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Energy Recovery Linacs as Drivers for Advanced Light Sources

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Status of MARS-L project of high power FEL and prototype of a diffraction limited X-ray source

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Free electron laser (FEL) are just starting to make a scientific impact on surface science, chemistry, biology and medicine. It is obvious that future contributions will be not only to basic science but also to various commercial enterprises. During the next five years 10÷100 kilowatt class FEL's are scheduled to be operating. A 100 kW FEL would produce light for about 0.2 cents/KJ, roughly 10^{-2} the cost of light from the excimer laser now used in a few places in industry.

Accelerators - Recuperators

Budker INP

Technological applications of the high-power continuous FEL

- Isotope separation
- Treatment of polymer surfaces
- Transportation of energy to space

Product Groups

Accelerators - Recuperators

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Technological applications of the high-power continuous FEL

Isotope separation:

- The main process is selective multiphoton dissociation of molecules. The region of resonance wavelengths is 2 to 50 microns. The energy in pulse should be not less 0.1 mJ and the monochromaticity should be 10^{-2}... 10^{-4} depending on the reaction type. The maximal pressure (and efficiency) in the reactor is inversely proportional to the radiation pulse duration and can exceed atmospheric pressure at ~10 ps.

- Mass production of stable isotopes:
  - *^{28}Si - thermal conductivity of a pure isotope is higher than that of a natural mixture by 50%. That gives a large advance at manufacture of high-power semiconductor devices and microchips. ^{28}Si is used also in spin electronics, which is the metrology and technics of the future.*
  - *^{13}C - is a spin mark for NMR tomography at development of new medicines and at medical diagnostics.*
  - *^{15}N is also a spin mark for study and running check of consumption of nitrogen fertilizers in agricultural chemistry and agriculture.*

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Technological applications of the high-power continuous FEL

Treatment of polymer surfaces:

- The aim is mechanical (abrupt increase of the surface area) or chemical (transformation of amid groups to amine ones) modification or pyrolysis (transformation to pure carbon) of the surface of polymer films and synthetic fibers.
- New properties:
  - *Higher adhesion of films (mechanical modification) to each other and other surfaces*
  - *Dull surface without mirror reflection. More saturate colors at coloring (mechanical modification)*
  - *Antiseptic properties of surface (chemical modification)*
  - *Conductive surface (pyrolysis)*
- Wavelength ranges: 5.8...6.2 μm (region of carbonyl adsorption) and 180...200 nm (the π - π^* transitions).
- Monochromaticity not worse than $5 \cdot 10^{-3}$ for the UV region and 10^{-2} for the IR one.
- Required exposure is 0.3...30 kJ/m^2 in dependence on the type of the process.
- Required continuous power is 6...600 kW for a 1000 m^2/min line.
- The need is hundreds of facilities for modernization of the world manufacture of polymer films and artificial fibers.

Accelerators - Recuperators

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Technological applications of the high-power continuous FEL

Transportation of energy to space

- At present, artificial Earth satellites (AES) are powered from solar batteries or nuclear reactors. The disadvantages are the restricted power of solar batteries and large mass and ecology hazard of nuclear reactors.
- The alternative is high-power continuous FELs with a 0.84 μm wavelength (the region of atmosphere transparency and maximal efficiency of solar batteries). In this case, density of power flow to solar batteries is many times higher than that from the Sun.
- Fields of application:
  - *Supply of AES during passage of the shadow region.*
  - *Periodical additional supply of energy for climb and correction of orbits of AES.*
  - *Permanent supply of AES at high consumed power.*
  - *Permanent supply of lunar stations.*
- Required power of FEL is from 100 kW to 10 MW in dependence on the field of application. Need in FELs makes up units to tens of facilities all over the Earth surface..

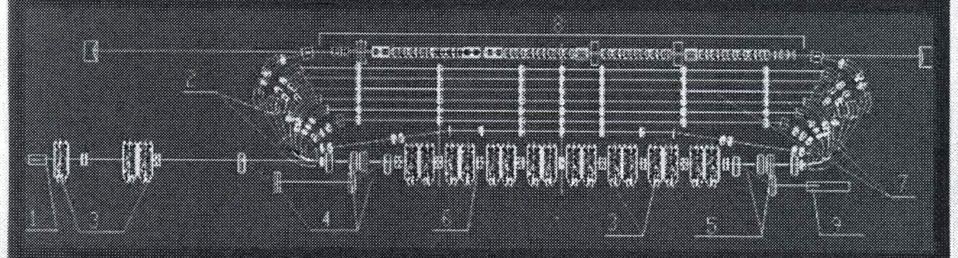

Fig. 2: Scheme of the microtron-recuperator (1 - electron gun, 2 - bending magnets; 3 - RF resonators; 4,5 - injection and outcoupling magnets; 6 - focusing solenoids; 7 -straight sections with the quadrupole lenses; 8 - FEL magnetic system; 9 - beam dump).

