Study on Induced Current of Iron Plate Irradiated by Pulsed Gamma Rays

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Abstract. To obtain the transient current response law of the metal component irradiated by pulsed gamma rays, the pulsed gamma ray irradiation experiment of the iron plate was carried out on "Qiangguang-I" accelerator. The transient current of iron plate generated by pulsed gamma rays was measured and analysed, and the relationship between the amplitude of pulse current and the dose rate of gamma rays was obtained. The results show that the current response sensitivity of the iron plate is about 5.7×10^{-7}(A/m^2)/(Gy/s) when the gamma rays with the energy of 0.8 MeV irradiate the iron plate. The charge deposition rate in the iron plate can be obtained by Monte Carlo simulation, and then it can be converted to gamma ray induced current of the metal component irradiated by gamma rays.

1 Introduction

When metal is irradiated with the gamma rays, electron emission will occur due to the interaction between the gamma rays and the atoms of the metal. When the distance of the electron to the metal surface is less than electron range, the electron will escape out the metal surface and lead to a change in the net charge of the metal. The change of net charge will result in the radiation effects such as displacement current, charge accumulation, and transient electromagnetic fields and so on[1-4]. In experiments related to gamma rays, such as experimental measurement of gamma ray shielding performance, experiment of gamma ray detector calibration, total dose and dose rate effect of gamma ray on apparatus, all kinds of metal components may be used. In gamma ray related experiments, the change in the net charge of the metal due to gamma rays irradiation may be an interference source of the experiment, which will affect the accuracy of the experimental results and even cause a failure of the experiment[5-7].

Researchers at home and abroad have done a lot of work on the behavior of electron emission from metal irradiated by X and gamma rays, the work are mainly focused on the system electromagnetic pulse generated after the emission of electrons, while few studies have been done on the formation of current of metallic components irradiated by gamma rays[8-10]. With the rapid development of computer simulation technology, Monte Carlo simulation of interaction of radiation with matter is becoming more and more popular[11-12]. For example, we can use Monte Carlo program MCNP to calculate the amount of charge deposited in metal after the interaction of gamma rays with metals[13]. However, the mechanism of how the deposited charge forms the current and the intensity of the formed current are not exactly clear. In this paper, for the most commonly used iron material, the net current produced in the iron plate caused by the electron escape after the interaction of the pulsed gamma ray with the iron plate is experimentally investigated. By comparing the results of the charge deposition rate obtained by Monte Carlo simulation method to the measured results of the current generated by gamma irradiation, the feasibility of calculating the gamma induced current with Monte Carlo simulation is verified.

2 Experiment principle and method

2.1 Experiment principle

The interaction of photon with matter mainly includes the photoelectric effect, the Compton scattering effect and the electron pair effect. The dominace of the interaction types mainly depend on the photon energy and the atomic number Z of the matter. For gamma rays with energy of about 1 MeV, the main interaction with iron atom is the Compton scattering effect. Assuming that the metal is irradiated by gamma ray, each absorption of a photon can produce an electron. Due to the randomness of the electron emission direction, the probability that the electron can escape out the metal is 1/2.

Therefore, when gamma rays inject perpendicularly to the iron plate, the number of electrons escaping from the iron plate per square centimeter is

$$n_{\mathrm{e}} = \frac{1}{2}\mu R_{\mathrm{e}}\phi_{\gamma} \quad \mathrm{e/cm^2}, \tag{1}$$

where, $\mu=NZ\sigma_c$ is the linear absorption coefficient of the matter to the gamma ray, in unit of cm^{-1}; N is the atomic

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number density of the metal, in unit of cm^{-3}; Z is the atomic number of the metal; σ_c is the cross section of Compton scattering for photon interacting with electrons in metal, in unit of cm^2; ϕ_γ is the fluence of gamma rays, in unit of cm^{-2}; R_e is the electron range corresponding to the most probable energy produced by a gamma photon interacting with a metal, in unit of cm. According to formula (1), when the fluence of gamma rays in a unit time and the energy of gamma rays are given, the electron emission rate per unit area (e/(s.cm^2)) can be calculated theoretically, and then the current (in unit of A) can be obtained approximately.

