HARD X-RAY GENERATION EXPERIMENT AT TSINGHUA THOMSON SCATTERING X-RAY SOURCE*

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Abstract

The ultra-fast hard x-ray source based on the Thomson scattering between the femtosecond TW laser and relativistic electron beam is a useful tool for the purpose of material investigation, plasma diagnostics, and shock wave measurement. Such a source was designed and built at Tsinghua University (TTX). Recently, the first light at 50keV was flashed successfully with 50MeV electron and IR laser in the head-on geometry. The X-ray was captured by a MCP detector and a CCD camera using a CsI scintillator. The measured X-ray yield with 200pC charge and 300mJ laser was about 1x10^6 photons/pulse. The local energy spectrum of the x-ray was measured and reconstructed with a series of 1.5mm thickness silicon wafers. And as an example of the application of the X-ray, an X-ray imaging experiment was demonstrated with the generated X-ray.

INTRODUCTION

Recently, with the innovative developments of the high brightness relativistic electron sources based on the photocathode RF gun as well as the ultra short laser technology based on the chirped-pulse amplification, the Thomson scattering X-ray source based on the high brightness electron beam and high peak power laser is attracting a growing interest among scientists. This type of source aims to generate quasi-monochromatic ultra-short x-ray pulse with energy range from several keV to hundreds keV with a peak brightness equivalent to the second generation synchrotron light source. The energy, polarization of the X-ray can be precisely tuned by adjusting the laser and electron parameters. In addition, it is more compact than the synchrotron light source due to the low energy electron requirement. For instance, the electron energy is about 50MeV for 50keV x-ray generation with the 800nm wavelength laser, which should be several GeV in synchrotron light source for same energy x-ray generation. It has important potential applications in several fields, including characterization of ultra-fast processes, protein crystallography, phase contrast imaging, medical imaging, material analysis, and the X-ray detectors calibration as a standard X-ray source. And it has been studied and developed in different laboratories rapidly since it was proposed and demonstrated in 1990s' [1, 2].

Such an X-ray source also has been designed and built at the accelerator laboratory at Tsinghua University [3,4,5]. This machine included a 50 MeV electron linac and a Ti: Sapphire laser system, aimed to generate high brightness polarized X-ray pulse with peak energy up to 150keV. Recently we successfully generated the 50keV x-ray pulse with the 50MeV electron and TW laser. The x-ray yield, transverse distribution and local energy spread were measured. An initial X-ray imaging experiment was also preformed. The experimental resultants will be presented and discussed in this paper.

Table 1: Parameters of Laser and Electron Beam

Electron		
Charge	200	pC
Energy	47	MeV
rms emittance	3	mm mrad
Bunch length	3	ps
Beam size at interaction position	50	um
Arriving time jitter	~500	Fs
Laser		
Wavelength	800	nm
Pulse duration	60	fs
Energy	<300	mJ
Beam size	~100	um

DESCRIPTION OF THE EXPERIMENT

The TTX machine included a 50MeV electron linac based on the photocathode RF gun and a Ti: Sapphire TW laser system. The laser system generated both the 266nm UV pulse for photocathode and the 800nm IR pulse for scattering interaction. The two pulses were derived from one 79.3MHz Ti:Sapphire oscillator in order to reduce the time jitter between the electron beam and the IR pulse. The linac system consisted of a BNL/KEK/SHI type 1.6 cell S-band photocathode RF gun, a 3m S-band SLAC type travelling wave accelerating section, generated

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40~50MeV ultra-short high brightness electron pulse for scattering interaction. The laser system was synchronized with the RF system through a timing circuit, with a timing jitter no greater than 0.5ps. The parameters of electron and laser were listed in the table 1.

The head on geometry was chosen in the first collision experiment, since the synchronization between the electron and laser was less critical and the yield was higher than those in other geometry. The electron beam was focused by a set of quadrupole magnets with a magnetic field gradient of up to 12T/m. The IR laser was focused by a 5 inch focal length, 90degree off-axis parabolic mirror and head-on scattered by the electron beam, and then guided to the laser dump by another parabolic mirror placed at upstream of the beam line. There was a 4mm diameter hole on the center of the parabolic mirrors to enable electron beam and generated X-ray photons to pass through. The mirrors in the chamber were remote controlled by the step motor which allows for control of the transverse alignment of the laser the interaction point. A 45degree bend dipole magnet was placed after the interaction chamber to bend the electron beam and separate the electron beam from the scattered X-ray, which propagate in the same direction as the electrons. A 100um thick Ti window was installed at the beam line exit as the X-ray window to separate the beam line vacuum from the atmosphere.

