

High quality beam generation and its application at Waseda University

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At Waseda University, we have started a new research project named “High-Tech Research Center Project” which is supported by the Ministry of Education, Culture, Sports, Science and Technology. In this project, a laser photo-cathode rf-gun with 1.6 acceleration cells has been installed for production of low emittance and short bunched electron beam. High quality electron beam is very powerful tool for the study on radiation physics, radiation chemistry, material science etc. Development of short X-ray pulse generation by the inverse Compton scattering between high quality electron beam and laser light obtained from an all-solid Nd:YLF laser will be started in 2001 fiscal year. The system will be applied to the pulse radiolysis experiments for the studies on radiation physics and chemistry. The X-ray generation experiment at Waseda University will be introduced in this paper.

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1. Introduction

Relativistic high quality electron beam in both transverse and longitudinal phase space is required for various experiments in wide research field. In particular, high quality electron beam plays vital role in ultra-short electron bunch production, coherent radiation, free electron laser (FEL) such as SASE, a pulsed X-ray generation and many other applications.

At Waseda University, low emittance electron beam is produced by BNL type 1.6 cells s-band photo cathode rf-gun¹², which has advantages that time structure of electron beam can be controlled by irradiating laser, a bunching system is not necessary and high accelerating field in the cavities of rf-gun can be suppress a emittance growth due to space charge effect. The electron beam will be used for the pulsed X-ray generation experiment for a biological investigation and a pulse radiolysis experiment for the observation of ultra-fast phenomena. In 2001 fiscal year, the short pulsed soft X-ray generation will be performed for applying the X-ray microscopy.

One of the most promising approaches to short pulsed X-ray sources is the Laser Synchrotron Source (LSS). It is based on inverse Compton scattering between pulsed laser beams and picosecond electron bunches³⁴. The LSS has many features, which are tunability of the wavelength, the yield, the spectrum and the spatial distribution of the scattered photons. Those characteristics of scattered photons can be controlled

varying the collision angle between electron beam and laser light, changing energy of electron beam or wavelength of laser light. We are planning to apply the LSS for X-ray microscopy to get the images of hydrated biological specimens without blurring caused by radiation damage and thermal diffusion. Soft X-ray generation experiment at Waseda University is introduced including numerical simulation for inverse Compton scattering.

2. High quality electron beam generation system

2.1 RF-gun system

Rf-gun system is composed of the BNL type 1.6 cell S-band rf cavities with Mg cathode⁵⁶, a set of solenoid magnets for emittance compensation⁷, a stabilized laser and rf power source. Using Mg cathode, which had developed at Brookhaven National Laboratory, we are able to get higher quantum efficiency than Cu cathode. Higher accelerating field is effective to reduce an emittance growth due to space charge effect for 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 (shown in Fig. 1).

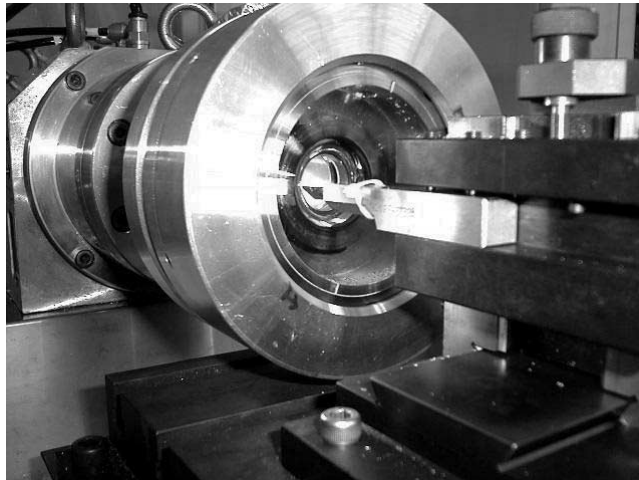


Fig. 1. Photograph of fine manufacturing of the rf-gun cavities at KEK machine shop.

The electron beam is emitted from the photo cathode using irradiation of UV laser light (262 nm, 4th harmonics of Nd:YLF fundamental light), therefore the characteristics of electron beam can be controlled by the laser injection timing, a beam profile of laser light in transverse and longitudinal direction.

