DEVELOPMENT OF COMPACT SOFT X-RAY SOURCE BASED ON LASER UNDULATOR *

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Abstract

A compact soft X-ray source is required in various research fields such as material and biological science. The laser undulator based on Compton backward scattering has been developed as a compact soft X-ray source for the biological observation at Waseda University. It is performed in a water window region (250eV - 500 eV) using the interaction between 1047 nm Nd:YLF laser and 4.6 MeV high quality electron beam generated from rf gun system. The range of energy in the water window region has K-shell absorption edges of Oxygen, Carbon and Nitrogen, which mainly constitute of living body. Since the absorption coefficient of water is much smaller than the protein's coefficient in this range, a dehydration of the specimens is not necessary. As a preliminary experiment, about 370 eV X-ray generation was carried out. In this conference, we will report results of experiments and our future plan.

INTRODUCTION

Short-pulse X-ray source is required in various research fields, such as material and medical science. To meet these demands, R&D on the next-generation light source has been initiated at several laboratories in the world. One of the most promising approaches to short-pulse X-ray sources is the laser undulator, which is based on Compton or Thomson backward scattering [1, 2].

The Compton backward scattering, in which a photon reverses its on colliding head-on with an electron, has been proposed as a way to generate X-rays with optical laser beam and low energy electron beam either through the spontaneous emission or the free-electron laser (FEL) mechanism[3]. The mechanism is closely related to undulator radiation so that the laser field acts as an electromagnetic undulator generating up-shifted radiation in the X-ray regime. In this case, it is easily to generate picosecond X-ray using the recent developments of the laser and the accelerator technologies because the pulse length of the generated X-ray is roughly obtained from the electron and the laser pulse lengths.

On the other hand, Soft X-ray with the energy in "water window" region, which is 250 eV – 500 eV (2.5 nm – 5 nm), can be extensively applied to biological studies, because the absorption coefficients of proteins in this region are larger than that of water. Dehydration of biological specimens can be avoided in both studies *in vivo* and *in vitro*. K-shell absorption edges of O (532 eV), C (284 eV) and N (400 eV), which are main elements of living bodies, exist in "water window" region [4]. The monochrome X-ray with energy between these edges can be employed for the intrinsic contrast imaging in hydrated samples. The compounds containing these elements in the sample can be highlighted. The laser undulator possesses so many features including its wide energy tunability and its compactness of instruments X-ray with narrow energy bandwidth and good directivity can be selected by cutting out with the scattered angle.

HIGH QUALITY ELECTRON BEAM GENERATION SYSTEM

RF gun system

The rf gun system is composed of the BNL type 1.6 cell S-band rf cavity with Cu photocathode, a set of solenoid magnets for emittance compensation [5, 6, 7], a stabilized laser and rf power source. Figure 1 shows the total beam line which is within 2×2 m^2 as a table-top size. The photocathode surface of the rf gun cavity was polished using diamond powders. Present quantum efficiency of Cu cathode has been achieved about 5×10^{-5} without laser cleaning. High accelerating field is effective to reduce an emittance growth due to space charge effect for a high current beam. However, we will suffer the increase of dark current due to field emission in the high gradient operation. Therefore, in order to reduce the dark current, a diamond turning method has been applied for a fine manufacturing of the rf gun cavities.

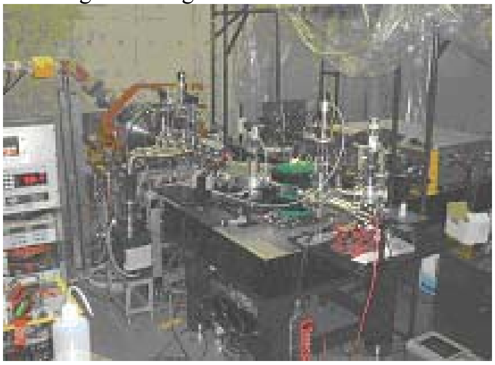

Figure 1: The view of the total beam line

Main parts of rf source consists of 10 MW S-band klystron (Tomson: TV2019B6) and a small pulse modulator (Nissin Electric Co., Ltd.). The pulse

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modulator has good stability and flatness of the output pulse.

Laser system

All solid state picosecond Nd:YLF laser system (PULRISE-V), which was developed by SHI (Sumitomo Heavy Industries, ltd.), is used not only for the irradiation onto potocathode to generate the electron beam, but also for the soft X-ray generation using the laser undulator. The laser system has an active timing and intensity stabilization systems against a temperature change and timing jitter from a reference rf signal. Fluctuation of air and vibrations of mirrors on the laser optical path affect the laser intensity and pointing stability on the photocathode. The laser system is put inside the accelerator room to achieve short optical path length to the photocathode. The timing and amplitude fluctuation due to an electro-magnetic noise and radiation had been investigated using time domain demodulation technique between a seed laser and the reference rf signal [8,9]. As a previous result, the timing jitter was measured less than 0.5 ps and the effects of the electromagnetic noise and radiation were negligible for the laser stability. It is sufficiently small timing fluctuation for the soft X-ray generation.

