THE FREE ELECTRON LASER ACTIVITIES AT THE BUDKER INP

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Abstract

The high power infrared free electron laser is under construction in Novosibirsk. The 2-MeV injector for the accelerator-recuperator has been manufactured and tested recently. The design of the magnetic system was improved significantly to meet better the requirements of potential users. The features of the project and the current status are described. Other FEL-related activities are mentioned.

INTRODUCTION

The Budker Institute of nuclear physics is involved to the free electron laser (FEL) activity since 1977. The theoretical works on the understanding of the FEL physics, in particular the storage ring FEL physics, where performed [1-3]. This understanding leads to the invention of the optical klystron [1, 4], the hybrid permanent magnet undulator [5] and other new devices and techniques [6, 7]. Correspondingly, the use of these inventions in the experiments on the VEPP-3 storage ring enables us to achieve the extremely short (0.24 micron) wavelength [8], extremely narrow ($3 \cdot 10^{-6}$) bandwidth [9] and other interesting results [10, 11]. Nevertheless, the storage ring FELs suffer from the intrinsic power limitation. This is the well-known Renieri limit [2, 3, 12, 13], caused by the increase of the beam energy spread during the interaction with light in the undulator. Therefore for the kilowatt average power range FEL one can not use a storage ring [14].

Typically, the efficiency of the conversion of the beam power to the radiation power is rather small in an FEL, being typically not more than a few percent. For high power applications, therefore, it is necessary to recover the beam power after the FEL interaction. The main reason for the energy recovery, except of simple energy saving, is the dramatic reduction of the radiation hazard at the beam dump.

One of the possible methods of the beam energy recovery is to return the beam to the radiofrequency (RF) accelerating structure, which was used to accelerate it [3, 15]. If the length of path from the accelerator through the FEL to the accelerator is chosen properly, the deceleration of particles will occur instead of acceleration, and therefore the energy will return to the accelerating RF field (in other words, the beam will excite RF oscillations in the accelerating structure together with the RF generator). Such a mode of accelerator operation was demonstrated at the Stanford HEPL [16]. An obvious development of such an approach is the use of multipass recirculator [17, 18] instead of simple linac. By increasing of the number of passes, cost and power consumption can be reduced. However, the threshold currents for instabilities also decrease, so the "optimal" number of passes exists [19]. The general scheme of such FEL is shown in Fig. 1.

The electron beam from the injector 1 enters the RF accelerating structure 2. After the first acceleration in the accelerating structure the beam passes through the magnetic system (bends 3 and focusing quadrupoles), which returns it to the accelerating structure for the second time. To have the acceleration of the beam at each pass though the accelerating structure it is enough

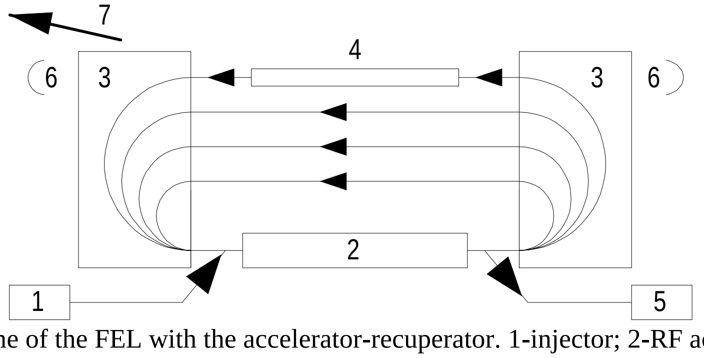

Figure 1. The scheme of the FEL with the accelerator-recuperator. 1-injector; 2-RF accelerating structure 3-180-degree bends; 4-FEL magnetic system; 5-beam dump; 6-mirrors; 7 output light beam.

to choose the orbit lengths to be integer of the RF wavelength (approximately). After several passes through the accelerating structure the beam reach the required energy and enters the FEL magnetic system 4, which is installed in the straight section of the last orbit. Here the small (about 1%) amount of the electron beam power is converted to the light. The exhaust beam returns to the accelerating structure. To provide a deceleration of the exhaust beam instead of an acceleration, the length of the last orbit is approximately half-integer of the RF wavelength. Due to the relatively small energy difference the decelerating beam follows almost the same orbits, as the accelerated one. Finally, the low-energy exhaust beam is absorbed in the beam dump 5. Some desirable features of an accelerator-recuperator are listed below.

