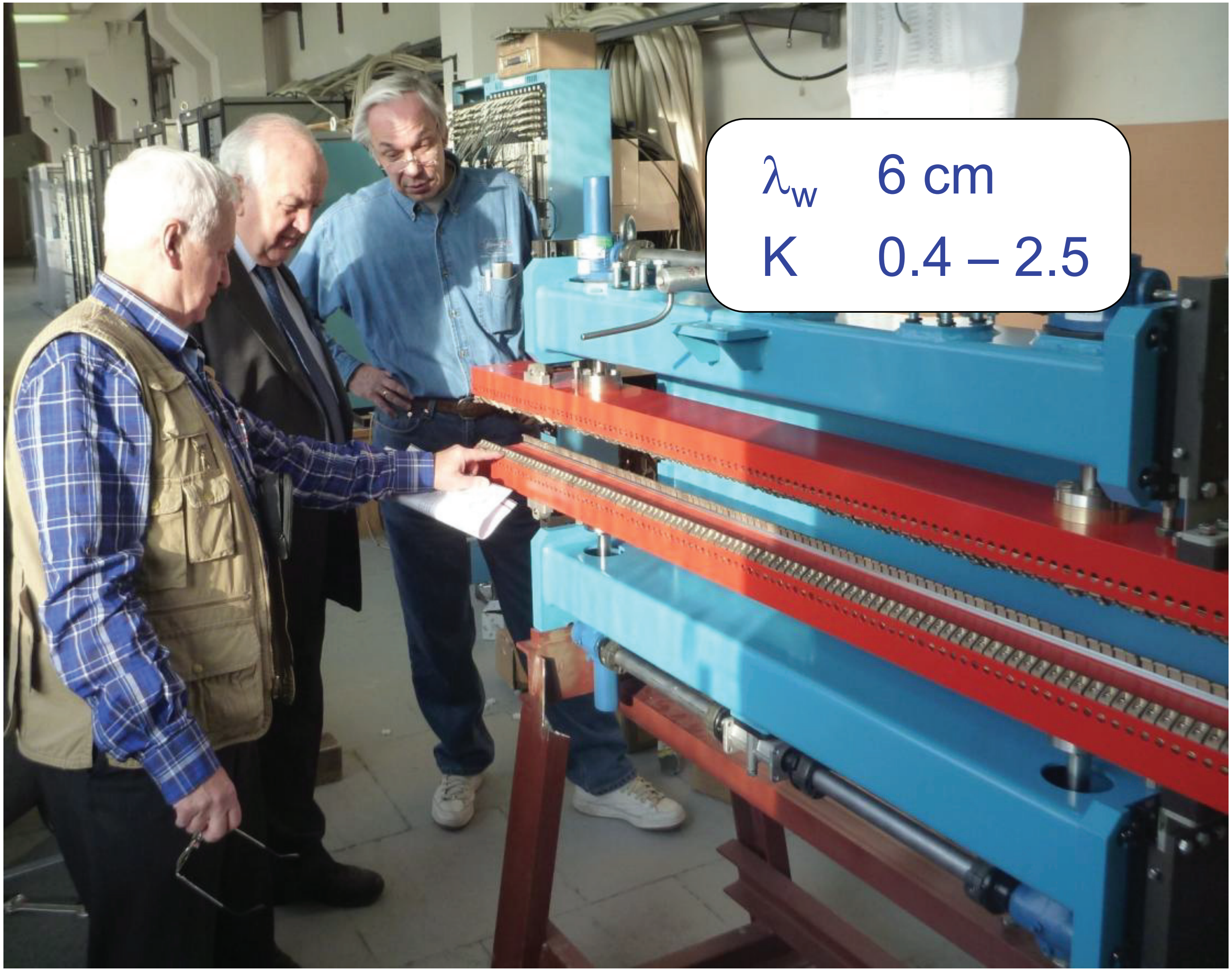
The third stage FEL undulator



The third stage FEL undulator



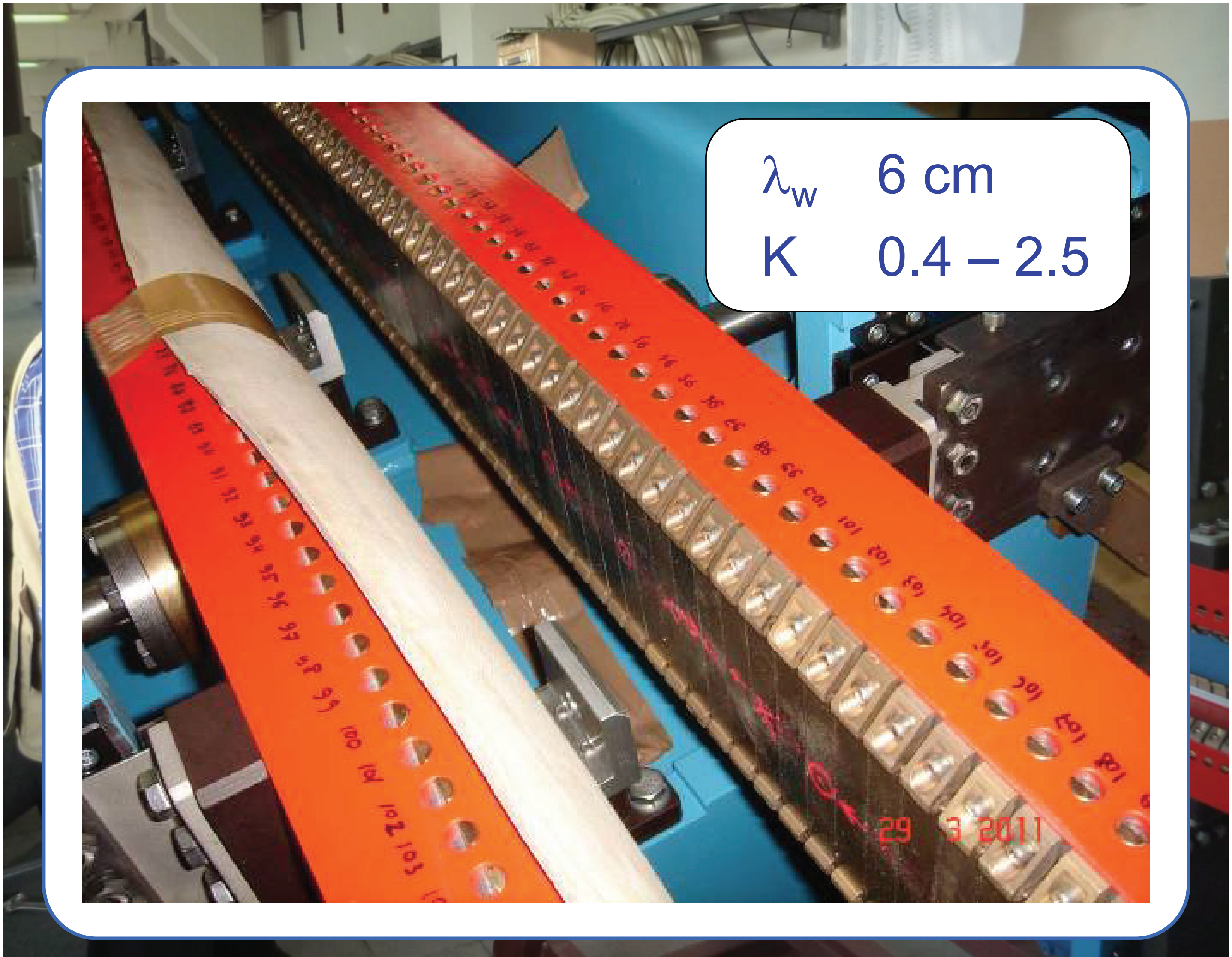
The third stage FEL undulator



λ_w 6 cm

K 0.4 – 2.5

