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THE PROJECT OF HIGH FREE ELECTRON LAZER USING RACE-TRACK MICROTRON-RECUPERATOR

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ABSTRACT

The high power free electron laser is under construction in the Novosibirsk scientific center. The goal of this project is to provide the user facility for especially organized Siberian Center of Photochemical Researches. The features of installation and the project status are discussed.

It is well-known, that free electron lasers (FEL) have both advantages and disadvantages in the competition with another types of lasers (see, for example, [1,2]). The main advantages are tunability and high average power. The main disadvantages are radiation hazard and large sizes and cost. One of the prospective goals in the FEL technology is the creation of the FEL with average power 0.1 ÷ 1 MW.

During last five years we developed the project of such FEL for operation in visible and infrared diapasons. The main distinguished features of this projects are:

(i) the use of energy recovery in race-track microtron-recuperator;
(ii) the low frequency accelerating RF system;
(iii) the use of so-called "electron output" of light.

Some notation on this design philosophy issues are briefly described below.

(i) The electron energy is to have the order 100 MeV (for the modest undulator period). If we take rather conservative value of the FEL electron efficiency 1%, we obtain easily the power in electron beam 1 MW/0.01 = 100 MW. For operation in near IR directing such a beam to a beam dump we should have a very powerful source of neutrons, γ-rays and dangerous isotopes. So the radiation hazard is to be a serious problem. There are also some problems with the total "from the plug" power for the installation operation, which is to be in a few times more than the electron beam power. The recovery of the electron beam energy make it possible to move across these obstacles. There are different possibilities to provide the energy recovery (see Fig. 1). The Los-Alamos group demonstrate the deceleration of electrons in the special RF linac, connected with the accelerating linac by RF couplers [3]. The other technique, demonstrated first in Stanford, is the use acceleration and deceleration of electrons in the same RF cavities [4]. The third approach - the use of electron storage ring - is now very popular and explored [5,6].It was shown [7,8] that the storage ring FEL have the specific power limitation (Renieri limit) caused by multiple (each turn) interaction of electron with light in the optical resonator. The optimization of this scheme leads to the conclusion that the light power can not exceed 10 kW [6]. Comparing schemes (a) and (b) in Fig. 1, we are to mention that almost whole electron beam power is to pass through the couplers and RF power consumption in the decelerator is the same as in accelerator. Thus the power consumption in scheme (b) is at least in factor two less and there is no couplers there. Speaking generally, the electrons take and return the energy to electromagnetic field inside just the same space volume. Another problem which is to be taken into account is the transverse instabilities due to excitation of high order modes in RF cavities (see, for example [9]). For the scheme (b) this limitation is very serious (the instability was experimentally investigated in Stanford [10] and methods of its suppression were developed). Coming from scheme (a) to (b) we may do the next stop using the recirculator (or the racetrack microtron) with few passes through the RF accelerating structure (Fig. 2). The power consumption in the RF system in this machine is N times less (N - the number of passes at acceleration), than for recirculator of Fig. 1b. But the instability problems are more severe for N>1. To make a choice between variants from Fig. 1a, 1b, and 2 we are to estimate the value of power consumption in RF structure