RF Accelerator-Recuperator: Basic Parameters

Accelerated beam:

♦ **Bunch repetition rate, MHz**	**up to 22.5**
♦ **Average electron current, mA**	**up to 50**
♦ **Electron energy, MeV**	**up to 100**
♦ **Electron energy spread (relative)**	10^{-3}
♦ **Bunch duration, ps**	**10...20**
♦ **Peak current, A**	**100...200**

RF Accelerator-Recuperator: Basic Parameters

Machine itself:

♦ RF accelerating frequency, MHz	181
♦ Number of RF-cavities	16
♦ Amplitude of accelerating voltage per cavity, MV	up to 0.8
♦ Total RF-power, MW	up to 1.2
♦ Injection and extraction energy (full), MeV	2

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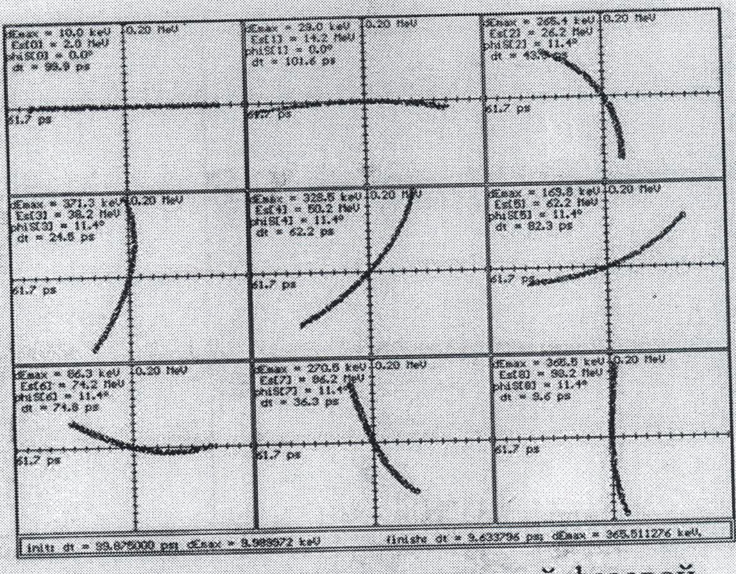
IR-FEL: Basic Parameters

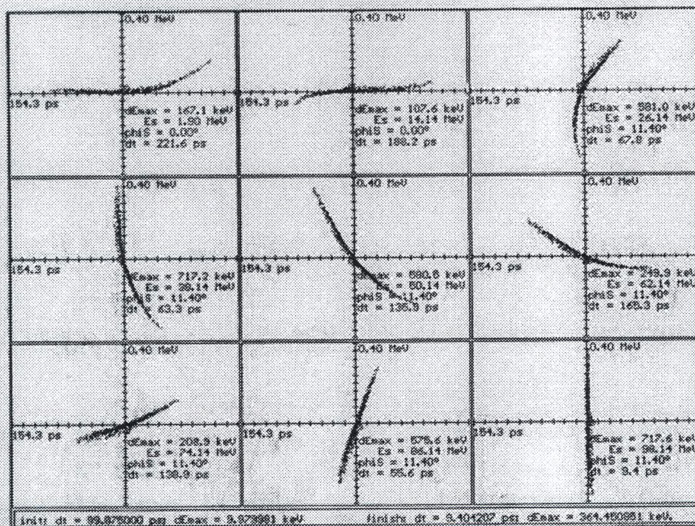
♦ Wavelength of emitted radiation, μm	3...10, 10...30, 30...100
♦ Pulse duration, ps	10...100
♦ Pulse energy, J	up to $5 \cdot 10^{-3}$
♦ Repetition rate, MHz	2.25...22.5
♦ Average power, kW	up to 100
♦ Relative bandwidth of emission spectrum	$3 \cdot 10^{-5}...10^{-3}$

The specific features of MARS-L - the high power FEL project

- High reactive power of the electron beam because of energy recovery (like in storage rings)
- High power capability (like in linac-based FELs)
- Low radiation hazard (like in storage rings)
- Sophisticated techniques:
  - Low RF frequency - possibility of high currents: big (10 cm) diameter of holes in RF cavities, low impedances of high order modes, no coupling between RF cavities, each RF cavity is feeded by its own tetrode generator.
  - Phase motion - final bunching at final energy (to have high peak current and small emittances), big acceptable energy spread of used electron beam.
  - «Electron output» of high optical power - use of FEL only for bunching and utilization of coherent radiation from last undulator. This technique was experimentally approved at the bypass on VEPP-3.