The third stage FEL undulator



λ_w	6 cm
K	0.4 – 2.5

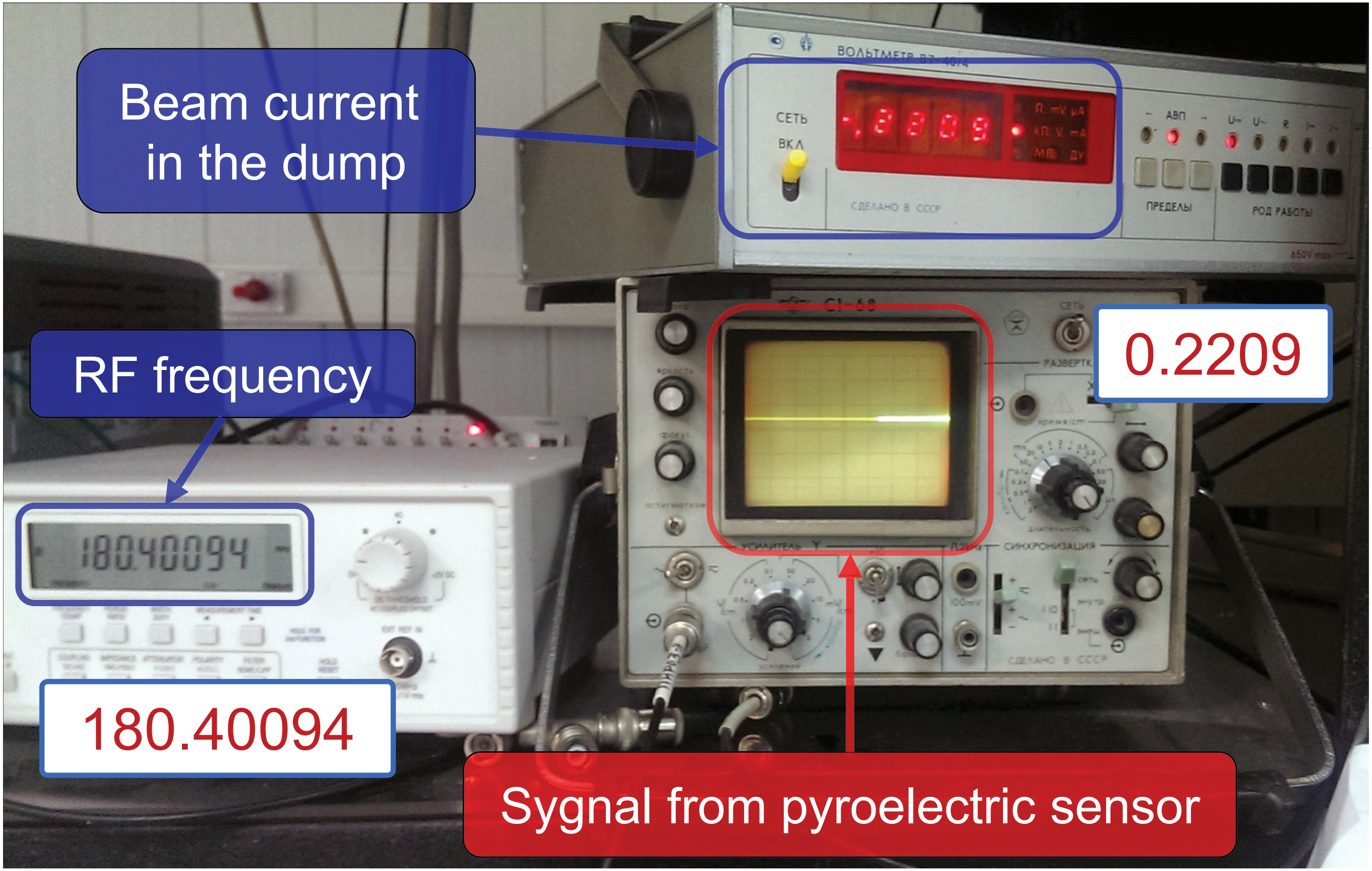
First lasing

Challenges

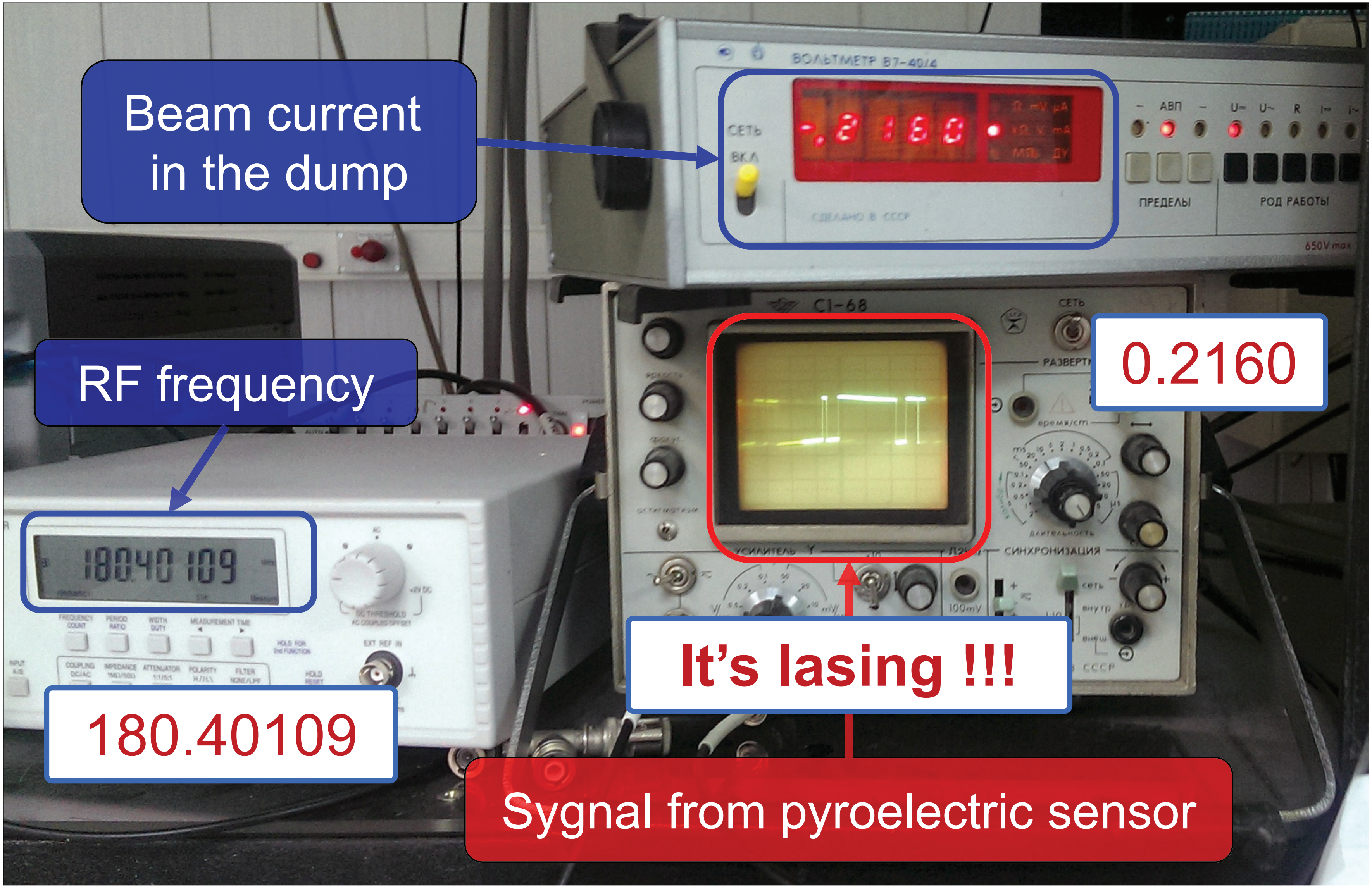
- Align mirrors of 40 meters long optical cavity and adjust the distance between them with accuracy better than 0.3 mm
- Obtain high recovery efficiency in multiturn ERL
- Adjust the beam trajectory in undulator with submillimetric accuracy