1. The ejection (and, correspondingly, the injection) energy is to be less than 10 MeV, to avoid neutron generation in the beam dump.
2. The electron optical system has to provide proper focusing for the accelerating and the decelerating beams. It is not so trivial, as each orbit, except for the last one, is used to transport two beams (accelerating and decelerating) with the different initial conditions simultaneously, and there are many beams with very different energies inside the linac.
3. Energy acceptance is to be a few percents or larger to decelerate the spent electron beam. This can be achieved by employing magnetic system consisting of achromatic bends with low enough transverse dispersion function inside.
4. It is preferable to have a zero transverse dispersion function in the straight line sections to allow the optimization of the betatron phase advances at each orbit to increase the threshold current for the transverse beam breakup.
5. The frequency of the RF system tends to be low to decrease the longitudinal and transverse impedances and increase the longitudinal acceptance. Another advantage of low frequencies is the possibility of using the separated (uncoupled) RF resonators with individual tunes of fundamental and asymmetric modes.

To preserve low transverse emittance it is preferable to have a high peak current only at high energies. So the rotation in the longitudinal phase space by $\pi/2$, $3\pi/2$,... may be useful.

The high power infrared FEL for the Siberian center of photochemical research, which is under construction now, is the implementation of this approach.

ACCELERATOR-RECUPERATOR

The accelerator - recuperator layout is shown in Fig. 2. The 2 MeV electron beam from the injector passes 8 times through the accelerating structure, getting the 98 MeV energy, and comes to the FEL, installed in the last straight section. After the loss of about 1% of its power the beam passes 8 times more through the accelerating structure, returning the power, and comes to the beam dump at the injection energy.

Some parameters of the accelerator are listed in the table:

RF wavelength, m	1.66
Number of RF cavities	16
Amplitude of accelerating voltage at one cavity, MV	0,8
Number of orbits	8
Injection energy, MeV	2
Final electron energy, MeV	98
Bunch repetition frequency, MHz	2 - 22,5
Average current, mA	4 - 50
Final electron energy dispersion, %	0,2
Final electron bunch length, ps	20 - 100
Final peak electron current, A	100 - 20

The 300 keV electron gun of the injector produces the 1 ns electron bunches with a repetition frequency up to 22.5 MHz. It has the DC power supply (rectifier) and termionic cathode with the greed. After passing the modulating RF cavity, the electron bunch is compressed in a drift section down to 200 ps and accelerated up to 2 MeV in the next two RF cavities. After that electrons are injected into the common straight section of the microtron - recuperator, using two pairs of the identical bending magnets with opposite magnetic field signs. At the entrance to the main accelerating system the bunch length is 100 ps. The project of the 300 keV photoinjector was developed [20] to replace the thermionic gun in future.

The accelerating structure consists of 16 RF cavities. Each cavity has mechanical tunings for the fundamental and high order modes. The effective accelerating voltage is 0.8 MV at the thermal power consumption about 0.1 MW. So, the total RF power is near 2 MW. The details of the RF system design and tests were described in paper [21].

The orbit geometry was chosen to meet the following conditions:

- the lengths of all orbits (except of the eighth one) are equal to integer number of the RF wavelength;
- the distances between straight sections are equal;
- each 180 - degree bend is achromatic.

First condition is necessary for synchronous acceleration [17]. The eighth orbit is longer, than the seventh one by 1.45 of the RF wavelength to obtain deceleration at the next eight passes through the RF structure. The second make the design more compact. The third condition eliminates coupling of horizontal betatron and longitudinal motions and makes focusing more flexible. The splitting magnets are round. The quadrupoles into the 180-degree bends makes each of these bends achromatic. The quadrupoles at the long straight sections are optimized to focus properly both accelerating and decelerating beams.

