A SHORT-PULSE HARD X-RAY SOURCE WITH COMPACT ELECTRON LINAC VIA LASER-COMPTON SCATTERING FOR MEDICAL AND INDUSTRIAL RADIOGRAPHY

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Abstract

An intense, quasi-monochromatic hard x-ray beam has been generated via the laser-Compton scattering of an electron bunch with a laser pulse. An s-band linear accelerator of 40 MeV and Ti:Sapphire femtosecond terawatt laser were used to generate x-rays. We plan to increase the x-ray intensity up to two-orders than the current one until FY2008. Specifications of the electron accelerator and the laser systems are presented, together with the developments and modifications being undergone.

INTRODUCTION

We have installed a short-pulse hard x-ray source with a compact electron linac via laser-Compton scattering to National Institute of Advanced Industrial Science and Technology (AIST) in FY 2005. The x-ray source was originally developed by Sumitomo Heavy Industries Ltd., [1, 2] in a framework of Femtosecond Technology Association (FESTA) under contraction of industrial technology development program by Ministry of Economy, Trade and Industry of Japan (METI).

The x-ray source generates two kinds of x-ray pulses. One is a femtosecond pulse in 90-degree scattering, and the other one is a few tens picosecond pulse in 165-degree scattering. The x-ray intensity is approximately one order lower for the femtosecond x-ray pulses with 90-degree scattering, compared to the picosecond pulses with 165-degree.

These x-rays are very interesting and worthy for medical and industrial imaging because they have unique characteristics such as the ultra short-pulse, energy-tunability and monochromaticity. The compactness of the total system is worthy for many users. Familiarity to pump-probe experiments using ultra-short laser pulse is also attractive.

SYSTEM DESCRIPTION

The x-ray source consists of an electron linac and two laser systems. The linac consists of a photocathode rf-gun as an injector [3], two 1.5 m s-band accelerating tubes of alternating periodic structure (APS), 90-degree achromatic arc, and the interaction chamber for laser-Compton scattering (Compton chamber).

The injector consists of a laser-driven, BNL-type s-band 1.6-cell cavity photocathode rf gun with a solenoid magnet for emittance compensation [4]. The accelerating tubes have APS structures of $\pi/2$ mode, which are designed to accelerate a single electron-bunch of 5 nC bunches up to 45 MeV. It consists of 27 accelerating cells and 26 coupling cells with a coupling iris of 24 mm in diameter. Compared to a conventional traveling-wave accelerating structure, the phase and voltage of the APS structure are quite stable against beam loading, because the energy-propagation velocity is high. We have accelerated 5 MeV, 1 nC electron bunches from rf-gun up to as high as 42 MeV.

The 90-degree arc section sweeps electrons from intense background bremsstrahlung x-rays from the accelerating structures. One of the most important properties of this accelerator is to focus an electron beam at the center of interaction point for the laser-Compton scattering, and to keep it steady. So, we applied an achromatic design, which consisted of two 45-degree bending magnets with four quadrupole magnets. The beam is, then, focused in the Compton chamber with a strong triplet-quadrupoles.

The two laser systems we use are well synchronised with each other, and stabilized to master oscillator (s-band; 2856 MHz) with a very small jitter. One laser is for the photocathode, and the other one for the laser-Compton scattering. The first one consists of a mode-locked picosecond laser of LD-pumped Nd:YLF (Time-Bandwidth Products Inc., PULRISE series). We used its 4th harmonic light (262 nm). The laser system for the laser-Compton scattering consists of a Ti:Sapphire system with terawatt peak power by the chirp pulse amplification. It generates a 100 fs laser pulse in 140 mJ at 800 nm. Both laser systems are mode-locked to the 36th sub-harmonic frequency (79.3 MHz) of s-band. Two laser systems are synchronised to the master oscillator by the timing stabilizer operated in 36th harmonics of 79.3 MHz, that is 2856 MHz.

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X-RAY GENERATION AND ITS APPLICATION

We observed 10^7 photons/s of x-rays of maximum energy of 40 keV using electron bunch of 0.8 nC. The repetition rate was 10 Hz. The specifications of the accelerator, lasers and the x-rays are summarized in table 1.

