

DEVELOPMENT OF ADVANCED QUANTUM RADIATION SOURCE BASED ON S-BAND COMPACT ELECTRON LINAC

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Abstract

We have developed the advanced quantum radiation sources such as a laser Compton scattering (LCS) X-ray and high intense THz sources based on S-band compact electron linac at AIST. In case of the LCS X-ray source, its biological and medical applications have been started using the in-line phase-contrast imaging. And now, the upgrade plan to increase X-ray yields has been executed for these applications. In case of the THz source, coherent THz radiation has been obtained using an ultra-short electron bunch and the THz scanning transmission imaging system has been developed for the investigation of unknown materials.

INTRODUCTION

Advanced quantum radiation sources such as a laser Compton scattering X-ray and a high intense THz radiation sources have been developed based on 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 advanced quantum radiation sources. Figure 2 shows a top view photograph of the S-band compact electron linac. The injector consists of a laser photo-cathode rf gun which has the BNL type S-band 1.6 cell cavity with a Cs₂Te photocathode load-lock system and a solenoid magnet for emittance compensation. The linac has two 1.5-m-long accelerator structures 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. 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]. The high intense THz radiation source based on the electron linac has 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 will be generated with coherent radiation such as synchrotron radiation and transition radiation using an ultra-short electron bunch with bunch length of less than 0.5 ps (rms). The coherent synchrotron radiation in the THz region has been already generated and it will be applied to the THz time domain spectroscopy (TDS) and THz scanning transmission imaging systems [4]. In this conference, we will report present status of our advanced quantum radiation sources.

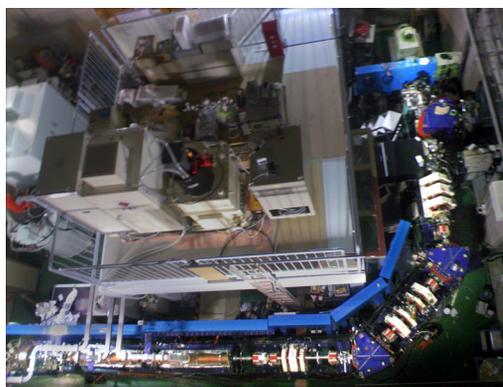


Figure 2: Top view photograph of S-band compact electron linac.

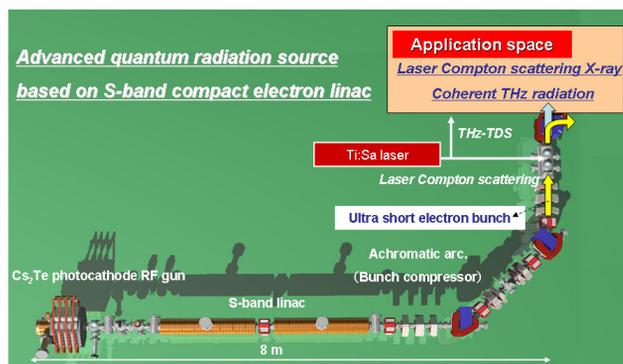


Figure 1: Top view of conceptual diagram for advanced quantum radiation source.

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LASER COMPTON SCATTERING X-RAY SOURCE

In case of the 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 [5], which is to enhance the contrast of the difference of densities in bone and soft-tissues of living specimens. Figure 6 shows the imaging results with 26.4-keV LCS X-rays obtained for the human bone when the distance between the specimen and the IP is 0 cm and 20 cm. The images obtained at distances of 0 cm and 20 cm are the absorption image (Top figure) and the phase-contrast image (Bottom figure), respectively [6]. The enlarged areas in Fig. 3 show the close up of a part of the fractured bone. And a bone trabecula is also clearly visible in Fig. 3.

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 multi-pulse LCS, that is to generate a train of X-ray pulses using laser and electron pulse-trains [7].

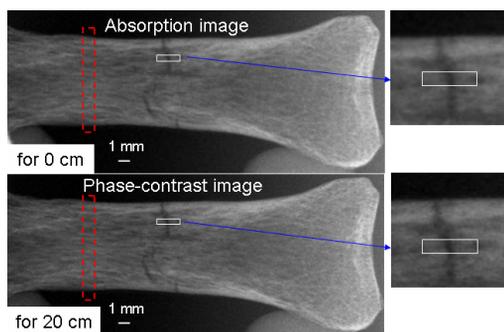


Figure 3: Results of the in-line phase contrast imaging

INTENCE COHERENT THZ 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 of the beam line downstream from the bunch compressor [8]. The THz CSR pulse is extracted from a z-cut quartz window for THz applications. Typical electron beam parameters for the THz CSR generation and our expected THz specification were described in Table 2. The observed temporal width of the CSR pulse depends on the frequency response of the measurement system. In this system with Electro-Optic (EO) sampling method, it is supposed to be about 700 fs (rms) because of the frequency response of the quartz window, the EO crystal and the detector [9].

