MEASUREMENT OF ENERGY SPECTRUM OF BETATRON X-RAYS FROM LASER-PLASMA ACCELERATION

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ABSTRACT

Betatron X-ray radiation can be generated by transverse betatron motion in the laser-plasma wake field. It has a comparatively small scale and a femtosecond duration. Therefore, betatron X-rays is advantageous to be used in femtosecond pump detection; meanwhile it has prospective applications in material science and bioscience. Measurement of its energy spectrum is valuable to learn the quality of betatron X-rays and its radiation sources. In our research, transmission attenuation method was used to measure its spectrum. A detection system was tailor-designed and fabricated for the betatron X-ray source of SIOM (Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences) to meet the demand that the energy spectrum of each X-ray pulse be acquired through every pulse within a small angle. The reconstruction algorithm to solve the energy spectrum was also well optimized correspondingly. To test the properties of the system and the developed algorithm, we did comparison measurement experiments using the fabricated system and commercial HPGe detector respectively on Philips X'Unique II current steady X-ray source. The measured spectrum gained by our detection system fit quite well with that measured by HPGe detector. On the basis, the developed system was successfully applied in detection of X-ray spectra of Tesla repetitive frequency X-ray source.

Keywords: energy spectrum measurement; transmission attenuation; pulsed gamma; Betatron; laser-plasmas;

1. INTRODUCTION

Since their discovery in 1896[1], X-rays have a profound impact on science, medicine, and technology. In order to meet the scientific needs on faster time and smaller spatial scales, new x-ray sources became hotspot in research. When an intense femtosecond laser pulse interacts with gas, a plasma is formed and the ponder motive force of the pulse generates a large amplitude plasma wave[2-3]. This wave break, trap, accelerate electrons; and then short-duration of x-rays, which is called betatron radiation, burst into generation. One of the key features of betatron X-rays enabling their new applications is ultrafast pulse duration below 100 femtoseconds. Characterization of the time profile as well as the energy profile is crucially important for understanding and analyzing the physical phenomena and for its development and application. As far as the time profile is concerned, it is still an obstacle to measure the radiation pulse with sub-picosecond, which is not discussed in the paper. As regards the energy profile, the measurement of energy spectrum of pulsed γ/X rays has baffled us over a long period of time. It is more challenging and difficult especially to get energy spectra through one single pulse in a small bunch. In this paper, we developed the transmission attenuation method to determine the energy spectrum for pulsed X-ray sources.

SIOM betatron radiation source[4] driven by laser-plasma wake field is expected to generate betatron X-ray with its energy over 10 keV–1 MeV, pulse duration about several femtoseconds, total flux 10^7~10^{12} particles per pulse and beam profile Φ10 ~ 50 mm. In terms of the parameters, we put forward two measurement systems to measure its energy spectrum—CCD camera with attenuators and photomultipliers coupled delaying optical fiber with attenuators, both of which can obtain the energy spectrum of each X-ray pulse for every pulse within a small angle. The expectation maximum algorithm was utilized to reconstruct the spectrum from transmission data. Based on the available sources, we conduct experiments to validate the CCD camera with attenuator system including spectrum unfolding algorithm on Philips X'Unique II current steady X-ray source. As an application sample, the developed photomultipliers coupled delaying optical fiber with attenuator system is applied in energy spectrum detection of Tesla repetitive frequency X-ray source[5].

2. METHODS

When a beam of gamma/X with the photon fluence F is casting on a detector, the signal measured can be expressed as

$$T(0) = \int_0^{\infty} F_E S(E)\,\mathrm{d}E, \tag{1}$$

where $F_E = dF/dE$ is the derivative energy spectrum, $S(E)$ is the energy response of detectors to gamma/X rays with energy E, i.e. the signal produced by unit fluence of photon with energy E.

