

## PRESENT STATUS OF QUANTUM RADIATION SOURCES ON THE BASIS OF THE S-BAND COMPACT ELECTRON LINAC

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### Abstract

Quantum radiation sources such as a laser Compton scattering (LCS) X-ray and coherent THz radiation sources have been developed on the basis of the S-band compact electron linac at AIST in Japan. The compact X-ray source is required for biological, medical and industrial science because it has many benefits such as short pulse, quasi-monochromatic, energy tunability and good directivity. The X-ray source is conventionally operated with the single collision system between an electron pulse and a laser pulse for the medical imaging. 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 generation has already been carried out with a Cs-Te photocathode rf gun system. The prototype of the laser optical cavity has preliminary built like a regenerative amplifier including the collision point. The coherent THz radiation have been performed using an ultra-short electron bunch and been applied for a THz scanning transmission imaging. The THz Time-domain spectroscopy (TDS) has also developed using this high power THz pulse. In this conference, we will describe a present status of the LCS X-ray, coherent THz radiation sources, and their applications.

### INTRODUCTION

Quantum radiation sources such as a laser Compton scattering X-ray and a coherent THz radiation sources have been developed on the basis of the S-band compact electron linac at AIST in Japan [1-2]. 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. Figure 1 shows a top view of the quantum radiation sources. The injector consists of a laser photo-cathode rf gun which has the BNL type S-band 1.6 cell cavity with a Cs-Te photocathode and a solenoid magnet for the emittance compensation. The linac has two 1.5-m-long accelerator tubes which is a  $1/2 \pi$  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, 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 [3-5]. The coherent THz radiation source using an ultra-short electron bunch from the S-band compact linac have been also

developed instead of a conventional laser based THz source. The designed THz pulse has high peak power more than 1 kW in frequency range between 0.1 - 2 THz. The THz pulse has been generated with coherent radiation such as coherent synchrotron radiation (CSR) using an ultra-short electron bunch with bunch length of less than 0.5 ps (rms). The coherent THz pulse was applied to the THz time-domain spectroscopy (TDS) and THz scanning transmission imaging systems [6-9]. In this conference, we will report present status of the quantum radiation sources and their applications.

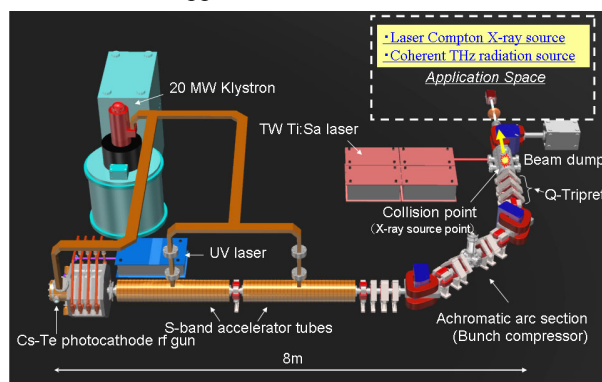


Figure 1: Quantum radiation source on the basis of the S-band compact electron linac.

### LASER COMPTON SCATTERING X-RAY SOURCE

#### Single collision mode

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. The pulse width and energy per pulse were 100 fs (FWHM) and 140 mJ, respectively. 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.

We have already applied the LCS X-ray to medical and biological imaging using an in-line phase-contrast imaging [3-5], which is to enhance the contrast of the difference of densities in bone and soft-tissues of living specimens.

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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 [10].

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 $\mu\text{m}$ x 30 $\mu\text{m}$ (rms)
Ti:Sapphire laser	Wavelength	800 nm
	Pulse width	100 fs (FWHM)
	Pulse energy	140 mJ
	Spot size	28 $\mu\text{m}$ (rms)
X-ray	Energy	~40 keV
	Yield @10Hz	$10^7$ photons/s
	Stability	~6% (15 min)

**Multi-collision mode**

The multi-collision laser Compton scattering (Multi-LCS) is realized between electron multi-bunches and amplified laser multi-pulses in a laser cavity like a regenerative amplifier including a laser crystal, a telescope and a collision point. The multi-bunch beam generation has already been carried out with a Cs-Te photocathode rf gun system and multi-pulse UV laser. In our laser cavity design, 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 frequency of the Ti:Sa mode-locked seed laser to be induced to the cavity was locked to 79.33 MHz (36<sup>th</sup> sub-harmonic frequency of RF frequency 2856 MHz). It 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 the preliminary experiment, the number of seeded pulse and the cavity length are defined 2 pulses and 3.76 m, respectively.

In our design, while the laser pulse is built up, 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. In figure 2, the laser pulse build-up was calculated with design values. 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. Figure 3 shows the experimental results

of the pulse build-up with the 3.76 m-long cavity and 2 seed laser pulses in the preliminary experiment.

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 x 100 laser pulses and 1.5 nC x 100 electron bunches with repetition rate of 10 Hz. The yield of Multi-LCS X-ray has been estimated to be about 5 x 10<sup>9</sup>/s with parameters in table 2.