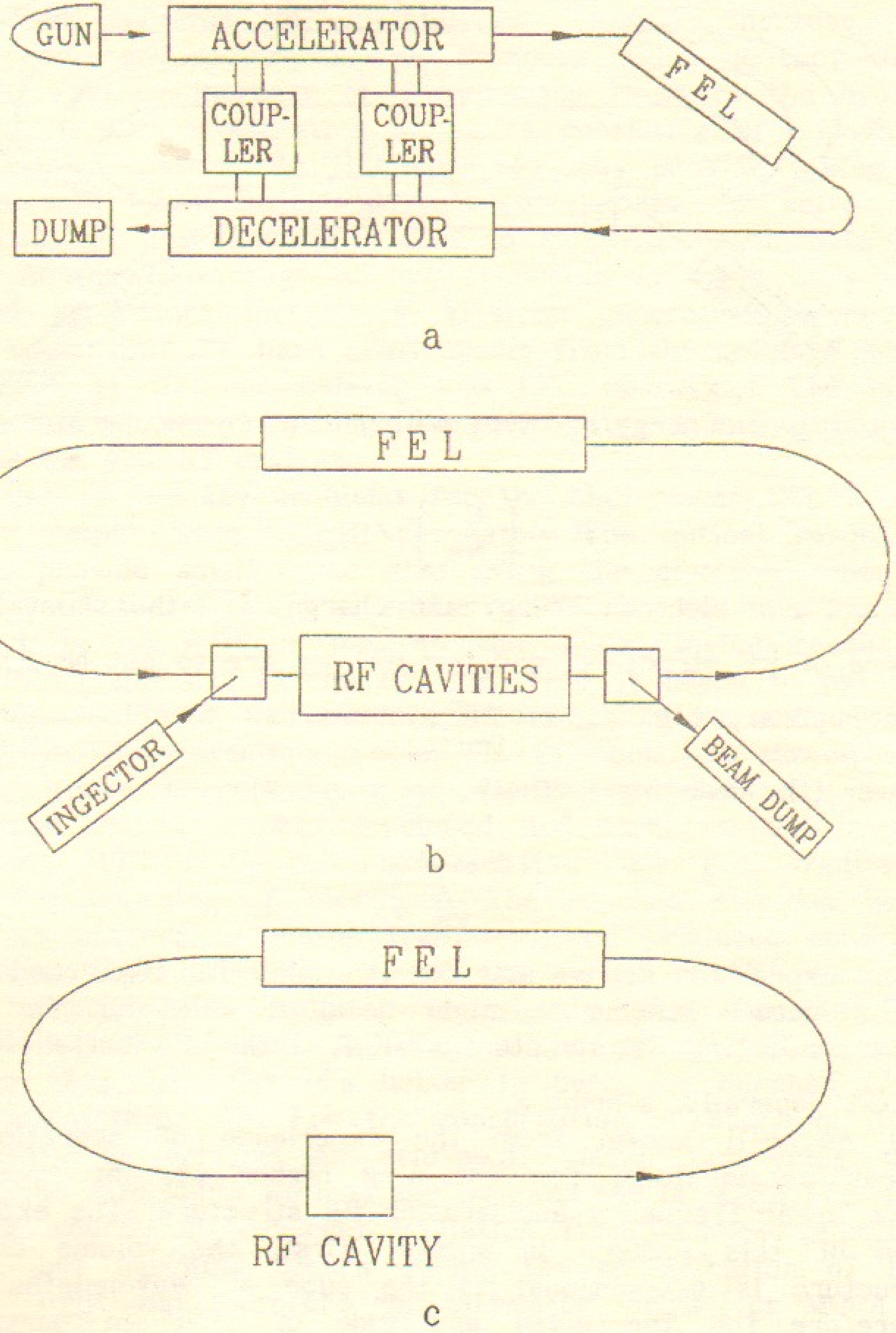


Fig. 1. Different possibilities of FEL with energy recovery.

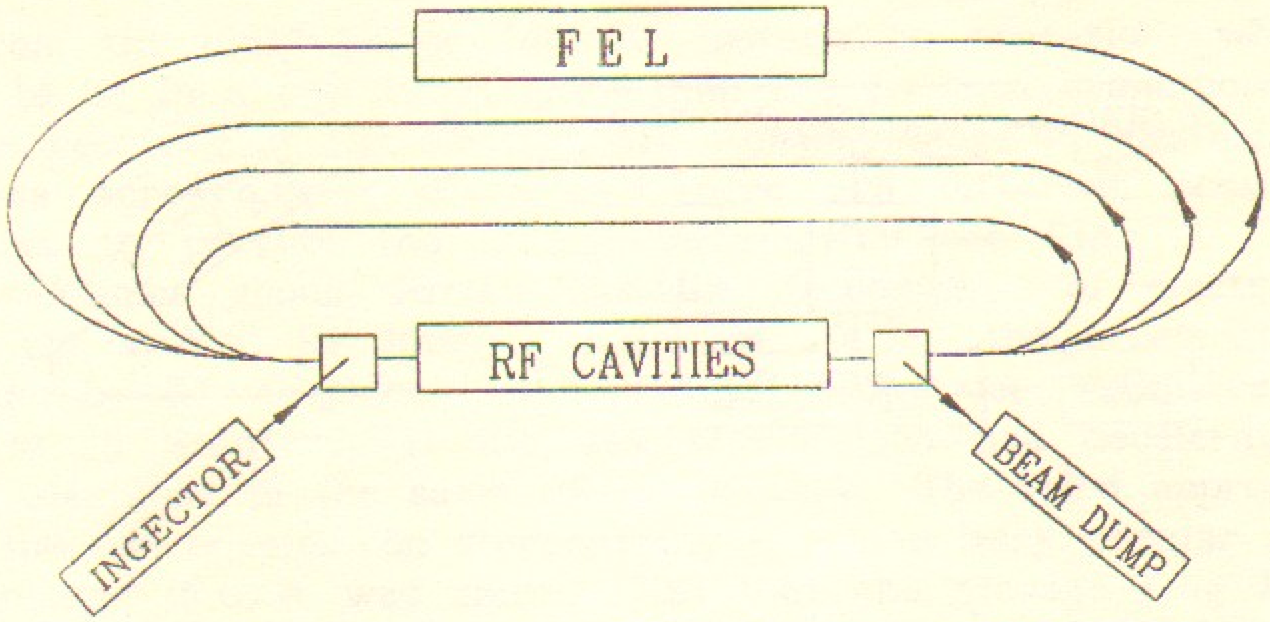


Fig. 2. Energy recovery with microtron-recuperator.

$$P = \left(\frac{E}{Ne}\right)^2 / R_s \, , \qquad (1)$$

(E and e - electron energy and charge, R_s - the shunt impedance of RF structure, and for 1(a) we are to put $N< \frac{1}{2}$). The contemporary high power RF systems are capable to provide the power of order 10 MW, so it's the scale for typical power (1). Assuming $P<10$ MW, we obtain

$$N > \frac{1}{\sqrt{R_s \, (G\Omega)}} \qquad (2)$$

From expression (2) we may conclude that for superconducting RF structure scheme 1a might be preferable, but for non-superconducting RF structure with $R_s<1$ GΩ it's better to use 1b or, generally, scheme 2.