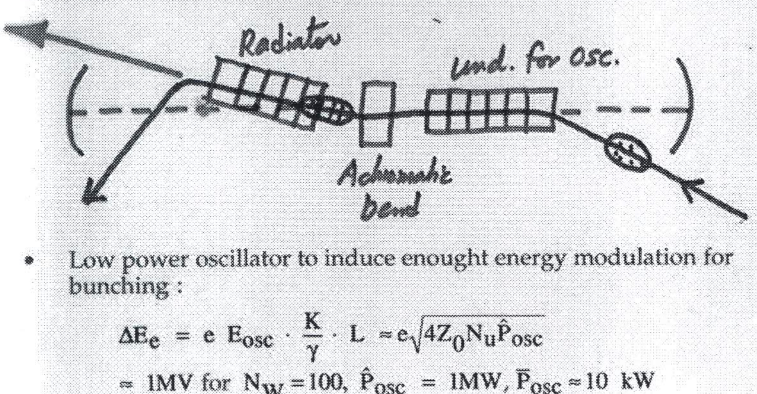


Движение частиц в продольной фазовой плоскости (ускорение).



Движение частиц в продольной фазовой плоскости (замедление).

Electron Out Coupling Scheme



- Low power oscillator to induce enought energy modulation for bunching :

$$\Delta E_e = e\ E_{osc} \cdot \frac{K}{\gamma} \cdot L \approx e\sqrt{4Z_0 N_u \hat{P}_{osc}}$$

$$\approx 1MV \text{ for } N_W = 100,\ \hat{P}_{osc} = 1MW,\ \bar{P}_{osc} \approx 10\ kW$$

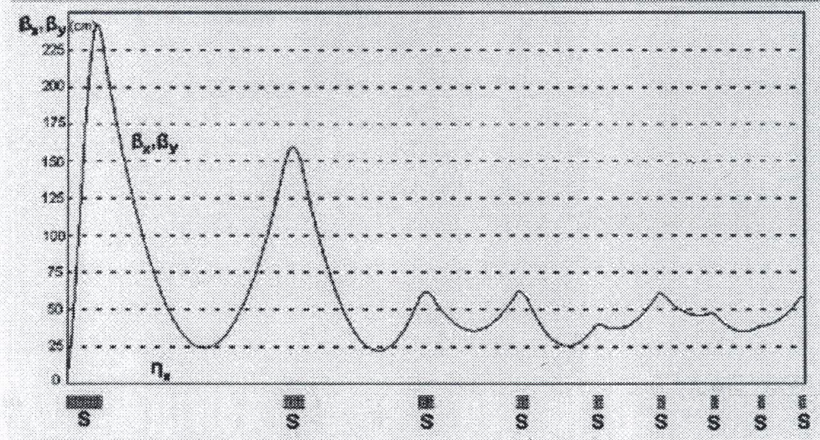
- Coherent spontaneous emission of bunched beam from radiator generated high power

$$\bar{P}_L \approx 100\ \Omega\ N_R \times \hat{I}_e\ \bar{I}_e$$

$$= 100\ kW \text{ for } N_R = 100,\ \hat{I}_e = 100\ A,\ \bar{I}_e = 0.1\ A$$

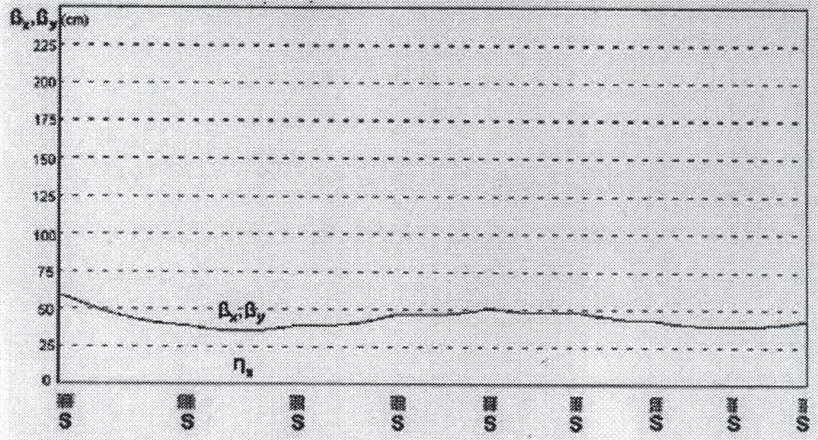
KJK, 2/8/96
Pwr Beam FEL Disc.

