Laser-Electron Storage Ring

Zhirong Huang and Ronald D. Ruth
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 30 September 1997; revised manuscript received 9 December 1997)

A compact laser-electron storage ring (LESR) is proposed for electron beam cooling or x-ray generation. The LESR uses an intense laser pulse stored in a high-finesse resonator to interact repetitively with a circulating electron beam in the energy range from a few MeV to a few hundred MeV. The rapid damping caused by laser-electron interaction counterbalances the intrabeam scattering effect, thus allowing electron beams with relatively low energy to be cooled or stabilized in the storage ring to very low transverse emittances. Intense x rays are produced simultaneously from Compton backscattering and can be used for x-ray lithography and other applications. [S0031-9007(97)05245-9]

PACS numbers: 29.20.Dh, 07.85.Fv, 29.27.Eg

Many schemes of laser-electron interaction have been proposed for various applications such as compact x-ray sources [1–4], γ-γ colliders [5], and electron-beam diagnostics [6]. The basic principle is Compton (or Thomson) scattering off a high-energy electron beam with an intense laser pulse to produce the desired photon spectrum. Recent experiments at SLAC [7] and LBNL [8] have shown the practicality of such schemes. More recently, Telnov pointed out [9] that the process of laser-electron interaction is also a radiation damping process for the phase space of the electron beam and can be used to "cool" multi-GeV electrons.

In this Letter we propose a laser-electron storage ring (LESR) where the radiative laser cooling (RLC) [10] is used to overcome the intrabeam scattering (IBS) effect [11] encountered in a circular machine when the beam energy is only a few MeV up to a few hundred MeV. The LESR makes use of both electron beam storage ring technology as well as laser developments. The basic idea is shown in Fig. 1. An electron beam is injected into a storage ring and at the same time an intense laser pulse is built up inside a high-finesse optical resonator. The laser light path is chosen to match exactly the time it takes for the electron to circulate once around the ring so that an electron beam repeatedly encounters the light pulse at the focus of the resonator each turn. Normally, in the absence of the laser the electron beam would damp at the rate determined by the time it takes to radiate its complete energy in the bending magnets in the ring. In the LESR, the laser pulse acts like an extremely strong damping wiggler or undulator, and the fast radiative laser cooling leads to a very low emittance beam for very moderate electron energy (around 100 MeV). As the beam circulates around the ring, the lost energy is restored by an rf accelerating system, just the same as in a normal storage ring. This cooling effect can be also utilized as a stabilization mechanism to maintain a highly intense bunch of electrons for Compton scattering, even when the energy range of these electrons is less than 10 MeV. Therefore, such a compact LESR can be configured either for the production of low emittance electron beams or as a high intensity x-ray source.

Radiative laser cooling of electron beams is very similar to radiation damping in a bending magnet. When an electron counter-propagates through an intense laser pulse, it radiates energy in the form of scattered photons. The laser field acts like a static wiggler or undulator with the peak magnetic field given by [3]

$$B_W = \frac{2}{c}\sqrt{2Z_0 I}\,, \tag{1}$$

where I is the laser intensity, and $Z_0 = (c\epsilon_0)^{-1} = 377\ \Omega$ is the free space impedance. The factor of 2 in front of Eq. (1) is due to the addition of the magnetic and electrical forces in the electromagnetic wave. The radiated power becomes [12]

$$P_\gamma = \frac{4\pi\epsilon_0}{3}\, r_e^2 c^3 \gamma^2 B_W^2 = \frac{32\pi}{3}\, r_e^2 \gamma^2 I\,, \tag{2}$$

where $r_e = e^2/4\pi\epsilon_0 mc^2 \simeq 2.82 \times 10^{-15}$ m is the classical radius of the electron and γ is the electron energy in units of the rest energy mc^2. On the average, the electron

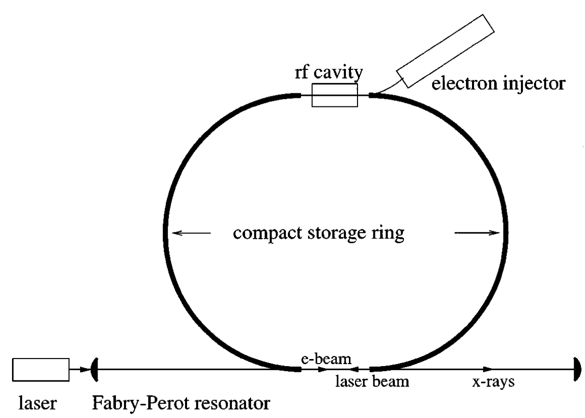

FIG. 1. The schematic diagram of a laser-electron storage ring.

