ANALYSIS OF UNCERTAINTY OF DOSE RATE MEASUREMENT ON THE ACCELERATOR “QIANG GUANG-I”

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Abstract

“QiangGuang-I”, working at short pulse state, can be used to research the transient radiation effects on electronic devices. The measurement of dose rate is significant for assessing devices’ radiation-resistant ability. This paper comprehensively analyzes the originations of uncertainty on dose rate’s measurement, such as thermoluminescent dosemeter’s linearity degree and response to X-rays energy spectrum, testing instruments’ resolution, waveforms’ transmission distortion , and positional error; figures out the extended uncertainty. The result shows that the extended uncertainty of dose rate’s measurement is less than 20%, which is satisfactory for researching on devices’ transient radiation effects, and proves that the method used to measure dose rate is reasonable.

INTRODUCTION

The accelerator “QiangGuang-I” working at short pulse state can generate X-rays with 20ns pulse width and 1MeV photons’ average energy. That is fit to transient ionizing radiation effects experiments in devices[1,2]. The measurement of dose rate is important as a result of its measurement dependability directly affecting the experimental result. The uncertainty of dose rate measurement depends on two aspects – the measurement error of total dose and the pulse’s effective width, and the two aspects are impacted by other factors. This paper widely analyzes the parameters could bring measurement error, and figures out the uncertainty of dose rate measurement.

METHOD OF PULSED X-RAYS DOSE RATE MEASUREMENT

The system used to measure dose rate of pulsed X-rays is illustrated as Fig. 1. It is composed of four sections – crystal LiF (measuring total dose), photoelectric cell (detecting the waveform of pulsed X-rays), cable (transmitting the waveform), and oscillograph (recording the waveform).

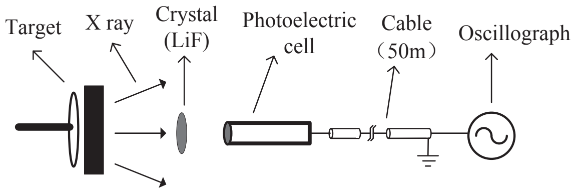

Figure1: The system of dose rate measurement.

At present, a majority of devices are based on Si substrate[3], using thermoluminescent dosemeter LiF equivalently measures absorbed dose in Si is a batter method. The effective width of pulsed X-rays is gained from the waveform recorded by oscillographs. So dose rate can be expressed as

$$\dot{D} = \frac{D}{t_{\text{eff}}} \tag{1}$$

Where, $\dot{D}$ – dose rate, Gy/s; D – total dose, Gy; t_{eff} – effective width of pulsed X-rays, s.

UNCERTAINTY’S ASSESSMENT IN PULSED X-RAYS’ DOSE RATE MEASUREMENT

According equation (1), the uncertainty of dose rate measurement[4] can be expressed as

$$u(\dot{D}) = \sqrt{c(D)^2 u(D)^2 + c(t_{\text{eff}})^2 u(t_{\text{eff}})^2} \tag{2}$$

Where $u(\dot{D})$, $u(D)$, $u(t_{\text{eff}})$ respectively is the uncertainty of dose rate, absorbed total dose and the effective pulse width of pulsed X-rays; $c(D)$, $c(t_{\text{eff}})$ respectively is the sensitivity coefficient of total dose and the effective pulse width of pulsed X-rays, those values are dominated by the equations as bellow,

$$c(D) = \frac{\partial \dot{D}}{\partial D} = \frac{1}{t_{\text{eff}}} \tag{3}$$

$$c(t_{\text{eff}}) = \frac{\partial \dot{D}}{\partial t_{\text{eff}}} = -\frac{D}{(t_{\text{eff}})^2} \tag{4}$$