Once a filter with the thickness of x is placed in the beam path, the spectrum of the photon changes to $F_E = F(0)\,\mathrm{e}^{-\mu(E)x}$, while the signal T becomes

$$T(x) = \int_0^{\infty} F_E\,\mathrm{e}^{-\mu(E)x}\,S(E)\,\mathrm{d}E, \tag{2}$$

where $\mu(E)$ is the filter's attenuation coefficient to photons with energy E. The discretization form of the equation can be displayed as

$$T(x_i) = \sum_{j=1}^{n} a_{ij}\rho_j, \tag{3}$$

of which $a_{ij} = \mathrm{e}^{-\mu(E_j)x_i}\,s(E_j)\Delta E$, where x_i (i=1,2, …, m) denotes thickness of the i^{th} attenuator, $T(x_i)$ denotes the intensity signal of the corresponding i^{th} attenuator, ρ_j (j = 1, 2, ..., n) denotes the intensity of gamma in the j^{th} energy zone under the condition of that the total energy zone is divided into n-1 intervals with each $\Delta E = (E_{\max} - E_{\min})/(\mathrm{n}-1)$. Since a series of m (m=16 in the paper) attenuators are employed, sixteen equations can be formulated. To solve the combined linear equations, the unfolding algorithm of Expectation Maximization Method[6-12] was developed to solve the problem, which has been tested to have good validation and strong robust in the well-designed experiments carried out on Philips X'Unique II X-ray source ahead with a good agreement of the spectra simulated by Monte Carlo method.

Based on theoretical parameters of SIOM betatron radiation source, two different spectrum measurement systems are designed to obtain all attenuation transmission data in solely one pulse, as shown in Fig. 1 and Fig. 2. CCD camera imaging system shown in Fig.1 can be used for both constant and pulsed gamma/X source. It has a characterization of low sensitivity, not so complicated setup but with a relatively low dynamic range. Optical fiber array time-delay spectrum measurement system based on photomultiplier is well designed only applicable in detection of energy spectrum of pulsed gamma/X sources, especially for low-intensity and narrow-duration gamma/X sources.

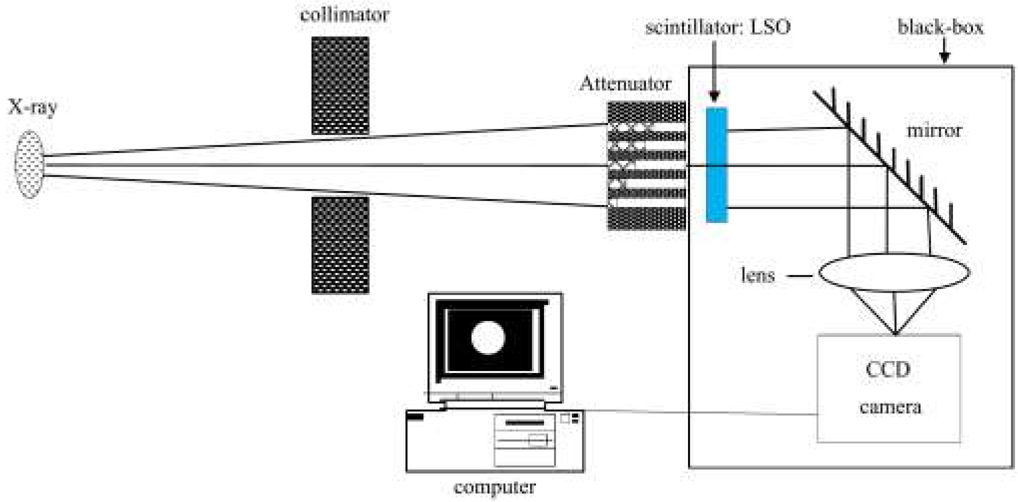


Fig.1 CCD camera imaging energy spectrum measuring system for pulsed gamma/X. Gamma/X rays are collimated to parallel beams, and irradiated directly onto the 16 holes of attenuators and the rear scintillator (e.g. LSO). The emission light is reflected by a mirror to the lens of CCD camera. The CCD signal is transferred to computer and can be displayed through developed software. The grey levels represent the intensity of incident gamma/X measured.