First lasing

When it's done all that remains is to adjust RF frequency and watch carefully



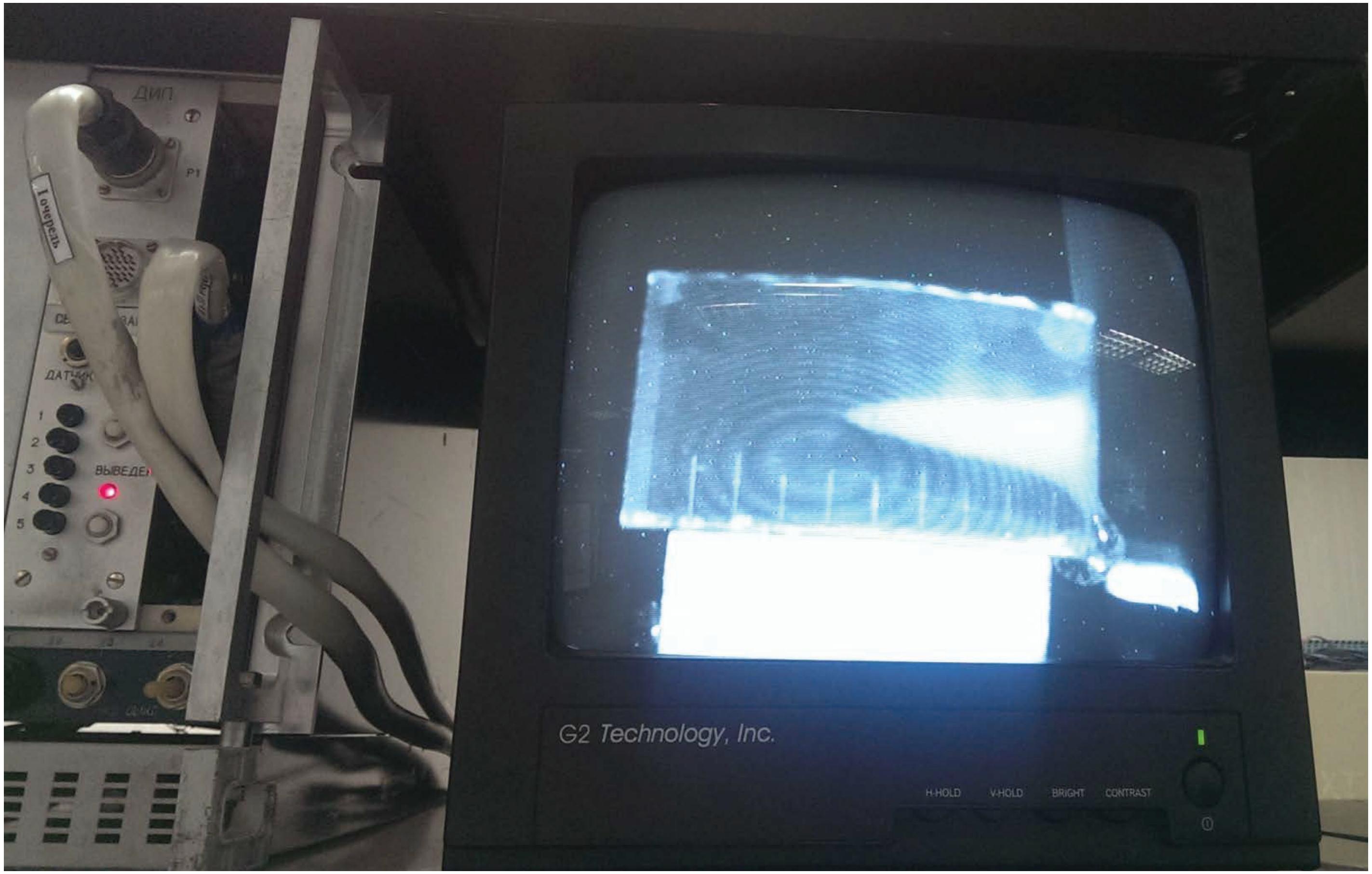
6 July 2015 – the first lasing



