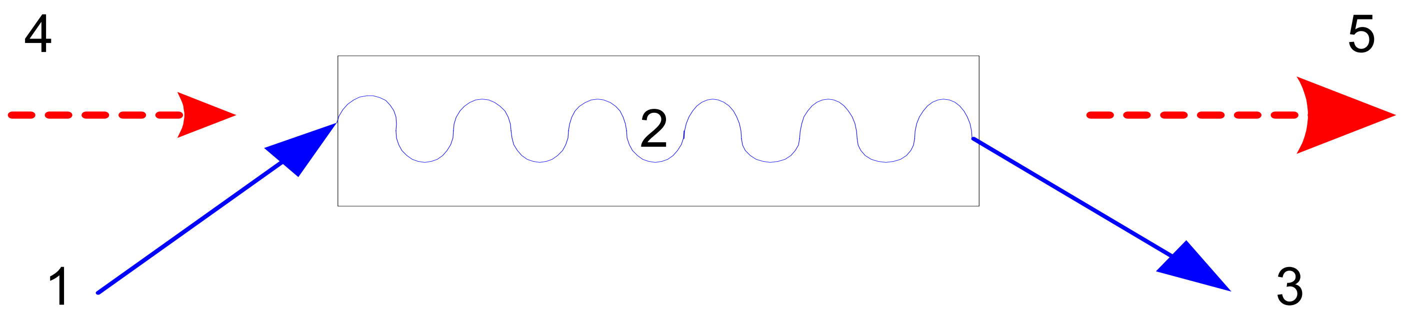
ERL at Budker INP

V.P. Bolotin, N.G. Gavrilov, D.A. Kayran, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, A.D. Oreshkov, V.K. Ovchar, V.M. Popik, T.V. Salikova, S.S. Serednyakov, A.N. Skrinsky, O.A. Shevchenko, M.A. Scheglov, V.G. Tcheskidov, N.A. Vinokurov

Budker INP, Novosibirsk, Russia

Free Electron Laser (FEL)



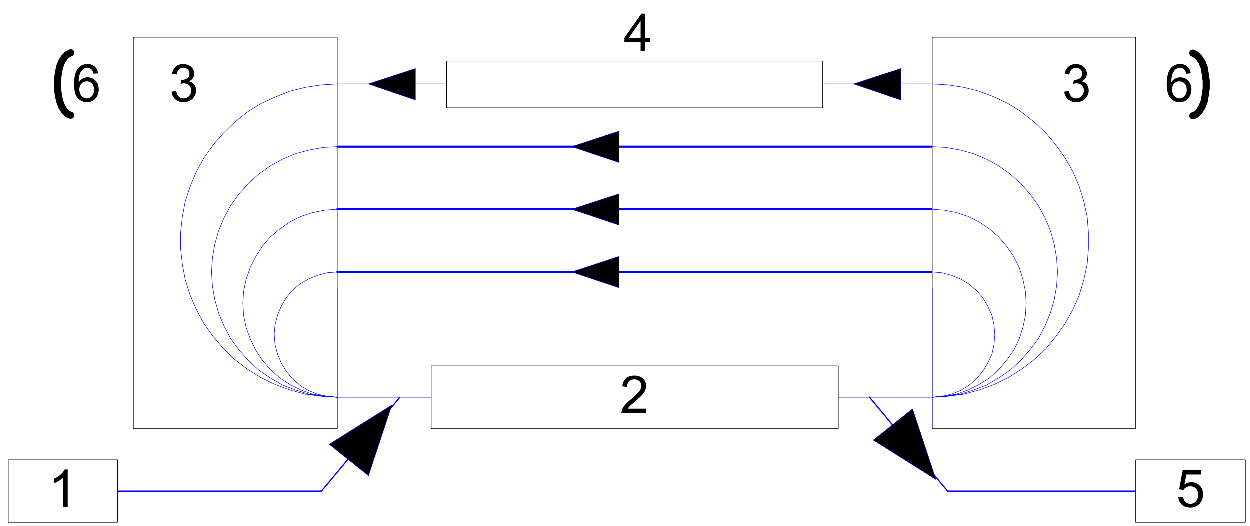
1 – incoming electron beam, 2 – undulator, 3- spent electron beam, 4 – input electromagnetic radiation, 5 – amplified radiation

As the electron efficiency of FEL is low (~1%), the energy recovery is necessary for a high average power FEL.

Energy recovery

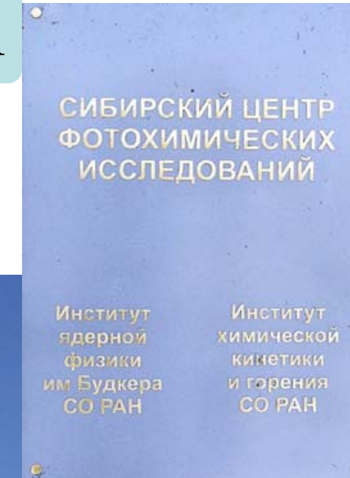
(i) decrease radiation hazard dramatically and
(ii) provide possibility to achieve high average beam current.

FEL based on accelerator-recuperator

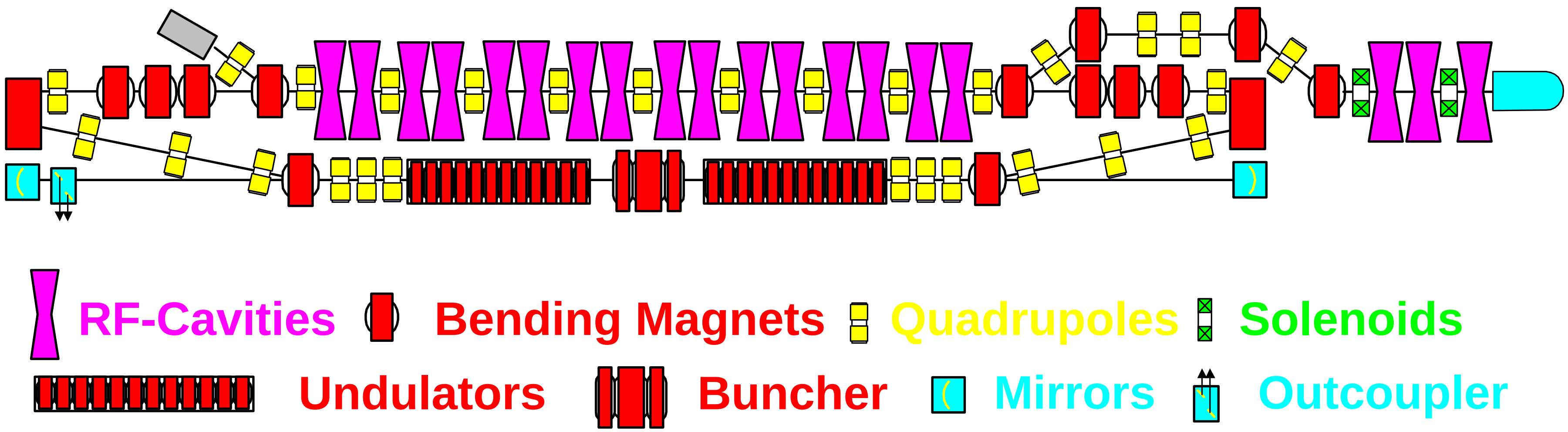


1 - injector, 2 - accelerating RF structure, 3 - 180-degree bends, 4 – undulator, 5 – beam dump, 6 – mirrors of optical resonator