0031-9007/98/80(5)/976(4)$15.00
© 1998 The American Physical Society

loses momenta in all three degrees of freedom to the scattered photons, and the normalized emittances damp proportionally to the energy decrement. Telnov estimated [9] that a 5 GeV electron can lose 90% of its initial energy in one single passage of a laser pulse with a flash energy of a few J. Thus, the normalized transverse emittances (in both x and y directions) of the electron beam would be reduced by a factor of 10. However, the energy spread induced in the process is quite large (more than 10%), and long sections of linac with a large energy gain are required to reaccelerate the beam back to its initial high energy. To significantly reduce the emittance, multiple cooling stages with special focusing systems would be necessary. Thus, this scheme does not seem very practical.

For electrons in the energy range around 100 MeV, this single-pass damping is not effective because the energy loss rate depends strongly on γ in Eq. (2). Nevertheless, using an intense laser pulse, the laser-electron interaction can still induce an energy loss which is a sizable fraction of the electron energy. In order to achieve a few e foldings of transverse damping, we can recirculate the electron beam with a storage ring and the laser pulse with a Fabry-Perot resonator that consists of highly reflective mirrors, and then let them interact for thousands of times. The beam dynamics in such a storage ring is somewhat different from a normal storage ring because of the existence of radiative laser cooling and the significant space charge effects in the energy range we consider.

The central part of this idea is the interaction between the electron and the laser beams. To illustrate the underlying physical effects, let us consider an electron encountering a focused Gaussian laser pulse near its transverse center (see Fig. 2). Suppose that the laser pulse length is short compared with the Rayleigh range of the optical resonator Z_R, and that the energy of the electron remains approximately constant during the interaction. For a given laser flash energy $E_L \equiv \int I\,dx\,dy\,dz/c$, the energy loss of the electron after passing through the laser pulse is

$$(\Delta E)_\gamma = \int P_\gamma \frac{dz}{2c} = \frac{32\pi}{3} r_e^2 \gamma^2 \frac{E_L}{Z_R \lambda_L}, \qquad (3)$$

where λ_L is the wavelength of the laser.

Let n_d be the number of turns needed to damp away the electron's initial energy E. In practical units, we can write

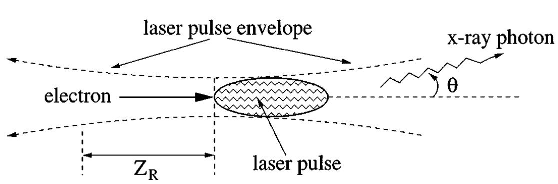

FIG. 2. The laser-electron interaction region.

$$n_d \equiv \frac{E}{(\Delta E)_\gamma} \simeq \frac{1.6 \times 10^5 \lambda_L[\mu\text{m}] Z_R[\text{mm}]}{E_L[J] E[\text{MeV}]}. \qquad (4)$$

As an example, with the laser energy $E_L \simeq 1$ J and wavelength $\lambda_L \simeq 1\ \mu$m, the Rayleigh range $Z_R \simeq 1$ mm, and the electron energy 100 MeV, it takes about $n_d = 1600$ turns for the electron to damp one e-folding. If T_{rev} is the revolution time of the electron beam around the ring, the average damping rate to the normalized transverse emittances $\varepsilon_{x,y}^n$ is given by

$$\Gamma_{x,y}^{\text{RLC}} \equiv -\frac{1}{\varepsilon_{x,y}^n} \left\langle \frac{d\varepsilon_{x,y}^n}{dt} \right\rangle = \frac{1}{n_d T_{\text{rev}}} = \frac{\Delta E_\gamma / E}{T_{\text{rev}}}. \qquad (5)$$

The laser-electron interaction also gives rise to quantum excitation of the transverse emittances. The quantum statistical nature of photon scatterings can in principle have two effects on the transverse dynamics of the electron, a random displacement of the reference orbit that depends on the energy of the electron (the dispersion effect), and a sudden change of direction if the scattered photon does not exactly follow the electron motion (the opening-angle effect). Both effects can contribute to the diffusion of the betatron amplitudes. Since the interaction region is designed to be free of dispersion, and the maximum wiggling angle of electrons in the laser pulse under consideration is much less than $1/\gamma$ (this corresponds to the laser parameter $a \equiv eB_W\lambda_L/4\pi mc \simeq 8.55 \times 10^{-10}\sqrt{I[\text{W/cm}^2]}\,\lambda_L[\mu\text{m}] \ll 1$), we can neglect the dispersion effect and treat the laser pulse as an equivalent magnetic undulator. Thus, we have the number of scattered photons into a given bandwidth $d\omega$ [12]

