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Status of the free electron laser for the Siberian centre for photochemical research

B.A. Baklakov[a], A.M. Batrakov[a], V.P. Bolotin[a], Y.A. Evtushenko[a], N.G. Gavrilov[a], E.I. Gorniker[a], D.A. Kairan[a], M.A. Kholopov[a], V.V. Kolmogorov[a], E.I. Kolobanov[a], A.A. Kondakov[a], S.A. Krutikhin[a], V.V. Kubarev[a], G.N. Kulipanov[a], E.A. Kuper[a], I.V. Kuptsov[a], G.Ya. Kurkin[a], L.E. Medvedev[a], A.S. Medvedko[a], E.G. Miginsky[a], S.V. Miginsky[a,*], L.A. Mironenko[a], A.D. Oreshkov[a], V.K. Ovchar[a], A.K. Petrov[b], V.M. Petrov[a], V.M. Popik[a], I.K. Sedlyarov[a], T.V. Shaftan[a], M.A. Scheglov[a], O.A. Shevchenko[a], E.I. Shubin[a], A.N. Skrinsky[a], S.V. Tararyshkin[a], A.G Tribendis[a], V.F. Veremeenko[a], N.A. Vinokurov[a], P.D. Vobly[a], N.I. Zinevich[a]

[a] *Budker Institute of Nuclear Physics, Lavrentiev Ave. 11, 630090 Novosibirsk, Russia*
[b] *Institute of Chemical Kinetics and Combustion, Novosibirsk, Russia*

Abstract

A high-power infrared free electron laser is under construction in Novosibirsk. As the full-scale machine seems to be complicated and quite expensive, the project was divided into two stages so that the first-stage machine can be assembled and commissioned as soon as possible. Main features of the project and the current status are described.

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1. Introduction

The described free electron laser (FEL) is a high-power continuous-wave IR machine. Its expected average power is ~100 kW. As the efficiency of conventional FEL is small enough and typically does not exceed a few percent, the idea of recuperation of electron energy seems to be very attractive. More important reason for energy recovery is the dramatic reduction of bremsstrahlung from the beam dump. It allows to significantly reduce the thickness of radiation shielding and hence to decrease the total cost of the machine.

One of the possible methods is to return the waste electron beam to the RF accelerating structure, that was used to accelerate it [1]. This

*Corresponding author. +7-383-239-4443; fax: +7-383-234-2163.

E-mail address: s.v.miginsky@inp.nsk.su (S.V. Miginsky).

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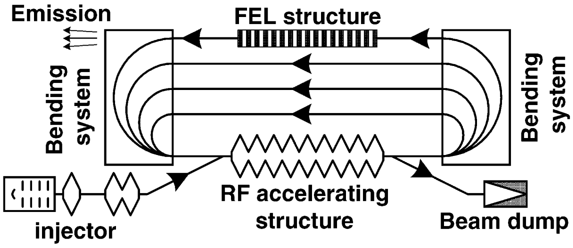

Fig. 1. Basic scheme of FEL with accelerator-recuperator.

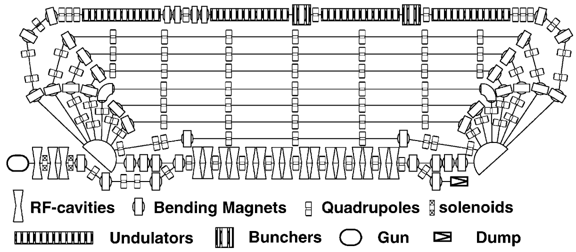

Fig. 2. Schematic layout of accelerator-recuperator.

mode of accelerator operation was demonstrated at the Stanford HEPL [2]. An obvious development of such an approach is the use of a multipass recirculator instead of a simple linac [3,4]. This scheme is shown in Fig. 1. It looks like a racetrack microtron, but the key difference is that this machine operates simultaneously as a decelerator. The total length of the last track is chosen so that the waste bunches are injected in the stable equilibrium decelerating phase into the accelerator-recuperator (AR). Thus, decelerated electrons transfer their energy to the RF accelerating system directly. In other words, the Fourier-component of the total electron current through the accelerating system at the RF accelerating frequency is almost zero. The extraction energy of the waste beam is equal to the injection energy of the accelerating beam, so one should expect the bremsstrahlung from the dump reduced by the factor equal to the squared ratio of the maximum energy and the injection energy. Actually the overall radiation hazard of the machine is caused by beam loss in high-energy tracks.

