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Laser-Electron Storage Ring as a Compact Source of High-Intensity X-rays *

Zhirong Huang and Ronald D. Ruth
Stanford Linear Accelerator Center,
Stanford University, Stanford, CA 94309

Abstract

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Recent progress in high power laser development has attracted a growing interest in generating x-rays by Compton (or Thomson) backscattering an intense laser pulse off a high energy electron beam [1,2]. If λ_L is the laser wavelength, γ is the electron energy in units of its rest mass $m_e c^2$, and θ is the angle of the scattered x-ray photon with respect to the direction of the electron trajectory, then the wavelength of the backscattered photon is

$$\lambda_x = \frac{(1+\gamma^2\vartheta^2)\lambda_L}{4\gamma^2}. \qquad (1)$$

These x-rays are tunable, collimated (with an opening angle of $1/\gamma$), and nearly monochromatic.

However, these Compton sources are somewhat limited by the relatively low x-ray yields. It is well known that the cross section of Compton scattering is quite small, and is approximately given by the Thomson cross section when the energy of the scattered photon is much less than the electron energy:

$$\sigma_T = \frac{8}{3}\pi r_e^2 = 6.66\times10^{-29}\ \mathrm{m}^2, \qquad (2)$$

where $r_e = 2.82\times10^{-15}$ m is the classical electron radius.

If we let N_e electrons encounter N_L photons with a common Gaussian rms transverse size σ_w at an interaction rate f, then the total number of scattered x-ray photons per unit time (or the average x-ray flux) is given by

$$\dot{N}_x = \frac{\sigma_T}{4\pi\sigma_w^2} N_e N_L f. \qquad (3)$$

Even with the state-of-art laser technology [1] and the development of photon storage systems [2], the x-ray flux has been limited because of either low electron intensity or low repetition rate of existing electron accelerators.

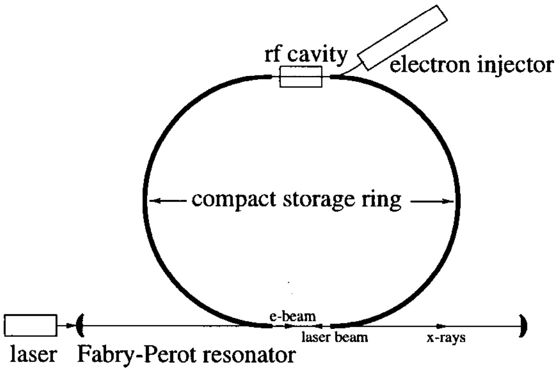

Fig. 1. The schematic of a laser-electron storage ring

In this paper, we propose a high-intensity x-ray source based on a novel Laser-Electron Storage Ring (LESR) [3] that overcomes these limitations. The basic idea is shown in Fig. 1. An electron bunch is injected into a compact storage ring that primarily consists of many identical FODO cells. At the same time a train of laser pulses is resonantly coupled into a highly reflective Fabry-Perot resonator to build up an intense pulse. At steady state, the power level of the accumulated pulse in the resonator can be maintained because the internal loss is compensated by the sequence of input laser pulses. The laser pulse path in the resonator is chosen to match the time it takes for the electron beam to circulate once around the ring, so that the focused light beam repeatedly Compton backscatters off the focused electron beam at the interaction region inside the resonator. As the electron beam circulates around the ring the energy lost to the x-rays is restored by an rf accelerating cavity as in a normal storage ring. As we have shown in Ref. [3], the laser-electron interaction provides a very fast cooling mechanism for the normalized emittances of the electrons, and can be used to counterbalance the strong intrabeam scattering effect when a dense electron beam is stored. Since the LESR provides both an intense electron beam and a high interaction rate, the resulting x-ray flux is significantly enhanced over previous proposals [1,2].