Table 1: Specifications of accelerator, laser and x-rays

Electron:	Energy	~42 MeV
	Charge per bunch	~1 nC
	Energy spread	0.2%
	Bunch length	3 ps (rms)
	Focused beam size	43 μm x 30 μm (rms)
	Rep rate	10 Hz
Ti:Sapphire laser:	Wavelength	800 nm
	Pulse length	100 fs (FWHM)
	Rep rate	10 Hz
	Pulse energy	140 mJ
	Spot size	28 μm (rms)
UV laser:	Wavelength	262 nm
	Pulse length	3 ps
	Pulse energy	150 μJ
X-ray:	Energy	~41.1 keV
	Yield @ 165 deg	10^7 photons/s
	Yield @ 90 deg	10^6 photons/s
	Stability	~6% (15 min)

Figure 1 shows an energy spectrum of the laser-Compton photons measured with an x-ray detector (AMPTEK, model XR-100CR). Because the beam repetition rate was 10 Hz, the spectrum piled-up.

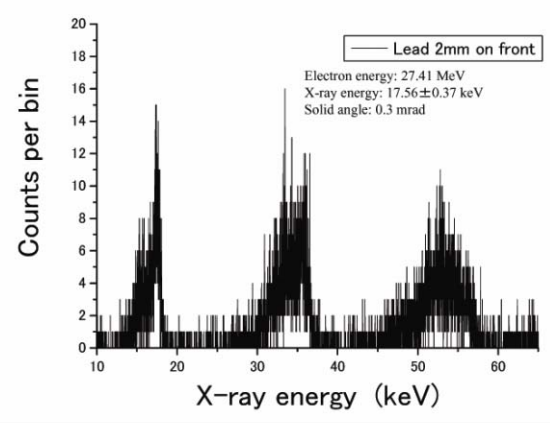

Figure 1: Pulse height spectrum for the laser-Compton photons measured with an x-ray detector (AMPTEK, model XR-100CR).

Figure 2 and 3 show examples of radiography experiments. The samples were a light bulb of 4 cm in height and a chicken born, respectively. The image was taken with an x-ray CCD camera (ROPER SCIENTIFIC, PI-SCX:1300-2.5-PW) of resolution of 50μm.

We see that high-resolution radiography is possible with the present system, but we need to increase the x-ray intensity, at least two orders, for medical application, such as mammography and angiography.

Figure 2: Radiography of light bulb measured with 18 keV x-rays.

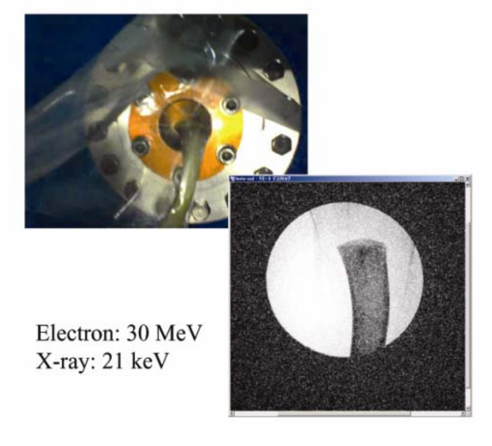

Figure 3: Radiography of chicken born measured with 21 keV x-rays. The field of view of the radiograph was 30 mm in diameter, which corresponded to the aperture size of the Be window.

ENHANCEMENT OF X-RAY INTENSITY

We plan to increase the x-ray intensity by increasing the bunch charge using Cs-Te cathode. Cathode load-lock system (Figure 4) fit to the rf-gun is being developed in collaboration with KEK. It will be installed in a few months.

We also generate and accelerate a train of high-charge electron bunches, and let them collide with a train of laser pulses to generate a train of x-ray pulses. A multi-pulse UV laser system for the bunch train is being developed. Schematic diagram of the system is shown in Figure 5. Our design goal is to generate a train of 100 bunches with 1 nC per bunch with 3π mm-mrad. Until now, a train of 100 bunches of 0.6 nC per bunch per macropulse of 1 μs in width have been generated (Figure 6).

The counterpart of the multi-pulse laser system for a bunch train is the multi-pulse laser system for laser-Compton scattering or the train of x-ray pulses. The basic concept and the design goal are schematically shown in Figure 7.

We plan to install a long laser-cavity in the Compton chamber whose cavity length corresponds to the bunch spacing (1.9 m, or 79.3 MHz) or its harmonics. It is temporarily set to 7.56 m, which corresponds to an injection of 3 seed-pulses. The laser gain medium is excited during the interaction of the laser pulses to the electron bunches. We chose a flat disc of a Ti:Sapphire crystal.

