

# DESIGN OF LINAC BASED COMPACT X-RAY SOURCE VIA INVERSE COMPTON SCATTERING AT WASEDA UNIVERSITY\*

A. Masuda<sup>†</sup>, T. Gowa, C. Igarashi, T. Kashino, N. Mitsuda, K. Sakaue, M. Washio,  
RISE, Waseda University, Tokyo, Japan  
R. Kuroda, AIST, Ibaraki, Japan  
S. Kashiwagi, ISIR, Osaka University, Osaka, Japan  
H. Hayano, J. Urakawa, KEK, Ibaraki, Japan  
K. Ushida, RIKEN, Saitama, Japan

## Abstract

A table-top size soft X-ray source based on inverse Compton scattering has been developed at Waseda University. We have already succeeded in generating X-rays via inverse Compton scattering between 4.6 MeV electron beam generated from a photocathode RF-gun and 1047 nm Nd:YLF laser. The energy of the X-ray is within the Hwater window ! region which can be applied to the soft X-ray microscope for biological observation. In 2007, new RF-gun cavity with Cs-Te photocathode in place of copper has been installed. The energy of electron beam has become up to 5.5 MeV due to the increase of Q-value of the gun cavity. With this achievement, generated X-ray energies will cover overall the Hwater window ! region. We have been planning a multi-pulse inverse Compton scattering X-ray generation system in order to enhance a luminous intensity of the X-rays. For this purpose, we are considering a multi-pulse UV laser system for generating a multi-bunch electron beam, the method for beam loading compensation, and the multi-pulse IR laser system for the Compton collisions.

## INTRODUCTION

Linac based compact soft X-ray generation system via inverse Compton scattering has been built in Research Institute for Science and Engineering (RISE), Waseda University[1]. Inverse Compton scattering is an interaction between a high energy electron beam and a laser beam which generates X-rays as shown in Figure 1 and the energy of generated X-rays are expressed as

$$K_S = \frac{\gamma^2 k_0 m c^2 (1 + \beta \cos \phi) (1 - \beta \cos \theta)}{m c^2 + (1 - \cos \theta) (1 + \beta \cos \phi) \gamma k_0} \quad (1)$$

and this can be one of the advanced methods of generating high-quality X-rays which has advantages such as short pulse, quasi-monochromaticity and energy adjustability. Moreover, compared with synchrotron radiation X-ray sources, required energy of electron beam is much lower so that accelerator system can be compact. The energy of X-rays generated in our system is within Hwater window !

region which contains K-shell absorption edges of carbon and nitrogen while absorption rate of water is negligible small[2]. So our X-ray generation system will be suitable for a soft X-ray microscopy for biological bodies which consist of protein materials with water.

We have already succeeded in generating 370 eV soft X-rays using 4.6 MeV electron beam and 1047 nm Nd:YLF laser. However, the flux of generated X-rays is not enough because both the cross-section of inverse Compton scattering and the number of interactions per second are small. So we have been working on increasing of the X-ray yield based on multi-pulse X-ray generation system.

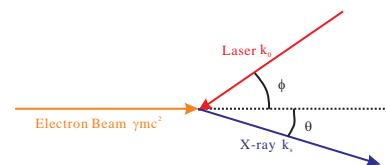


Figure 1: Schematic diagram of inverse Compton scattering.

## X-RAY GENERATION SYSTEM

Our soft X-ray generation system is shown in Figure 2. It includes a laser system! HPulrise V ! and a photocathode RF-gun and the whole system is table-top size ( $2.5 \times 2m^2$ ). IR laser (1047 nm; the fundamental of Nd:YLF) is guided to the collision point after passing through a flash lamp amplification system and delay stage which can adjust collision timing. UV laser (262 nm; the 4th harmonic of Nd:YLF) is injected to the photocathode RF-gun to illuminate the photocathode and generate photo-electrons. The timing synchronization of electron beam and collision laser is easy because both IR and UV laser are generated in the same laser system.

## APPROACHES FOR HIGHER X-RAY YIELD

The yield of generated X-rays had been too small and the S/N had not been good until 2006. In 2006, we installed a new collision chamber and built three-pass amplification

\* Work supported by MEXT High Tech Research Project HRC707, JSPS Grant-in-Aid for Scientific Research (B)(2) 16340079.