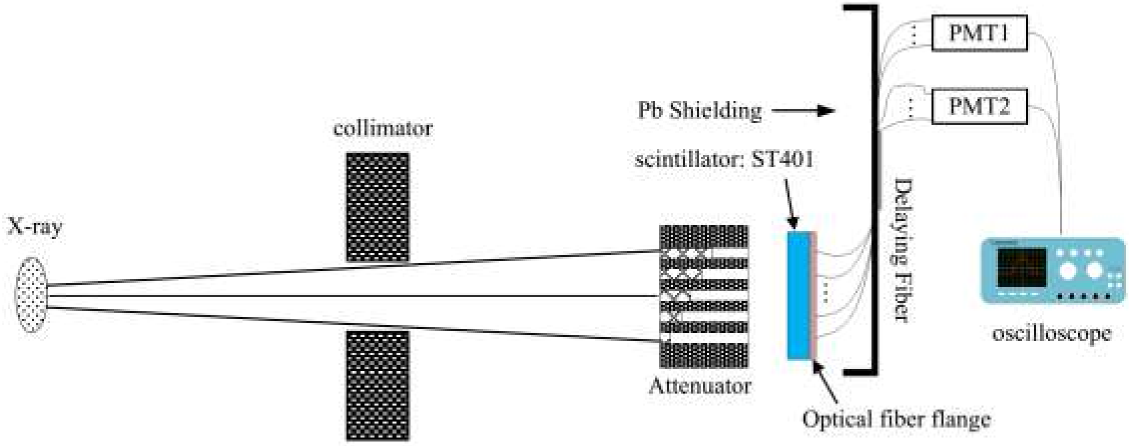


Fig.2 Optical fiber array energy spectrum measuring system for pulsed gamma/X. Gamma/X rays are collimated to parallel beams, and irradiated directly onto the 16 holes of attenuators and the rear scintillator (e.g. ST401). On the back panel of the scintillator, it is coupled with optical time delaying fiber in the rear position of corresponding hole of attenuator. The fibers are fixed by fiber flange. The length of the delaying fiber is 3 m more than the shorter one. The longer 8 paths of fibers are connected with one PMT while the shorter ones are connected with the other PMT. Both signals of the PMTs are transferred and recorded by an oscilloscope. The integral area of each waveform represents the intensity of incident gamma/X measured.

3. EXPERIMENTS

For experiments of gamma/X energy spectrum detection, we have developed and fabricated the above two measuring systems, displayed in Fig. 3. Based on the current constant X-ray source Philips X'Unique II (shown in Fig. 4), we carried out experiments to test the camera imaging system and spectra reconstruction. After this, the optical fiber array measuring system is applied in measuring energy spectrum of Tesla repetitive frequency X-ray source (displayed in Fig. 5), which is capable of producing tunable, hard X-ray pulses at maximum about 400 keV with short durations of ~400 ps.

