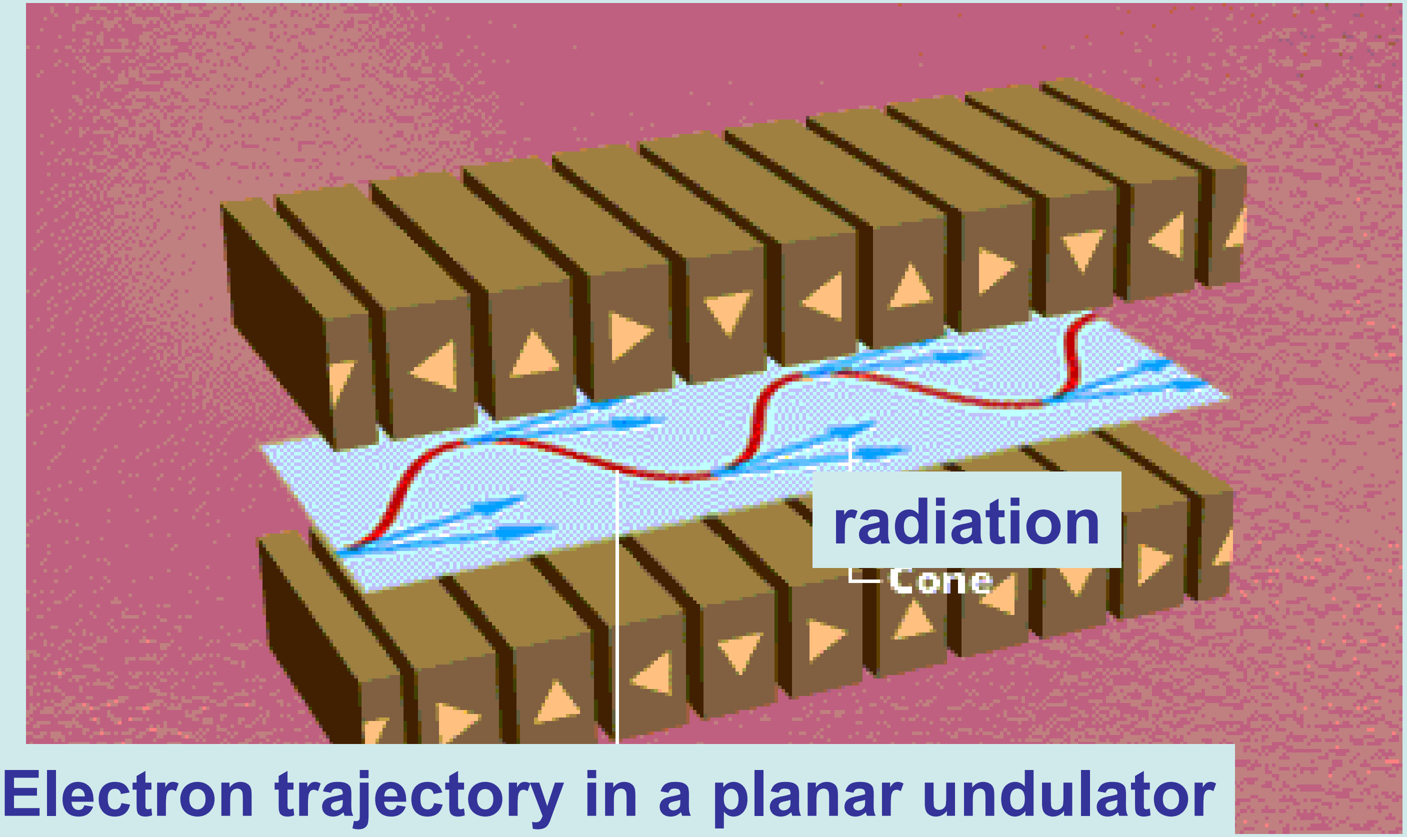
FREE ELECTRON LASER CONFIGURATIONS

Nikolay Vinokurov
Budker Institute of Nuclear Physics
Novosibirsk, Russia

Free electron lasers (FEL) provide monochromatic radiation at any wavelength (0.1 nm – 1 mm) and continuously tune this wavelength. Average power of radiation may be up to 100 kW.

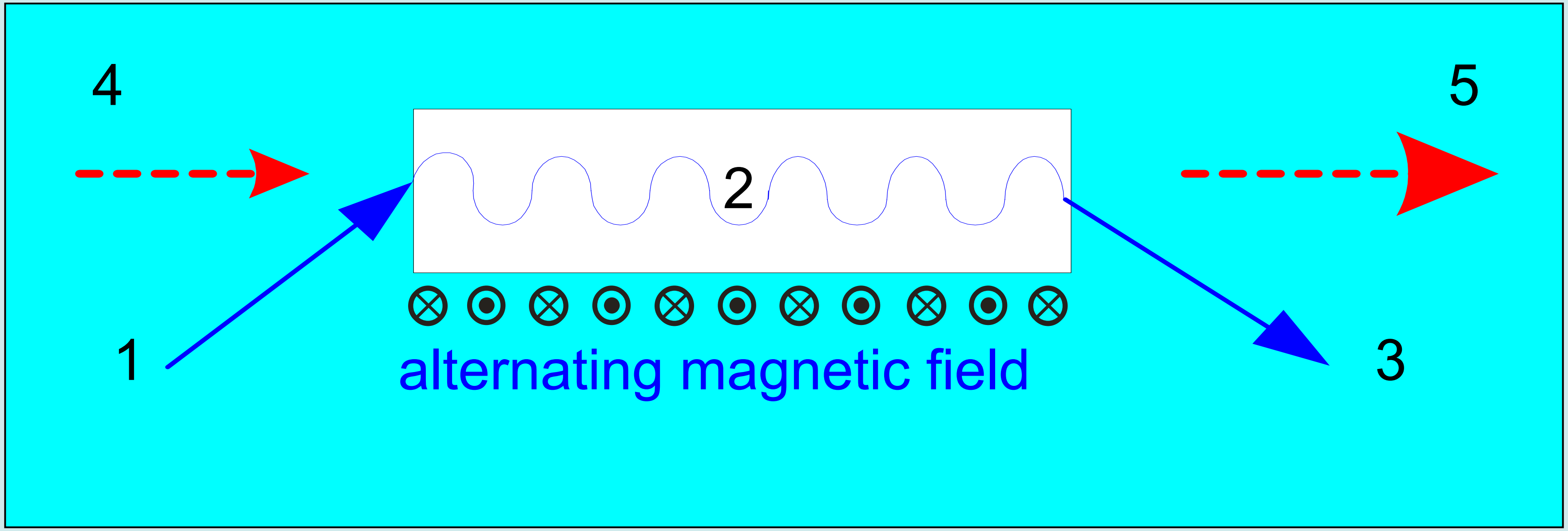
FEL use the phenomenon of *stimulated undulator radiation*.

Undulator is the magnetic system, which creates space-periodic alternating transverse magnetic field. In such a field electrons moves along slightly bent (sinusoidally, or helically) trajectory. An undulator was invented by V. L. Ginzburg in 1947.



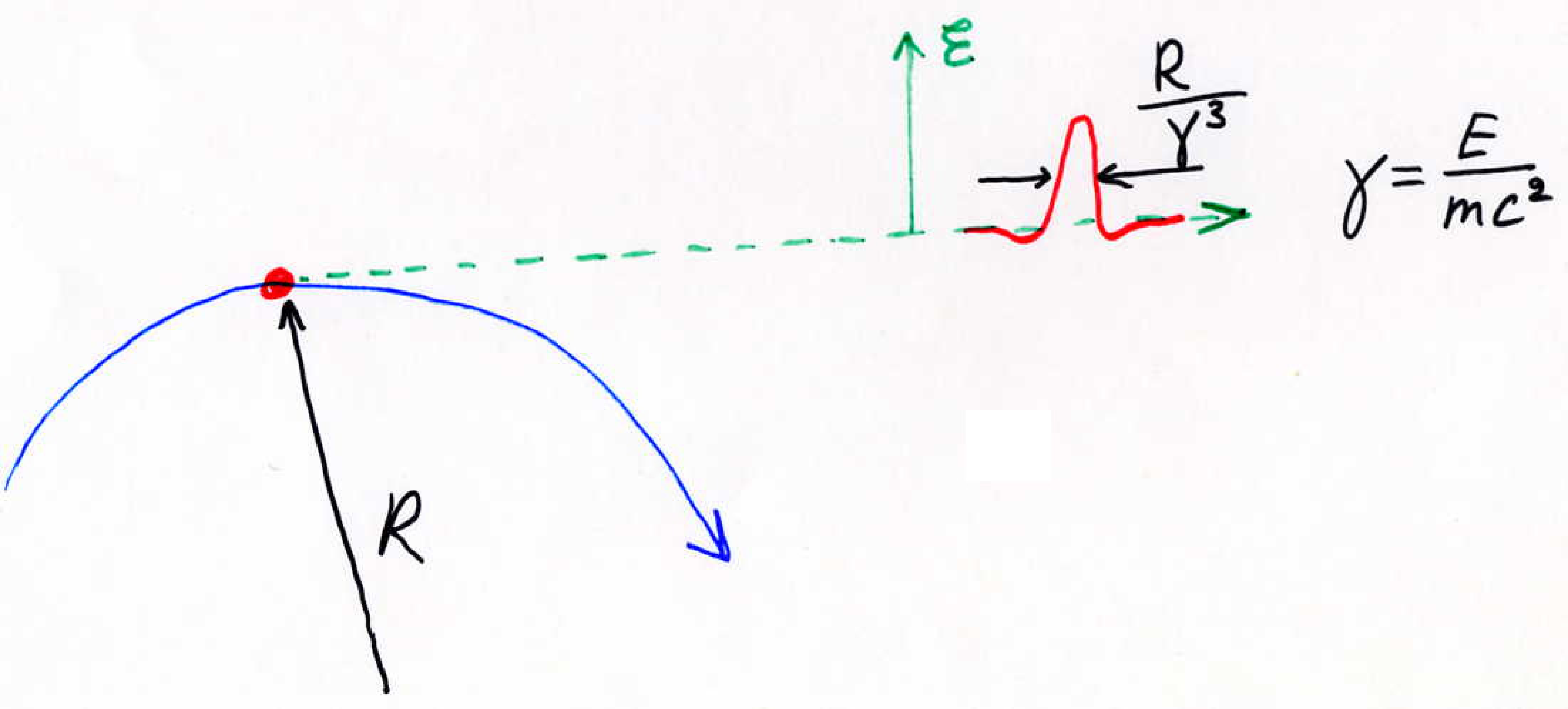
Electron trajectory in a planar undulator

The simplest FEL scheme

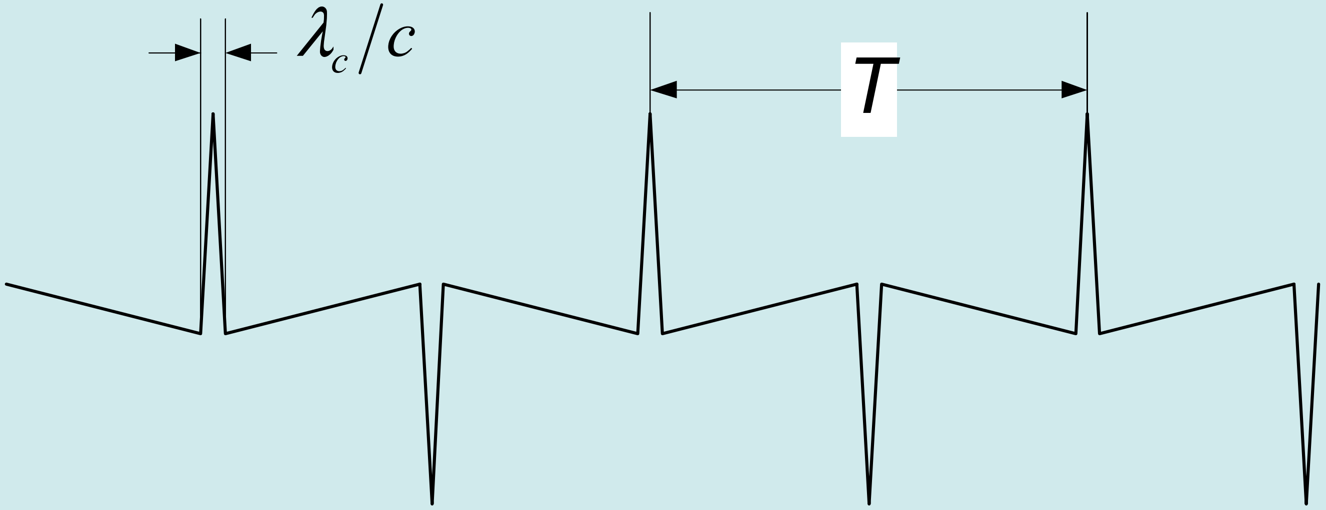


1 – input electron beam
2 – undulator
3 – used electron beam
4 – input radiation
5 – amplified radiation

Synchrotron radiation



Time dependence of the undulator radiation field



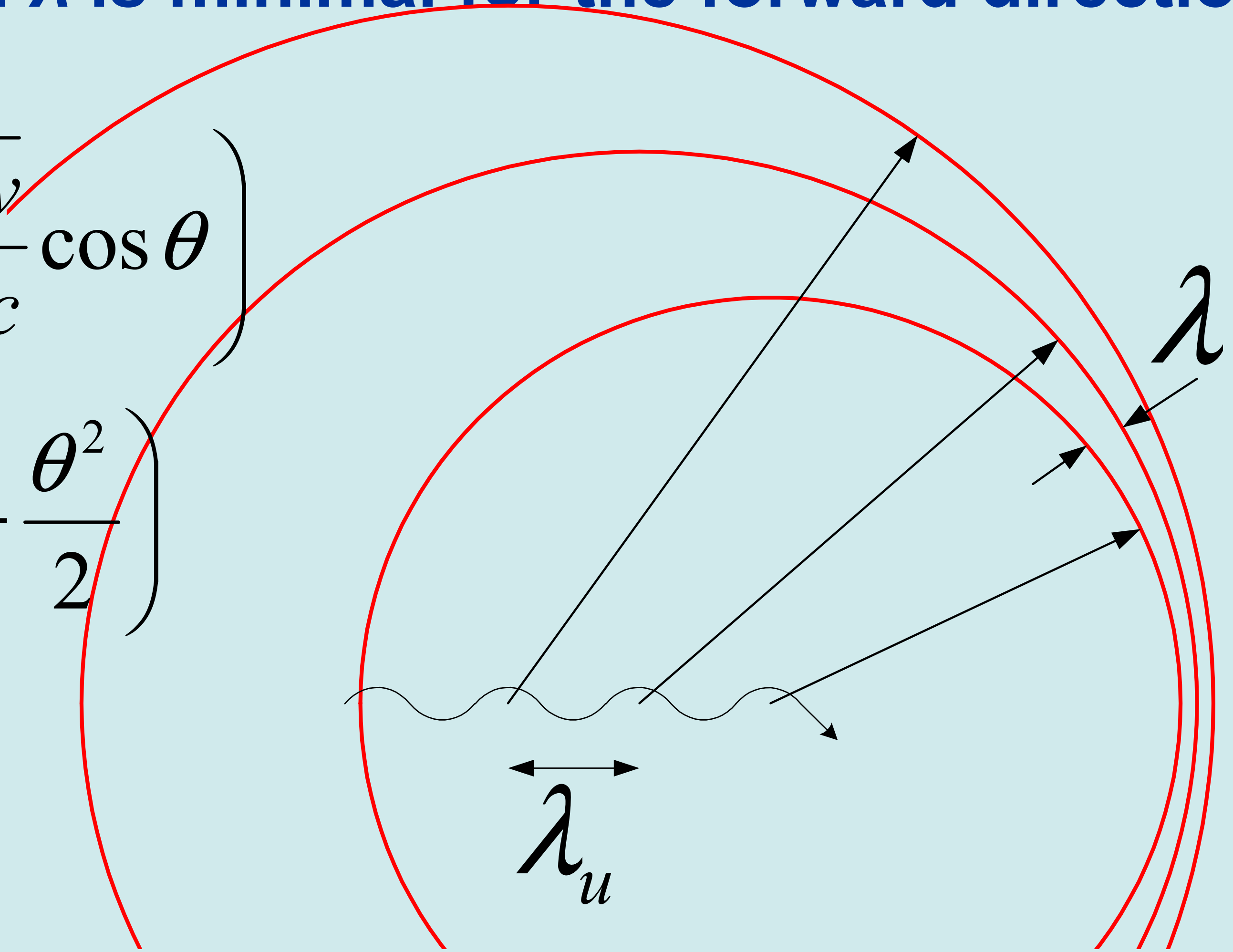
$$T=\int_0^{\lambda_w}\frac{dz}{v_z}-\frac{\lambda_w}{c}=\int_0^{\lambda_w}\sqrt{1+\left(\frac{dx}{dz}\right)^2}\frac{dz}{v}-\frac{\lambda_w}{c}\approx$$

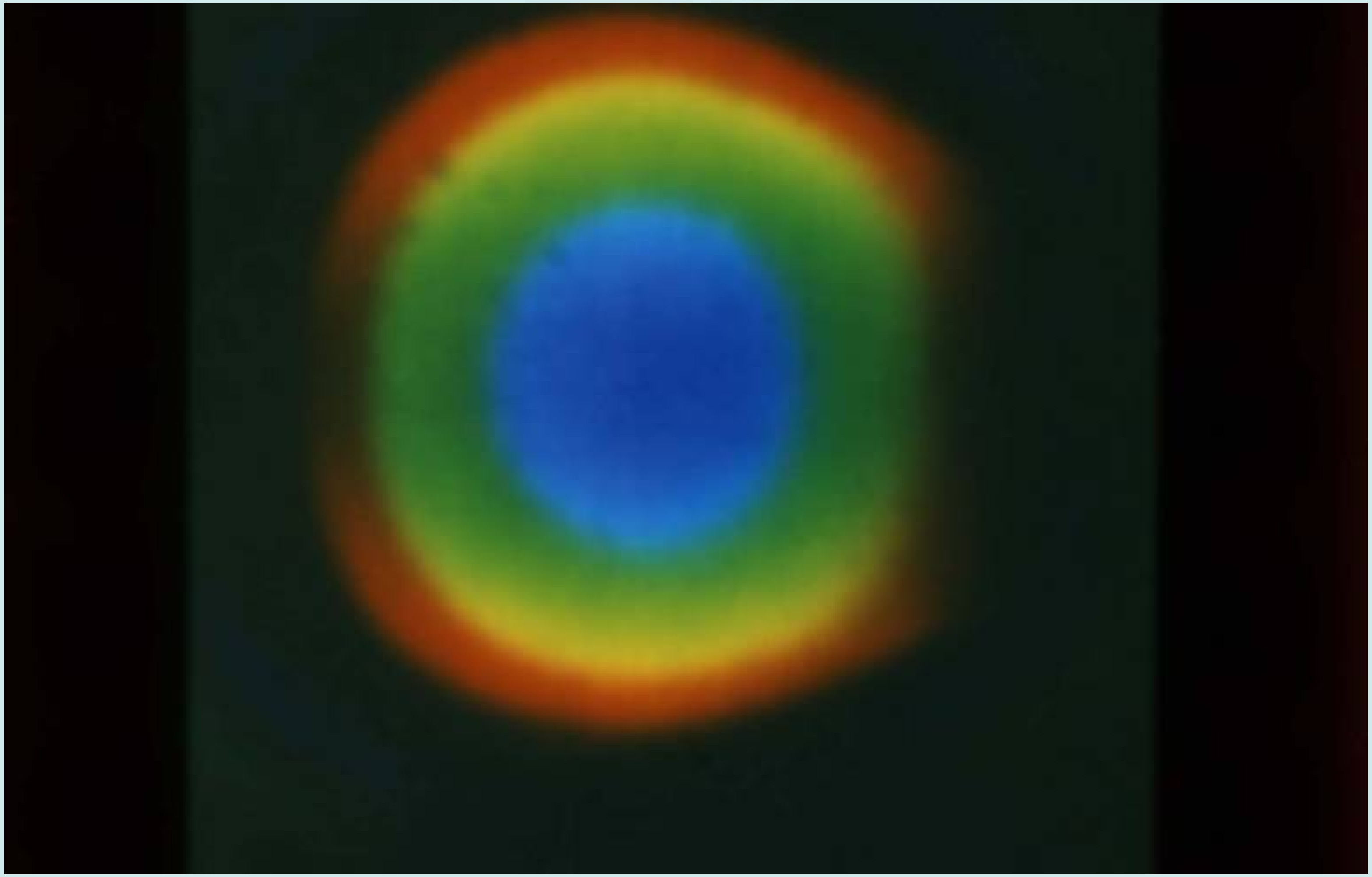
$$\frac{\lambda_w}{v}(1-\beta)+\frac{1}{2}\int_0^{\lambda_w}\left(\frac{dx}{dz}\right)^2\frac{dz}{v}=\frac{\lambda_w}{v}\left(1-\beta+\frac{1}{4k_w^2r^2}\right)$$

Wave fronts, propagating from points of the electron trajectory with maximum acceleration (undulator field maxima). The radiation wavelength *λ* is minimal for the forward direction.

$$\lambda = \lambda_u \left(1 - \frac{\bar{v}}{c} \cos\theta \right)$$

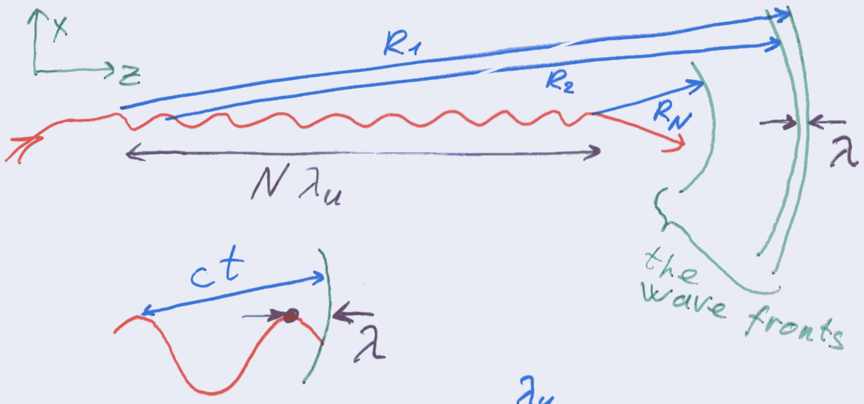
$$\approx \lambda_u \left(\frac{1}{2\gamma^2} + \frac{\theta^2}{2} \right)$$





Spontaneous undulator radiation. Photo was made at the VEPP-3 storage ring (Budker INP, 1978).