Siberian Center for Photochemical Research

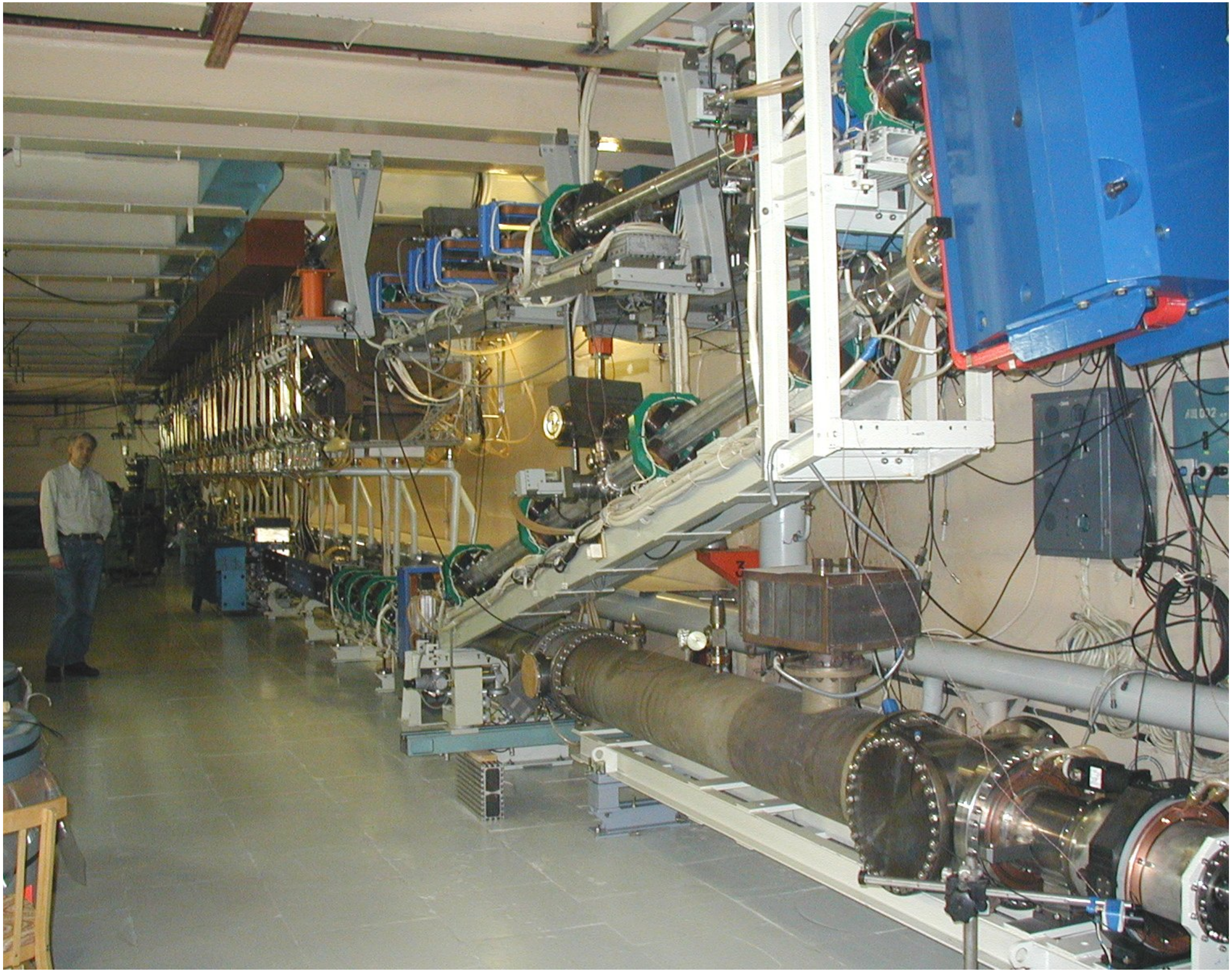


First stage: submillimeter (THz) FEL



Accelerator-recuperator for FEL

Free Electron Laser



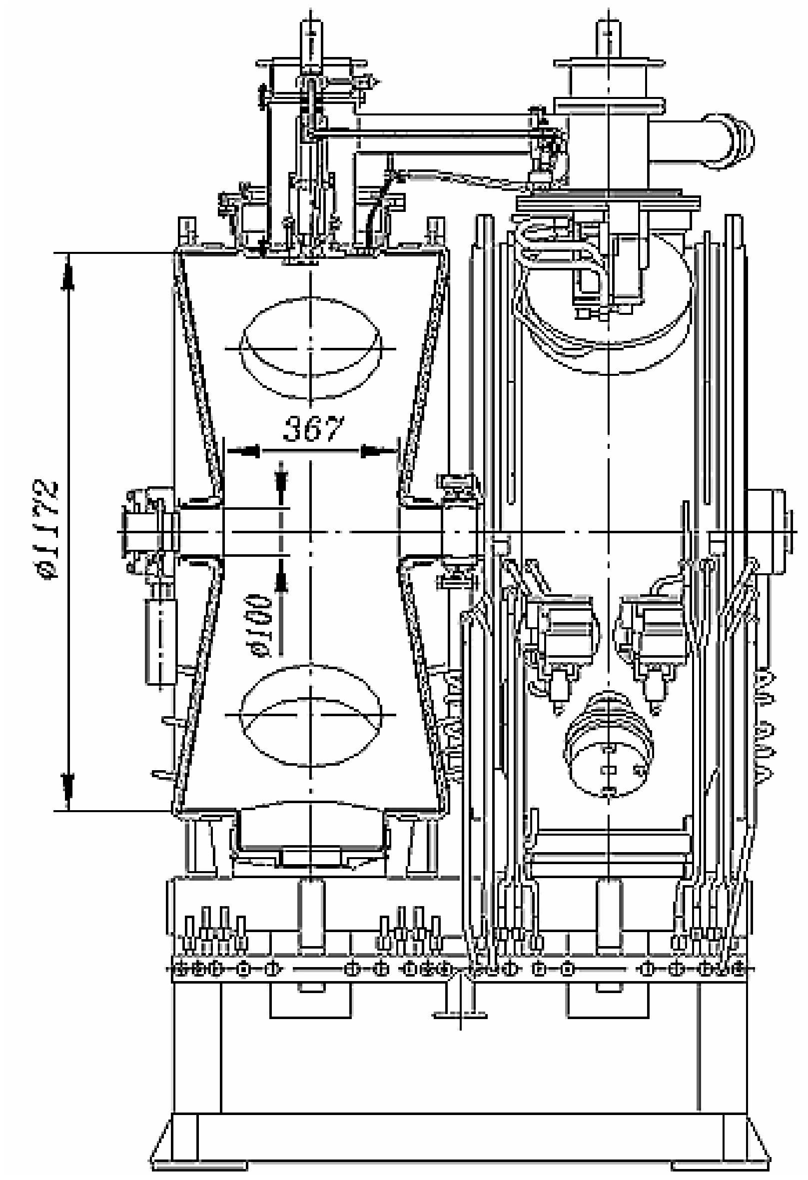
Features of RF system

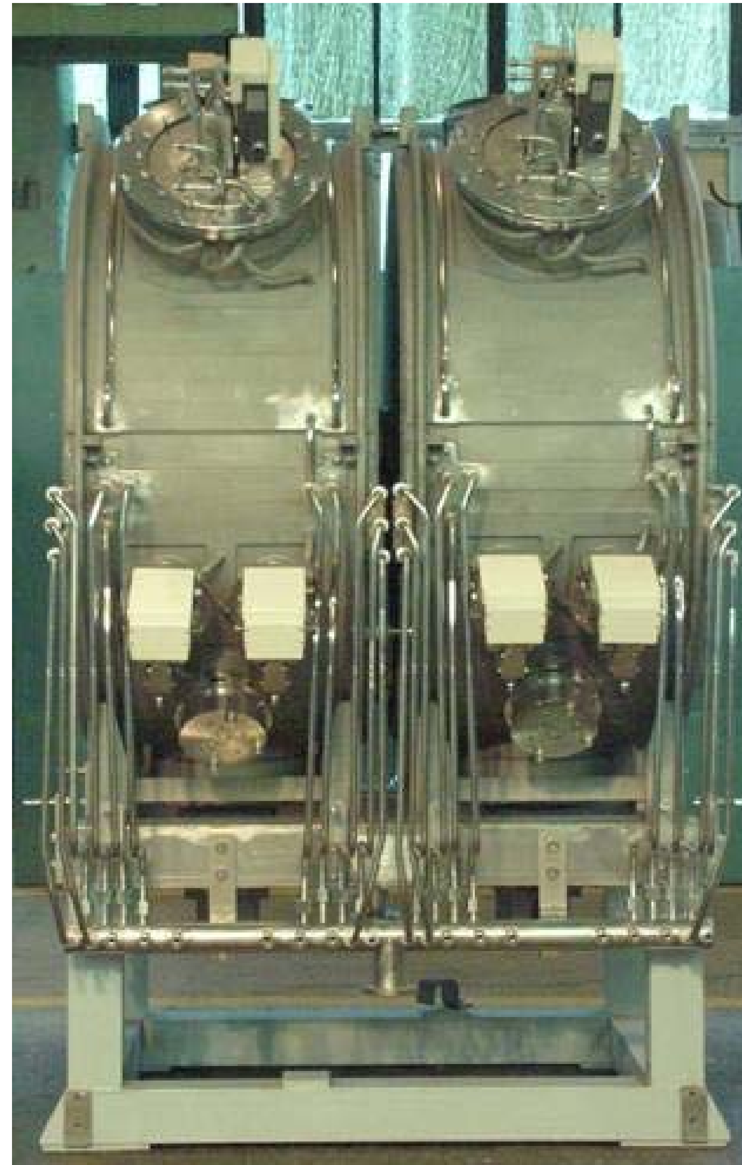
- Low frequency (180 MHz)
- Normal-conducting uncoupled RF cavities
- CW operation

Advantages

- 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

A pair of cavities (accelerating section) on a support frame





Bimetallic (copper and stainless steel) RF cavity tanks

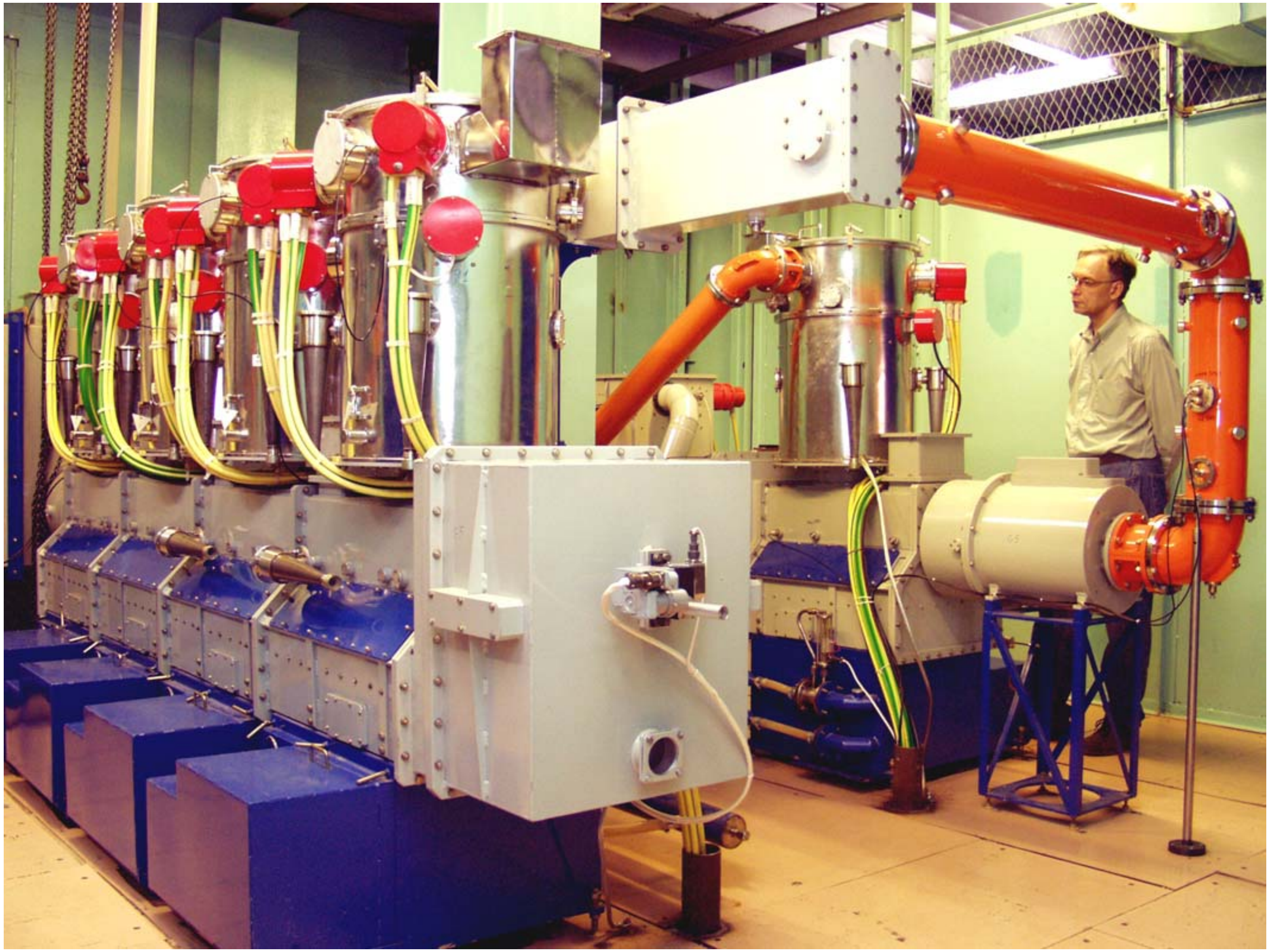
Main parameters of the cavity

(for the fundamental TM_{010} mode)

