X-RAY SPECTRA RECONSTRUCTION WITH HOPG CRYSTAL ON TTX

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Abstract

Thomson Scattering sources, as the new generation of bright X-ray sources, have drawn much attention of scientists. To get the detail information of the scattering X-ray, traditional spectra measurement methods, based on single photon counting, are often troublesome as the X-ray beam is too intense to cause pile up problems. In this article, we proposed and demonstrated a measurement method to reconstruct the spectra of the scattering X-ray by highly oriented pyrolytic graphite (HOPG) crystal based on the Bragg law. This method can reconstruct the central energy of the spectra and agree well with the simulation results. Improvement should be made to enhance single-to-noise ratio and measurement equipment be carefully arranged to be able to get more information about the spectra.

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 ultrashort 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 spectra requires the measurement to be exempted from the high rate of incidence of photons. There are several indirectly methods to measure the intense X-ray spectra. The first kind is to scatter the incident X-ray and detect the spectra at a certain angle. Then the spectra of the incident X-rays can be reconstructed by the measured results through the scattering law. This method is often adopted for high energy X-ray and has requirements to the transverse size of the incident beam to ensure the scattering angle. The second method is to analyse the attenuation data in certain materials[2]. Although there are some problems with this method[3]such as low accuracy, non-unique solution to ill-condition system and instability with different measurement error, this method can still be a good choice to estimate the spectra as it is easy to implement. Another way that can be chosen to measure the X-ray of high intensity is to take advantage of the X-ray diffraction[4] in the crystal based on the Bragg law. This method can show the incident X-ray energy directly from the reflected photons and should be able to further estimate the energy spread after taking the mosaic angle and the transverse size into consideration. One important advantage of this method for Thomson Scattering sources is that it can get reasonable results for the spectra with one or several shots. In this article, we use the highly oriented pyrolytic graphite (HOPG) crystal to reconstruct the spectra of Thomson Scattering source and the agreement in central energy between the experiment and simulation demonstrate the validity of this method. Improvement should be made to enhance single-to-noise ratio and measurement equipment be carefully arranged to be able to get more information about the spectra.

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DIFFRACTION IN HOPG CRYSTAL

The HOPG crystal is characterized by the highest degree of three-dimensional ordering. It belongs to lamellar material because its crystal structure, as showed in Figure 1, is characterized by an arrangement of carbon atoms in stacked parallel layers. The distance between the layers, which is termed as d , is equal 0.3354nm[5].

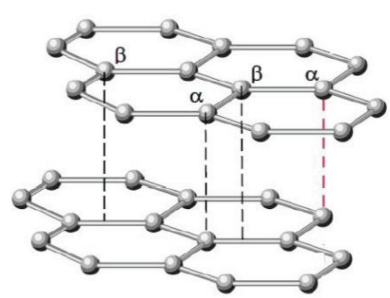

Figure 1: Three dimensional perspective of HOPG. The (α) position shows how some atoms are aligned between planes of the graphite. Alignment for the β position atoms only occurs at alternating plane level.

The X-ray diffraction in HOPG crystal is Bragg diffraction, showed in Figure **2**. Two beams with identical wavelength and phase approach a crystalline solid and are scattered off two different atoms within it. The lower beam traverse an extra length of $2d\sin(\theta)$. Constructive interference occurs when this length is equal to an integer multiple of the wavelength of the ray. It can be described by the Bragg law[4]:

$$n\lambda = 2d\sin(\theta) \quad (0)$$

where n is a integer determined the order of the diffraction. λ is the wavelength of the incident X-ray and d is the distance between layers of the crystal structure. θ is the angle between the incident ray and the scattering planes.

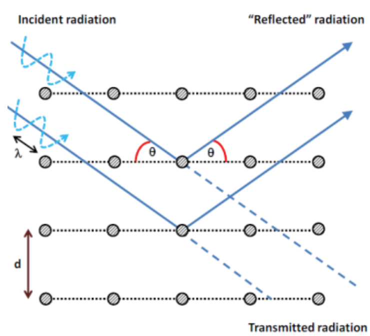

Figure 2: Bragg diffraction.

The reason that we choose HOPG to be the Bragg diffraction crystal is that it possesses some distinguish properties, determined by its mosaicity. These are (1) an order of magnitude higher integral reflectivity compared to all other known crystals in an energy range between a few keV and several tens of keV and (2) the effects of mosaic focusing, which in the symmetric geometry, i.e. so-called mosaic mode, enhance the intensity locally in the image plane[6].

For a given X-ray photon with energy of 50keV, its wavelength is about 0.025nm. The corresponding scattered is about 2.1 deg at the first order diffraction ($n=1$) when $d=0.3354$ nm for HOPG crystal. In the experiment, if we can measure the scattered angle for the incident ray, then we can reconstruct the spectra[6].

