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Section A

Status of the high power free electron laser using the race-track microtron-recuperator

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Abstract

The high power infrared free electron laser is under construction at the Novosibirsk Scientific Centre. The goal of this project is to provide a user facility for Siberian Centre of Photochemical Researches. The features of the installation and its status are described.

1. Introduction

Free electron lasers (FEL) have both advantages and disadvantages in the competition with other types of lasers (see, for example, Refs. [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 the last five years we developed the project of such FEL for operation in the infrared region [3,4]. The main concepts of this project are:

1) use of energy recovery in the race-track microtron (RTM) demonstrated earlier [5];
2) low frequency accelerating RF system [6];
3) use of "electron outcoupling" of light [7,8].

2. The race-track microtron-recuperator

The layout of the microtron and its parameters are shown in Fig. 1 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 the electrons of different energies), magnets for the injection 4 and extraction 5 systems, solenoidal magnetic lenses 6, four separated straight sections with magnetic quadrupole lenses 7, a FEL magnetic system 8 placed on the fourth straight section, and a beam dump 9.

The 300 kV electron gun of the injector produces 1 ns electron bunches with repetition frequency of 45 MHz. After passing through the RF cavity modulating the electron energy the bunch is longitudinally compressed in a drift straight section down to 200 ps and then accelerated up to 2.1 MeV in the next two RF cavities. The electrons are injected into the common straight section of the microtron using two pairs identical 65° bending rectangular magnets with alternating signs. The bunch length is equal to 100 ps at the exit of the injection system.

The RF cavities in the common straight section are distant from each other at the half of the wavelength.

The separating bend for the first three tracks of the microtron is a 180° magnetic mirror with two 65° bending magnets on each track. This magnetic system is achromatic, and its horizontal and vertical optical matrices are equal to the matrix of some empty straight section. The difference in the orbit length between the subsequent microtron tracks is one wavelength of the RF system. All

Table 1
The microtron-recuperator parameters

RTM RF wavelength	166.3 cm
Number of RTM RF cavities	20
Number of tracks	4
Energy gain per one RF cavity	0.7 MeV
Injection energy	2.1 MeV
Final electron energy	51 MeV
Final electron dispersion	0.45%
Final electron micropulses length	20-100 ps
Final peak electron current	20-100 A
Micropulses repetition frequency	2-45 MHz
Average electron current	4-100 mA

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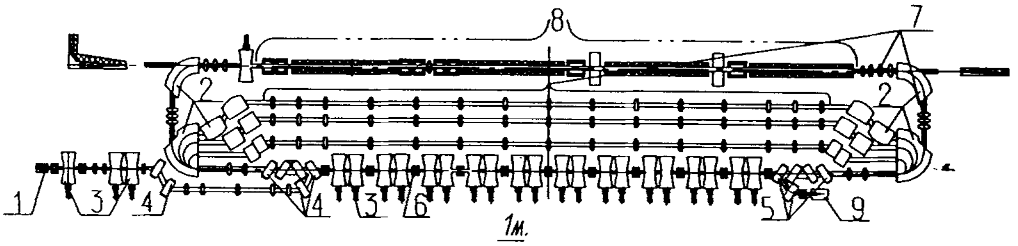

Fig. 1. The layout of the microtron.

these features allow the electron bunches with different energies to pass through RF cavities of the common straight section without overlapping, to reduce the horizontal beam size, and to simplify the matching of β-function on three isolated straight sections containing quadrupole lenses.

To enlarge the available space for the FEL magnetic system a 180° achromatic bend on the fourth track comprises two 90° bends. The distance between the 90° magnets is such that the length of the fourth track is different from the length of the third track by about $2\frac{1}{2}$ 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 stabilize 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 the RF system, the electrons release their energy to the RF system during the passage in the same direction through the same three microtron tracks. After that the electrons are extracted using the magnets of the extraction system (identical to the magnets of the injection system) and are directed to the beam dump.