$$\frac{dN_\gamma}{d\omega} \equiv \frac{1}{\hbar\omega}\frac{dE_\gamma}{d\omega} = \frac{3(\Delta E)_\gamma}{\hbar\omega_m^2}\left[1 - 2\left(\frac{\omega}{\omega_m}\right) + 2\left(\frac{\omega}{\omega_m}\right)^2\right], \qquad (6)$$

where $(\Delta E)_\gamma$ is given by Eq. (3), and $\omega_m = 4\gamma^2\omega_L = 8\pi\gamma^2 c/\lambda_L$ is the maximum photon frequency. The photon frequency ω and the scattering angle θ of the photon with respect to the direction of the electron trajectory are related through $\omega = \omega_m/(1 + \gamma^2\theta^2)$.

The electron receives a transverse recoil from the scattered photon and changes its direction by $\delta\psi = \hbar\omega\theta/E$. Integrating over the photon spectrum and projecting onto the x and y planes, we obtain an average diffusion of the transverse normalized emittances per turn

$$\Delta(\varepsilon_{x,y}^n) = \frac{\gamma\beta_{x,y}^*}{2}\int_0^{\omega_m} d\omega \frac{(\delta\psi)^2}{2}\frac{dN_\gamma}{d\omega} = \frac{3}{10}\frac{\lambda_c}{\lambda_L}\frac{(\Delta E)_\gamma}{E}\beta_{x,y}^*, \qquad (7)$$

where $\beta_{x,y}^*$ is the electron beta function (or the depth of focus) in the x or y direction at the laser-electron interaction region, and $\lambda_c = h/mc \simeq 2.43 \times 10^{-12}$ m is the Compton wavelength of the electron. Since quantum excitation from the rest of the storage ring is negligible at the energy range we consider, the average quantum excitation rate becomes

$$\left\langle \frac{d\varepsilon^n_{x,y}}{dt} \right\rangle_{\rm QE} = \frac{3}{10}\,\frac{\lambda_c}{\lambda_L}\,\frac{(\Delta E)_\gamma}{E}\,\frac{\beta^*_{x,y}}{T_{\rm rev}}\,. \tag{8}$$

The balance between the damping rate Eq. (5) and the excitation rate Eq. (8) leads to the minimum normalized transverse emittances

$$(\varepsilon^n_{x,y})_{\rm min} = \frac{3}{10}\,\frac{\lambda_c}{\lambda_L}\,\beta^*_{x,y}\,. \tag{9}$$

Note that we have obtained a different numerical coefficient from that of Ref. [9]. From Eq. (9), we conclude that in order to generate very low emittance electron beams, a reasonably small $\beta^*_{x,y}$ is necessary. For example, $\lambda_L \simeq 1$ μm and $\beta^*_{x,y} \simeq 1$ cm set a lower limit on the normalized transverse emittances at about 7.3×10^{-9} m, far below any known sources. In addition, a small $\beta^*_{x,y}$ is also necessary to focus the electron beam at the interaction region in order to match the small focal spot size of the laser beam.

In the longitudinal dimension, the energy spread can be increased by the energy fluctuation of the scattered photons. Averaging over one revolution time, we obtain the rate of quantum excitation to the energy spread

$$\left\langle \frac{d(\sigma_E^2)}{dt} \right\rangle_{\rm QE} = \frac{1}{T_{\rm rev}} \int_0^{\omega_m} d\omega\,(\hbar\omega)^2 \frac{dN_\gamma}{d\omega} = \frac{7}{10}\,\frac{\hbar\omega_{10}\Delta E_\gamma}{T_{\rm rev}}\,. \tag{10}$$

However, the energy spread σ_E^2 is also damped as in a normal storage ring [13]:

$$\frac{1}{\sigma_E^2}\left\langle \frac{d(\sigma_E^2)}{dt} \right\rangle = -2\,\frac{\Delta E_\gamma/E}{T_{\rm rev}} \equiv -\Gamma_s^{\rm RLC}. \tag{11}$$

The minimum energy spread is reached when both effects cancel. Thus, we have

$$(\sigma_\delta)_{\rm min} \equiv \left(\frac{\sigma_E}{E}\right)_{\rm min} = \sqrt{\frac{7}{5}\,\frac{\lambda_c}{\lambda_L}\,\gamma}\,. \tag{12}$$

For example, when 100 MeV electrons interact with 1 μm wavelength lasers, a minimum rms energy spread is near 2.6%. In spite of the fact that the energy spread is relatively large due to the hard photons scattered, it can actually help spread out the beam in the dispersive regions around the storage ring to reduce the Coulomb interaction between electrons, as we will demonstrate later. However, the chromaticity in this storage ring must be well corrected for beam stability. In addition, a high frequency rf cavity is needed to control the electron bunch length σ_s and the normalized longitudinal emittance $\varepsilon^n_s \equiv \gamma\sigma_\delta\sigma_s$. The rf voltage must also be high enough to obtain a reasonable beam lifetime.