Undulator radiation

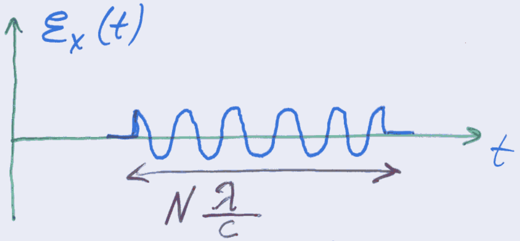


$$\lambda = ct - \lambda_u = c\int_0^{\lambda_u}\frac{dz}{V_z} - \lambda_u$$

$$V_z = V\cos\alpha \approx c\left(1 - \frac{1}{2\gamma^2} - \frac{\alpha^2}{2}\right)$$

$$\alpha \approx \frac{K}{\gamma}\sin\frac{2\pi z}{\lambda_u}$$

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

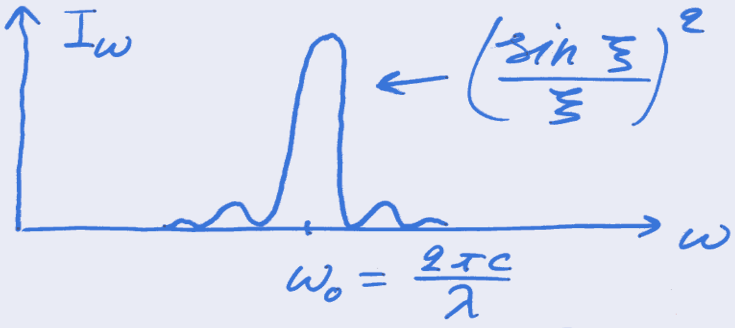


$$\mathcal{E}_x \approx -4(\gamma_{\parallel}^2)^2\frac{e\dot{V}_x}{c^2R} \approx 4\gamma^3\frac{e^2}{mc^2}\frac{1}{R}B_y(2\gamma_{\parallel}^2 ct)$$

Synchronism condition: at each undulator period electron lags behind its radiation by one wavelength.

The spontaneous undulator radiation spectrum

The spectrum of u.r.



$\leftarrow \left(\frac{\sin \xi}{\xi}\right)^2$

$\omega_0 = \frac{2\pi c}{\lambda}$

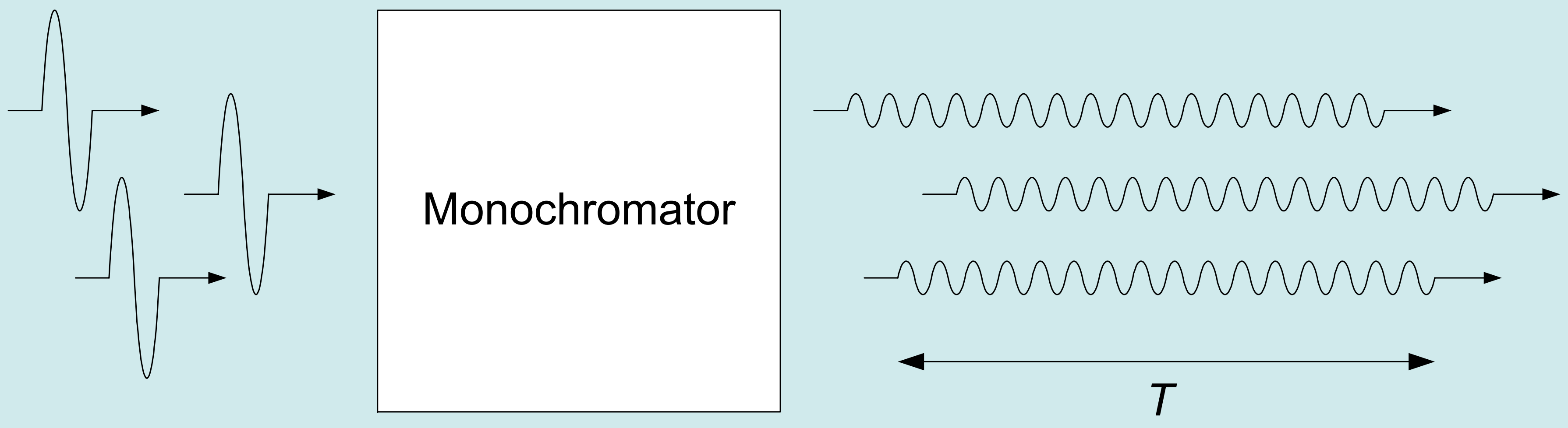
$\xi = \frac{\omega - \omega_0}{\omega_0} \pi N$

$$dI_\omega = \frac{c}{2\pi} |\mathcal{E}_{x\omega}|^2 R^2 do \frac{d\omega}{2\pi}$$

$$\left(\frac{\Delta\omega}{\omega}\right)_{FWHM} \approx \frac{1}{N}$$

Stimulated Emission – synchronization of radiators

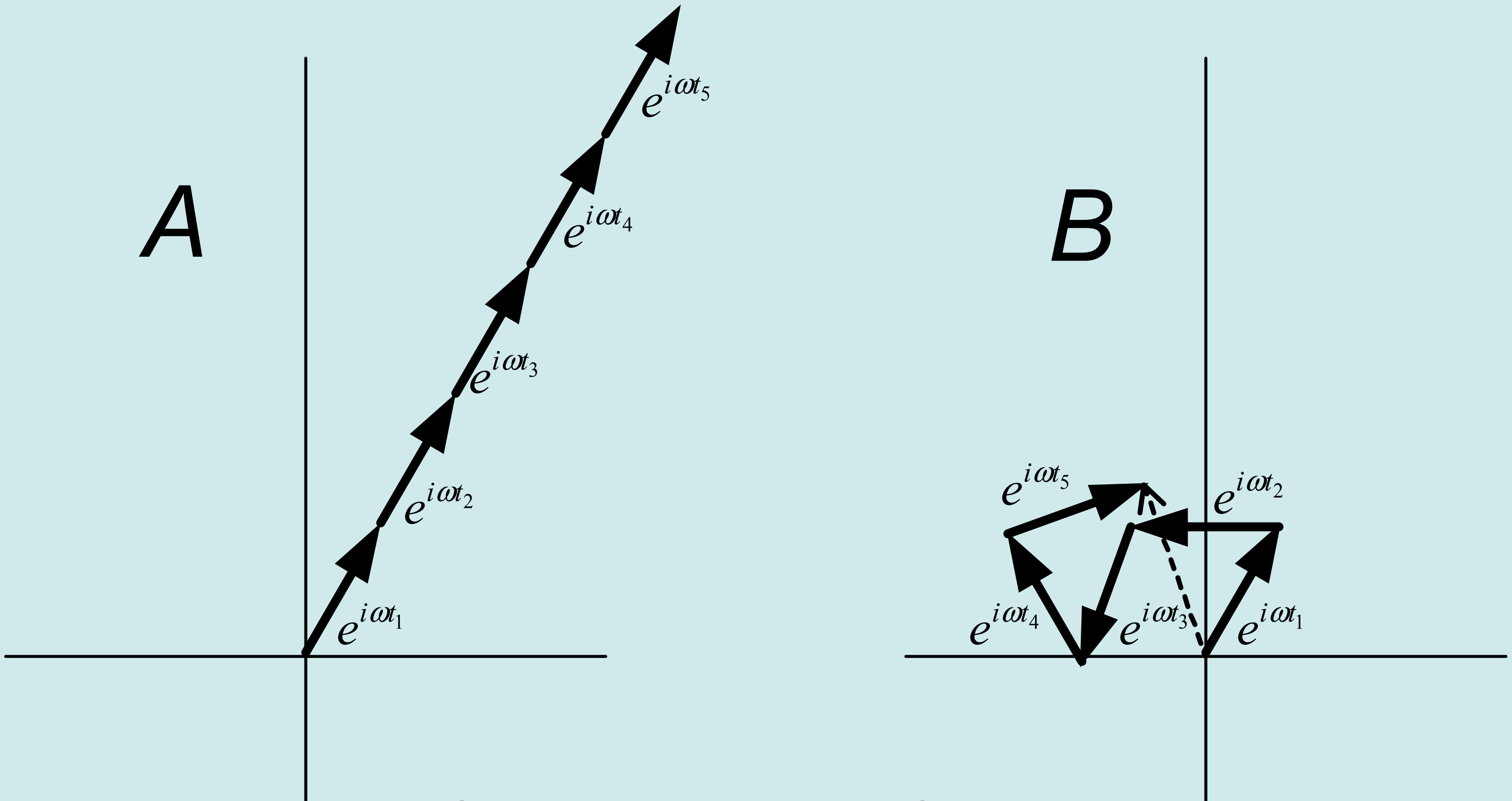
Radiation pulses from different radiators pass through a monochromator



$$E_M(t) = a\sum_n \cos\left[\omega\left(t-t_n\right)\right]\vartheta\left(t-t_n\right)\vartheta\left(T-t+t_n\right) = \mathrm{Re}\left[e^{-i\omega t}a\sum_n e^{i\omega t_n}\vartheta\left(t-t_n\right)\vartheta\left(T-t+t_n\right)\right]$$

The signal power (spectral density) is proportional to the amplitude square

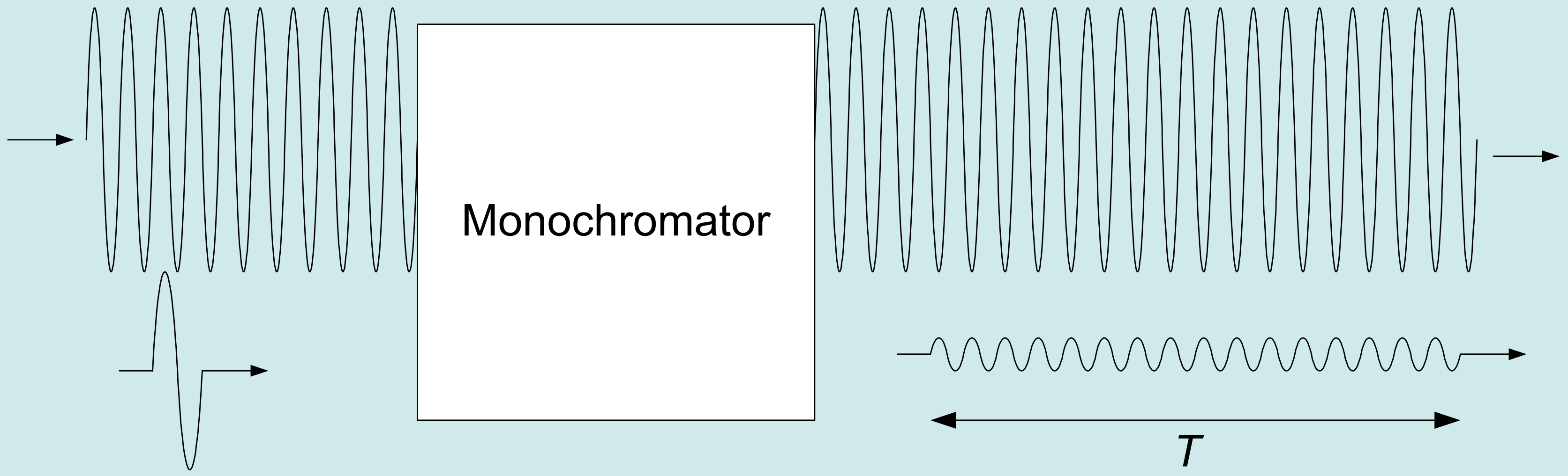
$$\left|\sum_n a e^{i\omega t_n}\right|^2 = \sum_m \sum_n a^2 e^{i\omega(t_n - t_m)}$$



A – coherent radiation (phased radiators)

B – “incoherent” radiation

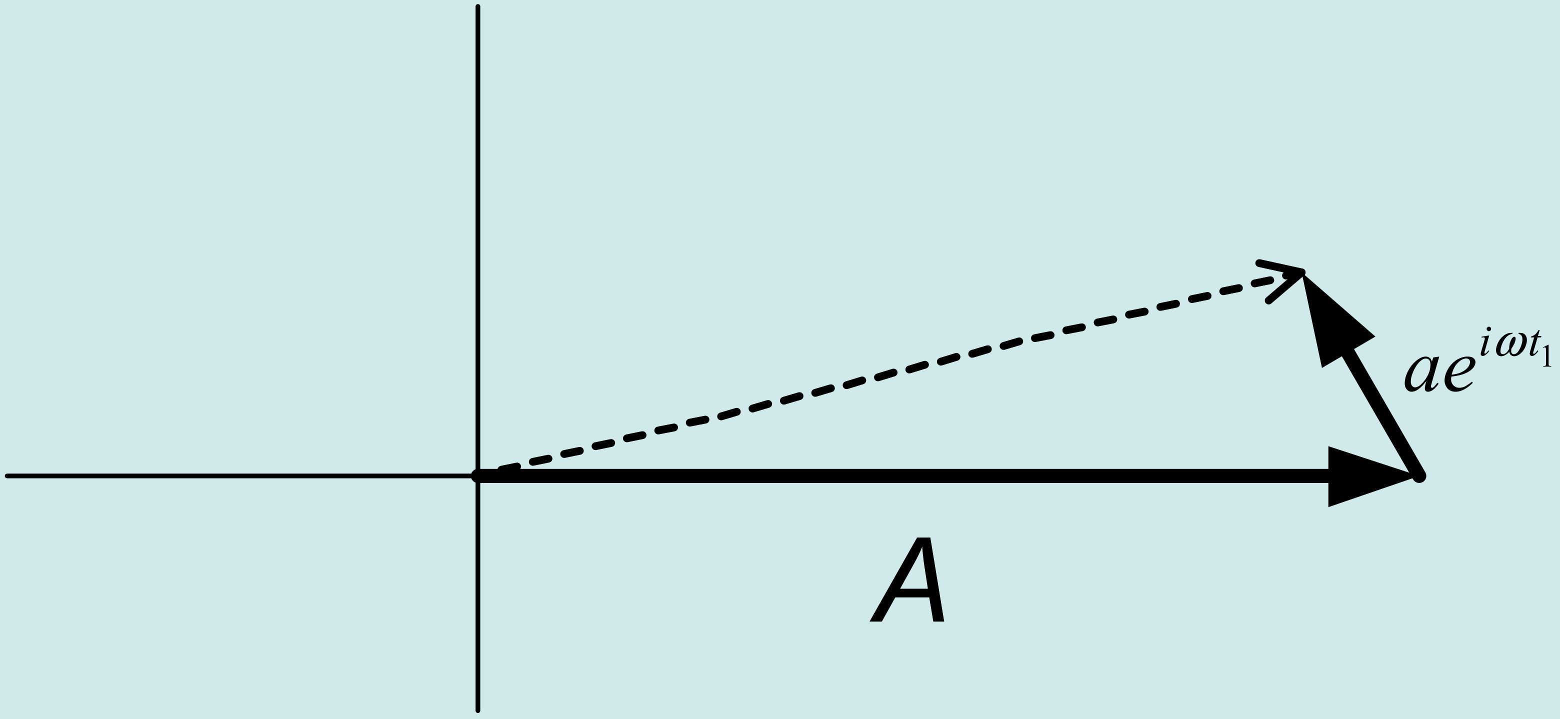
Summation of a single radiator pulse and a monochromatic wave



$$\left| A + a e^{i\omega t_1} \right|^2 = \left| A \right|^2 + 2\,\mathrm{Re}\left(A a e^{-i\omega t_1} \right) + a^2$$

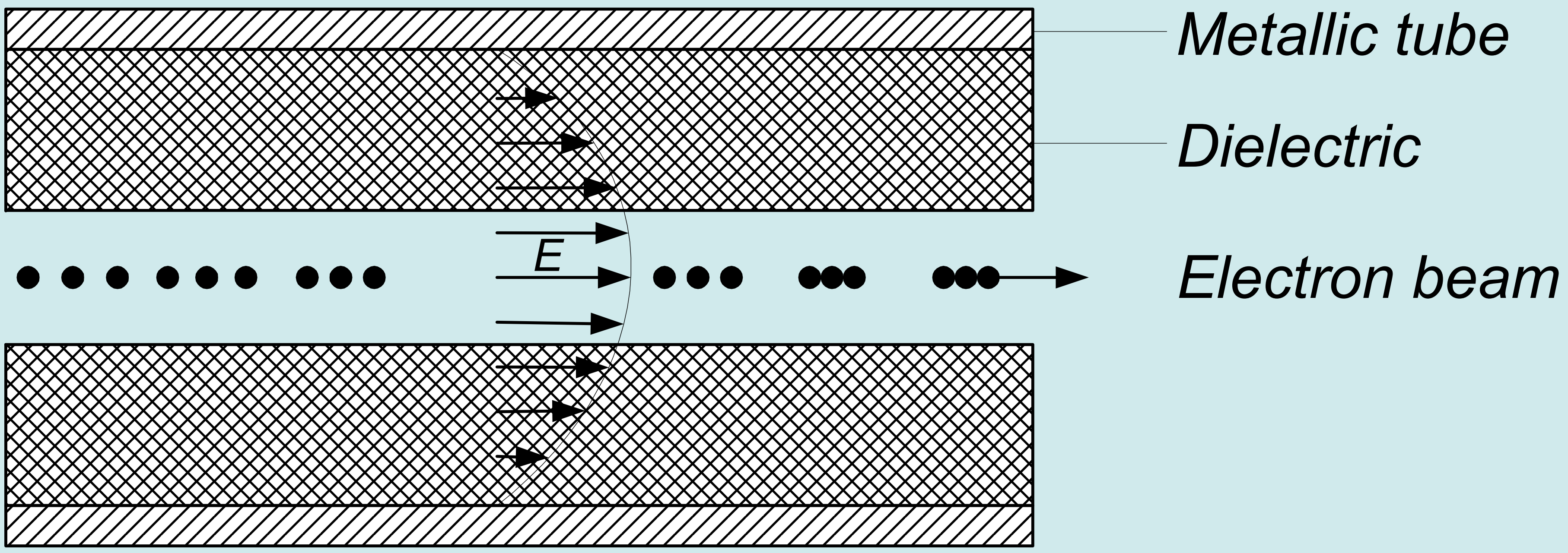
The wave power variation

$$\left|A + ae^{i\omega t_1}\right|^2 T = \left|A\right|^2 T + 2\,\mathrm{Re}\left(Aae^{-i\omega t_1}\right)T + a^2 T$$

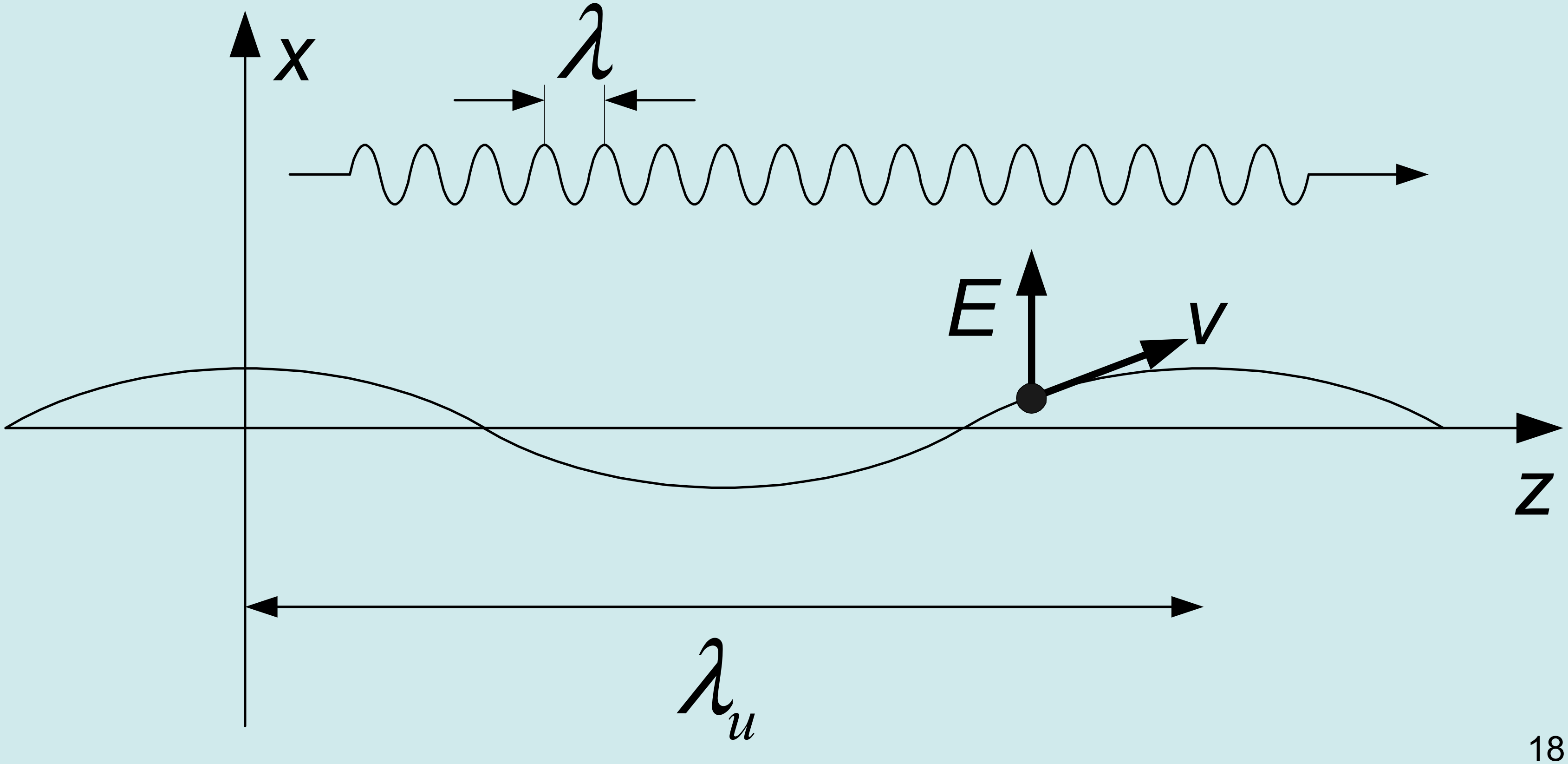


Stimulated emission is caused by synchronization of individual radiators. For an FEL it is simply the longitudinal bunching, as it takes place in all travelling wave tubes. The first FEL, made by R. Phyllips in 1959, was travelling wave tube with undulator, and called "ubitron".

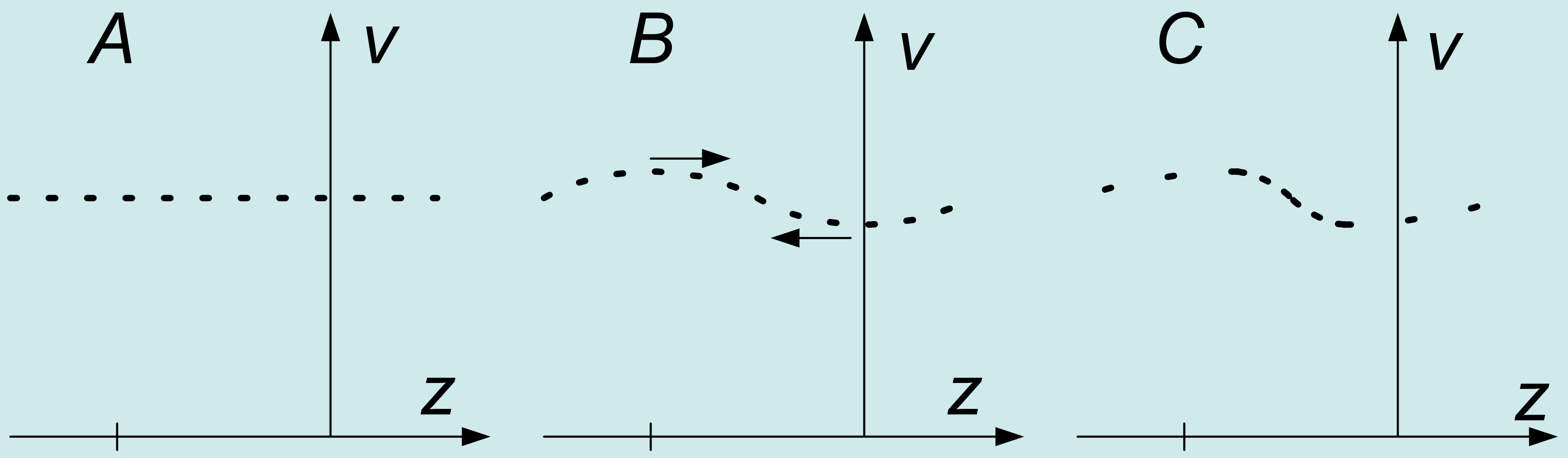
The simplest travelling wave tubes use the stimulated Cherenkov radiation.