(ii) As well known from the experience of operation of linear accelerators, for obtaining higher current needs to have lower frequency accelerating RF structure. The explanation of this pattern is simple. First, the volume of the structure is proportional to the cube of wavelengths, and therefore for the given amplitude of field in particular cavity mode the energy stored in mode increase with the increase of wavelength and correspondingly increase the threshold currents of instabilities. Second, increase the iris radius and correspondingly decrease high frequency wake fields. Further increase of wavelengths leads to the break-through - the accelerating structure consisting of separated (uncoupled) cavities. In this case we may provide tuning of fundamental and lowest high order modes to solve the problems of thermostability and to suppress beam instabilities. Another advantage of low frequency is using of simple tetrod generators instead of klystron generators. Moreover long wavelength RF have many assets from the point of beam dynamics in the recirculator and FEL operation. The main limitation of wavelength is the difficulty of manufacturing of the big size RF cavities.

(iii) One of the key problems for the high power FEL is the power output from optical resonator. The optical resonator is to provide small mode size along the electron beam in undulator, therefore it's rather difficult to have a big mode size on mirrors and so the power inside resonator typically might not exceed 100 kW. Thus it needs to put out more power than there exist inside optical resonator. One possibility to solve the problem is MOPA [11] - the use of FEL without mirrors as power amplifier. Another - the "electron output" - was developed and partly tested in our institute [12,13]. In this approach we use FEL oscillator only for bunching of electrons. The bunched electron beam goes to another undulator (radiator) and produced coherent radiation there (see Fig. 3). If the period or the magnetic field amplitude in radiator is slightly less than in FEL undulator the coherent radiation might detour the forward mirror (Fig. 3a). But it's better to bend the bunched electron beam (Fig. 3b). For the conservation of bunching it is necessary to arrange an achromatic bend. Comparing this technique with MOPA we may say that the end of MOPA FEL also is the source of coherent radiation from bunched electron beam, but bunching occurs during the amplification of low power light and therefore the undulator length for MOPA is to be much longer and correspondingly the tolerances for the beam quality are much more severe.