In addition to quantum excitation, intrabeam scattering provides additional diffusion in the phase space of the electron beam. Since the intrabeam scattering growth times $\tau^{\rm IBS}_{x,y,s}$ are complicated functions of the phase space properties of the electron beam [11], in general, one must solve the following three coupled equations to obtain the equilibrium emittances:

$$\left[\frac{2}{\tau^{\rm IBS}_a} - \Gamma^{\rm RLC}_a\right]\varepsilon^n_a + \left\langle \frac{d\varepsilon^n_a}{dt} \right\rangle_{\rm QE} = 0\,, \tag{13}$$

where $a = x, y, s$ stands for the horizontal, vertical and longitudinal direction, respectively. The second and third terms in Eq. (13) represent the radiative laser cooling and quantum excitation.

While the intrabeam scattering effect can be always counterbalanced by the radiative laser cooling, the space charge induced tune shift must be kept small (usually less than a quarter) in order not to have beam loss. Suppose that the ring is basically two half circles (of radius ρ) with two small straight sections for the rf cavity and the laser-electron interaction region (see Fig. 1). Using the smooth approximation, we have for the space charge incoherent tune shift around the ring [13]

$$\Delta\nu_{x,y} = -\frac{N_e r_e \beta_{x,y}\rho}{\sqrt{2\pi}\,\gamma^3\sigma_s}\,\frac{1}{\sigma_{x,y}(\sigma_x + \sigma_y)}\,, \tag{14}$$

where N_e is the number of electrons in the bunch, $\beta_{x,y}$ and $\sigma_{x,y}$ are the average beta function and the average beam size in the x or y direction. Suppose the dispersion exists only in the x direction (with the average value being D_x), then we have

$$\sigma_x = \sqrt{\frac{\varepsilon^n_x}{\gamma}\,\beta_x + D_x^2\sigma_\delta^2}\,, \qquad \sigma_y = \sqrt{\frac{\varepsilon^n_y}{\gamma}\,\beta_y}\,. \tag{15}$$

Because of the relatively large energy spread, the beam size in the x direction is increased in the dispersive region of the ring; thus, the space charge incoherent tune shift can be controlled (see the numerical examples in Table I).

Two configurations will be discussed to demonstrate some LESR design considerations for various applications. One is a transient mode device that is capable of producing very low emittance electron beams. The other is a steady state operation for the generation of intense soft x rays. Table I lists some typical parameters. In both configurations, we assume that the two half circles of storage rings consist of identical FODO cells, and that the Fabry-Perot resonators are made of mirrors with total reflectivity $R = 99.99\%$ [finesse $F \simeq \pi/(1 - R) \simeq 3.14 \times 10^4$]. To simplify the intrabeam scattering calculations, we consider a round beam for both cases.

In the transient mode, a high peak power (200 GW), pulsed (10 psec) laser pulse is built up inside the resonator. Suppose that the electron beam (100 MeV) is injected into this ring with both normalized transverse emittances initially at 1×10^{-5} m. The laser pulse

TABLE I. Two laser-electron storage ring configurations.

LESR mode	Transient	Steady state
Laser and resonator parameters		
Wavelength [μm]	1	1
Flash energy in the resonator	2 J[a]	20 mJ[b]
Laser pulse length [mm]	3	1
Rayleigh range [mm]	5	8
Focal transverse rms size [μm]	20	25
Electron storage ring parameters		
Energy [MeV]	100	8
Number of electrons	1.3×10^{10}	1.1×10^{10}
Average ring radius [m]	1	0.5
Horizontal/vertical tune	~10	~10
Energy loss per turn	25 keV	1 eV
Trans. damping time	80 μsec	80 msec
Equil. energy spread	2.6%[c]	2.3%[d]
rf frequency [MHz]	2856	1428
rf peak voltage	2 MV	60 KV
Momentum acceptance	15%	23%
rms bunch length [mm]	5.9	6.6
Beta function at IP	1 cm	2 mm
Equil. norm. long. emit. [mm]	31	2.4
Equil. norm. trans. emit. [m]	1×10^{-7}	6×10^{-6}
Max. space charge tune shift	0.012	0.19
X-ray parameters		
Wavelength	6.25 pm	1 nm
Photon energy [keV]	200	1.24
Photon flux [sec^{-1}]	2.6×10^{20} [e]	9.1×10^{14} [f]

