DEVELOPMENT OF LASER COMPTON SCATTERING X-RAY SOURCE ON THE BASIS OF COMPACT ELECTRON LINAC

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Abstract

A compact hard 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 yields, we have developed a multi-collision system with a multi-bunch electron beam and a laser optical cavity. The multi-bunch beam will be generated from a Cs-Te photocathode rf gun system using a multi-pulse UV laser. 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. In this conference, we will describe the results of preliminary experiments for the multi-collision system and future plans.

INTRODUCTION

A quasi-monochromatic X-ray source via laser Compton scattering has been developed on the basis of an S-band compact electron linac at AIST in Japan. All of system is built in one research room about 10 meters square including an electron injector, an electron linac, quadrupole magnets, bending magnets, an rf source and a high power laser system [1-2]. Figure 1 shows a top view of our conceptual diagram for the laser Compton scattering X-ray source. The injector consists of a laser photo-cathode rf gun which has the BNL type S-band 1.6 cell cavity with a Cs_2Te photocathode load-lock system and a solenoid magnet for emittance compensation. The linac has two 1.5-m-long accelerator tubes which have a 1/2 π mode standing wave structure. The electron beam can be accelerated up to about 42 MeV using the rf source of a 20 MW klystron. In case of the single collision mode of the laser Compton scattering X-ray source using a TW Ti:Sapphire laser can generate a hard X-ray pulse which has variable energy of 10 keV - 40 keV with narrow bandwidth by changing electron energy and collision angle for medical and biological applications [3].

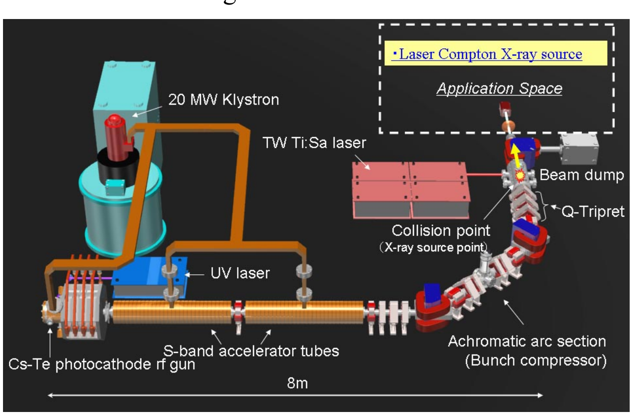

Figure 1: Conceptual diagram for the laser Compton scattering X-ray source.

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SINGLE COLLISION MODE OF THE LCS X-RAY SOURCE

In case of the single collision mode of laser Compton scattering (LCS) X-ray source, two mode-locked laser systems was operated in 10 Hz, whose mode-lock frequencies are synchronized to 36th sub-harmonic frequency (79.3 MHz) of the linac accelerating frequency (2856 MHz). An all-solid state UV laser (266 nm) was used for the photocathode rf gun. The other laser system was a femtosecond Ti:Sapphire laser with a chirped-pulse amplification (CPA), which is used as collision laser for LCS. It consists of a mode-locked oscillator, a pulse stretcher, a regenerative amplifier, a multi-pass pre-amplifier, a multi-pass main amplifier and a pulse compressor. The pulse width and energy per pulse were 100 fs (FWHM) and 140 mJ, respectively. Pulse width of the LCS X-rays is 150 fs – 3 ps depending on a beam sizes of the laser and electron, beam-beam crossing-angle, and pulse widths. The shortest X-ray pulse width is obtained at 90-degree collision angle. The maximum energy of the LCS X-rays can be tuned 10 – 40 keV in about 5 % energy spread, and total photon yields are about 10^7 photons/s at 165-degree collision angle. Overall system specifications are summarized in Table 1.

Table 1: Specification of laser Compton X-ray source

Electron beam	Energy	~42 MeV
	Bunch charge	~1 nC
	Energy spread	0.2%
	Bunch length	3 ps (rms)
	Beam size at collision point	43 μm x 30 μm (rms)
	Repetition rate	10 Hz
Ti:Sapphire laser	Wavelength	800 nm
	Pulse width	100 fs (FWHM)
	Repetition rate	10 Hz
	Pulse energy	140 mJ
	Spot size	28 μm (rms)
X-ray	Energy	~40 keV
	Yield at 165 deg	10^7 photons/s
	Yield at 90 deg	10^6 photons/s
	Stability	~6% (15 min)

We have applied the LCS X-ray to medical and biological imaging using a in-line phase-contrast imaging [3-4, which is to enhance the contrast of the difference of densities in bone and soft-tissues of living specimens. Figure 2 shows results of the Compton X-ray imaging. The specimens were hind limbs of a normal mouse and an ovariectomized (OVX) mouse which can suffer from the osteoporosis. The X-ray energy was 26 keV in this observation. This image was obtained using an imaging plate at 200 mm behind the specimens where the refraction contrast is expected to be effective. In case of the OVX mouse, the osteoporosis may cause some fragile structure inside its bones. Actually, the bone edge around the knee joint is observed to be clear and tight in the normal mouse (upper image), while it is found to be obscure in the OVX mouse (lower image) as shown in the dashed circle. This suggests the occurrence of bone erosion which may indicate a symptom of the osteoporosis. Father inspection will be necessary to verify this argument.

