Preliminary experiment of the Thomson scattering X-ray source at Tsinghua University*

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Abstract The X-ray source based on Thomson scattering of ultrashort laser pulse with a relativistic electron beam is a means of generating a tunable, narrow bandwidth and ultrashort pulse of hard X-rays. Such a sub-picosecond hard X-ray source is proposed at Tsinghua University, and a preliminary experiment with a 16 MeV Backward Traveling electron linac and a 1.5 J, 6 ns Q-switched Nd:YAG laser is carried out first. A 6 ns pulse X-ray with a peak energy of 4.6 keV and an intensity of 1.7×10^4 per pulse is generated successfully in the experiment. The experimental setup, result and discussion are reported in this paper.

Key words Thomson scattering, X-ray, laser

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1 Introduction

The development of a compact, tunable, ultrashort pulsed and monochromatic X-ray source is useful in a number of fields including medical imaging, solid state physics, material science, chemical, biological and industrial applications. With the ultrashort pulse X-ray pulse, we can measure the time resolved atomic motions which provide important information about material properties, chemical and biological reaction on ultrafast time scales. Some mechanisms, such as the X-ray free electron lasers[1, 2], the electron bunch slicing in synchrotron[3], and the Thomson scattering X-ray source[4—6] , have the potential to generate such X-ray pulse.

The Thomson scattering X-ray source, where an ultrashort laser pulse interacts with a relativistic electron beam to produce high-intensity X-ray beam, is one of the most promising approaches to the ultrashort pulsed X-ray. It has some advantages, such as a good directional radiation, a high brightness, a wavelength tunability, less energetic electrons and a short pulse in pico-second and femto-second regions. In the last ten years, with the development of table-top-tera watt (T3) laser system, some experimental studies have been carried out[7—19].

A sub-picosecond hard X-ray source based on Thomson scattering between the Ti:Sapphire T3 laser system and electron linac is proposed at Tsinghua University[20, 21]. A preliminary experiment of the Thomson scattering X-ray source with a 16 MeV Backward Traveling Wave linac and 1.5 J, 6 ns Nd: YAG Q-switched laser system has been carried out first. A 6 ns pulse X-ray with a peak energy of 4.6 keV and an intensity of 1.7×10^4/pulse is generated successfully in the preliminary experiment. The experimental setup and result are presented in this paper.

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2 Experimental setup

The preliminary experiment of Thomson scattering is made by the use of the 16 MeV Backward Traveling Wave electron linac and the Nd:YAG laser system. The schematic diagram of the experiment is shown in Fig. 1. The electron beam is generated by a triode electron gun, bunched and accelerated by the Backward Traveling Wave linac which is powered by a 2856 MHz klystron with the repetition rate of 5 Hz. The macro-pulse duration is 4 μs, which is composed of a train of micro-pulses about 10 ps in duration separated by 350 ps. At the exit of the linac, a 50 μm thick Ti window is used to separate the linac from the interaction chamber to maintain ultra-high vacuum in the linac. The electron beam is focused on the interaction region using four quadrupole magnets. Some steering magnets combined in the quadrupole magnets are used to adjust the beam's position. A bending magnet is placed at the exit of the electron beam, which is used to analyze the electron energy and separate from the generated X-ray. The beam is damped at the faraday cup shielded with lead block to measure the beam current and reduce the X-ray background caused by the electrons bombarding the wall.

The laser system consists of a flash lamp-pumped, active Q-switched Nd:YAG oscillator, two single passed 12 mm diameter Nd:Glass rod amplifiers which are mounted in water-cooled jacket and illuminated on the side surface using four Xe flash lamps. The laser system can produce 6 ns (FWHM) output pulse of λ=1064 nm with an energy about 1.5 J at a repetition rate of 5 Hz. A lens with a 1.5 m focal length is placed immediately before the vacuum window into the chamber, which focuses the laser to a rms focal size of 220 μm at the interaction region. A mirror inside vacuum is used for reflecting the laser to the interaction point. Head-on scattering geometry (~177°) is adopted to get the maximum X-ray yield and avoid the damage to the Ti window by laser pulse. After the interaction region, the laser is reflected to the laser dump, this is necessary, because if the laser beam is dump directly, the breakdown on the damaged optic generates visible and UV light, which results in spurious signals on the X-ray detector.