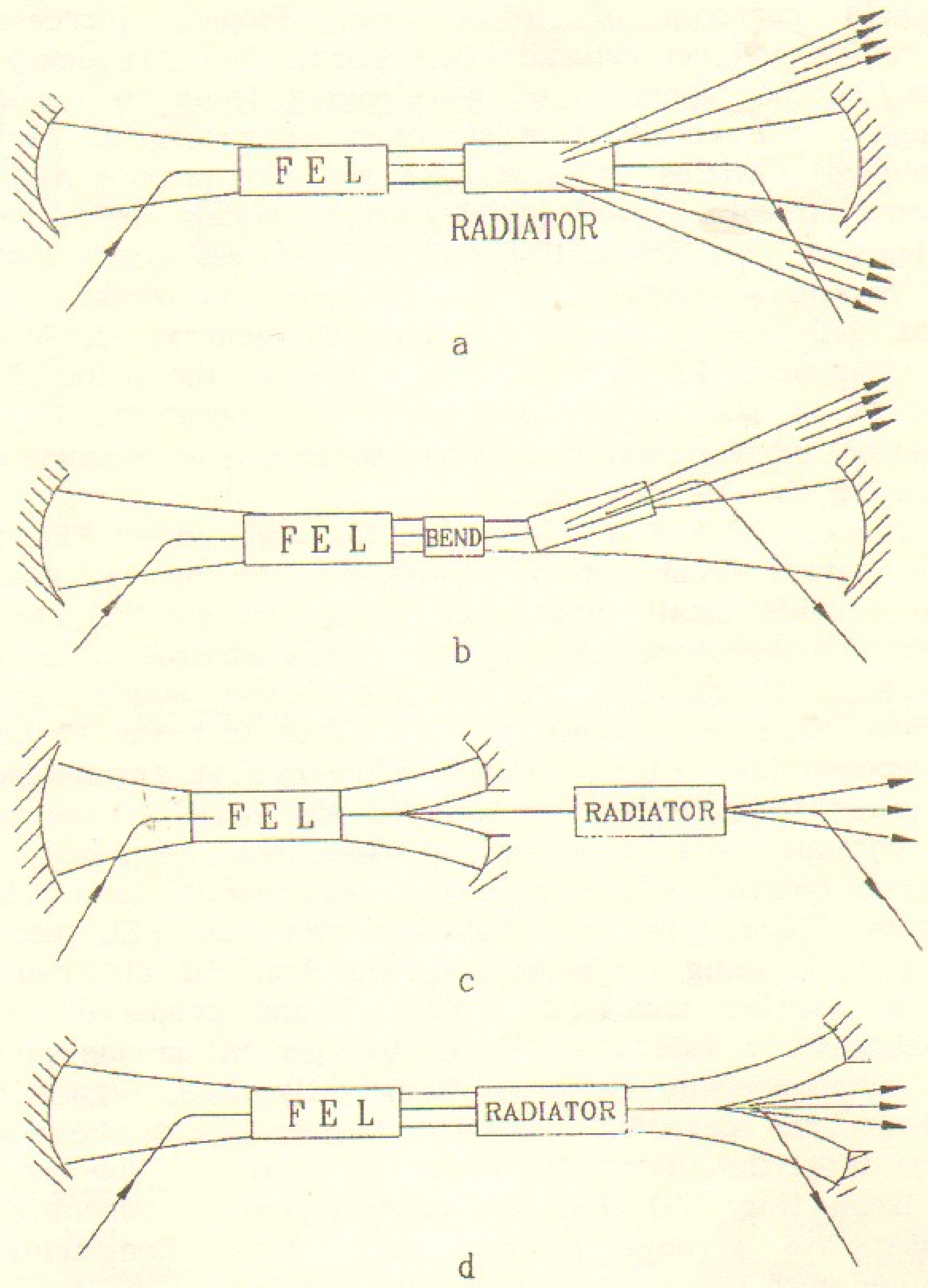


Fig. 3. Differnt schemes of the electron output.

The race-track microtron-recuperator

The first version of the project of this accelerator was published earlier [14]. Here we discuss the updated variant adapted for the FEL for the Siberian Center of Photochemical Researches.

The layout of the microtron is depicted in Fig.4 and Table 1. The microtron comprises an injector *1*, two magnetic systems of a 180° separating bend *2*, a common straight section with RF cavities *3* (the section is common to electrons of different energy), magnets for the injection *4* and extraction *5* systems and solenoidal magnetic lenses *6*, four separated straight sections with magnetic quadrupole lenses *7*, a FEL magnetic system *8* placed in the fourth straight section, and a beam dump *9*.

Table 1

CW Race-Track Microtron-Recuperator parameters:

RTM RF wavelength	165.3 cm
Number of RTM RF cavities	20
Number of tracks	4
Energy gain per one RF cavity	0.7 MeV (0.9 MeV)
Injected electron energy	2.1 MeV (2.7 MeV)
Final electron energy	51 MeV (66 MeV)
Final electron energy dispersion	0.45%
Final electron micropulses length	20÷100 ps
Final peak electron current	20÷100 A
Micropulses repetitions frequency	2÷45 MHz
Average electron current	4÷100 mA

FEL parameters:

FELs EM undulators period	9 cm
Undulators gap	4 cm
Undulators parameter K	1÷2
FELs wavelength	6.5÷13 μm (4÷8 μm)
FELs optical resonators length	79 m
Average FELs power	4÷100 kW
Peak FELs power	20÷100 MW