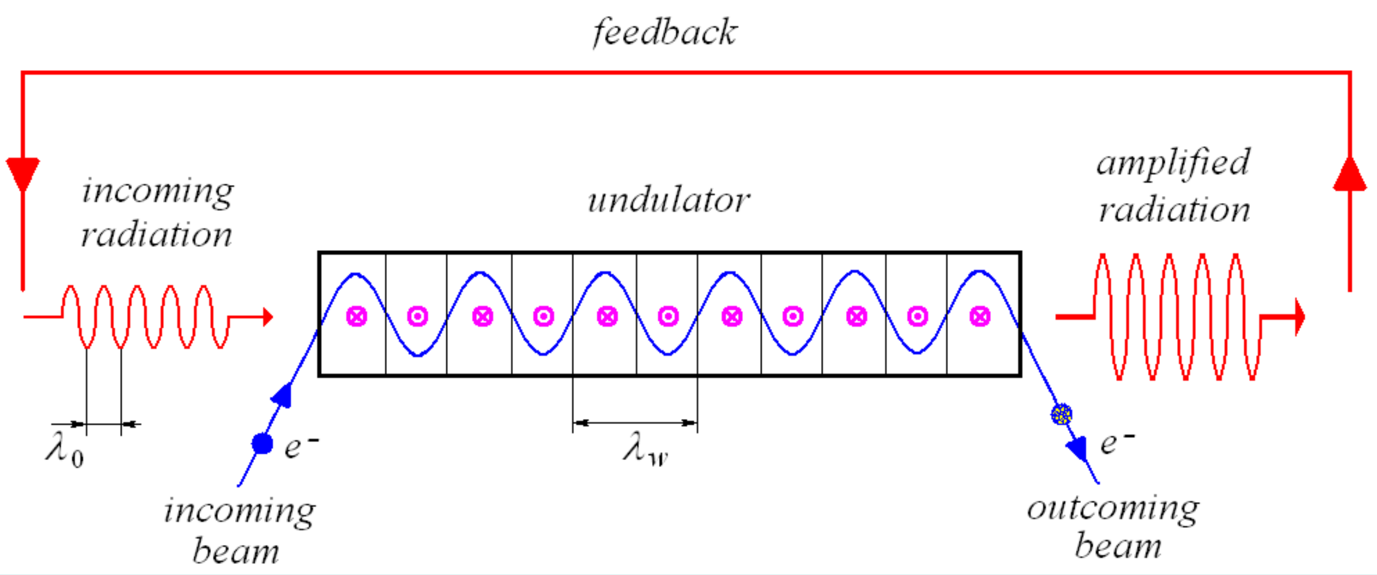
As the electron velocity in the undulator has the transverse component, the electric field of the transverse wave changes the electron energy. Let the time lag of an electron, passed one undulator period λ_u, with respect to the wave is one wavelength λ. Then the total variation of an electron energy in the undulator may be significant.

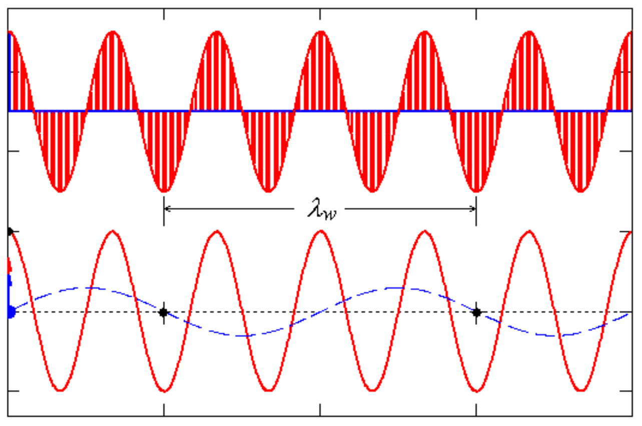


Electron bunching due to the energy (and, therefore, velocity *v*) modulation



Principle of the FEL oscillator operation





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

↑

synchronisme condition

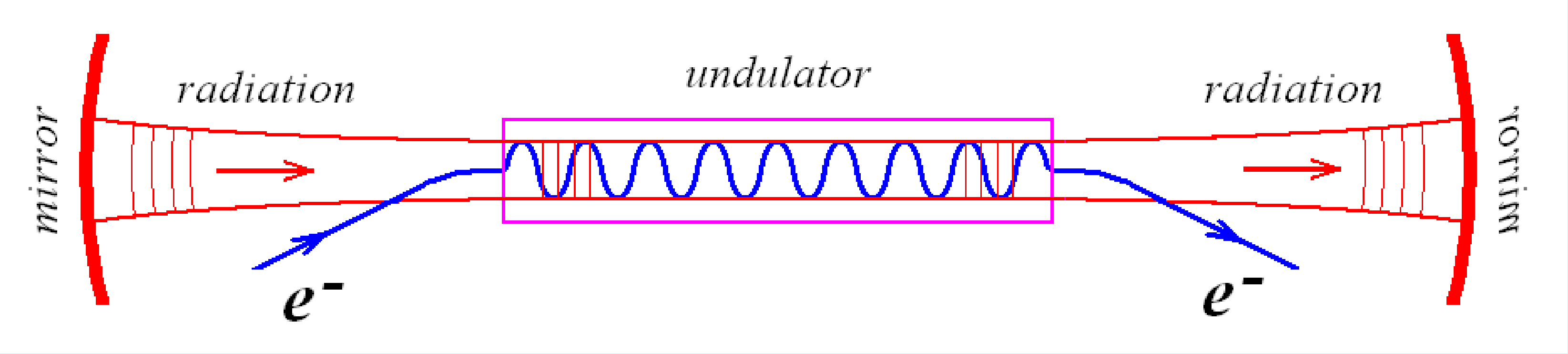
which is necessary for the

energy transfer

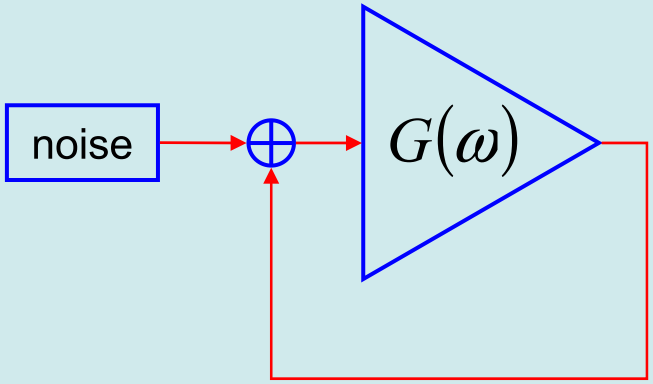
↓

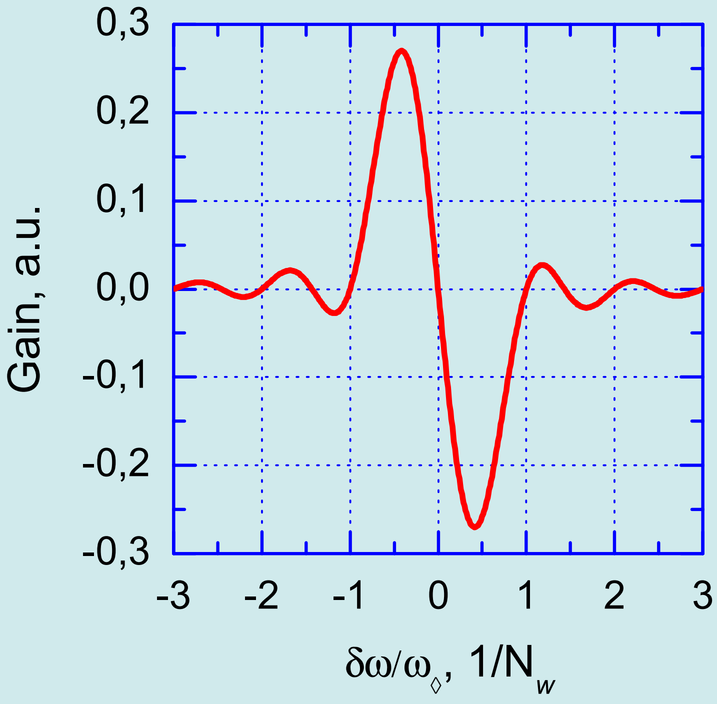
$$\boxed{\left\langle \frac{d\gamma}{dz} \right\rangle = \frac{e}{mc^3}\left\langle \mathcal{E}_x V_x \right\rangle}$$

The scheme of the FEL oscillator



Equivalent scheme of FEL oscillator





Narrow bandwidth amplifier with feedback

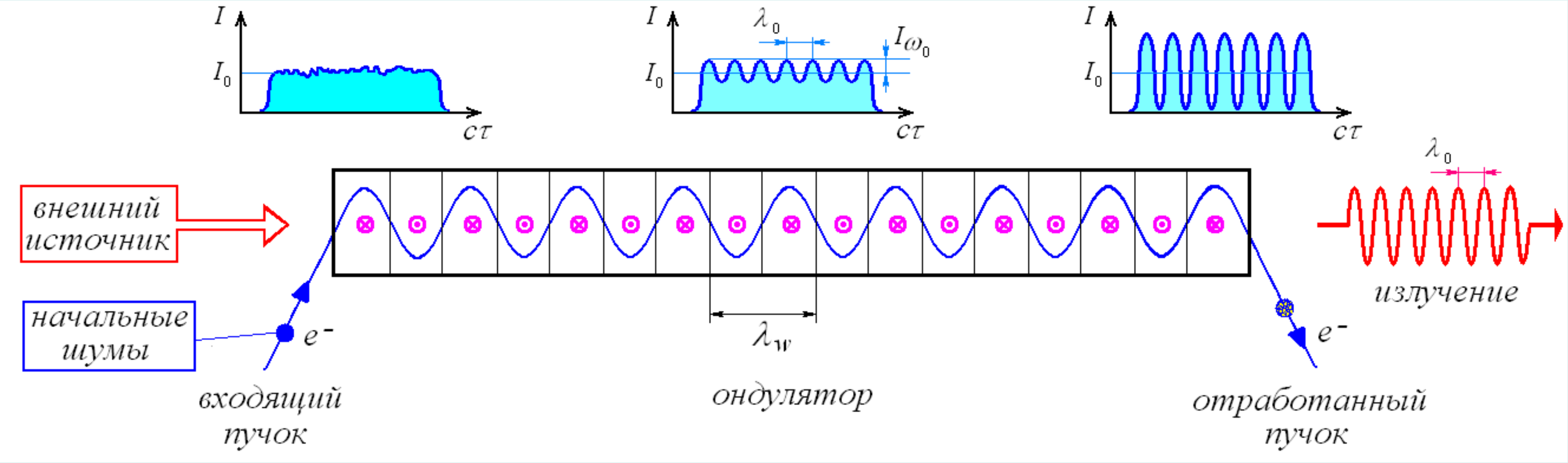
FELs cover seven orders of magnitude wavelength range – from 1mm to 0.1 nm.

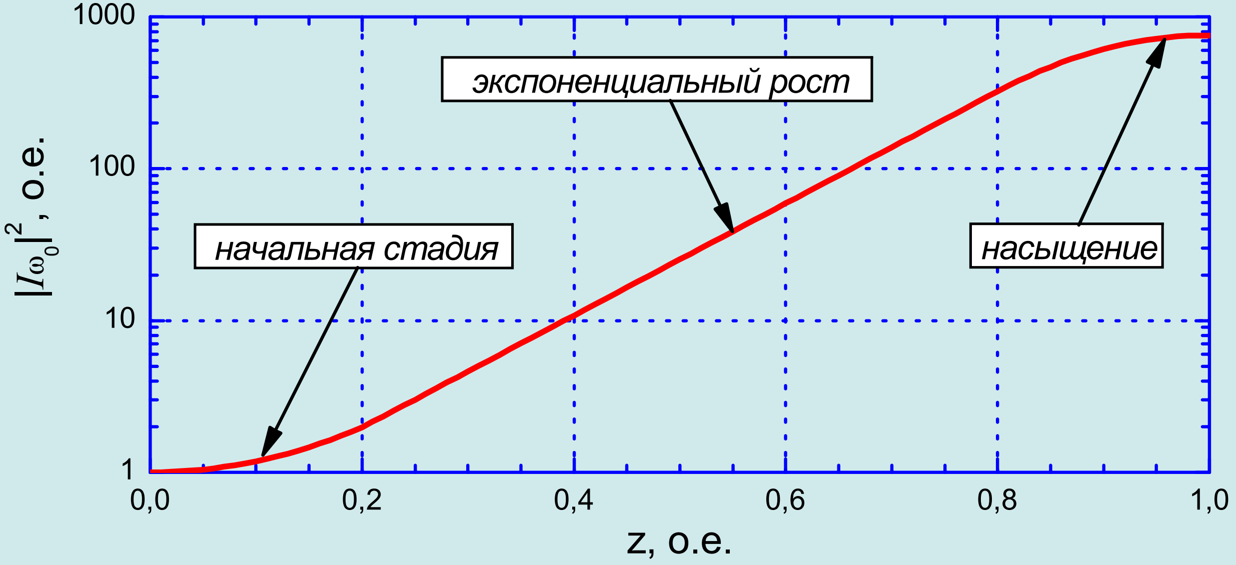
THz FELs works in Russia (Budker INP), Holland (FELIX), USA (UCSB), Korea (KAERI), France (CLEO), Japan, and other places.

X-ray FELs operate in USA (LCLS), and Germany (FLASH). X-ray FEL projects are in Japan, Germany, Korea, Italy, UK, and China.

FEL of the Duke University (USA) is used to generate 100 MeV ($\lambda=10^{-14}$m) photons.

High gain FEL

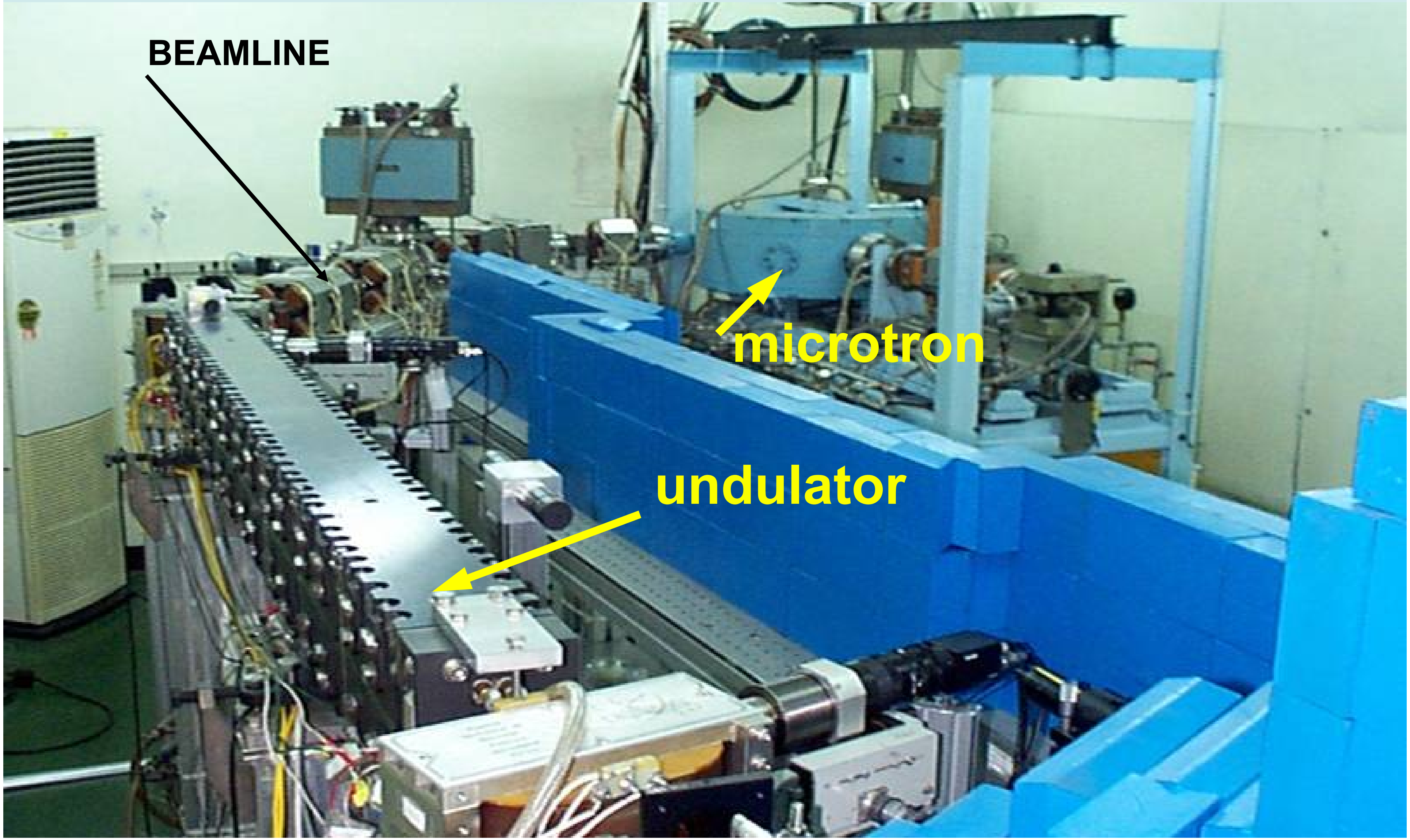




Bunching degree vs. undulator length

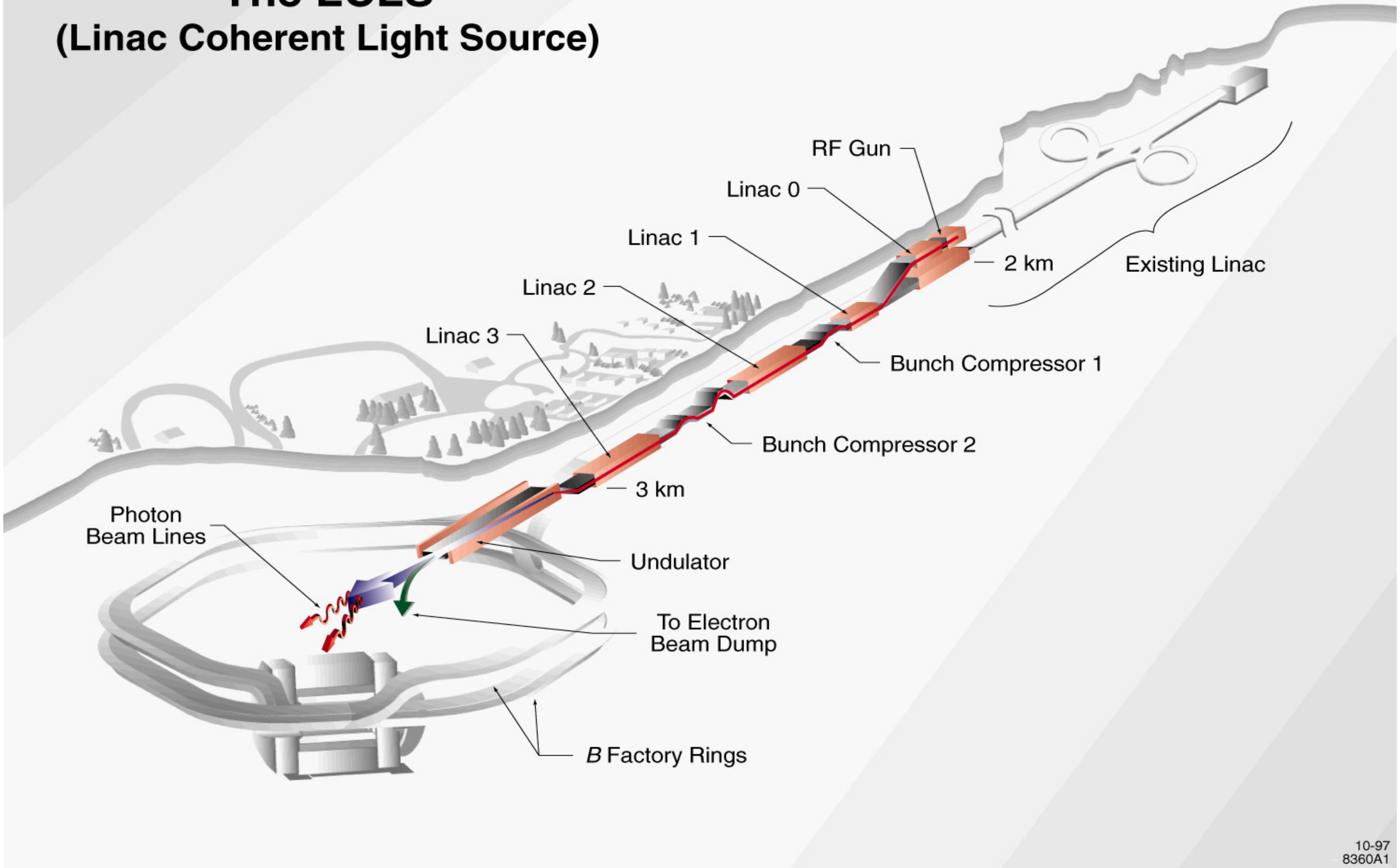
Examples: smallest and biggest FELs

Compact THz FEL. Developed and built by the Budker INP for KAERI (Korea). Operates since 1998.