6 July 2015 – the first lasing

First experiments with 3rd stage FEL

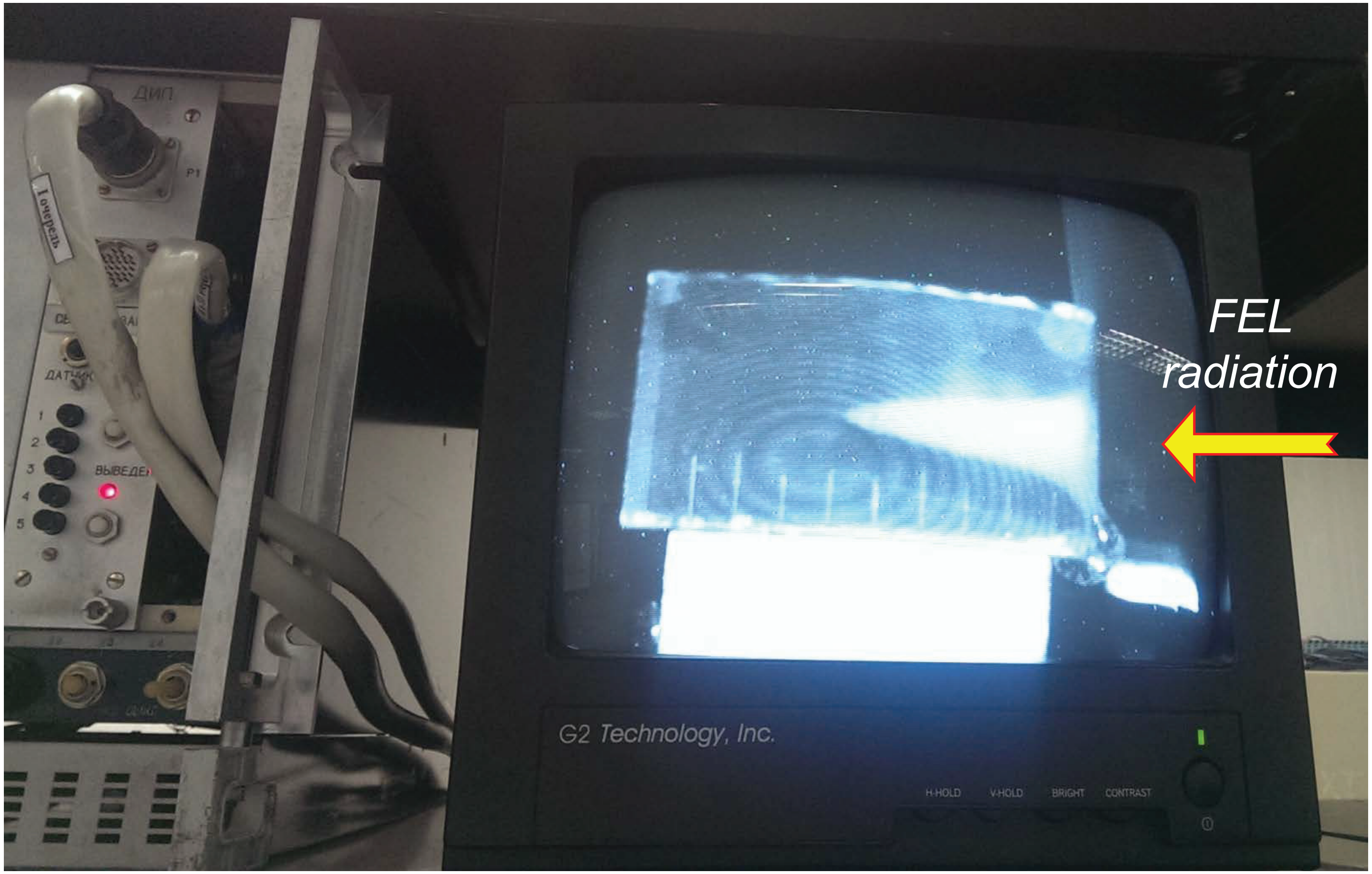
Drilling holes in plexiglass



Radiation power was about 30 watts
Wavelength 8.96 μm