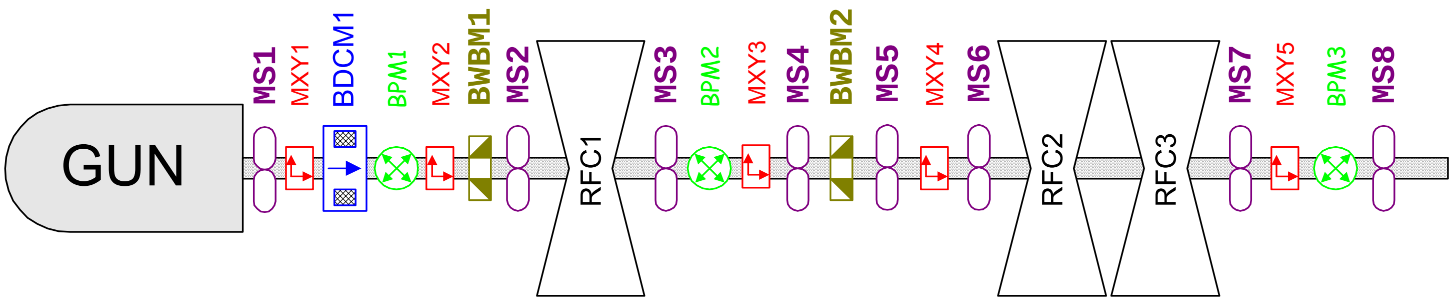
Resonant frequency, MHz	f_0	180,4
Frequency tuning range, kHz	Δf_0	320
Quality factor	Q	40000
Shunt impedance, MOhm	$R=U^2/2P$	5,3
Characteristic impedance, Ohm	$\rho=R/Q$	133,5
Operating gap voltage amplitude, MV	U	0-1.1
Power dissipation in the cavity, kW, at U=1100 kV	P	115
Input coupler power capability, kW (*tested, limited by available power*)	P_{in}	400

1 MW RF generator hall

Tetrode-based output amplifier stages



2 MeV injector



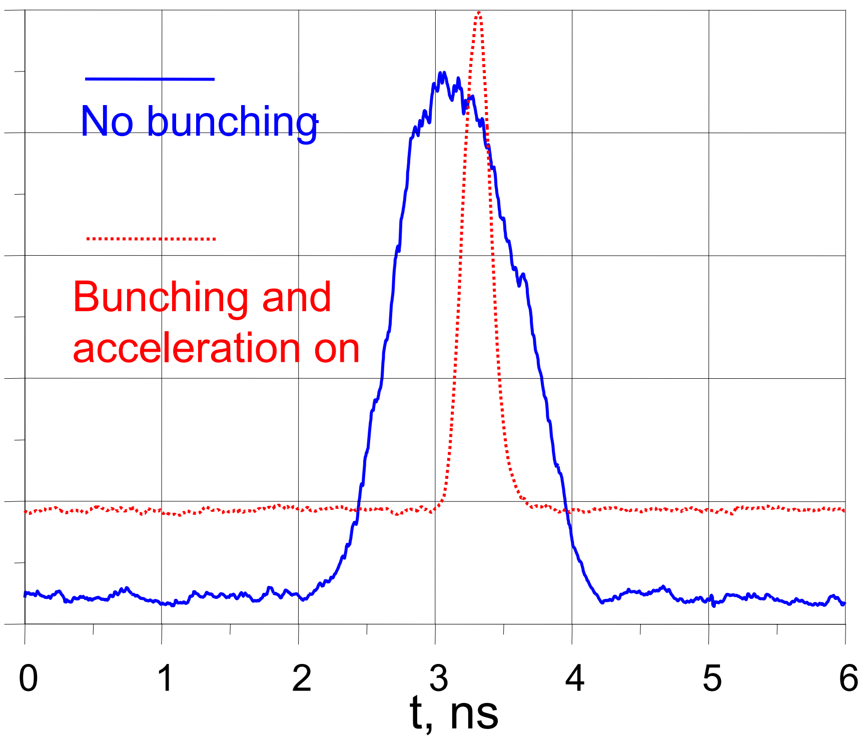
MS : focusing solenoid **MXY : steering magnet** **BDCM : beam current monitor**

BPM : bean position monitor **BWBM : strip line monitor** **RFC : RF cavity**

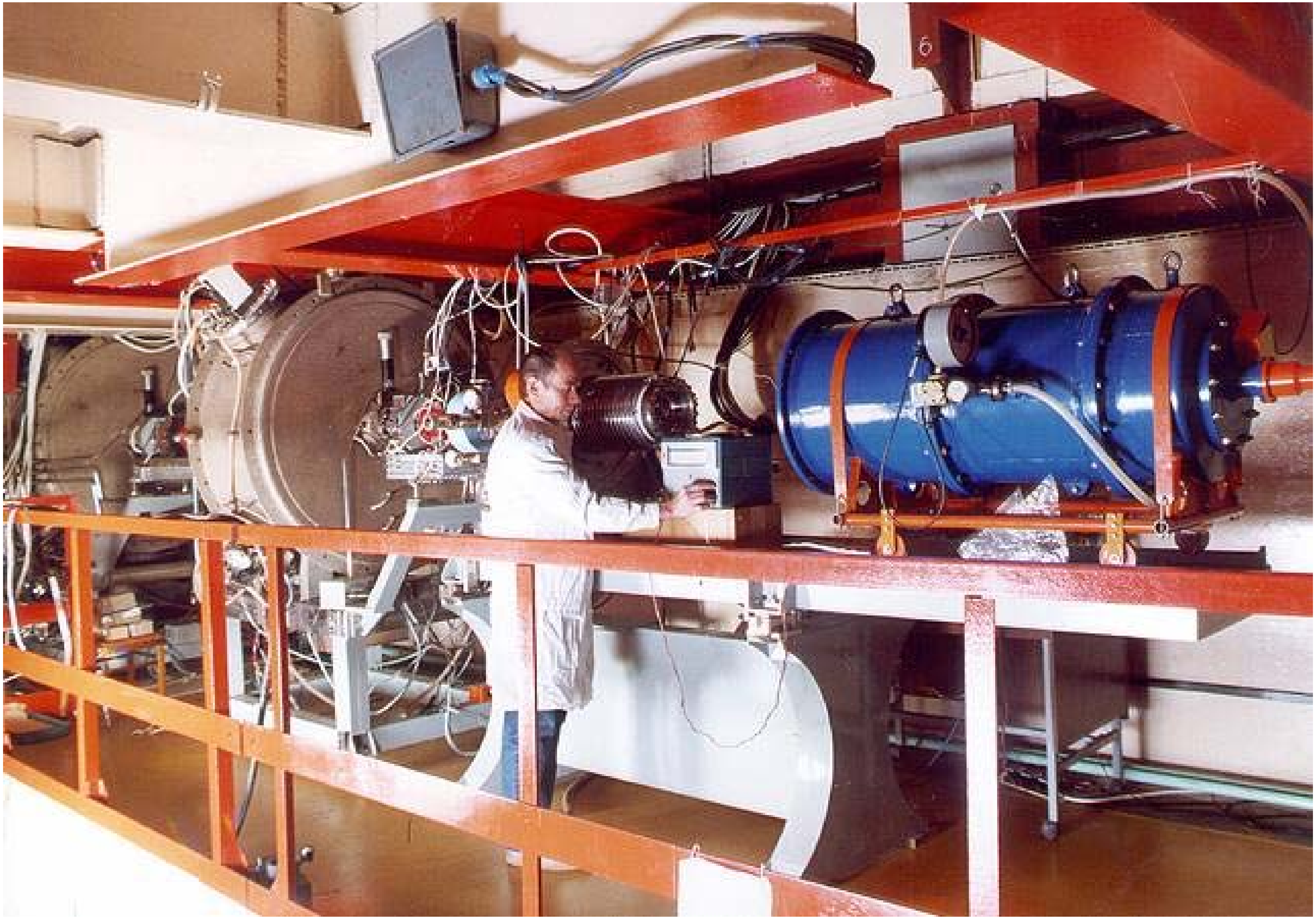
2 MeV Injector Parameters

♦ Bunch repetition rate, MHz	up to 22.5
♦ Charge per bunch, nC	1.5
♦ Start bunch length, ns	1.5
♦ Final bunch length, ns	0.12
♦ Final energy, MeV	2

