X-RAY LOCAL ENERGY SPECTRUM MEASUREMENT AT TSINGHUA THOMSON SCATTERING X-RAY SOURCE (TTX)*

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Abstract

Thomson scattering X-ray source, in which the TW laser pulse is scattered by the relativistic electron beam, can provide ultra short, monochromatic, high flux, tunable polarized hard X-ray pulse which is can widely used in physical, chemical and biological process research, ultra-fast phase contrast imaging, and so on. Since the pulse duration of X-ray is as short as picosecond and the flux in one pulse is high, it is difficult to measure the x-ray spectrum with traditional spectra measurement methods. In this paper, we introduce an iterative statistical algorithm (Expectation-Maximization) to reconstruct the spectra from the attenuation data, and the results of the X-ray spectrum measurement experiment on Tsinghua Thomson scattering is also presented.

INTRODUCTION

Thomson Scattering sources (also called Inverse Compton Scattering), which can be bright X-ray sources typically produce photons, have attracted a lot of interest as the technologies for producing low-emittance high-brightness relativistic electron sources and ultra-short high-power lasers have progressed. The X-rays that are generated by the interactions between laser and electron, exhibit high directivity, and have a polarized tunable quasi-monochromatic spectrum. The knowledge of the spectrum of an X-ray source is a key point for the development of any kind of application, for example in imaging both contrast and absorbed dose strongly depend on energy. However, direct methods performing a standard spectrometric measurement based on single photon energy measurement to detect the X-ray spectrum of Thomson Scattering sources have always been considered troublesome to implement because the beam is too intense to cause pulse pile up problems. Thomson Scattering source can produce up to 10^8 photons, bunched in 10ps long pulse [1]. An alternative way to measure the spectrum might request the measurement to be integral-type, which will not be affected by the high rate of incidence of photons. The analysis of attenuation data (transmission curves), which can provide some information about the spectral distribution of an X-ray source, as not affected by the rate of incidence of photons, is a good candidate to measure the X-ray spectrum of the Thomson Scattering X-ray source. Although there are several problems with this method, such as low accuracy, non-unique solution to ill-condition system and instability with different measurement error [2], this method can still give good estimation and reconstruction of spectra with some improvements based on the property of the measured spectra.

In this article, we introduce an iterative statistical algorithm (Expectation-Maximization) [3] to reconstruct the spectra from the attenuation data on simulated measurement. Results show that this method can give good approximations for the mean energy of the spectra, while it is not sensitive to the specific spectral distribution and the energy broadening. In order to reconstruct the shape of the spectra, especially the energy broadening, we present a new method based on the Expectation-Maximization algorithm. An preliminary experiment is also carried out on Tsinghua Thomson scattering X-ray source, the measured maximum X-ray energy is about 53keV, which is agreed well with the simulations.

OVERVIEW OF TTX

The scheme of TTX is shown in figure 1. This machine includes a 50MeV electron linac based on the photocathode RF gun and a Ti: Sapphire TW laser system. The laser system generates both the 266nm UV pulse for photocathode and the 800nm IR pulse for scattering interaction. The two pulses are 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 consists of a BNL/KEK/SHI type 1.6 cell S-band photocathode RF gun, a 3m S-band SLAC type travelling wave accelerating section, generates 40~50MeV ultra-short high brightness electron pulse for scattering interaction. The laser system is 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.

In previous experiment, we succeed to generate and detect the X-ray signal with head-on colliding mode. The results from the MCP and X-ray CCD are shown in figure 2.

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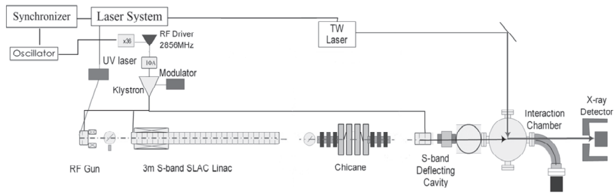
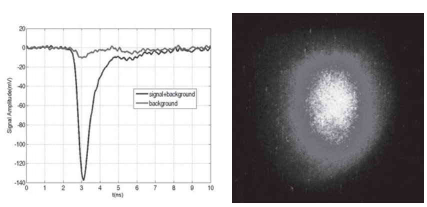


Figure 1: scheme of TTX.

