BEAM DIAGNOSTICS FOR LASER UNDULATOR BASED ON COMPTON BACKWARD SCATTERING

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Abstract

A low-emittance electron beam is required for the X-ray generation such as the synchrotron radiation and the laser undulator. 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. To generate the soft X-ray pulse stably, beam diagnostics is very important. In case of the laser undulator, the energy of the electron beam can be lower than other X-ray source such as synchrotron radiation but it is difficult to measure the beam characteristics about the low energy electron beam like a 5 MeV due to the space charge effect. Consequently, the slit scan technique has been developed to measure the beam emittance precisely. In case of the photocathode rf gun, the beam emittance strongly depends on the laser injection method. To generate the low-emittance beam, the emittance comparison experiments have been performed among three deferent methods, the slanting injection (the standard injection), the slanting injection with profile shaping and the perpendicular injection using the slit scan technique. In this conference, we will report results of the experiments.

INTRODUCTION

The relativistic high quality electron beam with short-bunch and low-emittance is required for various experiments in wide research fields. Especially, they play a critical role in the short-pulse X-ray generation using laser undulator, and coherent light source such as X-ray SASE-FEL [1].

The Compton or Thomson 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 [2-4]. 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.

The laser undulator based on Compton backward scattering has been developed as a short-pulse soft X-ray source at Waseda University [5]. Especially, 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* [6].

On the other hand, A low-emittance and short-bunch electron beam can be generated by the laser driven photocathode rf gun system [7, 8], which is based on BNL type of 1.6 cells S-band cavity and it has good advantages that time structure of electron beam can be controlled by laser pulse width, a bunching system is not necessary so that the total system can be compact, and high gradient electric fields in the rf cavities can be suppress emittance growth due to space charge effect.

At Waseda University, the high quality electron beam with energy of about 5 MeV generated from our rf gun system have been investigated to apply to the laser undulator as a compact soft X-ray source (in fig.1) for the biological observation [9]. The electron beam diagnostics such as the emittance and bunch length measurement is very important for laser undulator [10-11]. In particular, the transverse emittace is most sensitive value because it is changed by the laser injection phase to the input rf and laser injection method to irradiate to the photocathode. The comparison among the three deferent laser injection methods have been carried out by measuring the vertical emittance using the double slit scan technique.

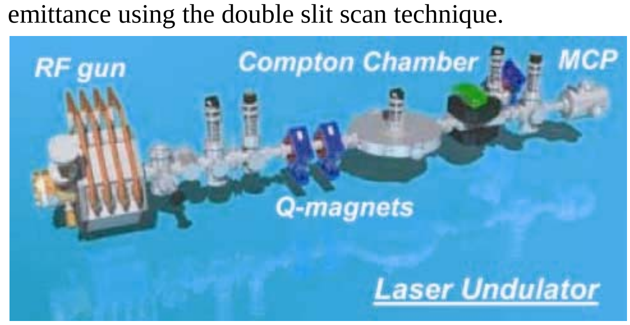

Figure 1: Laser Undulator as a compact soft X-ray source

HIGH QUALITY ELECTRON BEAM GENERATION SYSTEM

RF gun system with Nd:YLF laser

The rf gun system is composed of the BNL type 1.6 cell S-band rf cavity with Cu cathode, a set of solenoid magnets for emittance compensation [10], a stabilized

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laser and rf power source. The total system is very compact within 2×2 m^2 as a table-top size.

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 rf gun drive, but also for X-ray generation. 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 [12, 13]. As a previous result, the timing jitter was measured less than 0.5 ps and the affects of the electromagnetic noise and radiation was negligible for the laser stability. It is sufficiently small timing fluctuation for the soft X-ray generation. As a additional laser amplification for the beam applications, a flush lamp pumped laser amplification using Nd:YLF crystal (65 mmφ × 90mm) has been installed. 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.

LASER UNDULATOR BASED ON BACKWARD COMPTON SCATTERING

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 [2, 14]. 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

$$K = eA_0 / m_e c^2 \approx 0.85 \times 10^{-9} \lambda_0 \sqrt{I}, \tag{2}$$

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.

Soft X-ray generation

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. Figure 1 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.