2.2 Experiment method

Gamma ray irradiation experiments of iron plate were carried out by using the gamma ray generated by "Qiangguang-I" accelerator. The average energy of gamma rays produced by the accelerator is E_γ= (0.8 + 0.1) MeV. The fluence dose conversion factor of photon with energy of 0.8 MeV given in publication ICRP-21 is 1.47×10^{-6} (rem/hr)/(p/(cm^2s)), in which 1 rem/hr=2.78×10^{-6} Sv/s. Again, the radiation weighting factors for different energy photons are all 1. Therefore, the conversion factor between the absorbed dose and fluence for gamma ray with energy of 0.8 MeV is 4.9×10^{-12} (Gy/s)/(p/(cm^2s)). The corresponding gamma ray fluence rate of 1×10^9 Gy/s is 2.45×10^{20} $cm^{-2}s^{-1}$.

Using the electro-optic conversion system, the current of the iron plate irradiated by the pulse gamma ray is converted to the light signal, and then the optical signal is transmitted to the measurement room by the optical fiber, and the optical signal is converted to the electrical signal through the photoelectric conversion system in the measurement room, and the electrical signal is displayed and recorded by the DP04104 type oscilloscope. The schematic diagram of the experimental measurement system is shown in figure 1.

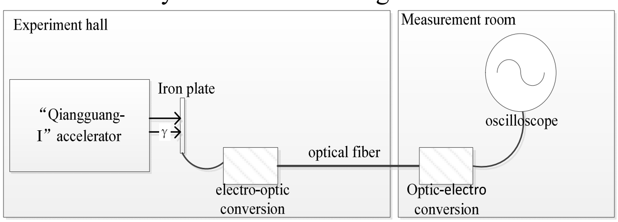

Fig.1 Schematic diagram of gamma radiation experimental measurement system for iron plate

The dose rate of gamma ray at the position of iron plate was measured with LiF (Mg, Ti) -M thermo-luminescence dosimetry in each experiment, and the measurement uncertainty of radiation dose rate was 20%. To avoid the large current signal generated by the experiment beyond the predetermined range, the generated current is diverted through the current shunt, then the electric light conversion is carried out, and a current attenuator is set in each of the shunt currents. Because of the interaction between the pulse gamma ray with the air or the metal, the electromagnetic field will be produced in the experiment. In order to prevent the interference of the electromagnetic field to the electro-optic conversion system, the current shunt, attenuator and the electro-optic conversion system are placed in a tin foil wrapped carton. Figure 2 (a) is a physical photo of the experimental system. The iron plate, which is 9 cm (long) × 10 cm (wide) × 0.47 cm (thick), is placed in front of the pulsed gamma ray source, the vertical distance from the plate to the ray source is 5 cm, the tin foil wrapped is located below the shelf, and figure 2 (b) is the four electro-optic converters in the tin foil wrapped carton.

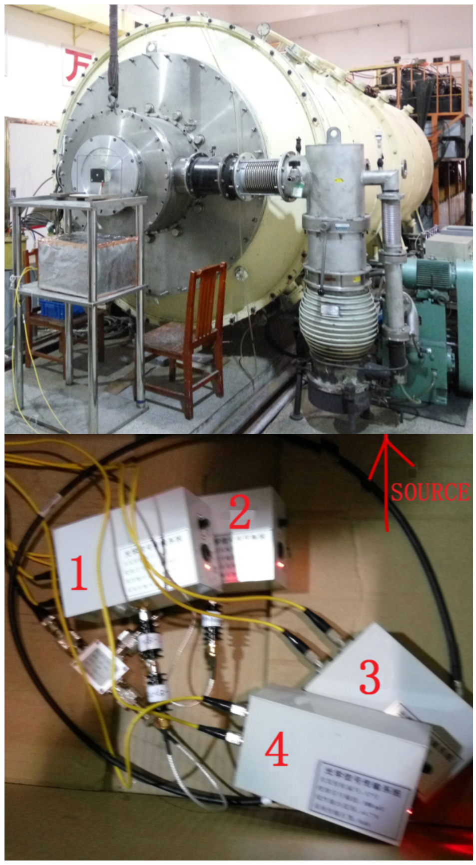

Fig. 2 The experiment system. (a) physical photo of the experimental system, (b)the four electro-optic converters in the tin foil wrapped carton.

