The Storage Ring Free Electron Lasers

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Abstract

The basic physical limitations on the parameters of FELs installed on storage rings are described. The prospects of these devices and projects of dedicated storage rings for FELs are discussed.

1. INTRODUCTION

Free electron lasers are devices where the energy of a relativistic electron beam converts to coherent electromagnetic radiation when the particles pass through a special magnetic system with an alternating periodic magnetic field (undulator). The appropriate electron beams are produced using accelerators of various types.

In the case of using electron storage rings, the FEL undulator is positioned in a straight section and the same electrons pass periodically through the FEL and interact with radiation in the undulator. Such a situation gives two attractive peculiarities. First, a high average power (the product of the average current and the energy divided by the electron charge) of the beam, which is reactive for this case. For example, at an energy of 1 GeV and a current of 0.1 A we obtain a power equal to 100 MW. The production of a beam of such power on other types of accelerators is very complicated and rather expensive. Second, owing to radiation damping in electron storage rings, beam emittances (transverse and longitudinal) can be fairly small, thereby allowing the creation of short-wavelength FELs (including the ultraviolet range). On the other hand, these advantages are likely to be illusory. Multiple interactions of the same electrons with radiation lead to "heating" of the electron beam and to a specific restriction of radiation power, and, as a consequence, the first advantage is reduced to a minimum. Progress in the development of electron guns (in particular, guns with photocathodes) has allowed the production of beams with a brightness considerably higher than that of the beams generated by storage rings. On the other hand, the FEL on an electron storage ring is the shortest wavelength FEL and the only tunable CW laser in the ultraviolet. This allows us to hope that the building of dedicated (optimized for this problem) storage rings will offer the possibility to design FELs of this type, which are applicable to science, technology, medicine and other fields of activity.

2. RESTRICTIONS IN POWER

We will consider a free electron laser installed at the straight section of an electron storage ring. Assuming the main information known from FEL and cyclic accelerator physics, we will confine ourselves to some specific effects occurring in such devices. This situation is characterized by multiple passage of the same electrons through the FEL and a high duty factor (100 - 1000) of the electron current.

Due to the interaction of electrons with the radiation field in the optical cavity, the energy of outcoming electrons proves to be modulated with the frequency of the optical radiation. For a "weak" field in the resonator (this is the case realized in storage ring FELs), an appropriate addition to the electron energy is insignificant compared to the energy spread σ in the electron beam. Because of the smallness of the radiation wavelength, $\lambda \ll \alpha\pi\sigma/E$ (π is the circumference of the storage ring, E is the mean electron energy, and α is the momentum compaction factor), the energy and the longitudinal coordinate of the beam particles stop to correlate nearly completely with the moment of the next beam radiation interaction in the FEL. In this case, the energy spread grows diffusively. Radiation damping of synchrotron oscillations gives rise to the equilibrium state. For the optimized parameters of the device, a simple estimation of the maximum average power can be made [1-4]:

$$P \approx P_{SR} \frac{s_{max}}{E} \qquad (1)$$

where P_{SR} is the SR power and σ_{max} is the maximum admissible energy spread.

3. PROSPECTS

Now we will discuss the prospects of FELs at storage rings (see also ref. [5, 26, 27]). The most important problem is the limitation on average power (eg.(1)). It seems that due to the limited dynamic aperture σ_{max}/E can not exceed 1%. To increase the SR power, it is desirable to raise the electron energy, E, because the losses in electron energy per turn, W, are strongly dependent on E:

$$W = \frac{4p}{3}\left(\frac{E}{mc^2}\right)^3 er_e H \qquad (2)$$

where r_e is the classical electron radius, and H is the field in the storage ring magnets (for simplicity, the field is assumed to be equal in all magnets). There are three other reasons for the increase of energy. First, as the energy grows, the current thresholds of the instabilities of the electron beam also grow strongly, thus allowing an increase of the electron current *I*. Second, the probability of intrabeam electron scattering (Toushek effect) decreases, hence the contribution of this process to the inverse lifetime of electrons becomes less. Third, the scattering of electrons by the atoms of the residual gas also contributes to the inverse lifetime to a lesser extent, and this makes it possible to decrease the aperture of the vacuum chamber. The small aperture of the vacuum chamber at the location of the FEL allows the improvement of the parameters of the magnetic and electrodynamical systems of free electron lasers.