First experiments with 3rd stage FEL

Drilling holes in plexiglass

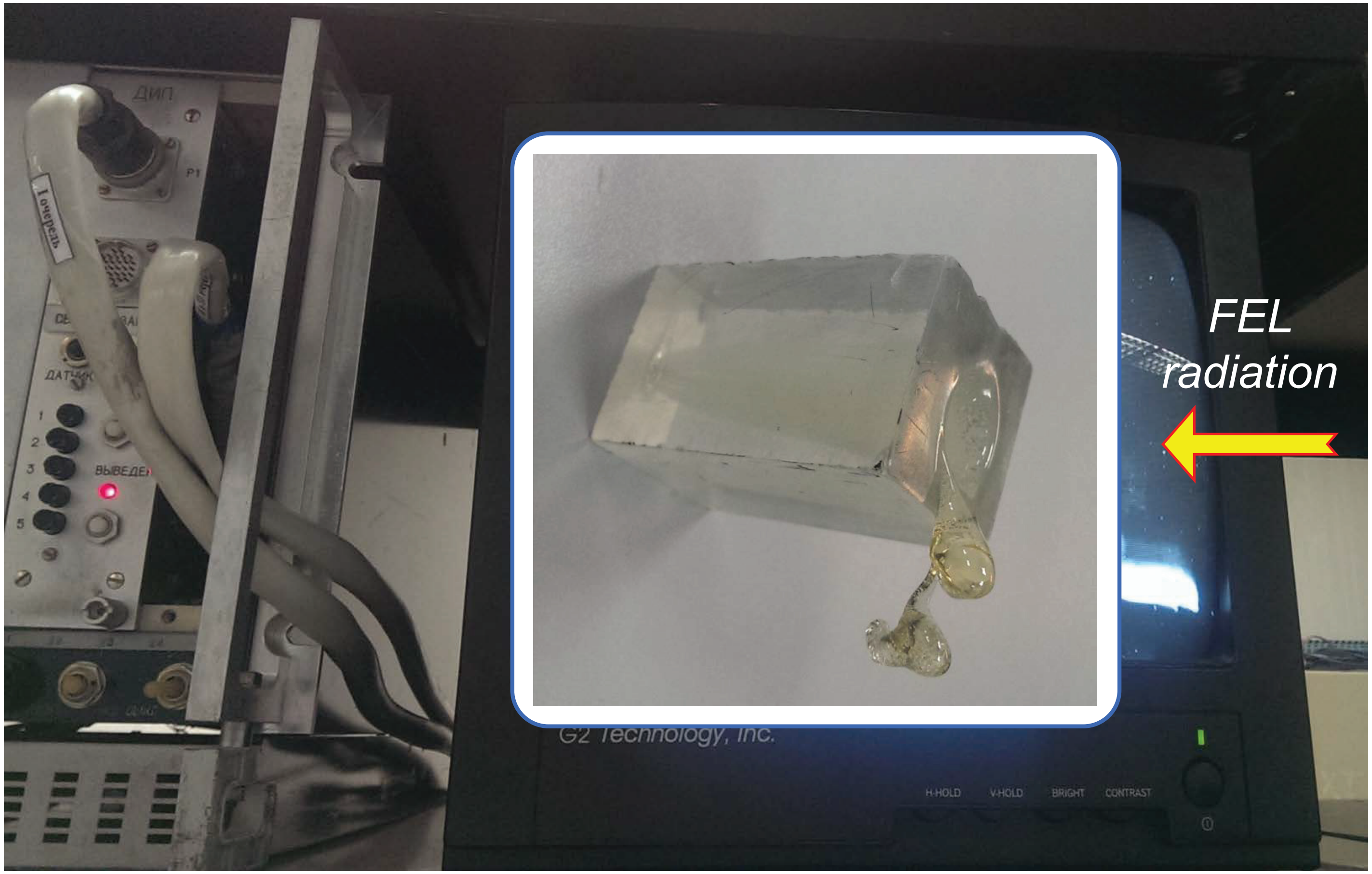


Radiation power was about 30 watts

Wavelength 8.96 μm

First experiments with 3rd stage FEL

