PROPOSAL OF A COMPACT HIGH BRIGHTNESS LASER SYNCHROTRON LIGHT SOURCE FOR MEDICAL APPLICATIONS

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Abstract

The present high-brightness hard X-ray sources have been developed as third generation synchrotron light sources based on large high energy electron storage rings and magnetic undulators. Recently availability of compact terawatt lasers arouses a great interest in the use of lasers as undulators. The laser undulator concept makes it possible to construct an attractive compact synchrotron radiation source which has been proposed as a laser synchrotron light source. This paper proposes a compact laser synchrotron light source for mediacal applications, such as an intravenous coronary angiography and microbeam therapy.

1 INTRODUCTION

The present high-brightness hard X-ray sources have been developed as third generation synchrotron light sources based on large high energy electron storage rings and magnetic undulators. A compact, tunable, narrow bandwidth, high-brightness, hard X-ray source has basic and industrial applications in a number of fields, such as solid-state physics, material, chemical, biological and medical sciences. Particularly for medical applications, such as X-ray diagnostics and therapy, it is essential to downscale the present synchrotron light sources into the environment of a hospital, keeping properties of X-ray radiations. Recently availability of compact terawatt lasers arouses a great interest in the use of lasers as undulators of which a period is $\sim 10^4$ shorter than the conventional undulator. This feature of laser undulators allows the use of ~ 100 times less energetic electrons to generate X-rays of a particular wavelength. The laser undulator concept makes it possible to construct an attractive compact synchrotron radiation source which has been proposed as a laser synchrotron light source[1]

It is known that intense monochromatic X-rays delivered by the synchrotron light sources take the advantage of X-ray imaging and medical diagnoses over conventional X-ray tubes. In particular the intravenous coronary angiography using synchrotron radiation is of great interest in medical applications as a powerful and safer diagnostic method for assesment of the coronary heart diseases. The method is known as iodine K-edge digital subtraction angiography. In this method the different absorption of quasi-monochromatic X-rays just above and below the K-edge of iodine at 33 keV photon energy is used to eliminate the contrast due to nonvascular body structures. It is necessary to provide sufficient radiation intensity at 33 keV for the short exposure times required to avoid blurring of images by periodic movement of the heart. The development of the coronary angiography has been undertaken on the synchrotron light sources based on large high energy electron storage rings[2]. Recently compact electron storage rings dedicated and optimized to the coronary angiography have been proposed to fit it into a clinical environment in a hospital within a diameter of 10 to 15 m[3, 4]. These compact storage rings are based on the synchrotron radiation from magnetic multipole wigglers made from superconducting magnets with a high magnetic field of 5 T to 8 T. The beam energy more than 1.5 GeV is needed. Because of a broad spectrum of the synchrotron radiation, the second and the third harmonic of 33 keV lead to an undesirable background on the angiography.

The features of laser synchrotron radiation can be applied to the coronary angiography with the much lower electron beam energy which leads to a smaller facility. This paper proposes a compact laser synchrotron light source capable of generating a high-brightness hard X-ray beam for medical applications. Two schemes, the single-pass and the intracavity schemes, are described to generate a sufficient photon flux required for the coronary angiography.

2 X-RAY GENERATION VIA THOMSON SCATTERING

When a laser beam interacts with an electron beam at an angle ϕ, Thomson scatterings of relativistic electrons in the laser undulator field generate frequency up-shifted radiation with the peak frequency given by

$$\omega_X = \frac{2\gamma^2(1-\cos\phi)}{1+a_0^2/2}\omega_0, \tag{1}$$

where γ is the Lorentz factor of the electrons, ω_0 the incident laser frequency and a_0 the normalized vector potential of the laser field, given by $a_0 = 0.85 \times 10^{-9} I^{1/2}[\mathrm{W/cm^2}]\lambda_0[\mu\mathrm{m}]$ for the peak intensity I in units of W/cm^2, the laser wavelength $\lambda_0 = 2\pi c/\omega_0$ in units of μm. In Thomson scatterings the radiation frequency is correlated to the scattering angle $\theta \ll 1$ as $\omega = \omega_X/(1+\gamma^2\theta^2)$. The maximum radiation photon energy $E_X = \hbar\omega_X$ is written as

$$E_X[\mathrm{keV}] = \frac{0.0095(1-\cos\phi)E_b^2[\mathrm{MeV}]}{\lambda_0[\mu\mathrm{m}](1+a_0^2/2)}, \tag{2}$$

where E_b is the electron beam energy.