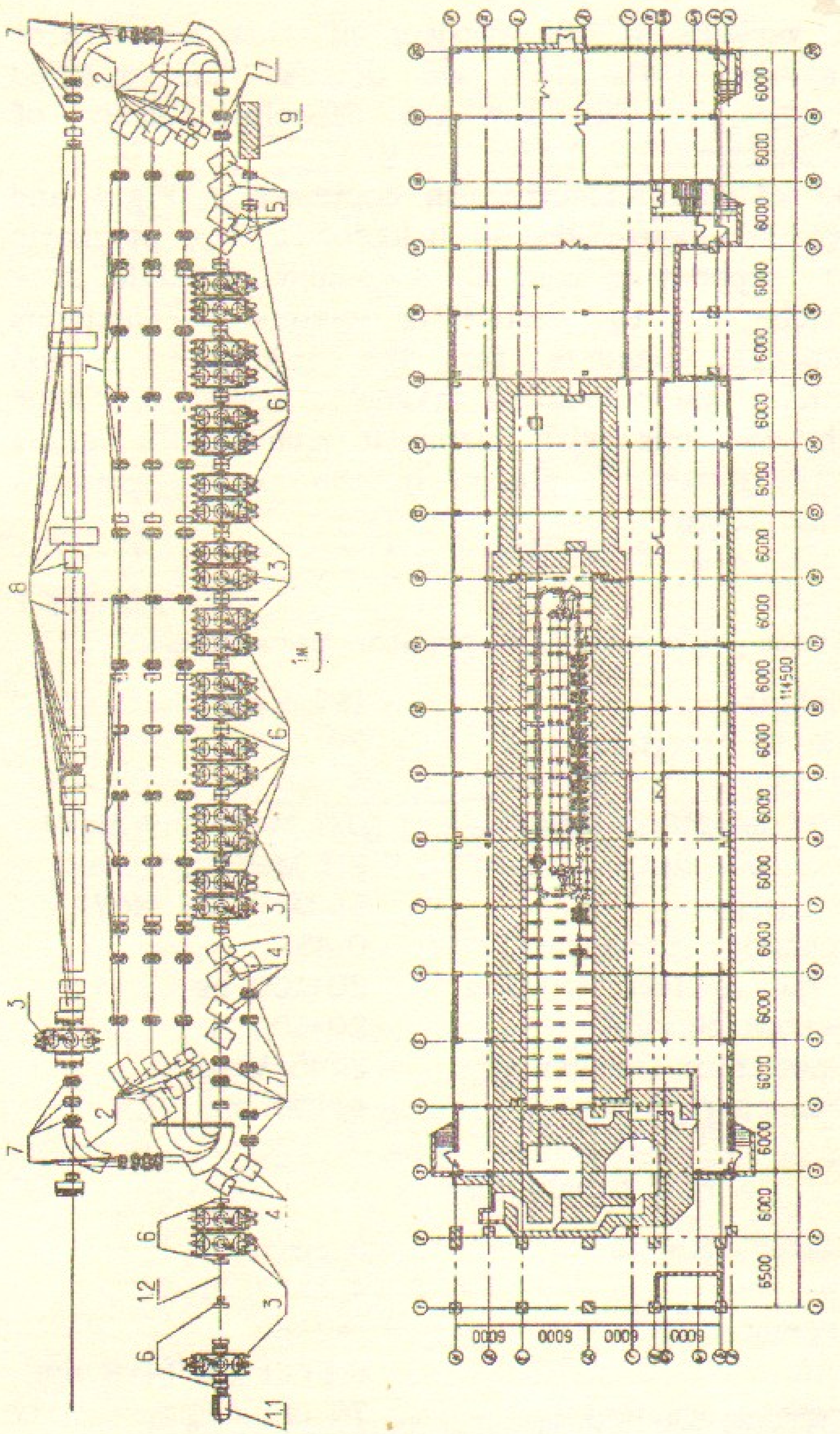


Fig. 4. The general layout of the race-track microtron-recuperator:
1- injector; *1.1* - electron gun of the injector; *1.2* - bunching straight section; *2* - magnets of the 180° separatingbend; *3* - RF cavities; *4* - magnets of the injection system; *5* - magnets of the extraction system; *6* - solenoidal magnetic lenses; *7* - quadrupole magnetic lenses; *8* - magnetic system of the FEL; *9* - beam dump.

A 300 kV electron gun of the injector *1.1* generates 1-ns electron bunches at a repetition frequency of 45 MHz. Having passed through an RF cavity *3*, which modulates the electron energy (velocity) and identical to all RF cavities of the device, the bunch is longitudinally compressed in a drift straight section *1.2* down to 200 ps and then accelerated up to 2.1 MeV in two RF cavities of the injection with the total 1.4 MV accelerating-voltage amplitude in the equilibrium phase $\varphi_0=9^\circ$. The electrons are injected into the common straight section of the microtron using four identical 65° bending rectangular magnets opposite in sign (*4*). Here the bunches length is equal to 100 ps.

The working-voltage amplitude of RF cavities, in the common straight section of the microtron is 700 kV for one cavity and, hence 14 MV for 20 cavities, with the flight factor taken into account. These RF cavities are half the wavelength, λ=165.3 cm, distant from each other, which corresponds to its resonance frequency f=181.3 MHz.