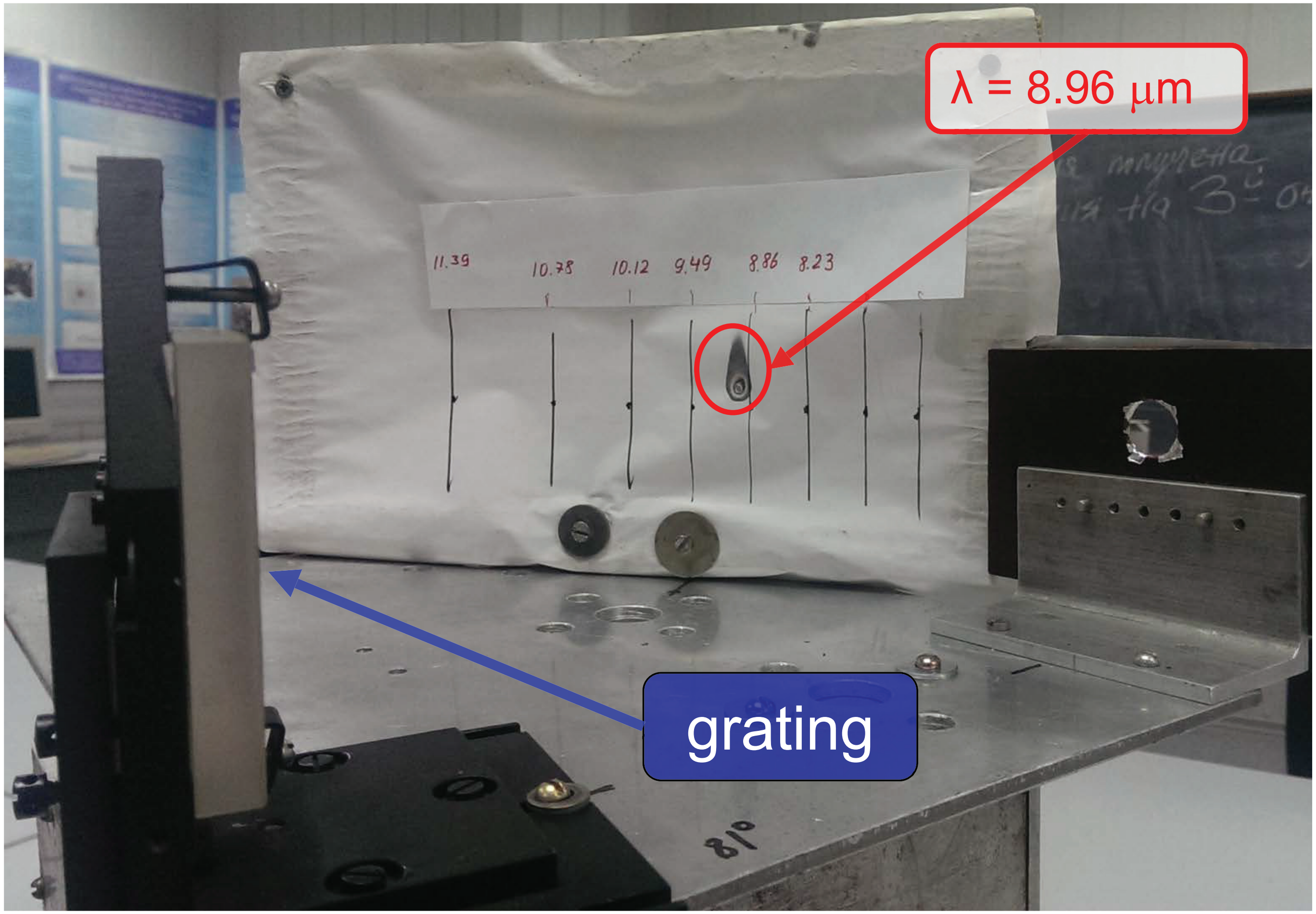
Drilling holes in plexiglass



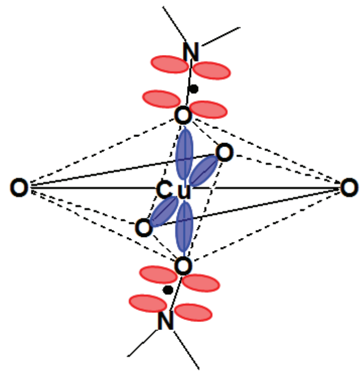
Radiation power was about 30 watts
Wavelength 8.96 μm