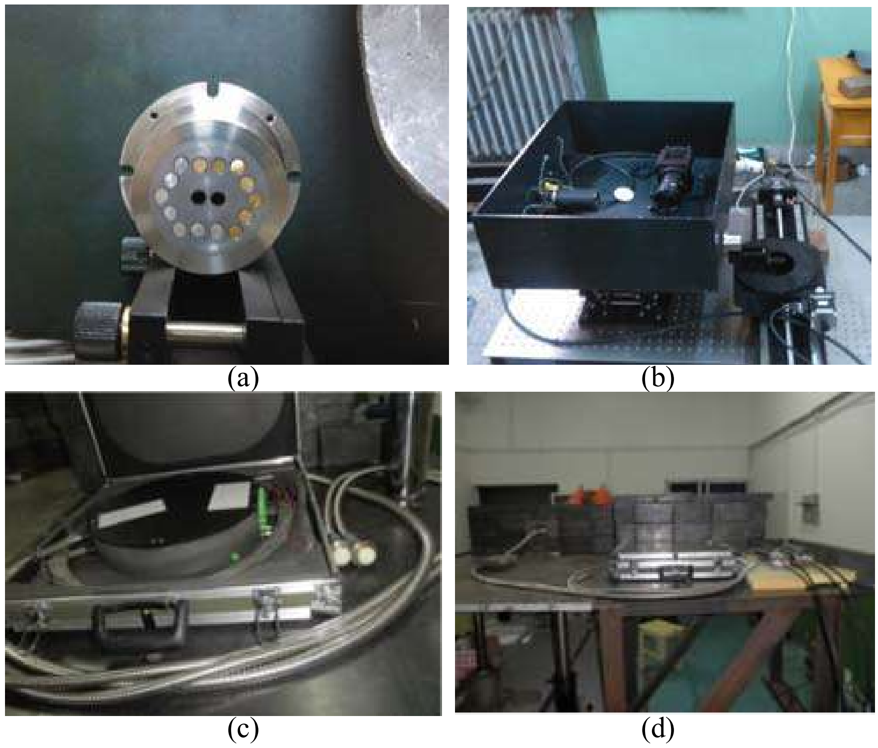


Fig. 3 The energy spectrum measuring system established. (a) 16 holes of attenuators, (b) CCD camera imaging system, (c)(d)optical fiber array system coupled with photomultipliers.

Fig.4 Philips X'Unique II X-ray source. It is a bremsstrahlung X-ray spectrometer with maximum voltage 100 kV, maximum current 60mA and rated power 3 kW. X-rays are generated by accelerated electrons stopped by W target. The right picture is HPGe detector used in experiments.

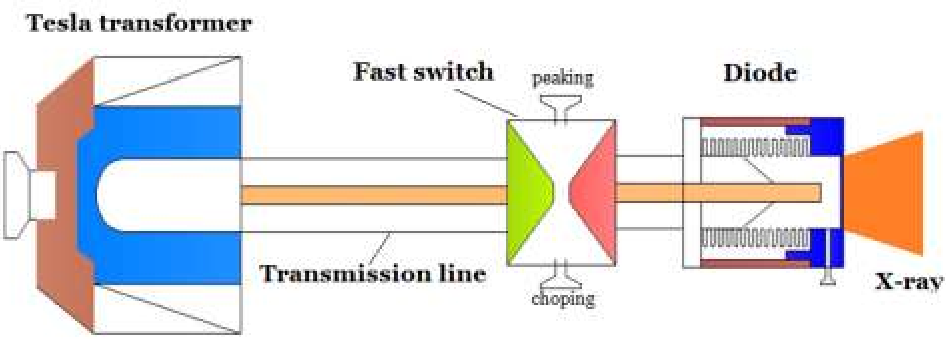
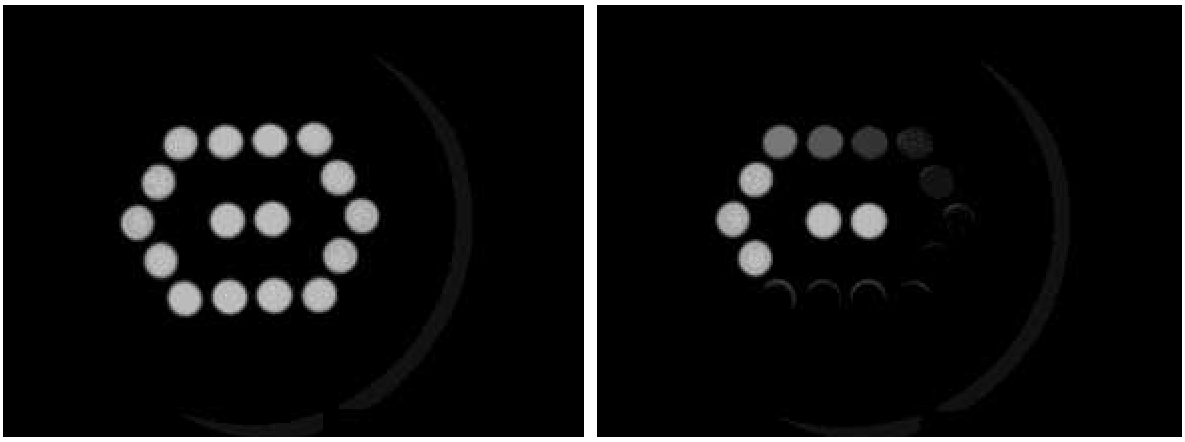


Fig.5 Schematic diagram of Tesla repetitive frequency X-ray source.