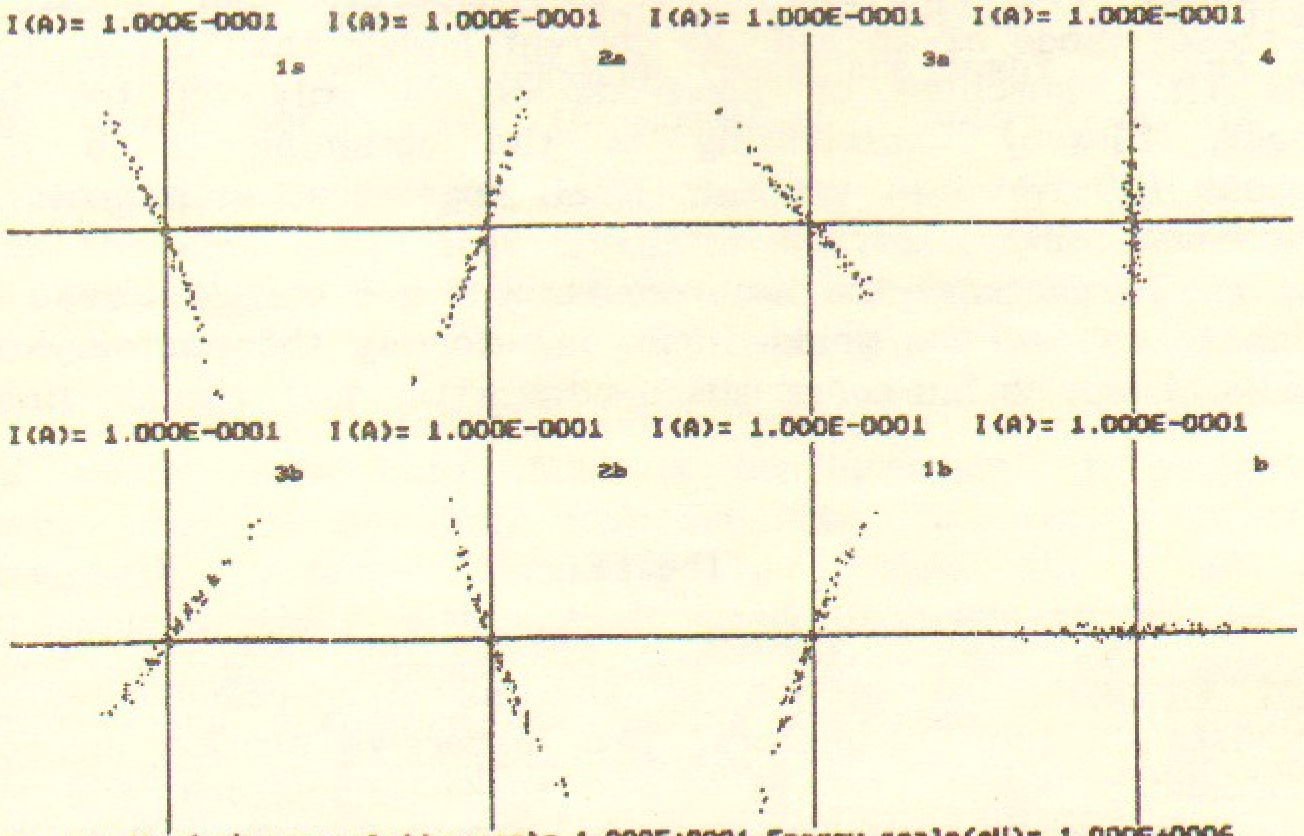
A separating 180° bend *2* for the first three tracks of the microtron is a 180° magnetic mirror with two 65° bending magnets on each track. This magnetic system of 180° bend is achromatic, and its horizontal and vertical optical matrices are mutually coincide and look like the matrix of the empty straight section. Variation in the orbit length is going from the next microtron track is one wavelength of its RF system. The choice of this type of bend and its achromaticity are due to the necessity for the beam to pass through RF cavities of the common straight section, the necessity to reduce the horizontal beam size and to simplify the matching of β-function on three isolated straight sections where there are quadrupole lenses 7.

The fourth straight section is intended for the FEL magnetics system *8*. To lengthen it, a 180° achromatic bend on the fourth track comprises two 90° bends. The distance between 90° magnets are such that the length of the fourth track is different from the length of the third track by about 2.5λ of the wavelength of the microtron RF voltage. At the exit from the FEL magnetic system there is the RF cavity to compensate the average losses in electron energy in the FEL. The RF cavities and a detector of horizontal beam displacement, installed behind a 90° bending magnet stabilizes the electron energy at the exit of the fourth straight section. Entering again the common straight section from the fourth track, but now in the decelerating phase of RF system, the electrons release its energy to the RF system during the passage in the same direction through the same three microtron tracks. Emphasis should be made that in this case the passages sequence is inverse. After that the electrons are extracted using the magnets of the extraction system *5* (identical to the magnets of the injection system) and are directed to the beam dump *9*.

To provide the proper focusing of both the accelerated and the decelerated electrons, the magnetic system (except for the fourth track) is mirror-symmetrical relative to the line going through the center of the straight sections. Here the matched β-functions are of the same symmetry.

To minimize the length of the electron bunch (maximize peak electron current) in the FEL magnetic system, the longitudinal phase motion of the beam in the microtron was optimized by means of small variations in the values of the equilibrium electron energy on each track (and, correspondingly, the microtron geometry). The equilibrium phases of four passages through the RF system are $\varphi_1 = \varphi_2 = 25.3^\circ$, $\varphi_3 = 47.2^\circ$, and $\varphi_4 = 0.6^\circ$. Figure 5 illustrates the longitudinal phase-energy diagrams of the position of the electron bunch on four separated straight sections. Electron energy dispersion on the fourth track is 0.45%.

The lengths of the straight sections of the microtron are such that with the injection of one electron bunch in each four periods of its RF voltage (i. e. at 45 MHz frequency), on the common track the accelerated and decelerated bunches are uniformly distributed in the longitudinal direction (i. e. with respect to the time of the passage through RF cavities) with an about 0.8 m interval. In this case, a mutual influence of the accelerated and decelerated



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Longitudinal phase scale(degrees)= 1.000E+0001 Energy scale(eV)= 1.000E+0006
Injections energy(eV)= 2.104E+0006 Long.foc.coefficient(rad/eV)= 1.650E-0007
RF periods number=    14801 Electron beams average current(A)= 1.000E-0001
Beams power losses instantaneous(W)= 0.000E+0000 and averaged(W)= 4.438E+0002
RF voltage(V)= 1.39957E+0007 RF detuning phase(degrees)=-5.96889E-0002
Total RF power(W)= 2.04632E+0004 Fine fast RF cavity detuning= 2.87120E-0005
Injections phase(degrees)= 2.530E+0001 Final electron enerdy(eV)= 3.093E+0007


Phase dispersion(degrees)= 2.898E-0001 Relative energy dispersion= 4.306E-0003
Peak electron current(A)= 1.31E+0002 Eff.dispersion= 4.46E-0003 Gain= 8.17E-0001

Maximal power(W): RF= 1.264E+0005
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Fig. 5. The longitudinal phase-energy diagrams of the electron bunch position: *1, 2, 3, 4* - at the 1st, 2nd, 3rd and 4th straight sections, *a* - on the accelerating way, *b* - on the decelerating way.

beams at different electron energies is drastically decreases.