3 Results and discussion

3.1 Results and analysis of gamma ray induced current

As shown in figure 2 (a) and (b), the radiation current signals produced on the iron plate are divided into two channels by a wire connection shunt, and then 60 dB and 40 dB are attenuated respectively into the channel Ch1 and channel Ch2, that is, the 1st and 2nd electro-optic converters in figure 2 (b). In addition, as a comparison, a wire with the same length, which is not connected with the iron plate, is directly connected to the channel Ch3, that is, the 3rd electro-optic converter in figure 2 (b) without the attenuator. The 4th electro-optic converter does not connect wire, and records the signals directly through the channel Ch4. The oscilloscope records the voltage signal. After converting the voltage signal, the current waveforms of the 4 channels can be obtained as

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shown in figure 3. The current amplitudes of these 4 channels are 21.6 mA, 37.9 mA, 15.2 mA and 22.2 mA, respectively.

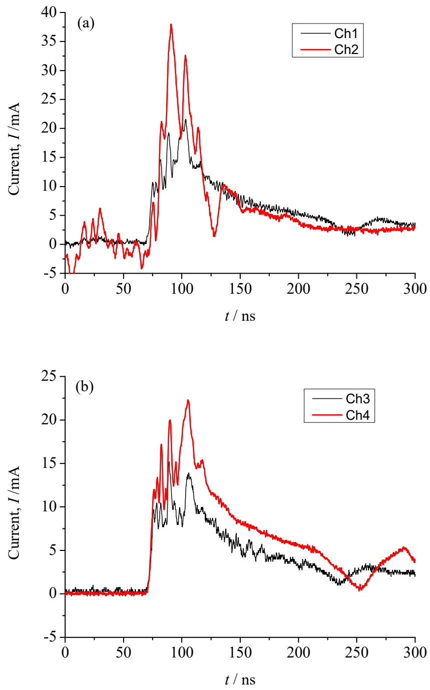

Fig. 3 The measurement current waveform. (a) Ch1 and Ch2, (b) Ch3 and Ch4.

Assuming that the iron plate is irradiated by gamma rays, the photocurrent produced is $2I_0$, and after being divided, one of the current I_0 passes through the 60 dB attenuation and is transported by the channel Ch1, and the other current I_0 is decayed by 40 dB and transported by the channel Ch2. The attenuator and the electro-optic converter may also be irradiated to produce interference current signals, and superimpose to the output signals, although the shape and size of the attenuator of 60 dB and 40 dB are slightly different, but the difference is little compared to the size of the iron plate. The gamma ray dose rate at the position of the attenuator and the electro-optic conversion system in the tin foil wrapped carton under the iron plate is about 100 times smaller than the gamma ray dose rate at the position of the iron plate, so it is assumed that the superimposed interference currents in the two paths are both $\triangle I$. The flow direction diagram of the current is shown in figure 4.

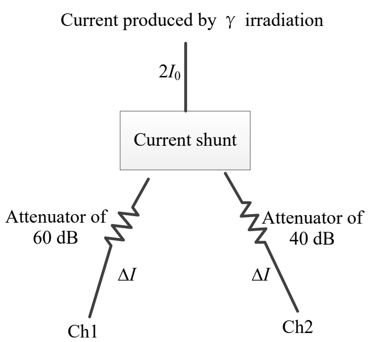

Fig.4 Schematic diagram of superimposed interference current generated by attenuator and electro-optical conversion system under gamma ray irradiation.