Bunch profiles before and after bunching and acceleration

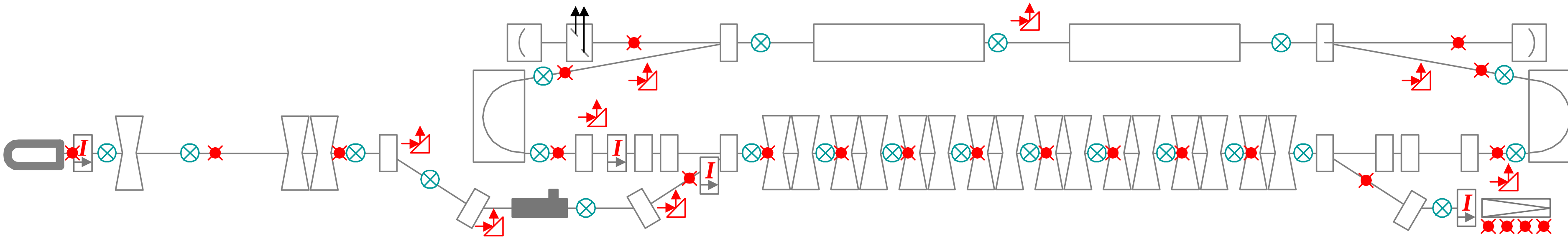


The 2 MeV injector

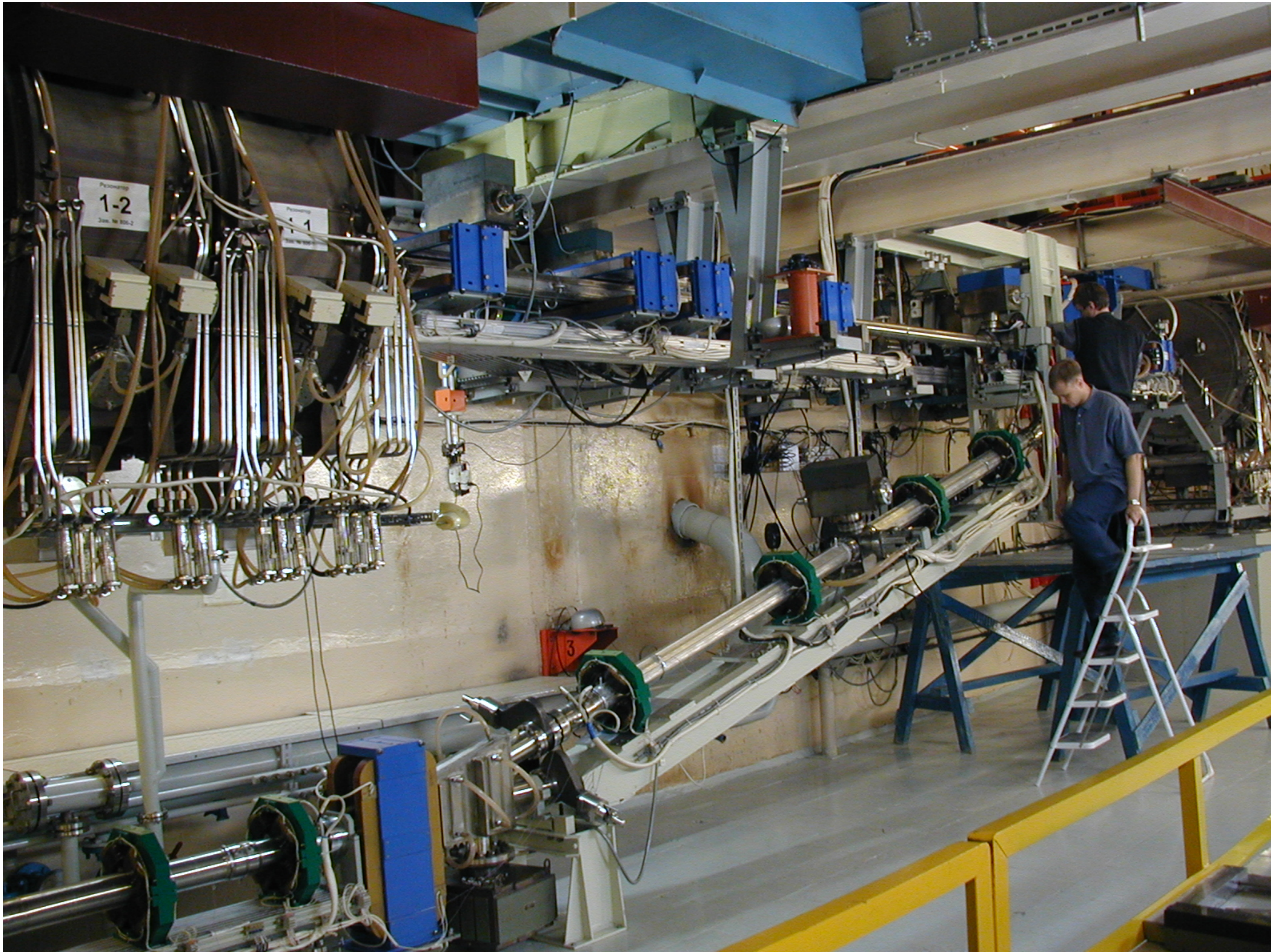


The second 2-MeV injector built for KAERI

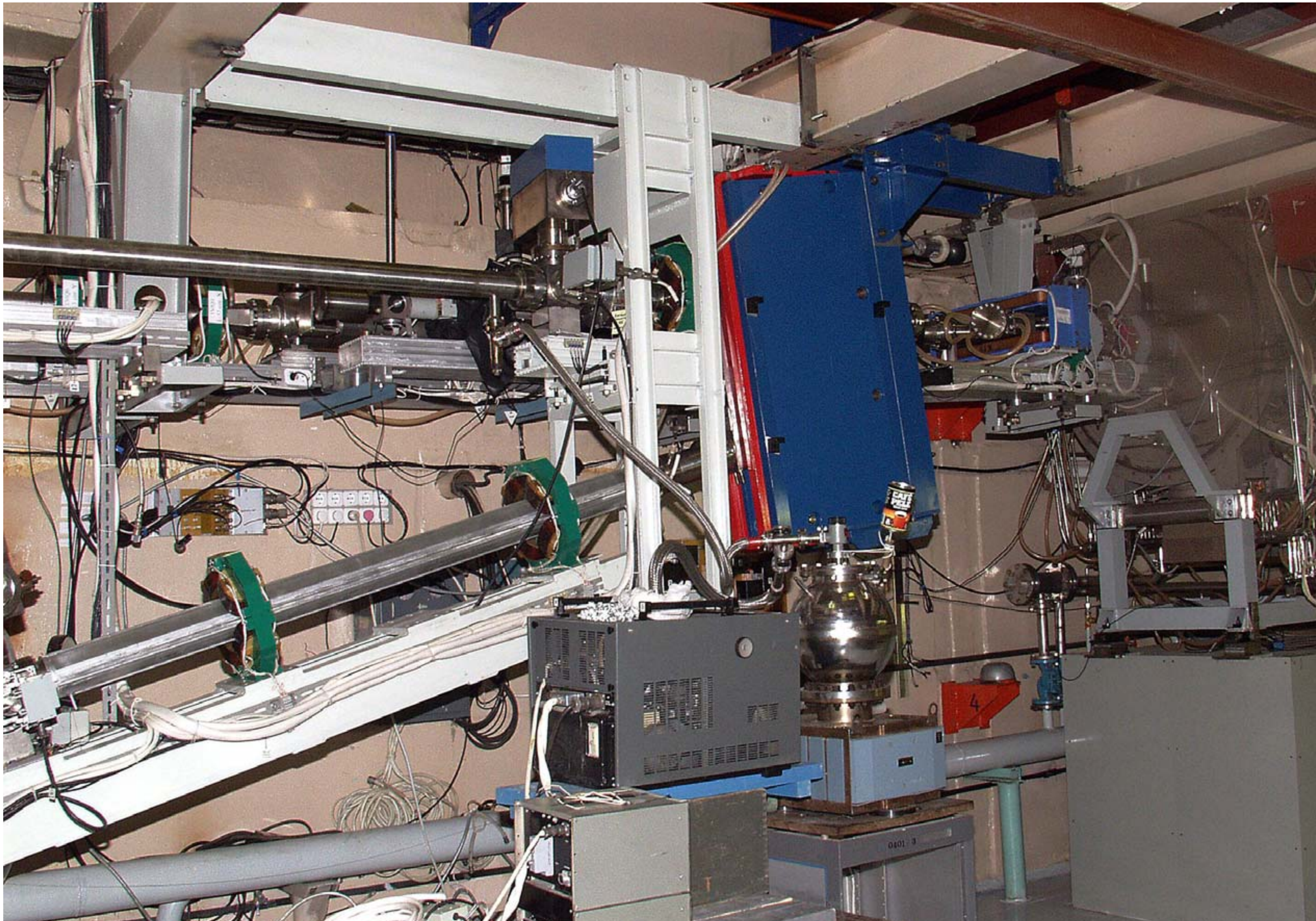
Beam diagnostic system



Injection chicane



Magnetic mirror returns electron beam to the RF structure



First Stage Accelerator-Recuperator: Machine Parameters

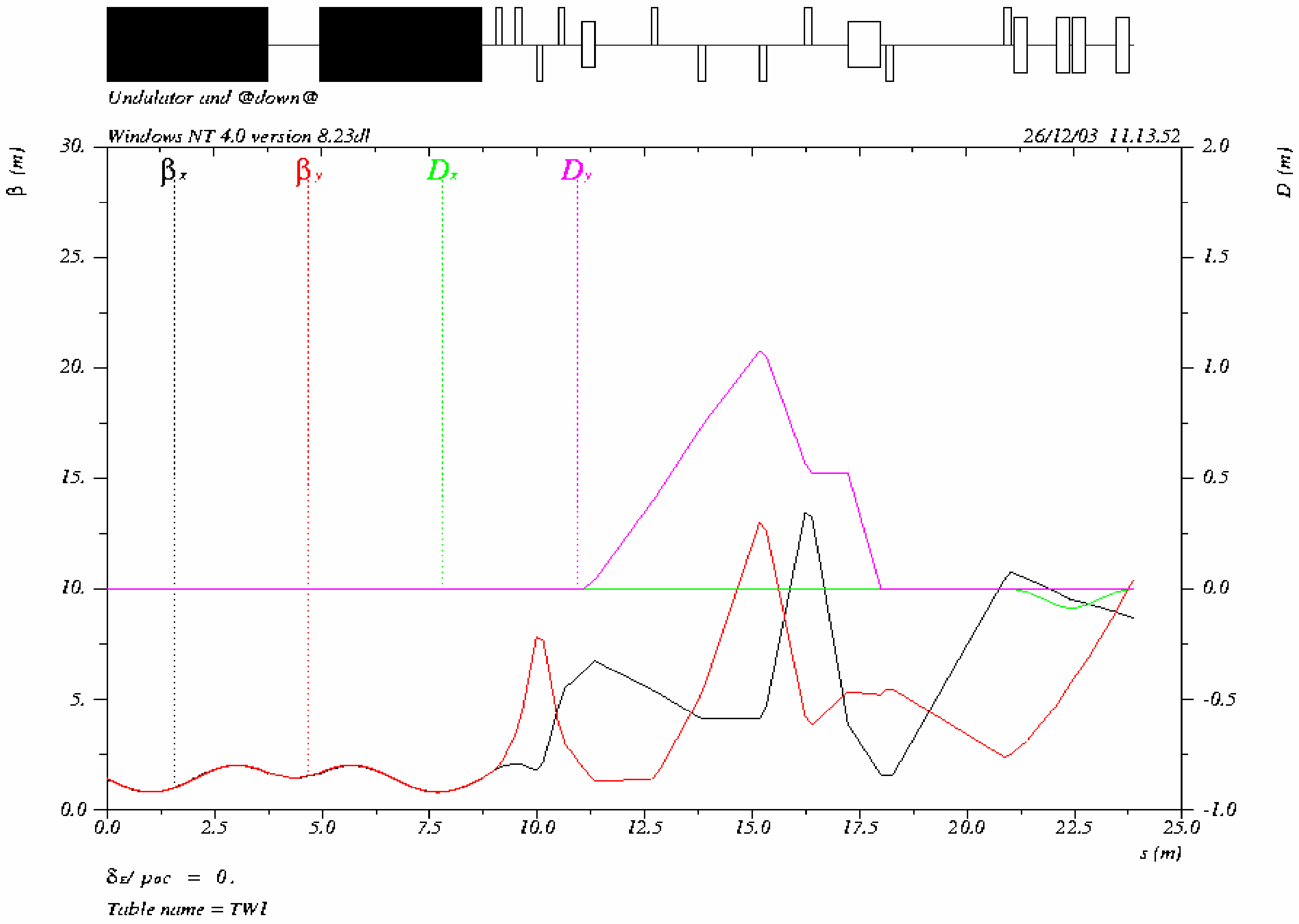
♦ Bunch repetition rate, MHz	22.5
♦ Average electron current, mA	20
♦ Maximum energy, MeV	12
♦ Bunch length, ps	100
♦ Normalized emittance, mm*mrad	30