Table 2: X-ray yield estimation

Electron energy	40 MeV
Electron charge	1.5 nC/bunch
Laser wavelength	800 nm
Average laser energy	100 mJ/pulse
Spot size ( $\sigma_x, \sigma_y$ )	40 $\mu\text{m}$
Bunch length and pulse width	10 ps (FWHM)
collision number	100
Collision angle	170 deg
Maximum LCS X-ray energy	38 keV
Total photon yield@10Hz	5 x 10 <sup>9</sup> /s

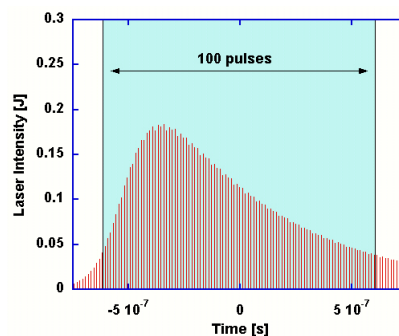


Figure 2: Calculation result of the laser pulse build-up in the regenerative-type laser cavity.

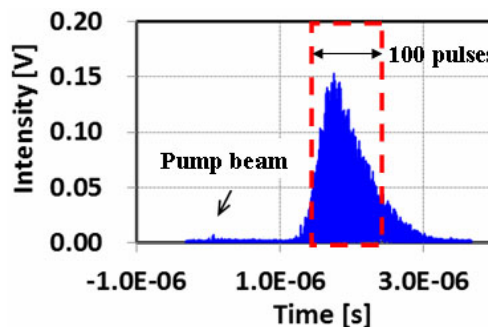


Figure 3: Experimental result of the laser pulse build-up in the regenerative-type laser cavity.

### COHERENT THZ RADIATION SOURCE

#### Coherent THz generation

The coherent synchrotron radiation (CSR) of the THz region was generated from the ultra-short and high charge electron bunch at the 90 degree bending magnet located at end the S-band compact electron linac at AIST [2, 6-7]. The THz CSR pulse was extracted from a z-cut quartz window for THz applications.

#### THz scanning transmission imaging

The THz scanning transmission imaging has been performed with rf detectors which have sensitivity in a THz region [8, 9]. The THz pulse was extracted from the quartz window and collected by the parabolic antenna. It passed through a W-band waveguide (WR-10) with an E-bend waveguide and it was guided to rf detectors (Fig. 4). In this experiment, we have used two types of detectors shown in table 3.

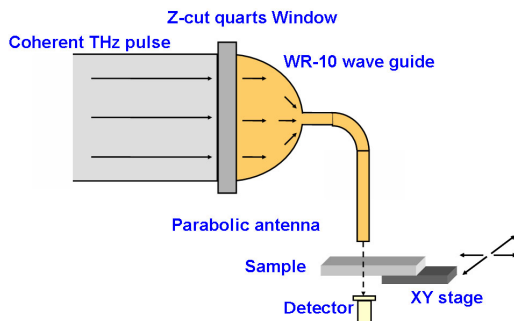


Figure 4: Setup of THz scanning transmission imaging.

Table 3: Specifications of rf detectors

	Wise Wave FAS-10SF-01	Virginia Diodes, Inc. WR-3.4ZBD
Aperture [mm]	1(H)×2(V)	1(H)×1(V)
Frequency [THz]	0.075~0.11	0.22~0.33

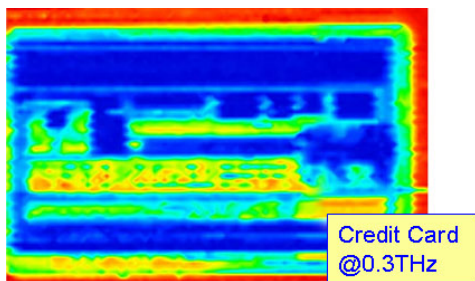


Figure 5: 0.3 THz image of a Credit Card with a IC chip

In a preliminary experiment, the imaging sample is a Credit Card with an IC chip. As a result, the transmission image using around 0.3 THz radiation is shown in figure 5. The sample is attached to the X-Y stage and scanned with 1 mm/step.

#### THz-TDS system

The THz-TDS system has been also developed using the coherent THz pulse [8]. The THz electric fields cause a complex refractive index of the crystal to change by the electro-optical effect (the Pockels effect). It changes the polarization of the laser when the laser and the THz pulse pass through the crystal at the same time. The EO sampling method is applied to measure the temporal waveform by detecting the polarization difference with the two photodiodes. We have developed this system described in Fig. 6.

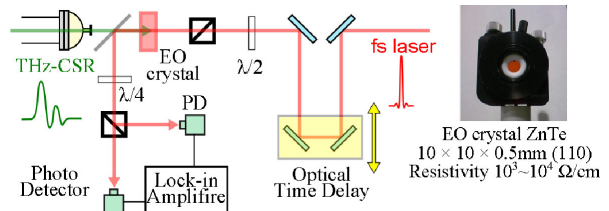


Figure 6: EO sampling THz-TDS system based on the accelerator system (under development).

### SUMMARY

We have developed quantum radiation sources such as the LCS X-ray and a coherent THz radiation sources on the basis of the S-band compact electron linac at AIST. In case of the LCS X-ray source, the total number of generated photons and maximum X-ray energy were  $10^7$  photons/pulse and approximately 40 keV, respectively. It has been successfully applied for the medical imaging. In near future, the X-ray yields will be increased more than  $5 \times 10^9$ /s using the multi-collision LCS scheme. In case of the coherent THz radiation source, the THz scanning transmission imaging has successfully performed using rf detectors which have sensitivity of a THz region. The THz Time-domain spectroscopy (TDS) has also developed using this high power THz pulse. In near future, this THz-TDS will be a powerful tool for the investigation of unknown materials.

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