RF ACCELERATOR FOR ELECTRON COOLING OF ULTRARELATIVISTIC HADRONS

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Outline

- Motivation
- Non-superconducting low RF frequency ERL
- Colling rate estimation

Introduction

New projects of high-energy hadron colliders could be improved by far by using the electron cooling technique. However, a source of high-current relativistic electron beam appears to be a technical challenge.

Indeed, the intrinsic energy limitations of high-voltage DC accelerators lead to necessity to perform acceleration using not static but vortex electrical fields. Induction and radiofrequency (RF) accelerators employ such fields. Moreover, to keep the damping times small enough at high energies, it is necessary to increase the electron peak current to tens of amperes.

The feasibility of RF energy recovery linac (ERL) application to electron cooling is discussed.

The ERL of the Novosibirsk free electron laser facility is used as a reliable prototype.

The necessity of high current and relatively low (less than 100 MeV) electron energy leads to the choice of an ERL with a low-frequency non-superconducting accelerating RF system. Indeed, the characteristic parameters for longitudinal stability of the average electron beam current I_{beam} is the ratio of the beam power to the power consumption in the RF cavities

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

where R/Q, Q, and U are the characteristic impedance, RF quality, and voltage amplitude of single cavity, respectively. For the typical values U = 1 MV and $2R/Q$ = 100 Ohm, $U/(2R/Q)$ = 10 kA. Then it gives the limitation for the average current:

$$I_{beam} < \frac{10\text{kA}}{Q}$$

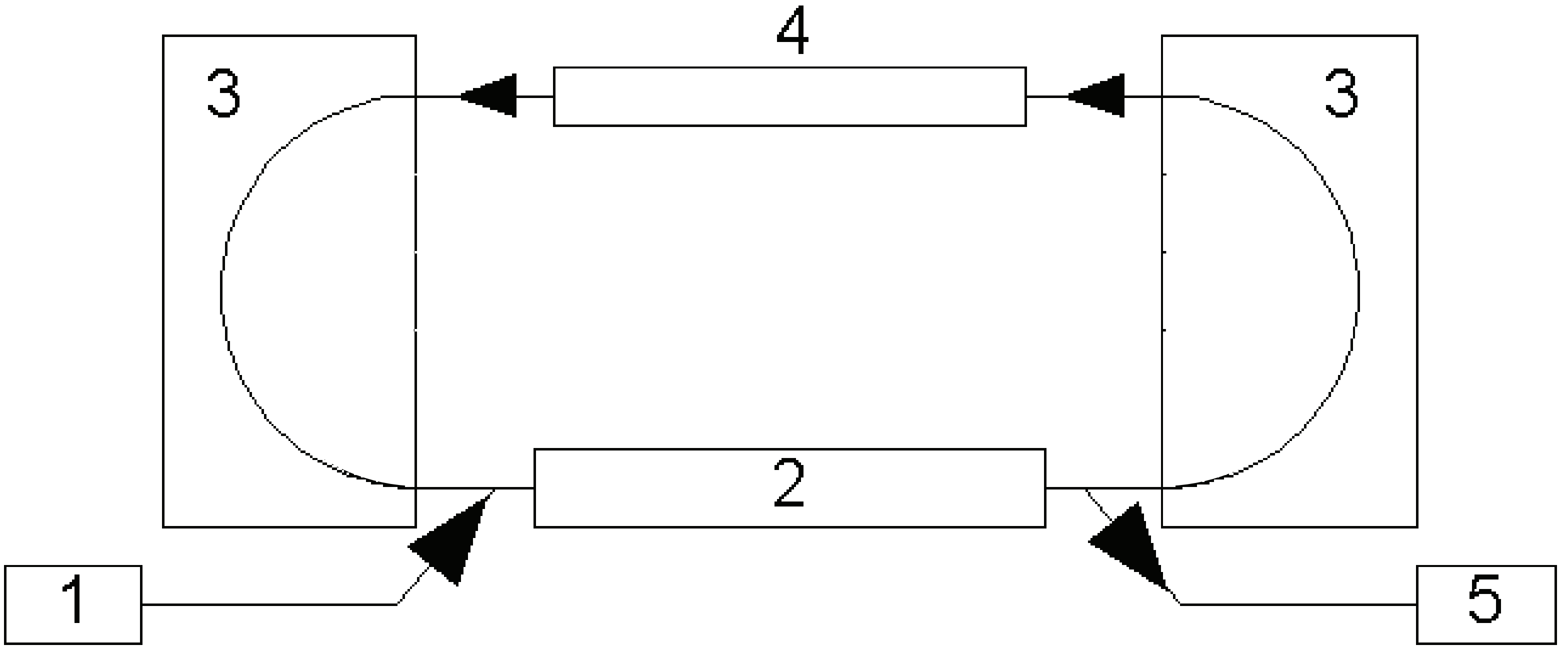
Expected electron beam parameters

Energy E, MeV		50
Charge q per bunch, nC		16
Number N_e of electrons		10^{11}
Longitudinal emittance ε_s, keV·ns		10
Normalized transverse emittances ε_t, mm·mrad		10

Novosibirsk ERL almost satisfies this requirements, except of the charge per bunch, which is less than 2 nC now.

NovoFEL

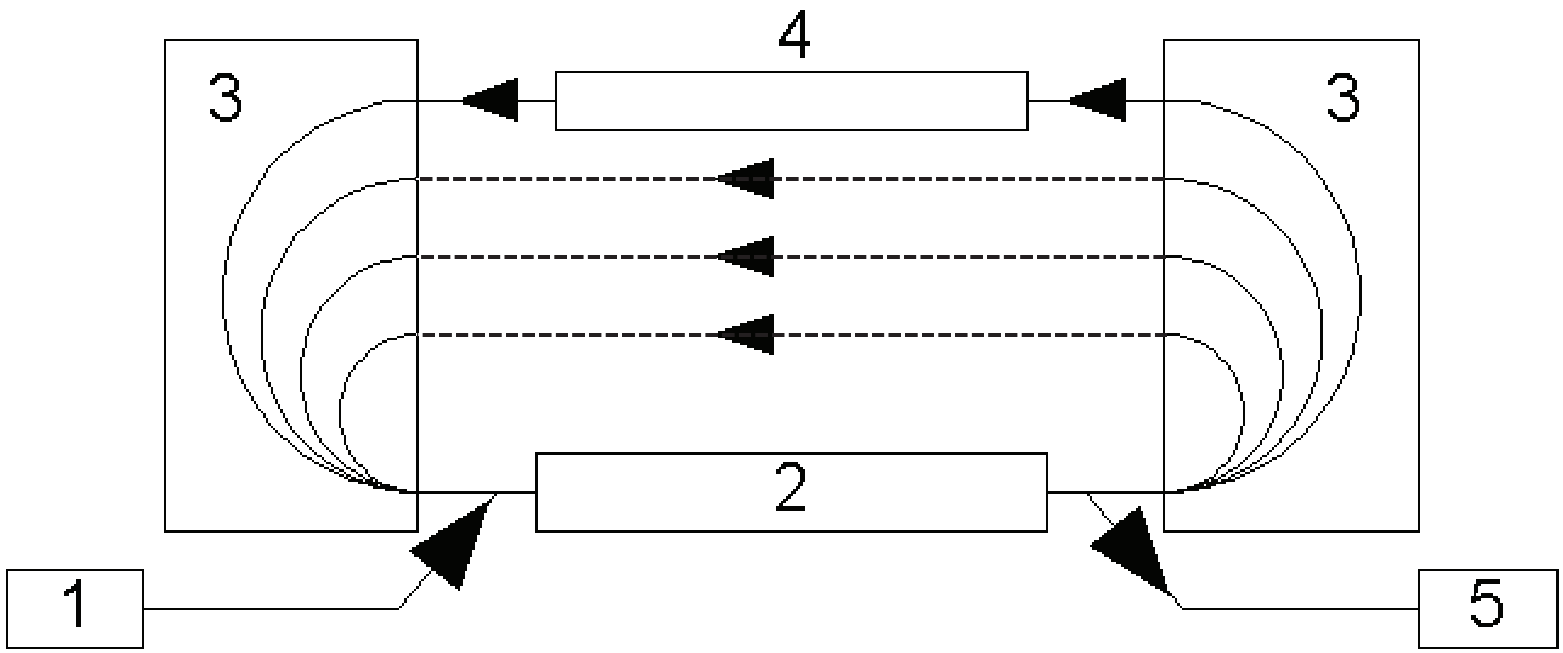
Energy Recovery Linac



1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator (or cooling device), 5 –dump