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



(a) (b)

Figure 2: typical X-ray signal and background from the MCP detector(a) and X-ray CCD.

LOCAL ENERGY SPECTRUM MEASUREMENT

X-Ray Spectrum Measurement from the Analysis of Attenuation Data

The relative transmission function $T(x)$ responding to an attenuator of thickness x is related with the spectrum of an X-ray beam in the following way[1]:

$$T(x) = \frac{S(x)}{S(0)} = \int_0^{E_{\max}} e^{-\mu(E)x} F(E)dE \qquad (1)$$

where $S(x)$ is the signal measured with an absorber of thickness x, and $S(0)$ is the signal measured without any absorber. $\mu(E)$ is the total attenuation coefficient of the attenuator in which are included both photoelectric and Compton effects for photons of energy E. $F(E) = \phi(E) \bullet C(E)$, where $\phi(E)$ represent the spectrum distribution of photons and $C(E)$ represent the energy response determined by the way to measure the signal $S(x)$. $E_{\max}$ is the maximum energy of the spectrum.

When we treat the problem from its numerical point of view by discretizing the integral, the Eq.(1) turns out a linear system of the form

$$T = A \bullet F \qquad (2)$$

where $T \in R^M$ represent the attenuation curve as a function of the attenuator and $F \in R^N$ is the discretized spectrum. Generally, the linear system described by Eq.(1) translates, after the disctretization, into an ill-conditioning linear system in Eq.(2). Here the Expectation-Maximization (EM) algorithm is used to obtain an approximation to the exact solution of the system Eq.(2)[2]. Expectation -Maximization algorithm is an iterative statistical algorithm with the form [3][4]:

$$F_n^{(k+1)} = F_n^{(k)} f_n, \quad f_n = \frac{\sum_m A_{nm}^{t} \dfrac{T_m}{\sum_{n'} A_{mn'} F_{n'}^{(k)}}}{\sum_m A_{nm}^{t}} \qquad (3)$$

Numerical Simulation

A Monte Carlo numerical simulation experiment is carried out to verify the method first. During the simulation process, Monte Carlo method is used to simulate the Thomson Scattering and calculate the attenuation curve through silicon with different thickness to justify the reliability and feasibility of this method. Figure 3 shows the results for the reconstruction of local spectra for different two points in the X-ray spot.

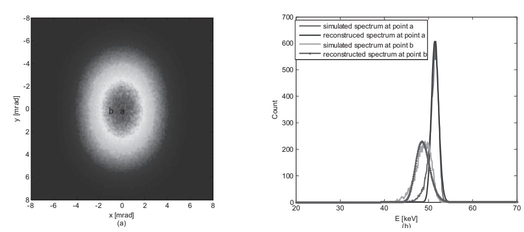


Figure 3: (a) X-ray profile simulated by CAIN and the two points selected to reconstruct local spectra. (b) Simulated and reconstructed spectra at two different points with 0.5 mrad collecting angles and 5% Gaussian random error.

It can be observed that the EM method performs well to reconstruct the local spectra of Thomson Scattering source. However, as the collecting angles increase, the X-ray spectra are not close to Gaussian distribution any more. To solve this problem, we propose an assumption that according to the spectral distribution features of Thomson Scattering, as the collecting angles increase, the right half of spectra remains almost unchanged. So we

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can treat the right-half spectra of the small collecting angles given by EM algorithm as the right half for spectra of other angles within a certain range. Then we can reconstruct the spectra with the attenuation data more accurately as under this assumption, the mean energy will have direct and close relationship with the shape of spectra. Fig.4 shows the reconstruction result (top) and the simulation result (bottom) for Thomson Scattering spectra within the collecting angle range from 0.5mrad to 5mrad.