Calculations of the longitudinal and transverse beam dynamics show that the microtron-recuperator can operate in a steady mode at an average current higher than 0.1 A. Here the final bunching of electrons occurs only on the last track, thereby contributing to the obtaining of a high (about 100 A) peak current, small transverse emittances of the beam being conserved.

To decrease the beam emittances and energy spread we plan to change the gridded gun injector by the photoinjector [15] which is under construction now.

The FEL

The magnetic system of FEL is installed just in the last straight line section of the microtron-recuperator. It consists of four undulators, two dispersive section and one achromatic bend (Fig. 6). First three undulators and two dispersive sections compose the optical klystron using as master oscillator. Optical resonator consists of two mirrors and have a 79 m length. The number of periods in each undulator is 40, the period length - 9 cm. For easy tuning of wavelength we use electromagnetic undulators which permit to vary the deflection parameter K from 1 to 2 . The reason of the using of two dispersive section is obtaining of a good frequency selectivity. To see this, let us remind that in conventional optical klystron there are many maxima of gain which corresponds to condition $s=(n-\frac{1}{4})\lambda$, (λ - wavelength, n - integer, s - the lag of electron, passed from the center of first undulator to the center of second one, from light). For the case of two dispersion sections we are to satisfy two such conditions for the wavelength simultaneously (for different s_1 and s_2) and so the maxima will occur more rare. Such a configuration of magnetic system provides not only fine but also fast tuning of the wavelength, because it's easy to change the field in dispersion sections with a high speed. It needs to emphasize that this multielement magnetic system of the master oscillator is optimized for having minimum of intracavity light power at reasonable bunching of electron beam and small energy spread in the fourth undulator (radiator).

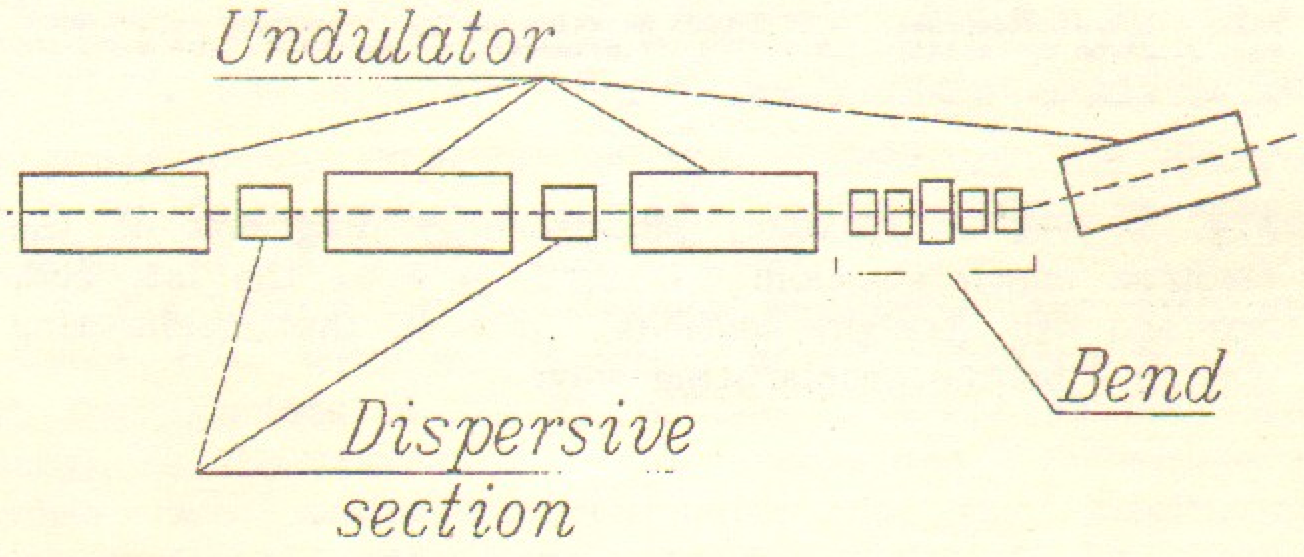

Fig. 6. The FEL magnetic system.