Using relative uncertainty, equation (1) is expected to change the form to

$$\begin{aligned} u(\dot{D})_{\text{rel}} &= \frac{u(\dot{D})}{\dot{D}} = \frac{t_{\text{eff}}}{\dot{D}} \sqrt{\frac{u(D)^2}{t_{\text{eff}}{}^2} + \frac{D^2 u(t_{\text{eff}})^2}{t_{\text{eff}}{}^4}} \\ &= \sqrt{[\frac{u(D)}{D}]^2 + [\frac{u(t_{\text{eff}})}{t_{\text{eff}}}]^2} \\ &= \sqrt{[u(D)_{\text{rel}}]^2 + [u(t_{\text{eff}})_{\text{rel}}]^2} \end{aligned} \tag{5}$$

Where $u(D)_{\text{rel}}$ and $u(t_{\text{eff}})_{\text{rel}}$ respectively is the relative uncertainty of absorbed total dose and the effective pulse width of pulsed X-rays.

The uncertainty of absorbed total dose is dominated by four factors, which are the thermoluminescent dosemeters’ repeatability (r_D), non-linearity (l_D), response to X-rays spectrum (s_D), and directivity (d_D). And assuming that the four factors are uncorrelated each other, so the relative uncertainty of total dose is expressed as

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$$u(D)_{\text{rel}} = \sqrt{u(r_D)_{\text{rel}}^2 + u(l_D)_{\text{rel}}^2 + u(s_D)_{\text{rel}}^2 + u(d_D)_{\text{rel}}^2} \qquad (6)$$

The uncertainty of effective pulse width of pulsed X-rays is dominated by photoelectric cell's sensitivity (m_t), waveform's transmission distortion owing to long cable (v_t), oscillograph's resolution (p_t), and the error of calculating the waveform's area, (i_t). And the four factors above are uncorrelated, so the relative uncertainty of effective pulse width of pulsed X-rays can be expressed as

$$u(t_{\text{eff}})_{\text{rel}} = \sqrt{u(m_t)_{\text{rel}}^2 + u(v_t)_{\text{rel}}^2 + u(p_t)_{\text{rel}}^2 + u(i_t)_{\text{rel}}^2} \qquad (7)$$

CALCULATING THE UNCERTAINTY'S COMPONENTS

The Relative Uncertainty of Absorbed Total Dose, $u(D)_{rel}$

(1) Under the condition of meeting independence and recurrence, the thermoluminescent dosemeters were repeatedly calibrated n times, obtained $k_i(i=1\sim n)$, and the arithmetical mean $\bar{k} = \frac{1}{n}\sum_{i=1}^{n} k_i$ could be considered as the optimum estimated value of overall mathematic expectation[5]. So the relative standard error of $\bar{k}$ is

$$u(\bar{k})_{\text{rel}} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(k_i - \bar{k})^2} \,/\, \bar{k} \qquad (8)$$

thermoluminescent dosemeters were calibrated and screened one by one, making sure the relative standard uncertainty less than 5.0%.

In dosemeters' calibration procedure, the apparatus used to measure the radiation field is PTW-UNIDOS, which is the measuring basis for dose measurement, its extended uncertainty is 1.7%, coverage factor k = 2. So the uncertainty of $\bar{k}$ can be combined as

$$\begin{aligned} u(r_D)_{\text{rel}} &= \sqrt{u(\bar{k})^2 + (\frac{U_s}{2})^2} \\ &= \sqrt{0.05^2 + 0.0085^2} \qquad (9) \\ &\approx 5.1\% \end{aligned}$$

(2) Five groups thermoluminescent dosemeters' nonlinearity was calibrated, every group contained ten dosemeters. Those absorbed doses respectively set as 0.1Gy, 1Gy, 5Gy, 10Gy and 100Gy, and measured the dosemeters just after irradiating in standard radiation field, the measuring apparatus was RGD-3A thermoluminescent host machine. The parameter wanted is max nonlinear error, which can be figured out according to the method mentioned in reference [6]. The result figured out is 2.5%, obeying even distribution, so cover coefficient is 1.73, and the standard uncertainty is

$$u(l_D)_{\text{rel}} = 2.5\%/1.73 \approx 1.4\% \qquad (10)$$

(3) Figure 2[7] shows the measured spectrum of "Qiang Guang-I" working on short pulse state. From Fig. 2 we can know photons' average energy is 1.04MeV, max energy is 3MeV, and few proportion energy bellows 200keV. According to the spectrum, the proportion of photons' energy between 0.2MeV~0.9MeV is the largest, about 46.5%; the photons within 0.9MeV~1.6MeV is about 42.4; the photons within 1.6MeV~2.3MeV is 6.7%; the last is 4.4%.