Table 2: Design values of the coherent THz source

Electron beam	
Max. Energy	30 ~ 42 MeV
Charge per bunch	1 nC – 2 nC
Energy Spread for compression	~ 5%
Bunch length (after compression)	300 fs (rms)
Bunch number	1 – 100
Rep. rate	10 Hz ~ 50 Hz
THz pulse	
Frequency	0.1 – 2 THz
Pulse energy	65 nJ
Peak power	25 kW
Rep. rate	10 – 50 Hz
Pulse width	700 fs (rms)



Figure 4: Achromatic arc section for bunch compression

THz scanning imaging system

The THz scanning transmission imaging as the preliminary experiment was demonstrated with an IC (integrated circuit) card in the previous article [9]. Figure 3 shows the setup of the imaging experiment with the THz CSR pulse. In this work, 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 a W-band rf detector (WiseWave FAS-10SF-01) whose sensitive area is $1\text{ mm} \times 2\text{ mm}$ with sensitive range of $0.075 - 0.11\text{ THz}$. Its signal of 500 mV corresponds to 1 mW . In this work, a vegetable leaf with about 50 mm length was selected for the imaging sample. The THz transmission imaging has been performed with a scanning step of $500\text{ }\mu\text{m}$. Although the aperture size of the W-band waveguide is about $1\text{ mm} \times 2\text{ mm}$, its resolution is less than 1 mm limited by a pin-hole located at the end of the waveguide due to the near field effect. Figure 7 shows results of the THz imaging of the vegetable leaf with the passage of the time from 0 hour to 14 hours after plucking it [10]. The image indicates the water distribution in corresponding to the freshness of the vegetable because the THz radiation is strongly absorbed by water in the fresh leaf. In case of the fresh leaf, it is found that sufficient water is observed along veins of the leaf. However, after 14 hours later, the freshness was quickly lost. As a result, it is found that the THz imaging is a powerful tool for the freshness measurement of the vegetable with the passage of the time.

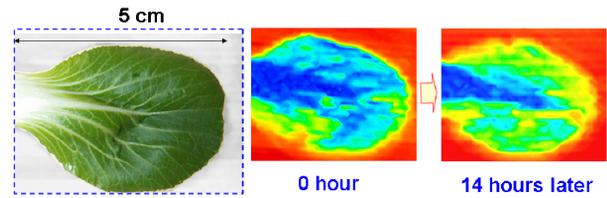


Figure 7: THz imaging of a fresh vegetable leaf.

SUMMARY

We have developed the advanced quantum radiation sources such as a laser Compton Scattering (LCS) X-ray and high intense THz sources based on 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, at a crossing angle of 165° . We have successfully demonstrated the use of our in-line phase-contrast imaging system with 26.4-keV LCS X-rays for the observation of a fractured human bone. In this study, we observed good contrast enhancement in the absorption and phase-contrast images of the bone fracture and bone trabecula.

In case of the coherent THz radiation source, the generation of the THz coherent synchrotron radiation (CSR) in the 90 degree bending magnet has been successfully performed using the ultra-short electron bunch. The THz scanning transmission imaging of the vegetable leaf has been also successfully demonstrated with the W-band rf detector. As a result, it is found that the intense THz radiation source is a powerful tool for imaging of THz absorption with the passage of the time such as the freshness measurement of the vegetable.

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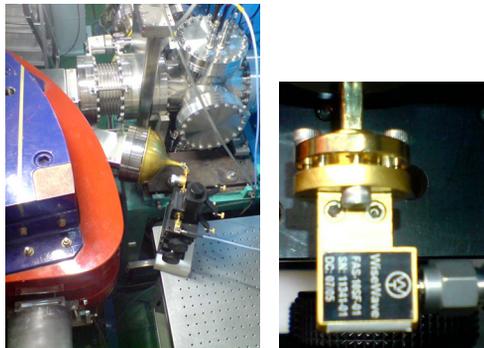


Figure 5: Setup of THz transmission imaging using THz CSR pulse with W-band waveguide, detector and X-Y sample stage.

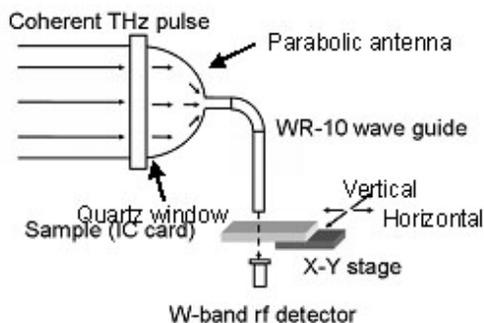


Figure 6: Setup of THz transmission imaging using THz CSR pulse with W-band waveguide, detector and X-Y sample stage.

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