Main parts of rf source for the rf-gun consists of 10 MW S-band klystron (Tomson: TV2019B6) and a small pulse modulator (Nissin Electric Co., Ltd.). The pulse modulator has good stability and flatness of the output pulse. The amplitude jitter of klystron voltage was about 0.38 % (p-p) for 20000 pulses and the pulse flatness was 0.25 % (within $>1.5 \mu\text{s}$ pulse flat-top).

On the other hand, we have started the simulation work using MAGIC code and PARMELA for the BNL type s-band rf-gun to find good operation parameters, such as setting of solenoid magnet system, laser injection phase and so on. From these simulations, we found that transverse emittance growth due to the electric field in radial direction could not be neglected in the case of high gradient acceleration⁸. More careful analysis taking account of slice emittance to clarify the relation between the transverse emittance growth and the strength of accelerating field is necessary.

2.2 Laser system

All solid state picosecond Nd:YLF laser system (PULRISE-V), which was developed by SHI (Sumitomo Heavy Industries, Ltd.), is used for the irradiation of cathode of rf-gun system and X-ray generation and pulse radiolysis experiment. Table 1 shows the specification of the PULRISE-V.

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 affects the laser intensity and spatial profile on the cathode, so that the laser system is put inside the irradiation room for achieving short optical path length from the main body of the laser to the cathode of rf-gun. Such the location, an electromagnetic noise and radiation may influence the laser system to increase timing and amplitude jitters. Therefore, the timing and amplitude fluctuation between a seed laser and the reference rf signal had been investigated using time domain demodulation technique⁹. As the result of the measurement, the timing fluctuation between the seed laser and reference signal was less than 1 ps with timing stabilization system, therefore the electromagnetic noise and radiation had given no effect to timing stability. So that we can achieve the small timing jitter between the laser light and electron beam down to sub-picosecond time region. It is sufficiently small timing fluctuation for the X-ray generation and the pulse radiolysis experiment under the picosecond time resolution. On the other hand, the laser intensity was fluctuated through certain damage onto a pumping laser diode. By putting electromagnetic and radiation

shielding around the laser body, it is possible to operate the laser system under the good intensity and pointing stabilities.

Specification	
Laser Medium	Nd:YLF
Pulse width: IR (1047 nm)	11.6 ps
Pulse Energy: IR(1047nm)/UV(262nm)	4.0/0.3 mJ
Repetition Rate	1-25 Hz
Time Jitter from Reference RF Signal	0.5 ps
Pointing Stability	< 50 μ rad
Divergence	< 2.0mrad
Beam Profile	TEM ₀₀
Energy Stability (UV,Long term:10hours) Energy stabilization ON	< 0.5 % RMS
Energy Stability (UV,Short term:10000 shots)	< 0.6 % RMS

Table 1. PULRISE-V Specifications

3. Soft X-raygeneration experiment

Soft X-rays having different energy spectrum are very useful for biological observation, because wavelength dependence of absorption coefficients is different in each element in the biomolecules. We can observe only a certain element by taking the difference of two images, which are observed using two different wavelength of the soft X-ray. K-shell absorption edges of Oxygen, Carbon and Nitrogen, which mainly constitute of a living body, are 2.322 nm, 4.368nm and 3.099 nm, respectively¹⁰. Those absorption edges are included in the range of “water window”. Since the absorption coefficient of water is much smaller than protein’s absorption coefficient in this range of “water window”, a dehydration of the specimens is not necessary.

Inverse Compton scattering with different collision angles will generate soft X-rays, which have different energy spectrum. Fig. 2 shows the coordinate of scattering between relativistic electron beam and laser light in laboratory frame and electron rest frame, where it is assumed that electron beam energy and

incident photon energy are $E_b (= \gamma mc^2)$ and k_0 in laboratory frame. The scattered photon energy k_s is given as

$$k_s = \frac{\gamma^2 k_0 (mc^2)(1 + \beta \cos \varphi)(1 - \beta \cos \theta)}{mc^2 + (1 - \cos \theta)(1 + \beta \cos \varphi)\gamma k_0} \quad (1)$$

