Commissioning of the accelerator-recuperator for the FEL at the Siberian Center for Photochemical Research†

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A 100 MeV eight-turn accelerator-recuperator intended to drive a high-power infrared free-electron laser (FEL) is currently under construction in Novosibirsk. The first stage of the machine includes a one-turn accelerator-recuperator that contains a full-scale RF system. It was commissioned successfully in June 2002.

Keywords: free-electron lasers; accelerator-recuperators.

1. Introduction

The efficiency of the conversion of beam power to radiation power is rather small in a 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 for simple energy saving, is the dramatic reduction of the radiation hazard at the beam dump.

One of the possible methods of beam-energy recovery is to return the beam to the radio-frequency (RF) accelerating structure which was used to accelerate it. This was proposed first by Tigner (1965) for a collider, and then applied to a FEL (Skrinsky & Vinokurov, 1978, 1979). If the length of the path from the accelerator through the FEL to the accelerator is chosen properly, deceleration of particles will occur instead of acceleration, and therefore the energy will return to the accelerating RF field (in other words, the used beam will 'pump' RF oscillations in the accelerating structure together with the RF generator). Such a mode of accelerator operation was demonstrated at the Stanford HEPL (Smith *et al.*, 1987). The first high-power FEL using such an accelerator-recuperator (or energy-recovery linac) was successfully commissioned recently (Neil *et al.*, 2000). An obvious development of such an approach is the use of a multipass recirculator (Rand, 1984; Gavrilov *et al.*, 1991) instead of a simple linac. By increasing the number of passes, the cost and power consumption can be reduced. However, the threshold currents for instabilities also decrease, so an 'optimal' number of passes exist (Vinokurov *et al.*, 1997). The general scheme of such a FEL is shown in Fig. 1.

The high-power infrared FEL for the Siberian Center of Photochemical Research, which is currently under construction, is the implementation of this approach.

Table 1
Main accelerator parameters.

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)	8–100
Final electron energy dispersion (%)	0.2
Final electron bunch length (ns)	0.02–0.1
Final peak electron current (A)	100–20

2. Accelerator

The accelerator-recuperator layout is shown in Fig. 2. The 2 MeV electron beam from the injector passes through the accelerating structure eight times, reaching an energy of 98 MeV, and arrives at the FEL, which is installed in the final straight section. After a loss of about 1% of its power the beam passes through the accelerating structure a further eight times, returning the power, and arrives at the beam dump at the injection energy. Various parameters of the accelerator are listed in Table 1.

The 300 keV electron gun of the injector produces the 1.5 ns electron bunches with charge $2nQ$ and repetition frequency up to 22.5 MHz. It has a DC power supply (rectifier) and termionic cathode with a grid. After passing through 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. The measured emittance of the 2 MeV beam is $4\pi \times 10^{-6}$ m rad and the measured energy spread is less than 15 keV. Then, electrons are injected into the common straight section of the accelerator-recuperator, using two pairs of identical bending magnets with opposite magnetic field signs (injection chicane). At the entrance to the main accelerating system the bunch length is 100 ps. A 300 keV photoinjector project has been developed (Gavrilov *et al.*, 1993) in order to replace the thermionic gun in the 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 a thermal power consumption of about 70 kW. Therefore the total RF power is more

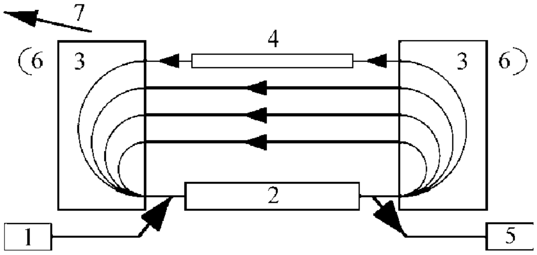

Figure 1
Scheme of the FEL with the accelerator-recuperator. 1, injector. 2, RF accelerating structure. 3, 180° bends. 4, FEL magnetic system. 5, beam dump. 6, mirrors. 7, output light beam.