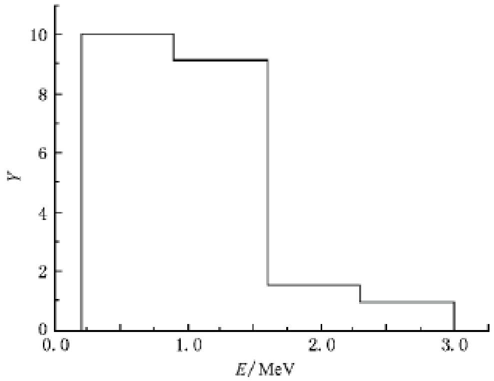

Figure 2: Energy spectrum of "Qing Guang-I" working at short pulse state.

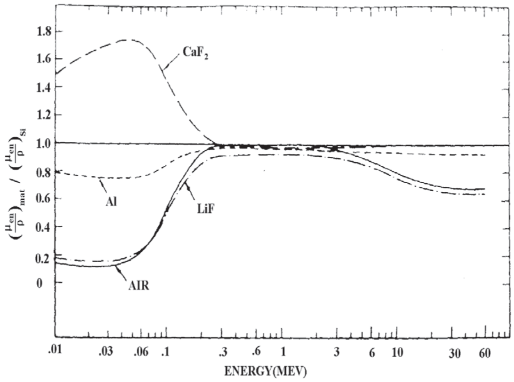

Figure 3: Ratio of mass-energy absorption coefficient between Si and several materials.

What must be noted is that the absorbed dose in Si is not directly measured, but measures in LiF(Mg,Ti), so the mass energy absorption coefficient of Si and LiF should be considered. In Fig. 3, the ratio curve of mass energy absorption coefficient between Si and LiF is illustrated. Apparently, at a large range of photons' energy between 0.2MeV~2.5MeV, the relative quality energy absorption coefficient of Si and LiF is quite even, about 0.94[8]; as for the photons within 2.5MeV~3.0MeV, the relative quality energy absorption coefficient of Si and LiF is about 0.9. Consequently, when using the absorbed dose in LiF equaling that in Si, the error brought is

$$\begin{aligned} u(s_D)_{\text{rel}} &= (1 - 0.9) \times (5/7) \times 4.4\% + (1 - 0.94) \\ &\quad \times [1 - (5/7) \times 4.4\%] = 6.1\% \end{aligned} \qquad (11)$$

(4) The thermoluminescent dosemeters are generally shaped square flakes, and when calibrating or using them the surface plane and the incident X-rays beam is vertical, the direction error within ±10°. Furthermore the photons with energy 0.2MeV or higher can be easily transmitted through the hole flake. Considering the reasons above, the error about directivity can be ignored,

$$u(d_D)_{\text{rel}} = 0 \qquad (12)$$

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Combining the equation (6) and (8)~(12), the uncertainty of absorbed total dose can be figured out,

$$u(D)_{\rm rel}=\sqrt{u(r_D)^2+u(l_D)^2+u(s_D)^2+u(d_D)^2} \tag{13}$$
$$=\sqrt{0.051^2+0.014^2+0.061^2+0}=8.1\%$$

The Relative Uncertainty of Effective Pulse Width of Pulsed X-Rays, $u(t_{eff})_{rel}$