EXPERIMENTAL SETUP

We implement our experiment on the Tsinghua Thomson X-ray (TTX) source. The electron of 40~50 MeV interacts with laser of 800nm wavelength in TTX and X-ray photons of ~50 keV can be produced along the electron beam direction. The experimental setup to measure the spectra of the scattered X-ray is illustrated in Figure 3.

The scattered X-ray photons is collimated to a linear source through a slit before the HOPG crystal. Diffraction occurs in the crystal and ray will divide into two beams. CsI screen is to deposit the X-ray energy and produce the visible light that can be seen by the EMCCD. We can get the diffraction angle through the span of the two rays imaging and the distance between the HOPG crystal and CsI screen. Then the wavelength of the scattered X-ray photons can be obtained by the Bragg law in Eq.(0).

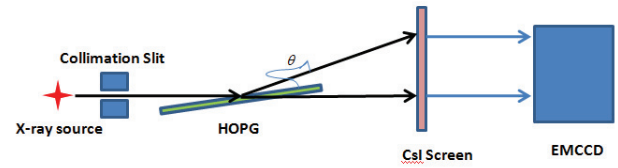

Figure 3: The experiment setup to measure the spectra of scattered x-ray on TTX.

EXPERIMENTAL RESULT

The preliminary experimental results are illustrated in Fig. 4 and Figure 5. In both figures, the strip imaging is the ray containing photons that transmitted the crystal and the crescent-shaped one is the photons that reflected by the crystal. The imaging in Figure 5 is processed by deducting the background to strength the crescent-shaped signals.

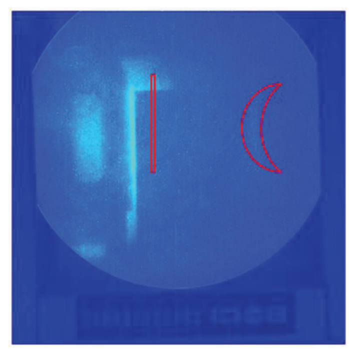

Figure 4: The imaging of the two rays after the HOPG crystal. The strip is the imaging for the ray that transmitted the crystal and the crescent-shaped imaging is the reflected ray by the crystal.

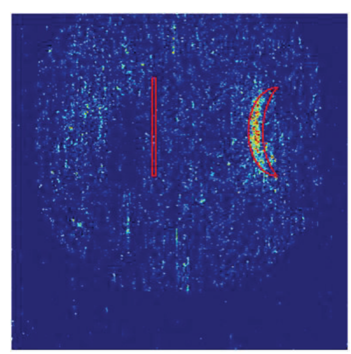

Figure 5: The imaging of the two rays after the HOPG crystal and the background has been deducted to strength the crescent-shaped imaging.

Through the imaging in Figure 5, we can reconstruct the central energy along the linear strip source. The final results are showed in Figure **6** compared with the simulation results. We simulate the whole experiment process from start to end. We use Astra to simulate the electron emission and acceleration, CAIN to the

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scattering process and MCNP to the photons passing through the Ti window to get the spectra of the scattered X-ray photons.

It can be observed that the reconstructed central energy from the imaging agree well with the simulation results. This agreement demonstrates the validity of the method to some extent. However, the reconstructed spectra have poor resolution in the energy spread due to the low signal-to-noise ratio of the crescent-shaped imaging. In addition, the mosaic angle of the crystal and the X-ray incident angle will have influence on the span of the crescent-shaped imaging. More work is needed to be done to make this method be able to reconstruct more information of the spectra.

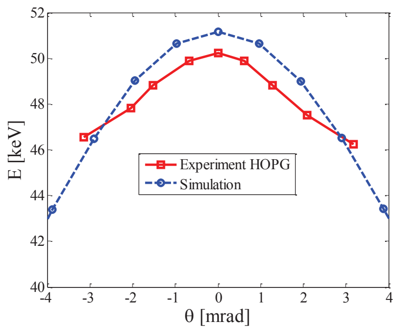

Figure 6: (Red line) The reconstructed central energy from the imaging along the linear strip. The angle θ denotes the distance from the interaction point (Blue dotted line) The start-to-end simulation results.

DISCUSSION

The preliminary experimental results justify the validity of the method to reconstruct the spectra by Bragg diffraction with HOPG crystal, especially in estimating the central energy of the spectra. The low signal-to-nose ratio impose restrictions to estimate the energy spread. And the effect of the mosaic angle and incident angle on the final imaging also should be taken into consideration to reconstruct more information of the spectra for Thomson Scattering source.

In the present experiment, the first order diffraction was used to measure the spectra. We may further consider the higher order diffraction. For higher order, the energy resolution will be promoted as the diffraction angle becomes lager, while the proportion of the reflected photons may decrease to low the signal-to-noise ratio.

It can be seen that there is a distinct advantage for Bragg diffraction method. The large mosaic angle of HOPG crystal makes it possible to reconstruct the spectra of X-ray of Thomson Scattering source by one or several pulses if the quantity of photons in one pulse is large and the detection efficiency is high enough.

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