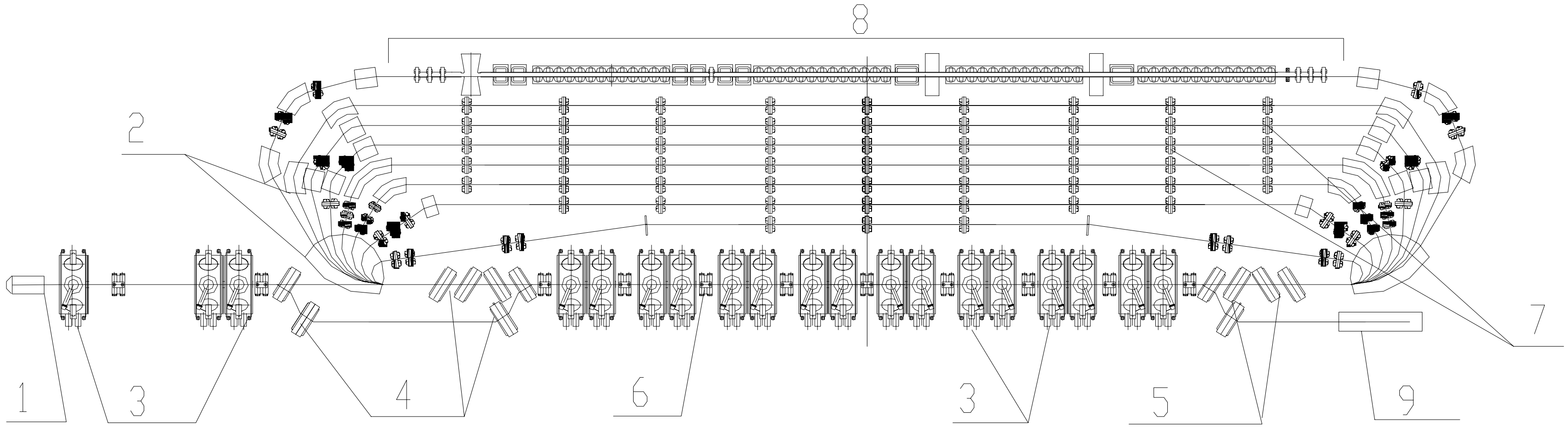

Figure 2. Scheme of the microtron-recuperator (1 - electron gun; 2 - bending magnets; 3 - RF resonators; 4,5 - injection and extraction magnets; 6 - focusing solenoids; 7 - straight sections with the quadrupole lenses; 8 - FEL magnetic system; 9 - beam dump).

The length of the straight sections was chosen such, that, when the electron bunches are injected at every eighth period of the RF voltage (e.g. with a frequency of 22.5 MHz), the bunches under acceleration and deceleration are not overlapping each other on the common track, but fill all available equilibrium phases homogeneously. In this case the interaction of the electron bunches, having various energies, decreases dramatically.

Computer simulations of the longitudinal and transverse beam dynamics show that the microtron - recuperator is capable to operate with an average current above 0.1 A. The final bunching occurs on the last track, and that allows to achieve a high peak current (about 100 A) without significant emittance degradation.

THE FEL MAGNETIC SYSTEM

The scheme of FEL, with the electron outcoupling [22] is shown in Fig. 3. The FEL-oscillator is the optical klystron with undulators 1 and 3, dispersive section 2 and mirrors 6. The microbunched (in the FEL-oscillator and the bend 4) electron beam passes through radiator 5. As the electron beam in the radiator is deflected from the optical cavity axis, the coherent undulator radiation leaves the cavity.

As the FEL is used here only to bunch the electron beam, it has to be optimized for minimal intensity of light on the mirror surfaces. To limit the intracavity power it is convenient to choose a high value of longitudinal dispersion of the dispersive section. In addition, it is preferable to have the second undulator sufficiently longer than the first one. Then «useful» energy modulation in the second undulator, which causes the density modulation in the radiator, is significantly more than « harmful» modulation in the first undulator, which increases the effective energy spread in the radiator. To minimize this increase of the effective energy spread, the intracavity power loss must be minimized (so, mirror reflectivity has to be good).