<sup>†</sup> a-masuda@suou.waseda.jp

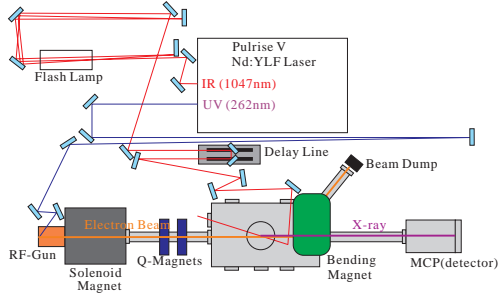


Figure 2: X-ray generation system at Waseda University. (Single pulse setting.)

system[3]. With these improvements, the yield of generated X-rays has been increased up to  $3.28 \times 10^4$  and S/N up to 123.

Toward of the practical use of X-ray biological microscopy, the yield of X-rays has to be enhanced more than thousand fold again. However, the power of the collision laser is limited by the damage threshold of optical components and the nonlinear effect of inverse Compton scattering. The charge amount of electron beam bunch is also limited due to a space charge effect. More than 800 pC/bunch electron beam cannot be focused adequately at the collision point and simply causes large background. So we cannot enhance the luminosity of inverse Compton scattering anymore on single pulse operation.

We are considering multi-pulse inverse Compton scattering system to enhance the yield of generated X-rays more than thousand fold. If 1000 pulses/train multi-pulse inverse Compton scattering is achieved with the same electron beam and laser parameters per pulse, the yield of generated X-rays per second will be simply increased thousand fold. In order to achieve the multi-pulse inverse Compton scattering, multi-bunch electron beam and multi-pulse collision laser are required.

## MULTI-BUNCH ELECTRON BEAM GENERATION

### *Cs-Te photocathode new RF-gun*

In order to generate multi-bunch electron beam, high quantum efficiency photocathode RF-gun and multi-pulse UV laser to illuminate photocathode is required. The former can moderate the required output power of the latter. We have developed a new photocathode RF-gun with high quantum efficiency Cs-Te photocathode, which has achieved not only high quantum efficiency but the higher Q-value than the old one due to the new structure of its bond part and frequency tuner. This system has been already installed in Waseda University and succeeded in generating electron beam[4]. As a result of the increment of Q-value, the energy of electron beam has become up to 5.5 MeV and the energy of generated X-rays has become up to 530 eV and covers whole of !Hwater window ! region.

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### *Design of multi-pulse UV laser amplification system*

The multi-pulse UV laser system has been designed as Figure 3. This system consists of a pulse picker, dual amplification modules and a frequency converter. The pulse picker consists of a pockels cell and polarizing optics which picks up 100 - 1000 pulses per train from 119 MHz Nd:YLF 1047 nm mode-lock laser. Pulse train length is 840 ns - 8.4  $\mu$ s and repetition rate is assumed to be 5Hz. Then the pulse train is amplified by dual amplification modules. The first amplification module is pumped up by laser diode arrays and the second one is by flash lamps. The required laser pulse energy at the photocathode is 30  $\mu$ J/pulse. Considering an efficiency of frequency conversion and various losses, each pulse has to be amplified up to 80  $\mu$ J/pulse using two amplification modules.

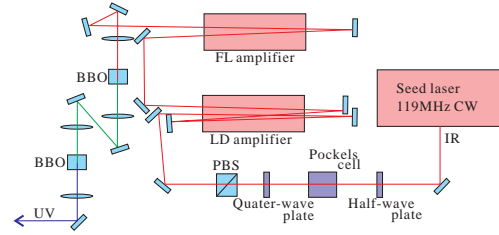


Figure 3: Schematic design of multi-pulse laser amplification system for cathode illuminating UV laser.

In the laser amplification, small signal gain coefficient  $g_0$  is calculated as

$$g_0 = \frac{P\kappa}{AI_S} \quad (2)$$

where  $P$ ,  $\kappa$  and  $A$  are the pump up power, effective absorption efficiency and mean value of pump area respectively.  $I_S$  is saturation intensity described as

$$I_S = \frac{h\nu}{\sigma\tau} \quad (3)$$

where  $h$ ,  $\nu$ ,  $\sigma$  and  $\tau$  are the Planck's constant, frequency of laser light, stimulated emission cross section and the life time of the upper level of the laser medium. Actual gain  $g$  is limited by saturation intensity as

$$g = \frac{g_0}{1 + \frac{I_0}{I_S}} \quad (4)$$

The intensity of single pass amplified laser light  $I$  is expressed as following with original laser intensity  $I_0$  and laser rod length  $L$ ,

$$I = I_0 \cdot e^{g \cdot L} \quad (5)$$

Using these formulae, we designed LD module which can amplify pulse trains up to 25  $\mu$ J/pulse after 4-passes. The calculation conditions are listed in Table 1. To consider the losses in the optics, the estimate value will be less than 1  $\mu$ J/pulse. Therefore pulses should be amplified by flash

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lamp pumped module up to 80  $\mu\text{J}/\text{pulse}$  after the diode pumped one. Finally, at the frequency converter consists of two BBO crystals, the 4th harmonic 262 nm UV laser with enough pulse energy is generated.