[a]Maximum flash energy.
[b]Constant flash energy.
[c]Determined by quantum excitation effect.
[d]Determined by both quantum excitation and intrabeam scattering effects.
[e]Peak x-ray flux.
[f]Average x-ray flux.

scatters off the electron bunch each round trip with little change of intensity because of negligible laser depletion and internal loss. From Table I, the electron beam damps rapidly (within 5 damping times) to the equilibrium transverse normalized emittances 1×10^{-7} m determined by Eq. (13). At the same time, very bright, energetic x rays are also produced. The electron beam is then extracted from this ring. A new laser pulse can be built up, and a new electron beam can be injected to repeat the process. The normalized transverse emittances achieved in the LESR are much smaller than those of SLC damping ring, and are also well below present rf gun technology [14]. Since the relative energy spread can be made much smaller by adiabatic acceleration, such a low emittance beam might be suitable for x-ray free electron lasers, linear colliders, and other advanced accelerator experiments.

For the steady state configuration, in order to sustain the energy level of the laser pulse in the Fabry-Perot resonator, a 200 W average power, mode-locked Nd:YAG laser (96 MHz pulse train) is resonantly coupled to the resonator. As we can see from Table I, when the accumulated laser pulse scatters off an 8 MeV electron bunch in the resonator, the interaction not only gives rise to soft x rays with wavelength around 1 nm, but also provides a cooling and stabilization mechanism to maintain the intense compact bunch (1.1×10^{10} electrons) so that all electrons participate in each laser pulse collision. As a result of the radiative laser cooling, an average flux of 9.1×10^{14} x-ray photons per second is generated. The intensity of this x-ray source is orders of magnitude higher than other schemes based on Compton scattering [1–4]. Because both the laser wavelength and the electron energy can be adjusted to produce x rays in a wide wavelength range, the x-ray source based on a compact laser-electron storage ring may have many industrial and medical applications such as lithography, radiography, and angiography [15].

We would like to thank R. Byer, A. Chao, S. Drell, A. Hofmann, K.-J. Kim, D. T. Palmer, T. Raubenheimer, J. Simpson, T. Smith, and H. Winick for many useful discussions. This work is supported by Department of Energy Contract No. DE-AC03-76SF00515.

[1] P. Sprangle *et al.*, J. Appl. Phys. **72**, 5032 (1992).
[2] J. Chen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **341**, 346 (1994).
[3] K.-J. Kim, S. Chattopadhyay, and C. V. Shank, Nucl. Instrum. Methods Phys. Res., Sect. A **341**, 351 (1994).
[4] A. A. Zholents and M. S. Zolotorev, Nucl. Instrum. Methods Phys. Res., Sect. A **358**, 455 (1995).
[5] Proceedings of the Workshop on Gamma-Gamma Colliders, Berkeley, CA, 1994 [Nucl. Instrum. Methods Phys. Res., Sect. A **355**, (1995)].
[6] T. Shintake, Nucl. Instrum. Methods in Phys. Res., Sect. A **311**, 453 (1992).
[7] V. Balakin *et al.*, Phys. Rev. Lett. **74**, 2479 (1995).
[8] R. W. Schoenlein *et al.*, Science **274**, 236 (1996).
[9] V. Telnov, Phys. Rev. Lett. **78**, 4757 (1997).
[10] K.-J. Kim, in *Proceedings of the 7th Workshop on Advanced Accelerator Concepts, Lake Tahoe, CA, 1996* (AIP, Woodbury, NY, 1997).
[11] A. Piwinski, in *Proceedings of the 4th Advanced Accelerator Physics Course, 1991* (CERN, Geneva, 1992), p. 226.
[12] A. Hofmann, SSRL ACD-Note 38 (1986).
[13] H. Wiedemann, *Particle Accelerator Physics I & II* (Springer-Verlag, New York, 1993).
[14] D. T. Palmer *et al.*, in Proceedings of the 17th IEEE Particle Accelerator Conference, Vancouver, Canada (Report No. SLAC-PUB-7422, 1997).
[15] Z. Huang and R. D. Ruth, in Proceedings of the 19th International Free Electron Laser Conference, Beijing, China (to be published).