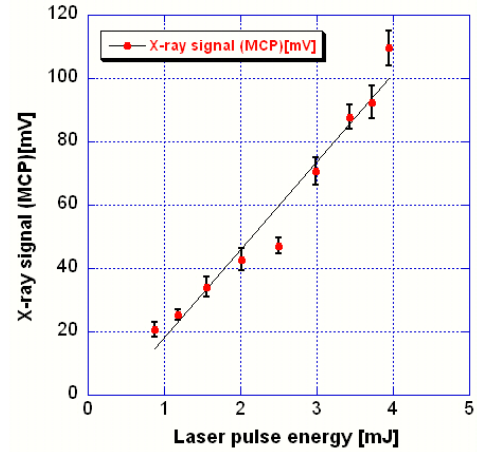

Figure 2: the typical soft X-ray signals as a function of the laser energy

Figure 2 shows the typical X-ray signals detected by the Microchannel plate (F4655-10: HAMAMATSU PHOTONICS K. K.) by changing the laser energy. This result indicates the flux linearity of the laser undulator against the laser energy. Up to now, the total number of generated photons is approximately 1.9×10^4 /pulse and the maximum X-ray energy is approximately 370 eV with 0.2 % energy bandwidth in the "water window" region. It is expected that this soft X-ray will have many application to the biological observation.

BEAM DIAGNOSTICS FOR LOW-EMITTANCE BEAM GENERATION

Transverse emittance is most important value of the electron beam for the laser undulator. In case of the rf gun, the transverse emittance is not only varied by changing the rf phase and the solenoid magnetic field, but also depends on the laser injection method to the photocathode. In case of the photocathode rf gun, the laser profile on the photocathode is the ellipse shape to the horizontal direction with the standard slanting injection at the incident angle of about 30 degree so that the horizontal size of the laser spot is three times larger than the vertical size. This fact occur the emittance growth of the beam due to the rf effect. To make the circular profile of the laser on the photocathode, two different methods were adopted. The first method is the slanting injection with profile shaping using anamorphic prisms (in fig. 3). In this method, the laser profile were made the ellipse shape to the vertical direction and compressed in the horizontal direction into one-third of the vertical size in advance of the injection to photocathode using two prisms.

The second method is the perpendicular injection using the reflective prism and the linear motion located at downstream of the beam line. In this method, it was easily to make the circular profile on the photocathode but the reflective prism probably obstruct the beam's way and it was required to set up carefully

The emittance comparison experiments have been performed among three deferent methods, the slanting injection (the standard injection), the slanting injection with profile shaping and the perpendicular injection.

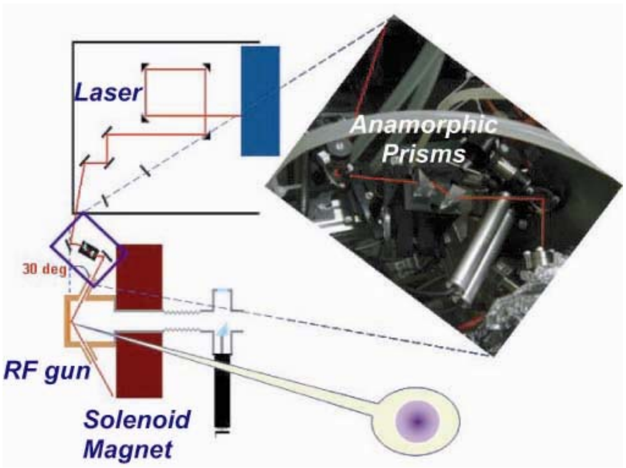

Figure 3: Top view of the slanting injection method with the anamorphic prisms.

As the emittance measurement method, the double slit scan technique has been developed at Waseda University [10]. This technique can give the phase space distribution without Gaussian assumption and reduce the space charge effect better comparing with Q-scan technique. Figure 4 show the experimental set up of the emittance measurement using the double slit scan technique. In this technique, electron beam was sliced by the first slit (Slit1) located at about 90 cm down stream of the beam line from the photocathode. The sliced beam was sliced again by the second slit (Slit2) located at about 20 cm downstream from Slit1 and the electron charge of the beam was measured by the Faraday cup monitor. By scanning the slit1 and slit2, the phase space distribution of the beam was reconstructed and the emittance value was calculated. This slit is made of 1mm-thick tungsten and the slit width is 200 μm. The slit can be moved in the step of 200 μm.

