ACCELERATOR-RECUPERATOR FOR HIGH POWER FREE ELECTRON LASER

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Abstract

A 100-MeV 8-turns accelerator-recuperator intended to drive a high-power infrared free electron laser (FEL) is under construction in Novosibirsk now. The first stage of the machine includes one-turn accelerator-recuperator that contains full-scale RF-system. It was commissioned successfully in June 2002.

1 INTRODUCTION

The efficiency of 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. It was proposed first by M. Tigner [1] for collider, and after that applied to FEL [2,3]. 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 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 [4]. The first high power free electron laser using such accelerator-recuperator (or energy recovery linac) was successfully commissioned recently [5]. An obvious development of such an approach is the use of multipass recirculator [6,7] 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 [8]. The general scheme of such FEL is shown in Fig.1.

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

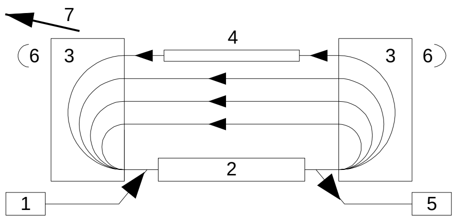

Figure 1: The scheme of the FEL with the accelerator-recuperator. 1-injector; 2-RF accelerating structure 3-180-degree bends; 4-FEL magnetic system; 5-beam dump; 6-mirrors; 7-output light beam.

2 ACCELERATOR

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 1:

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

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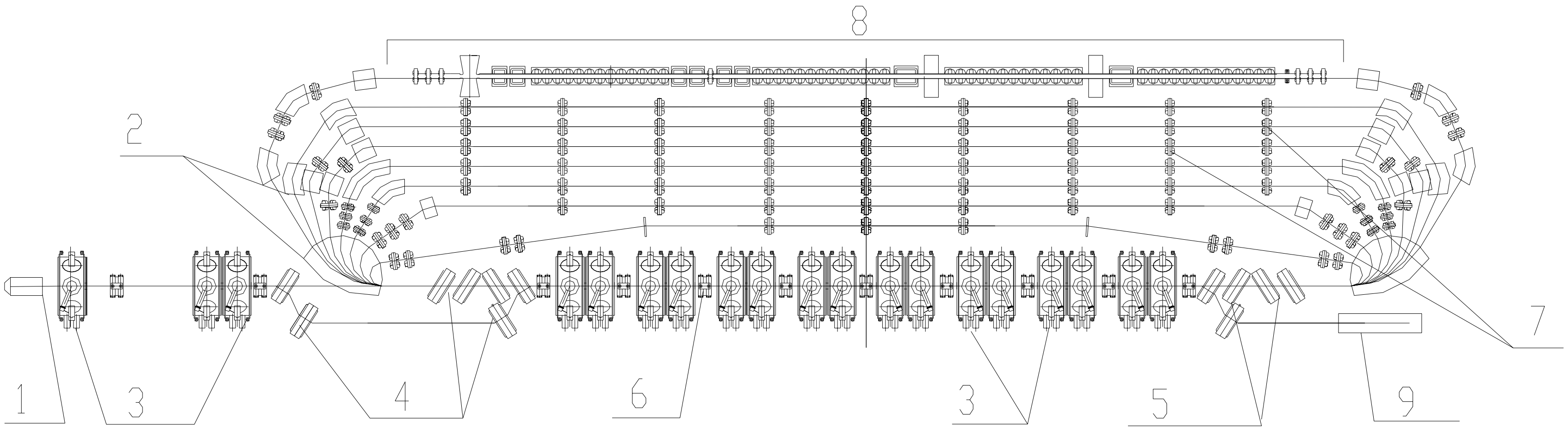

Figure 2. Scheme of the microtron-recuperator (1 - electron gun; 2 - bending magnets; 3 - RF resonators; 4,5 – injection and extraction magnets; 6 - focusing quadrupoles; 7 - straight sections with the quadrupole lenses; 8 - FEL magnetic system; 9 - beam dump).