, where $\cos \theta = (\cos \theta_s - \beta)/(1 - \beta \cos \theta_s)$ and angles of φ , θ , θ_s are the crossing angle in laboratory frame, the scattered angle in electron rest frame and laboratory frame, respectively (shown in Fig. 2). From Equation (1), maximum energy of scattered photon is given as

$$k_s(\text{max}) = \frac{\gamma^2 k_0 (mc^2)(1 + \beta \cos \varphi)(1 + \beta)}{mc^2 + 2 \cdot (1 + \beta \cos \varphi)\gamma k_0} \quad (2)$$

Fig. 3 shows the maximum energy of scattered photon as the function of crossing angle and the energy of K-shell absorption edge of Oxygen, Carbon and Nitrogen, in which it is assumed electron beam is 5 MeV and wavelength of laser is 1047 μm . Fig. 4 gives the scattered photon energy versus scattered angle at different collision angles. To select the energy of X-ray, the generated X-ray photons will be collected within a few degrees along the direction of electron beam propagation.

The total number of produced X-ray photons by inverse Compton scattering is given by the product of the cross section of Compton scattering (σ) and Luminosity (L), which is determined by the scattering geometry of electron beam and laser. In the case of head-on collision (zero crossing angle), the number of produced X-ray photons is maximized.

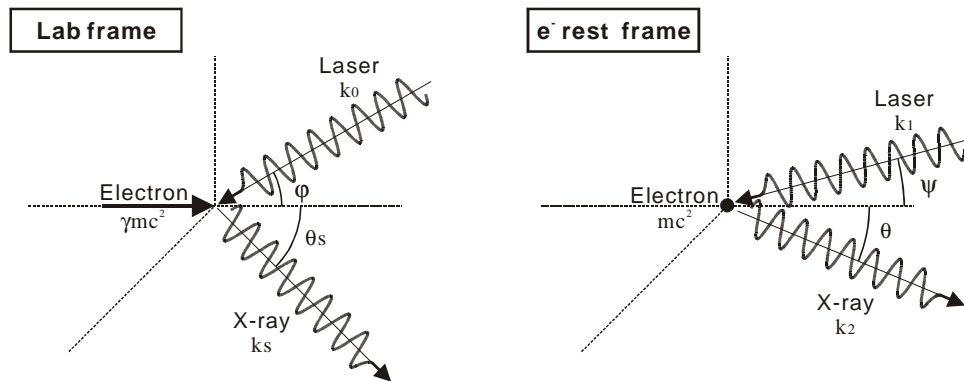


Fig. 2. The coordinate of scattering between electron beam and laser light in laboratory frame and electron rest frame.