3.1 Test experiment on Philips X'Unique II X-ray source

The detection system including the attenuators shown in Fig. 3(a) and Fig. 3(b) is set up in accordance with the diagram of Fig.1. In order to validate the results measured by the developed CCD imaging system, the HPGe detector was taken into use as comparison measurement. The CCD camera used is type VT-8MC. The scintillator is LSO scaled Φ50×5 mm. Attenuators used are 2.5/5/10/15/20/25 mm thickness of Al. We measured the X-rays and acquired the grey scale images (Fig. 6) under conditions of attenuators filled in the collimator and collimator without attenuators. The ratio of the grey scale of each corresponding hole represents the transmission data of X-rays through the attenuator.

The energy response of the system including the scintillator LSO is calculated by MCNP[13]. The energy bin is divided into 100 shares. Initial spectrum for iteration is sine spectrum. Solving the simultaneous equations using EM method, the reconstructed energy spectrum is obtained, as shown in Fig. 7.



(a)without attenuator (b) with attenuator

Fig.6 Grey scale images of X-rays through collimator with or without attenuators in operation voltage 70 kV of Philips X'Unique.

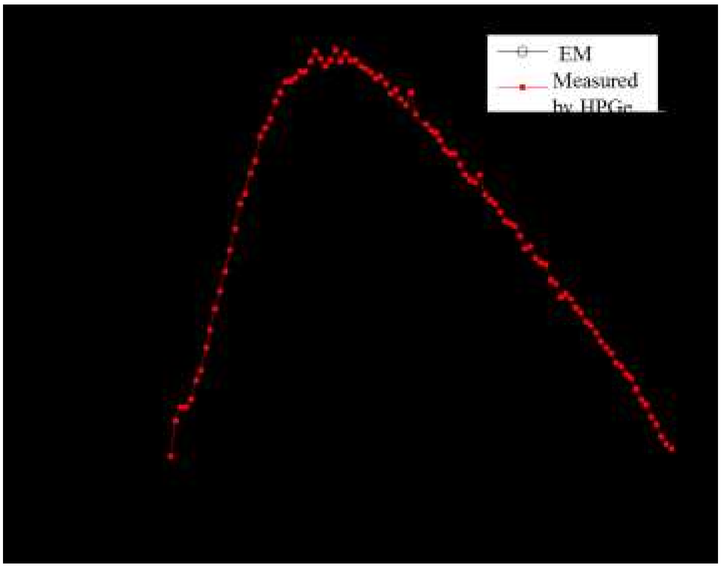


Fig.7 Reconstructed energy spectrum versus HPGe measured energy spectrum of Philips X'Unique II with operation voltage 70 kV.

3.2 Application experiment on Tesla repetitive frequency X-ray source

To further study whether the developed energy spectrum detection system is suited for detection of pulsed rays, it is necessary to perform a pulsed-ray radiation experiment.

The detection system shown in Fig. 3(c) and Fig. 3(d) is set up in accordance with the diagram of Fig. 2. Attenuators are 2.5/5/10/15/20/25/30/35/40 mm thickness of Al/Cu and 2.5/5/7.5 mm thickness of Pb. The collimator used is with 24 holes instead of 16 holes. The optical fiber array consists of 24 paths of fibers with diameter Φ600 μm and length 1, 4, 7, …, 70 m(3 m interval). The shorter 12 paths of fibers is fixed to one fiber flange and transferred to ETL9815B PMT. The others are transferred to the other ETL9815B PMT. The gapped length of fiber used is to delay the scintillating florescence signal time, ensuring every path of signal transferred to the PMT and can be recorded by only one channel of oscilloscope. Just two channels of oscilloscope are enough for recording the total 24 paths of signals. Three meters’ fiber gap is equivalent of 15 ns time-delay. In order to discriminate the adjacent waveforms, the X-ray source should be fast and the time response of the scintillator should also be as fast as nanosecond. So, organic scintillator ST401 with ~3 ns time response to gamma/X ray is employed instead of inorganic scintillator LSO with ~15 ns time response. The measured waveforms are shown in Fig. 8.