The selection of the proper X-ray detector is crucial in the preliminary experiment, because a large number of bremsstrahlung hard X-rays are generated while the electron beam goes through the Ti window, and most of them are transmited in the same direction of the Thomson scattering X-ray photons, they can't be distinguished from the Thomson scattering X-ray in space. The detector should be sensitive to the scattered 4.6 keV photons of interest, but should be insensitive to the hard X-ray generated by the electron beam. Initially a 1 mm thickness CsI scintillator coupled to the photomultiplier tube (PMT) is used, but it is too sensitive to the background hard X-ray. Last we find that the MCP proves to be a good choice for it is not so sensitive to the hard X-ray and its fast response speed. The F4655-11 MCP detector from HAMAMATSU is selected in the preliminary experiment. The diameter of the sensitive area of the detector is 14.5 mm, and the distance between the collision and detector is about 1.5 m, only the X-ray scattered within 4.8 mrad from the direction of electron beam propagation will be detected under these conditions. In order to reduce the background caused by bremsstrahlung, two steps have been taken: one is to shorten the electron pulse duration from 4 μs to 160 ns; the other is to mount two collimators in front of the detector, as shown in Fig. 2.

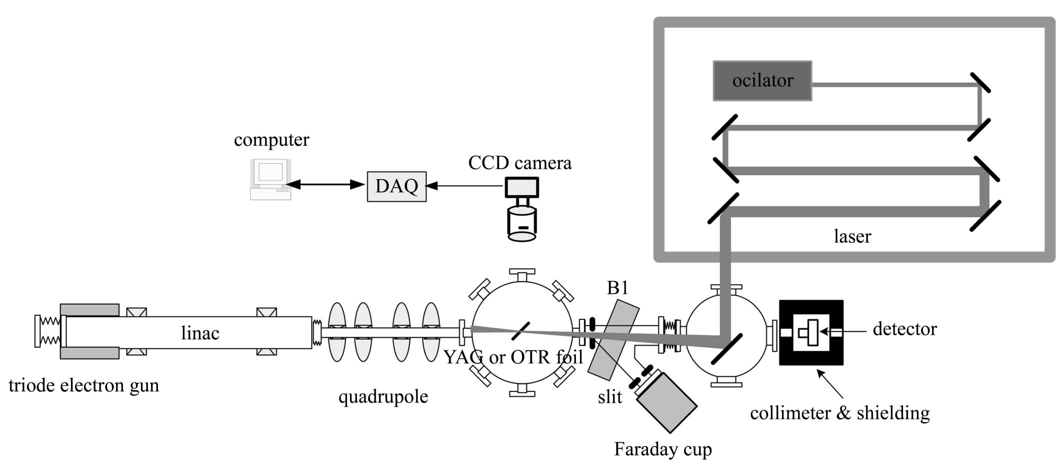

Fig. 1. Schematic diagram of the preliminary experiment at Tsinghua University.

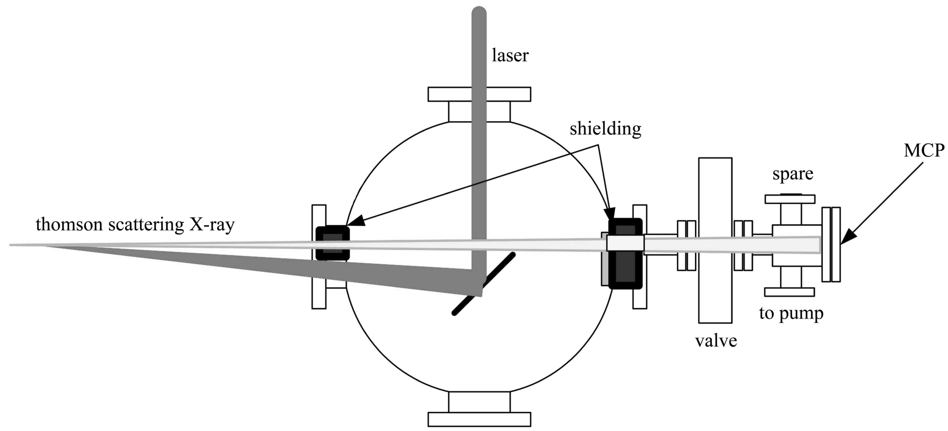

Fig. 2. Schematic diagram of the collimators in front of the MCP.