Table 1: Parameters for the calculation of laser amplification.

Lifetime of upper level	520 $\mu\text{s}$
Cross section	$1.8 \times 10^{-19} \text{ cm}^{-2}$
Effective absorption efficiency	20 $\text{m}^{-1}$
Laser wavelength	1047 nm
Pump up power	1 kW
Mean value of pump area	0.32 $\text{cm}^2$
Laser spot size	0.13 $\text{cm}^2$
Laser rod length	13.6 cm
Seed laser power (CW)	0.2 W (1.7nJ/pulse)

### Beam loading effect calculation and its compensation system

In accelerating multi-bunch electron beam, an electrical field which the former electron bunches woke constricts acceleration of latter electron bunches. This effect is called beam loading effect. The beam loading effect which affect the N th electron bunch is calculated as

$$V_{b,N} = \frac{\omega_0 R_S q}{2Q_0} \left( \frac{1 - e^{-(N-2)\tau}}{1 - e^{-\tau}} - \frac{1}{2} \right) \quad (6)$$

where  $\omega_0$ ,  $R_S$  and  $Q_0$  are the resonant frequency, the shunt impedance and the unloaded Q-value of the acceleration cavity respectively.  $\tau$  is expressed with the filling time of the cavity  $t_f$  and the bunch distance  $t_b$  as

$$\tau = \frac{t_b}{t_f} \quad (7)$$

$$t_f = \frac{2Q_0}{\omega_0 (1 + \beta)} \quad (8)$$

where  $\beta$  is the coupling constant of the input coupler. Flat energy multi-bunch electron beam is needed for multi-pulse inverse Compton scattering. So we have to compensate this effect. We are planning to compensate the effect by using the rising edge of RF pulse calculated as

$$V_{RF} = \frac{2}{1 + \beta} \sqrt{\beta R_S P_0} \left( 1 - e^{-\frac{t}{t_f}} \right) \quad (9)$$

where  $P_0$  is the RF peak power. A numerical calculation of this method is shown in Figure 4 and calculation conditions are shown in Table 2. A blue line is a cavity voltage without beam loading effect. Red cross plots show the acceleration voltages of each electron bunch. Balancing the rising edge of RF and beam loading effect, energy difference in a pulse train is controlled to be 1.9%. If this method is not sufficient, we would consider modulating RF pulse wave form.

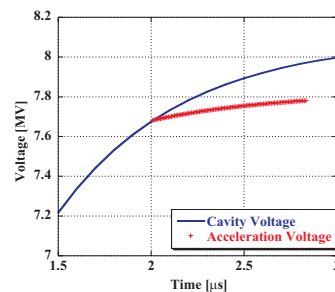


Figure 4: Numerical calculation of beam loading effect compensation.

Table 2: Parameters for beam loading effect and its compensation calculation.

Unloaded Q-value	12230 $\mu\text{s}$
Resonance frequency	2856 MHz
Shunt impedance	4.5 $\text{M}\Omega$
Coupling constant	1.0217
Bunch distance	8.4 ns (119 MHz)
Electric charge	700 pC/bunch
RF peak power	10MW
Number of electron bunches	100 bunches/train

### Multi-pulse collision laser

For the achievement of a multi-pulse inverse Compton scattering, multi-pulse collision laser is required. We have already built multi-pulse collision laser system based on pulsed laser super-cavity in LUCX project collaborated with KEK-ATF[5]. We are planning upgraded super-cavity system after establishment of the multi-bunch beam generation.

## CONCLUSION

In order to enhance the yield of X-ray from inverse Compton scattering, we are planning to establish multi-pulse collision system. We have already installed new RF-gun for multi-bunch beam generation and designed multi-pulse UV laser system which can generate sufficient pulse energy in calculation. Also we consider beam loading effect and decided the policy of its compensation. Hereafter we will generate a high quality multi-bunch electron beam with flat energy and design a collision laser system.

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