Нормализованные β-функции в общем ускоряющем промежутке.



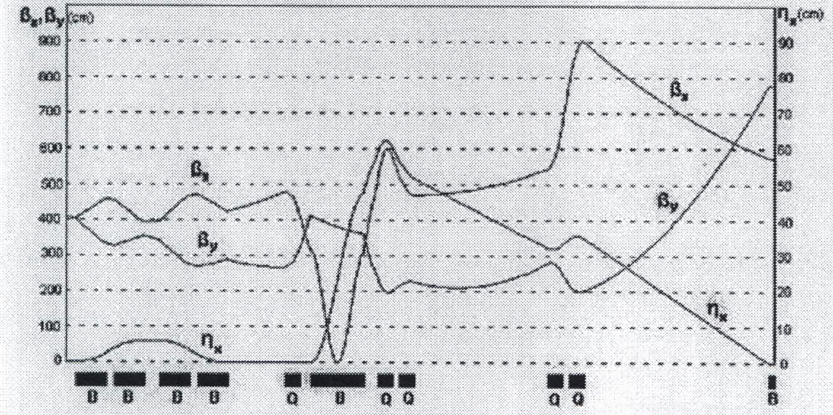
Первый проход (набор энергии от 2 до 14 МэВ)

Нормализованные β-функции в общем ускоряющем промежутке.



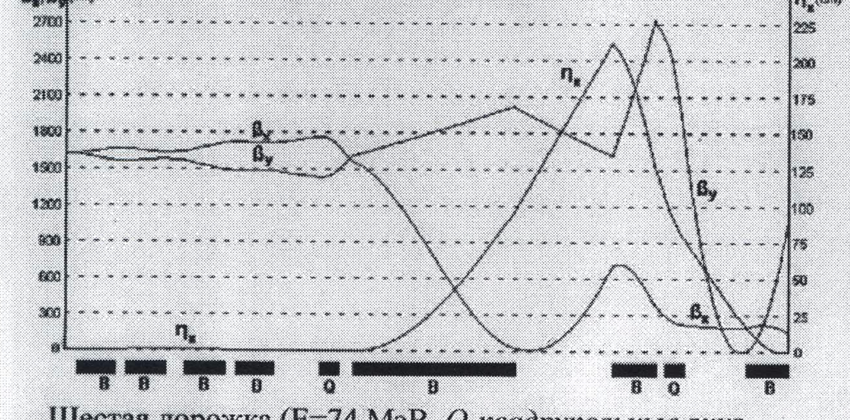
Первый проход (набор энергии от 14 до 26 МэВ)

β- и η- функции в **ахроматических** поворотах.