3 Experimental result

First, the parameters of the linac and the laser system are measured. A 100 μm thick YAG screen doped 0.3% Ce and a CCD camera are used to monitor the electron beam and the laser beam profile and determine the electron and laser beam positions at the interaction point[22]. The measured rms beam size is about 0.8 mm, and it can be fine-tuned from 0.6 mm to 1.4 mm by adjusting the quadrupoles' current. The quadrupole scan method is used to measure the electron beam emittance in experiment. We also measure the laser pulse duration, energy per pulse, profile and size at the interaction point. The parameters of the linac and laser system are summarized in Table 1.

Table 1. Parameters of the linac and laser system.

electron beam	
beam energy	16 MeV
macro-pulse current	100 mA
radius at focus	∼ 0.8 mm(rms)
emittance	12 πmm·mrad
macro-pulse length	160 ns
laser pulse	
wavelength	1064 nm
energy	1.5 J/pulse
pulse duration	6 ns(FWHM)
focal spot size	220 μm
repetition	5 Hz

The parameters of the generated X-ray pulse including the effects of beam emittance, energy spread, interaction position and synchronization errors of both beams are simulated by the code Cain[23]. First,the angle distributions of the scattered X-ray for different electron beam radius are calculated, as shown in Fig. 3. Because of the large emittance of the electron beam, the detected X-ray count on the detector does not become more while the beam size becomes smaller. The electron beam radius at the interaction is optimized to 1 mm for getting the maximum number of the scattering X-ray photons on the detector. The generated X-ray pulse is composed of a train of micro-pulse about 10 ps in duration separated by 350 ps, and the macro-pulse duration is about 6 ns (FWHM). The parameters of the X-ray based on simulation are summarized in Table 2, and the simulated X-ray energy spectra on the detector is shown in Fig. 4.

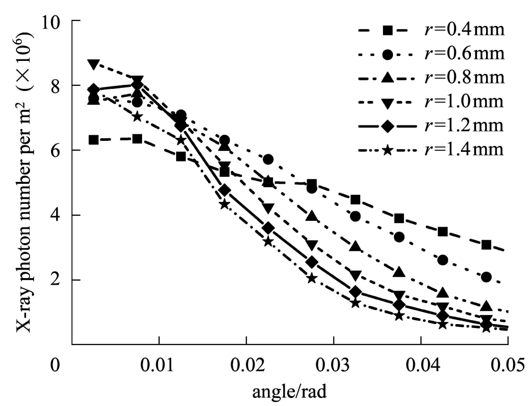

Fig. 3. Scattered X-ray intensity as a function of angle for different electron beam's size at focus.

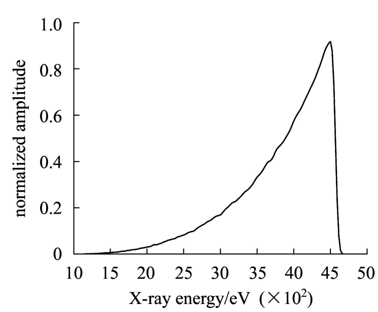

Fig. 4. The simulated X-ray energy spectra on the detector.

Table 2. Parameters of the scattered X-ray pulse.