The 300 keV electron gun of the injector produces the 1 ns electron bunches with charge 2nQ and 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. The measured emittance of the 2 MeV beam is 4π 10-6 m·rad and the measured energy spread is less than 15 keV. After that electrons are injected into the common straight section of the accelerator-recuperator, using two pairs of the identical bending magnets with opposite magnetic field signs (injection chicane). At the entrance to the main accelerating system the bunch length is 100 ps. The project of the 300 keV photoinjector was developed [9] 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 70 kW. So, the total RF power is more than 1 MW. The details of the RF system design and tests were described in paper [10].

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. 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 condition makes the design more compact. The third condition eliminates coupling of horizontal transverse and longitudinal motions and makes magnetic lattice more flexible. The splitting magnets are round. The quadrupoles into the 180-degree bends make each of these bends achromatic. The quadrupoles at the long straight sections are optimized to focus properly both accelerating and decelerating beams.

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 are not overlapping each other on the common track (in the accelerating cavities), but fill all available buckets phases 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 to operate with an average current above 0.1 A. The final bunching takes place on the last track, and that allows to achieve a high peak current (about 100 A) without significant emittance degradation. The expected power of the FEL is up to 100 kW.

3 FIRST STAGE

The first stage of the machine [11] is a single-orbit accelerator-recuperator, that contains full-scale RF-system, but reduced number of orbits (Fig. 3).

Main parameters of the first stage of accelerator-recuperator are listed in Table 2.

Table 2: The 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

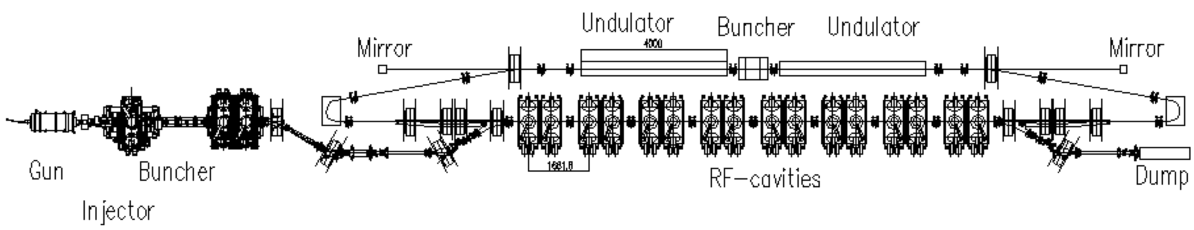

Figure 3. Scheme of the first stage of the high power free electron laser.

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, two mirrors of optical resonator, and an outcoupling system. Both undulators are identical. They are electromagnetic planar ones, of length 4 m, period is 120 mm, gap is 80 mm, and deflection parameter K is up to 1.2. One can use one or both undulators with or without the magnetic buncher. Both mirrors are identical, spherical, made of gold plated copper, and water-cooled. The outcoupling system contains four adjustable planar 45 copper mirrors (scrapers). These mirrors scrape radiation inside the optical resonator and redirect small part of it to user. This scheme preserves the main mode of 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 undulators.

The expected radiation parameters are shown Table 3.

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

The reliable operation of the 2 MeV injector at average current 50 mA was achieved last year. The measured beam parameters are suitable for the FEL operation. The commissioning of the first stage of accelerator-recuperator was done successfully in June 2002. The commissioning of FEL is expected by the end of 2002.

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 (i.e. low emittances, low energy spread and significant current) electron beams in Multiturn Accelerator-Recuperator Source (MARS), was proposed recently [12,13]. This scheme combines the main advantages of storage ring (low radiation hazard and relatively low RF power consumption) and linac (low normalized emittance and energy spread can be conserved during the acceleration process). 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) can not “spoil” emittance and energy spread. The energy recovery is necessary for such a projects, as at several-GeV energies the beam power is significant and the reduction of the radiation hazard is one of the critical issues of the project.

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

5 CONCLUSION

Accelerators–recuperators are the new step in accelerator technology. They became possible due to a significant progress in the CW RF accelerating systems. Their possible applications are very wide [2] and the prospects are very promising.

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[2] In addition to radiation source applications, mentioned in this paper, the nuclear physics experiments using internal target technique at accelerators-recuperators were proposed recently [14].