Another key feature of the machine is the relatively low RF accelerating frequency. It allows to get a better beam quality and greater charge of bunch, with all other factors being equal. Both parameters are extremely significant in getting lasing at lower wavelengths.

2. Full-scale machine

2.1. Accelerator-recuperator

The AR layout is shown in Fig. 2. The electron beam from the injector comes through the injection beamline to the AR, passes eight times through the RF accelerating structure, and gains 98 MeV energy. Then it is directed to the FEL structure, that transfers a small part of electron energy to the emission energy, passes eight more times through the RF accelerating structure in decelerating phase, and goes to the beam dump at the injection energy. The basic parameters of the AR are the following:

Machine itself:	
RF accelerating frequency, MHz	180
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
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

The injector provides electron beam that consists of bunches of charge ≈ 2 nC and repetition rate up to 22.5 MHz. It consists of an electron gun and three RF-cavities. The electron gun is composed of a cathode-grid unit manipulated by a controlled pulser and a 300 kV static linear accelerating tube. It produces electron bunches of ≈ 1 ns duration. One RF-cavity is used for bunching, the other two for accelerating. Each bunch gains time-correlated energy spread in the bunching cavity and is compressed in the drift

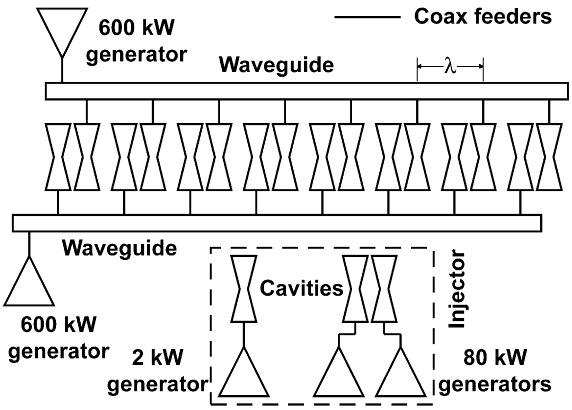

Fig. 3. Scheme of RF system of accelerator-recuperator.

space between the cavities. Then it gains energy in the pair of accelerating cavities. The time-correlated energy spread is also partially compensated there. The injection energy (full) is 2 MeV and the bunch duration is ≈ 100 ps. The RF frequency is the same as in the whole machine. The RF-cavities of the same design are used both in the injector and in the AR itself.

The RF system of the AR contains a number of RF-cavities, RF-generators, waveguides and coaxial feeders (Fig. 3). The RF-cavities of the injector are fed by separate RF-generators and can be manipulated independently. The sixteen cavities of the accelerating structure are divided into two groups, and each one is driven by a 600 kW RF-generator unit. The distance between two consequent RF cavities in a group is the wavelength of RF frequency oscillation. It is also equal to a half wavelength in the waveguide. The waveguide is used as a power distribution unit. The details of RF system design were described in [5].

The orbit geometry of the AR was chosen to meet the following conditions:

(1) the lengths of all orbits (except the last one) are equal to the integer number of the RF wavelengths;
(2) the length of the last orbit differs from the integer number of the RF wavelengths so that an accelerated bunch is injected in the stable decelerating phase after it;
(3) the lengths of all orbits were chosen so that no bunches of different energies pass the accelerating structure simultaneously;
(4) the distances between straight sections are equal;
(5) each 180° bend is achromatic.

The first condition is necessary for synchronous acceleration [3]. (3) is significant to avoid the emittance growth due to space charge effect. Due to this reason the maximum repetition rate is $\frac{1}{8}$ of the RF frequency. (4) allows the minimization of the total width of the machine. The last one eliminates the coupling of horizontal transverse and longitudinal motions and makes focusing more flexible. The splitting magnets are round. The quadrupole lenses inside the 180° bends make them achromatic. Those at the long straight sections are optimized to properly focus on both accelerating and decelerating beams.