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Table 2
First-stage accelerator parameters.

RF wavelength (m)	1.66
Number of RF cavities	16
Amplitude of accelerating voltage at one cavity (MV)	0.8
Injection energy (MeV)	2
Final electron energy (MeV)	14
Bunch repetition frequency (MHz)	2–22.5
Average current (mA)	4–50
Final electron energy dispersion (%)	0.2
Final electron bunch length (ns)	0.02–0.1
Final peak electron current (A)	50–10

than 1 MW. Details of the RF system design and tests have already been described (Arbuzov *et al.*, 1993).

The orbit geometry was chosen to meet the following conditions:

(i) the lengths of all orbits (except of the eighth orbit) are equal to an integer number of the RF wavelength;

(ii) the distances between straight sections are equal;

(iii) each 180° degree bend is achromatic.

The first condition is necessary for synchronous acceleration. The eighth orbit is longer than the seventh by 1.45 of the RF wavelength in order to obtain deceleration at the next eight passes through the RF structure. The second condition makes the design more compact. The third condition eliminates coupling of horizontal transverse and longitudinal motions and makes the magnetic lattice more flexible. The splitting magnets are round. The quadrupoles into the 180° bends make each of these bends achromatic. The quadrupoles at the long straight sections are optimized to focus both accelerating and decelerating beams properly.

The lengths of the straight sections were 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 do not overlap each other on the common track (in the accelerating cavities), but fill all available buckets phased homogeneously. In this case the interaction of the electron bunches, having various energies, decreases significantly.

Calculations of the longitudinal and transverse beam dynamics show that the microtron-recuperator is capable of operating with an average current above 0.1 A. The final bunching takes place on the last track, which allows a high peak current (about 100 A) to be achieved without significant emittance degradation. The expected power of the FEL is up to 100 kW.

The potential applications of this FEL are stable isotope separation and development of other prospective photochemical technologies.

3. First stage

The first stage of the machine (Bolotin *et al.*, 2000) is a single-orbit accelerator-recuperator that contains a full-scale RF system but a reduced number of orbits (Fig. 3). The main parameters of the first stage of the accelerator-recuperator are listed in Table 2.

The FEL is installed in the long straight section of the single orbit of the accelerator-recuperator. It consists of two undulators, a magnetic buncher, double-mirror optical resonator, and an outcoupling system. The two undulators are identical. They are electromagnetic planar undulators, of length 4 m, period 120 mm, gap 80 mm, and the deflection parameter K can be as high as 1.2. One or both undulators can be used with or without the magnetic buncher. Both mirrors are identical, being spherical, made of gold-plated copper and water-cooled. The outcoupling system contains four adjustable planar 45°-tilted copper mirrors (scrapers). These mirrors