First experiments with new FEL

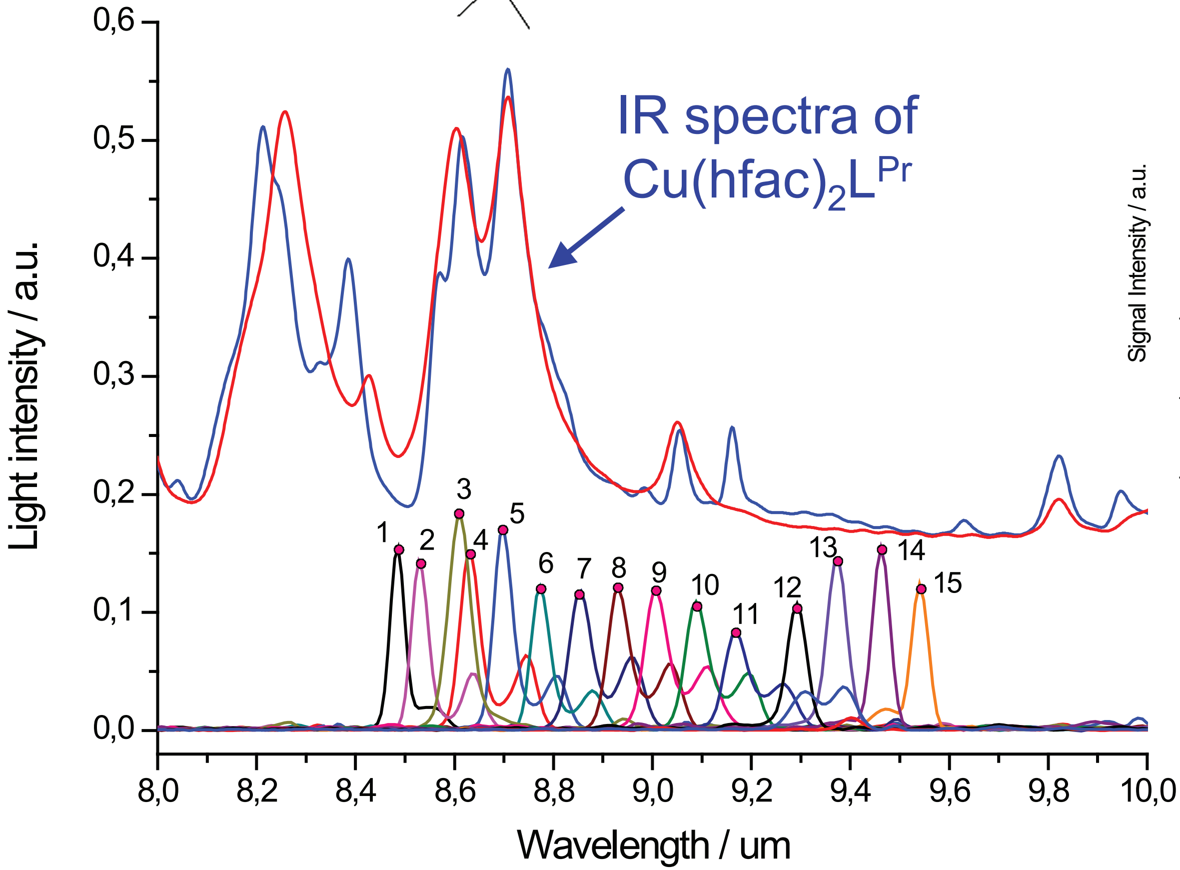
Measurement of the radiation wavelength



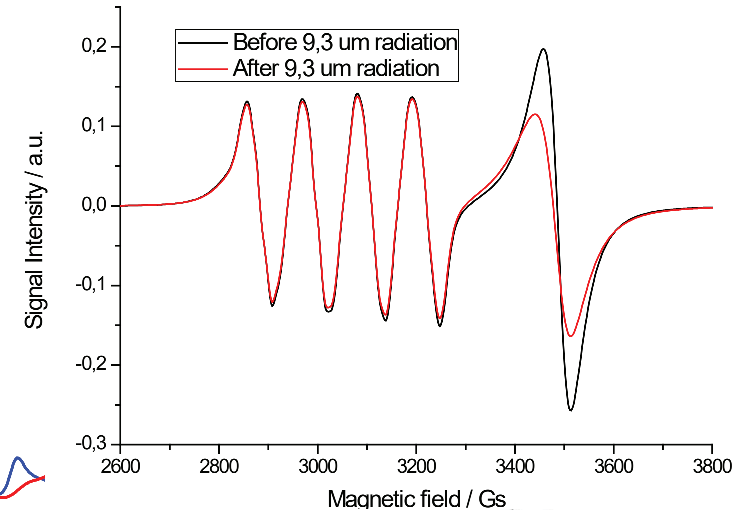
International Tomography Center SB RAS – the first user of the third FEL

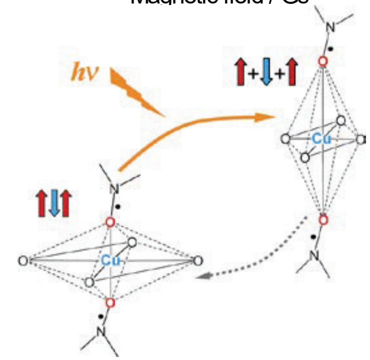


Influence of IR-light to the spin state of photoswitchable copper(II)-nitroxide magnetoactive compound $Cu(hfac)_2L^{Pr}$



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





Electron beam and radiation parameters

	1st	2nd	3rd	
Energy, MeV	12	22	**42**	46
Current, mA	30	10	**3**	50
Wavelength, μm	90-240	37-80	**8-11**	5-20
Radiation power, kW	0.5	0.5	**0.1**	5
Electron efficiency, %	0.6	0.3	**0.2**	0.5

Nearest and far future plans

- Optical (SR) diagnostics of electron beam parameters
- Decrease beam losses and increase average current
- Increase DC gun voltage and improve beam quality in injector
- Optimize electron efficiency of FEL
- Improve x-ray and neutron radiation shielding
- Install RF gun

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Nearest and far future experiments

- Selective photochemical reactions
- Infrared laser catalysis
- Separation of isotopes
- …

Overview of the NovoFEL facility

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

- The second stage of NovoFEL based on two track energy recovery linac, working in spectral range (37 – 80) μm, was commissioned in 2009.

- The third stage of NovoFEL based on four track ERL was commissioned on July of 2015. Spectral range now is (8-11) μm. First operation for users was done in 2017.

Thank you for your attention!