

## DEVELOPMENT OF LASER SYSTEM FOR COMPACT LASER COMPTON SCATTERING X-RAY SOURCE

R. Kuroda<sup>#\*</sup>, H. Toyokawa, M. Koike, K. Yamada, AIST, Ibaraki, Japan  
 T. Gowa, A. Masuda, K. Sakaue, M. Washio, RISE, Waseda University, Tokyo, Japan  
 S. Kashiwagi, ISIR, Osaka University, Osaka, Japan  
 T. Nakajyo, F. Sakai, SHI, Tokyo, Japan

### Abstract

A compact X-ray source via laser Compton scattering is required for biological, medical and industrial science because it has many benefits about generated X-rays such as short pulse, quasi-monochromatic, energy tunability and good directivity. Our X-ray source is conventionally the single collision system between an electron pulse and a laser pulse. To increase X-ray yield, we have developed a multi-collision system with a multi-bunch electron beam and a laser pulse. The multi-bunch electron beam has been successfully generated from a Cs<sub>2</sub>Te photocathode rf gun using a multi-pulse UV laser system. The laser optical cavity will be built like the regenerative amplification including the collision point between the electron pulse and the laser pulse to enhance the laser peak power per 1 collision on laser Compton scattering (LCS).

### INTRODUCTION

A quasi-monochromatic and short pulse X-ray source has been investigated via laser Compton scattering (LCS) between a high quality electron bunch and a high power laser pulse for the various research fields [1-2]. The compact LCS soft and hard X-ray source have been developed based on S-band electron linac with a photocathode rf gun system at Waseda University [3] and AIST [4], respectively. The most disadvantage of the linac based LCS X-ray source is low X-ray yields. Typical soft X-ray and hard X-ray yields were about 10<sup>5</sup> and 10<sup>7</sup> photons/s. Present system of the compact LCS soft X-ray source has only a Cs<sub>2</sub>Te photocathode rf gun for the electron source which can generate a high quality electron beam up to 5 MeV. The laser system is based on a multi-pass Nd:YLF laser amplification. In case of the present LCS hard X-ray source at AIST, a compact S-band electron linac with a Cs-Te photocathode rf gun system and a 3 m-long accelerator structure can generate the electron beam up to about 42 MeV. The laser system for LCS is a CPA Ti:Sa laser system.

Our applications of LCS soft and hard X-ray source are the biological imaging in the “water window” region and the medical and biological uses, such as mammography, angiography and protein crystallography, respectively. Enhancement of more 10<sup>2</sup> times than the present X-ray yield should be required for these applications. Most promising approach for these purposes is the multi-pulse X-ray generation via multi-collision laser Compton

scattering (Multi-LCS). Figure 1 shows the scheme of Multi-LCS is designed using multi-bunch electron beam and a laser cavity for the hard X-ray source at AIST. The laser cavity includes a laser crystal and a collision point for LCS so that a few laser pulses are seeded into the cavity through a coupling mirror and pulse energy is built up at every pass through the laser crystal like the regenerative amplification. The laser pulse is focused at the collision point by concave mirrors in the cavity. In this paper, calculation results of Ti:Sa laser cavity and multi-pulse X-ray generation via Multi-LCS are described with a experimental result of multi-bunch electron beam generation.

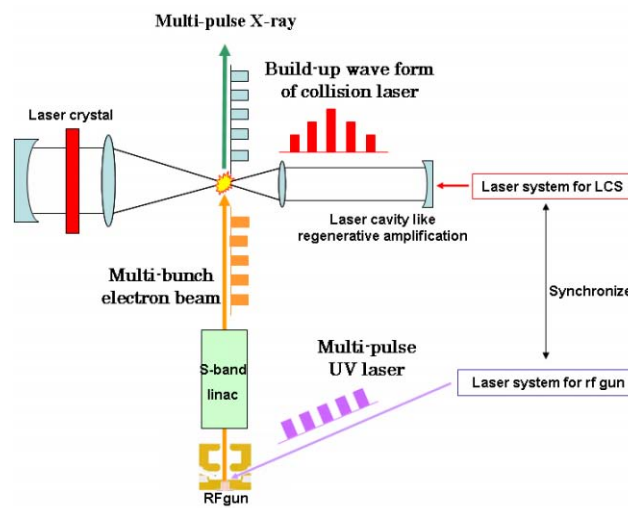


Figure 1: Scheme of multi-collision laser Compton scattering (Multi-LCS) using laser cavity.