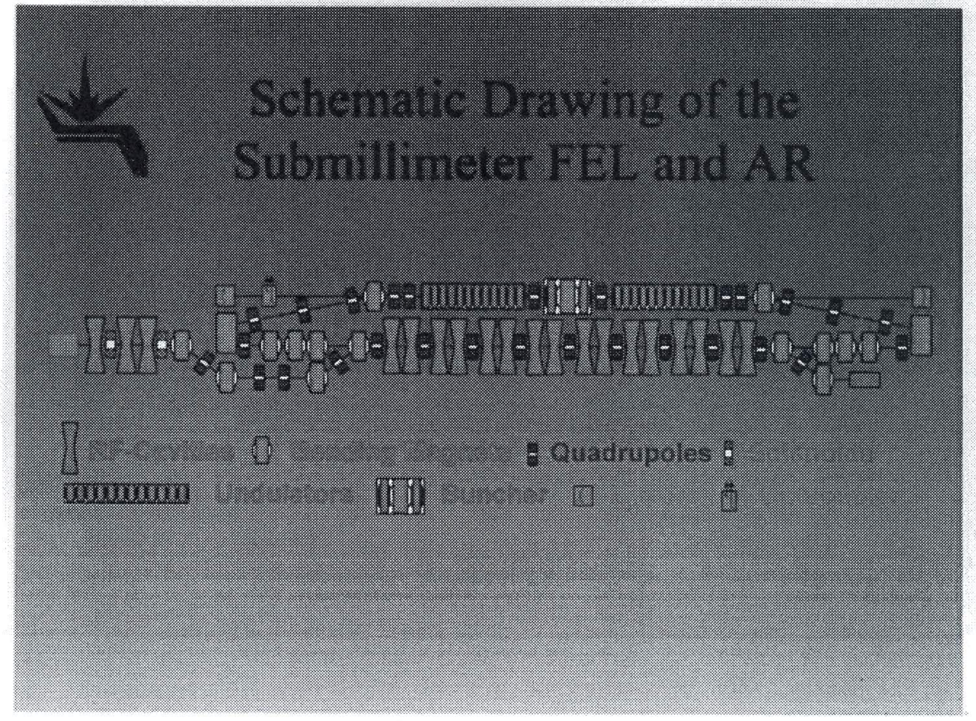


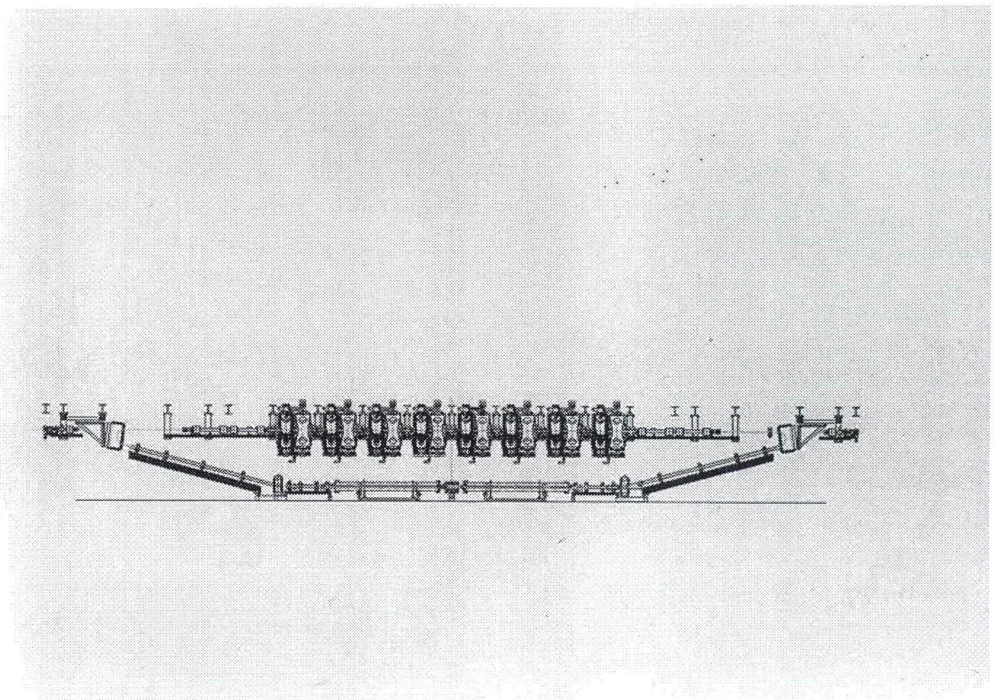
Первая дорожка (E=14 МэВ, *Q-квадрупольные линз, B-магниты;)*.

β- и η- функции в **ахроматических** поворотах.



Шестая дорожка (E=74 МэВ, *Q-квадрупольные линз, B-магниты;)*.


Schematic Drawing of the
Submillimeter FEL and AR
Quadrupoles
Undulators
Buncher



First-Stage Accelerator-Recuperator: Basic Parameters

♦ **Maximum electron energy, MeV**	**14**
♦ **Bunch duration, ps**	**20...100**
♦ **Peak current, A**	**up to 50**