The cavity itself is a regenerative amplifier with a beam expansion telescope inside. The electron beam is focused on the waist of the laser cavity, and generates the laser-Compton x-rays. Installation of the laser system starts in this autumn, and complete by Jan 2008.

We are also interested in focusing the electron beam down to 10 ~ 20 μm using a strong-focus quadrupole magnets, to enhance the x-ray intensity up to one order. Discussion to install a permanent-magnet quadrupoles in somewhere in the beamline is still undergoing.

CONCLUSION

We briefly introduced our x-ray source with the laser-Compton scattering of a bunch of 40 MeV electrons with an 800 nm, 1.5 terawatt laser pulse. Several research activities for the enhancement of the x-ray intensity are being undergone. Cs-Te cathode and the rf-gun load-lock system will be installed, soon. A multi-pulse laser system for the generation of electron bunch train is being developed. It is under a commissioning stage. A long-axis cavity for multiple laser-Compton scattering to generate a train of x-ray pulses is planned. Design of the main cavity is done, and we will install the system in this autumn.

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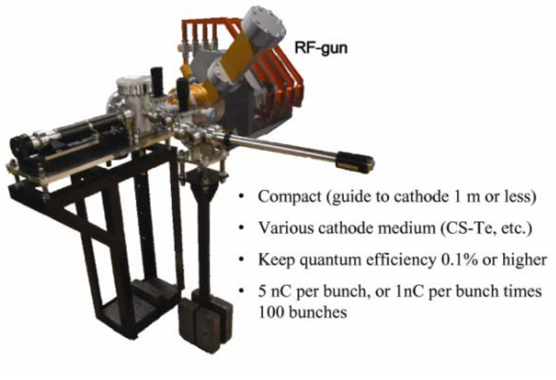

Figure 4: Cathode load-lock system being developed in collaboration with KEK.

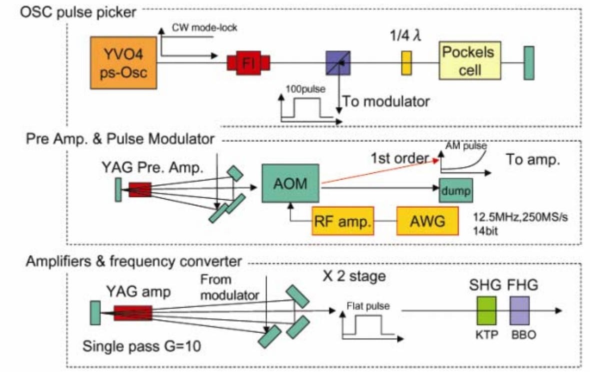

Figure 5: Schematic drawing of the multi-pulse laser system for electron bunch train.

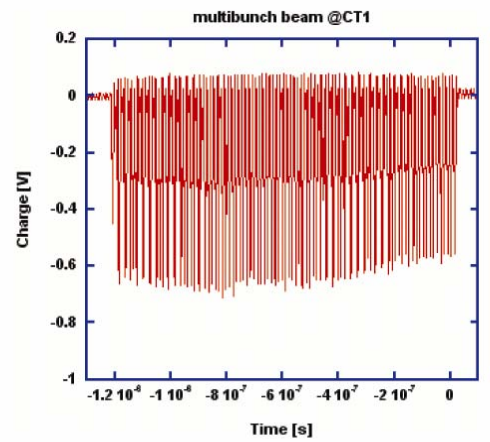

Figure 6: A train of electron bunches generated with multi-pulse UV laser. Macropulse width is 1 μs.

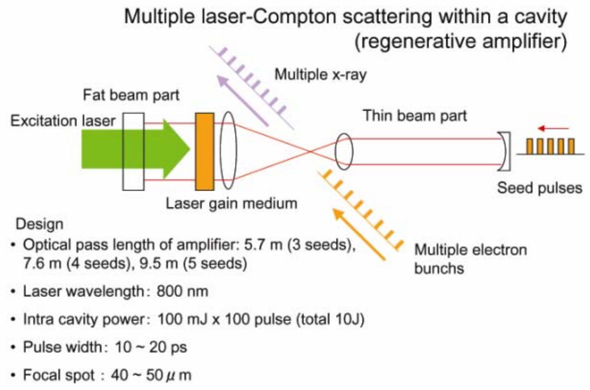

Figure 7: A multi-pulse laser cavity for generation of a train of x-ray pulses via the laser-Compton scattering.