RESEARCHES OF THOMSON SCATTERING X-RAY SOURCE AT TSINGHUA UNIVERSITY*

CH.X. Tang, W.H. Huang*, H.B. Chen, C. Cheng, Y. Cheng, Q. Du, T.B. Du, Y.CH. Du, X.Z. He, J.F. Hua, G. Huang, Y.CH. Ge, Y.ZH. Lin, B. Xia, M.J Xu, X.D. Yuan, SH.X. Zheng

Department of Engineering Physics, Tsinghua University, Beijing 100084, PR China

Abstract

The bright and tunable short pulse X-ray sources are being widely used in various research fields. Thomson scattering is one of the most promising approaches to short pulsed x-ray. Researches on Thomson scattering x-ray sources are being carried out in Tsinghua University. Some theoretical results and the preliminary experiment on the Thomson scattering between electron beams and laser pulses are described in this paper.

INTRODUCTION

Tunable, ultrashort pulsed x-ray source are useful in various research fields, such as solid-state physics, material, chemical, biological, medical sciences and industrial applications. The x-ray can be produced with different mechanisms, such as x-ray free-electron lasers [1], electron bunch slicing in synchrotrons [2], and relativistic Thomson scattering[3,4]. The x-ray source based Thomson scattering will possibly generate ultrashort hard x-rays with comparatively low energies electron beams.

The generation of x-ray by scattering between laser light and relativistic electrons was originally proposed in 1960s. With the development of table-top-terawatt (T3) lasers, a number of experimental studies of Thomson scattering have been performed recently. It is shown that Thomson scattering is one of the most promising approaches to ultrashort pulsed x-ray. Researches on Thomson scattering x-ray sources are being carried out in Tsinghua University.

In this paper some theoretical results and the preliminary experiment setup on the Thomson scattering between electron beams and laser pulses are described.

X-RAY GENERATION VIA LINEAR THOMSON SCATTERING AT ARBITRARY INTERACTION ANGLES

To describe the kinematics of the linear Thomson scattering at arbitrary interaction angle α, we consider the frames as given in figure 1. The two frames are both laboratory frame: the electron beam is along the $+z$ axis of the electron frame and the laser beam is along the $-z'$ axis of the laser frame. We assume that the Rayleigh range of laser beam is much longer than laser pulse length, the intensity profile of laser beam satisfy the Gaussian distribution,

$$\rho_l = \frac{n_l}{(2\pi)^{3/2}\sigma_{lx'}\sigma_{ly'}\sigma_{lz'}} \times \exp\left[-\frac{(x'-x'_{l0})^2}{2\sigma_{lx'}^2} - \frac{(y'-y'_{l0})^2}{2\sigma_{ly'}^2} - \frac{(z'-z'_{l0}+ct)^2}{2\sigma_{lz'}^2}\right] \tag{1}$$

where $\sigma_{lx'}, \sigma_{ly'}, \sigma_{lz'}$ and $x'_{l0}, y'_{l0}, z'_{l0}$ are the laser beam's rms size and position offset in x', y', z' direction, respectively. n_l is the total number of laser photons in one pulse. Similarly, we assume that the envelope function of electron beam is much greater than then electron beam pulse length, the intensity of electron beam can be given by

$$\rho_e = \frac{n_e}{(2\pi)^{3/2}\sigma_{ex}\sigma_{ey}\sigma_{ez}} \times \exp\left[-\frac{(x_e-x_{e0})^2}{2\sigma_{ex}^2} - \frac{(y_e-y_{e0})^2}{2\sigma_{ey}^2} - \frac{(z_e-z_{e0})^2}{2\sigma_{ez}^2}\right] \tag{2}$$

where $\sigma_{ex}, \sigma_{ey}, \sigma_{ez}$ and x_{e0}, y_{e0}, z_{e0} are the laser beam's rms size and position offset in x, y, z direction, respectively. n_e is the total number of electrons in one pulse.

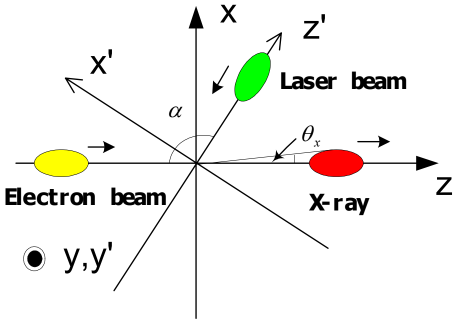

Figure 1: A schematic illustration of Thomson scattering(xyz -electron frame; $x'y'z'$ -laser frame)

