GENERATION OF INTENSE X-RAYS AND LOW-EMITTANCE ELECTRON BEAMS IN A LASER-ELECTRON STORAGE RING

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Radiation damping and quantum excitation in an electron storage ring with a laser-electron interaction region are analyzed. Two interesting regimes and their perspectives to the generation of intense x-rays and low-emittance electron beams are investigated. In the first regime, a high-average-power laser beam inside a high-finesse resonator intersects with the electron beam every pass to produce very intense, hard x-rays. Although the transverse laser cooling effect is still weak compared with the normal synchrotron radiation damping, the increased energy spread induced by the Compton scattering stabilizes the electron beam against intrabeam scattering in a compact, low-energy ring. In the second regime, a high-peak-power laser pulse confined in the optical resonator is proposed to cool the electron beam transversely for the generation of low-emittance electron beams. We consider some basic optical system and storage ring requirements and discuss potential demonstration experiments at the existing accelerator facilities.

1 Introduction

High-energy electron storage rings are excellent sources of high-brightness electron and photon beams. Synchrotron radiation created in the bending magnets damps the electron beam in all three degrees of freedom, and the low-emittance electron beam in turn generates very bright x-rays. All electron damping rings and most light source facilities are based on storage ring technology. The energies of these storage rings are normally around or above 1 GeV.

In recent years, the advances of high-peak-power and high-average-power lasers make it possible to generate x-rays through Compton scattering [1]. Because of the short laser wavelength, the required electron beam energy is typically in the MeV range and the necessary accelerator can be very compact. To achieve very short x-ray pulse length, a linac accelerator is often used in these experiments [2,3]. However, the total x-ray flux is very limited because of the small Compton cross section (about 7×10^{-29} m^2) and the low interaction rate.

Huang and Ruth propose [4] a laser-electron storage ring (LESR) that utilizes a compact electron storage ring and a high-power laser beam in a high-finesse optical resonator for repetitive laser-electron interaction. The advantage of such a configuration is twofold: the laser pulse stored in the resonator acts like a strong damping wiggler to stabilize or damp the electron beam in a low-energy storage ring where the intrabeam scattering (IBS) effect is significant; the total x-ray flux can be many orders of magnitude higher than other Compton scattering schemes because of the enhanced intracavity laser power and the high interaction rate.

In the present paper, we review the basic principle of the laser-electron storage ring and discuss the equilibrium emittance and energy spread when both the synchrotron radiation damping and the laser-electron interaction are important. We find three dimensionless parameters that characterize the influence of the laser-electron interaction on beam dynamics. In Sections 3 and 4, we illustrate two different parameter regimes by considering some possible demonstration experiments for intense x-ray and low-emittance electron beam generation.

2 Equilibrium Emittance and Energy Spread in a LESR

For simplicity, we assume an isomagnetic (bending radius $\rho(s) = \rho_0$), separated-function storage ring (with average radius R). The damping rates of the normalized transverse emittances and the energy spread are [5]

$$\left\langle \frac{d\varepsilon^n_{x,y}}{dt} \right\rangle_{sd} = -\Gamma_b \varepsilon^n_{x,y}, \quad \left\langle \frac{d\sigma^2_\delta}{dt} \right\rangle_{sd} = -2\Gamma_b \sigma^2_\delta, \tag{1}$$

where the characteristic synchrotron radiation damping rate is

$$\Gamma_b = \frac{\langle P_\gamma \rangle}{E_0} = \frac{2}{3} c r_e \gamma_0^3 \frac{1}{\rho_0 R}. \tag{2}$$

Here $E_0 = \gamma_0 mc^2$ is the nominal energy and $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius.