The actual magnetic system of the FEL consists of four undulators, two bunchers (dispersive sections), and one achromatic bend. The first three undulators and two dispersive sections compose the optical klystron using as a master oscillator. The optical resonator of about 79 m length consists of two mirrors. The number of periods in each undulators is 36, length of the period is 9 cm. To simplify the wavelength tuning we use electromagnetic undulators with the maximum of deflection parameter K about 2. The reason for using of two dispersive sections is to improve the frequency selectivity. To make it clear, consider the two-undulator optical klystron. Let s is the delay of an electron, passing from the middle of the first undulator to the middle of the second one, with respect to the wavefront of light, propagating between these two points (s is also the delay between the wavetrains, emitted by an electron in undulators). The maximum amplification takes place at the wavelengths λ, which satisfy the condition $s = (n - 1/4)\,\lambda$, where n is the integer. If there are two bunchers and three undulators, we must satisfy two similar conditions simultaneously (for two different s_1 and s_2) to obtain the maximum. Therefore, the maxima will occur more rarely. Such a configuration offers fine and fast wavelength tuning.

The magnetic system of the achromatic bend consists of four bending magnets and focusing

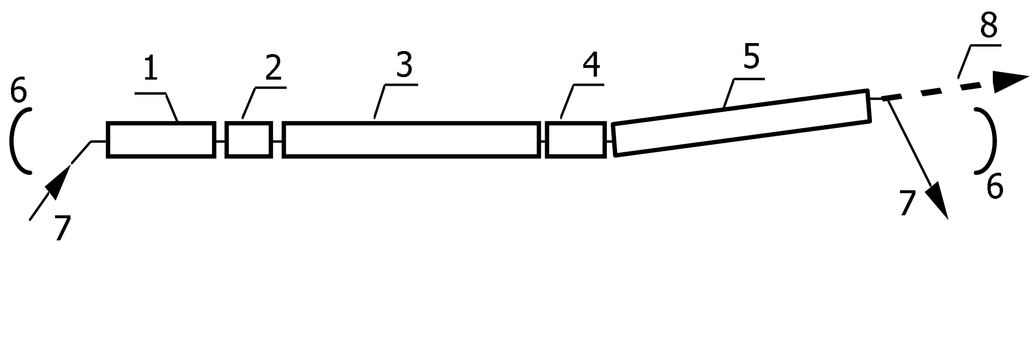

Figure 3. The scheme of the FEL. 1 – first undulator; 2 – dispersive section; 3 – second undulator; 4 – achromatic bend; 5 – undulator-radiator; 6 – mirror;7 – electron beam; 8 – coherent undulator radiation.

quadrupole lens. The detail consideration and results of tests of such achromatic bend are described in papers [22, 23]. Taking into account the angular divergence of the fundamental eigenmode of the optical resonator and of the coherent radiation we chose the 4 mrad deflection angle. The distance between the center of the mirror and coherent radiation axis is 14 cm. The fourth undulator (radiator) is the same, as the previous three, but with slightly lower field amplitude (it is easy, as the undulators are electromagnetic) to maximize the output power [24].

For the initial operation we have chosen the simplest two-mirror optical resonator. Its large length decrease the light intensity on the mirror surfaces and makes possible to obtain oscillation with a low (2 MHz) repetition frequency of the electron bunches. Therefore, we will have a low average power (and therefore, negligible heating of the mirrors), while the peak power will be high. After that we will be able to increase the average power, increasing the repetition rate of the injector pulses.

The FEL radiation will consist of pulses with 10-30 ps duration, 2-22.5 MHz repetition rate, and 2-10 micron wavelength.

THE CURRENT STATUS

The building update is finished now. The 2-MeV electron injector was installed and commissioned recently. The assembly of the RF generators and manufacturing of the RF cavities for the main accelerating structure are in progress.

OTHER FEL-RELATED ACTIVITY

Our last optical klystron OK-4 was transferred from VEPP-3 to the storage ring of Duke university (USA) in 1995. Now this FEL is in operation [25].

The 8-MeV microtron and the undulator for the compact far infrared FEL where build for the Korea Atomic Energy Research Institute [26]. They where commissioned successfully and the spontaneous undulator radiation was detected this spring.

The use of the recirculating accelerator-recuperator with long undulator at the last orbit as the high brightness X-ray source was proposed by G. N. Kulipanov recently [27]. The feasibility study is under way now.

We also participate in the SASE ultraviolet range FEL project in the Argonne National Laboratory (USA) [28].

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