A conventional storage ring usually consumes more than 1 MW (from the mains). Modern RF systems are able to transfer P_{SR} = 1MW to the circulating electron beam. In this case, the radiation power of a FEL will be up to 10 kW, and thus the corresponding efficiency from the mains is about 0.1%. Assuming the average current in the storage ring to be equal to 1 A, we obtain W = 1 MeV. Using eq.(2) at H = 18 kG (nonsuperconducting magnets), we have E = 2.8 GeV, while at H = 6 kG (superconducting magnets) E = 1.8 GeV. The magnetic system of the storage ring VEPP-3, which was built at the INP 20 years ago, is an illustration of the former type of magnetic system [6]. A magnetic system of the latter type may be illustrated by that being developed for SR source intended for X-ray angiography [7]. Both machines are rather compact: the overall dimensions of VEPP-3 are 18 m x 30 m, and those of the superconducting storage ring are a little less. There are, however, two circumstances which prevent further increase of the electron energy. The first is the increase in the horizontal transverse emittance of the electron beam ε_x. This sets a lower bound on the range of FEL wavelengths: $\lambda > \varepsilon_x$. For VEPP-3, $\varepsilon_x = 0.7$ µm at energy of 3 GeV corresponding to a 1 MeV loss per turn. For the superconducting storage ring $\varepsilon_x \sim 0.1$ µm. The above magnitudes of the emittances refer to the particular magnetic systems. Optimization of the magnetic systems of the storage rings, which is aimed at minimizing the emittance [8, 9], enables (at the expense of a certain complication of the magnetic lattice) the emittance to be reduced by a factor of tens and the limitation on the energy increase in such storage rings to be eliminated. The second limitation is connected with the fact that the wavelength of a fundamental harmonic of undulator radiation depends on the electron energy

$$l = \frac{d}{2g^2}\ (1 + K^2 + \theta^2\gamma^2) \qquad (3)$$

where $\gamma = E/mc^2$ is the relativistic factor, θ the angle at which radiation is observed, d the undulator period,

$$K = \frac{ed}{2pmc^2}\sqrt{<H^2>} \qquad (4)$$

the deflection parameter, and $<H^2>$ is the square of the transverse magnetic field which is averaged along the undulator axis. The axis of the optical resonator in a FEL, the undulator axis and the mean orbit of electrons in the undulator usually coincide. In this case, θ = o, and for the given wavelength λ and electron energy E we derive the condition for the parameters of an undulator:

$$d(1 + K^2) = 2\gamma^2\lambda \qquad (5)$$

It is clear that at high energies the condition of eq.(5) is "easier" for short wavelengths λ and, hence, we choose $\lambda = 0.1$ µm. For shorter wavelengths, radiation is absorbed considerably more strongly in materials, thus making it impossible (at least for the time being) to fabricate mirrors for the FEL optical resonator with a reflectivity close to unity. At E = 1.8 GeV, we obtain $d(1 + K^2) = 2.5$ m. This is easily achieved, for example, at d = 0.1 m and $\sqrt{<H^2>} = 5.2$. kG. Thus large K are required for FEL performance at high energy. As known [10, 11], the power of spontaneous emission on the harmonics of the fundamental wavelength (eq. (3)) is relatively high at large K; note that for $K \gg 1$ and large harmonic numbers this radiation converts to conventional SR. Arriving at the front mirror of the optical resonator, such radiation spoils the mirror (for details see ref. [12, 13]. At high electron energies, high K and electron currents, the situation worsens dramatically. One of the possible solutions is to use helical undulators [14]. The bulk of the radiation power from ϕ in such undulators is concentrated near $\theta = K/\gamma$. The radiation at the fundamental harmonic is concentrated in the vicinity of $\theta = 0$ with the angular spread $(1/\gamma)\sqrt{(1+K^2)/N}$ (N is the number of undulator periods), which is considerably less than K/γ at $N \gg 1$. Thus, it is possible to provide conditions under which only the "useful" portion of radiation arrives at the mirror. So, we see that the condition of eq. (5) can be fulfilled for short wavelengths, but sets an upper bound on the wavelength range.

To extend this range, the electron energy can be somewhat reduced, compensating for the decrease in energy losses per turn. For this purpose, either additional superconducting wigglers could be installed at the equilibrium orbit of the storage ring, or a major magnetic system with an alternating magnetic field could be used. For example, to decrease the storage ring energy down to 1 GeV, it suffices either to position a 20 m long superconducting wiggler with a 60 kG rms field, or to make a four-fold increase in the number of bending magnets in the superconducting storage ring. To generate long wavelength radiation, we may use the ϕ-dependence of λ in eq. (3). For example, we insert a waveguide inside the undulator (let the waveguide comprise two conducting planes which are at a distance α from each other). For the lowest H-wave, we have $\theta = \lambda/2a$. At $\lambda \to \infty$, from eq. (3) we obtain $\lambda = 4a^2/d$. Another possibility to generate long wavelength radiation is to use a Cherenkov FEL [15, 16] (to be more precise, a Cherenkov optical klystron to provide electron bunching at high energy).