We consider the horizontal emittance here because the vertical emittance is normally determined by the x-y coupling. The rate of quantum excitation due to synchrotron radiation in the bending magnets is given by [5]

$$\left\langle \frac{d\varepsilon^n_x}{dt} \right\rangle_{se} = \frac{55\sqrt{3}}{96} \lambda\!\!\!^{-}_c \Gamma_b \frac{\gamma_0^3 \bar{H}}{\rho_0}, \tag{3}$$

where $\lambda\!\!\!^{-}_c = 3.86 \times 10^{-13}$ m is the Compton wavelength, $\bar{H}$ is the average of

$$H = \beta \eta'^2 + 2\alpha\eta\eta' + \gamma\eta^2 \tag{4}$$

in the dipoles only, and β, α, γ and η are the lattice functions. The quantum excitation of the energy spread is [5]

$$\left\langle \frac{d\sigma_\delta^2}{dt} \right\rangle_{se} = \frac{55\sqrt{3}}{96} \lambda\!\!\!^{-}_c \Gamma_b \frac{\gamma_0^2}{\rho_0}. \tag{5}$$

Thus, the natural emittance and the energy spread due to synchrotron radiation are [5]

$$(\varepsilon_x^n)_0 = \frac{55\sqrt{3}}{96} \lambda\!\!\!^{-}_c \frac{\gamma_0^3 \bar{H}}{\rho_0}, \quad (\sigma_\delta)_0 = \sqrt{\frac{55\sqrt{3}}{96} \frac{\gamma_0^2 \lambda\!\!\!^{-}_c}{2\rho_0}}. \tag{6}$$

The bunch length is determined by the rf system and the momentum compaction of the ring. The γ dependence in Eq. (6) suggests that lower emittance and energy spread can be obtained from a storage ring with lower electron energy. However, the intrabeam scattering rate [6] increases with decreasing electron energy and increasing phase space density. As a result, the equilibrium emittance and energy spread are limited by intensity effects such as intrabeam scattering and are usually much larger than those determined by quantum excitation in a low-energy storage ring.

Now suppose we introduce a laser-electron interaction region in a straight section of the ring with a beta function β^* and a residual dispersion η^*. The intense laser beam is stored in a high-finesse optical resonator so that the electrons Compton scatter off the laser photons head-on every time through the resonator. Thus, the laser pulse inside the resonator acts like a (strong) damping wiggler to shake away the electrons' energy in the form of scattered x-rays. Assuming that the electron beam counterpropagates the laser pulse and that the cross section of the electron beam is smaller than the laser spot size at the interaction point (IP), the fractional energy loss per turn due to the laser-electron interaction is [4]:

$$\frac{\langle \Delta E \rangle}{E_0} = \frac{32\pi}{3} \frac{r_e^2 \gamma_0}{mc^2} \frac{E_L}{Z_R \lambda_L} \approx \frac{E_0[\mathrm{MeV}] E_L[\mathrm{J}]}{1.6 \times 10^5 \lambda_L[\mu\mathrm{m}] Z_R[\mathrm{mm}]}, \tag{7}$$

where E_L is the stored laser energy at the interaction region, Z_R is the Rayleigh range, and λ_L is the laser wavelength. Averaging over the revolution period T_0, the additional damping rates to the transverse emittances and the energy spread are

$$\left\langle \frac{d\varepsilon_{x,y}^n}{dt} \right\rangle_{ld} = -\Gamma_L \varepsilon_{x,y}^n, \quad \left\langle \frac{d\sigma_\delta^2}{dt} \right\rangle_{ld} = -2\Gamma_L \sigma_\delta^2, \tag{8}$$

with the laser cooling rate defined by

$$\Gamma_L \equiv \frac{1}{T_0} \frac{\langle \Delta E \rangle}{E_0} = \frac{16}{3} \frac{r_e^2 \gamma_0}{mcR} \frac{E_L}{Z_R \lambda_L}. \tag{9}$$