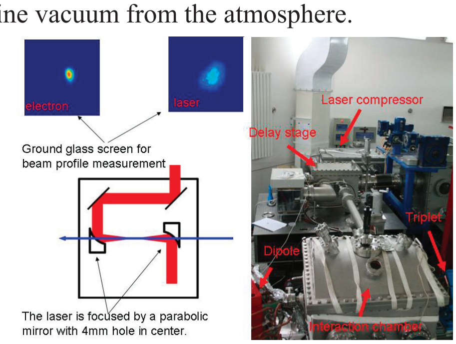


Figure 1: Layout of the interaction region of TTX.

Two X-ray detectors were used for the X-ray diagnostics. One was a removable MCP detector with fast decay time, and it was used to find the scattered x-ray signal from the bremsstrahlung background and to estimate the X-ray yield. The other was a CCD camera with a CsI crystal. This was used to measure the transverse distribution, local energy spectrum and X-ray image.

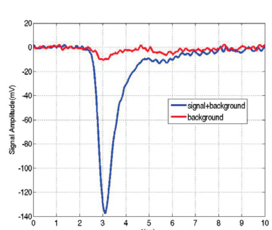
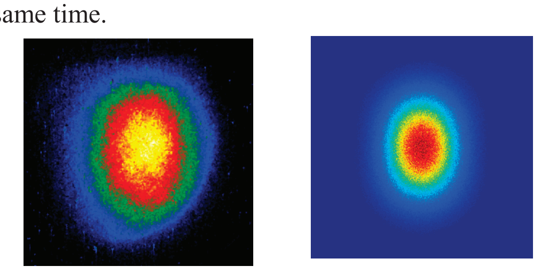


Figure 2: typical X-ray signal and background from the MCP detector.

The spatial alignment of the laser and electron was carried out with the help of a ground glass at the interaction point and a CCD camera focused on the point. The position of the electron beam and laser were observed with the CCD. Then the laser was steering to the electron position and overlapped with each other. The alignment error should be less than 30um, the resolution of the CCD camera, which was sufficient for the experiment with the beam size listed in table 1. The temporal alignment was a little complex. First, the focused laser and the electron beam struck the edge of the glass at the same time, the MCP detector was used to monitor the harmonic photos from the IR and the bremsstrahlung X-rays from the electron beam. The charge and IR energy was reduced to avoid the saturation of MCP and the damage on the screen. Generally, we could detect the two similar signals as ~400ps FWHM pulses with ~100ps rising timing by an oscilloscope, and the time delay between the two pulses corresponded to the arriving timing difference of electron and laser. By changing the optical path of the IR laser, the two pulses were overlapped on the oscilloscope. The time resolution was about 100ps with this method. Second, the charge and IR energy were set to the normal value, then the delay line of the IR laser was scanned and the scatted X-ray signal was detected by the MCP. The adjustment range of the delay line is about +/- 3cm, which was large enough after the first stage of temporal synchronization. Generally, the X-ray signal could be detected by the MCP during the scan, and then the timing could be optimized by maximizing the X-ray signal as a function of the timing delay between the electron and IR laser.

EXPERIMENTAL RESULTS AND DISCUSSION

Typical background and scattered X-ray signal detected by the MCP from the oscilloscope is shown in figure 5. The red line was the background signal while the electron beam was on and IR laser was off, there are two small peaks on the background signal. The first one comes from the beam loss at the upstream beam line, especially from the two parabolic mirrors. The second peak which is later about 3ns than the first comes from the beam dump following the dipole magnet. The blue line is scattered X-ray signal while the electron and IR laser are on at the same time.



(a) (b)

Figure 3: (a) X-ray profile measured with CCD. The left-bottom edge is cut by the Ti window; (b) X-ray profile simulated by CAIN.