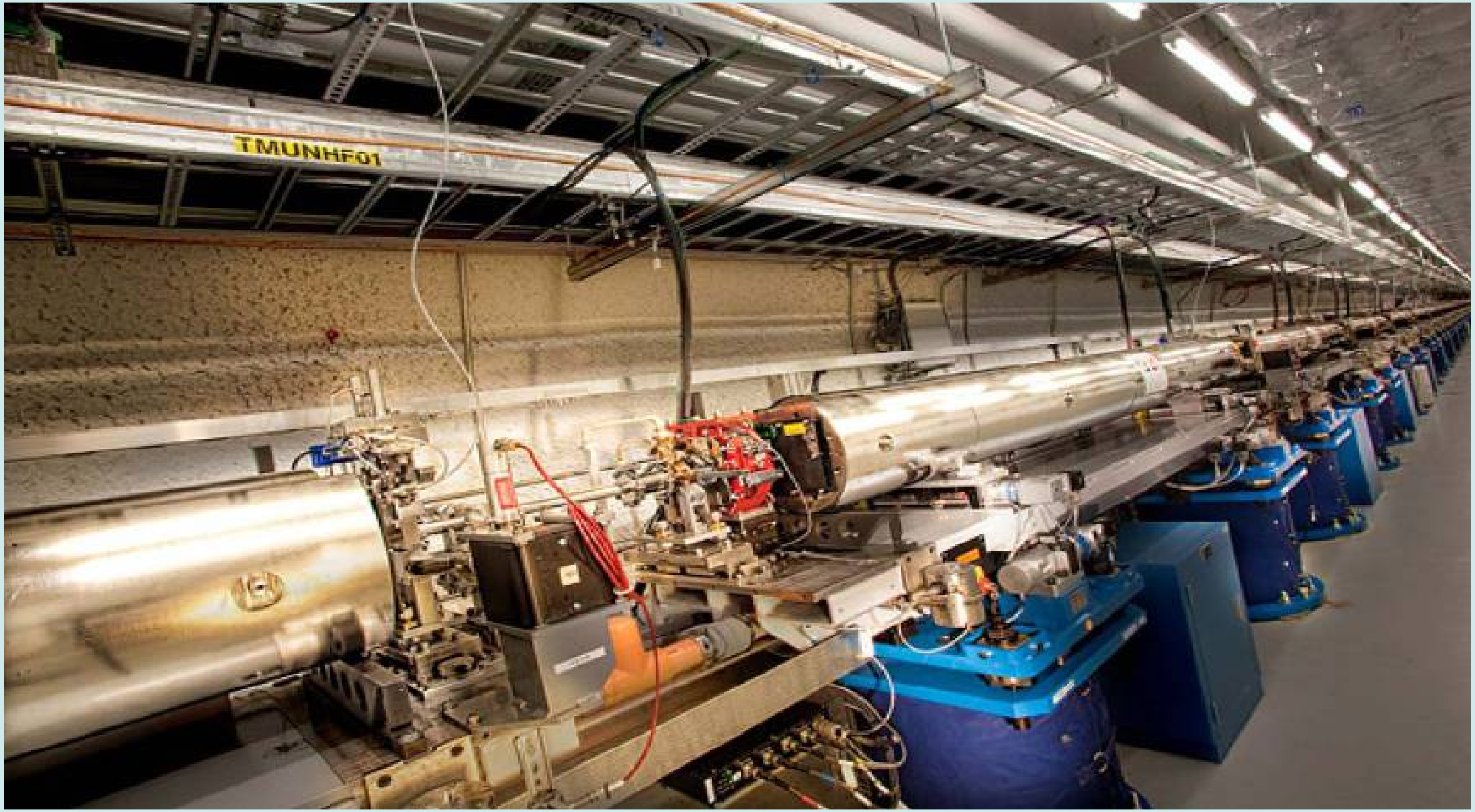


X-ray FEL (SLAC, США)

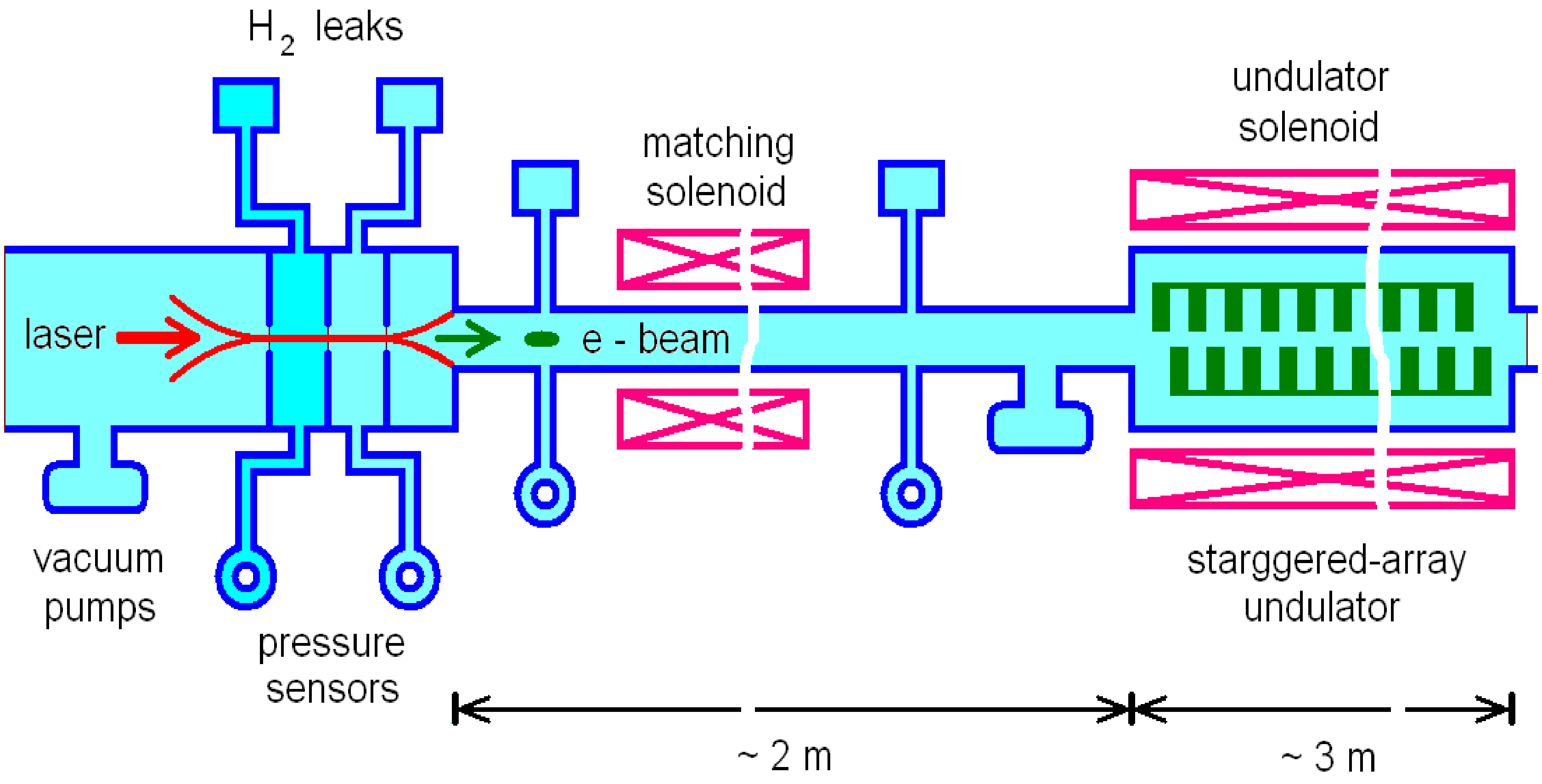
The LCLS
(Linac Coherent Light Source)



Undulator of the x-ray FEL (total length about 50 m)

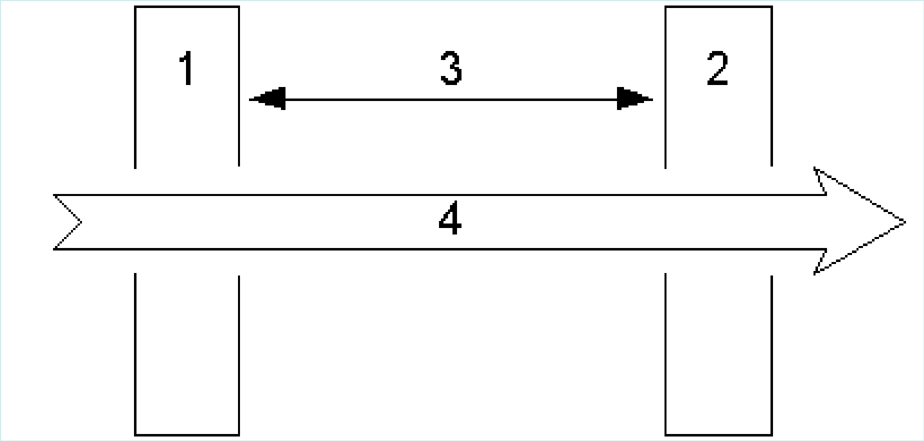


Possible scheme of the combined LWFA and X-ray FEL experiment

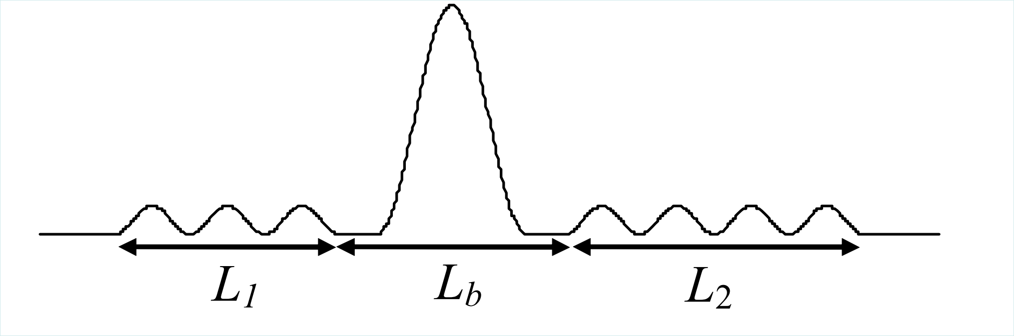


FEL development in the Budker INP

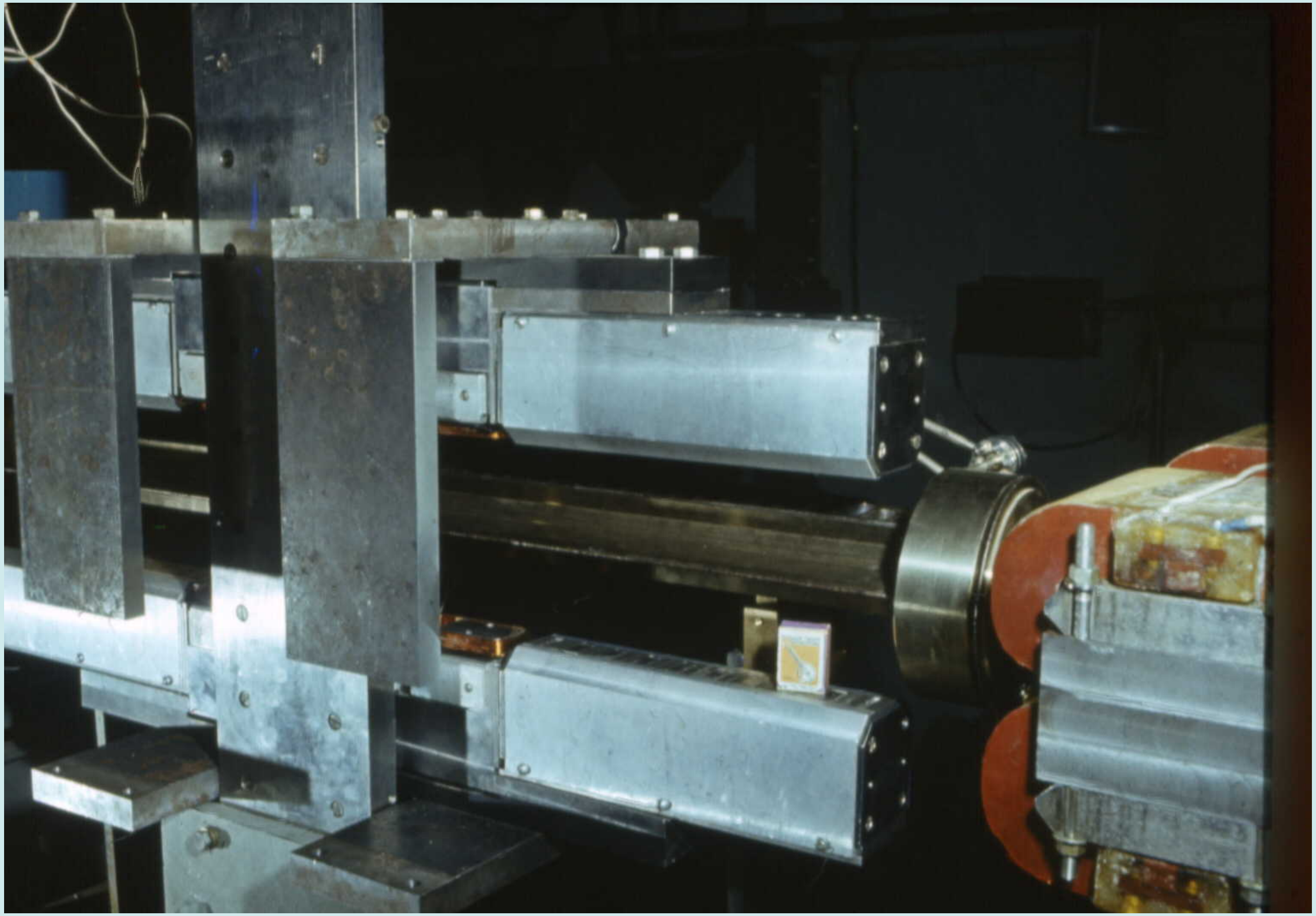
Klysrton and optical klystron



The microwave klystron. 1, 2 - resonators, 3 - drift space, 4 - electron beam.



The electron trajectory in the optical klystron.



First in the world hybrid permanent magnet undulator (Budker INP, OK-2, 1980). Used in optical klystron, which was proposed and developed theoretically and experimentally in Budker INP.

FEL-related activity of Budker INP

- 1977-1985 – invented and built: optical klystron, variable-gap permanent magnet undulator, hybrid permanent magnet undulator;
- theoretical investigation of FEL physics;
- experimental study of spontaneous and stimulated emission of optical klystron was performed.

- 1985-1994 – visible and UV range FEL was built.
- long electromagnetic undulators of original design;
- short-wavelength record for FEL (0.24 micron);
- linewdith narrowing by intracavity Fabry-Perot etalon;
- electron outcoupling of radiation in FEL was proposed and tested.

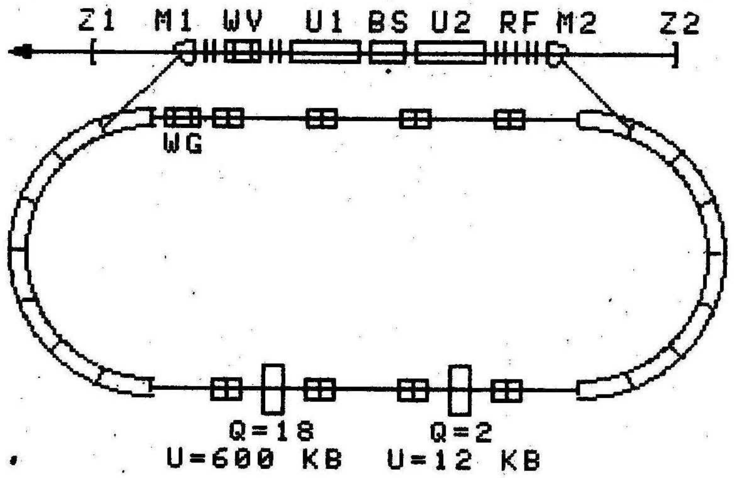


Рис. 1. Схема накопителя ВЭПП-3 с байпассом.

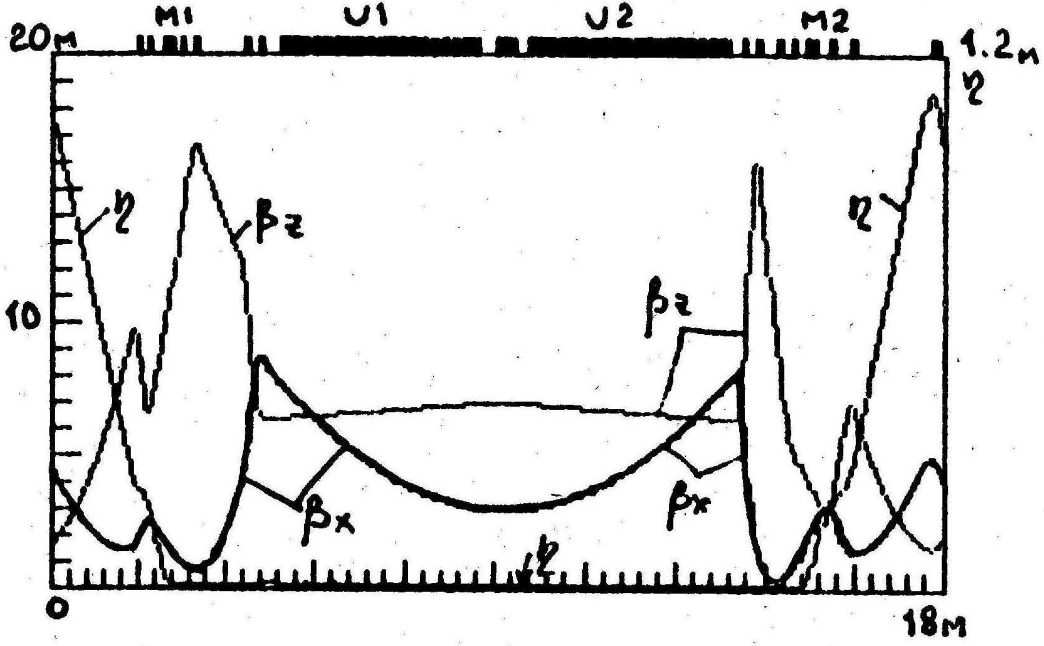
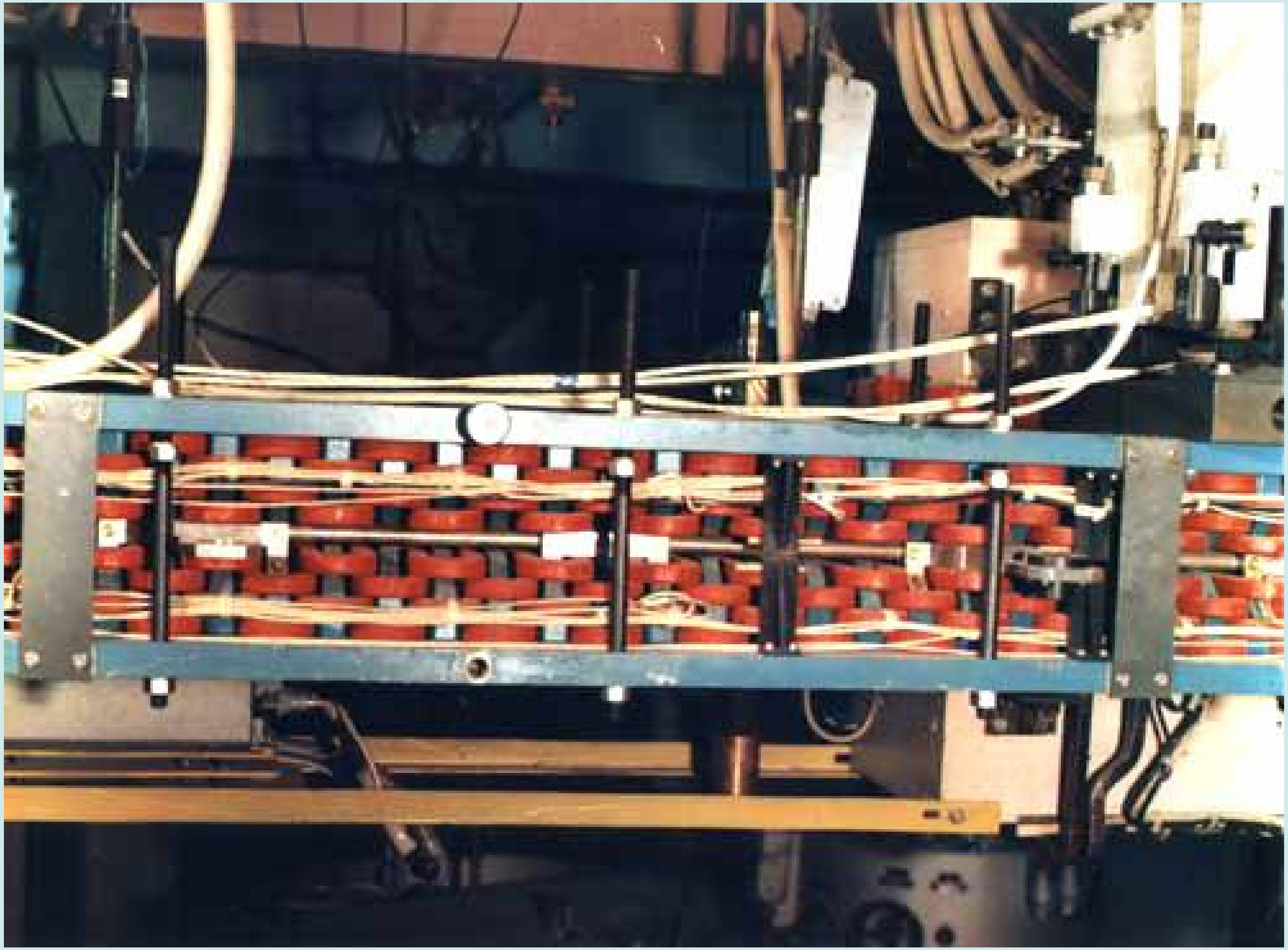


Рис. 2. Оптимизированные β- и η-функции в байпассе для работы ОК в ультрафиолетовой области спектра.

FEL at bypass on the VEPP-3 storage ring

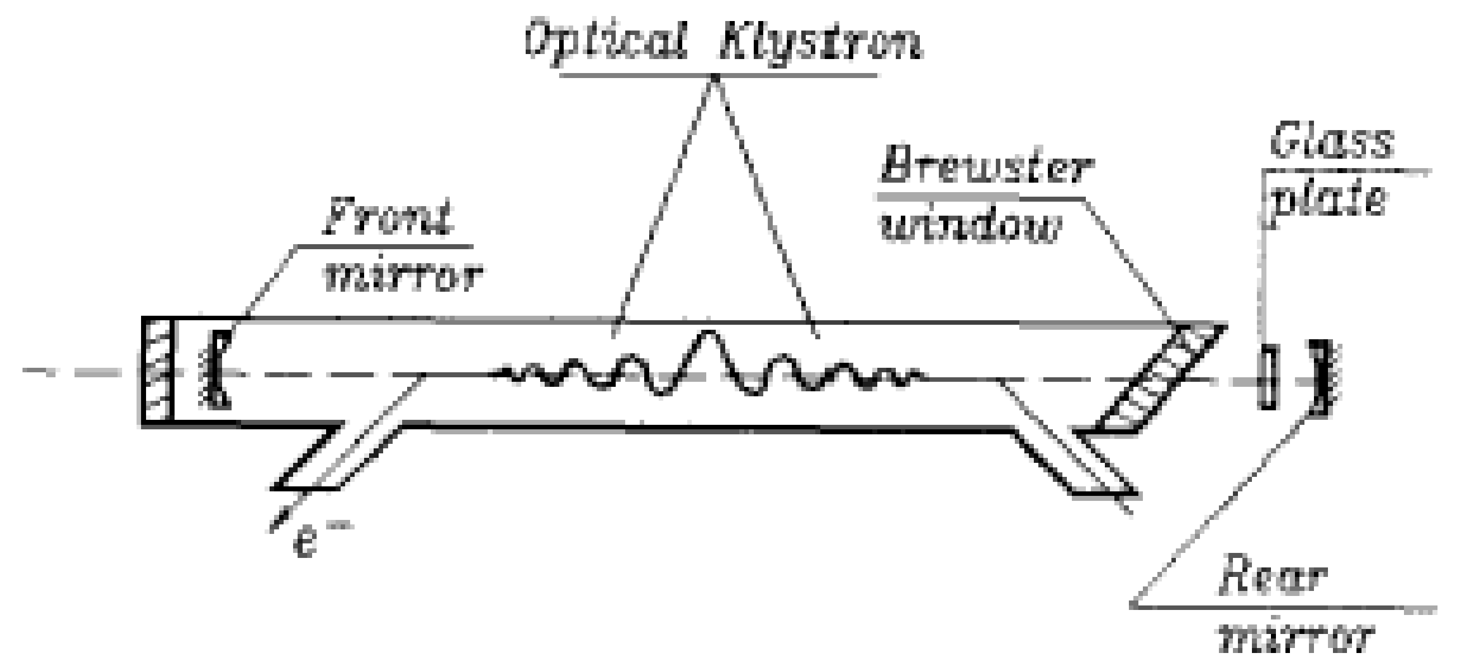
(Budker INP, 1987-1995).