The laser-electron interaction also gives rise to quantum excitation. There are two effects on the horizontal emittance: the dispersion effect and the scattering angle effect. The sources of dispersion at the IP includes those from the laser wiggler and the residual dispersion from the ring. It can be shown [4] that the dispersion effect due to the laser wiggler is normally much smaller than the scattering angle effect even in a very intense laser pulse. However, due to the presence of the residual dispersion, the growth of the normalized horizontal emittance after the scattering of an x-ray photon $\hbar\omega$ is

$$\Delta\varepsilon_x^n = \frac{\gamma_0}{2} H^* \left(\frac{\hbar\omega}{E_0}\right)^2, \tag{10}$$

where H^* is the H-function at the interaction region. Integrating over the photon spectrum, we obtain the additional quantum excitation per turn

$$\langle\Delta\varepsilon_x^n\rangle_{le} = \frac{14\pi}{5}\frac{\lambda\!\!\!^{-}_c}{\lambda_L}\frac{\langle\Delta E\rangle}{E_0} H^*\gamma_0^2 + \frac{3\pi}{5}\frac{\lambda\!\!\!^{-}_c}{\lambda_L}\frac{\langle\Delta E\rangle}{E_0}\beta^*. \tag{11}$$

We have included the opening angle contribution [4] in the second term of Eq. (11) for completeness. In the case that $(\beta^*)' = 0$ and $(\eta^*)' = 0$, the residual dispersion should be roughly less than $\beta^*/(2\gamma_0)$ in order to make the dispersion effect negligible. However, such a tight dispersion tolerance at the IP may not be necessary for a practically interesting emittance. In the longitudinal direction, quantum excitation to the energy spread per turn is [4]

$$\langle\Delta\sigma_\delta^2\rangle_{le} = \frac{14\pi}{5}\frac{\lambda\!\!\!^{-}_c}{\lambda_L}\frac{\langle\Delta E\rangle}{E_0}\gamma_0. \tag{12}$$

Combining all these effects, we have for the equilibrium normalized emittance and the energy spread in a LESR

$$(\varepsilon_x^n)_{eq} = (\varepsilon_x^n)_0 \frac{1 + r_d r_x}{1 + r_d}, \tag{13}$$

$$(\sigma_\delta)_{eq} = (\sigma_\delta)_0 \sqrt{\frac{1 + r_d r_\delta}{1 + r_d}}, \tag{14}$$

where we have defined

$$\begin{aligned} r_d &= \frac{\Gamma_L}{\Gamma_b} = 8\frac{\rho_0 r_e}{Z_R\lambda_L}\frac{E_L}{\gamma_0 E_0}, \\ r_x &= \frac{96\sqrt{3}\pi}{275}\frac{\rho_0}{\gamma_0^3\lambda_L}\frac{\beta^* + 14H^*\gamma_0^2/3}{\bar{H}}, \\ r_\delta &= \frac{448\sqrt{3}\pi}{275}\frac{\rho_0}{\gamma_0\lambda_L}. \end{aligned} \tag{15}$$

Through these three dimensionless parameters, the laser-electron interaction changes the beam dynamics in such a storage ring. By introducing a small beta function and a (nearly) dispersion-free section at the IP, r_x can be kept as small as possible to minimize any additional quantum excitation to the transverse emittance. However, r_δ is normally much larger than 1 since the laser wavelength is very short (a few μm) while the ring radius is on the order of a few meters, resulting in the longitudinal "heating" of the energy spread due to the Compton-scattered photons. r_d is the parameter that is most sensitive to the characteristics of the laser and the optical resonator. In the following two sections, we discuss two different configurations and applications of the laser-electron storage ring depending on the strength of r_d.

3 Intense X-ray Source

In the regime where $r_d \ll 1$, the laser-electron interaction is not strong enough to damp the electron beam transversely (i.e., $(\varepsilon_x^n)_{eq} = (\varepsilon_x^n)_0$), but the hard x-ray generated through the Compton scattering induces a larger energy spread than the natural energy spread $\sigma_{\delta 0}$ when $r_d r_\delta \gg 1$. The new equilibrium energy spread is

$$(\sigma_\delta)_i \approx (\sigma_\delta)_0 \sqrt{r_d r_\delta} = \sqrt{\frac{7\pi}{5}\frac{\gamma_0 \lambda_c}{\lambda_L} r_d}. \tag{16}$$

This $\sqrt{r_d r_\delta}$ increment of the energy spread from the natural energy spread can be beneficial for the stability of the electron beam in a compact, low-energy storage ring. For example, it spreads the beam longitudinally against intra-beam scattering and other collective effects. As a result of the longitudinal laser "heating," the intensity of the electron beam that can be stored, and hence the x-ray flux, may be much improved.