### PREPARATION OF MULTI-COLLISION LASER COMPTON SCATTERING

#### Laser Cavity for Multi-LCS

Multi-collision laser Compton scattering (Multi-LCS) is realized between multi electron bunches and focused laser pulses in the laser cavity including a laser crystal and a telescope while its seed laser is built up like the regenerative amplification (fig. 1).

In our model for LCS hard X-ray source at AIST, a thin laser crystal of Ti:Sa is located nearby the end mirror so that the first laser pulse passes twice through the laser crystal before the second pulse reaches at the laser crystal. The mode-lock frequencies of both a rf gun driving laser

<sup>#</sup>E-mail: ryu-kuroda@aist.go.jp

\*Visiting Assistant Professor at Waseda Univ. Japan

and a seeded Ti:Sa laser for the LCS cavity are locked to 79.33 MHz (36<sup>th</sup> sub-harmonic frequency of 2856 MHz) and synchronized to RF frequency (2856 MHz) for the accelerator. The mode-lock frequency corresponds to 12.6 ns pulse spacing so that the cavity length and the number of seeded pulse are able to be chosen as a half of some harmonic of pulse spacing and the harmonic number, respectively. The number of seeded pulse and the cavity length are defined 4 pulses and 7.56 m. The build-up waveform in the laser cavity and the intra-cavity stored energy can be calculated by summing 100 build-up pulses which will collide to 100 electron bunches in case of the LCS hard X-ray source.

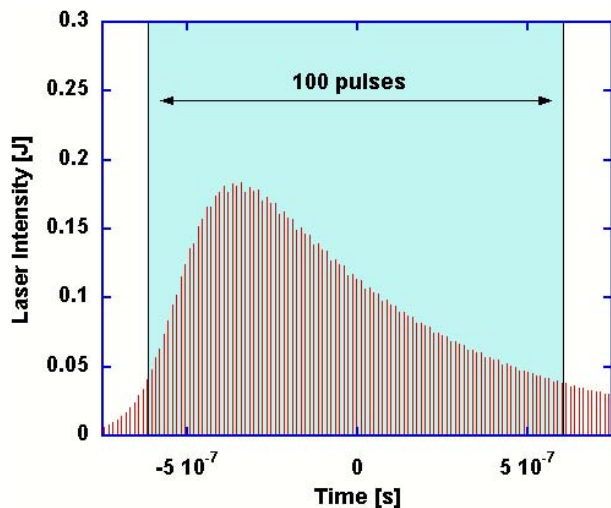


Figure 2: Build-up pulses in the laser cavity like regenerative amplification for Multi-LCS.

In the build-up process in the laser cavity like the regenerative amplification, the maximum energy of amplified pulse is limited by the damage threshold of the optical mirror which has assumed damage threshold of 8 J/cm<sup>2</sup> at 800 nm, 300 ps corresponding to 1.5 J/cm<sup>2</sup> at 10 ps (chirped pulse by the pulse stretcher) so that the maximum energy is limited about 180 mJ/pulse due to the waist size of 2 mm in the contracting region of the laser cavity. Figure 2 shows the build-up waveform in the cavity by calculating with modulated seed laser pulses. The intra-cavity stored power was estimated by summing 100 build-up pulses around the peak energy pulse of 180 mJ to be approximately 10 J corresponding the average energy of 100 mJ/pulse.

A new Compton chamber which has size of about 50 cm × 1.5 m × 25 cm with a profile monitor of the electron beam has been designed to mount the laser cavity for Multi-LCS in vacuum and manufactured in last year (fig. 3). This chamber has a removable insided plate for the cavity mirror mount and many connection ports such as aquator ports of cavity mirrors, incidence port of seed laser, monitor ports of laser power, view ports of beam profiles and a couple of ports for a main beam line. The electron beam is focused on the waist of the laser cavity

for the LCS hard X-ray generation. Installation of the new chamber will be started from end of 2008 fiscal year.