NovoFEL

Energy Recovery Linac



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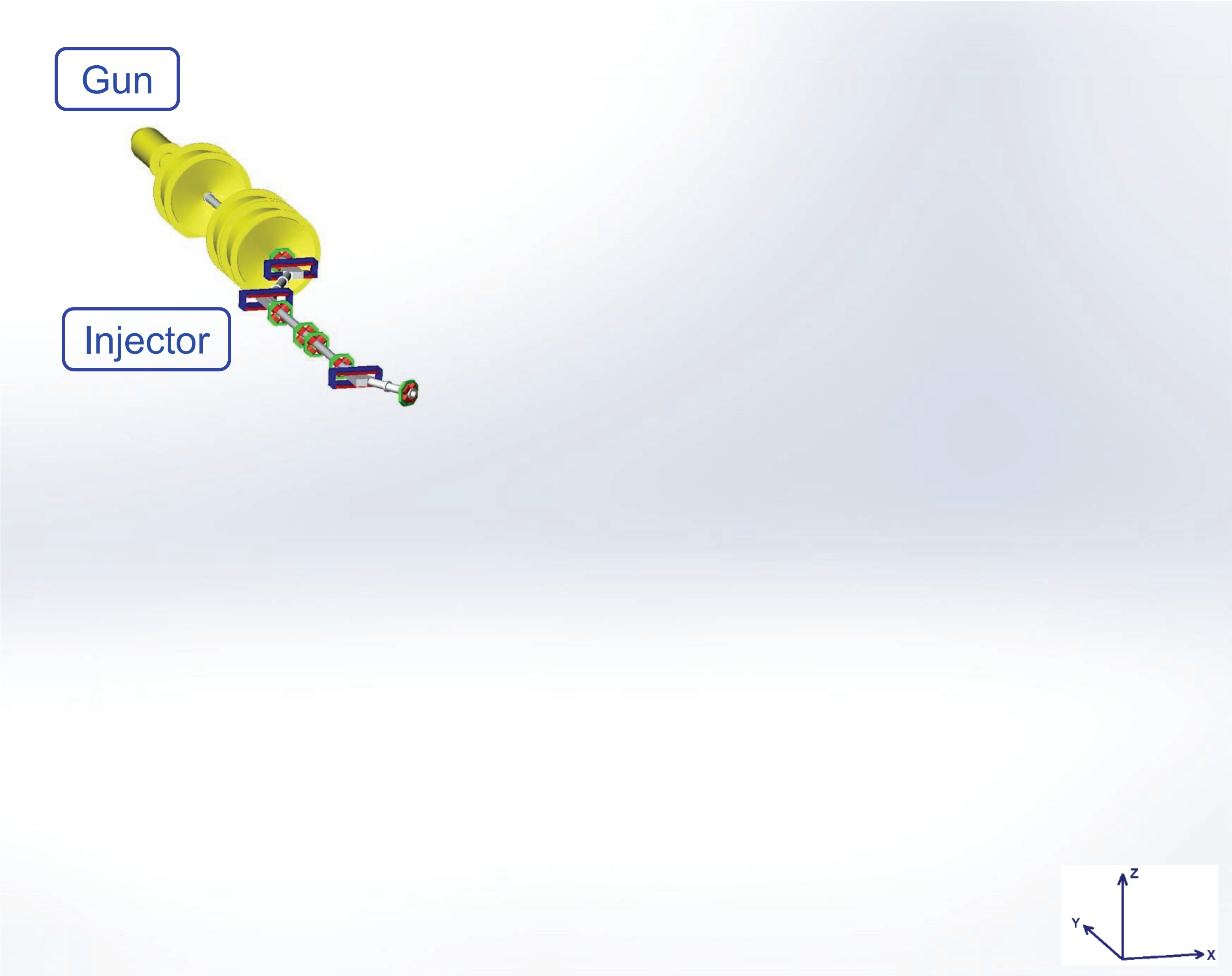
Novosibirsk FEL Facility Based on Non-suprconducting Multiturn ERL

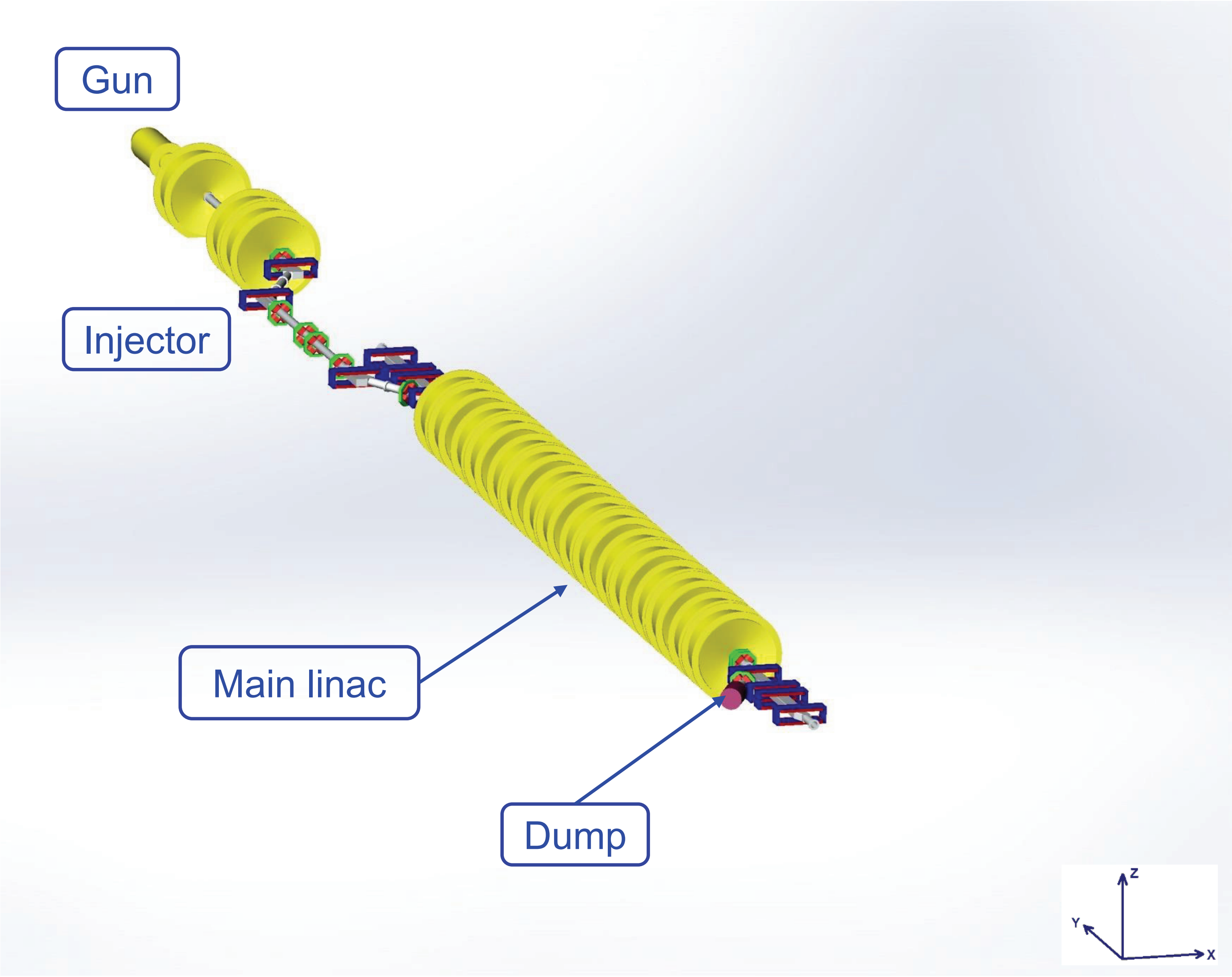
The Novosibirsk FEL facility has three FELs, installed on the first, second and fourth orbits of the dedicated energy recovery linac (ERL). The first FEL covers the wavelength range of 90 – 240 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 5.6 or 11.2 MHz and a peak power of up to 1 MW. The second FEL operates in the range of 40 - 80 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 7.5 MHz and a peak power of about 1 MW. These two FELs are the world's most powerful (in terms of average power) sources of coherent narrow-band (less than 1%) radiation in their wavelength ranges. The third FEL covers the wavelength range of 8 – 11 µm. The Novosibirsk ERL is the first multiturn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and a *rather compact (6×40 m^2) design*. The facility has been operating for users of terahertz radiation since 2004.