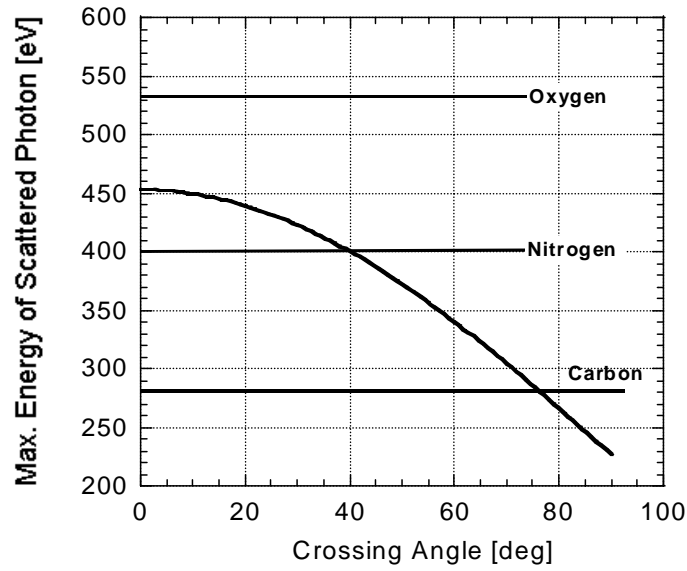


Fig. 3. Maximum scattered photon energy at different crossing angle

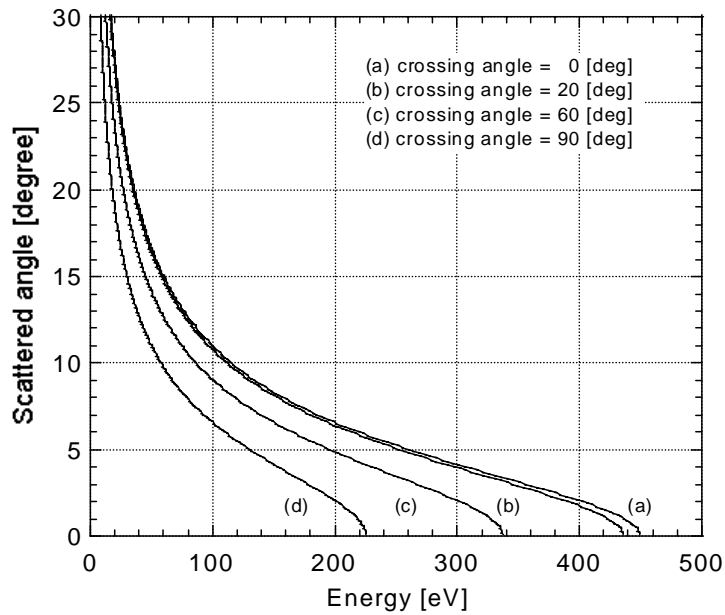


Fig. 4. Angular distribution of generated X-rays at different crossing angle

The interaction chamber for the laser Compton scattering experiment is designed to change the crossing angle between laser light and electron beam. Three crossing angles, for example 20, 60 and 90 degrees, can

be selected to generate X-rays having different energy spectrum. Laser optical path at each injection angle to the interaction chamber is selected using a combination pockels cells and polarizer as shown in Fig. 5.

The 4 mJ, 10 ps (FWHM) pulsed Nd:YLF (IR:1047nm) laser beam is introduced through the window and focused at the centre of the chamber. After interaction, laser beam go through from the opposite window. A dipole magnet separates the electron beam and the scattered soft X-ray after the interaction point. The timing jitter between the Nd:YLF laser and electron bunches is negligible in comparison with the electron pulse width, since source of UV for the photo cathode illumination of the rf-gun and IR for the Compton scattering is the same laser light.

Electron bunch	
Beam energy	5.0 MeV
Bunch charge	3 nC
Bunch length (FWHM)	10 ps
Beam size at focal point (σ_x/σ_y)	100/100 μm
Nd:YLF laser	
Wave length	1.047 μm
Energy/pulse	4 mJ
Pulse length (FWHM)	10 ps
Beam size at focal point (σ_x/σ_y)	30/30 μm

Table 2. Electron beam and Nd:YLF laser parameters

The 10 ps (FWHM), 3.0 nC electron bunches produced by the photo cathode rf-gun are focused at the middle point of the interaction cell to the $\sigma_e = 100 \mu\text{m}$ spot. Focal spot size of the Nd:YLF (IR) laser beam is $\sigma_L = 30 \mu\text{m}$, pulse length is 10 ps (FWHM) and laser pulse energy is about 4 mJ. As shown in Table 3, the total number of back-scattered photons at different crossing angle with 5 MeV electron bunch having 3 nC is calculated using CAIN which is a computer simulation code for the interaction of electron, positron, gamma beams and strong lasers. About 35 % of total scattered photon is included within 3 degrees of scattered angle at each crossing angle.