X-ray pulse	
max. photon energy	4.6 keV
macro-lulse duration	6 ns(FWHM)
micro-pulse duration	10 ps
number of photons (in 4.8 mrad scattered angle)	480 photons/pulse
total number of generated photons	2.1×10^4/pulse

A Tek 7404 oscilloscope is used to measure the signal from the MCP detector. A photodiode is placed immediately after the laser oscillator, and serves for timing fiducial. In order to subtract the background X-ray signal from Ti window and beam line, two sets of X-ray signals are taken with laser pulses and without them as the background. The oscilloscope trace of the experiment is presented in Fig. 5. The signal is averaged over 256 shots to reduce a signal fluctuation. The X-ray signal in Fig. 5 is detected 90 ns before the laser signal. The delay between the two signals is the sum of the time for the laser to propagate from the oscillator to the interaction point, the time for the X-ray to propagate from the interaction point to the detector, and the difference in cables length which is 40 m for photodiode signal and 17 m for X-ray signal.

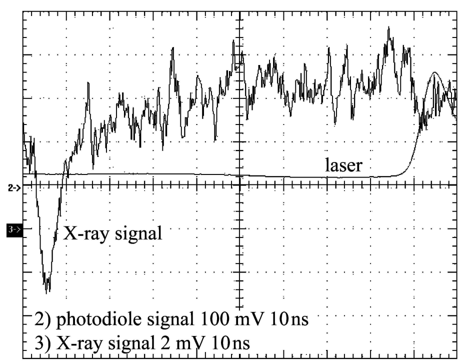

Fig. 5. Oscilloscope trace showing the laser pulse, the signal obtained from MCP, and the detected X-ray signal.

In order to demonstrate that the X-ray signal is due to the interaction of the laser pulse with the electron beam, several null tests are performed. No X-ray signal is observed when the electron or the laser beam is fired individually. No X-ray signal is detected while changing the focus point of electron beam with the steering magnets. If the laser is fired before and after the electron beam, no X-ray signal pulse is detected. The relative timing between the laser and the MCP signal is an important factor in discriminating between the desired Thomson scattering X-ray and the background X-ray signals.

The X-ray signal fitted by a Guass curve is shown in Fig. 6. The backgrounds coming from the electron and the laser system are subtracted. The full width of half maximum (FWHM) of the X-ray pulse is 5.8 ns, which agrees with the estimated value from the parameters of the linac and the laser. The total number of photons scattered in the 4.8 mrad is obtained from the X-ray signal intensity on the MCP using its gain and quantum efficiency of detection. The gain of the detector is about 2×10^5 with 1400 volt dc, and the quantum detection efficiency of MCP is about 5% for about 4 keV X-ray. The intensity of the X-ray signal, about 6 mV in Fig. 5, corresponds to about 20 detected photons. In this case, the total number in 4.8 mrad is analytically estimated to be about 410. This number, which is about 15% smaller than the simulated value, is acceptable because of the mismatch of the electron beam and the laser at the interaction point, the measurement errors of the beam and laser parameters, and so on. The total number of generated photons is estimated to be about 1.7×10^4/pulse from the measured signals.

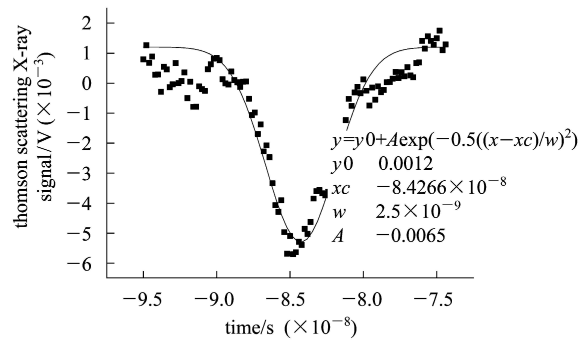

Fig. 6. X-ray signal subtracting the background.

4 Summary

A preliminary experiment of the Thomson scattering X-ray source has been performed at Tsinghua University based on the interaction of a 1.5 J, 6 ns laser pulse with a 16 MeV, 100 mA electron beam. The measured X-ray characteristics are about 1.7×10^4 per pulse with 6 ns pulse duration, which is in good agreement with the simulation result. In order to minus the influence of the hard X-ray generated from the bremsstrahlung radiation, a new experiment is underway to reflect the scattered X-ray photons with X-ray mirror. Work is also continuing on new experiment to generate sub-ps X-ray pulse with a photocathode RF gun and fs TW laser system.

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