FEL #	1	2	3
Energy, MeV	12	22	42
Current, mA	30	10	3
Wavelength, µm	90-240	37-80	8-11
Radiation power, kW	0.5	0.5	0.1
Electron efficiency, %	0.6	0.3	0.2

NovoFEL Accelerator Design



NovoFEL Accelerator Design



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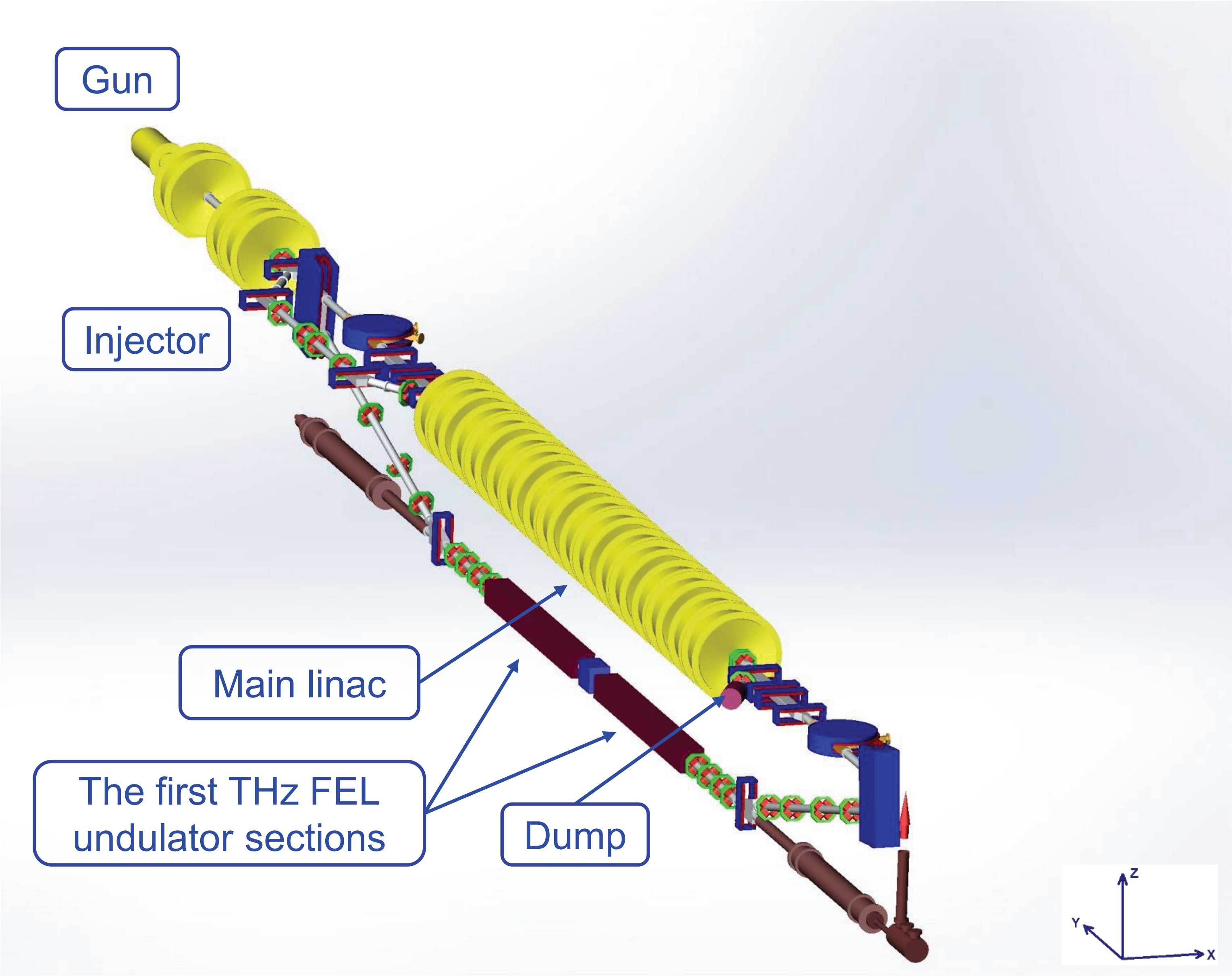

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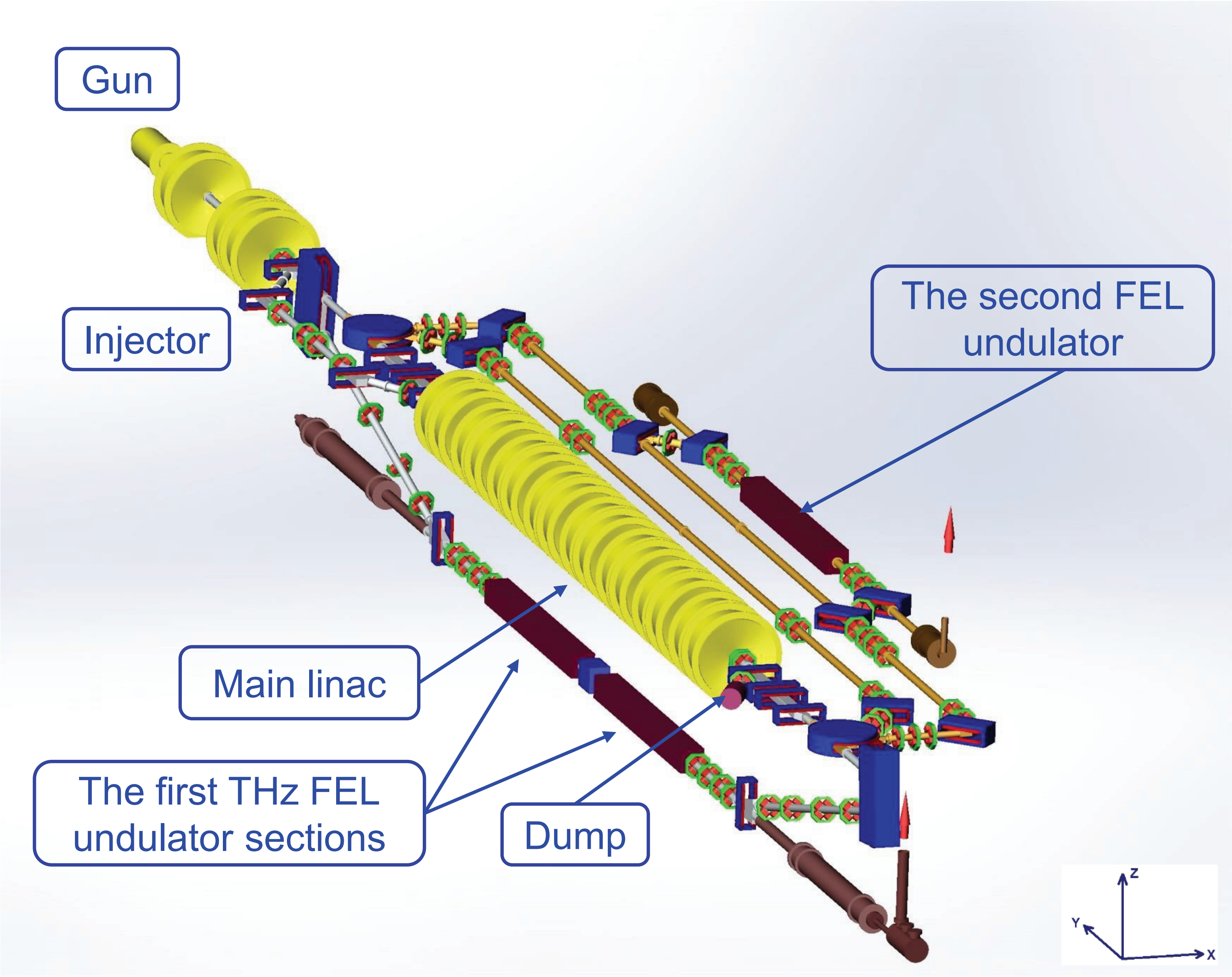