The magnetic system of achromatic bend is similar to that discussed and tested previously [3,4]. Taking into account the angular divergences of the fundamental eigenmode (of the optical resonator) and of the coherent undulator radiation we choose the 4 milliradians deflection angle. Therefore corresponding distance between the axis of optical resonator and the center of coherent radiation beam near the forward mirror is 14 cm. For the beginning of operation we choose the simplest optical resonator. Its big length decrease the light intensity on the mirror surface but also make possible to obtain oscillations with low repetition frequency of the electron bunches (less than 2 MHz). Therefore we'll have low average power (and so negligible mirrors heating) at the regular operating peak power and can concentrate on the careful adjustment of all systems. After that we may increase the power by the increase of the repetition rate of the injector pulses. For example, at repetition rate 45 MHz it'll increase 24 times and at 180 MHz - 96

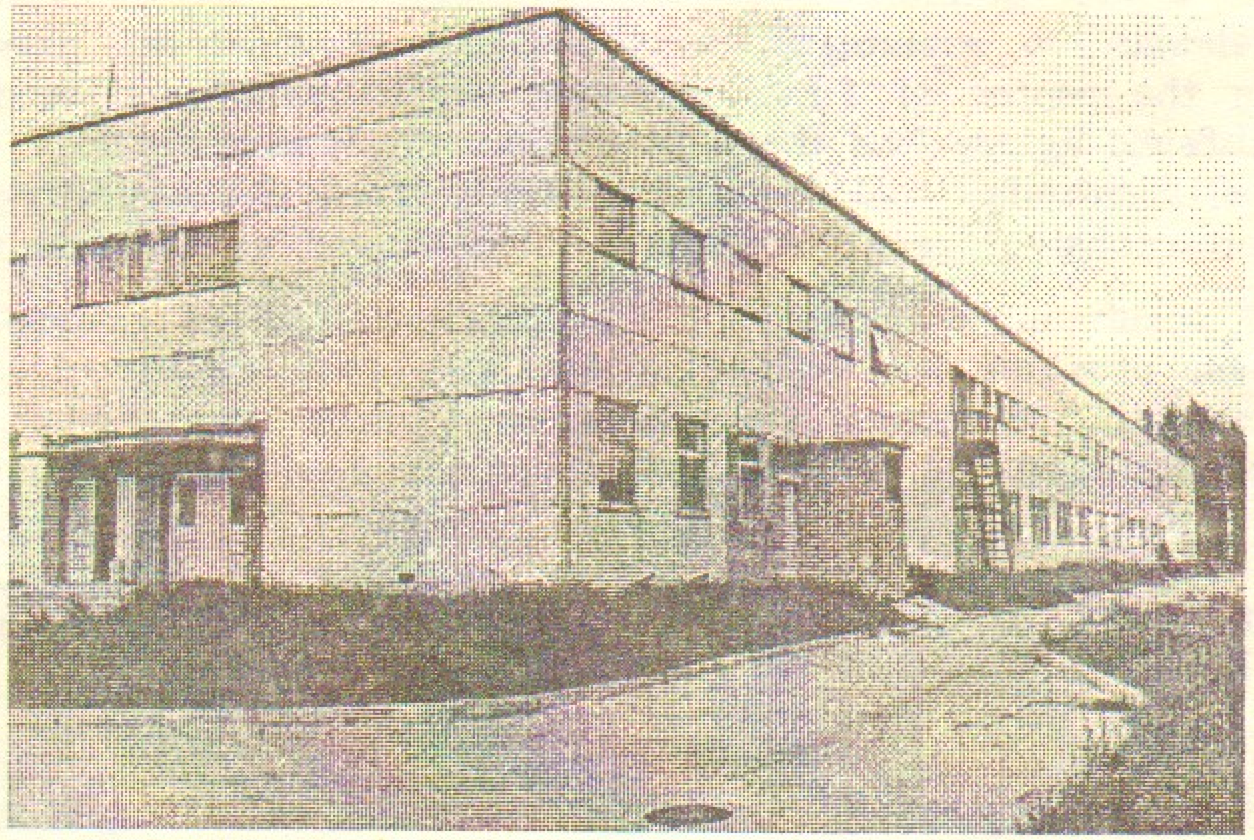

Fig. 7. The building for the Siberian Center of Photochemical Reseach.

times. The estimation of the coherent radiation power from the radiation gives the value of its characteristic resistance about few kΩ. Then at the 100 A peak current we are to have few tens of MW peak power and at 0.1 A average current - few tens of kW average power.

The radiation parameters

The FEL radiation will consist of pulses with 10-30 ps duration, 2-45 MHz repetition rate and 4-13 μm wavelength. Varying the electron energy from one bunch to another with the round-trip period of the optical resonator we may modulate the wavelength.

Status of the project

The mechanical design of installation is to be finished this year. The hardware for the RF generators is manufactured. The existing building for the Siberian Center of Photochemical Researches is shown on Fig. 7. The updating of this building is in progress now and should finish in the middle of next year. The facility is to be available for users in 1996.

Prospects

In the conclusion we are to point out that the Novosibirsk installation was adapted to meet the demands of the Center of Photochemical Researches. But our approach was developed to provide much higher light power for another applications. Therefore using the same components (RF generators, accelerating cavities, undulators etc.) and techniques it's possible to create FEL of the megawatt power diapason.

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с использованием разрезного микротрона-рекуператора

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