The energy loss of the electron beam due to the radiation is

$$U_L[\text{keV}] = 4.2 \times 10^{-5} \frac{L}{Z_R} \frac{E_b^2[\text{MeV}]P_0[\text{GW}]}{\lambda_0[\mu\text{m}]}, \quad (3)$$

where $L = \min[2Z_R, L_0/2]$ is the laser-electron interaction length, $Z_R = \pi r_0^2/\lambda_0$ the Rayleigh length with the spot radius r_0, P_0 the incident laser power, and L_0 the laser pulse length. The total radiation power radiated by an electron beam with current I_b is given by $P_T = U_L I_b$.

In the backscattering, the spectral flux within the spectral width $\Delta\omega/\omega_X$ is given by

$$F[\text{photons/s}] = 8.4 \times 10^{16} I_b[A] P_0[GW] \frac{L}{Z_R} (\frac{\Delta\omega}{\omega_X}). \quad (4)$$

In case the laser pulse length is $L_0 \leq 2Z_R$, the photon flux is expressed as $F[\text{photons/s}] = 2000W[\text{J}]N_e f_I/Z_R[\mu\text{m}](\Delta\omega/\omega_X)$, where N_e is the total number of electrons per bunch, W the laser pulse energy, f_I the interaction frequency. In the backscattered radiation, only the odd harmonic intensities are finite along the $\theta = 0$ axis and the even harmonics vanish. An estimate of the ratio of the 3rd harmonic intensity I_3 to the fundamental intensity I_1 is $I_3/I_1 \sim (81/64)(a_0^4/(1+a_0^2/2)^2$, assuming $a_0^2 \ll 1$.

The radiation spectrum is broadened by effects of emittance and energy spread of actual electron beams. The total natural spectral width of the radiation is given by $(\delta\omega/\omega_X)_T = [(\delta\omega/\omega_X)_0^2 + (\delta\omega/\omega_X)_\epsilon^2 + (\delta\omega/\omega_X)_i^2]^{1/2}$, where $(\delta\omega/\omega_X)_0 = 1/N_0$ is the spectral width due to the finite interaction length, $N_0 = L_0/\lambda_0$ is the number of laser wavelengths within the laser pulse length, and $(\delta\omega/\omega_X)_\epsilon = \epsilon_n^2/(\gamma^2 r_b^2)$ is the emittance broadened spectral width for the normalized beam emittance ϵ_n, and $(\delta\omega/\omega_X)_i = 2(\delta E/E_b)$ is the intrinsic energy spread broadening effect. The radiation with the total spectral width is confined to the angle $\theta_T \simeq (\delta\omega/\omega_X)_T^{1/2}/\gamma$.

3 DESIGNS OF THE LASER SYNCHROTRON LIGHT SOURCE

The intravenous coronary angiography using iodine as a contrast agent requires the photon flux of 2×10^{15} photons/sec in the bandwidth of 0.3% at the photon energy of 33 keV[4]. The exposure area of the radiation should be at least 150 mm × 150 mm. In order to produce such sufficient photon flux by means of the laser synchrotron radiation , two schemes are conceivable; the single-pass and the intracavity schemes