Undulators parameters (one section)

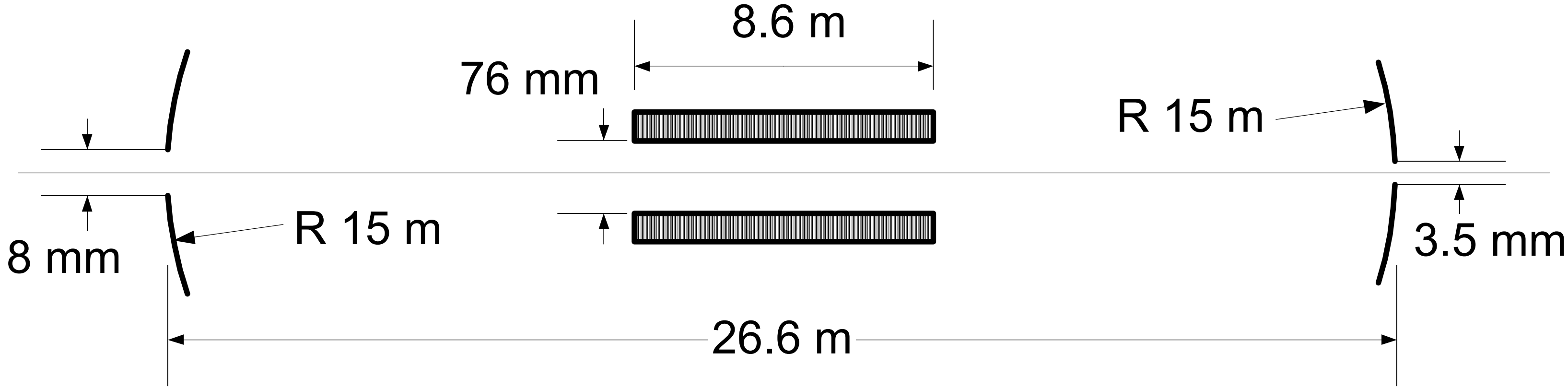
♦ Length, m	4
♦ Period, mm	120
♦ Number of periods	32
♦ Gap, mm	80
♦ Undulator parameter K	0 - 1.2

Undulators, buncher and accelerating RF cavities

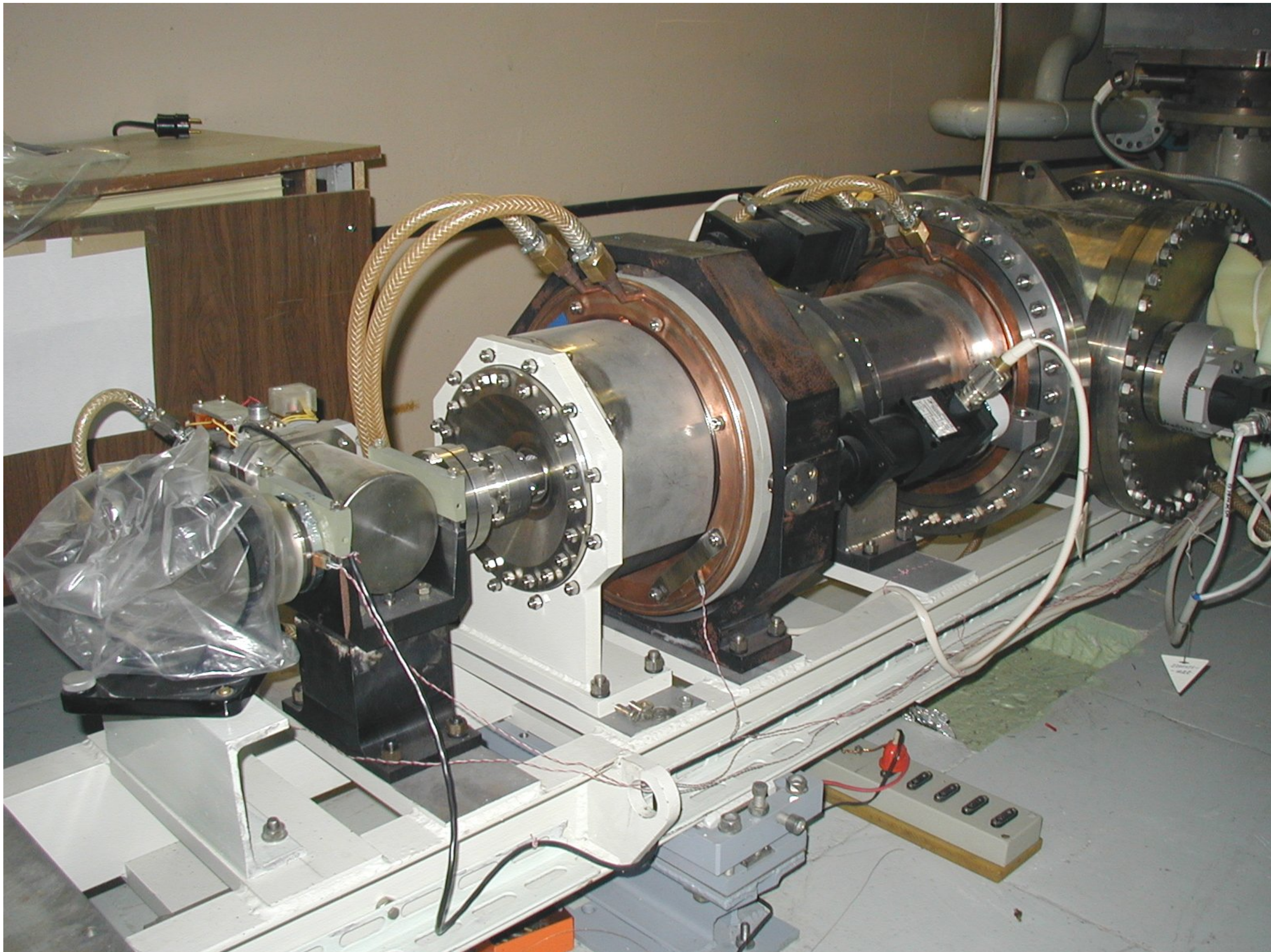
Lattice functions in undulator, 180-degree achromatic bend and injection chicane



Scheme of the optical resonator



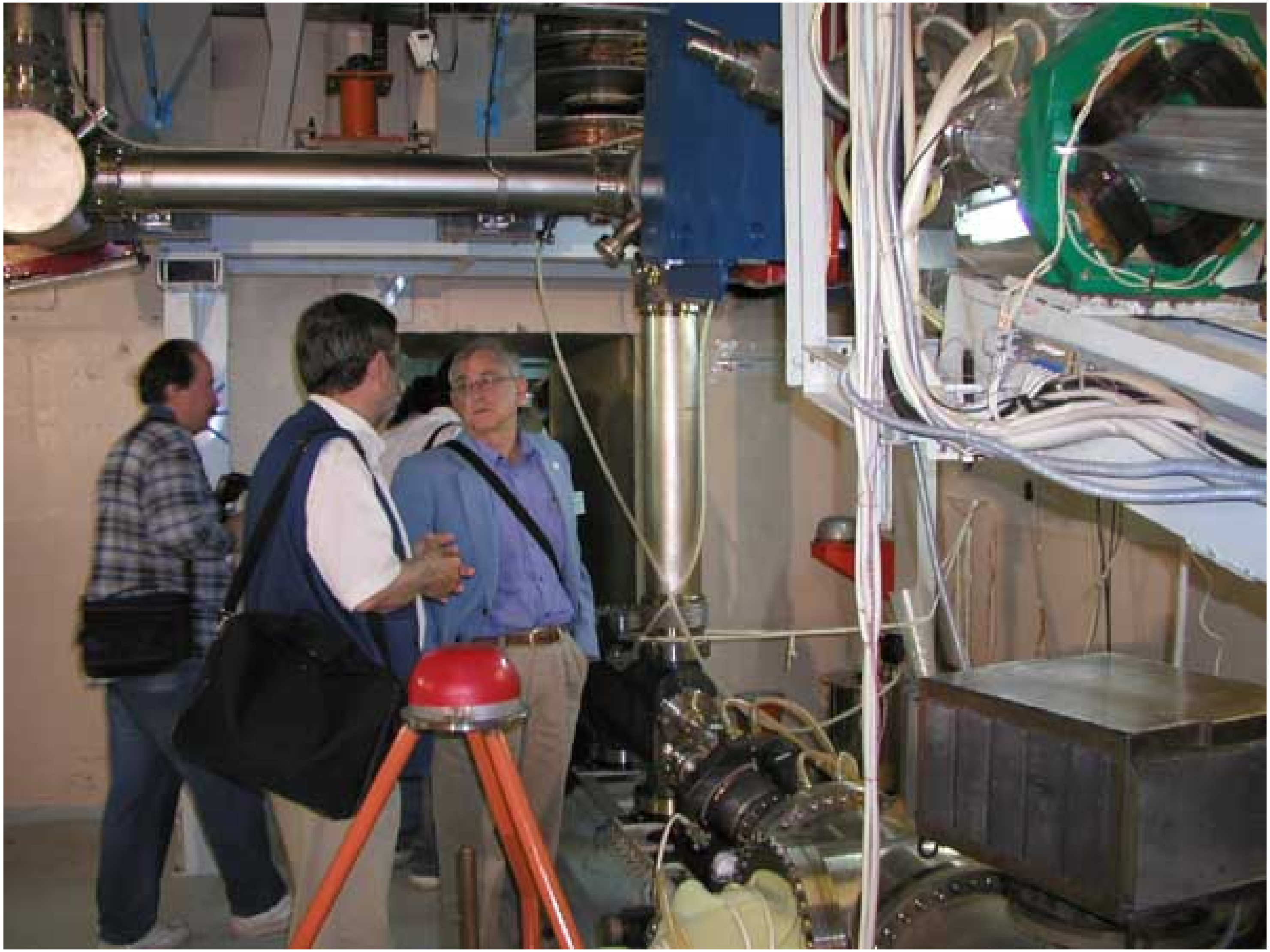
Mirror of the optical resonator (inside)



