DEVELOPMENT OF MULTI-COLLISION LASER COMPTON SCATTERING X-RAY SOURCE ON THE BASIS OF COMPACT S-BAND ELECTRON LINAC

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Abstract

A compact hard X-ray source via laser Compton scattering (LCS) 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. The LCS X-ray source has been developed conventionally the single collision system between an electron pulse and a laser pulse for the medical and biological imaging at AIST. 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 electron beam has been already generated from a Cs-Te photocathode rf gun system using a multi-pulse UV laser. The laser optical cavity has developed like a regenerative amplifier including the collision point between the electron bunch and the laser pulse which is based on the Ti:Sa laser with a mode-locked frequency of 79.33 MHz. As a preliminary experiment, the modulated seed laser pulses were generated and leaded to the cavity, so that laser build-up amplified pulse were obtained in the cavity with both single seed and double seed pulses. In this paper we will describe imaging results using the single collision LCS-X-ray, results of preliminary experiments for the multi-collision system and numerical simulation results.

INTRODUCTION

We have developed a quasi-monochromatic X-ray source via laser Compton scattering (LCS) with both the single collision and the multi-collision schemes on the basis of an S-band compact electron linac at AIST in Japan. All of system is constructed in one research room about 10 meters square. It consists of an electron injector, an electron linac, quadrupole magnets, bending magnets, an rf source and a high power laser system [1-2]. The injector is based on 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. In case of the single collision mode of the LCS X-ray source using a high power Ti:Sapphire laser system 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].

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SINGLE COLLISION LCS FOR IMAGING APPLICATIONS

The laser Compton scattering (LCS) X-ray source with the single collision scheme has been developed using two mode-locked laser systems operated in 10 Hz, whose mode-lock frequencies are synchronized to 36th sub-harmonic frequency (79.3 MHz) of the linac accelerating rf frequency (2856 MHz). An all-solid state UV laser (266 nm) was used for the photocathode rf gun. The linac with the rf gun can generate 1 nC, 40 MeV electron bunch. The collision laser system is a femtosecond Ti:Sapphire laser with a chirped-pulse amplification (CPA). 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 laser pulse width and maximum energy per pulse are 100 fs (FWHM) and 140 mJ, respectively. The LCS X-ray has been generated by interaction between the laser pulse and the electron bunch. The generated X-ray pulse can be arbitrarily controlled from 150 fs to 3 ps by changing the beam sizes and the crossing-angle. The shortest X-ray pulse width is obtained at 90-degree collision angle. The maximum energy of the LCS X-ray 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: Specifications of Single Collision LCS X-ray

Electron beam	Energy	~42 MeV
	Bunch charge	~1 nC
	Bunch length	3 ps (rms)
	Repetition rate	10 Hz
	Beam size at collision point	40 μm x 30 μm (rms)
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 collision angle	10^7 photons/s
	Yield at 90 deg Collision angle	10^6 photons/s
	Stability	~6% (15 min)

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The LCS X-ray has been applied to medical and biological imaging using a K-edge imaging and a in-line phase-contrast imaging [3-4]. Figure 1 shows one of the results of the LCS X-ray imaging. The sample is the human head phantom for angiography. It consists of the human-body equivalent materials such as polyurethane, epoxy resin. In Figure 1, we can clearly observe the back-bone and the carotid arterial vessel in the neck part using 40 keV LCS X-ray. According to these results, the quasi-monochromatic LCS X-ray is very useful for the biological and medical imaging. However, 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].

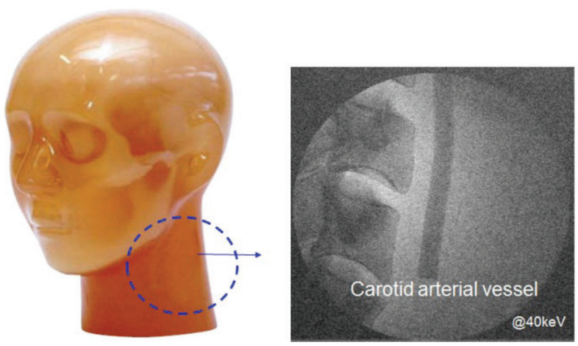

Figure 1: Result of the LCS X-ray imaging with single collision scheme.

MUTI-COLLISION MODE OF THE LCS X-RAY SOURCE

Laser Cavity for Multi-collision LCS

The laser Compton scattering (LCS) with multi-collision scheme will be realized between multi electron bunches and focused laser pulses in the laser cavity. The laser cavity includes a laser crystal and a telescope while its seed laser is built up like the regenerative amplifier. In this scheme, the thin laser crystal of Ti:Sa is located in the cavity. 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 accelerating rf frequency (2856 MHz). 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. In this experiment, the number of seeded pulses and the cavity length are defined 2 pulses and 3.78 m. The build-up waveform in the laser cavity and the intra-cavity stored energy can be estimated by summing 100 build-up pulses around the peak pulse which will be collided to 100 electron bunches. Regarding to the build-up process in the laser cavity like the regenerative amplification, the maximum energy of amplified pulsse 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 preliminary experimental build-up laser pulses in the regenerative-amplifier-type cavity with single seed laser pulse and modulated double seed laser pulses. As a results, the peak intensity of the amplifiered pulse with the single seed laser pulse was twice higher than using the double seed pulses. However, the stored pulse energy is same and the build-up pulse number with the single seed is half of the double seed case. The experimental sotred energy was not achieved to the designed value. In the final step, the designed intra-cavity stored power is estimated by summing 100 build-up pulses around the peak energy pulse to be apploximately 10 J corresponding the average energy of 100 mJ/pulse.