The absolute photon yield is estimated with the signal amplitude, gain, the detection efficiency and the collected angle of the detector. The average signal with 300mJ laser pulse energy is 2V in the experiment. The high voltage on the MCP is 1.5x10^3V, the gain with this voltage is about 1x10^5 measured with the single photon detection process, corresponding to about 2mV signal amplitude for per detected x-ray photon. The detection efficiency is estimated to be 1% with the manual and previous experimental results. The collected angle is 4.8mrad calculated with the radius of detector and distance from the interaction point to detector plane, which is 7.2mm and 1.5m, respectively. Simulation result with measured electron and laser parameters by CAIN shows that about 10% generated X-rays will fall on the effective area of the detector. With these values, the final x-ray yield with 300mJ laser pulse and 200pC electron beam is estimated to be about 1x10^6 photons/pulse.

Figure 3 shows a typical x-ray image captured by the CCD. The elliptical shape with long axis in vertical direction is due to the laser polarization in horizontal plane. A simulation result with experimental conditions is also shown in figure 3. It seems that they are agreed well with each other. The X-ray images with different integration time were obtained and compared. It is found the transverse distribution and pointing stability of x-ray was very good, because no significant change could be detected over long integration times.

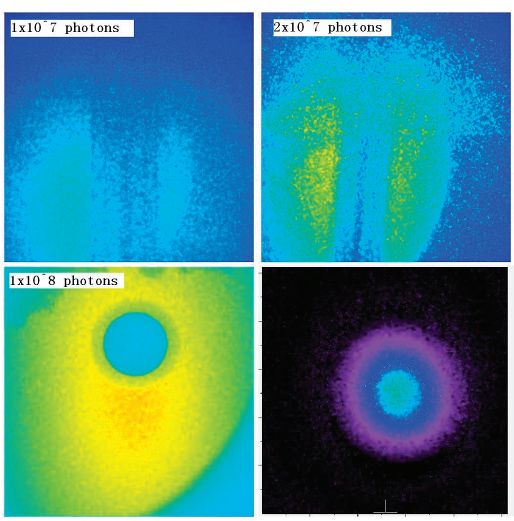
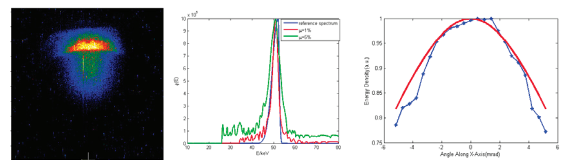


Figure 5: X-ray images with different integrated X-ray flux. The bottom-right image was the image for a three layer ball. The integrated x-ray flux is about 6x10^7 photons.

As an application of the x-ray source, an X-ray imaging experiment was performed. In order to test the necessary flux for single shot image, a series of images with different integrated X-ray flux was taken and shown in figure 5. The experimental resultants showed that it was possible to take an acceptable resolution x-ray imaging with 5x10^7 X-ray photons. In other words, we can take high quality single shot X-ray imaging with high efficient and sensitive detector while the x-ray yield is reached to its design value, 6x10^7 photons/pulse.

The energy spectrum, which was important for the experimental design of all application of Thomson scattering x-ray source, was measured with a series of 1.5mm thickness silicon wafers. The attenuation data with different thickness silicon were obtained with the CCD camera. Then the spectrum was reconstructed with a modified Expectation -Maximization algorithm method [6]. The initial analysis results were shown in figure 6, which were agreed well with the theoretical predictions.



(a) (b) (c)

Figure 6: x-ray spectrum measurement. (a) The image from the CCD camera with 15mm thick silicon. (b) The reconstructed spectrum compared with the simulation for the centre region. (c) The measured mean energy as a function of the observation angle. The blue points were reconstructed results, the red line were the theoretical predications.

CONCLUSION AND OUTLOOK

To date, we have demonstrated successfully X-ray generation at TTX. The first x-ray light is flashed in head-on geometry with 47MeV electron and 800nm IR laser. The X-ray yield measured with MCP corresponding to 1x10^6 photons/pulse. The angular divergence of the generated X-ray is about 7mrad in the plane of laser polarization and 11mrad in the perpendicular plane. The local energy spectrum with different observation direction is also measured. The on-axis x-ray energy is 51.2keV with 4% FWHM energy spread. The measured X-ray yield, beam profiles, local X-ray energy spectrum are agreed well with the theoretical and simulation values. In addition, we have demonstrated the x-ray imaging with the generated x-ray pulse. We believe that the experiments have proven the feasibility of advance applications with this source with farther optimization and upgrade.

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