(1) Using four way electron beam generator[9] calibrated the photoelectric cell. The nominal effective pulse width of the electron beam generated by four way electron beam generator is 2ns, whereas the effective pulse width measured by photoelectric cell is 4ns, so the response time of the photoelectric cell is less than 4ns. It measuring the pulse width of X-rays generated by "Qiang Guang-I" is 20ns, then the real pulse width can be estimated by the equation $\sqrt{20^2-4^2}=19.6ns$, so the max error of pulse width measurement is 0.4ns. Consequently, the relative uncertainty of thermoluminescent dosemeters' directivity is less than 2.0%, here set it to 2.0%, namely

$$u(m_t)_{\rm rel}=2.0\% \tag{14}$$

(2) The system of dose rate measurement used in "QiangGuang-I" experiment platform uses 50 meters SYV-75-9 coaxial-cable, and adopts software compensation[10] to mitigate the waveform distorting. The error owing to long cable' transmission is very small after software compensation, about 0.1%, which can be ignored, so

$$u(v_t)_{\rm rel}=0 \tag{15}$$

(3) The uncertainty of oscillograph's resolution comes from two parts – time resolution and amplitude resolution, which are respectively named as $u_{//}$ and $u_{\perp}$. The oscillograph is TDS684C, that's max sampling rate is up to 5GS/s, namely the time resolution is 0.2ns, and the measuring error obeys even distribution, so the uncertainty of time resolution should be $u_{//}$=0.2ns/1.73 =0.116ns. The pulse width's representative value is 20ns, so $(u_{//})_{\rm rel}$=0.116ns/20ns =0.58%.

The uncertainty of amplitude resolution can refer to the certificate of verification, where the relative standard uncertainty is 1.5% when measuring the signal with higher than 30V amplitude at 10V/div. The oscillograph's time resolution and amplitude resolution is correlated, so

$$u(p_t)_{\rm rel}=\sqrt{(u_{\perp})_{\rm rel}{}^2+(u_{//})_{\rm rel}{}^2}=1.6\% \tag{16}$$

(4) With the waveform of pulsed X-rays recorded, the effective pulse width can be easily calculated via the voltage amplitude dividing the waveform's area. The waveform's area is figured out using mathematics software Matlab, the effective portion is from the head of rise edge to the bottom of trailing edge. But some error is unavoidable when people operating, the relative error is 2.0% according empirical estimation, which obeys even distribution, so the relative standard uncertainty of the waveform's area measurement is

$$u(i_t)_{\rm rel}=2.0\%/2=1.0\% \tag{17}$$

Combining (7), (14)~(17), the relative uncertainty of effective pulse width of pulsed X-rays can be figured out.

$$u(t_{\rm eff})_{\rm rel}=\sqrt{u(m_t)_{\rm rel}{}^2+u(v_t)_{\rm rel}{}^2+u(p_t)_{\rm rel}{}^2+u(i_t)_{\rm rel}{}^2} \tag{18}$$
$$=\sqrt{0.02^2+0+0.016^2+0.01^2}=2.7\%$$

And using equation (5), (13), (18), the relative standard uncertainty of pulsed X-rays' dose rate measurement is expressed as

$$u(\dot{D})_{\rm rel}=\sqrt{u(D)_{\rm rel}{}^2+u(t_{\rm eff})_{\rm rel}{}^2}=\sqrt{0.081^2+0.027^2}=8.5\% \tag{19}$$

It obeys normal distribution, aiming at 95%, the coverage coefficient is *k*=2, so the extended uncertainty of dose rate is

$$U(\dot{D})_{\rm rel}=ku(\dot{D})_{\rm rel}=17.0\% \tag{20}$$

CONCLUSIONS

In "QiangGuang-I" pulsed X-rays' dose rate measurement, the uncertainty of absorbed total dose is 8.1%, which is dominated by thermoluminescent dosemeters' repeatability and the equivalent to Si material. The uncertainty of effective pulse width of pulsed X-rays is 2.7%, which is dominated by photoelectric cell's sensitivity and oscillograph's resolution. The extended uncertainty of dose rate is 17.0%, and the coverage coefficient is $k=2$.

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