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A Pb-TLD spectrometer to measure high energy photons in z-pinch experiments on the primary test stand

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HIGHLIGHTS

- A Pb-TLD spectrometer has been developed to measure spectra of high energy photons in wire-array z pinches on PTS.
- Energy spectra of high energy photons on PTS has been firstly obtained by unfolding programs developed with MATLAB code.
- The energy of high energy x-ray on PTS is obtained to be mainly within the region of 100 keV to 1.3 MeV.

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ABSTRACT

A Pb-TLD spectrometer has been developed based on attenuation techniques to measure high energy photons in wire-array z-pinch experiments on the primary test stand (PTS). It is composed of a stack of 18 lead filters interspersed with 19 thermoluminescent dosimeters (TLD). A shield is constructed for the spectrometer and scattered radiation is reduced to less than 5% by the shield. Response functions of the spectrometer are calculated by MCNP5 for 0–2 MeV photons. Based on response functions and 19 dose data measured in experiments, energy spectra of high energy photons on PTS has been firstly obtained by unfolding programs developed with MATLAB code using iterative least square fit. Results show that energy peak locates within 200 keV and 300 keV, and the fluence decreases to background level at energy higher than 1.3 MeV.

1. Introduction

The primary test stand (PTS), developed in China Academy of Engineering Physics, is a pulse power facility with a current up to 8 MA and a rise time 70 ns [1]. We are dedicated to perform wire-array z pinches and z-pinch driven inertial confinement fusion researches on PTS. Primary wire array experiments on PTS show that the total x-ray energy exceeds 500 kJ [2]. An extensive set of diagnostics are being fielded on PTS to study pinch physics [3]. It has been demonstrated on Z that high energy photons up to hundreds of keV or a few MeV are produced in z-pinch explosions [4]. High energy photons form serious background in fusion neutron diagnostic and x-ray imaging, and are of particular concern in designs of z-pinch diagnostics [5,6]. Besides, high energy photons may deposit energy into the capsule and create a potential preheat problem in z-pinch driven ICF researches [7]. Therefore it is necessary to measure high energy photons in wire array z-pinch experiments on PTS. The time scale of z pinches is dozens of nanoseconds, so high energy photons are pulsed x-rays which last only dozens of nanoseconds.

Few-channel spectrometers based on attenuation techniques are generally used in measuring spectra of pulsed x-rays [8–11]. Nolte designed a TLD-based few-channel spectrometer for use in mixed electron-photon fields [10]. However, photons in Nolte's study is up to 350 keV, while upper energy limit of high energy photons in z pinches is unknown and may be as high as several MeV. In addition, experimental environments on PTS are different from those in Nolte's paper.

In this paper, a Pb-TLD spectrometer has been developed to measure spectra of high energy photons in z-pinch experiments on PTS. Response functions of the spectrometer are calculated by MCNP5 [12] in consideration of practical experimental conditions on PTS. We have developed an unfolding program using iterative least square fit by MATLAB software. Doses are experimentally obtained from TLDs of the spectrometer and energy spectra are obtained by the unfolding program.

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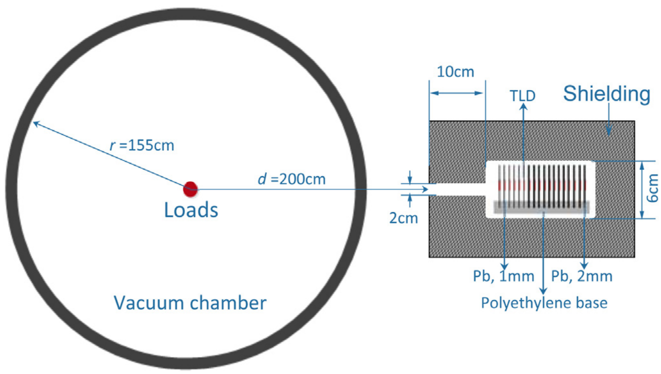

Fig. 1. Schematic diagram of experimental setup.

2. Pb-TLD spectrometer and experimental setup

The Pb-TLD spectrometer is shown in the right part of Fig. 1. It is composed of a straight stack of 18 lead sheets interspersed with 19 thermoluminescence dosimeters (TLDs). The 19 TLDs are labeled as TLD.1, TLD.2, . . ., TLD.19 in sequence. The first 6 lead sheets is 1 mm thick each, and the other 12 is 2 mm thick each. Thus the total thickness of lead sheets is 3 cm. The distance between two sheets is 2 cm. Each TLD is fixed to each filter. All filters are fixed in a polyethylene. TLDs used in our experiment are LiF(Mg, Cu, P), made in China.

As is known, LiF(Mg, Cu, P) material has nonlinear energy response [13]. In order to flatten energy response curve, energy compensation has been done for TLDs used in our measurements. Each TLD is plated with copper and aluminum in its surface, and encapsulated in a plastic box. As a result, TL efficiency curve for 100 keV to 2.0 MeV photons becomes flat within ±10% deviation. TLDs are calibrated by ^{137}Cs gamma rays (662 keV) and ^{60}Co gamma rays (1.25 MeV). Calibration results show that relative TL efficiency is 1 for ^{137}Cs gamma rays, and 1.05 for ^{60}Co gamma rays.