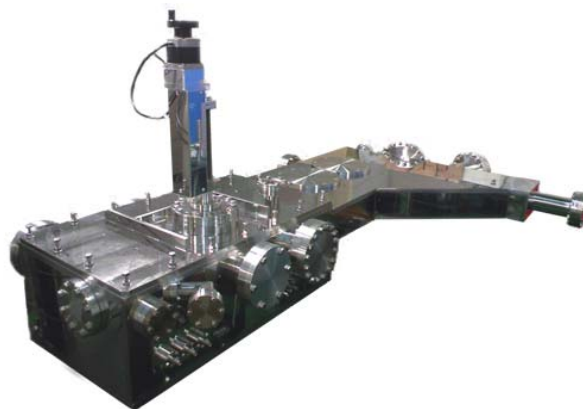


Figure 3: New Compton chamber for Multi-LCS.

### Multi-Bunch Electron Beam Generation and Calculation of LCS X-Ray

The multi-bunch electron beam generation should be also required for Multi-LCS. A multi-pulse UV laser system for the multi-bunch photoelectron emission has been developed at AIST. Schematic diagram of the system is shown in Figure 4. Mode-lock laser pulses which has 79.3 MHz mode-lock frequency were generated from a Nd:YVO<sub>4</sub> oscillator. 100 pulses were picked up from these pulses with the pockels cell and amplified at a Nd:YAG multi-pass pre-amplification. The amplified laser pulses were modulated with AOM and modulated 100 pulses were amplified at a Nd:YAG multi-pass main-amplification. The amplified 100 pulses were converted to SHG and FHG using KTP and BBO crystals, respectively. UV laser pulses have been successfully obtained about 10 μJ/pulse × 100 pulses.

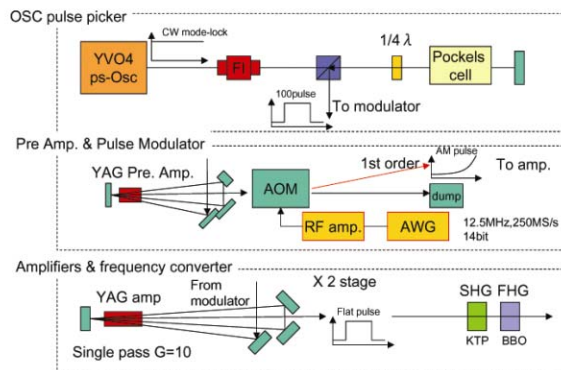


Figure 4: Schematic drawing of the multi-pulse laser system for multi-bunch electron beam generation.

The compact load-lock system to install the Cs<sub>2</sub>Te photocathode into the rf gun cavity with a length of about 1 m has been developed in collaboration with KEK and Waseda University. Figure 5 shows the compact Cs<sub>2</sub>Te

load-lock system with a rf gun cavity and a delivering unit which has a NEG pump to maintain a vacuum level

of about  $10^{-6}$  pa without electric power. The evaporation process was performed at KEK. At first, about 50 nm Te was evaporated on a Mo substrate and then more than 10 nm Cs was evaporated on the Te layer using a Cs dispenser. The  $\text{Cs}_2\text{Te}$  photocathode on the Mo plug was carried to AIST using the delivering unit. The cathode plug was installed into the rf gun cavity using the rotating chamber and the linear actuator of the load-lock system.

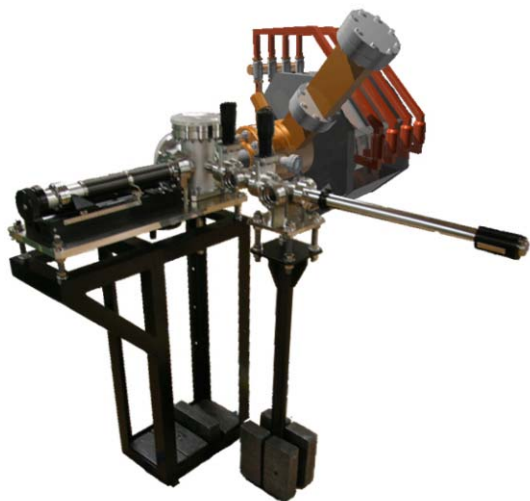


Figure 5: RF gun with  $\text{Cs}_2\text{Te}$  load-lock system.