3.1 *Single-pass scheme*

In the single-pass generation, the multi-bunch electron beams of 46.2 MeV are delivered by the linac or the microtron with the photoinjector producing the beam charge of 1.6 nC per bunch (i.e. the number of electrons $N_e \simeq 10^{10}$) with the emittance of $\epsilon_n = 1\mu$mrad and the intrinsic energy spread of 0.1%. For a 2 ps laser pulse with $\lambda_0 = 1\mu$m, $N_0 = 600$. As the natural spectral width is 0.2% within the cone $\theta = 1$ mrad. The required photon flux for the angiography can be achieved by interaction of the electron beam pulse consisting of 160 bunches at 100 Hz with the laser pulse energy of 2 J within a focal spot size $r_0 = 10\mu$m. The deflecting magnet with the field of 3.3 T is placed in the interaction region of $2Z_R = 0.63$ mm to create a fan X-ray beam horizontally spread over 15 mrad. This deflecting magnet is used to separate electron beams from X-rays by a bending angle of 30°.

Table 1: Design parameters of the single-pass laser synchrotron light source using the electron linac.

X-ray parameters	
Photon energy	33 keV
Photon flux	2×10^{15} s^{-1}
Natural spectral width	0.2%
Electron beam parameters	
Beam energy	46.2 MeV
Charge per bunch	1.6 nC/bunch
Bunch length	2 ps
Number of bunches	160
Repetition frequency	100 Hz
Normalized emittance	1 mm mrad
Beam radius at I.P.	10μm
Beam energy spread	0.1%
Laser parameters	
Wavelength	1μm
Pulse energy	2 J/pulse
Pulse duration	2 ps
Peak power	1 TW
Spot radius	10 μm

A laser system suitable for the single-pass scheme is a high average power solid-state laser (e.g. Nd:YAG laser) based on the chirped pulse amplification (CPA). The laser consists of a single mode-lock oscillator and 10 laser amplifiers each of which produces 4 pulses of 2.5 J/pulse at the repetition rate of 100 Hz. The output pulses of 10 amplifiers are combined to form a pulse train consisting of 40 pulses. Afterwards the pulse duration is compressed through a grating pulse compressor to obtain 1 ps, 2 J pulses. Finally the pulse train is injected into the optical storage ring to collide the electron bunches during its round-trip. In order to achieve synchronization between the laser pulses and the RF linac electron beam operated at 2856 MHz, a small part of the pulse energy is diverted to illuminate the laser photocathode at the 4th harmonic of the 1μm wavelength. The parameters of the single-pass X-ray generation scheme are summarized in Table 1. In this scheme, the third harmonic contamination of 99 keV is estimated to be $\sim 18\%$ with respect to the 33 keV radiation.