The emittance measurements on each injection method were carried out at rf phase of 10, 20, 30 degree under the same bunch charge of 100 pC, 200 pC, 300 pC, respectively, by controlling the laser energy.

First, the phase space distribution on the each electron charge and each laser injection method as a function of the solenoid field was investigated and the phase space distribution of the minimum emittance was observed on each phase. Figure 5 shows the vertical phase space distributions on the minimum emittance of the electron beam with charge of 300 pC in cases of the three laser injection methods. It is clearly found that the profile shaping and perpendicular method can make the vertical phase space small.

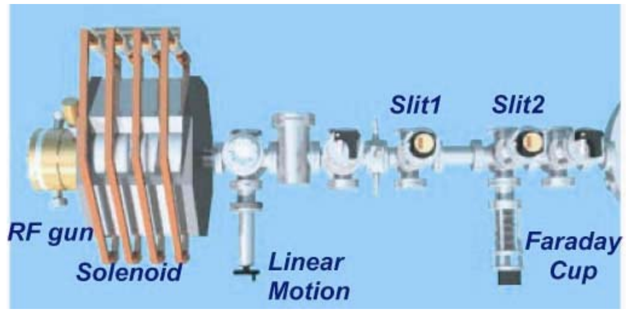

Figure 4: Top view of the experimental setup on the emittance measurement.

As a result in fig. 6, the perpendicular injection and slanting injection with profile shaping can generate the low emittance beam. In case of the perpendicular injection, bunch charge under the same laser energy was one third of the slanting injection due to the effect of the relation between the laser linear polarizing angle and the incident angle to the photocathode. Consequently, the slanting injection with profile shaping is the optimum method for the laser injection.

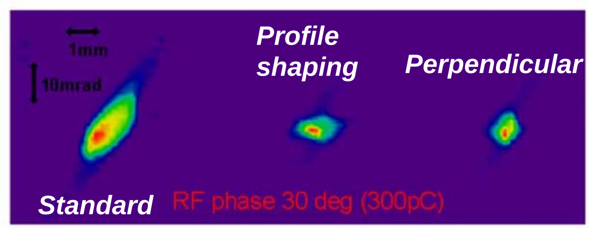

Figure 5: the minimum emittance distributions of the electron beam at 30 degree rf phase corresponding to charge of 300 pC .

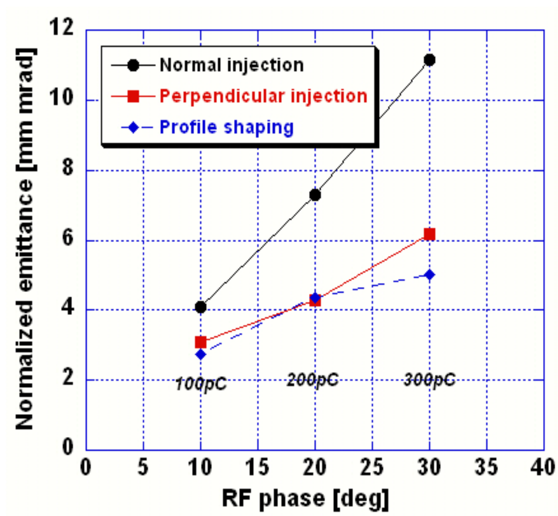

Figure 6: Minimum normalized emittance of each injection method as a function of rf phase

SUMMARY

Soft X-ray generation in "water window" region has been successfully carried out using laser undulator based on Compton backward scattering in 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.

To generate the low-emittance beam for laser undulator, beam diagnostics has been carried out such as emittance measurements. To investigate the laser injection method to irradiate to photocathode, the vertical emittance of the electron beam was measured using the double slit scan technique by changing the laser injection methods, standard injection, profile shaping and perpendicular injection. As a result, the slanting injection with the laser profile shaping made the best performance to generate the low-emittance beam among three injection methods.

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