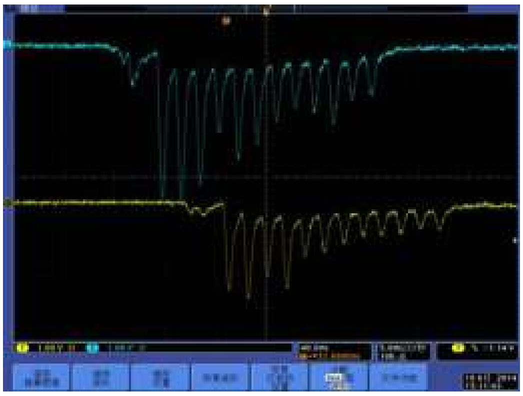


Fig.8 Measured waveforms of optical fiber array detection system. Channel 1 is one PMT signal while channel 2 the other one.

Fig.9 Reconstructed energy spectrum of Tesla repetitive frequency X-ray source through EM iteration using optical fiber array measurement system.

The transmission ratio of each channel of collimator with or without attenuators can be got by processing the total 24 paths of waveforms data. The energy response of the developed system including the scintillator ST401 is calculated by MCNP. The energy bin is divided into 100 shares. Initial spectrum for iteration is sine spectrum. Solving the simultaneous equations using EM method, the reconstructed energy spectrum is obtained, as shown in Fig. 9.

4. RESULTS

In Fig. 7, the black line is the directly measured energy spectrum by HPGe without reconstruction or restoration technique. By the developed CCD imaging system, the direct output data is grey scale images, the energy spectrum is indirectly gained through image reconstruction technique. By comparison of the reconstruction results with that of measured by HPGe detector, it indicates that the developed system and the exploited iteration algorithm are feasible and suited for the detection of gamma/X energy spectrum.

In Fig. 8, we can see each channel has 13 peaks of waveforms. But actually, only 12 paths of optical fiber signals are transferred to oscilloscope. By piercing the durations of each waveform, we can see the first peak waveform has longer duration and malformed wave shape. The possible reason is that the first waveform is signal of electromagnetic interference leaded by discharging of the fast switching of Tesla repetitive frequency X-ray source. So, during the experimental data analysis, the first peak waveform is eliminated. Another problem is needed to point out that the bottom width of the waveform is flooded in the former one and the rising edge is influenced severely by the former falling edge. To solve the problem, the time response of the system especially the scintillator should be faster or the delaying fiber gap should be longer enough to discriminate the whole neighbor waveforms.

In Fig. 9, the reconstructed energy spectrum of Tesla repetitive frequency X-ray source is given by EM iteration. Through current methods, the real energy spectrum cannot get by direct measurement. So it is still hard to evaluate the reconstructed result whether it is consistent with the real ones. One practical comparison method is to do the restoration with other algorithms, which need further research.

5. CONCLUSIONS

CCD camera imaging system and optical fiber array system are put forward to measure the energy spectrum for pulsed betatron X-rays from laser plasma acceleration. The expectation maximization iteration method is used and tested by experiments on constant and pulsed X-ray source respectively. The results show that EM method is suitable for the developed system and the developed systems can be applied in detection of pulsed gamma/X rays energy spectrum. To enhance our understanding of the developed system for ultrafast pulse gamma/X energy spectrum measurement, further work will be involved in performing experiments directly on the target betatron X-rays sources.

Acknowledgements

The authors would like to show their gratitude to the colleagues of the X-ray group and Radiation Metrology group at Northwest Institute of Nuclear Technology for the operation of Philips X'Unique II X-ray source and Tesla repetitive frequency X-ray source respectively.

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