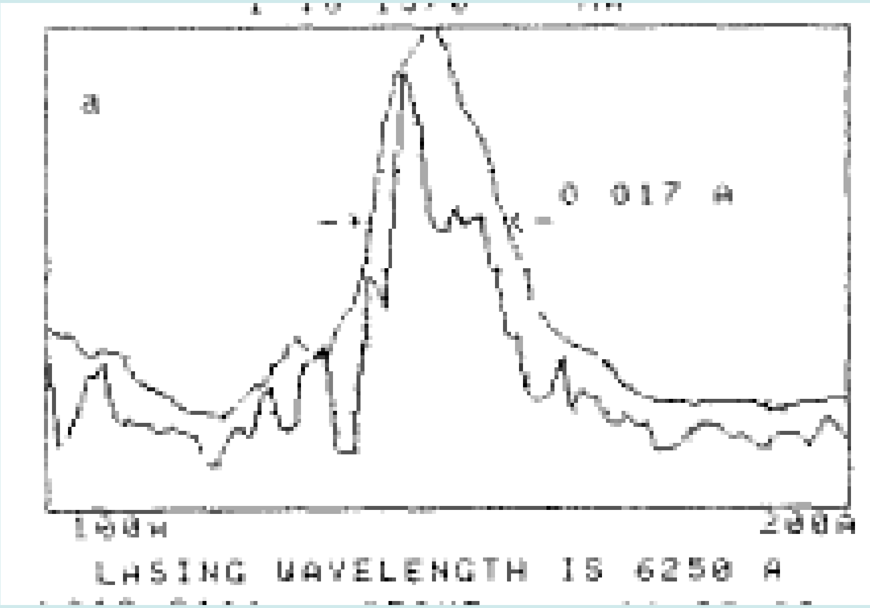
Electromagnetic undulator OK-4

(Budker INP, 1987-1995. Since 1996 – in Duke University, USA).

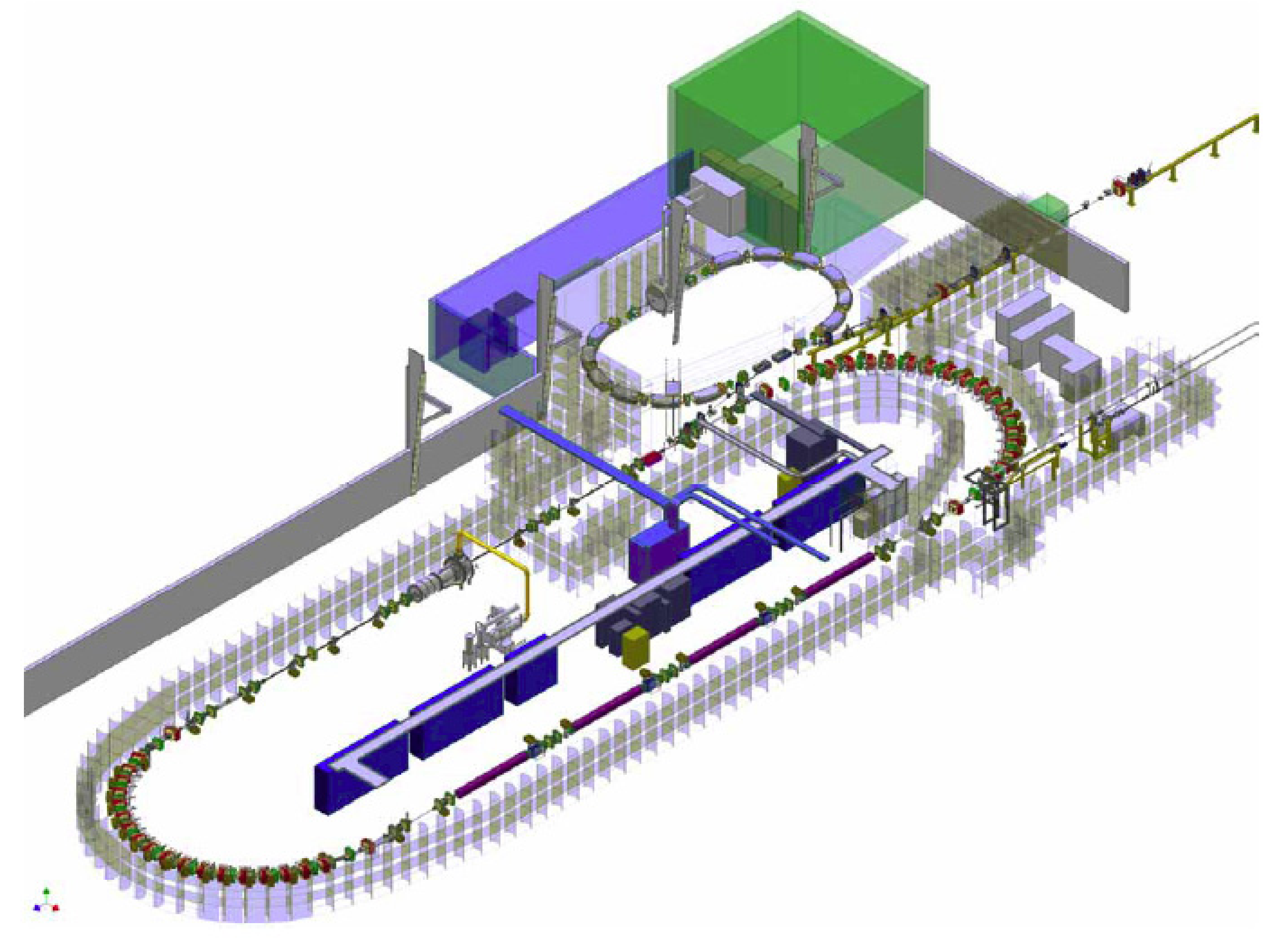
FEL linewidth narrowing with intracavity glass plate



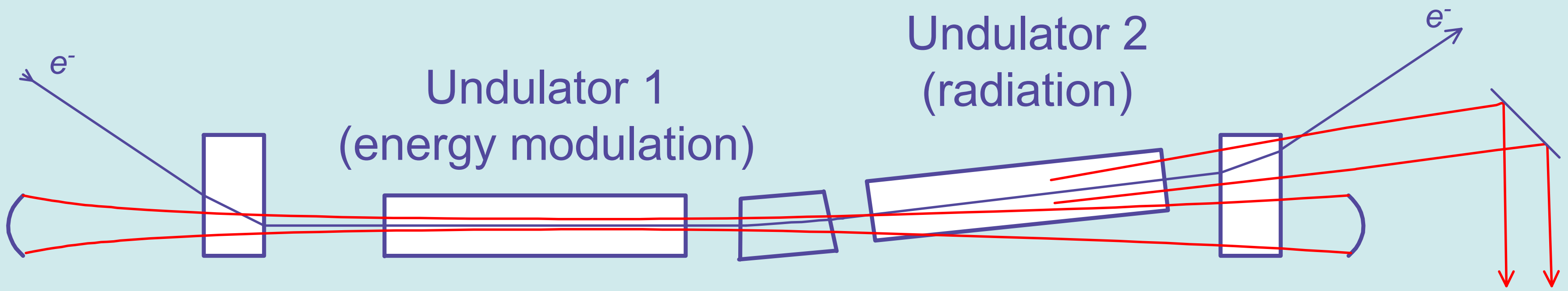
FEL linewidth $3 \cdot 10^{-6}$



Duke University FEL-based High Intensity Gamma-ray Source use the FEL intracavity radiation for the back Compton scattering.



Schematic diagram of electron outcoupling



Why electron outcoupling?

- lower load on optical cavity mirrors
- wavelength tunability (high power partially transparent mirrors have narrow band)

Electron outcoupling and Young experiment with two undulators

coherent radiation that passes around the front mirror of the optical cavity and exits the cavity. To conserve

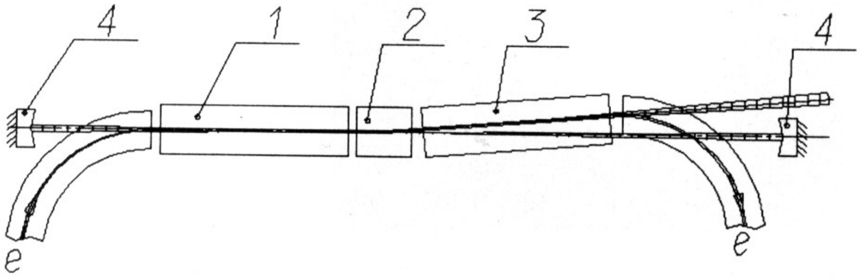


Fig. 1. Electron extraction of radiation: 1 – magnetic FEL system, 2 – bending magnetic system, 3 – additional undulator, 4 – mirrors of the optical cavity.

the bend is the same as the coherence condition for spontaneous radiation from two undulators, with one positioned before the bend, and the other after it [2]. In view of this, and to check experimentally the feasibility of the "electron extraction" scheme [3], we have em-

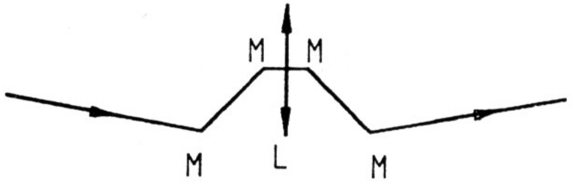


Fig. 2. A schematic view of the achromatic bend: *M* – bending magnets, *L* – lens.

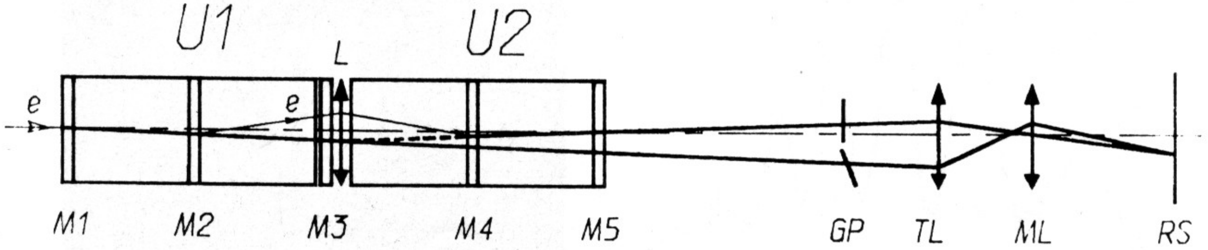
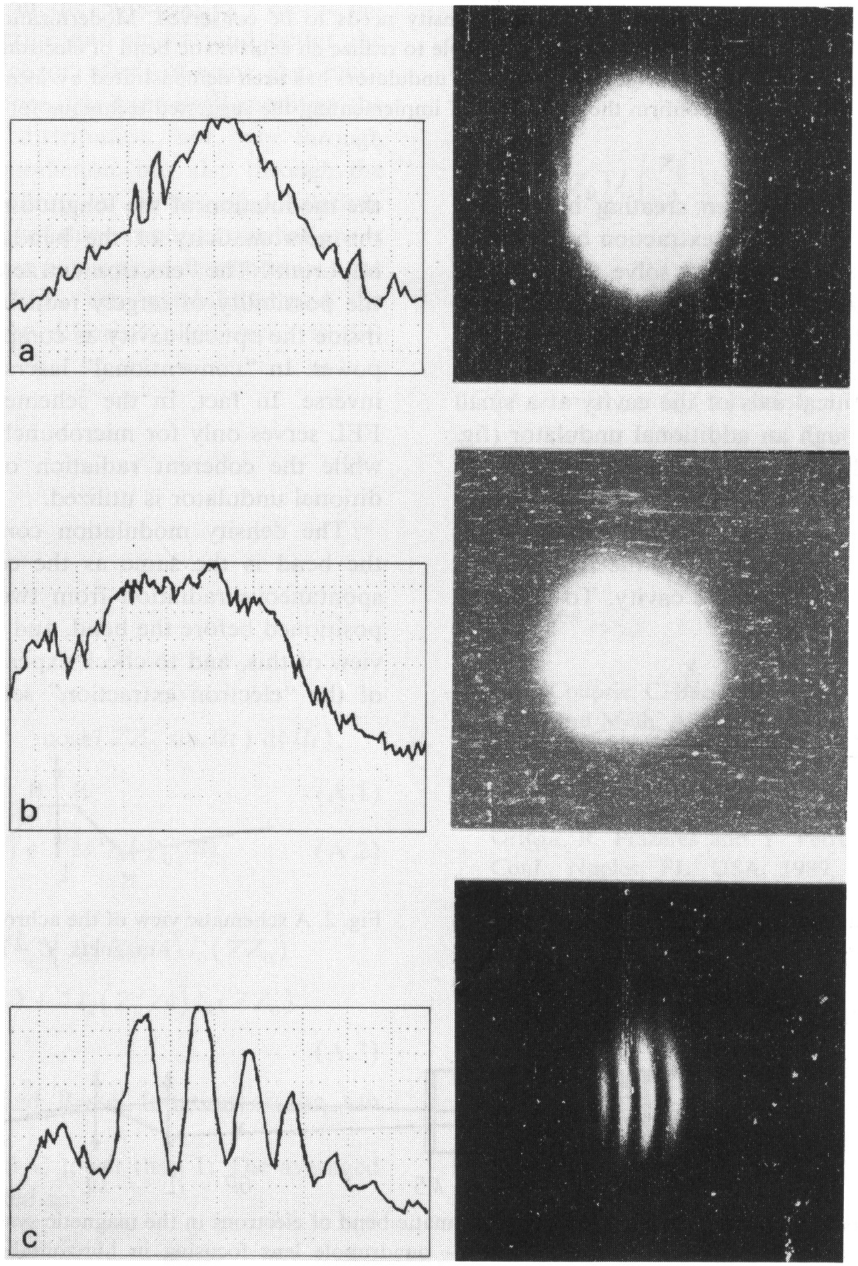


Fig. 3. The scheme to observe radiation coherency at the achromatic bend of electrons in the magnetic system of the optical klystron on VEPP-3: *M*1–*M*5 – horizontal bending correctors; *L* – quadrupole lens focusing in horizontal direction; *U*1 and *U*2 – undulators of the OK magnetic system; *TL* and *ML* – optical telescope lens and imaging lens respectively; *RS* – registering screen (Micrat or a one-dimensional CCD structure).

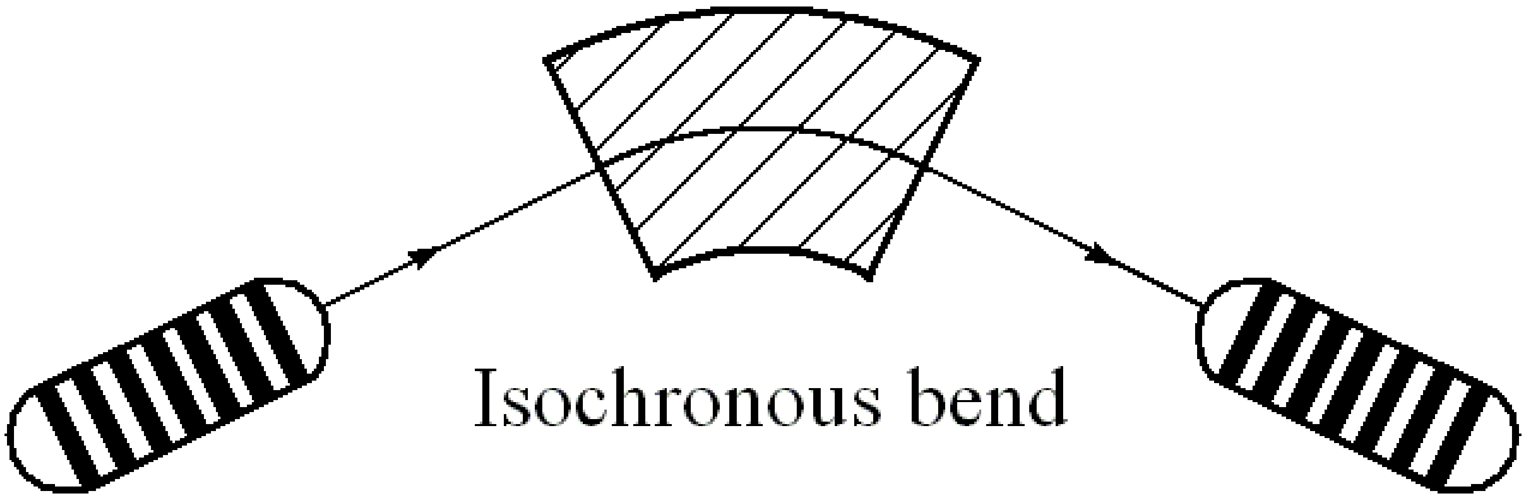


ctures observed at a conventional (nonachromatic) bend (*a*), at an achromatic bend
nd with the delay compensation (*c*) (registered by Micrat on the right and by a CCD struct

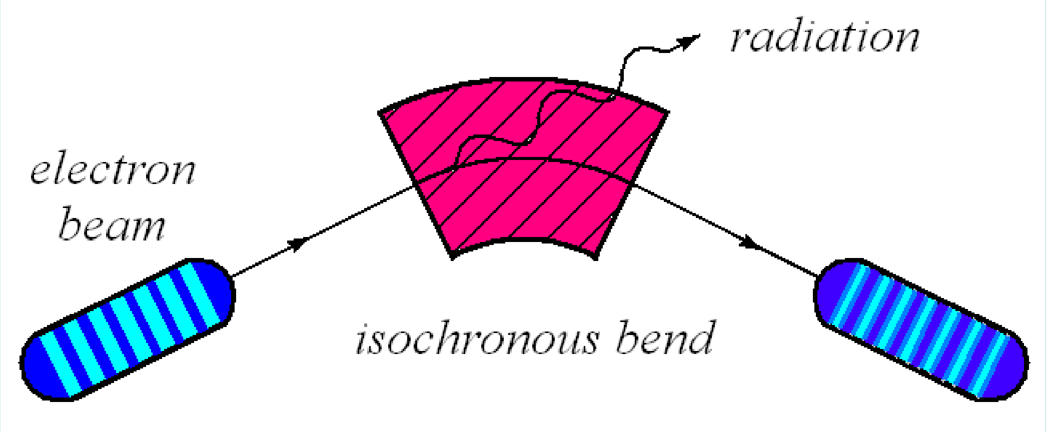
Interference pictures, observed at

a) non-achromatic bend,
b) achromatic bend without delay compensation,
c) achromatic bend with delay compensation.

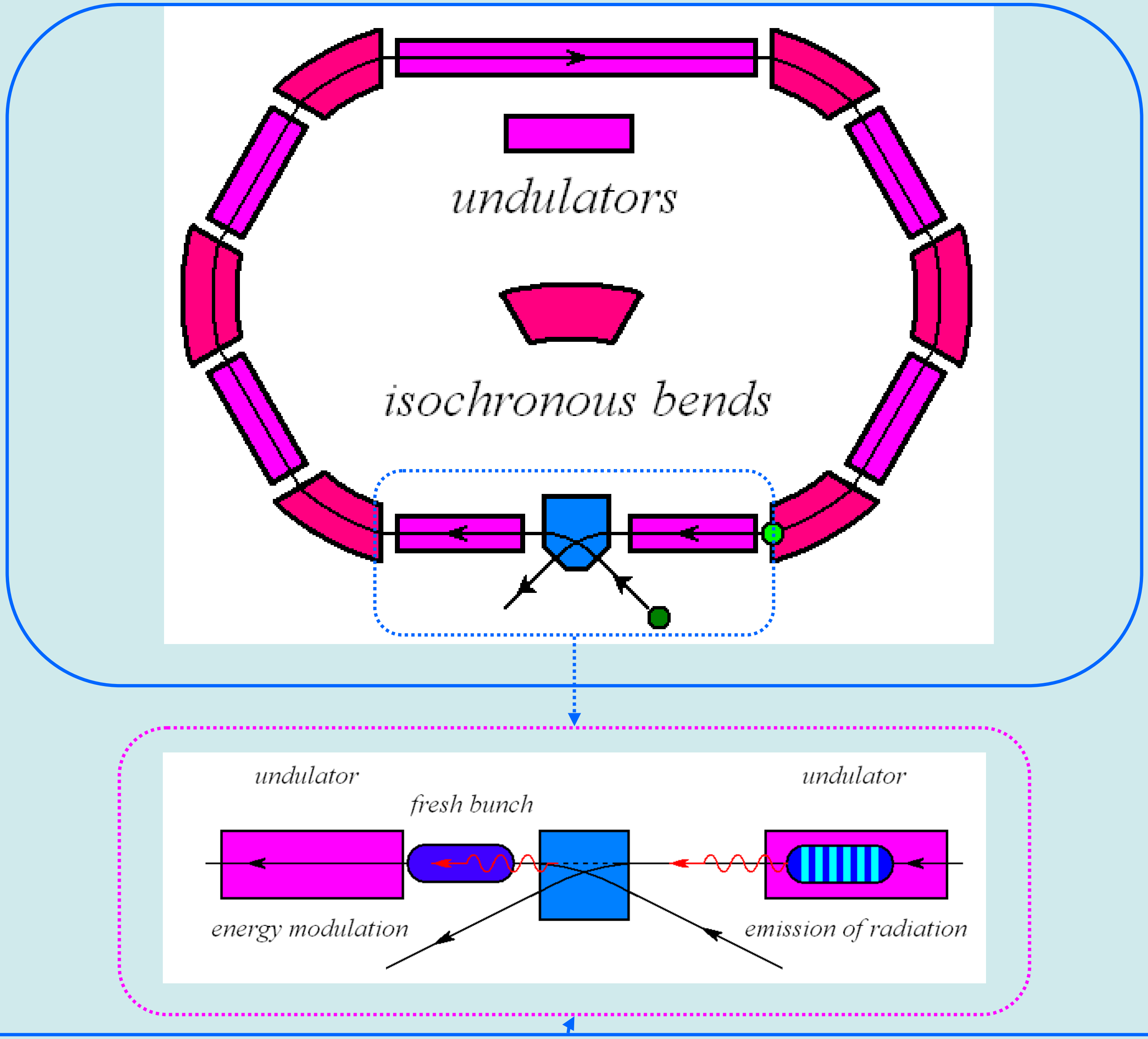
Conservation of microbunching in the isochronous bend



General scheme and principles of operation of ring FEL



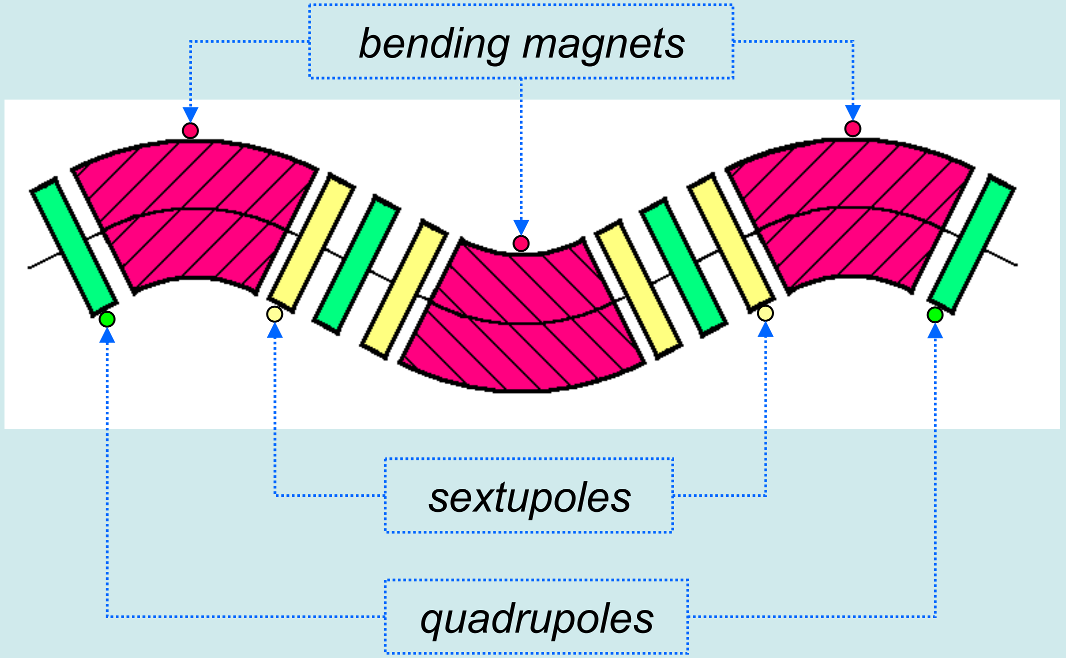
The beam microbunching is partly conserved in the isochronous bend



