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A PRELIMINARY SCHEME FOR X-RAY EMISSION BASED ON MICRO-PULSE ELECTRON GUN

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Abstract

X-ray is now widely used in many areas of physics, biology, chemistry and materials. And how to achieve emission, monochrome, and focusing of x-ray is of great significance to study. Micro-pulse electron gun (MPG) is a new type of electron source, with characteristics of high repetition frequency, short-pulse and low cost. Generating x-ray with better monochromaticity is one of the potential applications of MPG. And a preliminary scheme of X-ray based on MPG is proposed in this paper. The scheme is designed by comparing different anode materials and the thickness of filters. The simulation results based on the software MCNP5 show that the proposed scheme can effectively improve the monotonicity of the generated X-rays.

INTRODUCTION

The emission of characteristic radiation is a type of x-ray that is widely-used because of its low power, easy to obtain and characteristic of elements. Miniature transmission x-ray tube generates x-ray with smaller spot dimension. Compared with traditional reflective x-ray tube, it benefits of its low cost and limiting the scattering of incident electron beam. Basically, the key component of miniature transmission x-ray tube is the transmission anode [1], which is a target film (~μm) with metallic elements deposited onto the inner surface of Beryllium (Be) foil (0.3 mm) (Fig. 1).

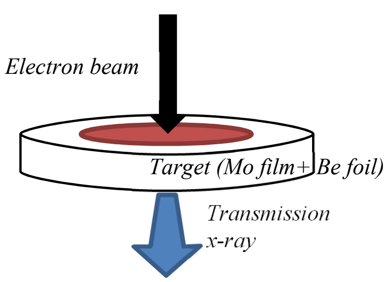

Figure 1: Electron bombardment of Mo target.

The element Argentum (Ag) is widely chosen as the target film, because miniaturization of transmission x-ray tube gives the limitation of electron energy about 30keV. It means characteristic x-ray of Ag excited by injected electrons with low energy has the highest yield than W. Mo, etc. However, by increasing the electron energy the element Molybdenum (Mo) also has a good performance on the emission spectrum. What's more, the melting point of Mo is 2617°C much higher than Ag which is 961.78°C. For MPG, Mo is a better choice for target film for electron beams with higher energy. MPG (Micro-pulse Electron Gun) is a kind of electron gun that provides electron beams with advantages of short pulse, high current, high tolerance and low cost. In Peking university, MPG-MTBMS and MPG-BMAS have been established and can operate steady for more than 10 hours. The energy of electron beams extracted from MPG-BMAS is adjustable ranging form 0-100keV, the spot diameter is about 4mm, and the emittance $\varepsilon_x/\mathrm{mm} = 1.47 \pm 0.06\ \mathrm{mm\cdot mrad/mm}, \varepsilon_y/\mathrm{mm} = 1.51 \pm 0.06\ \mathrm{mm\cdot mrad/mm}$. According to these measured parameters, MPG-BMAS already have the initial conditions for x-ray experiments now. It is urgent to solve the design of x-ray tube.

To analyse the performance of x-ray tube, two main methods are numerical analysis and Monte Carlo simulations. Numerical analysis gives the evaluation of intensity for characteristic radiation and bremsstrahlung, while Monte Carlo simulation such as MCNP5 code gives the spectrum, and enables us to improve the applicability of analytical techniques based on emission of characteristic radiation [2-3]. The MCNP5 code is a Monte Carlo transport code for photons, neutrons, and electrons [4]. In x-ray tube electrons interact with the target material, the resulting x-ray is absorbed and scattered by the target and filter atoms, making the emission spectrum further complex. The Monte Carlo method can greatly simplify the calculation of these processes.

THEORETICAL BACKGROUND

The principle behind miniature transmission x-ray tube is the excitation of atomic shells by primary radiation, resulting in the emission of characteristic x-rays. The energy and intensity depend on the elements of target and the quality of incident electrons.

Miniature transmission x-ray tube with MPG as the electron source, the exiting electrons focused through the collimator directly interact with target. The initial diameter of the electron beam is 4mm and incident area would be submicron scale. The anode target uses a thin film structure, and the thickness of the film is determined by the range of electrons in the material.

The electrons lose energy in the material by collision and radiation. The mass collision stopping power and the mass radiation stopping power depend on the material and the energy of electrons. The greater the initial energy of the electron have, the greater the loss of energy in the unit thickness, and the electron energy loss occurs mainly on the anode surface (~μm). The range of electrons in the material can be derived from the Tabata, Ito and Okabe empirical formula [5]:

$$R(m) = a_1\left(\frac{ln[1+a_2(r-1)]}{a_2} + \frac{a_3(r-1)}{1+a_4(r-1)^{a_5}}\right)\rho \quad (1)$$

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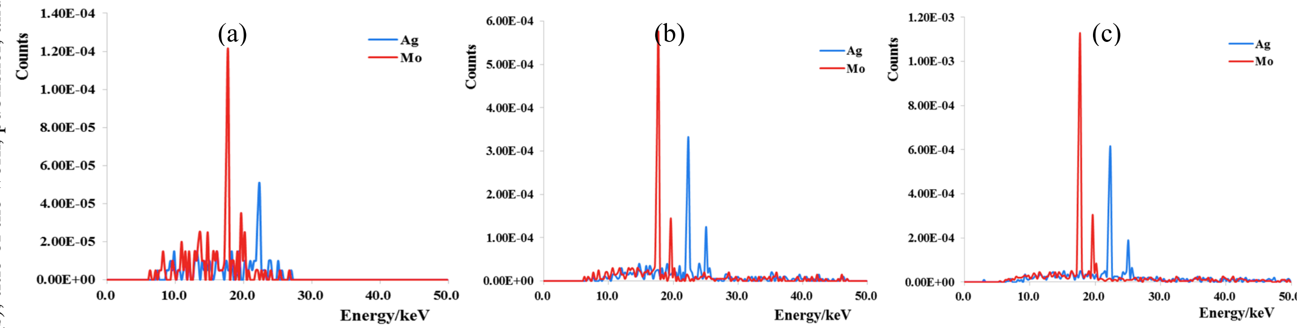