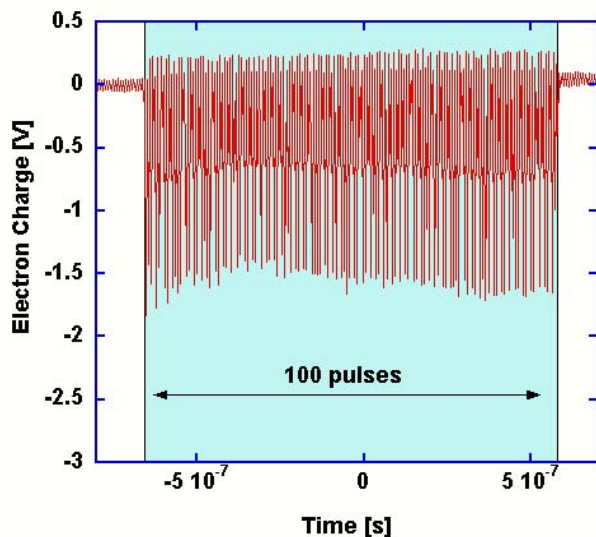


Figure 6: Multi-bunch electron beam using multi-pulse UV laser and  $\text{Cs}_2\text{Te}$  photocathode rf gun.

Multi-bunch electron beam generation has been carried out using the  $\text{Cs}_2\text{Te}$  photocathode rf gun and the multi-pulse UV laser system. As a result, the multi-bunch electron beam has been successfully generated and measured about  $1.5 \text{ nC} \times 100$  bunches at 40 MeV with a current monitor (fig. 6). In this case, the quantum efficiency of the  $\text{Cs}_2\text{Te}$  cathode was achieved about 0.3 %.

The bunch spacing was locked about 12.6 ns depended on the mode-lock frequency of the Nd:YVO<sub>4</sub> oscillator.

In the next step, the multi-bunch electron beam will be focused to the collision point in the laser cavity inside of the new chamber after installation to the beam line. The laser pulse to pulse duration will be controlled and synchronized to electron bunch spacing about 12.6 ns by adjusting the laser cavity length with the end mirror on a high accuracy linear stage in vacuum. The multi-LCS will be realized between about  $100 \text{ mJ} \times 100$  laser pulses and  $1.5 \text{ nC} \times 100$  electron bunches with repetition rate of 10 Hz. The yield of Multi-LCS hard X-ray on our design has been estimated to be about  $5 \times 10^9$  /s with parameters in table 1.

Table 1: Parameters of LCS hard X-ray calculation.

Electron energy	40 MeV
Electron charge	1.5 nC/bunch
Bunch number	100
Electron spot size ( $\sigma_x, \sigma_y$ )	40 $\mu\text{m}$
Electron bunch length	10 ps (FWHM)
Laser wavelength	800 nm
Stored laser power	10 J / 100 pulse
Average laser energy	100 mJ/pulse
Laser spot size ( $\sigma_x, \sigma_y$ )	38 $\mu\text{m}$
Laser pulse width	10 ps (FWHM)
Collision angle	170 deg
Maximum LCS X-ray energy	38 keV
LCS photon number	$5 \times 10^6$ /pulse
Repetition rate	10 Hz
Total photon yield	$5 \times 10^9$ /s

## SUMMARY

The calculation of the laser cavity for the Multi-LCS hard X-ray source has been successfully performed about Ti:Sa laser system. The development of the multi-pulse UV laser system and the  $\text{Cs}_2\text{Te}$  rf gun system have been also carried out at AIST. The multi-bunch electron beam generation has been already demonstrated about  $1.5 \text{ nC} \times 100$  bunches at 40 MeV. As a result, the yields of LCS hard X-ray will be expected more than  $5 \times 10^9$  /s via Multi-LCS. However, the intra-cavity stored laser power is strongly depended on quality of the laser cavity. It is found that quite high reflectivity of optical mirrors in the cavity should be required for our Multi-LCS model.

## REFERENCES

- [1] R. W. Schoenlein et al, Science **274**, 236 (1996).
- [2] K-J. Kim et al, Nucl. Instr. Meth. A **341**, 351 (2000).
- [3] S. Kashiwagi et al., J. Appl. Phys. **98**, 123302 (2005).
- [4] H. Ikeura et al., Appl. Phys. Lett., **92**, 131107 (2008)