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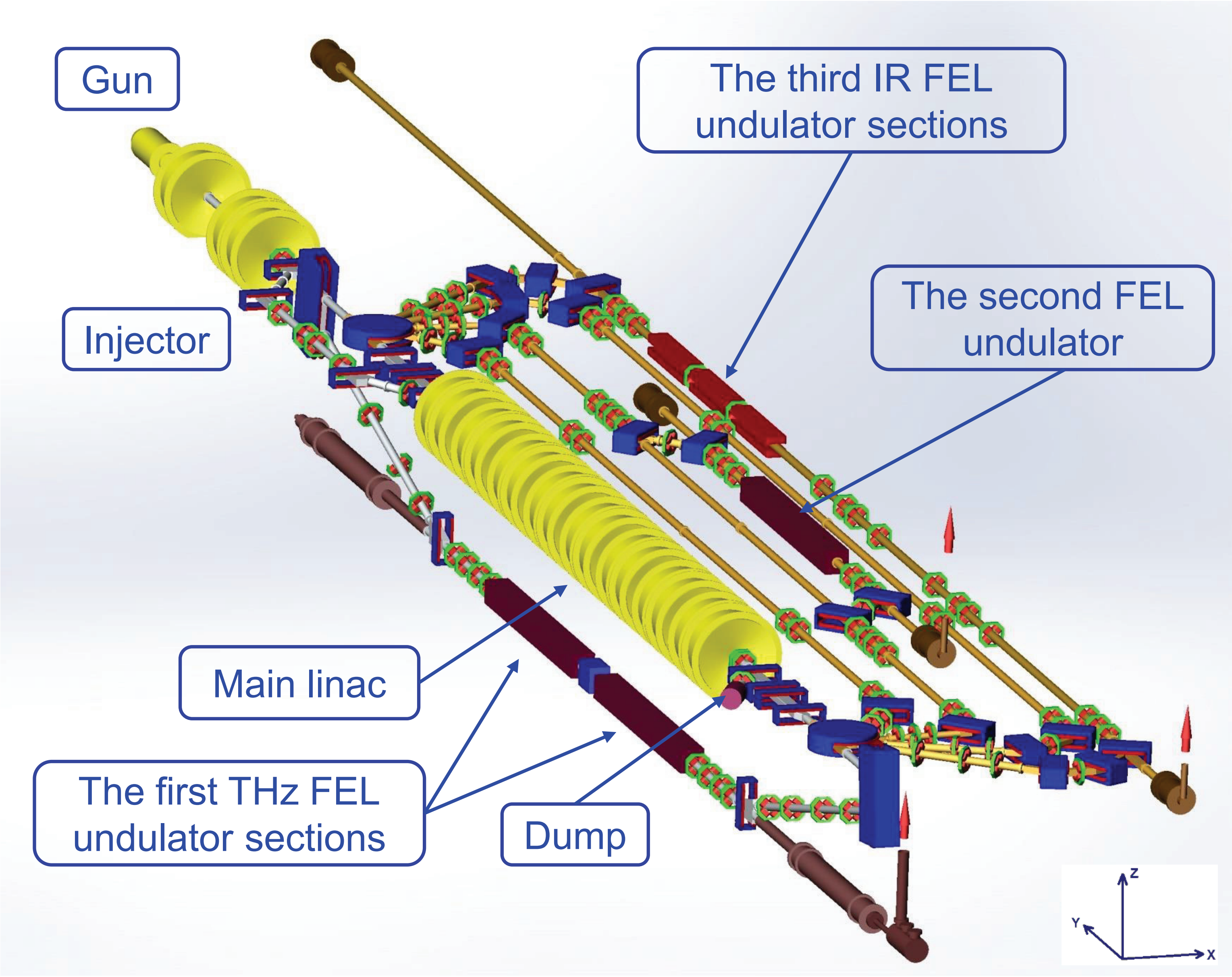
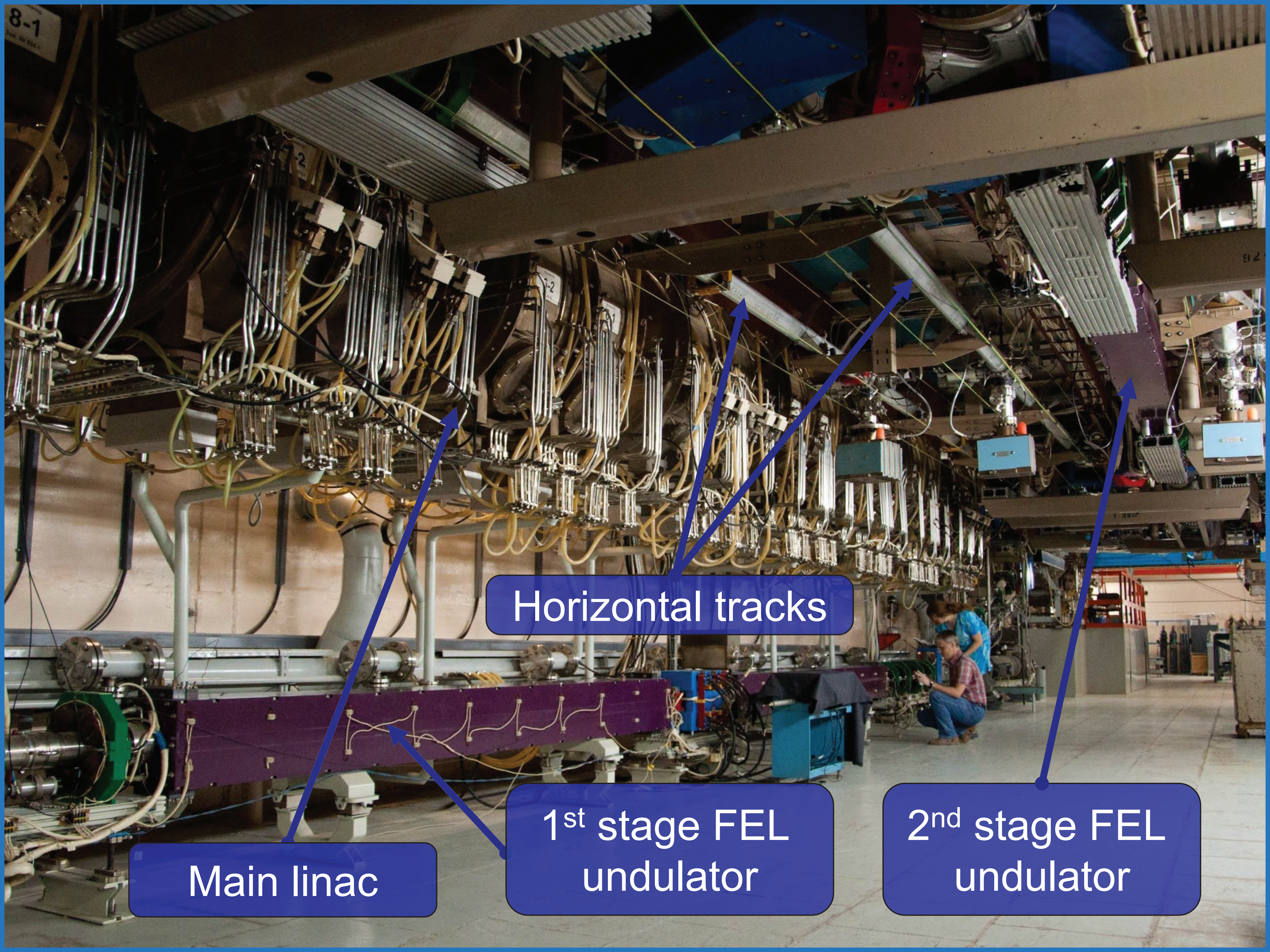
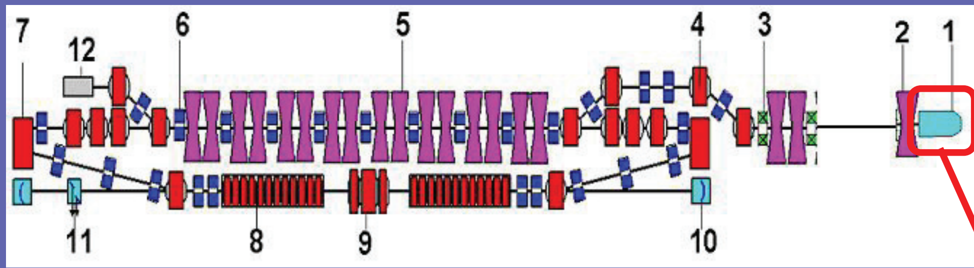