According to the schematic diagram of the current flow shown in figure 4, the equations are listed according to the amplitude of the current measured in channel Chl and Ch2.

$$\begin{cases} I_0/1000 + \Delta I = 0.0216 \text{ A} & \text{Ch1} \\ I_0/100 + \Delta I = 0.0379 \text{ A} & \text{Ch2} \end{cases} \tag{2}$$

From the formula (2), the radiation current produced by gamma rays is $2I_0$=3.62 A, and the interference current in the test system is $\triangle I$ =18.3 mA. The current measured by channel Ch3 and Ch4 are the interference currents of the electro-optic conversion system after irradiation. The amplitude of the current is 14.9 mA and 21.1 mA respectively, which is equivalent to the obtained $\triangle I$. In the experiment, the gamma ray dose rate of the positive center of the iron plate and the top corner of the iron plate was 0.91×10^9 Gy/s and 0.49×10^9 Gy/s, respectively. According to the experimental results, the average gamma ray dose rate of the center and the top cornor of the iron plate is approximately taken as the dose rate of the gamma ray source, that is, 0.7×10^9 Gy/s, the current produced in the iron plate with an area of 0.009 m^2 is about 3.62 A, that is, the current response sensitivity of gamma ray irradiation is 5.7×10^{-7} $(A/m^2)/(Gy/s)$ or 2.35×10^{-22} (A/cm^2) $(p/(cm^2s))$.

3.2 Simulation of current induced by gamma ray irradiation

The Monte Carlo simulation program MCNP 4B is used to establish the calculation model as shown in figure 5 according to the experimental conditions. By theoretical calculation, the amount of charge deposited in the iron plate at a unit time, that is, the electron charge deposition rate, is obtained.

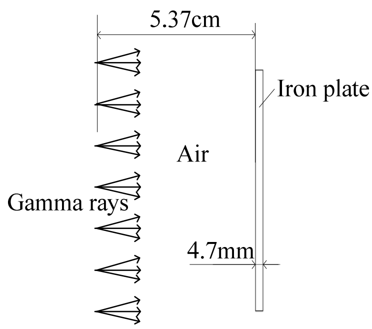

Fig. 5 A schematic diagram of Monte Carlo simulation model.

In the simulation model, the gamma ray source is in the same shape as the gamma ray source produced by the "Qiangguang-I" accelerator, that is, the radiation source is a position uniform distributed disk surface source with a radius of 7.5 cm. The gamma ray source is located at the front of the iron plate, the distance between gamma ray and iron plate is 5.37 cm. Gamma rays are isotropic within the range of 0-90° from the normal angle to the iron plate. The size of the irradiated surface of the iron plate is 9 cm×10 cm. Electron emission will occur after the iron plate is irradiated by gamma rays with energy of 0.8 MeV, and then the positive charge is deposited in the iron plate. When the dose rate is 0.91×10^9 Gy/s and

0.49×10^9 Gy/s, that is, the gamma ray fluence rate is 2.23×10^{20} (p/(cm^{2}s)) and 1.20×10^{20} (p/(cm^{2}s)), the simulated charge deposition rate in the iron plate is 2.86×10^{19} e/s and 1.54×10^{19} e/s, respectively. The deposition charge rate is then converted to current, and the current is 4.58 A and 2.46 A, respectively.

Based on the measured dose rate of gamma rays, the gamma ray induced current is 2.46 A-4.58 A. The result of measurement current is 3.62 A, which is within the range of theoretical simulation results. On one hand, the dose rate distribution of gamma rays produced by the "Qiangguang-I" accelerator is not a homogeneous [14]; on the other hand, the gamma rays produced in the experiment are not entirely isotropic. Therefore, the upper and lower limits of gamma ray induced current are calculated by setting the dose rate of the iron plate center and the dose rate at the top cornor of the iron plate as the irradiation source parameters, and the experimental results are within the range of the theoretical simulation results. It can be seen that after setting reasonable parameters of gamma ray source, it is feasible to calculate the charge deposition rate in the iron plate by MCNP program and convert it to the gamma ray induced current of the iron plate.

4 Conclusions

A pulsed gamma ray irradiation experiment of iron plate was carried out on the "Qiangguang-I" accelerator. The transient current produced by the pulsed gamma ray irradiation was measured, and the relation between the amplitude of the pulse current and the dose rate of gamma ray was obtained and analysed. The measured results show that the response sensitivity of the iron plate irradiated by gamma ray with energy of 0.8 MeV is about 5.7×10^{-7} (A/m^2)/(Gy/s). By comparing the experimental results with the Monte Carlo simulation results, it can be concluded that the method that calculating the electron charge deposition rate in the iron plate by MCNP program firstly and then converting it to gamma ray induced current of iron plate is feasible.

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