Numerical simulations of longitudinal beam dynamics and a transverse one show that instability occurs only at an average electron current over 0.1 A. Due to longitudinal motion in the AR around the equilibrium trajectory (rotation in the longitudinal phase plane) the accelerating bunches are compressed 5–10 times, while their energy spread is increased.

2.2. FEL

The scheme of FEL with electron outcoupling [6] is shown in Fig. 4. The FEL-oscillator is an optical klystron with two undulators, a buncher, and two mirrors. The microbunched (in the FEL-oscillator and an achromatic bend) electron beam passes through the last undulator emitting a part of its energy to coherent undulator radiation. As

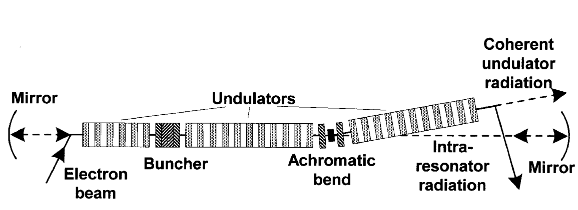

Fig. 4. Scheme of FEL with electron outcoupling.

the electron beam in the radiator is deflected from the axis of the optical resonator, the coherent undulator radiation leaves the resonator.

The main advantage of this scheme is the dramatic decrease of the intra-resonator power compared to the extracted one. To get this advantage, the longitudinal dispersion of the buncher should be high enough to lower the intra-resonator power. The second undulator ought to be sufficiently longer than the first one for the same reason. Then "useful" energy modulation in the second undulator causing bunching in the achromatic bend and the radiator is much more than "harmful" modulation in the first undulator, that increases the effective energy spread in the radiator.

Actually the FEL structure contains four similar undulators, the first three together with two bunchers combine to form the optical klystron. The total length of the optical resonator will be about 40 m (totally placed in the shielded room) or 80 m (one mirror is outside the shielded room). The longer the resonator, the lower is the power density at the mirror surfaces. Also, lower repetition rate is available in this case ($\approx$2 MHz for $\approx$80 m length), which is very significant for a safe adjustment of the machine. Each undulator contains 36 periods of length 90 mm. Their maximum deflection parameter K is about 2, that permits comparably wide tuning of the FEL without changing the electron energy. The reason for using two bunchers is to improve the frequency selectivity and to avoid multi-frequency operation. In a simplest optical klystron, maximum amplification takes place if $s = \left(n - \frac{1}{4}\right)\lambda$, where λ is the wavelength, n an integer, and s the delay of the electron with respect to the wave between the centres of the undulators. In the case of three undulators and two bunchers, two similar conditions for different values of s have to be met. Therefore, the maxima will occur more rarely.

The achromatic bend consists of four bending magnets and a quadrupole lens. The detailed description and results of tests of this achromatic bend are presented in [6,7]. The bending angle is 4 mrad, which is enough to divide the fundamental eigenmode of the resonator and the radiated wave. The bend has to be achromatic to keep the fronts of microbunches perpendicular to the direction of motion. In the other case, no coherent radiation could be obtained from the last undulator.

The basic parameters of the FEL are the following:

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

2.3. Possible applications

The machine is intended for basic and applied research and industrial purposes:

- Physics:
  - semiconductors—admixture levels, excitation, and dynamics of recombination;
  - superconductivity—conductivity zones, and admixtures;
  - optical reflecting surfaces and monomolecular layers;
  - physics of surface;
  - energy transfer to artificial satellites.
- Spectroscopy:
  - rotational and vibrational transitions in molecules;
  - diagnostics of combustion zone;
  - lidar;
  - calibration of IR-sensors.
- Chemistry:
  - selective reactions and isotope separation;
  - dynamics of molecular excitation;
  - laser catalysis;
  - modification of surfaces of polymers.
- Medicine:
  - microsurgery;
  - phototherapy;
  - photodynamic destruction of tumours.