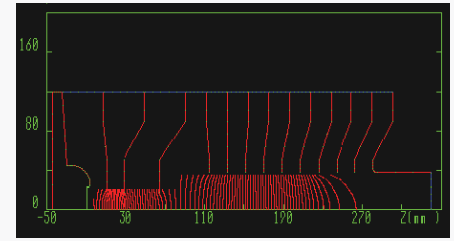


Horizontal tracks
Main linac
1st stage FEL undulator
2nd stage FEL undulator


3d stage FEL undulator

Electrostatic Gun



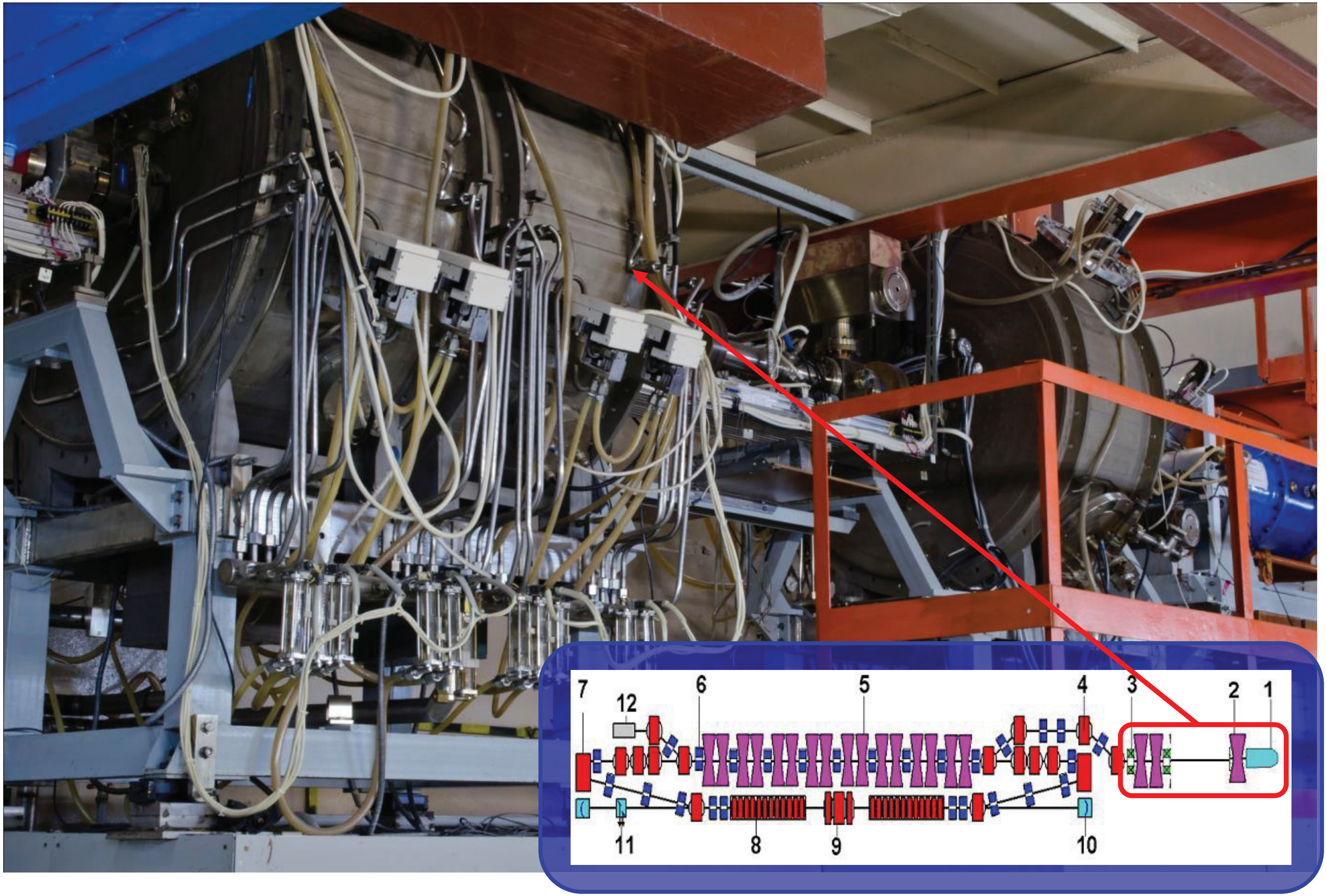


Power supply:

U_{max} = 300 kV

I_{max} = 50 mA

Injector



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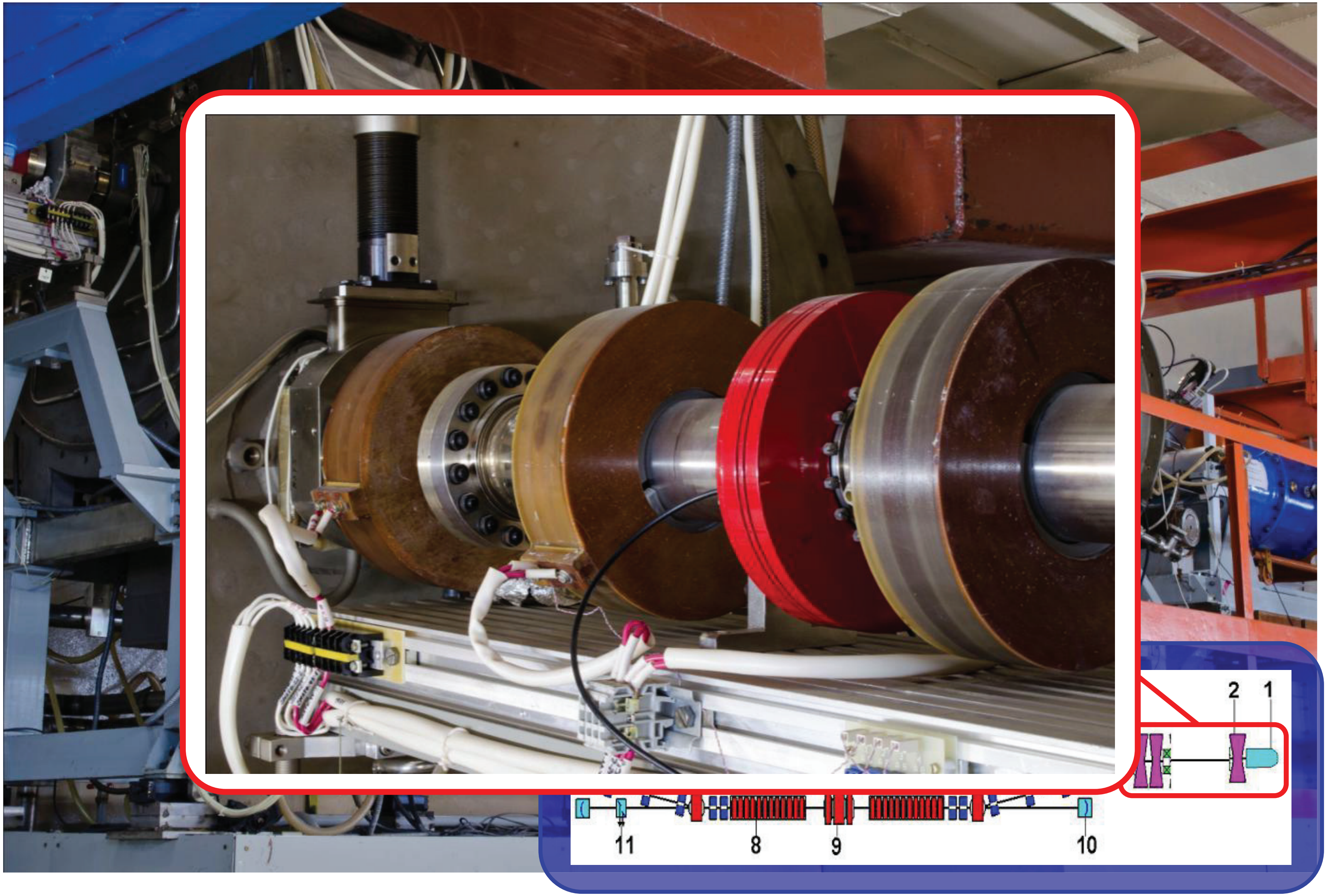
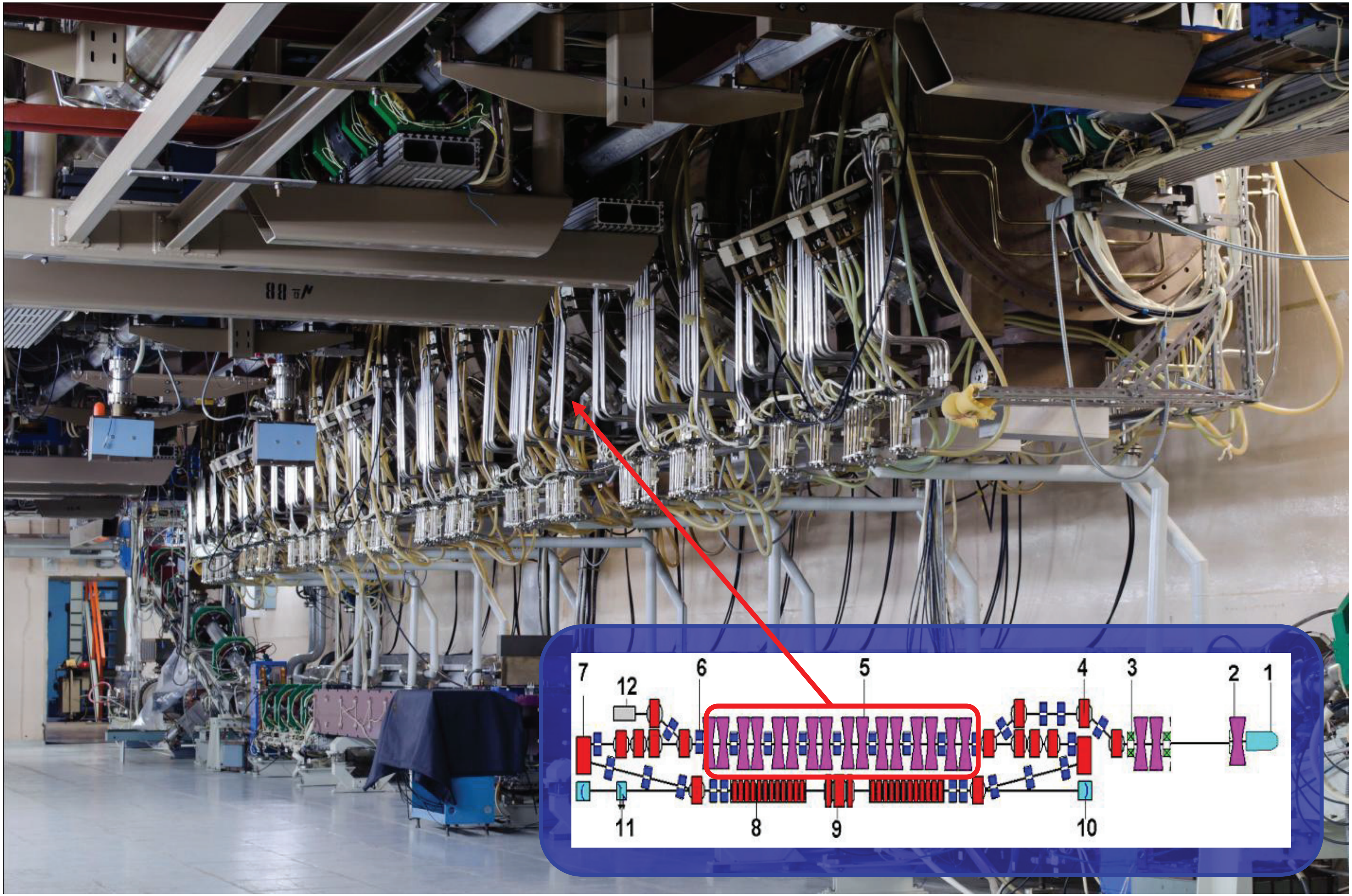