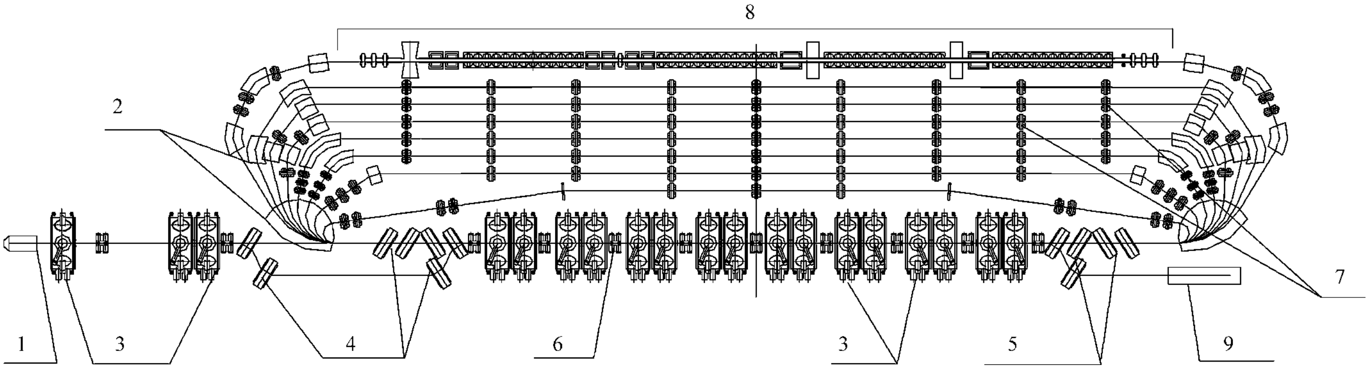

Figure 2
Scheme of the microtron-recuperator. 1, electron gun. 2, bending magnets. 3, RF resonators. 4, 5, injection and extraction magnets. 6, focusing quadrupoles. 7, straight sections with quadrupole lenses. 8, FEL magnetic system. 9, beam dump.

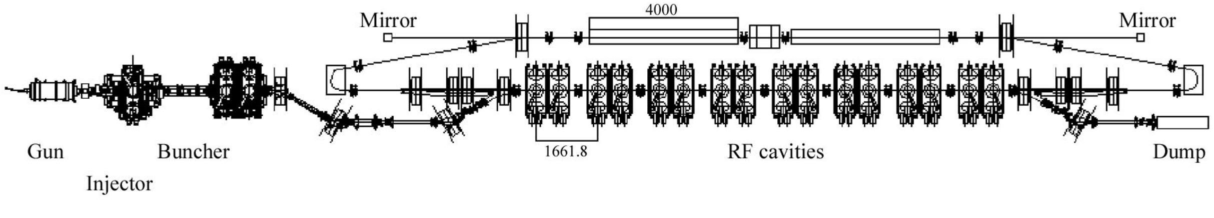

Figure 3
Scheme of the first stage of the high-power FEL. Dimensions in mm.

Table 3
Expected radiation parameters.

Wavelength (mm)	0.1–0.2
Pulse length (ns)	0.02–0.1
Peak power (MW)	1–7
Average power (kW)	0.6–7

scrape radiation inside the optical resonator and redirect a small part of it to the user. 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. It is necessary to optimize the relative phasing of the undulators.

The expected radiation parameters are shown Table 3.

Reliable operation of the 2 MeV injector at an average current of 50 mA was achieved in 2001. Commissioning of the first stage of the accelerator-recuperator was carried out successfully in June 2002. The maximum beam current in the energy-recovery mode was 10 mA. Current losses are now less than 5%, but further reduction is planned. The first lasing was obtained at a wavelength of 120 μm in April 2003.

4. Fourth-generation X-ray source

The idea of a diffraction-limited fourth-generation X-ray source, based on the use of long undulators and high-quality electron beams (*i.e.* low emittances, low energy spread and significant current) in a multiturn accelerator-recuperator source (MARS), was recently proposed (Kulipanov *et al.*, 1997, 1998; Kayran *et al.*, 1998). This scheme combines the main advantages of a storage ring (low radiation hazard and relatively low RF power consumption) and a linac (low normalized emittance and energy spread can be conserved during the acceleration process). The time of acceleration in the accelerator-recuperator is small in comparison with the radiation dumping time in a storage ring (10^3–10^4 times); therefore diffusion processes (quantum fluctuation of synchrotron radiation in arcs and intrabeam scattering) cannot ‘spoil’ the emittance and energy spread. Energy recovery is necessary for such a project because at energies of several GeV the beam power is significant and reduction of radiation hazards is one of the critical issues of the project.

Our eight-turn accelerator recuperator for FELs can serve as a low-energy prototype for MARS.

5. Conclusion

Accelerator-recuperators are a new step in accelerator technology. They have become possible owing to significant progress in the CW RF accelerating systems. Their possible applications are very wide† and the prospects are very promising.

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† In addition to the radiation source applications mentioned in this paper, nuclear physics experiments using the internal-target technique at accelerator-recuperators have been recently proposed (Dmitriev *et al.*, 2000).

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