3.2 Intracavity scheme

Electron beams in the storage ring interact with the CW laser inside the optical cavity made of high reflectivity mirrors referred to as a supercavity. The electron storage ring with the circumference of 10m stores the average beam current 1.2 A at 132 MeV to produce a sufficient radiation of 33 keV X-rays via Thomson scattering on the laser at $\lambda_0 = 10\mu$m (e.g. CO_2 laser). The required photon flux can be obtained by the interaction of the circulating electron beam with the laser field of the average power of 10 MW in the interaction length $2Z_R = 63$ mm for the focal spot radius $r_0 = 100\mu$m. As $N_0 = 6.3\times10^4$, the spectral width is determined by the intrinsic beam energy spread in the storage ring. The beam energy loss due to interaction with the laser field is $U_L = 1.5$ eV. The energy loss per turn due to the normal synchrotron radiation is $U_M = 27$ eV in the arc with the bending radius of $\rho_M = 1$ m. The damping time is given by $\tau_d = E_bT_r/(U_M+U_L) = 1/(\tau_{dM}^{-1}+\tau_{dL}^{-1}) = 0.15$ s, where $T_r = 33$ ns is the revolution time of the electron beam in the ring, $\tau_{dM} = E_bT_r/U_M = 0.16$ s and $\tau_{dL} = E_bT_r/U_L = 3.0$ s is the damping time contributed by the energy loss in the laser field and in the bending magnets, respectively. The equilibrium normalized emittance resulting from the balance between damping and the quantum excitation via Thomson scatterings is given by[5] $\varepsilon_{nL} = 0.73\times10^{-6}\beta^*/\lambda_0[\mu\mathrm{m}]$, where β^* is the beta function at the interaction point. For $\beta^* = 1$ m, $\varepsilon_{nL} = 7.3\times10^{-8}$ m. The equilibrium normalized emittance determined from the synchrotron radiation in the bending magnets is $\varepsilon_{nM} = 4.1\times10^{-7}$ m. The equilibrium normalized emittance due to both effects of Thomson scatterings and synchrotron radiation in the storage ring is given by $\varepsilon_n = (\tau_d/\tau_{dL})\varepsilon_{nL} + (\tau_d/\tau_{dM})\varepsilon_{nM} = 3.9\times10^{-7}$ m. The equilibrium energy spread caused by Thomson scatterings becomes[5] $\sigma_{EL}/E_b = 1.84\times10^{-3}(\gamma/\lambda_0[\mu\mathrm{m}])^{1/2} = 9.4\times10^{-3}$. The energy spread caused by the bending magnet is given by $\sigma_{EM}/E_b = 0.44\times10^{-6}\gamma/\sqrt{\rho_M[\mathrm{m}]} = 1.1\times10^{-4}$. The energy spread due to both effects is $\sigma_E/E_b = [(\tau_d/\tau_{dL})(\sigma_{EL}/E_b)^2 + (\tau_d/\tau_{dM})(\sigma_{EM}/E_b)^2]^{1/2} = 2.1\times10^{-3}$. In order to obtain a sufficient quantum beam lifetime, say 1 hour, the energy aperture for the synchrotron oscillation must be 1.1%. The required peak RF voltage becomes 126 kV. Since the energy aperture is large enough to keep the electron beam in the phase space, effects of the diffusion provided by intra-beam scatterings are negligible.

The high finesse Fabry-Perot resonator, a supercavity, can be made of high reflective mirrors with reflectivity of $R = 99.999\%$[6]. The finesse of this optical resonator is Finesse $= \pi\sqrt{R}/(1-R) = 3.1\times10^5$. In this supercavity the laser power builds up to $P_0 \simeq P_i/(1-R) = 10$ MW with the incident power $P_i = 100$ W pumped by the CW laser. In order to produce a fan of the X-ray radiation horizontally spread over 20 mrad, a single period of the linear undulator magnet with the field of 0.46 T and the wavelength of $2Z_R \simeq 60$ mm is placed in the interaction region. The design parameters for the intracavity generation scheme are summarized in Table 2. In this scheme, the third harmonic contamination of 99 keV is negligible because of $a_0 = 2.2\times10^{-3} \ll 1$.

Table 2: Design parameters of the intracavity laser synchrotron light source using the electron storage ring.

X-ray parameters	
Photon energy	33 keV
Photon flux	2×10^{15} s^{-1}
Natural spectral width	0.4%
Electron beam parameters	
Beam energy	132 MeV
Beam current	1.2 A
Number of bunches	50
Circumference	10 m
Bending radius	1 m
Energy loss per turn	28.5 eV
Damping time	155 msec
Equil. energy spread	0.2%
Equil. norm. emittance	3.9×10^{-7} m
rms Bunch length	4.9 mm
RF frequency	1500 MHz
Peak RF voltage	126 kV
Energy aperture	1.1%
Quantum beam lifetime	1 hour
Beam radius at I.P.	30μm
Laser parameters	
Wavelength	10μm
Average power	10 MW
Spot radius at I.P.	100 μm

4 CONCLUSIONS

A compact high brightness hard-X ray source can be achieved by Thomson scatterings of relatively low energy electron beams in laser fields. Two laser-electron beam interaction schemes has been proposed for application to the coronary angiography. Tunability, compactness, high energy photon capability, and relatively low cost may provide an important useful tool for the other medical applications and the basic sciences.

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