Main Linac



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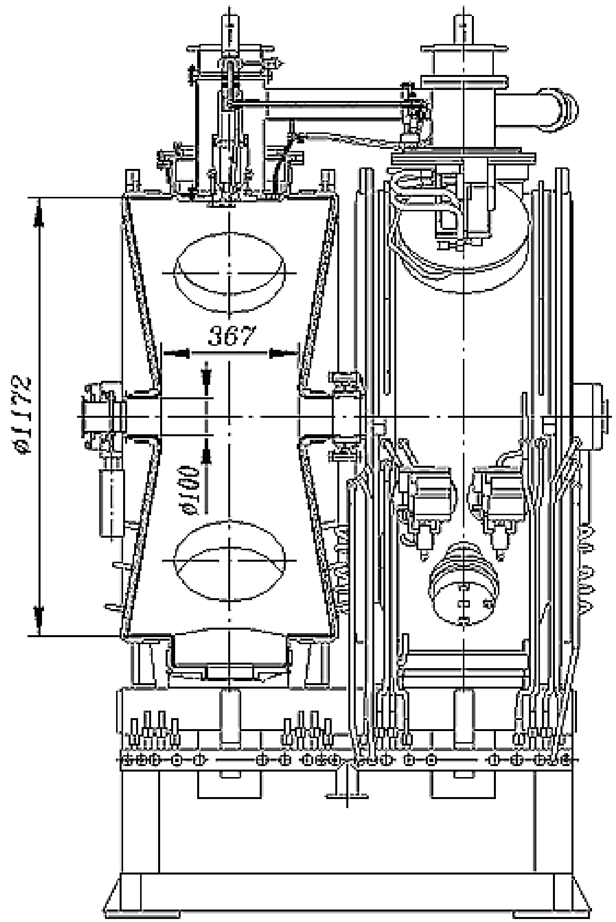

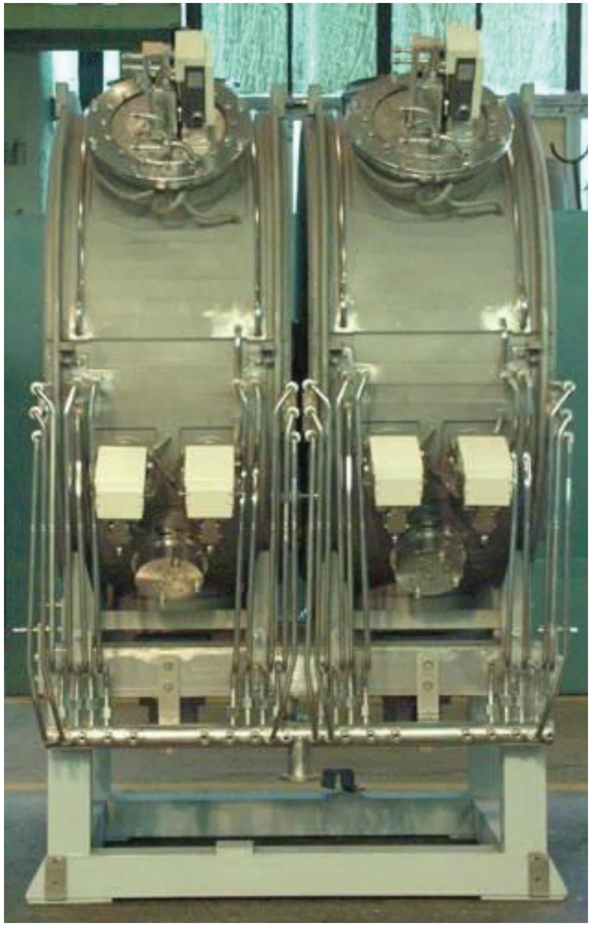

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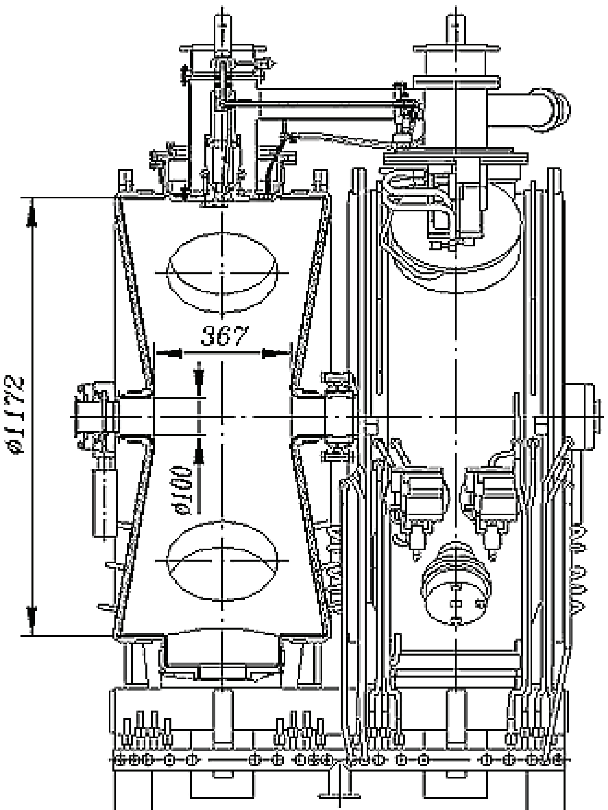


$$f_0 = 180\ \text{MHz},\quad \Delta f_0 = 320\ \text{kHz},\quad U_{max} = 950\ \text{kV},$$