4. EXPERIMENTAL RESULTS

We will consider briefly the basic results of FEL experiments. In 1983, induced radiation was first generated using an optical klystron at the ACO storage ring (Orsay, France) [17]. The average power achieved by this device is 30 mW (we present the power taken away from the electron beam) and the giant pulse regime was demonstrated. Coherent radiation was produced in the 0.655-0.463 µm range. In this case, the generation bandwidth was about 1 A. In addition, experiments were made on the generation of radiation harmonics of an outer solid laser at the 0.177 µm and 0.106 µm wavelengths. A detailed description of these experiments may be found in ref. [18].

In 1988, induced radiation generation was achieved using the bypass of VEPP-3 within the 0.69-0.24 µm range. Further shortening of the wavelength is limited only by the absence of the appropriate mirrors. The maximum average power was roughly equal to 5 mW. The duration of the light pulses (about 0.2 ns) was measured with a dissector [19] and observations were made concerning the change of the longitudinal electron distribution in the bunch as a result of the interaction between the electrons and the radiation in the optical resonator. Thus, the measured increase in the energy spread up to $\sigma/E = 1 \times 10^{-3}$ is in agreement with the calculated value and with the value of the radiation power. In the regime of giant pulse generation we obtained a maximum mean-inmacropulse power equal to 20 W for light (0.63 μm) and to 5 W for ultraviolet (0.25 μm). Taking into consideration that the repetition frequency is 8 MHz, i.e., a duty factor of 625, we obtain peak powers equal to 12 kW for red light and 4 kW for ultraviolet. The "natural" bandwidth of the radiation was 0.5 Å. After a glass plane-parallel plate of 1.2 mm thick was placed inside the optical resonator, we succeeded in narrowing the band to 0.03 Å (without any substantial reduction in power). The results obtained are consistent with the calculations. A thorough description of the work we have done is presented in refs. [20-22].

In 1989 the optical klystron installed at the new positron storage ring SUPER ACO was put into operation [23]. For the time being, the experiments are being performed at wavelengths of 0.63 μm and 0.37 μm. The mean power obtained amounts of 300 mW. The high energy (600 MeV) contributes to obtaining this relatively high power.

In 1991 the group from Electrotechnical Laboratory (Tsukuba, Japan) obtained oscillations in their optical klystron on storage ring Teras. The experiments with FEL are also performed on UVSOR (Institute of Molecular Sciences, Okazaki, Japan).

We would like to mention the trend towards increasing energy in storage rings for FELs: the FEL at ACO operates at energies of 150 to 250 MeV. VEPP-3 at 350 MeV, and SUPER ACO at 600 MeV. In the USA and Germany, dedicated storage rings for FELs at 1-1.5 GeV energy are being constructed [24,25].

5. THE DEDICATED STORAGE RING PROJECT

Now we will discuss the project of the dedicated FEL storage ring developed in our Institute. It is based on specially designed components. First, the superconducting bending magnets with magnetic field 65 kGs and bending radius 0.5 m. Second, the RF system with frequency 180 MHz. Third, the long electromagnetic helical undulator. The storage ring is racetrack with two achromatic 180 degree bends and the fourteen metres straight line sections between them. Each achromatic bend contains two 90 degree magnets. The main parameters of the machine are listed below:

Energy	0.97 GeV
Losses per turn (in the bends)	160 keV
Momentum compaction	0.04
Energy spread	1.1×10^{-3}
Horizontal emittance	6×10^{-5} cm
RF voltage	800 kV
Bunch length (standard deviation)	3 cm.

I suppose it is possible to have a few hundred Watts of the FEL radiation power with this storage ring. For operation of this machine in UV, it is preferable to decrease emittance by decreasing energy and by strong betatron coupling.

6. CONCLUSION

Thus we have seen that the gap in power between the existing FELs at storage rings and those of the near future is four orders of magnitude. This is not so much if one takes into account the speed at which today's FELs are being installed at storage rings intended for other purposes. The progress in accelerator techniques, which is due to the creation of "wide use" SR sources, gives the hope that the cost of FELs under discussion will be quite reasonable. The most probable spectral range for such FELs is the wavelength range from near infrared to ultraviolet. In this region they have sufficient advances in comparison with FELs on linacs and microtrons from the reasons of radiation hazard and the power consumptions.

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