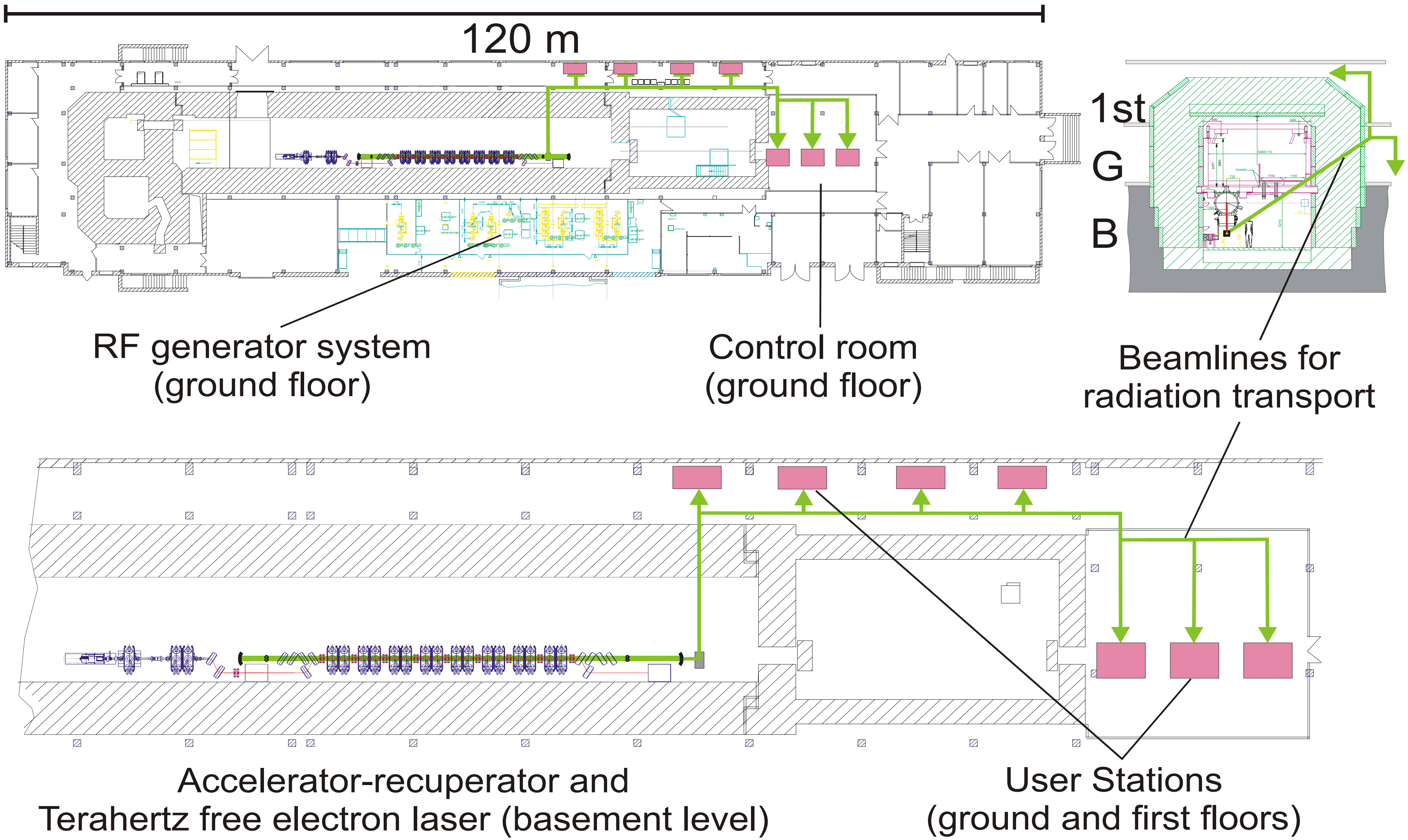
Free Electron Laser Parameters

♦ Wavelength, mm	0.12-0.18
♦ Pulse duration, FWHM, ps	70
♦ Pulse energy, mJ	0.04
♦ Repetition rate, MHz	5.6 (22.5)
♦ Average power, kW	0.2
♦ Minimum relative linewidth, FWHM	$3\cdot10^{-3}$

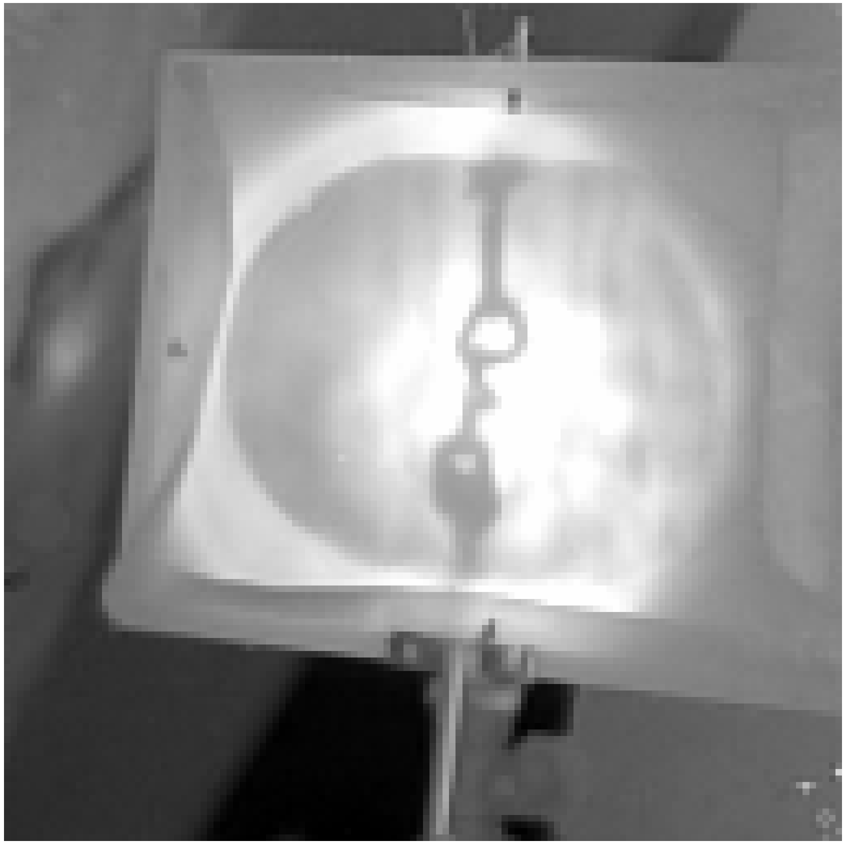
The beamline from the hole in the rear mirror to the user hall



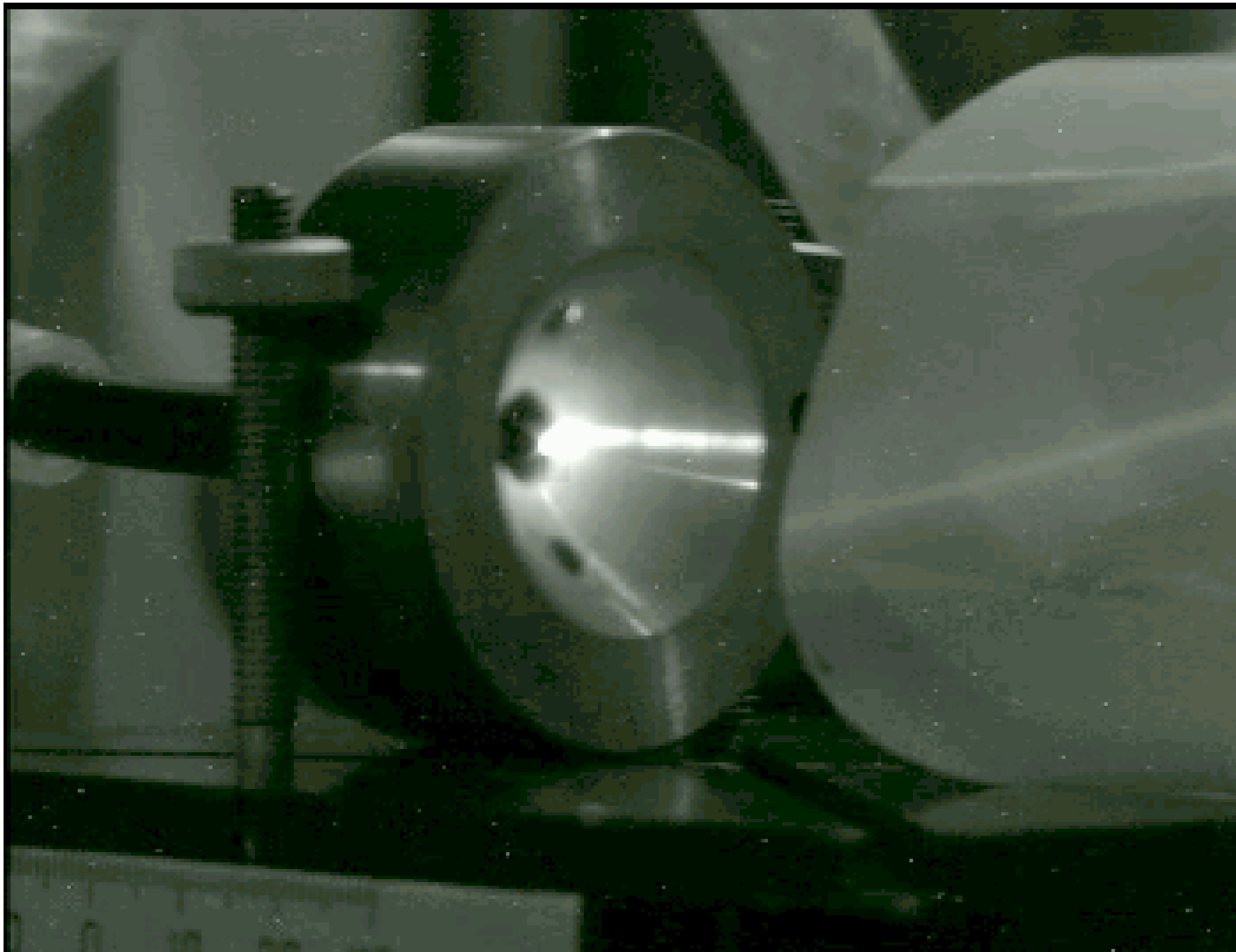
Layout of terahertz FEL and user stations