Following Eq. (3), we can determine the x-ray flux as a function of laser and resonator parameters. Assume that the average power of the laser is P_L, and the total mirror reflectivity of the optical resonator is R, so that the average power inside the resonator can be as high as $P_L/(1-R)$. If the Rayleigh range (the depth of the focus) of the optical resonator is Z_R, then the laser focal spot area is $4\pi\sigma_w^2 = Z_R \lambda_L$. The total number of x-ray photons produced per unit time is

$$\dot{N}_x = \frac{4}{3} N_e \frac{r_e^2}{Z_R \hbar c} \frac{P_L}{(1-R)}, \tag{4}$$

with $\hbar c = 1.97\times10^{-7}\,\mathrm{eV\,m}$.

Table 1 Electron storage ring parameters

nominal electron energy	8 MeV
number of electrons in the bunch	1.1×10^{10}
average ring radius	0.5 m
horizontal / vertical tune	~ 5
transverse damping time	80 msec
equilibrium rms energy spread	1.5 %
rf frequency / voltage	2856 MHz / 0.2 V
momentum acceptance	12 %
rms bunch length	4.2 mm
normalized transverse emittances	20 mmmrad
maximum space charge tune shift	0.069

As an illustration for x-ray lithography (XRL) application, suppose that we use a 100 W average power, mode-locked Nd:YAG laser (wavelength 1 μm, pulse length ~ 10 psec, pulse separation ~ 10 nsec). This laser is then resonantly coupled to a Fabry-Perot resonator with Rayleigh range Z_R = 4 mm and mirror reflectivity R = 99.99%. If we focus the laser pulse to a spot size of 35 μm and repetitively collide it with a matched electron beam in a compact storage ring characterized by Table 1, 9.1×10^{14} x-ray photons per second are generated along the forward direction of the electron trajectory over an opening angle of ±64 mrad. If the laser beam is slightly tilted with respect to the electron beam direction at the interaction region (see Fig. 2), one can collect the scattered x-rays in the forward direction from 0 to -25 mrad through a thin Beryllium window that is transparent to x-rays. From Eq. (1), the bandwidth of the collected x-rays is

$$\frac{\Delta\lambda_x}{\lambda_x} = (\gamma\Delta\theta)^2 = 16\%, \tag{5}$$

and the wavelengths of these x-rays are between 1.2 nm and 1 nm. Thus, at a distance 1 m away from the interaction point, a field size of 25 mm in diameter can be uniformly (< 5% variation) illuminated. The power density is estimated to be on the order of 10 mW/cm^2, which is adequate for high throughput x-ray lithography [4].

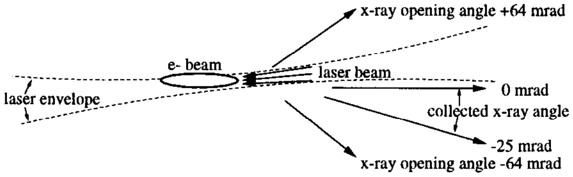

Fig. 2. The laser-electron interaction region

Compared with synchrotron based XRL [4], the x-ray source based on the LESR is naturally concentrated around the desired XRL wavelength (1 nm) instead of a broad band spectrum. The necessary electron energy is about two orders of magnitude lower than that of synchrotrons. Thus, the device can be made extremely compact, and both the electron injector and the radiation shielding are much easier. It is also conceivable to orient the whole system in the vertical direction so that traditional wafer production facilities could be adapted to XRL manufacturing.

The x-ray source described here is completely tunable and can be extended to cover both soft x-ray and hard x-ray ranges. We choose to use solid-state lasers in the example because of both high peak and high average power developments. Nevertheless, recent progress in terawatt picosecond CO_2 laser technology [5] opens up the possibility that the LESR could be built with a CO_2 laser (available for a power level greater than 1 KW). Having an order of magnitude longer laser wavelength means that the accessible wavelength of the scattered photons may be extended to softer x-rays (between 1 nm to 10 nm), and even into the extreme ultraviolet (EUV) range (above 10 nm). On the other hand, by raising the electron energy in the storage ring, bright and energetic x-rays with energies up to a few hundred KeV can be generated [3]. With the flexibility in wavelength, this high-intensity x-ray source may have many industrial and medical applications such as lithography, radiography, and angiography.

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