A shield is constructed for the spectrometer to decrease scattered radiation. It consists of a 10-cm-thick collimator to restrict the viewing area to a 2-cm-diam circle, and a cube shield constructed from 5-cm-thick lead walls. When x-rays burst in z-pinch explosions, they propagate out and interact with the steel wall by photoelectric effect, Compton scattering, and pair annihilation. X-rays are partly absorbed by the steel wall, partly scattered, and partly pass through the steel wall without interaction. As a result x-rays reaching the Pb-TLD spectrometer consist of both uncollided photons and scattered radiation. Pb-TLD spectrometer is applied to measure uncollided photons (high energy photons) at the measuring point. Scattered radiation is calculated by MCNP5 and results show that it is reduced to less than 5% by the present shield.

Furthermore, schematic diagram of experimental setup for high energy photon measurements on PTS is also given in Fig. 1. The load is located in a vacuum spherical chamber sealed by a steel wall which is 2 cm in thickness (as shown in left part in Fig. 1). The diameter of the vacuum chamber is 310 cm. The spectrometer is placed outside the chamber, and it is 200 cm away from the load in the radial direction. Therefore, the spectrometer is to measure high energy photons at the measuring point.

3. Measurement theory

Measurement theory of the spectrometer is based on attenuation law of photons in material. Incident photons are attenuated when transmitting filters of the spectrometer. Assuming that fluence of incident photons is ϕ_0 and normalized spectra is $S(E)$. As a result attenuated fluence of photons before TLD No.i can be derived in Eq. (1),

$$I_i = \phi_0 \int_0^{E_{max}} S(E) e^{-\mu(E)t_i} B(t_i, E)\, dE \quad (i = 1, 2, \cdots, n), \tag{1}$$

where n is the total number of TLDs in the spectrometer, $n = 19$. t_i is accumulative thickness of lead filters before TLD.i. $\mu(E)$ is linear attenuation coefficient. $B(E, t_i)$ is accumulative factor.

There is a quantitative relationship between dose and fluence under electron equilibrium, $D = E\ I(\mu_{en}(E)/\rho)$. Then Eq. (1) can be written as Eq. (2),

$$D_i = \phi_0 \sum_{j=1}^{m} \Delta E S(E_j) e^{-\mu(E_j)t_i} B(t_i, E_j) E \mu_{en}(E_j) \eta_j / \rho. \tag{2}$$

where η_j is TL efficiency for photons with energy E_j. The deviation between η_j is within ±10% for 0.1–2.0 MeV photons. Thus η_j approximates 1 in the following calculations.

As normalized spectra $S(E)$ is complicated and unknown, discrete ordinate method is introduced to solve Eq. (2). Energy is equally divided into m sections and fluence for the jth energy section is $\phi_j = \phi_0 S(E_j)\Delta E$, $(j = 1, 2, \cdots, m)$. Let $R(i, j) = e^{-\mu(E_j)t_i} B(t_i, E_j) E \mu_{en}(E_j)/\rho$, and Eq. (2) is turned to Eq. (3),

$$D_i = \sum_{j=1}^{m} \phi_j R(i, j). \tag{3}$$

In Eq. (3), D_i is measured doses from readings of the Pb-TLD spectrometer, and ϕ_j is energy spectra we have to obtain in this paper. The parameter $R(i, j)$ is called response function which is $n \times m$ matrix. $R(i, j)$ is correlated to design of the spectrometer and energy of incident photons. Once the spectrometer is designed, $R(i, j)$ is determined. If $R(i, j)$ is obtained, energy spectra of incident photons can be derived with measured doses through Eq. (3).

The lower part of high energy photons might be absorbed by the steel wall of the vacuum chamber. MCNP5 is used to calculate transmission of the steel wall to 0–2 MeV photons. The maximum energy of high energy photons is related to input voltage of Marx on PTS and it is below 2 MeV. Results are shown in Fig. 2. Transmission ratios refer to the proportion of uncollided photons to incident photons. It is obvious to see that transmission ratios are closely correlated to photon energies. Photons of low energies are seriously absorbed by the steel wall, while photons of high energies

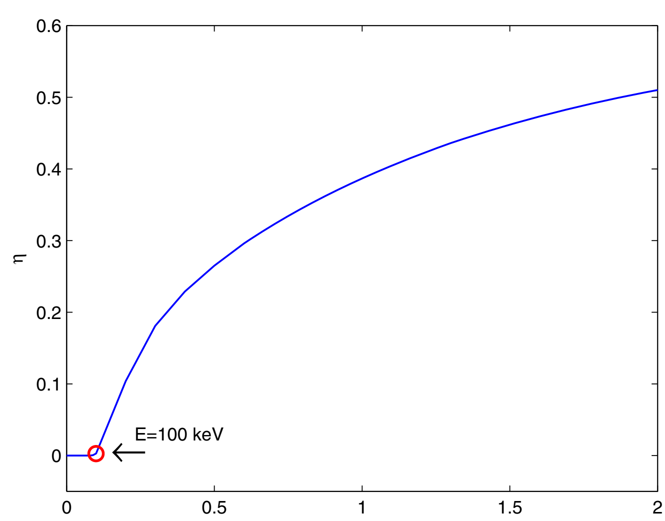

Fig. 2. Transmission of the steel wall to 0–2 Mev photons. There is a turning point in the curve corresponding to 100 keV photons.