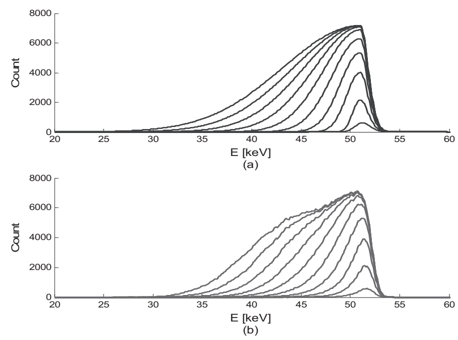

Figure 4: (a): Representative reconstruction results of spectra for collecting angles ranging from 0.5 mrad to 5 mrad with an equal interval of 0.5 mrad (b): The simulated spectra for the Thomson Scattering source with collecting angles of the same range with CAIN.

Experiment Results

A preliminary experiment is carried out on TTX to measure the X-ray spectrum. The scheme of the experiment is shown in figure 5. The silicon wafers with different thickness are used as attenuator, a CsI screen and CCD camera are used as the X-ray intensity monitor.

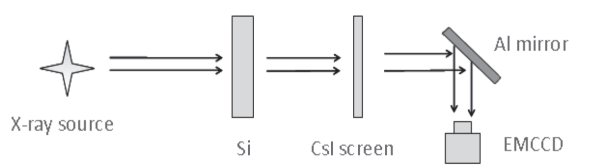

Figure 5: The scheme of the X-ray spectrum measurement.

The typical X-ray profile with attenuators is shown in figure 6. The sheltered part is used to obtain the attenuation curve and the unsheltered part is used to X-ray intensity normalization to cancel the jitter influence. The attenuation curves for point a, b, and c, the reconstructed X-ray spectrum from the attenuation curves are also shown in figure 6. The maximum X-ray energy at the center of profile is 53keV, which is agreed well with the theory expectation and simulations.

In Thomson scattering X-ray source, the X-ray energy is a function of scattered angle. In figure 7, the mean energy of the X-ray as a function of scattered angle is shown and compared with the theory and simulation expectations. The measured results are a little different to the theory curve but agreed well with the simulation results, since in theory curve the emittance effect of the electron beam is not included.

Reconstruction spectra results from measured attenuation for collecting angles ranging from 0.5mrad to 5mrad with an equal interval of 0.5mrad are shown in figure 8:The deposition efficiency of CsI screen is considered.

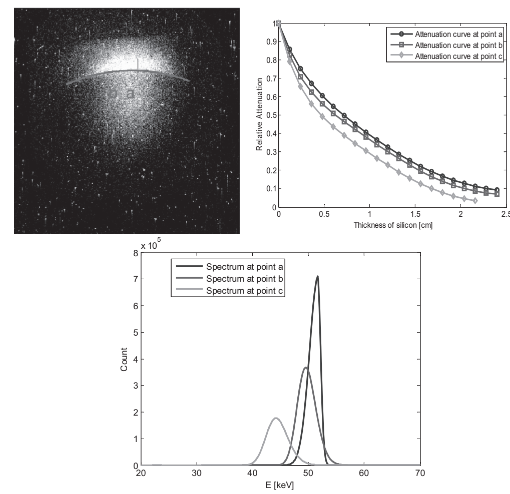

Figure 6: (top left)X-ray profile measured by EMCCD sheltered by 1.5cm silicon. (top right) Attenuation curves at points a, b, and c. (bottom) The reconstructed local X-ray spectrum from the attenuation curves.

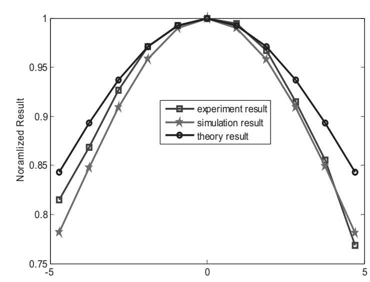

Figure 7: Mean energy along the line b-a-c in the profile, and compared with theory and simulation.

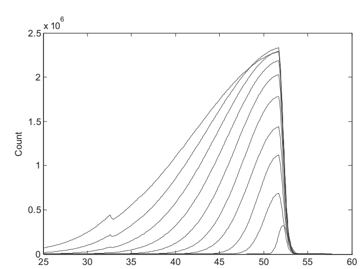

Figure 8: The x-ray spectrum with different collecting angle.

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