Additional laser amplification

Our all solid state Nd:YLF laser system (PULRISE-V) can provide about 1 mJ/pulse at fundamental wavelength. However, our requirement for the soft X-ray generation experiment and the pulse radiolysis experiment is larger than 10 mJ/pulse. Therefore, a flush lamp pumped 2-pass laser amplification using Nd:YLF crystal (65 mmϕ × 90mm) has been installed. The maximum gain of the amplifier is about 10^2 at 900 V flushing voltage. The optimum laser energy can be arbitrary obtained by changing the flushing voltage. High power laser beam was obtained by amplifying the residual fundamental laser beam (IR: 1047 nm) to collide with the electron beam for the laser undulator.

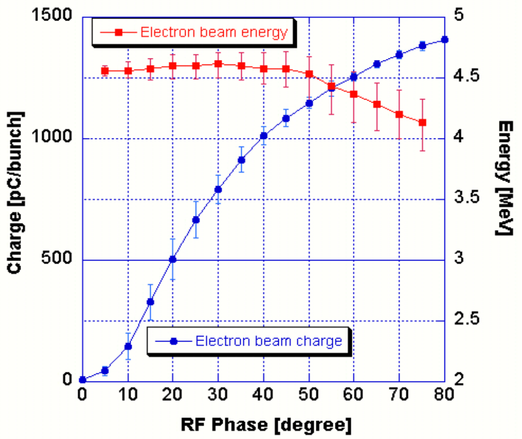

Figure 2: The charge and energy of the electron beam as a function of the rf phase.

Electron beam status

High quality electron beam is produced by a photocathode rf gun system. The 4th harmonic laser (UV: 262 nm) which is irradiated onto the photocathode of the rf gun is obtained from a Nd:YLF fundamental laser (IR: 1047 nm) by passing through two beta barium borate (BBO) crystals in the PULRISE-V laser system. The electron bunch charge and beam energy was measured as a function of rf phase. The typical results are shown in Fig. 2. The bunch charge of 1 nC is achieved at the beam energy of 4.6 ± 0.1 MeV. UV laser to drive the rf gun and IR laser for the applications were generated from a same seed oscillator, so that it was easily to make synchronization between them. Figure 3 shows the block diagram of the synchronization system.

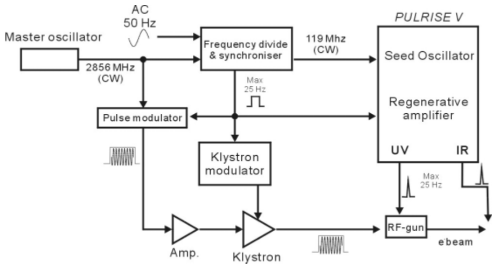

Figure 3: Block diagram of the synchronization system

The beam emittance and the bunch length measurements were carried out using slit scan method and two-frequency analysis technique, respectively [10]. Comparing between results of experiments and simulations, these were agreed well [11].

SOFT X-RAY GENERATION

Analysis

A simple approach to analyze the Compton scattering in a general configuration is to notice the similarity between the role of a laser beam and a static magnetic undulator in inducing a sinusoidal motion of the electrons[1, 12]. The wavelength of the up-shifted radiation as the X-ray can easily be calculated from energy and momentum conservation as

$$\lambda \cong \frac{\lambda_0 (1 + K^2/2 + \gamma^2\theta^2)}{2\gamma^2(1-\cos\phi)}, \tag{1}$$

where the Compton shift has been neglected. Here, γ is the Lorentz factor, K the wiggler strength, θ the angle of observation, ϕ the angle of the laser propagation toward the electron beam and λ_0 the incident laser wavelength. The wiggler strength is expressed by

$$K = eA_0/m_e c^2 \approx 0.85\times10^{-9}\lambda_0\sqrt{I}, \tag{2}$$

where I [W/cm^2] and λ_0 [μm] are the intensity and the wavelength of the incident laser, respectively. Here, c is the light velocity, e the elementary electric charge, m_e the electron rest mass, A_0 the vector potential of the incident laser.