Signal from the old bunch to the fresh one is transferred by radiation

Lattice of isochronous bends

Typical lattice of short isochronous bend

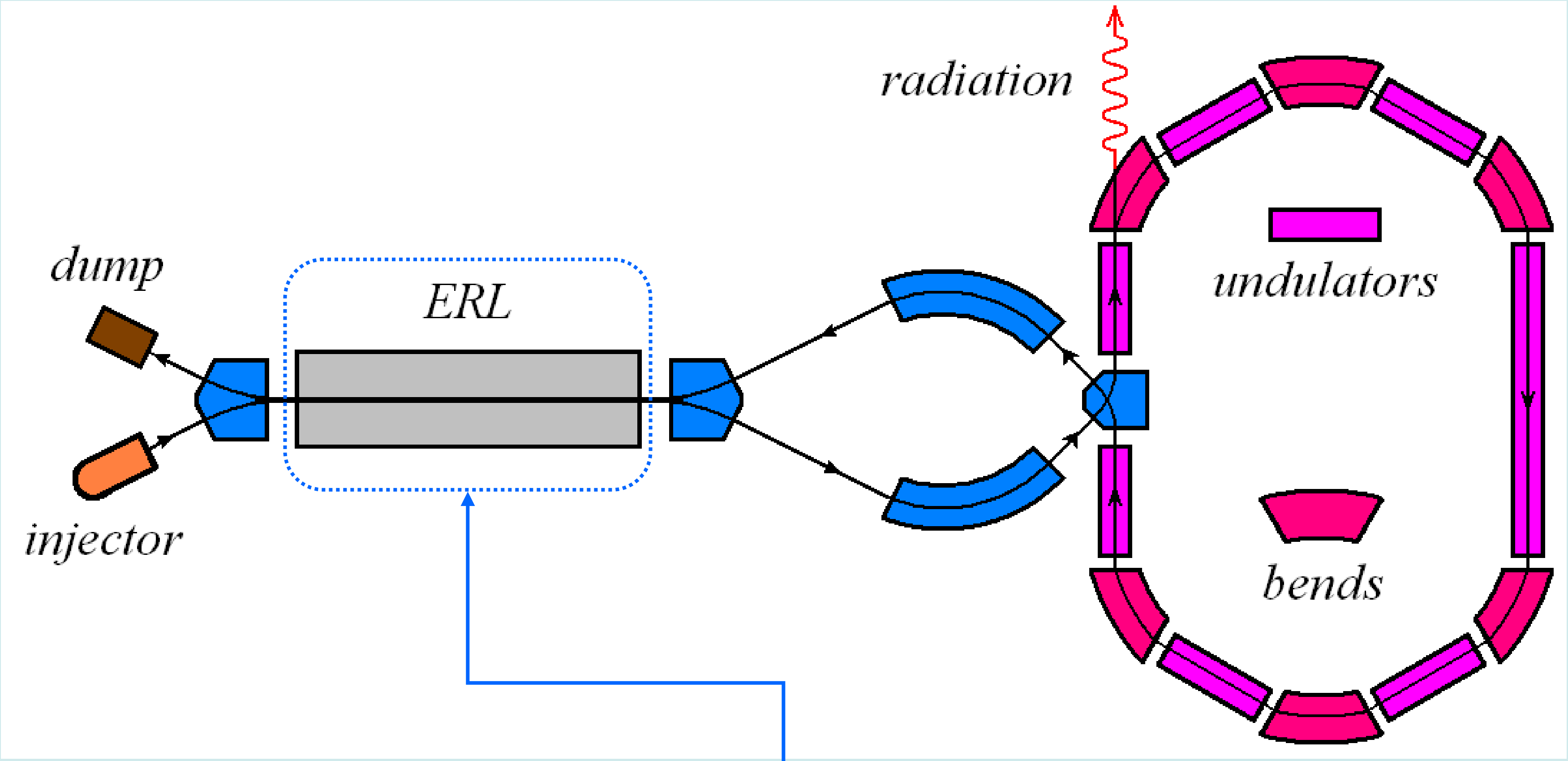


bending magnets

sextupoles

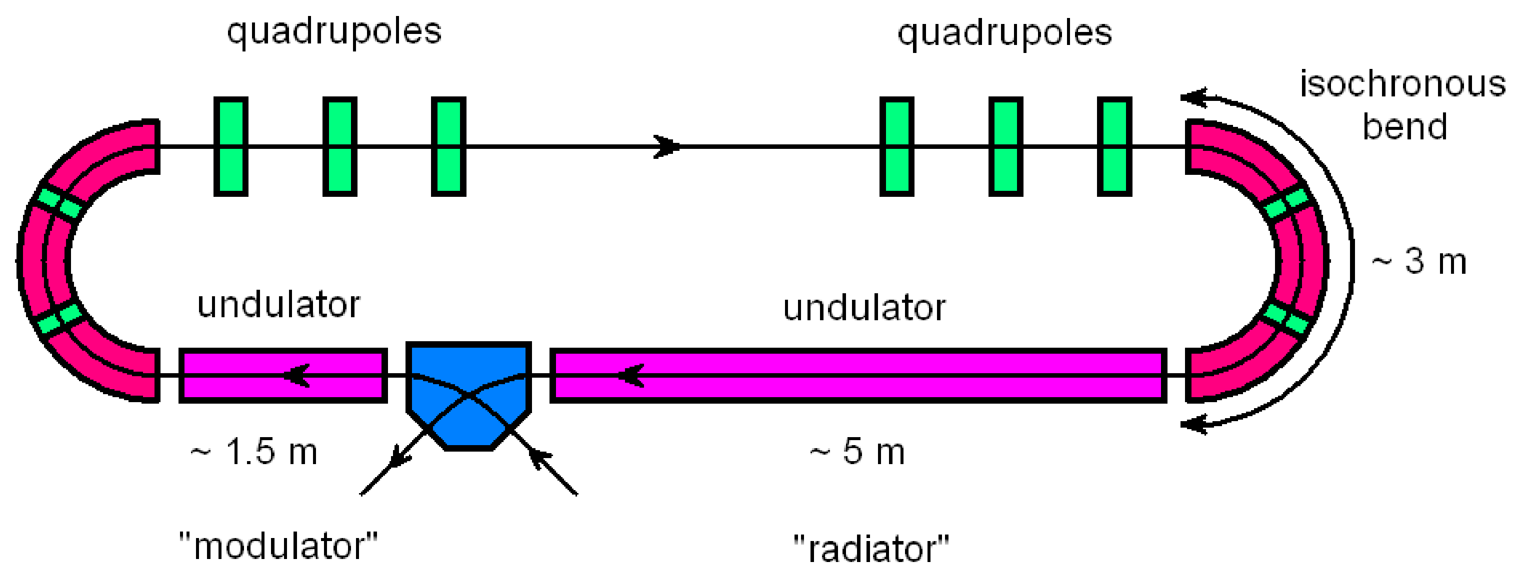
quadrupoles

Second order aberrations are compensated by sextupoles



Ring FEL requires ERL as a source of electron beams, as the average beam power can be very high.

Possible layout of the infrared ring FEL



Novosibirsk high power THz FEL

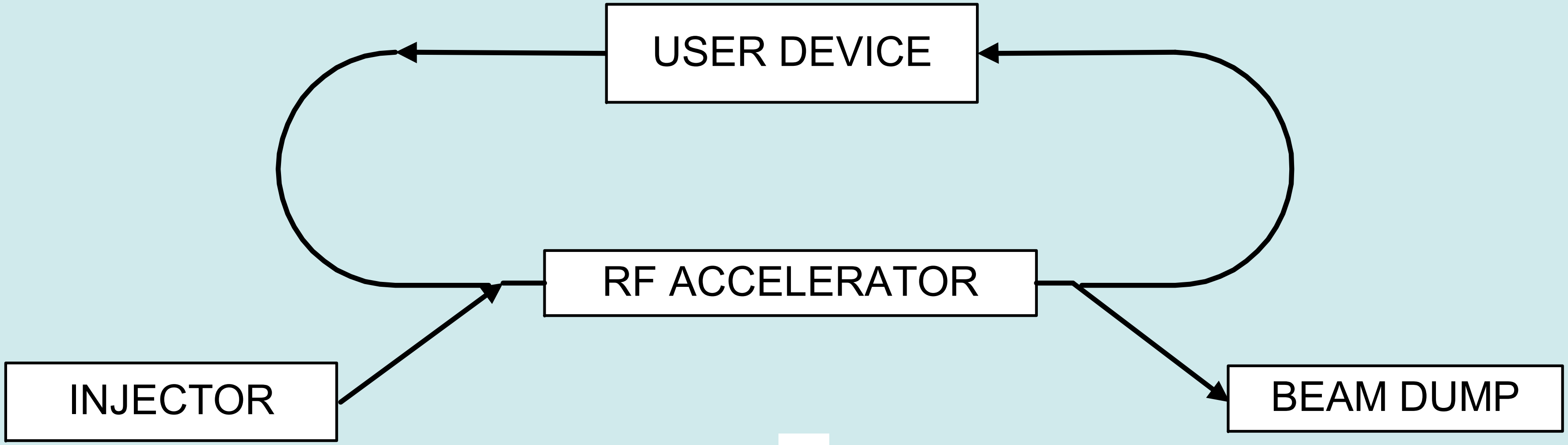
Electron efficiency of FEL is rather low (~1%), therefore energy recovery is necessary for a high power FEL.

Energy recovery

- **decreases radiation hazard and**
- **makes possible operation at high average current.**

Energy recovery linacs (ERLs)
with the same-cavity energy recovery

a



b

Problems: a – colliding beams, b – focusing of two beams with different energies in the RF accelerator.

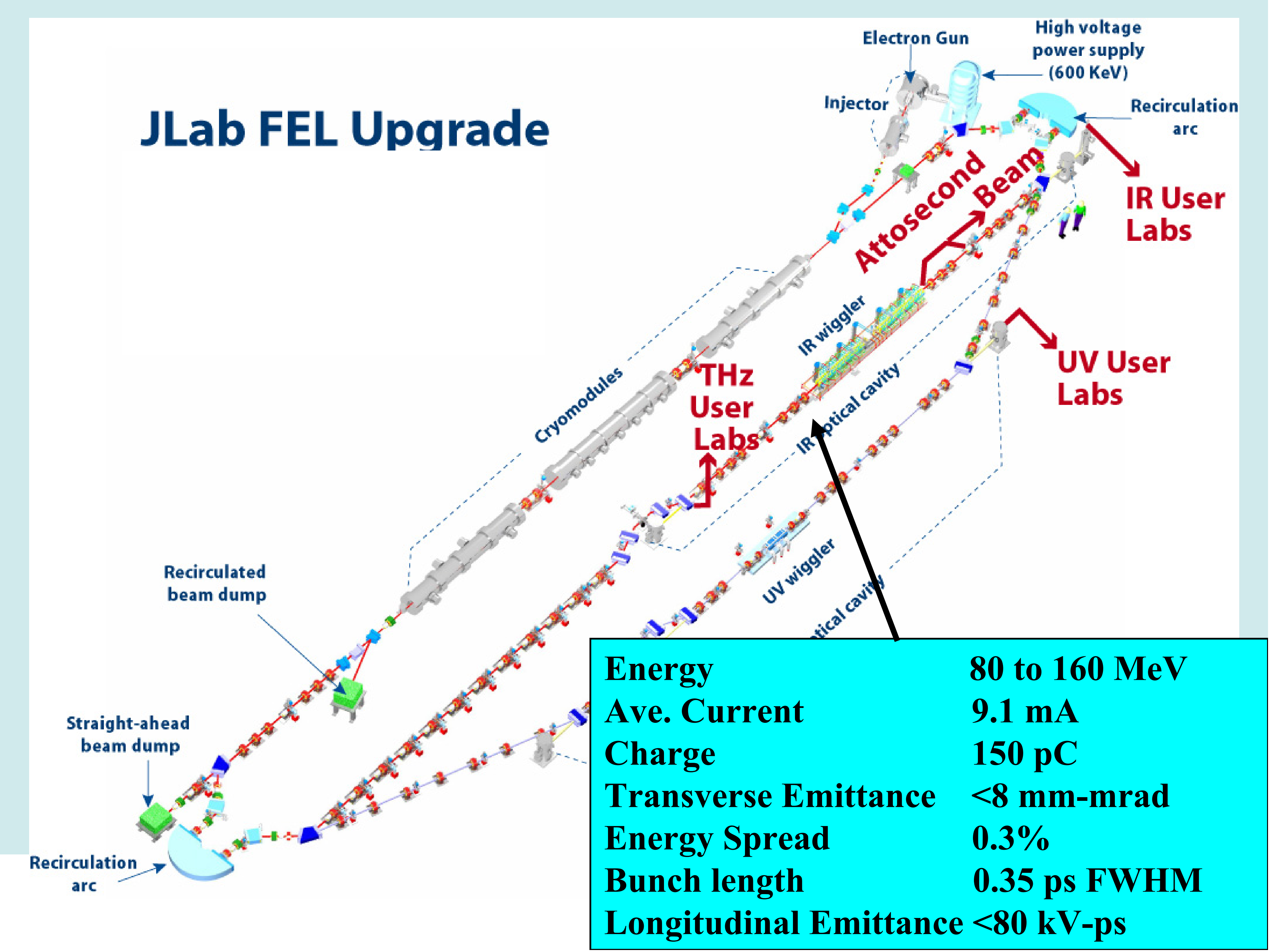
ERLs for FELs

3 ERLs are in operation now. All they works for FELs.

Jefferson Lab. (USA) and JAERI (Japan) ERLs use superconducting RF.

Novosibirsk ERL uses normal-conducting RF. It is the only one with two orbits (two accelerations and two decelerations).

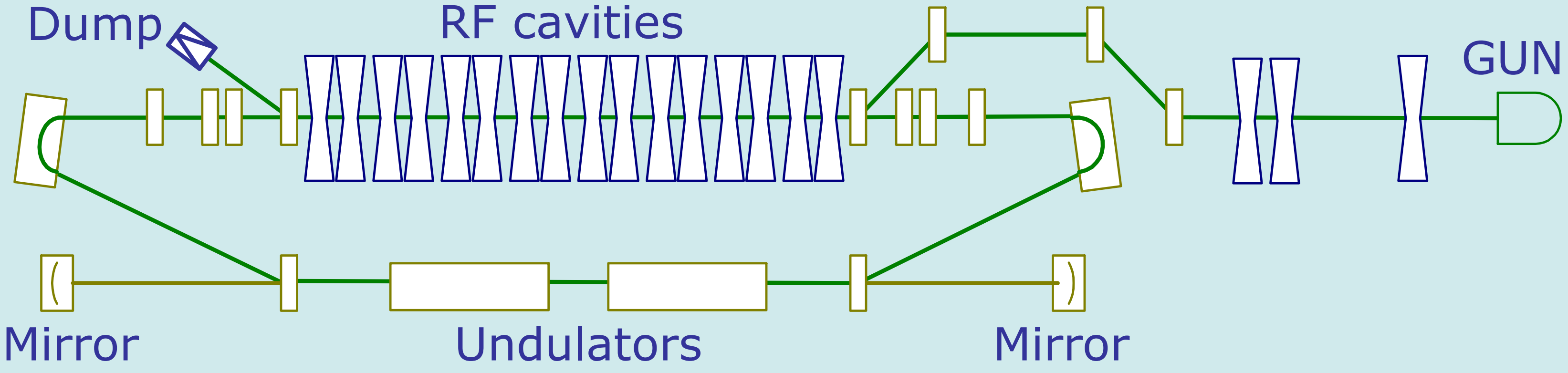
JLab FEL Upgrade



Energy	80 to 160 MeV
Ave. Current	9.1 mA
Charge	150 pC
Transverse Emittance	<8 mm-mrad
Energy Spread	0.3%
Bunch length	0.35 ps FWHM
Longitudinal Emittance	<80 kV-ps

Siberian center of photochemical research

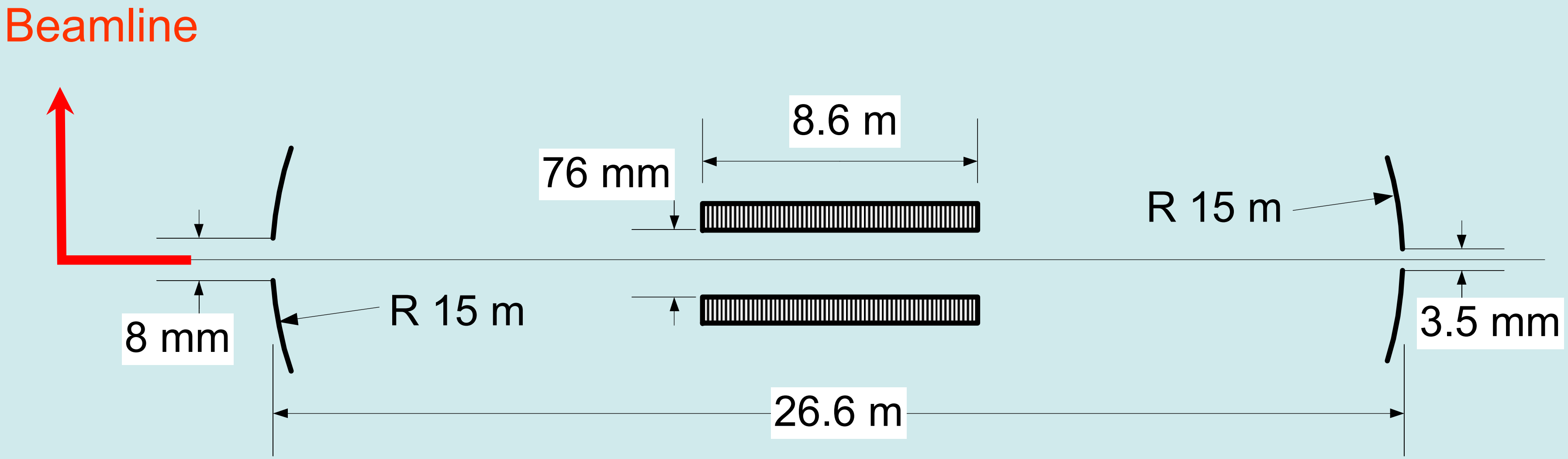
First stage: submillimeter (THz) FEL



Electron beam from the gun passes through the bunching RF cavity, drift section, two 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.

Layout of the optical resonator

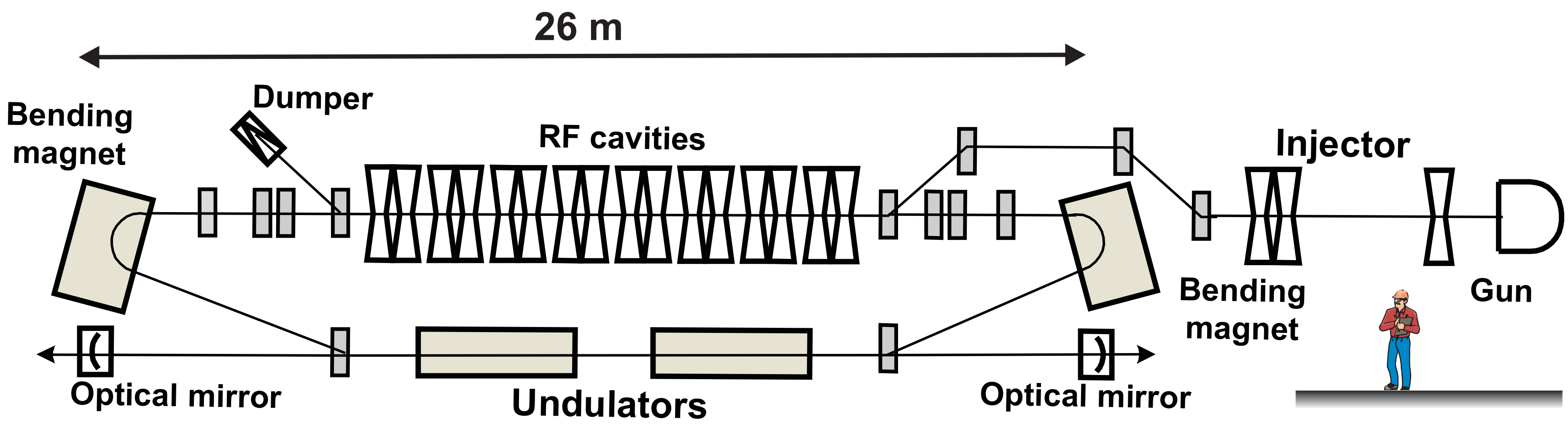


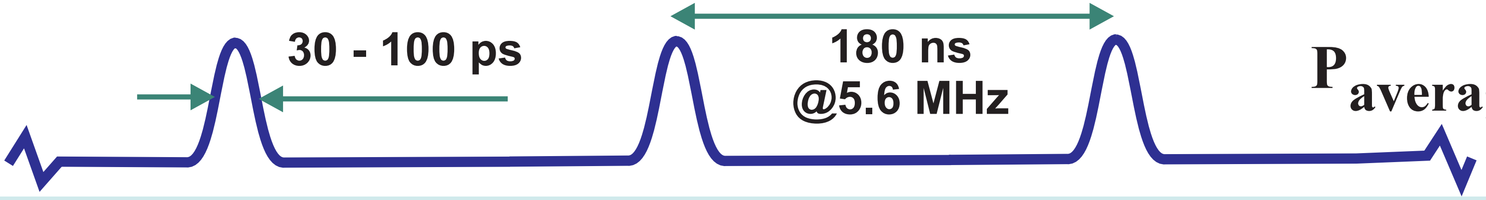
THz FEL (old)

Free Electron Laser (old) Parameters

◆ Wavelength, mm	0.12-0.24
◆ Pulse duration, FWHM, ps	~50
◆ Pulse energy, mJ	0.04
◆ Repetition rate, MHz	11.2
◆ Average power, kW	0.5
◆ Peak power, MW	1
◆ Minimum relative linewidth, FWHM	$3 \cdot 10^{-3}$