The positron accumulator ring (PAR) at the Advanced Photon Source (APS) is a relatively small ring that is capable of storing the positron/electron beams from the linac in an energy range from 150 MeV to 450 MeV [7]. It could become available for beam physics experiments after its likely decommissioning because of the conversion from positron to electron operation at APS. For the generation of intense x-rays, we assume the use of a 150-MeV electron beam stored in the PAR and a continuous wave (CW), 500-W sealed CO_2 laser beam stored in a high-finesse resonator with a total reflectivity of 99.99%. The intracavity power is $P_c = 5$ MW. The effective laser energy involved in the interaction is $E_L \approx P_c(\pi Z_R/c)$. From Eq. (15), we have $r_d \approx 0.017$ and $r_\delta \approx 3.3 \times 10^3$ for $\rho_0 = 1$ m. Thus, the laser-electron interaction is not effective to cool the electron beam transversely, and the normalized emittance at low electron currents is determined by the natural emittance of the PAR lattice (which is about 11 π mm mrad if the lattice functions remain the same from 450 MeV to 150 MeV). However, the energy spread is increased to 0.096% from the natural energy spread (0.013%). Using the 12^{th} harmonic rf cavity and the nominal momentum compaction (0.25), the electron bunch length is confined to be about 120 mm. For a beam with 10^{10} electrons (corresponding to about 16 mA), the intrabeam scattering calculation [6] yields the equilibrium normalized emittances of about 14 π mm mrad in both transverse directions (assuming full x-y coupling), while the energy spread is almost unchanged. (Without any laser-electron interaction, the normalized emittance and the energy spread determined by the intrabeam scattering at this current are about 33 π mm mrad and 0.034%, respectively.) The average x-ray flux (within 0.2% bandwidth and over 3 mrad opening angle) is given by

$$F_x = \frac{4}{3} N_e \frac{r_e^2}{\hbar c} \frac{P_c}{2R} = 1.5 \times 10^{12}\ \mathrm{s}^{-1}. \tag{17}$$

The average brightness of the scattered x-rays is on the order of 10^{13} (π mm mrad)$^{-2}$s^{-1}(0.1% bandwidth)$^{-1}$, in the range of the second-generation light sources operating at GeV levels.

The parameters for demonstrating this intense x-ray source at PAR are summarized in Table 1. We have used the existing PAR lattice and the 12^{th} harmonic rf cavity (running CW mode instead of pulsed). The only major change required is to replace the fundamental rf cavity with a laser resonator system. Due to the compact, sealed design, the CO_2 laser can be placed inside the optical resonator to minimize any coupling loss. It is conceivable to fill the ring with as many bunches as possible (maximum 12) to increase the x-ray flux by an order of magnitude. Since the average flux is proportional to the stored laser power, one could use a pulsed laser with a much higher peak power in a matched resonator instead of the CW laser to further increase the x-ray flux. Such a compact, intense x-ray source may find many applications in industrial processing and medical imaging. For example, by slightly decreasing the PAR energy to 130 MeV, the intense x-rays generated by this method, about 33 keV, may be suitable for K-edge digital subtraction angiography. Because the effective laser undulator parameter $K \ll 1$, the second and the third harmonic (66 keV and 99 keV) contamination to the sample is negligible.

Table 1. Parameters for Intense X-ray Generation at PAR

Laser and resonator parameters	
laser wavelength [μm]	10 (CO_2)
average laser power	500 W (CW)
Rayleigh range	110 mm
mirror reflectivity	0.9999
focal spot size	300 μm
E-beam and lattice parameters	
energy	150 MeV
average ring radius	5 m
energy loss per turn	50 eV
transverse damping time	300 ms
equilibrium energy spread	0.096%
rf frequency	117.3 MHz
rf peak voltage	30 kV
momentum compaction factor	0.25
momentum acceptance	0.65%
rms bunch length	120 mm
beta function at IP	1 m
dispersion at IP	$<$ 100 mm
natural normalized emittance	11 π mm mrad
number of electrons/bunch	1×10^{10}
normalized emittance with IBS (assume full x-y coupling)	14 π mm mrad
X-ray parameters	
wavelength	0.27 Å
photon energy	44 keV
average photon flux/bunch	1.5×10^{12} s^{-1}