The differential cross section of the relativistic Thomson scattering under the linear interaction is

$$\frac{d\Sigma}{d\Omega} = \frac{r_0^2}{2}\frac{(1+\beta^2)(1+\cos^2\theta_x) - 4\beta\cos\theta_x}{\gamma^2(1-\beta\cos\theta_x)^4} \tag{3}$$

where θ_x is emitting angle of x-ray, β is the velocity of electron, r_0 is the classical radius of electron. From equation (1)-(3), we can get the number of photons in the produced x-ray[5]

*huangwh@mail.tsinghua.edu.cn

$$\frac{dn_x}{d\Omega} = C_{off}\frac{n_e n_l}{\sqrt{2\pi}}\frac{d\Sigma}{d\Omega}\times \frac{1}{\sqrt{(\sigma_{ey}^2+\sigma_{ly'}^2)\left[(1-\cos\alpha)(\sigma_{ex}^2+\sigma_{lx'}^2)+(1+\cos\alpha)(\sigma_{ez}^2+\sigma_{lz'}^2)\right]}} \tag{4}$$

where

$$C_{off} = \exp\left(-\frac{(y_{e0}-y'_{l0})^2}{2(\sigma_{ey}^2+\sigma_{ly'}^2)} - \frac{\left[(z_{e0}+z'_{l0})\cos(\alpha/2)-(x_{e0}-x'_{l0})\sin(\alpha/2)\right]^2}{(1-\cos\alpha)(\sigma_{ex}^2+\sigma_{lx'}^2)+(1+\cos\alpha)(\sigma_{ez}^2+\sigma_{lz'}^2)}\right) \tag{5}$$

is the decrease ratio of x-ray due to the mismatch of position and time. The pulse length of the produced x-ray is

$$\sigma_T = \frac{\sigma_{ez}\sqrt{(1-\cos\alpha)(\sigma_{ex}^2+\sigma_{lx'}^2)+(1+\cos\alpha)\sigma_{lz'}^2}}{c\sqrt{(1-\cos\alpha)(\sigma_{ex}^2+\sigma_{lx'}^2)+(1+\cos\alpha)(\sigma_{ez}^2+\sigma_{lz'}^2)}} \tag{6}$$

which is consistent with the result in Ref.[6] when scattering angle $\alpha = 90°$.

PRELIMINARY THOMSON SCATTERING EXPERIMENT

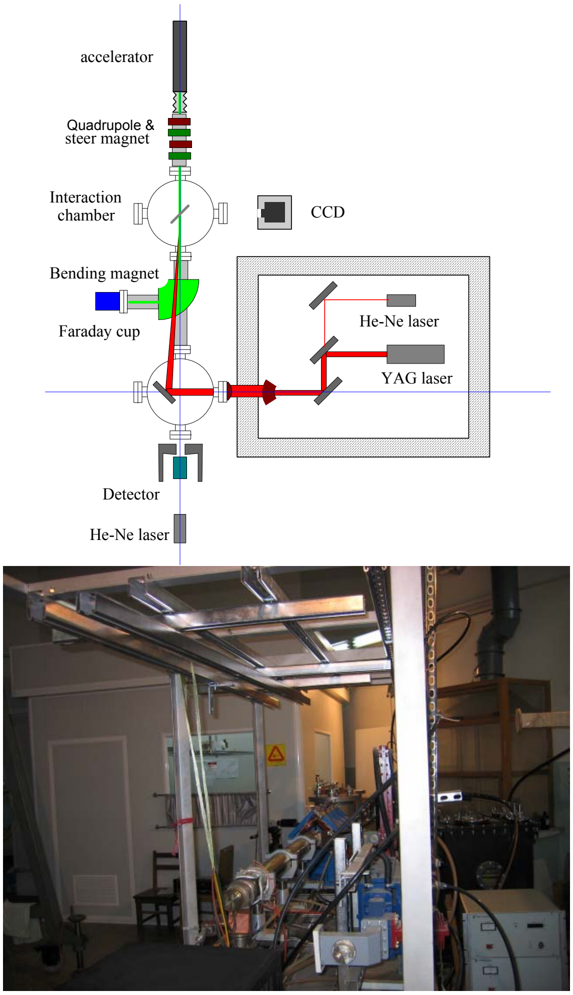

Figure 2: The experimental layout for head-on Thomson scattering

Preliminary experiments of x-ray generation through Thomson scattering are made with the backward travelling wave 16MeV electron linac[7] and the YAG laser system. The electron beams are delivered from the 2856MHz RF linac with a 4μs macrobunch duration and 35ps total microbunch duration at a repetition rate of up to 250 Hz. The YAG laser system produces ~10 ns output pulses of λ=1064 nm with an energy ~2J at a repetition rate of 10Hz. Head-on scattering geometry(177°) is adopt to get the maximum x-ray yield. Due to long duration of electron macrobunch, the need of synchronization between two beam is easily fulfilled.