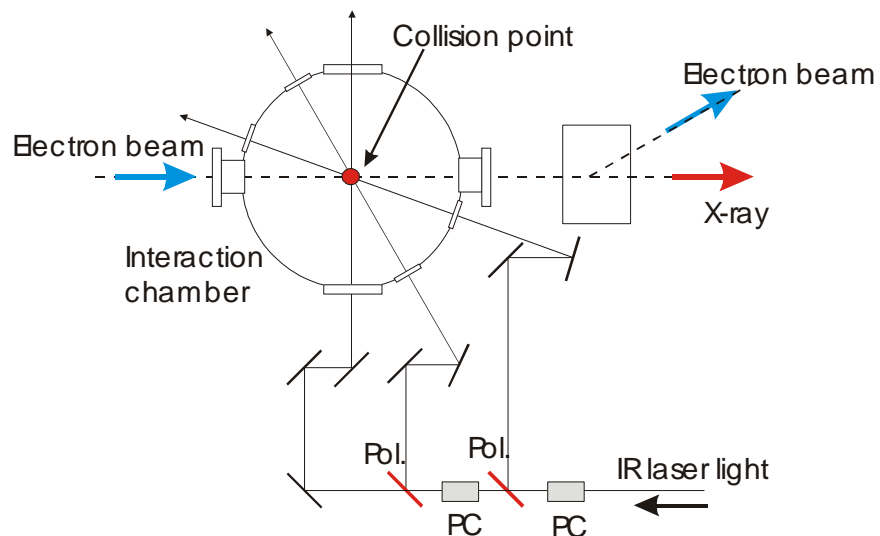


Fig. 5. Optical switching system for inverse Compton scattering

Crossing angle (ϕ)	Maximum scattered photon energy [eV] ([nm])	Number of Photons/pulse (within 3 deg. of scattered angle)
0	453 (2.74)	3.8×10^5 (1.4×10^5)
20	440 (2.82)	1.2×10^5 (4.3×10^4)
60	340 (3.65)	3.7×10^4 (1.3×10^4)
90	227 (5.46)	2.1×10^4 (7.4×10^3)

Table 3. Total number of photon at different crossing angle

4. Pulse Radiolysis Experiment

Pulse radiolysis is one of most powerful experimental method to investigate early events in radiation physics and chemistry. We will develop two different experimental setups using emission spectroscopy and absorption spectroscopy.

The emission spectroscopy system will be used for the experiments on singlet excited states of various kind of materials. For the first step of these experiments we will perform a conventional technique using a photo-detector such as PIN-photodiode in combination with monochromator and oscilloscope with time resolution up to 1ns. In this system, time resolution is determined by the cut-off frequencies of PIN-photodiode and oscilloscope. In near future, streak camera system, instead of PIN-photodiode and oscilloscope system, will be introduced. In such a case, time resolution will be up to 10ps.

The absorption spectroscopy system will be used for the experiment not only on singlet excited states but also on triplet states and on ionic states. Stroboscopic pulse radiolysis experiments will be performed using laser light as the probe light, which is divided from excitation laser light for RF-Gun cathode. Using this experimental setup, the measurement with 10 ps time resolution will be demonstrated to detect the absorption of hydrated electrons.

These pulse radiolysis experiments will give us very important knowledge on the primary reactions of molecules, atoms and other material complexes. Through the experiments, we will have datum on relaxation mechanism of electrons and excited states, dissociation mechanism of molecules to radicals and other states, etc.

5. Summary

In 2001 summer, we will start the operation of rf-gun system and measure the characteristics of electron beam precisely. Experiment of soft X-ray generation will be performed using inverse Compton scattering between high quality electron beam and stabilized laser light at different crossing angle. To apply the LSS to X-ray microscopy, high intensity of soft X-ray is necessary and X-ray optical system. To get as high luminosity as possible at the LSS, good focusing and bunching of electron beam and upgrade of laser is required.

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- ¹ X. J. Wang et al., Physical Review E **54-4**, p. 3121 (1996).
- ² X. Qiu et al., Phys. Rev. Lett. **76 No. 20**, p. 3723 (1996).
- ³ W. Leemans et al. in *Particle Accelerator Conference*, 1995, p. 174.
- ⁴ S. Kashiwagi et al., Nuclear Instrument and Methods A **455**, p. 36-40 (2000).
- ⁵ T. Srinivasan-Rao et al., J. Appl. Phys. 77 (3) **77 (3)**, p. 1275-1279 (1995).
- ⁶ T. Srinivasan-Rao et al., in *Particle Accelerator Conference*, 1997, p. 2790.
- ⁷ D. T. Palmer et al., in *Particle Accelerator Conference*, 1997, p. 2843.
- ⁸ R. Kuroda et al. in *European Particle Accelerator Conference*, 2000, p. 1666.
- ⁹ H. Tsuchida, Opt. Lett. **23**, p. 286 (1998).
- ¹⁰ B. L. Henke et al., Atomic Data and Nuclear Data Tables 27, (1982).