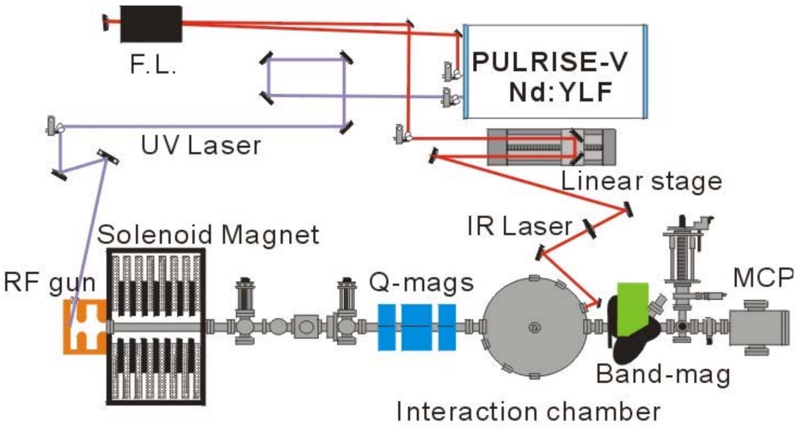

Figure 4: Experimental layout including the rf gun system and the laser system

Soft X-ray generation experiment

Figure 4 shows the experimental layout for the laser undulator. Our system is a table-top size within 2 × 2 m^2 including the rf gun system and Nd:YLF laser system. The electron beam parameters and the laser beam parameters in this experiment are given in Table 1 and 2, respectively.

Table 1: Electron beam parameters

Electron beam	
Ave. beam energy	4.6 MeV
Beam charge	0.60 nC/bunch
Bunch length	10 ps (FWHM)
Beam size σ_x	280 μm
Beam size σ_y	250 μm
Repetition rate	5 Hz

Table 2: Laser beam parameters

Laser beam	
Wavelength	1047 nm
Energy / pulse	10 mJ
Pulse length	10 ps (FWHM)
Beam size σ_x	80 μm
Beam size σ_y	80 μm
Repetition rate	5 Hz

In this experiment, Short-pulse soft X-ray generation using the laser undulator based on the Compton backward scattering between a 4.6 MeV electron beam and a 1047 nm laser beam at 160 deg of the laser propagation angle ϕ toward the electron beam has been successfully performed. A spatial overlap between the electron beam and the laser beam is confirmed by observing both beam images on the identical phosphor screen located at the collision point using a CCD camera. Cherenkov light is emitted by electron beam passing through a 5 mm-thickness glass plate and reflected by an Al mirror with a small pinhole at the collision point, so that the Cherenkov light can be guided toward the same direction of the laser beam to make time and spatial coincidence between them. The laser beam passes through the pinhole and both the laser beam and the Cherenkov light are guided to a streak camera. The generated X-ray is separated from the electron beam using the analyzer magnet and guided to an X-ray detector. The detector is a circular microchannel plate (MCP) (F4655-10: HAMAMATSU PHOTONICS K. K.) with high speeded response that has about a gain of 5 × 10^6 and the quantum detection efficiency of the MCP is about 10 % at 370 eV X-ray [13]. The distance between the collision point and the detection point is about 840 mm and the effective diameter is 15mm. The X-ray scattered within about 8.9 mrad was detected.

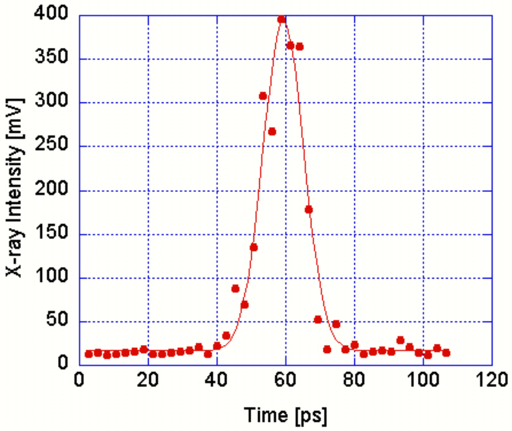

Figure 5: The typical X-ray signals

Figure 5 shows the typical X-ray signals detected by the Microchannel plate (MCP) by changing the timing between the electron beam and the laser beam. The total number of the detected photons is obtained from the amplitude of the maximum X-ray signal using its gain and the quantum detection efficiency. The amplitude of X-ray signal that is about 380 mV corresponds to the number of detected photons about 1.9×10^2 /pulse. In this case, the total number of generated photons is analytically estimated to be approximately 1.9×10^4 /pulse This X-ray has maximum energy of about 370 eV with 0.2 % energy bandwidth that is between the K-shell absorption edges of N and C. It is expected that this soft X-ray will have many application to the biological observation.

SUMMARY

Soft X-ray generation in "water window" region based on the laser undulator have been successfully performed using the rf gun system with Nd:YLF laser system which is a table-top size within 2×2 m^2. This X-ray has maximum energy of about 370 eV and the total number of generated photons is analytically 1.9×10^4 photons/pulse. Out of total generated X-ray, the useful soft X-ray that has energy between the K-shell absorption edges of N and C is analytically about 4.0×10^3 photons/pulse within about 50 mrad scattered angle that correspond to about 5.2 % energy bandwidth and we can select such useful soft X-ray by cutting out within the scattered angle. It is expected that this X-ray will have many application to many wide research fields such as biological observation. As next step, soft X-ray optics with zone plates or an X-ray CCD camera was proposed for the soft X-ray microscopy to apply to the biological observation.

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