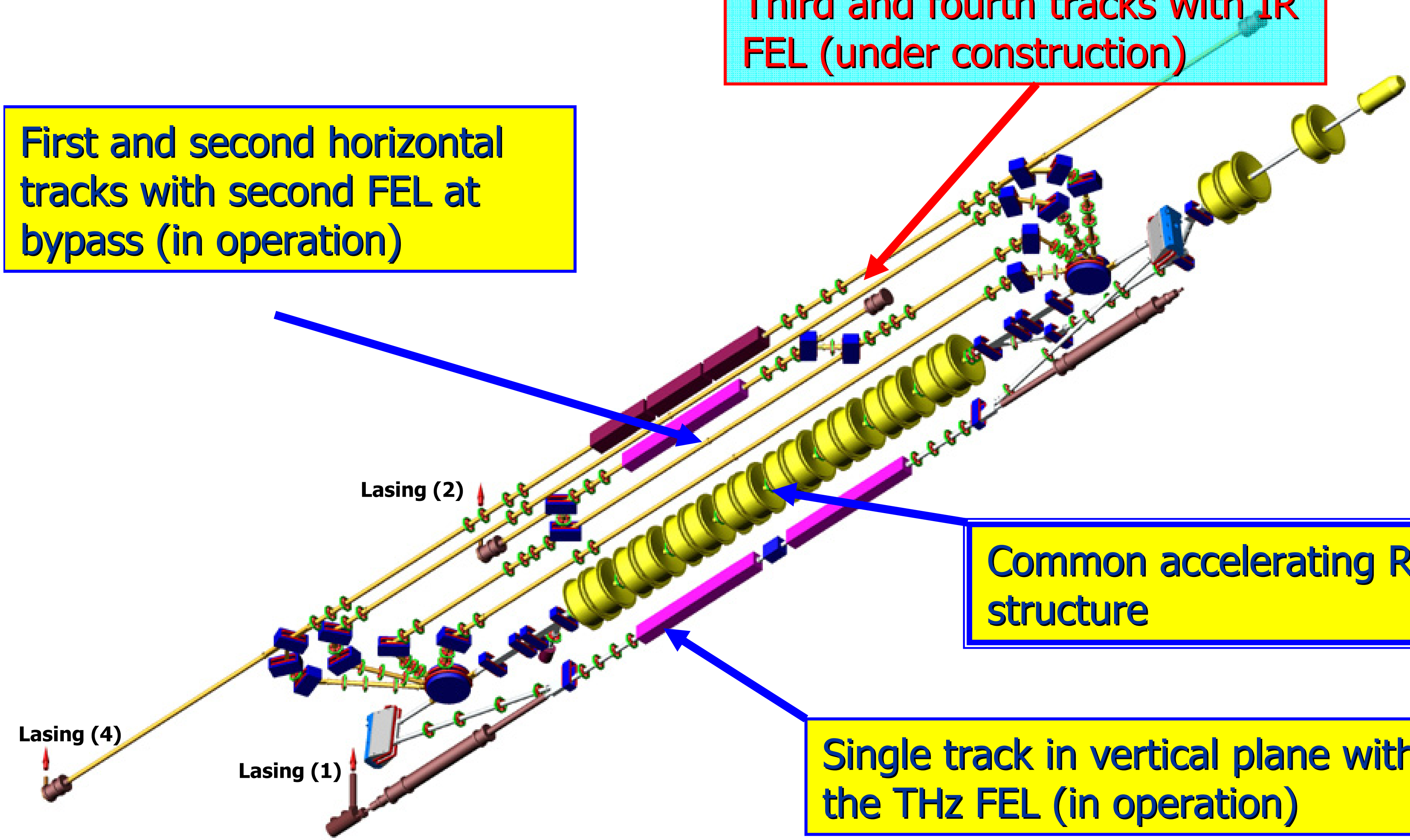
Novosibirsk FEL (1st stage) and radiation power time-dependence





$P_{average} \leq 0.4$ kW

Novosibirsk ERL with 3 FELs



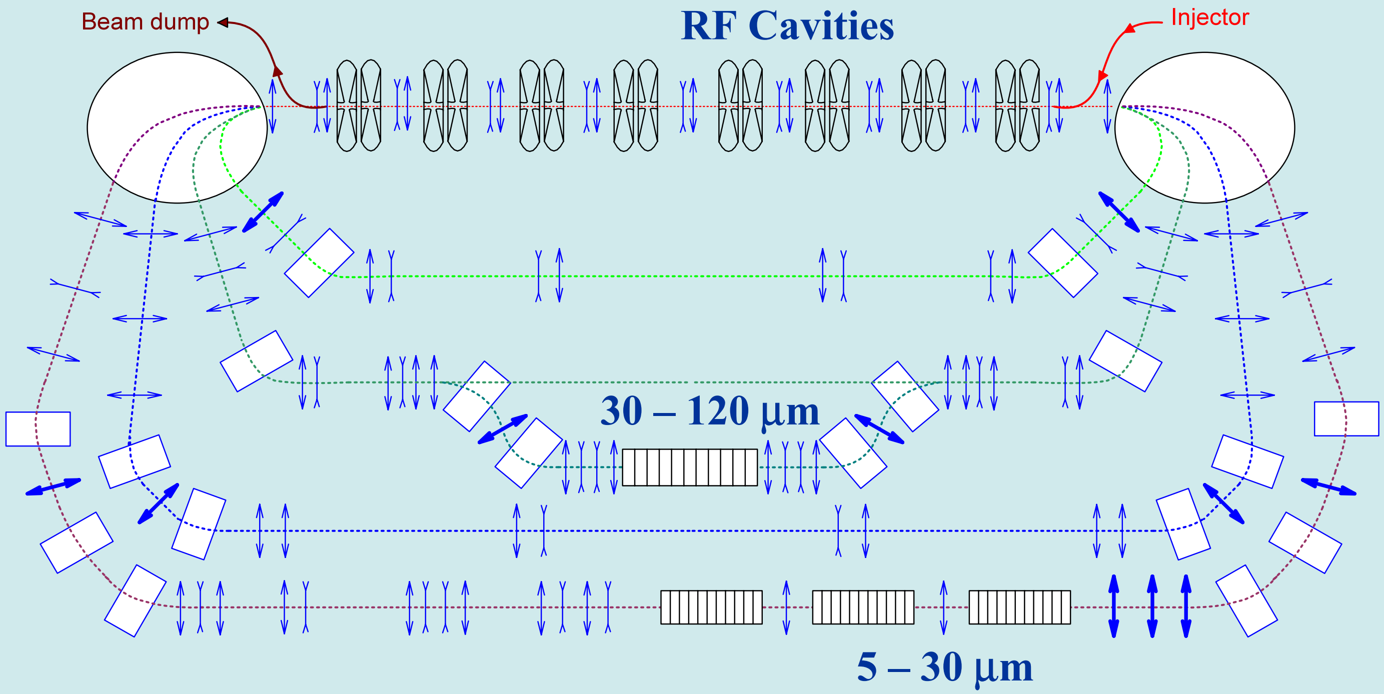
Third and fourth tracks with IR FEL (under construction)

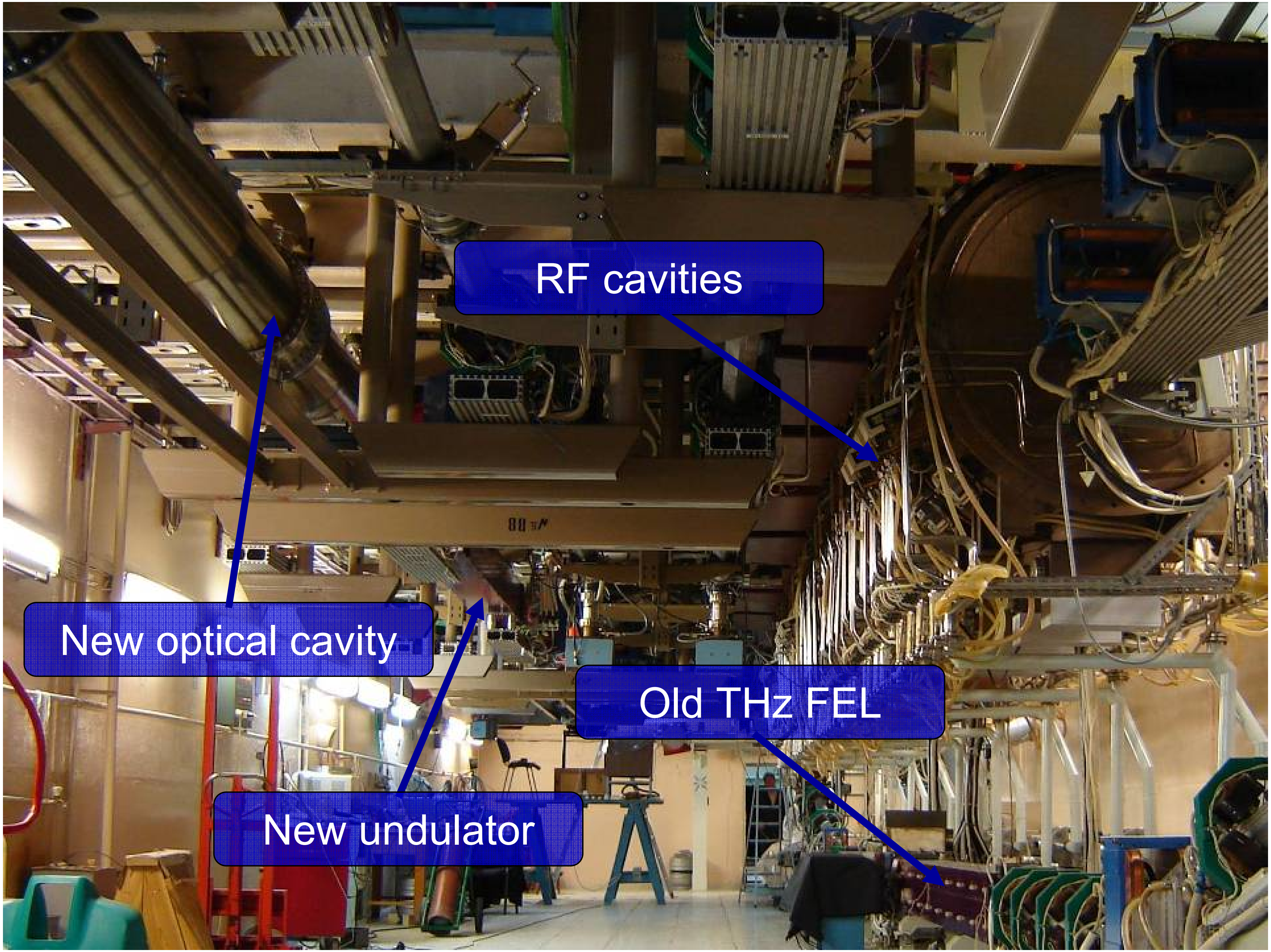
First and second horizontal tracks with second FEL at bypass (in operation)

Common accelerating RF structure

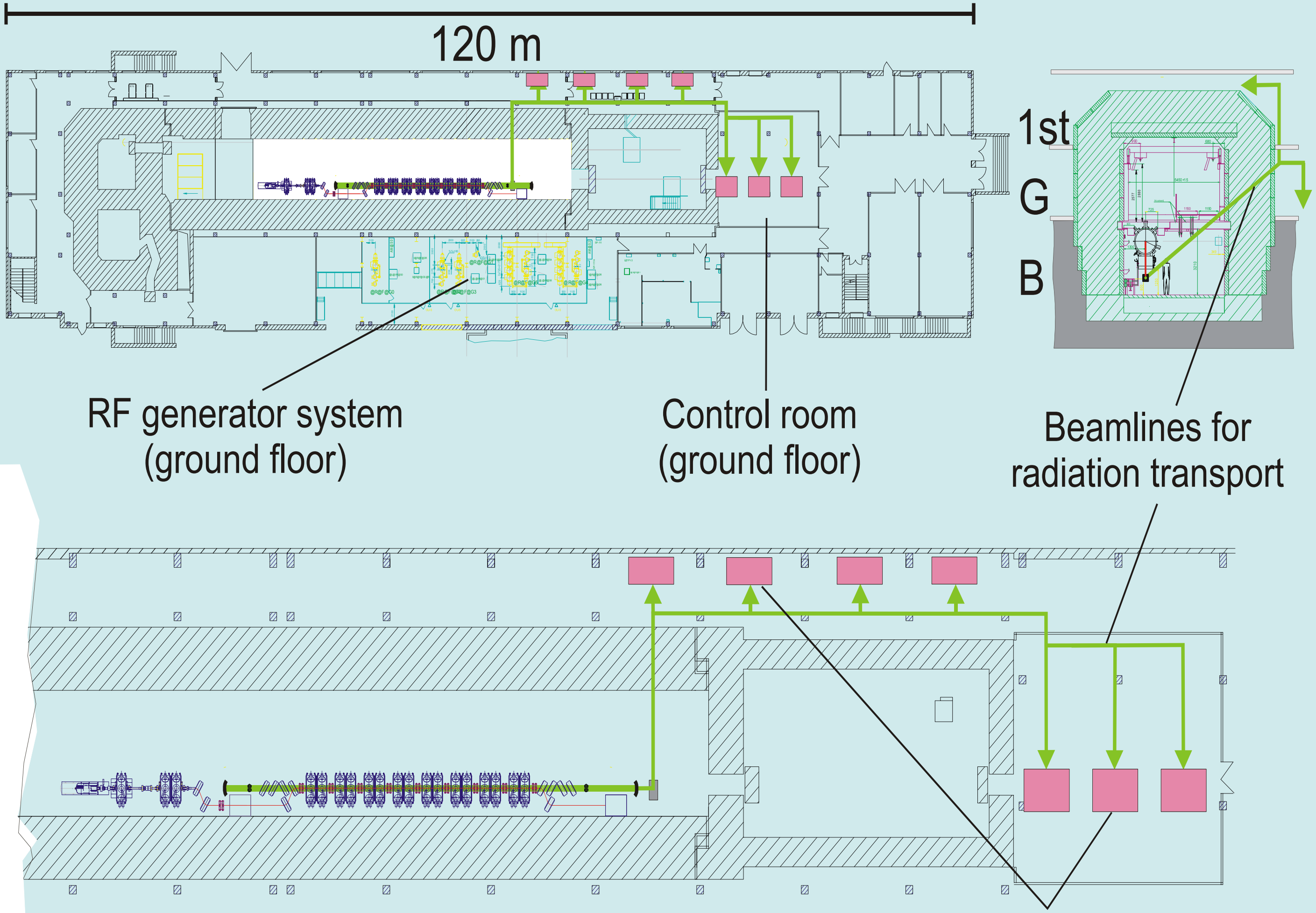
Single track in vertical plane with the THz FEL (in operation)

2-nd stage Novosibirsk FEL (in horizontal plane)




RF cavities
New optical cavity
Old THz FEL
New undulator

Layout of terahertz FEL and user stations



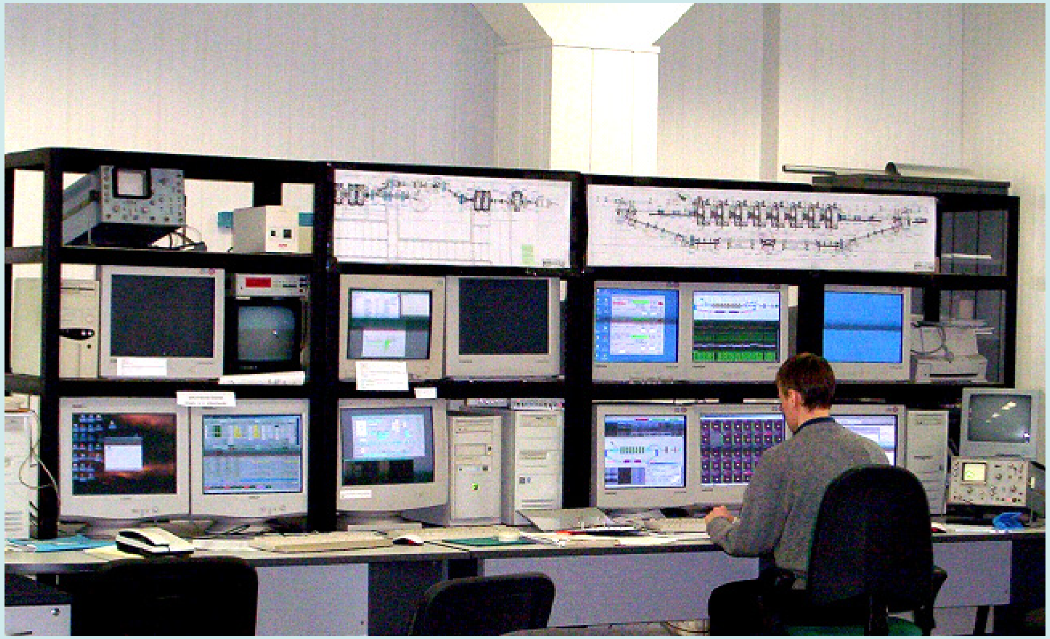
RF generator system
(ground floor)

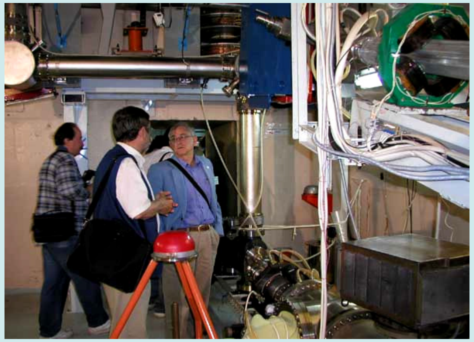
Control room
(ground floor)

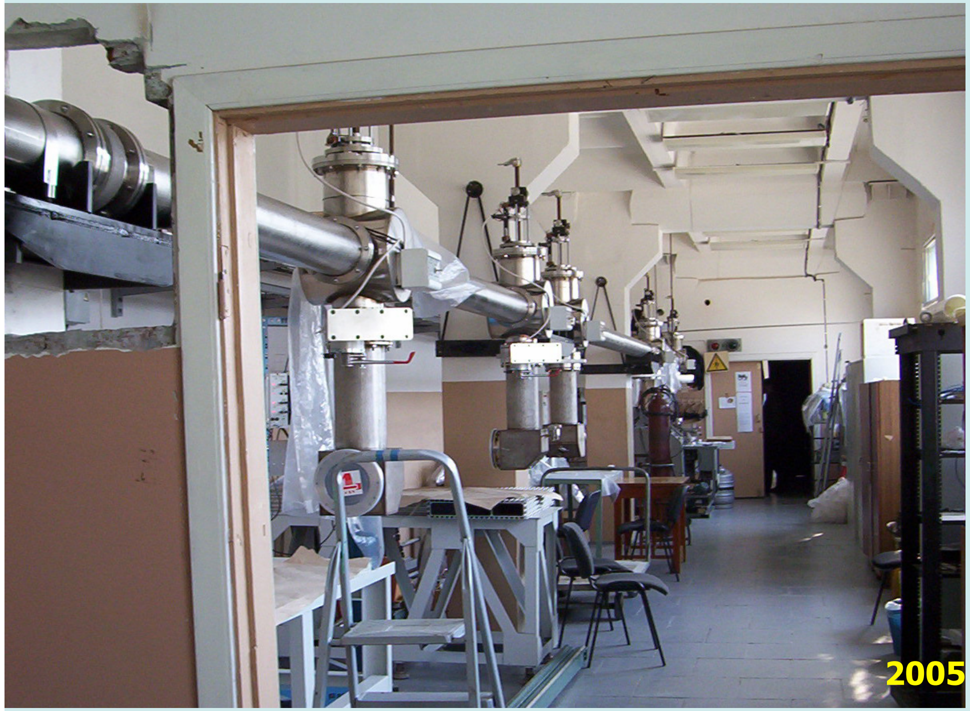
Beamlines for
radiation transport

Accelerator-recuperator and
Terahertz free electron laser (basement level)

User Stations
(ground and first floors)

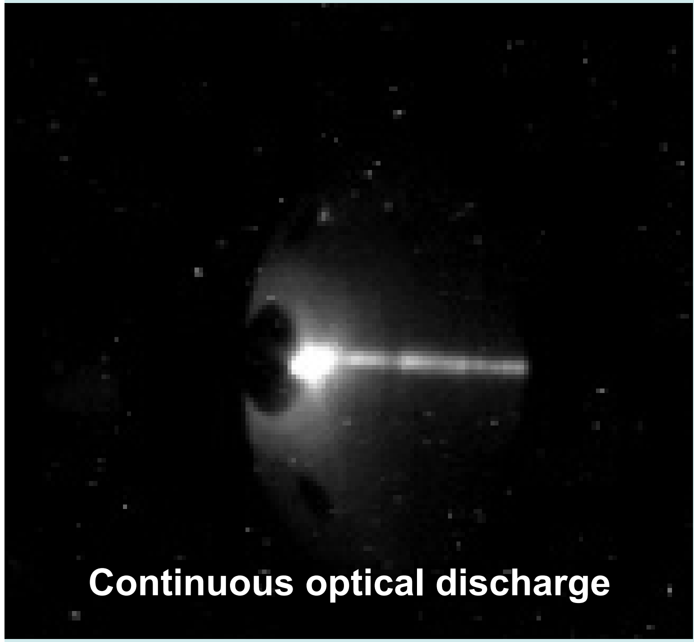


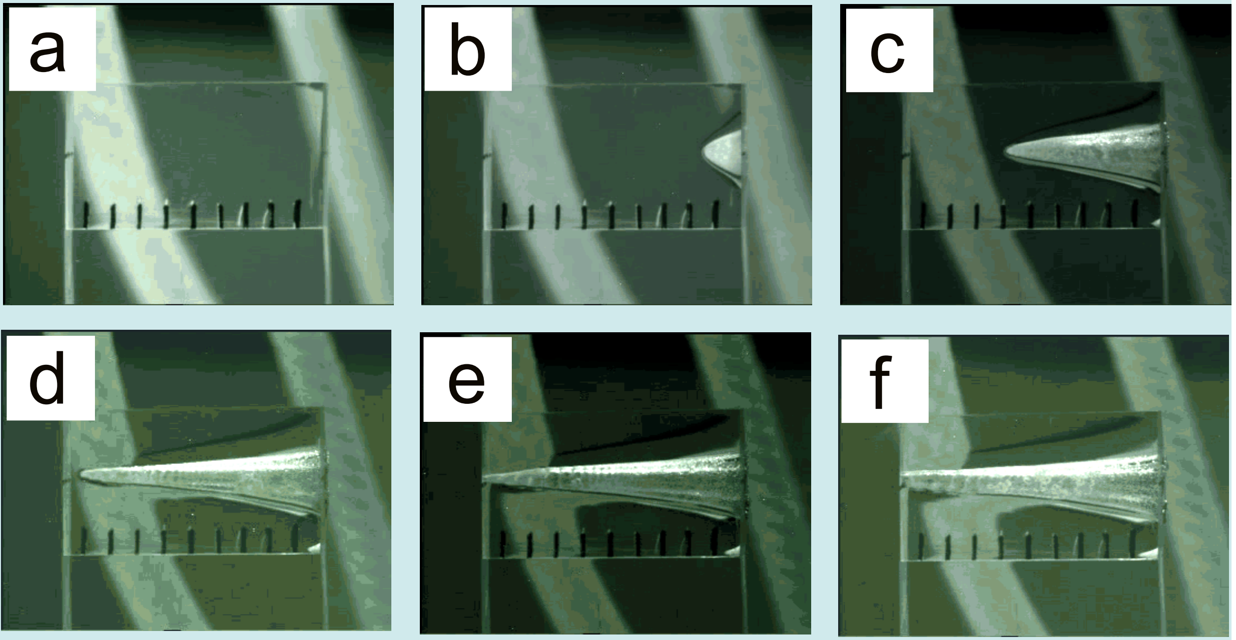



2005


2006

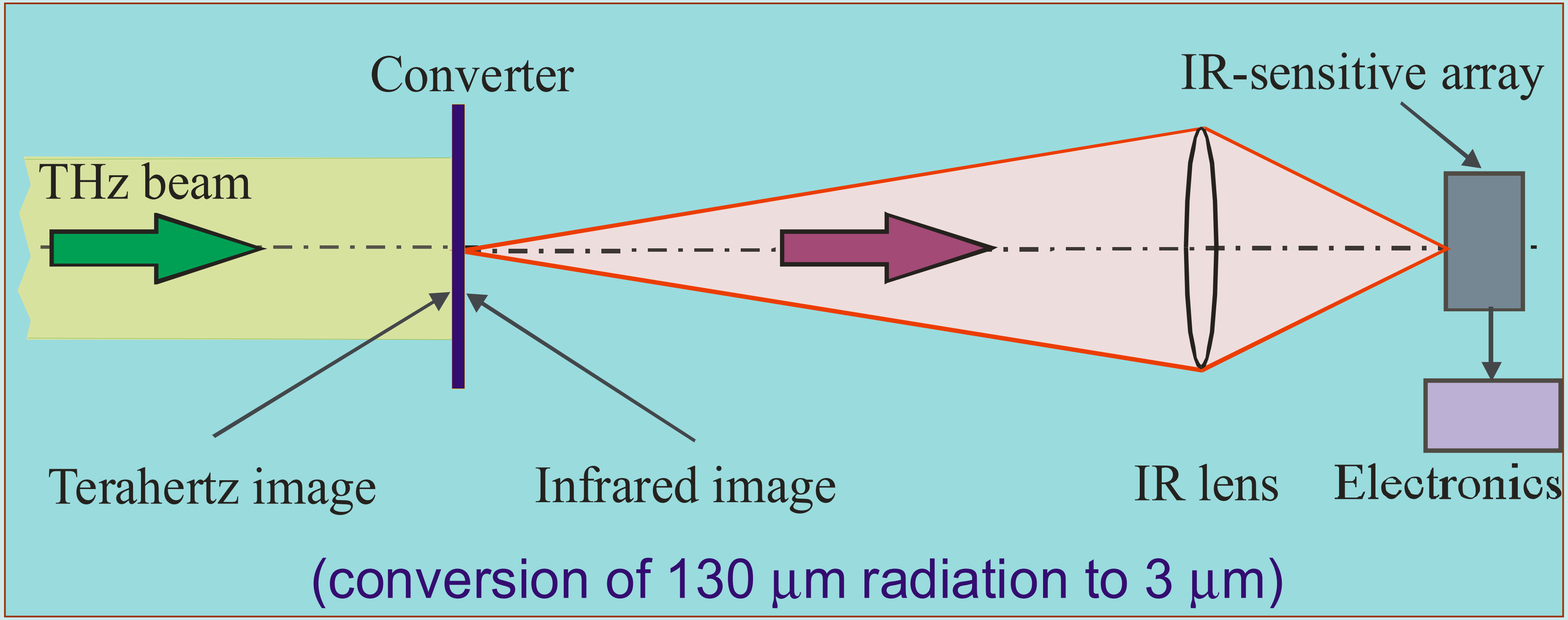
High average power of radiation (up to 500 W) in combination with high peak power (up to 1 MW) enables performing high power density experiments