$$U_{eff} = 850\ \text{kV},\quad P_{dis} = 85\ \text{kW}$$

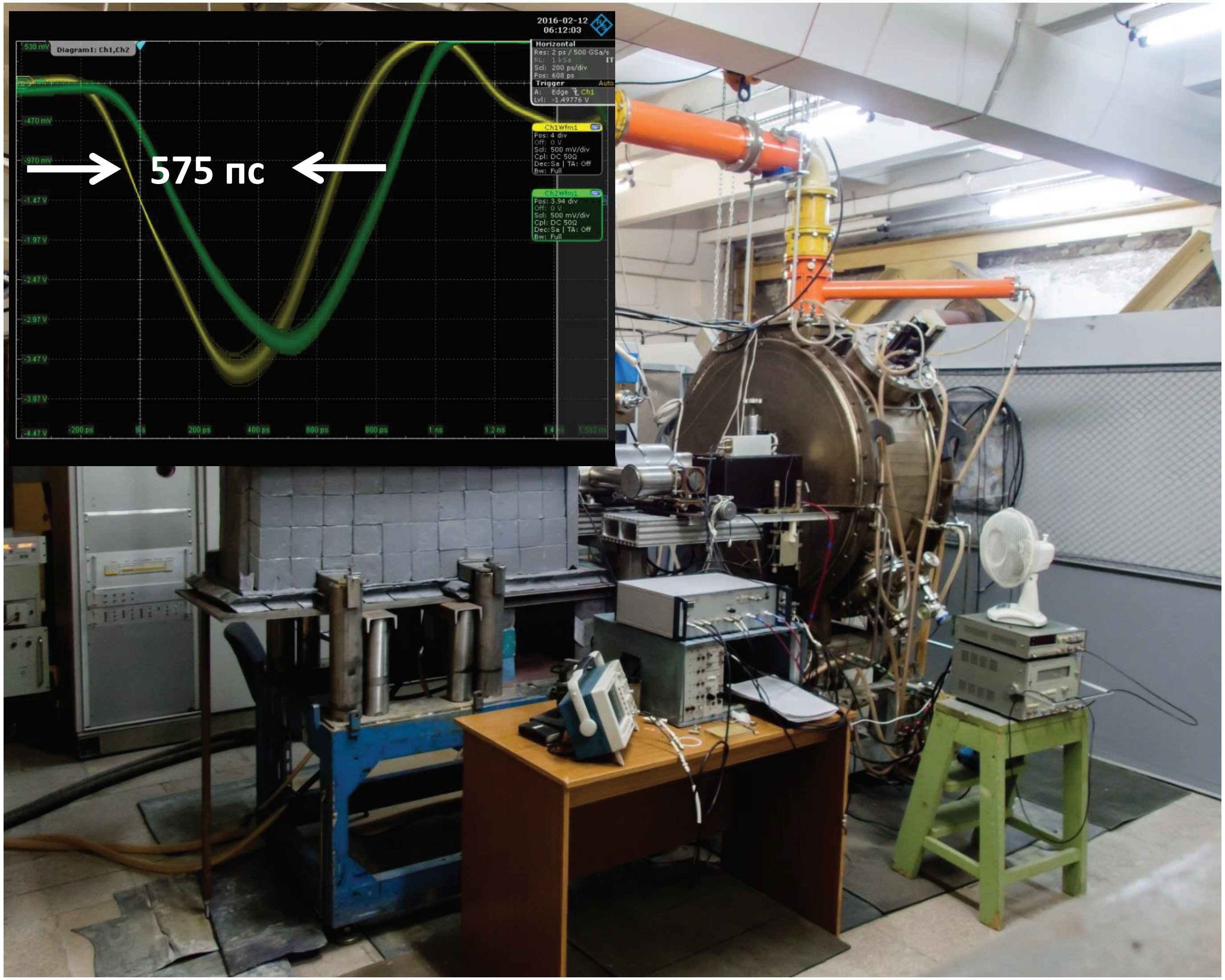
Siberian Center of Photochemical Research

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

RF Gun Test Setup



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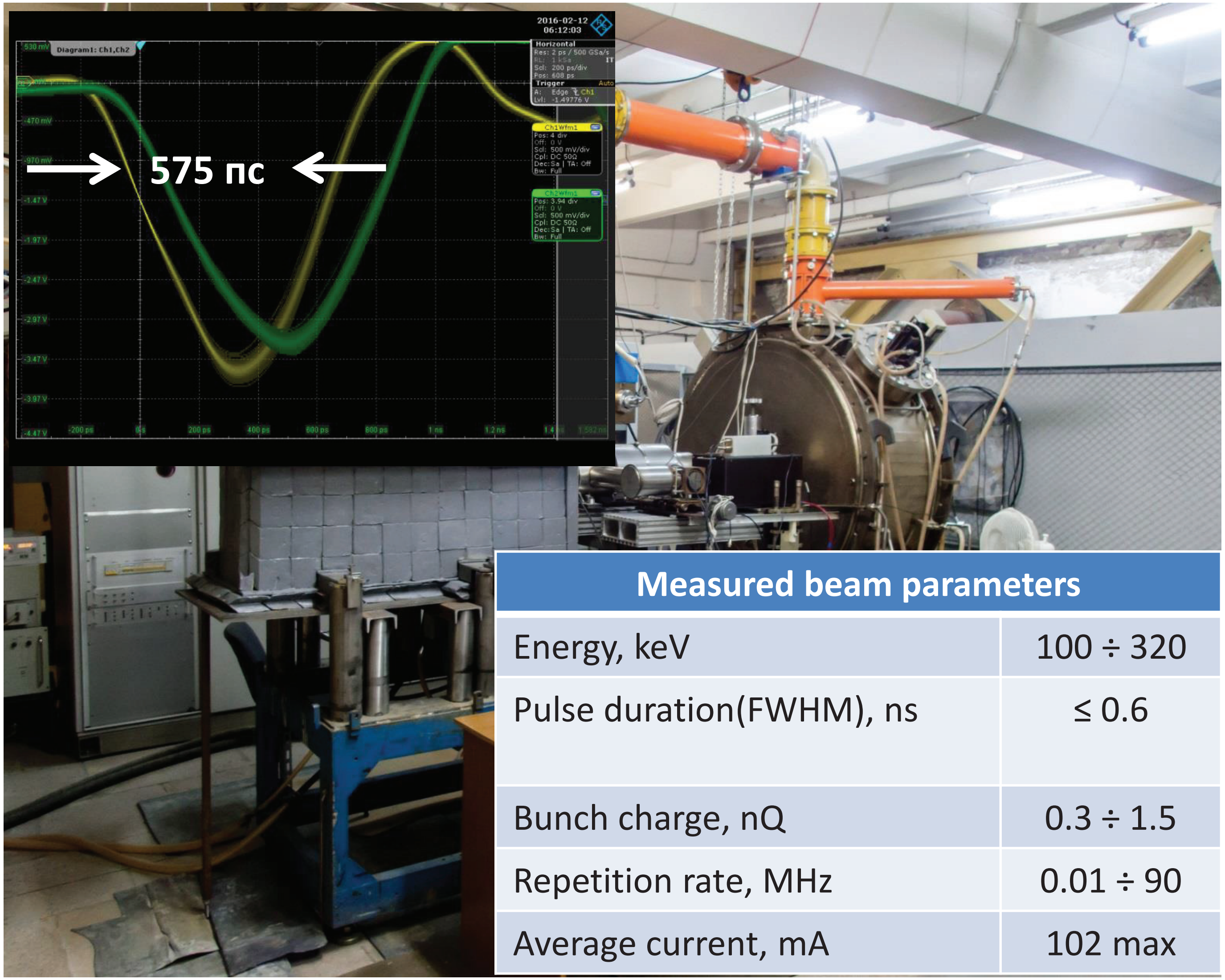

Measured beam parameters	
Energy, keV	100 ÷ 320
Pulse duration(FWHM), ns	≤ 0.6
Bunch charge, nQ	0.3 ÷ 1.5
Repetition rate, MHz	0.01 ÷ 90
Average current, mA	102 max