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

To minimize the length of the electron bunch (to 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) [9]. The equilibrium phases of four passages through the RF system are $\phi_1 = \phi_2 = 25.3°$, $\phi_3 = 47.2°$, and $\phi_4 = 0.6°$. 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 not overlapping. In this case, a mutual influence of the accelerated and decelerated beams at different electron energies is drastically decreased.

Calculations of the longitudinal and transverse beam dynamics show that the microtron-recuperator can operate in the 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 the high (about 100 A) peak current, and 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 [10,11] which is under construction now.

3. The FEL

The magnetic system of FEL consists of four undulators, two dispersive section and one achromatic bend. 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 is 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 use of two dispersive sections is obtaining of a good frequency selectivity. To see this, let us remember that in the conventional optical klystron there are many maxima of gain which corresponds to the condition $s = (n - \frac{1}{4})\lambda$, ($\lambda$ is the wavelength, n is any integer, s is the lag of the electron passing from the centre of the first undulator to the centre of second one from light). For the case of two dispersion sections we should satisfy two such conditions for the wavelength simultaneously (for different s_1 and s_2) and so the maxima will occur more rarely. Such a configuration of magnetic system will provide not only fine but also fast tuning of the wavelength, because it is easy to change the field in the dispersion sections with a high speed. It needs to be emphasized that this multi-element 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).

The magnetic system of achromatic bend is similar to that discussed and tested previously [7,8]. Taking into account the angular divergences of the fundamental eigenmode (of the optical resonator) and of the coherent undulator radiation we choose the 4 mrad deflection angle. Therefore the corresponding distance between the axis of the optical resonator and the centre of the coherent radiation beam near the forward mirror is 14 cm. For the beginning of operation we choose the simplest optical resonator. Its big length decreases the light intensity on the mirror surface but also makes it possible to obtain oscillations with low repetition frequency of the electron bunches (less than 2 MHz). Therefore we will 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 increasing the repetition rate of the injector pulses. For example, at repetition rate 45 kHz it will increase 24 times and at 180 MHz 96 times. The estimation of the coherent radiation power at the 100 A peak current gives the value of a few tens of MW peak power and at 0.1 A average current a few tens of kW average power.

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.

4. Survey and alignment concept

A primary goal of the survey and alignment activity for microtron-recuperator is to set its components into the desired position with the required accuracy. There are a few specific peculiarities that we should keep in mind developing an alignment system: (i) the beam orbit is 2.6 meter above the building floor, (ii) there are a number of small size components positioned close one to another, (iii) global effects like geoid undulations, deflections of the vertical, site-wide water table changes, etc. are not needed to be taken into account due to the small size of machine.

The common alignment tasks to be carried out are the following: fiducialization, alignment of the module components in the laboratory, network measurements and adjustment, rough alignment of the supports, supervision under assembling of RTM, final alignment of the components, quality control survey.

Each component of the RTM should have at least two fiducial marks: a bush with 2.54 cm diameter socket for housing either a calibrated dowel pin or a tooling ball of the same diameter. The position of the magnetic axis of quads, dipoles and solenoids are to be fixed with respect to the fiducial marks by means of magnetic measurements. Because of possible warping of the RF-cavity body during its heating the fiducial mark positions are mapped thereafter with the use of theodolites.

Because of the large quantity of small size components they are to be coupled in a few modules. Thus their relative positions are aligned on the laboratory and are not adjusted in the RTM-building. Each module should have two reference points and a base surface for housing an invar staff and a bubble level.

We use BINP-designed monuments. A reference point of the monument is exactly the same bush as that used in the fiducial mark. There is a possibility to adjust the bush axis vertically and to move it in the horizontal plane within ±5 mm range in both directions.

A rectangle righthanded coordinate system is used: the X-axis is directed along the optical resonator, the Y-axis points inside the building and the Z-axis points in zenith. The origin is chosen so that all coordinates will be positive.