4 Low-Emittance Electron Beams

The transverse laser cooling will occur if $r_d \gg 1$ and $r_x < 1$. From Eq. (13), the equilibrium normalized emittance is approximately given by

$$(\varepsilon_x^n)_l \approx \frac{\varepsilon_0^n}{r_d} + \frac{14\pi}{5}\frac{\lambda\!\!\!^{-}_c}{\lambda_L}H^*\gamma_0^2 + \frac{3\pi}{5}\frac{\lambda\!\!\!^{-}_c}{\lambda_L}\beta^*. \tag{18}$$

Each of these terms can be made small in a laser-electron storage ring. When the first two terms are neglected, we recover the result of Ref. 4. Since we also have $r_\delta >> 1$, the equilibrium energy spread becomes [8]

$$(\sigma_\delta)_l \approx \sqrt{\frac{7\pi}{5}\frac{\gamma_0 \lambdabar_c}{\lambda_L}}. \tag{19}$$

For $\gamma_0 = 200$ (100 MeV beam) and $\lambda_L = 1\ \mu m$, Eq. (19) yields the equilibrium energy spread of 1.8%. Since the energy spread is relatively large due to the hard photons scattered, it spreads out the beam in the longitudinal phase space as well as the transverse phase space in the dispersive sections around the ring, reducing the space charge effect and the intrabeam scattering. Combining with the rapid damping rate obtained from the laser-electron interaction, the final emittance obtained for an intense electron beam can be quite small. For example [4], using a short-pulse (10 ps), high-peak power (200 GW) solid-state laser and a high-finesse resonator to sustain the laser energy for thousands of interactions, a 100-MeV beam with 10^{10} electrons can reach a normalized transverse emittance of 0.1 π mm mrad, determined by the balance between the laser cooling and the intrabeam scattering. Such a low-emittance electron source might be suitable for x-ray free-electron lasers, linear colliders, and other advanced accelerator experiments.

Because of the relatively large energy spread, both the rf momentum acceptance and the dynamic aperture (for on and off momentum particles) must be sufficient to confine the beam, and the chromaticity in this storage ring must be well corrected for beam stability. These lattice requirements are usually not satisfied in most existing storage rings. Recently, Bulyak *et al.* have suggested a reconstruction of the operating storage ring N-100 [9] in order to carry out the Compton scattering and laser cooling experiments at their facility. Perhaps the most interesting feature of their design is the adjustment of the dispersion function at the injection section while keeping the beta functions almost unchanged. During the beam injection, the lattice has zero dispersion in the injection section, and the momentum compaction factor is relatively large. During the laser-electron interaction, they introduce high dispersion into the injection section to reduce the momentum compaction factor, so that the beam can be confined longitudinally with reasonable rf voltage. The dynamic aperture for their lattice is studied numerically and is shown to be sufficient for beam injection and storage [9]. The optical system under consideration [9] is a solid-state Nd:YAG laser that generates light pulses of 50 ps length, with a pulse-repetition frequency of 10^4 Hz and an average power of 100 W, and is matched into a high-reflective optical resonator. The resulting energy loss from the laser-electron interaction is much larger than the synchrotron radiation loss at the electron energy of 100 MeV (i.e., $r_d \gg 1$) [10], and hence permits experimental verification of the laser cooling effect.

5 Conclusion

In summary, the laser-electron storage ring is a promising method to generate both intense x-rays and low-emittance electron beams. In this paper, we have attempted to illustrate the underlining beam dynamics and the LESR configurations in two interesting operating regimes. Although the design for a laser-electron storage ring is very different from the conventional storage rings, it appears possible to use the existing low-energy storage rings to demonstrate some basic features of this device.

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