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

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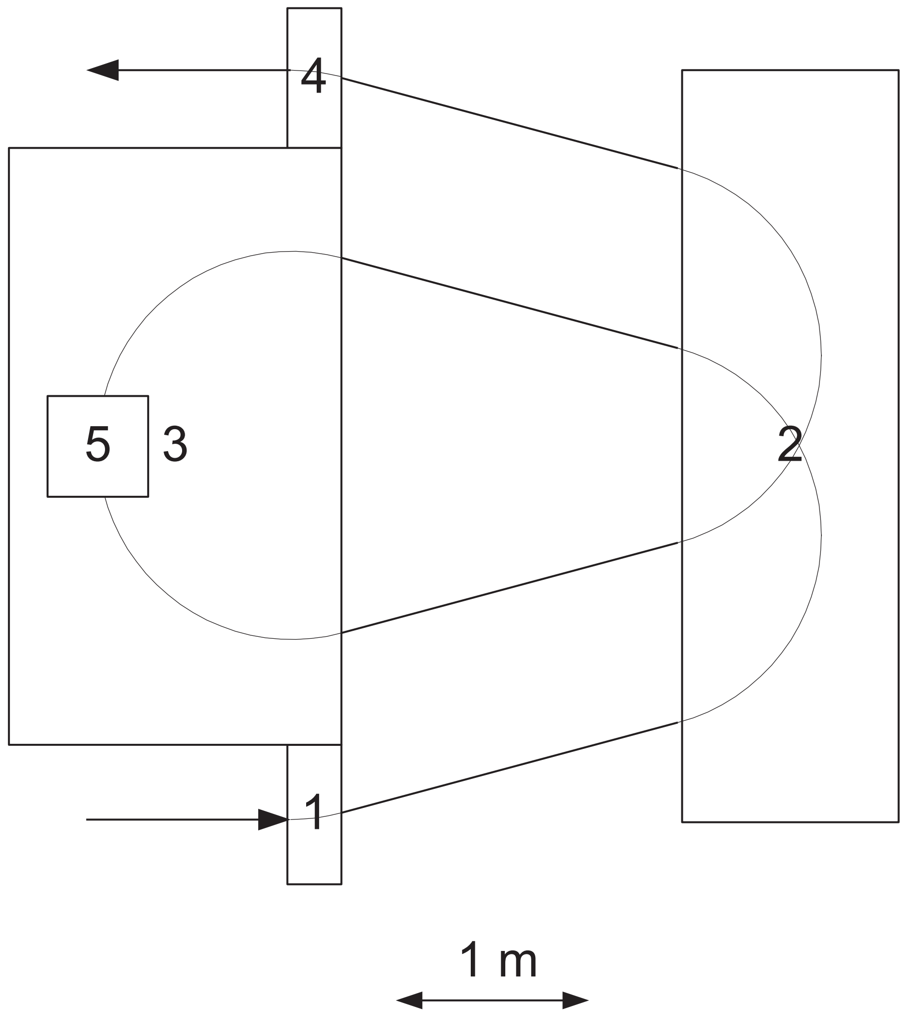
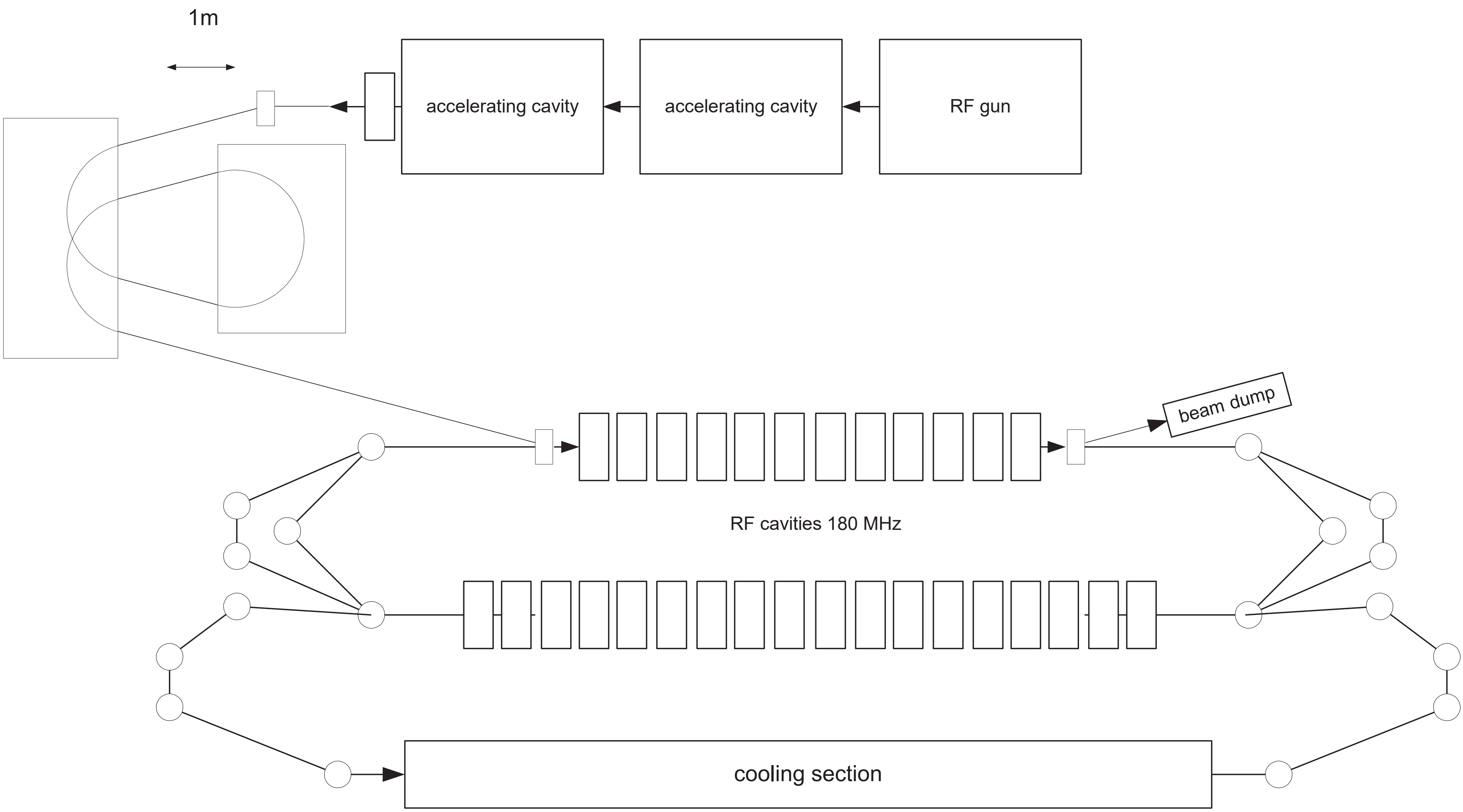
For further gain in the bunch charge, it is necessary to increase the cathode diameter and decrease the RF and bunch repetition frequencies. A frequency of 30 MHz seems to be as a reasonable compromise between in-creasing the RF cavity size and obtaining more than 10 nC in each bunch. With a peak cathode current of 4 A and an initial bunch duration of about 4 ns, one can obtain a bunch charge of 16 nC. To have a significant accelerating gradient in an RF structure, it is necessary to use a higher RF frequency. Then, for further RF acceleration it is necessary to compress the bunch.

The proposed compression system compresses the 2 MeV, 16 nC bunch from 4 ns to 0.5 ns duration. It uses the energy chirp of 2 MeV bunches, additional energy modulation in an auxiliary RF cavity, operating at a sub-harmonic of the main accelerating structure frequency of 180 MHz, and a magnetic buncher. For the required energy modulation to have an acceptable value (less than ±10%), the buncher shall have a high value of the longi-tudinal dispersion R_{56}. A second-order achromat is desirable for operation with large energy spread.



Magnetic buncher. 1 and 4 – parallel-edge magnets, 2 and 3 – magnetic mirrors, 5 – sextupole corrector.

Scheme of cooling ERL



Let us estimate the cooling rate in the case of a long superconductive solenoid with a magnetic field B = 1 T.

Let the electron bunch length l_b be 60 cm. The longitudinal emittance ε_s = 10 keV·ns will define the energy spread of bunch $\sigma_E = c\varepsilon_s / l_b$ =5 keV, where c is the velocity of light. Then the longitutinal electron velocity spread in the beam rest frame is $V_{se} = c\sigma_E / E =$ 3·10^6 cm/s. For an ion beta function β_i = 3·10^4 cm and an ion normalized transverse emittance ε_i = 10^{-4} cm, the transverse velocity spread in the beam rest frame is $V_{xi} = c\sqrt{\gamma\varepsilon_i / \beta_i}$ = 1.7·10^7 cm/s, and the

transverse beam size is $a_i = \sqrt{\varepsilon_i\beta_i / \gamma}$ = 0.17 cm (γ is the Lorentz factor). Let the flat electron beam enter the flat solenoid edge. For a vertical beta function β_y = 100 cm, the vertical beamsize is $a_y = \sqrt{\varepsilon_t\beta_y / \gamma}$ = 0.032 cm, and the

vertical angular spread is $\theta_x = \sqrt{\varepsilon_t / (\gamma\beta_x)}$ = 3.2·10^{-4}.

For a horizontal beta function β_x = 40000 cm, the horizontal beamsize is $a_x = \sqrt{\varepsilon_t \beta_x / \gamma} =$ 0.64 cm and the horizontal angular spread is $\theta_x = \sqrt{\varepsilon_t / (\gamma \beta_x)} =$ $1.6 \cdot 10^{-5}$, which is much less than the r. m. s. horizontal kick a_y/R = $2 \cdot 10^{-3}$ ($R = \gamma mc^2/(eB)$ = 17 cm) at the flat edge of the solenoid. Then the r. m. s. Larmor radius is equal to a_y. After transformation in solenoid we obtain a round beam with an r. m. s. sizes a_e of 0.15 cm, which exceeds the r. m. s. Larmor radius 5 times. The peak electron current is $qc / (\sqrt{2\pi} l_b) =$ 3.2 A, and the electron rest-frame density is $n_e = N_e / (2^{3/2} \pi^{3/2} l_b a_e^2 \gamma)$ $=5 \cdot 10^7$. The cooling rate in the lab frame can be estimated as

$$\delta_{cool} = \frac{2\pi n_e r_e r_i c^4}{\left(V_{xi}^2 + V_{se}^2\right)^{3/2}} \frac{\eta}{\gamma} \ln \frac{a_e}{R}$$

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where r_e is the classical radius of electron, r_i is the classical radius of ion, and η is the fraction of the collider perimeter occupied by the cooling section.

For ions with the charge Z = 92, atomic weight A = 200, and η = 0.01,

$$\tau_{cool} = 1/\delta_{cool} = 100 \text{ s.}$$

This result shows good prospects for using this cooling system with a low-frequency ERL.

Thank you for attention.