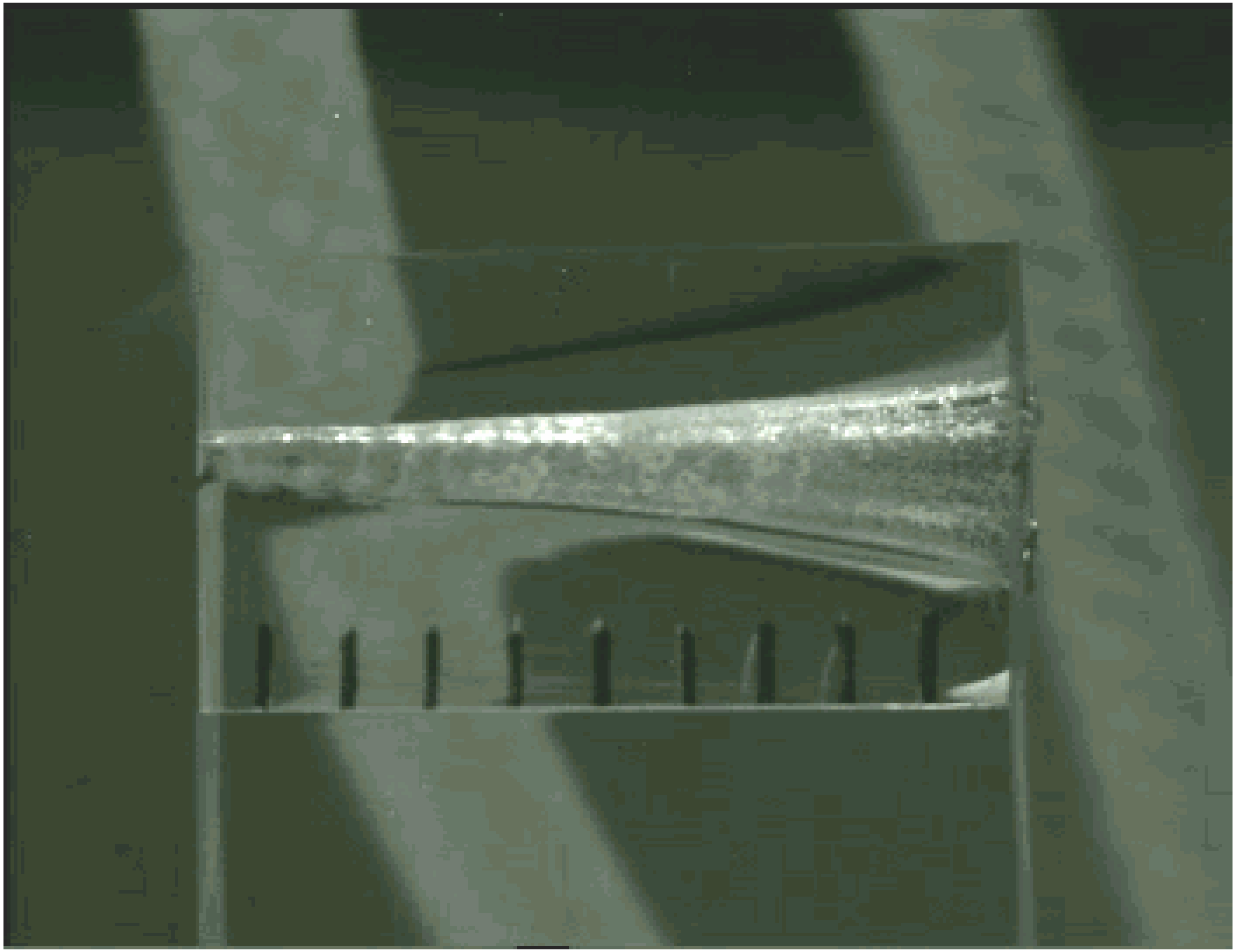
The terahertz image of keys inside the non-transparent envelope.



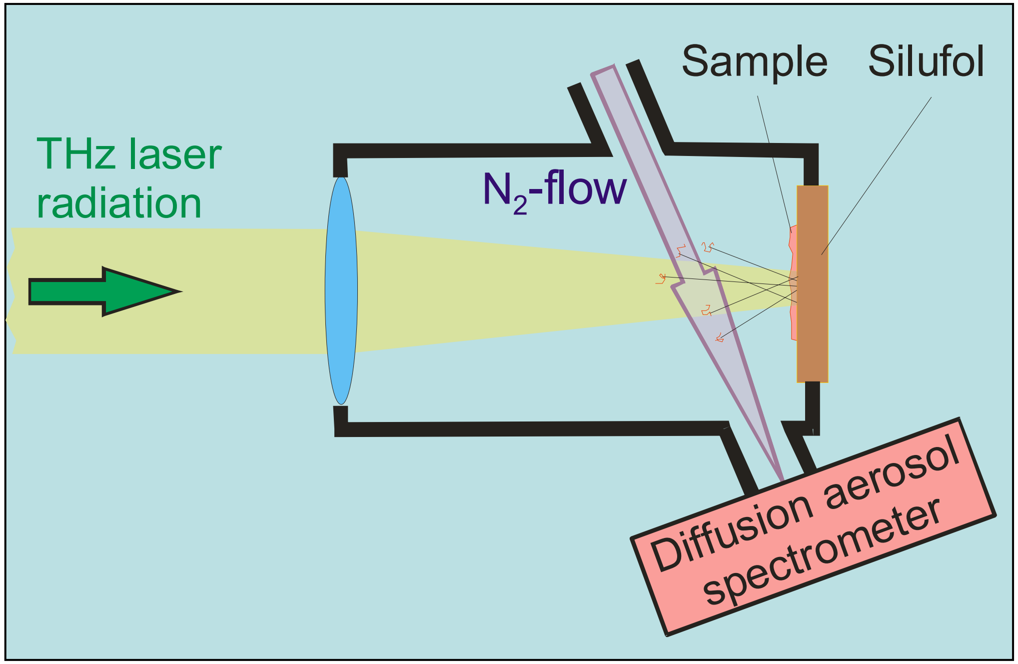
CW terahertz discharge in air

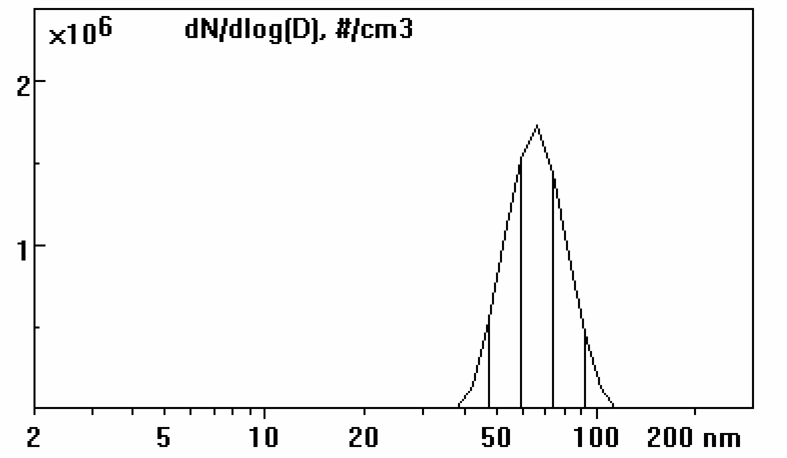


The conic hole in the PMMA cube, done with the terahertz radiation ablation. One division is 5 mm.