The experimental layout of Thomson scattering is shown in figure 2. Laser pulses are finally focused by a mirror with a focal length of 1.5m and reflected into interaction chamber. The linac is separated with a 100μm thick titanium widow from the interaction chamber to maintain ultrahigh vacuum in the linac. The electron beams are focused by quadrupole magnets before interaction and swept off by a 45° bending magnet. The x-ray photons are detected by a CsI(Tl) scintillator that is coupled to the photomultiplier tube.

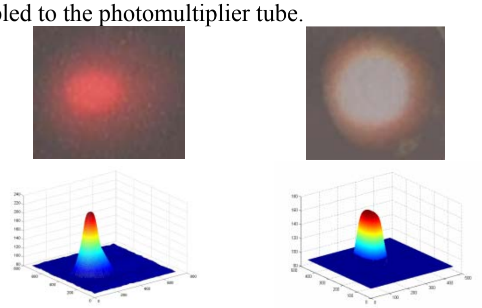

Figure 3: CCD image of electron and laser beam at interaction point(left:electron, right:laser)

Table 1: Parameters of Preliminary Thomson scattering experiments

Laser beam	
Wavelength	1064 nm
Pulse energy	2 J
Total pulse duration	~10 ns
Focal spot radius	0.5 mm
Electron beam	
Energy	16 MeV
Microbunch peak current	1.2 A
Total microbunch duration	35 ps
Macrobunch duration	4 μ s
Charge/microbunch	0.042 nC
RMS beam radius	1.25 mm
x-ray pulse	
Maximum photon energy	4.5 keV
Microbunch pulse duration	35 ps
Number of photons/microbunch	$\sim 1\times 10^3$

Due to head-on geometry and long duration of electron beam macrobunch, the laser beam will interact with several electron microbunchs, depending on the Rayleigh range of laser beam and beta function of electron beam.

This will help to increase the x-ray photon flux. Up to now, the electron beam and the laser pulse focusing have been tested at the interaction point. The focal spot of electron and laser beam at interaction point are shown in figure 3. The parameters that both laser system and linac now can provide and estimates of x-ray based on equation (4)-(5) are summarized in Table 1. Some upgrade with linac and laser system are going on. The effects of emittance, energy spread, interaction position and time mismatch of both beams are simulated by the code CAIN[8].

PROPOSAL OF A THOMSON SCATTERING X-RAY SOURCE FACILITY IN TSINGHUA UNIVERSITY

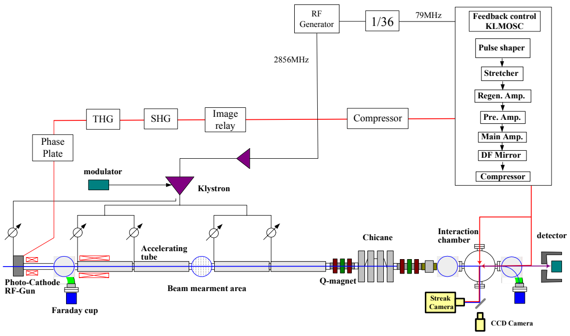

Figure 4: The schematic layout of proposed Thomson scattering x-ray source

As a next step we propose to build up a sub-picosecond hard x-ray source based on Thomson scattering between Ti:Sapphire T3 laser system and electron linac. The simplified schematic layout is shown as Figure 4. The laser pulses from oscillator are splitted into two beams after the pre-amplification: one is tripled to 266 nm after amplification to excite the photocathode RF gun; the other one is coupled into interaction chamber after chirped-pulse-amplification. The electron beam generated by the photoinjector is accelerated with four traveling wave accelerating tube up to 60~100 MeV. The electron beam from the linac is focused by quadrupole magnets and compressed by the bunch compression chicane, then interacts with laser pulse via orthogonal and head-on scattering geometry. Table 2 summarizes the design parameters of Thomson scattering x-ray source.

Table 2: Design parameters of Proposal Thomson scattering x-ray source

Laser beam	
Wavelength	800 nm
Pulse energy	500 mJ
Pulse duration	25~50 fs
Focal spot radius	~0.1 mm
Electron beam	
Energy	60~100 MeV
Bunch duration	1~10 ps
Charge/microbunch	1.0 nC
Beam radius	0.1 mm
x-ray pulse	
Photon energy	36~200 keV
Pulse duration	50~1000 fs
Number of photons	9.5×10^5~1.5×10^8

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