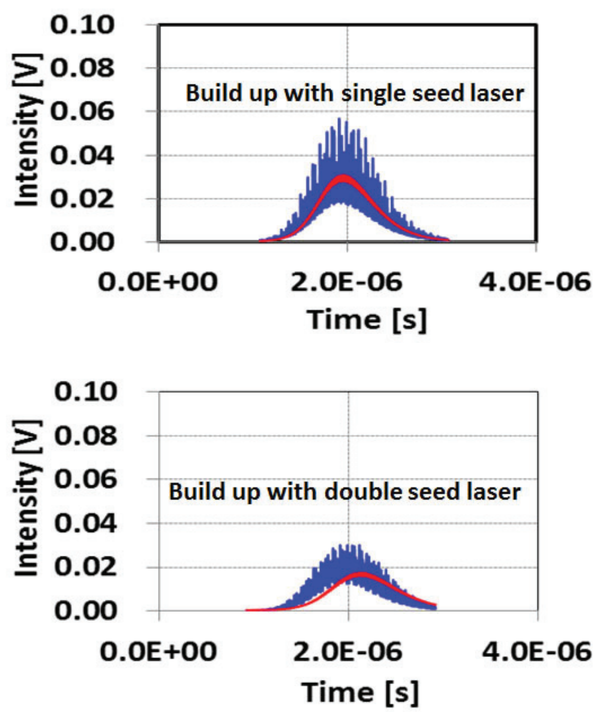

Figure 2: Experimental results of build-up laser pulses by changing the number of seed pulses.

X-ray Yield Calculation Including Energy Spread and Beam Emittance

In the multi-collision LCS scheme to increase the X-ray yield, the 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 beam1has been successfully generated and measured about 1 nC × 100 bunches at 40 MeV with a current monitor. In the next step, the multi-bunch electron beam will be focused to the collision point in the cavity.

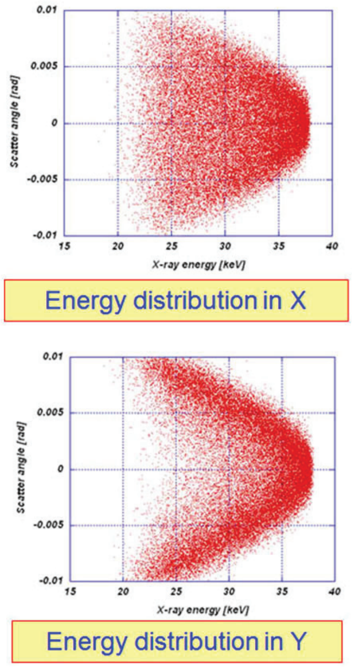

Figure 3: Calculated energy distribution of X-ray.

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 nC × 100 electron bunches with repetition rate of 10 Hz. The X-ray yield of multi-collision LCS X-ray has been calculated with the 3 dimensional collision model including beam divergence and emittance. The calculation parameters are described in table 2. The total photon yield has been estimated to be about 3.3×10^9 /s. In the multi-collision LCS, the electron energy spread is a little bit larger than the spread of the single collision mode due to the electron beam loading effects. We have also calcurated the X-ray energy distribution and the X-ray profile in Figure 3 and 4 and have checked the capability of the LCS X-ray.

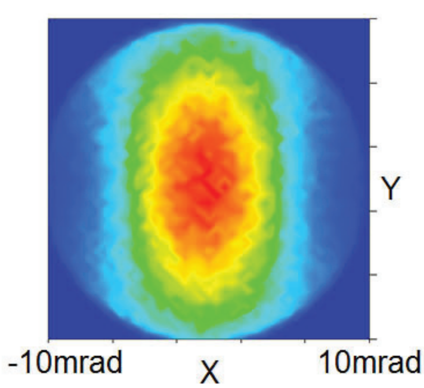

Figure 4: Calculated X-ray profile.

Table 2: Parameters of LCS Hard X-ray Calculation

Electron energy	40 MeV
Energy spread(rms)	0.2 %
Electron charge	1 nC/bunch
Emittance	3π mm mrad
Bunch number	100
Electron spot size (σ_x, σ_y)	40 μm
Electron bunch length	10 ps (FWHM)
Laser wavelength	800 nm
Wavelength spread	0.4 %
Stored laser power	10 J / 100 pulse
Average laser energy	100 mJ/pulse
Laser spot size (σ_x, σ_y)	38 μm
Laser focal length	250 mm
Spot size at focusing lens	1 mm
Laser polarization	Horizontal
Laser pulse width	10 ps (FWHM)
Collision angle	170 deg
Maximum LCS X-ray energy	38 keV
LCS photon number	3.25×10^6
Repetition rate	10 Hz
Total photon yield	3.3×10^9 /s
Photon yield within 10 mrad	$1.3\ 10^9$/s

SUMMARY

The laser Compton Scattering (LCS) X-ray source has been developed on the basis of the S-band compact electron linac at AIST with both the single collision scheme and the multi-collision scheme. In case of the single collision mode for the biological and medical imaging, the total number of generated photons and maximum X-ray energy were 10^7 photons/pulse and about 40 keV, respectively. In the development of the multi-collision scheme, the laser build-up pulses in the regenerative-type laser cavity have been successfully obtained as a preliminary experiment. The expected X-ray yield was also calculated to be about 3.3×10^9 /s. In near future, multi electron bunches will be collided with build-up laser pulses in the cavity to increase

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