Continuous optical discharge



- ❑ Laser beam focused in the atmosphere with a parabolic mirror (f=1.0 cm) ignites a continuous optical discharge.
- ❑ Unfocused laser beam drills an opening in 50-mm organic glass slab within three minutes (ablation without burning).
- ❑ These fenomena can be used for many fundamental and applied experiments (plasma physics, aerodynamics, chemistry, material processing and modification, biology…)

THz imaging with an IR thermograph



(conversion of 130 μm radiation to 3 μm)

- Converter of THz radiation is a carbon paper
- Time resolution is limited by thermal relaxation time (about 1 sec for this screen)
- Converters with fast relaxation time are under consideration

Liquid nitrogen cooled 124x124 thermal recorder

Keys in an opaque paper envelope

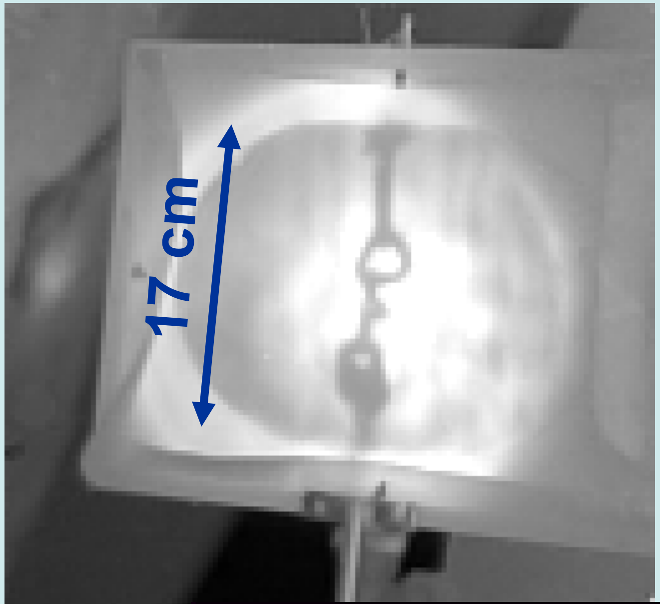
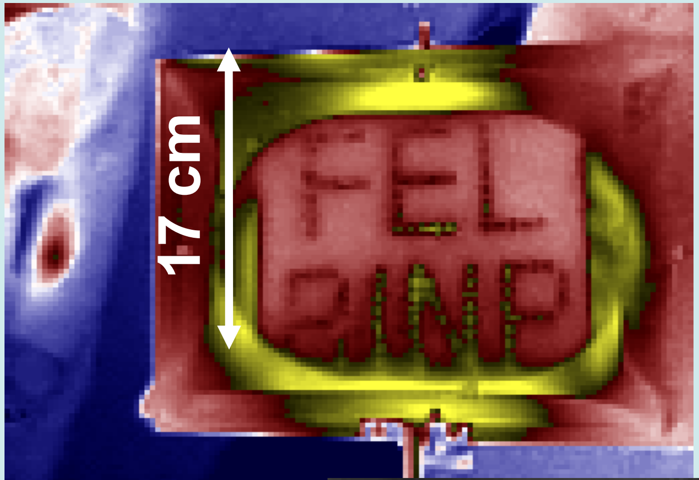
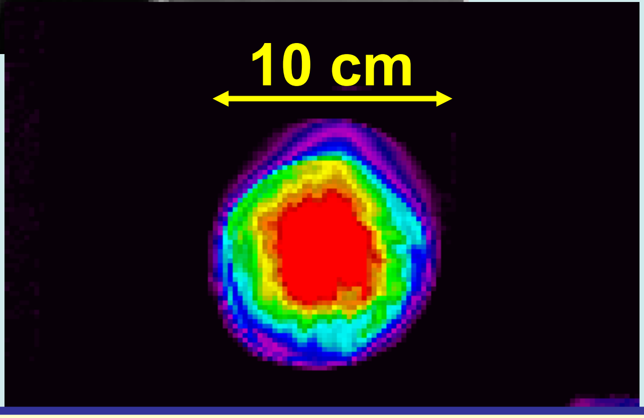


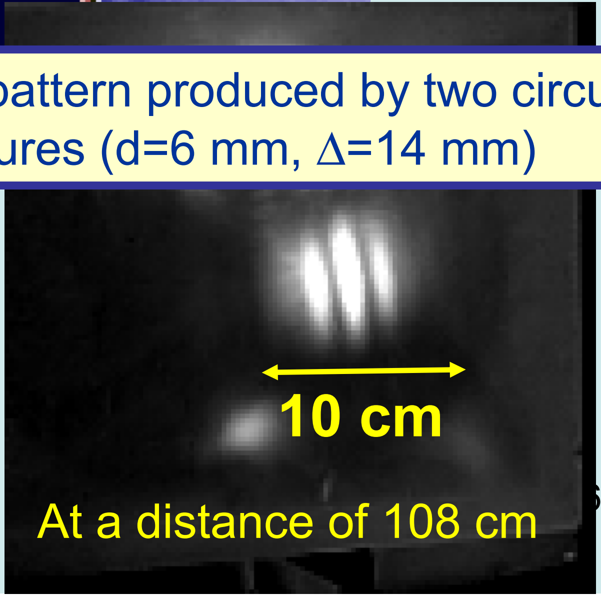
Image of 6-mm holes drilled in a metal plate (“FEL BINP” letters)





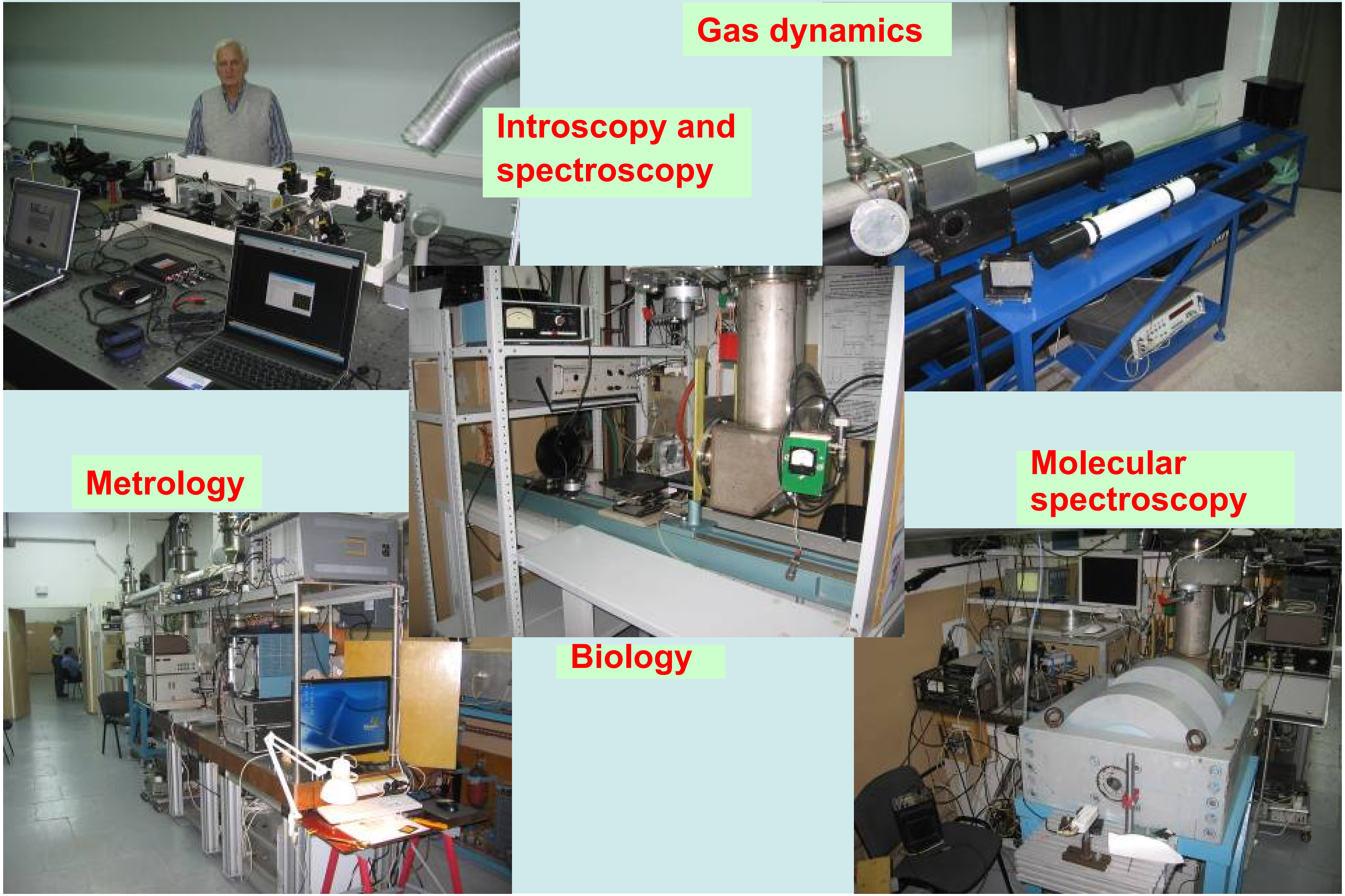
THz laser beam cross-section at the beamline output (13 meters from the laser)

Diffraction pattern produced by two circular apertures (d=6 mm, Δ=14 mm)



At a distance of 108 cm

User stations at NovoFEL



Introscopy and spectroscopy

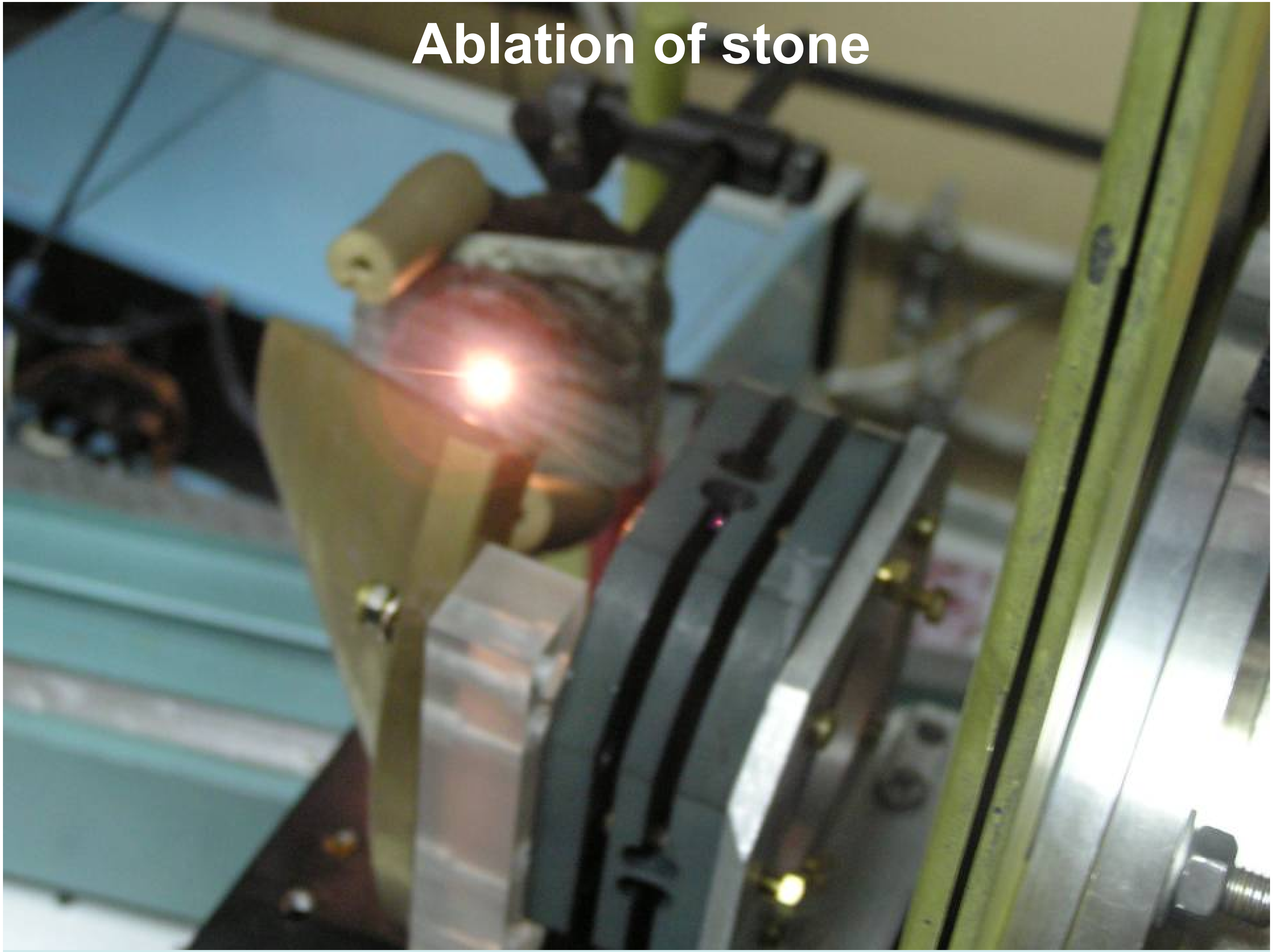
Gas dynamics

Metrology

Biology

Molecular spectroscopy

Ablation of stone



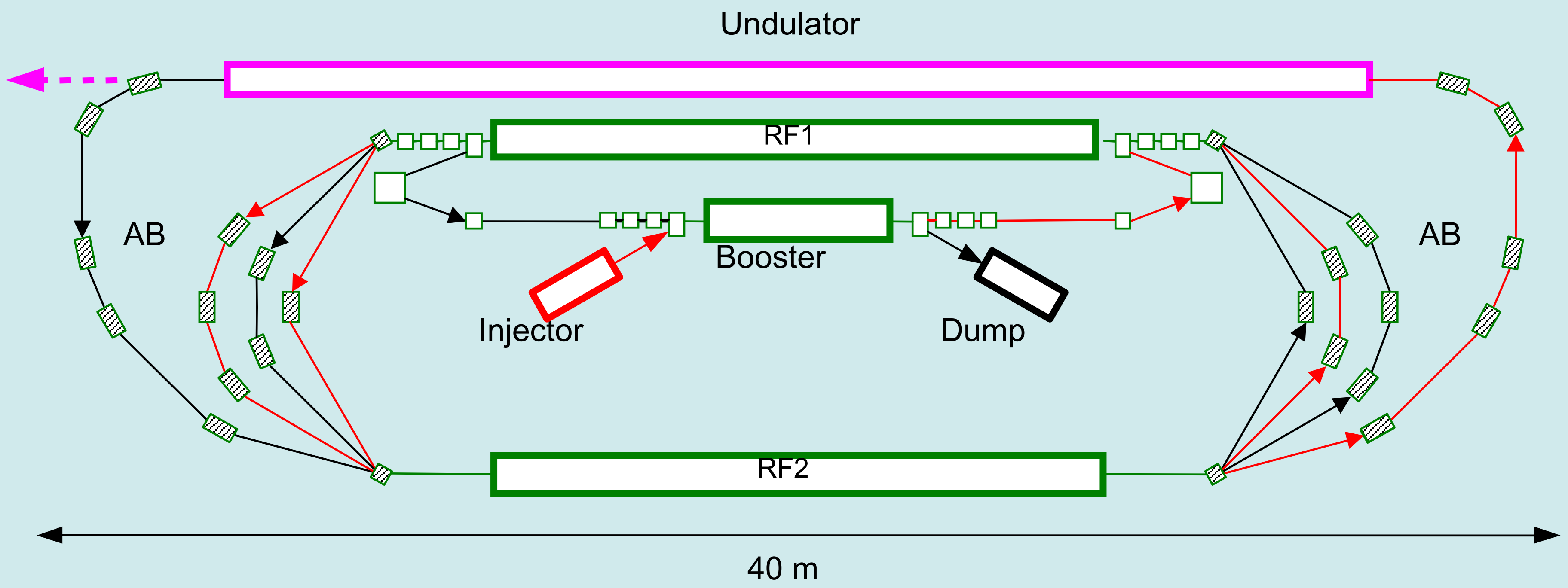
Result of Treatment of Marble by THz Radiation

Status

- Up to 500 W of average power at 110 – 240 and 40 - 80 micron wavelength range is available for users. Linewidth is less than 1%, maximum peak power is about 1 MW.
- Six user stations are in operation.
- We are looking for more users for this unique radiatiion.

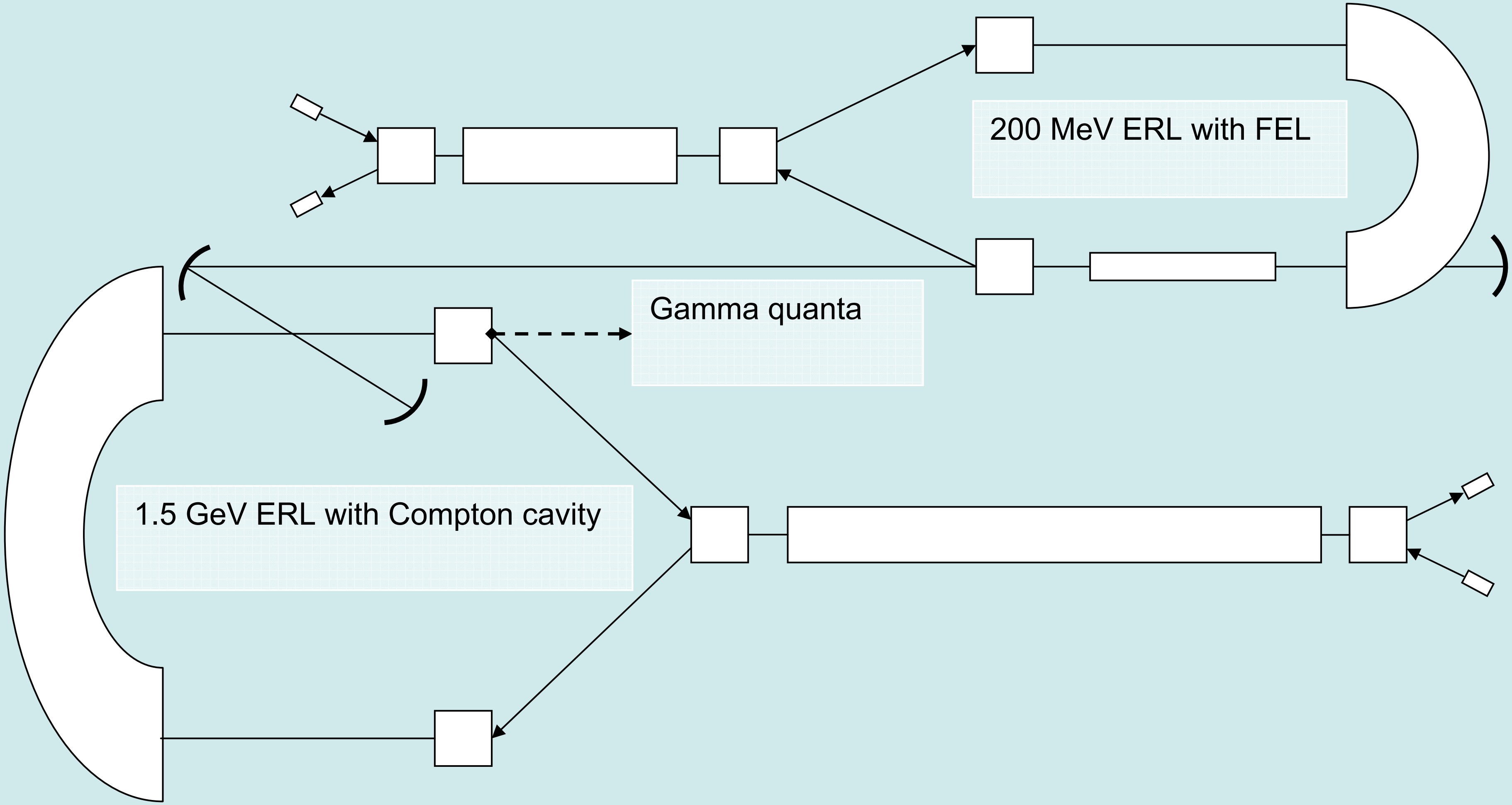
Compact 13.5-nm free-electron laser for extreme ultraviolet lithography

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.

Possible use of FEL for gamma-production (for ILC and nuclear physics)



200 MeV ERL with FEL

Gamma quanta

1.5 GeV ERL with Compton cavity