Even though the quasi-monochromatic LCS X-ray is very useful for the biological and medical imaging,, the photon yields are not enough for the real-time imaging and the much higher resolution imaging. The upgrade plan to increase the X-ray yields several orders of magnitude has been executed with a multi-collision LCS system, that is to generate a train of X-ray pulses using laser and electron pulse-trains [5].

Figure 2: Results of the in-line phase contrast imaging.

MUTI-COLLISION MODE OF THE LCS X-RAY SOURCE

Laser Cavity for Multi-LCS

The 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. 3).

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 and a seeded Ti:Sa laser for the LCS cavity are locked to 79.33 MHz (36^{th} 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.

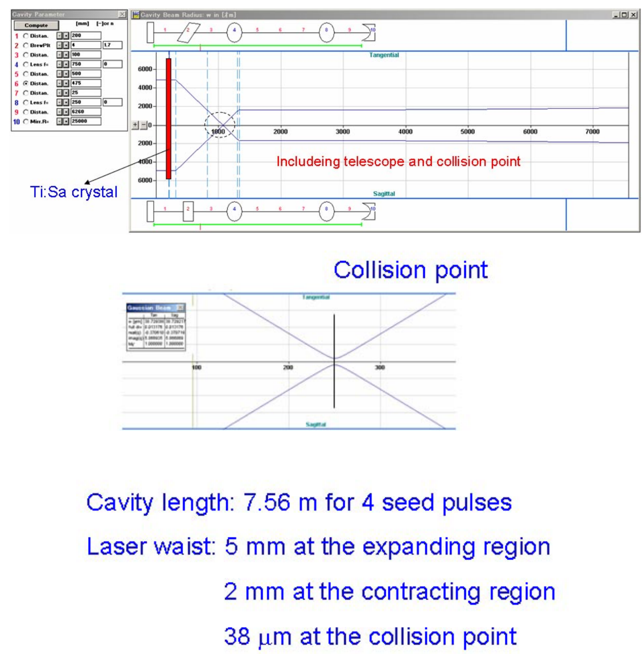

Figure 3: Laser cavity design for Multi-LCS.

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^2 at 800 nm, 300 ps corresponding to 1.5 J/cm^2 at 10 ps (chirped pulse by the pulse strecher) so that the maximum energy is limitted 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 apploximately 10 J corresponding the average energy of 100 mJ/pulse.

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. Top view 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_4 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. The compact load-lock system to install the Cs_2Te photocathode into the rf gun cavity with a length of about 1 m has been developed in collaboration with KEK and Waseda University. The compact Cs_2Te load-lock system with an rf gun cavity has 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 in a small chamber. 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 Cs_2Te 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.

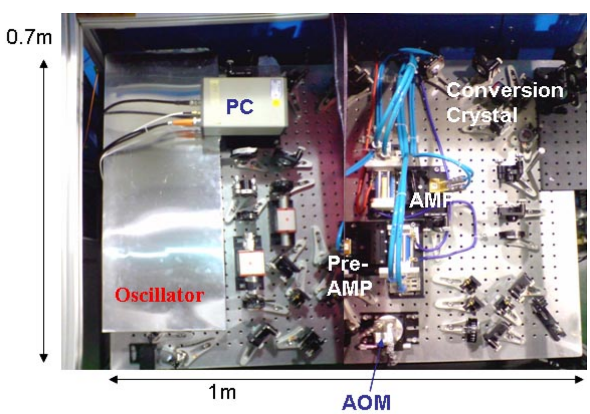

Figure 4: Top view of multi-pulse UV laser system.

Multi-bunch electron beam generation has been carried out using the Cs_2Te 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 nC × 100 bunches at 40 MeV with a current monitor. In this case, the quantum efficiency of the Cs_2Te 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_4 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 mJ × 100 laser pulses and 1.5 nC × 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 × 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 (σ_x, σ_y)	40 μm
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 (σ_x, σ_y)	38 μm
Laser pulse width	10 ps (FWHM)
Collision angle	170 deg
Maximum LCS X-ray energy	38 keV
LCS photon number	5 × 10^6 /pulse
Repetition rate	10 Hz
Total photon yield	5 × 10^9 /s

SUMMARY

We have developed the laser Compton Scattering (LCS) X-ray source on the basis of the S-band compact electron linac at AIST. In case of the single collision mode, the total number of generated photons and maximum X-ray energy were 10^7 photons/pulse and approximately 40 keV, respectively, at a crossing angle of 165°. We have successfully demonstrated the use of our in-line phase-contrast imaging system with 26 keV LCS X-rays. In case of the multi-collision mode, development of the multi-pulse UV laser system and the Cs_2Te rf gun system have been carried out. In near future, the X-ray yields will be increased more than 5 × 10^9 /s.

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