The alignment network is made in two stages. A primary network includes ten monuments mounted on the building wall at one meter level from the floor. Distances between all monuments of primary network are measured by invar tapes with accuracy of 0.04 mm. In addition, for rigidity, we measure offsets from two straight lines. Simulations show that the coordinates of primary monuments are calculated with 0.1 mm absolute and 0.04 mm relative accuracy. With use of the dial indicator the position of the monuments are corrected to the desired coordinate values with 0.01 mm accuracy. After that the control survey of primary monument position is carried out. The monuments of the secondary network are placed at the beam orbit level exactly above the primary ones. A special plumbing device is applied to transfer the coordinates of primary monuments to the secondary one. A plumbing accuracy is about 10 in.

To align the modules and bending magnets, auxiliary monuments are set exactly underneath their fiducial marks by means of distance intersection from primary monuments. Thereafter the module is moved till the plumbing device indexes zero. For the final alignment of the beam track components a straight wire technique is applied. The secondary monuments are placed close enough to the tracks 1 and 5. To form straight lines close to the beam tracks 2–4, additional marks are mounted in the corresponding position on the bending magnets during the fiducialization procedure. Allowing for possible errors, resulted from the fiducialization, the plumbing, etc, the final alignment accuracy of RTM components in horizontal directions is 0.2 mm. Alignment in the vertical direction is made by means of precision sight level and invar staff. The accuracy of 0.2 mm can be easily achieved for machines of the similar size.

After completion of the alignment, the position of all components is mapped to confirm that the alignment tolerances have been met.

5. Status and prospects

The mechanical design of installation will be finished this year. The hardware for the RF generators was manufactured. The existing building for the Siberian Centre of Photochemical Researches is under updating.

The computations and optimization of the FEL system are in progress now [12-14].

In the conclusion we want to mention that the Novosibirsk installation was adapted to meet the requirements of the Centre of Photochemical Researches. But our approach was developed to provide much higher light power for other applications. Therefore using the same components (RF generators, accelerating cavities, undulators etc.) and techniques it is possible to create an FEL of the megawatt power.

References

[1] R.H. Pantell, Nucl. Instr. and Meth. A 304 (1991) 798.
[2] O. Svelto, Principles of Lasers (Plenum, New York, 1976).
[3] N.G. Gavrilov et al., IEEE J. Quantum Electron QE-27 (1991) 2626.
[4] N.A. Vinokurov et al., Proc. 4th European Particle Accelerator Conf., EPAC-94, vol. 1, London (1994) 858.
[5] T.I. Smith et al., Nucl. Instr. and Meth. A 259 (1987) 1.
[6] V.S. Arbuzov et al., Proc. 1993 Particle Accelerator Conf. PAC-93, vol. 2, p. 1226.
[7] G.N. Kulipanov et al., IEEE J. Quantum Electron QE-27 (1991) 2566.
[8] N.G. Gavrilov et al., IEEE J. Quantum Electron QE-27 (1991) 2569.
[9] A.S. Sokolov and N.A. Vinokurov, Nucl. Instr. and Meth. A 341 (1994) 398.
[10] N.G. Gavrilov et al., Nucl. Instr. and Meth. A 331 (1993) ABS17.
[11] N.G. Gavrilov et al., Nucl. Instr. and Meth. A 359 (1995) 44.
[12] D.D. Quick, J. Blau, R.K. Wong and W.B. Colson, Nucl. Instr. and Meth. A 341 (1994) ABS92.
[13] J. Blau, R.K. Wong, D.D. Quick and W.B. Colson, Nucl. Instr. and Meth., A 341 (1994) ABS94.
[14] G.N. Kulipanov et al., these Proceedings (17th Int. Free Electron Laser Conf., New York, NY, USA, 1995) Nucl. Instr. and Meth. A 375 (1996) 576.