3. First-stage machine

3.1. Accelerator-recuperator

As building up the full-scale machine takes a long time and more resources, it looks reasonabe to divide the project into two stages. The first-stage machine includes the AR with the full-scale RF-system and only one turn of electron beam. Its scheme is shown in Fig. 5. Most important parameters of the first-stage AR are:

Energy of injection and extractions, MeV	2 (full)
Maximum electron energy, MeV	14
Average beam current, mA	up to 50
Accelerating RF-frequency, MHz	180
Bunch duration, ps	20–100
Peak current, A	up to 50

Bunch duration and peak current depends on whether bunching is used in the AR or not. Short bunches with comparably great current and energy spread seem to be not so convenient for a long-wave FEL, but the opportunity of bunching is still provided.

It should be noted that the first-stage machine is placed in the vertical plane while the full-scale one is in the horizontal plane. Thus, both machines can exist at the same time, although they cannot operate simultaneously. Nevertheless, one can choose the machine by switching only the bending magnets, without reassembling the beam-line.

3.2. FEL

A submillimeter-wave FEL will be installed on the single backward track of the AR. The FEL consists of two undulators, a buncher, two mirrors of optical resonator, and an outcoupler. Both undulators are identical. They are electromagnetic planar ones, of length 4 m, period 120 mm, gap 80 mm, and K up to 0.8. One can use one or both undulators with or without the buncher. Both mirrors are identical, spherical, made of polished copper, and water cooled. The outcoupler contains two or four adjustable planar copper mirrors. These mirrors scrape radiation inside the optical resonator and redirect a small part of it to the consumer. This scheme preserves the main mode of the optical resonator well and reduces amplification of higher modes effectively. The buncher is simply a three-pole electromagnetic wiggler.

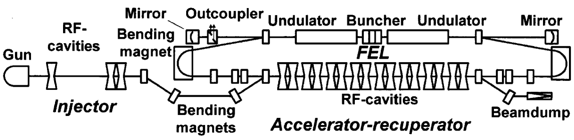

Fig. 5. Schematic diagram of the 14-MeV accelerator-recuperator and the submillimeter FEL.

Basic parameters of the FEL can be estimated as

Wavelength of emitted radiation, μm	100–200
Pulse duration, ps	20–100
Peak power, MW	1–7
Average power, kW	0.6–7

Thus, after commissioning the first stage of the project one gets an operating FEL, and in addition, a unique testing area to work up the technique of recuperation of beam energy and adjustment procedure of the FEL.

3.3. Possible applications

Finally, as the machine is a unique source of radiation of high average power and can be tuned continuously in a broad band, it can be used in various basic and applied researches:

- IR spectroscopy:
  - barriers of the internal rotations in molecules and torsion vibrations;
  - hydrogen bonds and systems with the charge transfer;
  - inorganic complexes;
  - metalorganic compounds;
  - crystalline lattice spectroscopy.
- Electron paramagnetic resonance spectroscopy:
  - some spin systems, that cannot be observed at lower frequencies; these include, for

example $S = 1, 2, 3$, (such as Ni(II) in catalysts and Fe(II) in proteins), and $S = \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$ with large zero-field splitting (e.g. Co(II));

- systems with small g-anisotropy, that requires extremely high fields to make the spectral dispersion significant relative to the line width;
- some samples are available only as small crystals or fibres, so very high sensitivity is needed to study them (examples include protein crystals);
- small molar spin concentration in biomedical samples, that claim high sensitivity.

4. Current status

Recently, necessary reconstruction of the accelerator building was accomplished; the injector for the AR was assembled, adjusted, commissioned and is in operation now; the RF-system of the AR is nearing completion: most parts of RF-cavities are ready for using, others are in the process of manufacturing; assembling of RF-generators will be completed soon, and RF-feeding and anode PS systems were put into production; all other systems of the FEL and the AR are being manufactured too. Then, according to the current situation one can expect the first-stage machine to be started in 2001.

5. Conclusions

- Significant progress in building up the FEL was achieved last year [8].
- It seems to be reasonable to divide the project into two stages, in order to get an operating machine as soon as possible. The first-stage machine is expected to be started in a year.
- Both the first-stage machine and the full-scale one will exist simultaneously.

Acknowledgements

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