Other parameters as for the full-scale machine

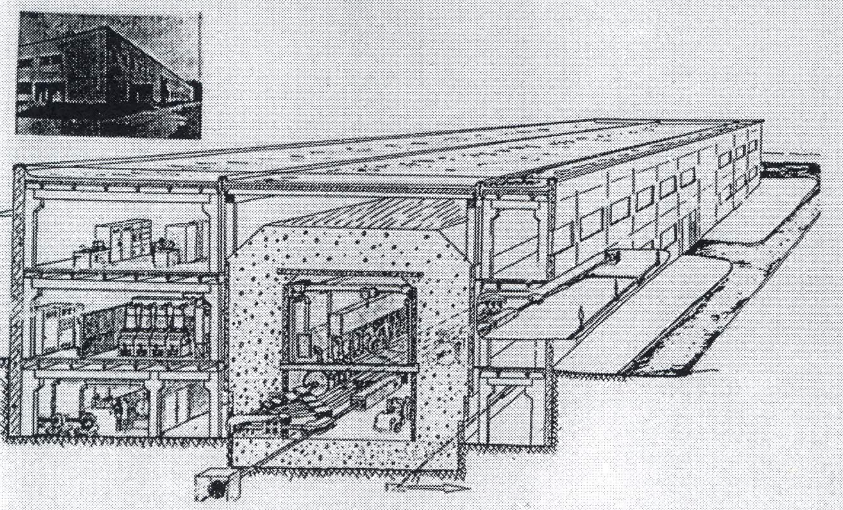


Схема размещения оборудования ЛСЭ в здании Центра фотохимических исследований.

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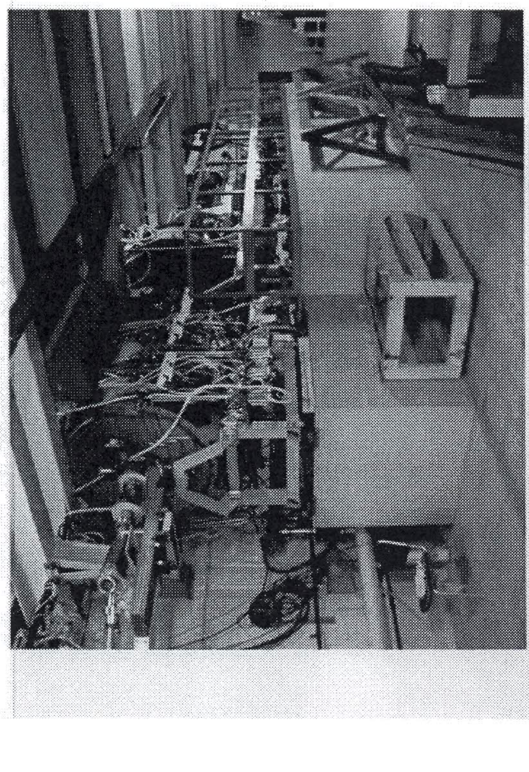
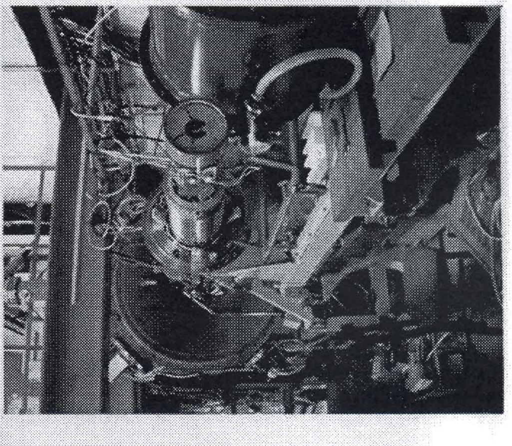
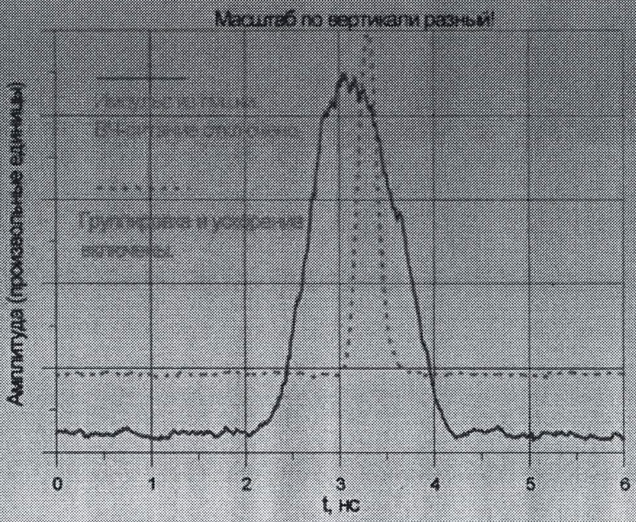
Submillimeter FEL: Basic Parameters

- Wavelength of emitted radiation, μm — 100...200
- Pulse duration, ps — 20...100
- Pulse energy, J — up to $3 \cdot 10^{-4}$
- Repetition rate, MHz — 7.5...22.5
- Average power, kW — 0.6...7
- Relative bandwidth of emission spectrum — $3 \cdot 10^{-3} ... 3 \cdot 10^{-2}$







Группировка пучка. Измерения с помощью диссектора.