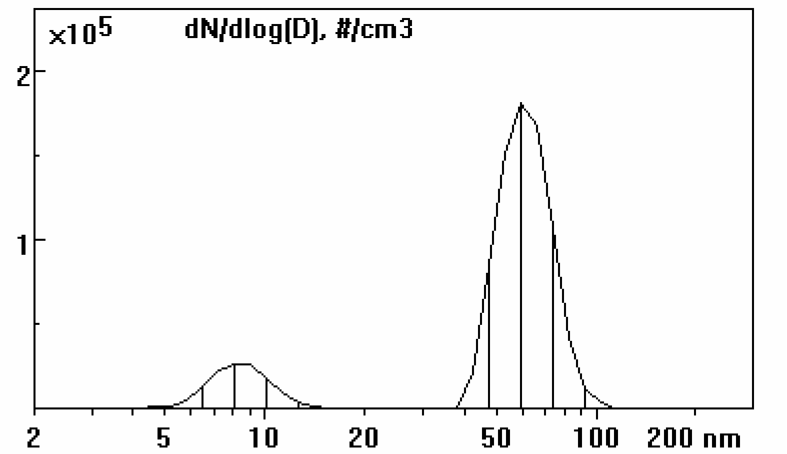


Ultra-soft laser ablation of DNA





Phage DNA

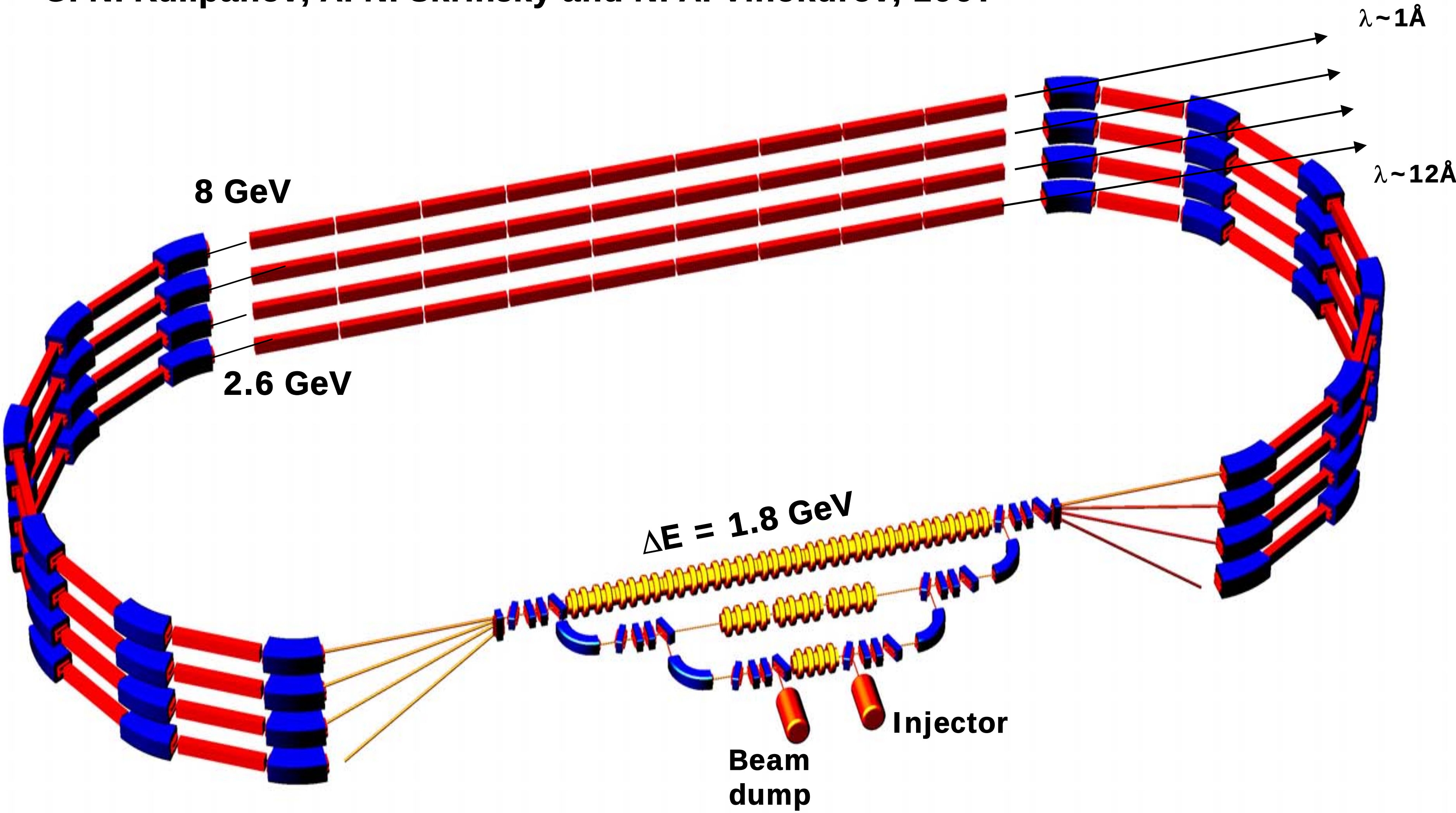


Phage DNA + plasmide DNA

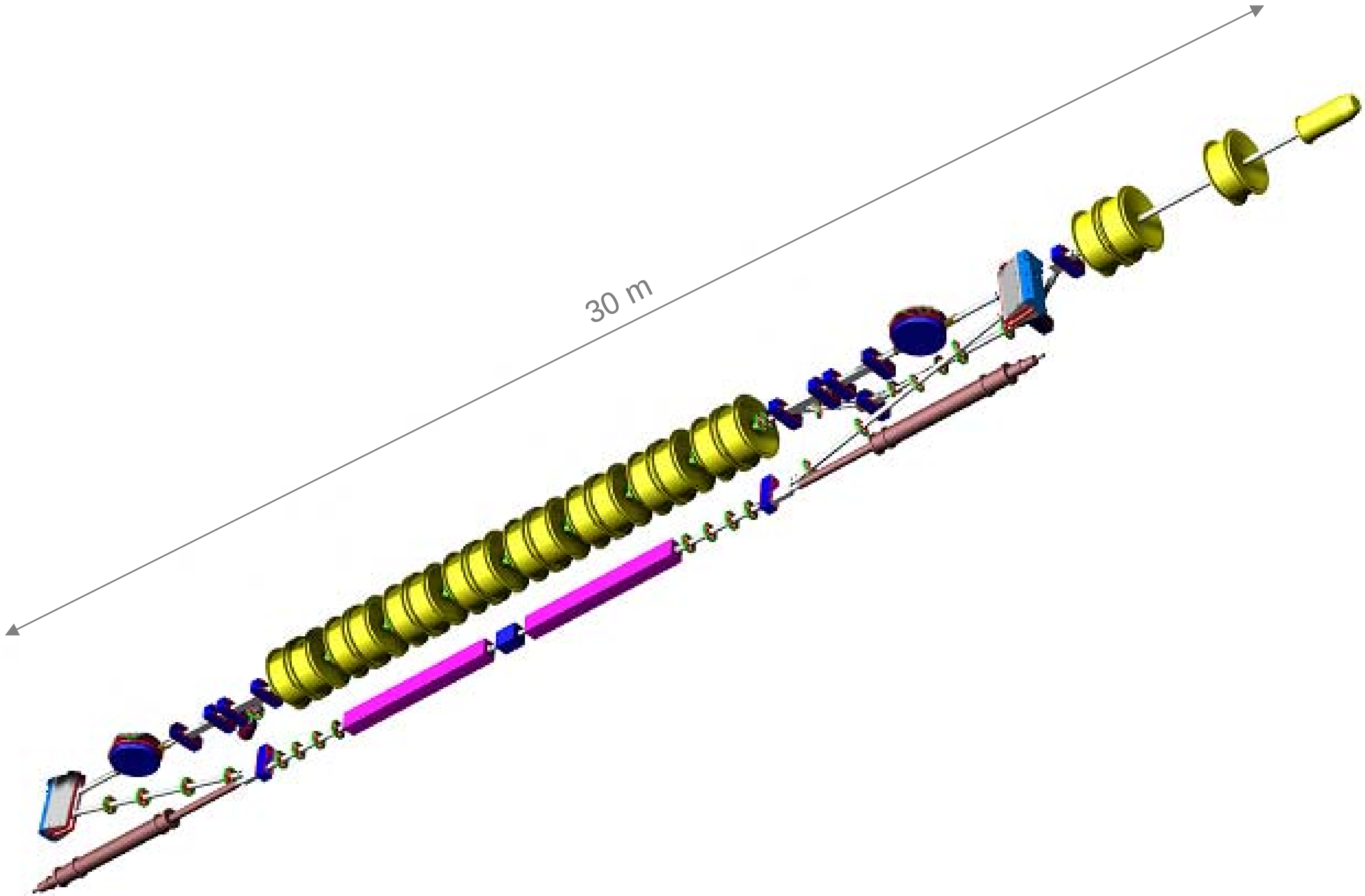
Demonstration of ultra-soft ablation of DNA samples without denaturation: when the power density of THz radiation is optimal, particle size spectra contain only the peaks corresponding to the initial particles. For higher power densities multi-peak spectra are observed.

MARS (Multiturn Accelerator-Recuperator Source)

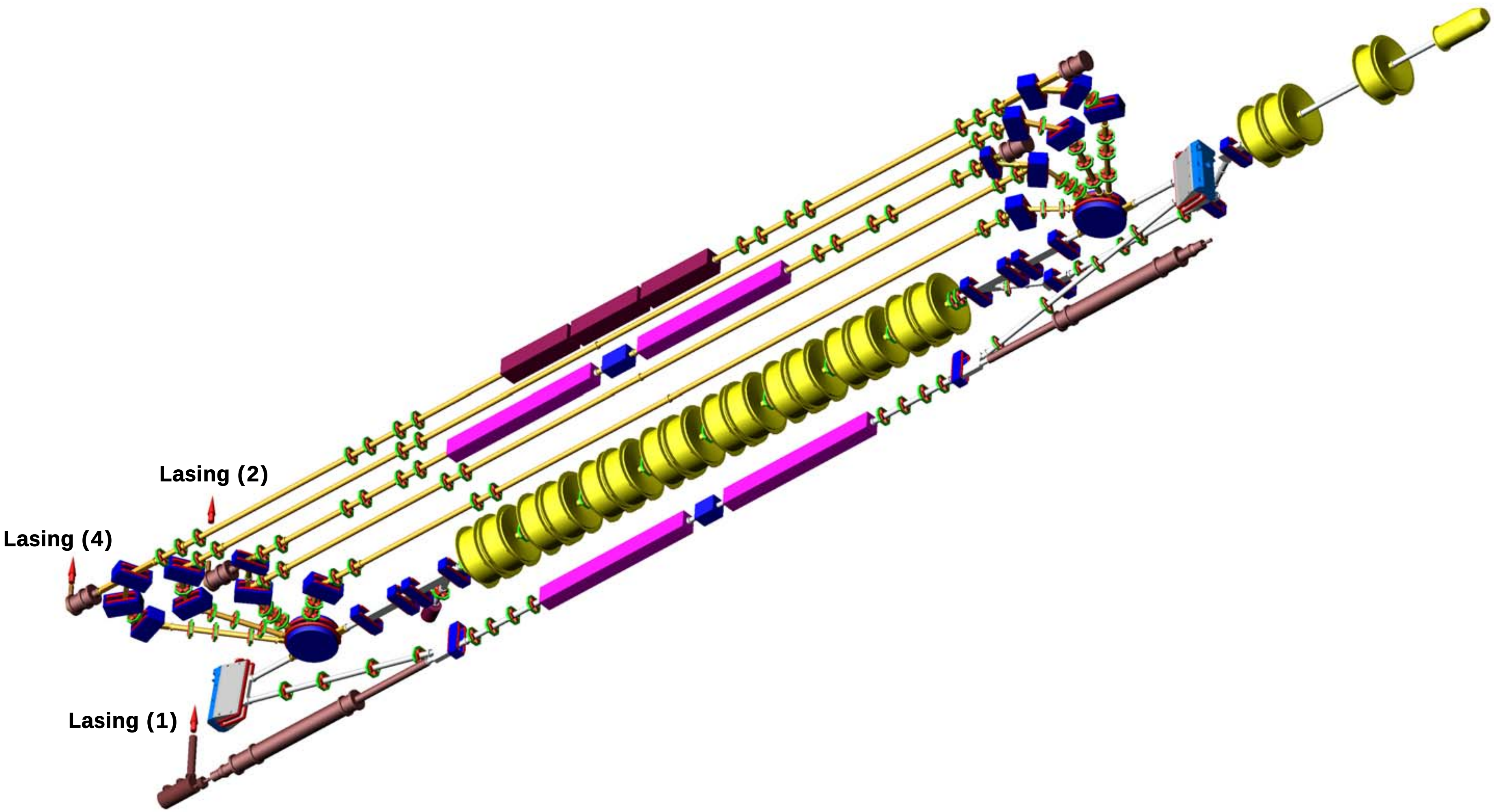
G. N. Kulipanov, A. N. Skrinsky and N. A. Vinokurov, 1997



First stage of accelerator-recuperator and FEL



The full scale project with (4+1) track accelerator-recuperator with a maximum energy of 50 MeV.



Second stage FEL Parameters

Electron beam energy, MeV	50
Number of orbits	4
Maximum bunch repetition frequency, MHz	90
Beam average current, mA	150
Wavelength range, micron	3-20
Output power, kW	10

Conclusion

- Free electron laser on ERL is in operation now.
- The work to increase the average power is continuing.
- First optical experiments were performed.
- The design and manufacturing of the second stage of FEL is in progress.