Figure 2: x-ray spectrum simulation of different electron energy (film thickness is 10 μm and Be window thickness is 300 μm. a. incident energy of 30 keV; b. incident energy of 50 keV; c. incident energy of 70 keV). Mo has a better signal-noise ratio when electrons have higher energy.

where $a_1 = 2.335A/Z^{1.209}$; $a_2 = 0.9891 - (3.01 \times 10^{-4}Z)$; $a_3 = 1.78 \times 10^{-4}Z$; $a_4 = 1.468 - (1.180 \times 10^{-2}Z)$; $a_5 = 1.232/Z^{0.109}$; $r = 1/\sqrt{1-(\frac{v^2}{c^2})}$.

Considering the characteristic spectrum and electron range distributions of common metal materials, the average depth of reaction of electron range from 30keV to 80keV with different targets is obtained (Table 1). Choosing the appropriate target thickness plays an important role in optimizing the emission x-ray spectrum.

Table 1: Average Depth of Electrons Range from 30 keV to 80 keV in Different Material

Energy/keV Depth/μm	30	40	50	60	70	80
Ni	1.69	3.11	4.94	7.17	9.81	12.86
Cu	1.74	3.22	5.13	7.46	10.21	13.39
Mo	0.96	2.31	4.05	6.17	8.68	11.57
Pd	0.51	1.67	3.17	4.99	7.15	9.64
Ag	0.47	1.79	3.49	5.57	8.02	10.85
W	—	—	—	—	0.07	1.73

Following simulation select Mo as the target material, not only because of its characteristic line is close to silver which is already widely used, but also its melting point is much higher. In the electron beam bombardment of MPG which has higher power than thermal emission of x-ray tube, it is not easy to melt. According to the calculated average penetration depth of Mo, the target film thickness can be 10μm.

The X-rays generated by the electron bombardment target passing through the target, the beryllium window and filters are finally received by the detector (receiving area is S). The received ray intensity is given [1]:

$$I \approx \frac{I_0 S}{sin\theta} e^{-\frac{\mu_1(h_1-\bar{X})+\mu_2 h_2}{sin\theta}} \quad (2)$$

Where $\bar{X}$ is the average depth of x-ray generation, θ is the angle between outgoing x-ray and the normal direction of the target, $\mu_1 h_1$ are the x-ray linear attenuation coefficient and thickness of target while $\mu_2 h_2$ of Be window. $\mu_2 h_2$ can be regarded as a constant, then there is a maximum value at 0~90°, where: $\mu_1(h_1 - \bar{X}) = sin\theta$. This indicates that the x-ray exit-direction is the same as the electron incident-direction and transmission occurs.

RESULTS AND DISCUSSION

The spectrum of the x-ray tube is determined by the target element (Fig. 3). Miniature transmissive X-ray tube anode target commonly consist of Ag, to meet the elements analysis of materials and x-ray imaging requirements. Considering that the electron beam current and the energy of MPG can reach the order of milliampere, silver may melt due to overheating. As for the elements with high melting point, the peak of the characteristic spectrum of W is not obvious. The x-ray characteristic energy of Mo and Pd is close to that of Ag, while ensuring the signal-noise ratio. Mo is selected as the target element of the x-ray tube based on MPG.

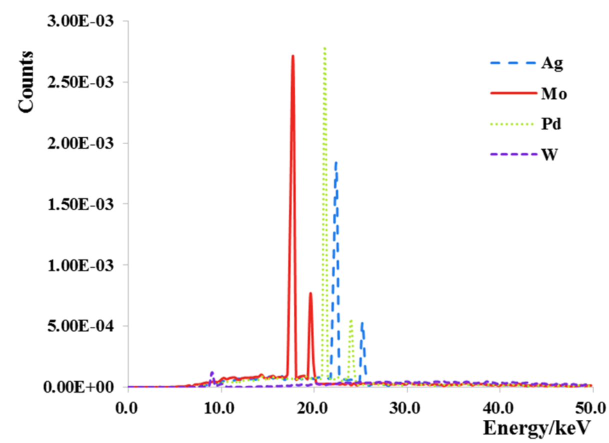

Figure 3: X-ray spectrum of different materials (thickness is 10 μm, energy is 70 keV). Ag, Mo and Pd characteristic energy are all in the vicinity of 20 keV.

Figure 2 shows the x-ray energy spectrum emitted by different incident electron energies. With the increase of electron energy, the ratio of the main peak to the secondary peak is larger and the signal-noise ratio is becoming better. Comparing the spectrum of Ag and Mo, it is possible to obtain a greater improvement on the signal-to-noise ratio of Mo when electrons have higher energy. MPG electron beam energy can range 0-100 keV, and at above 50 keV Mo is more suitable than Ag as the target element.

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In addition to the selection of the target, the filter also needs to be considered. First, the bremsstrahlung which results the background of the emission spectrum, will cause the decline of x-ray quality. And a large number of low-energy photons will cause damage to the detector. Usually the filter used aluminum alloy as a material. And the following x-ray tube simulation select 10% content of copper and aluminum alloy. For different materials of the filter, the different thickness of the filters have different effect (Fig. 4).

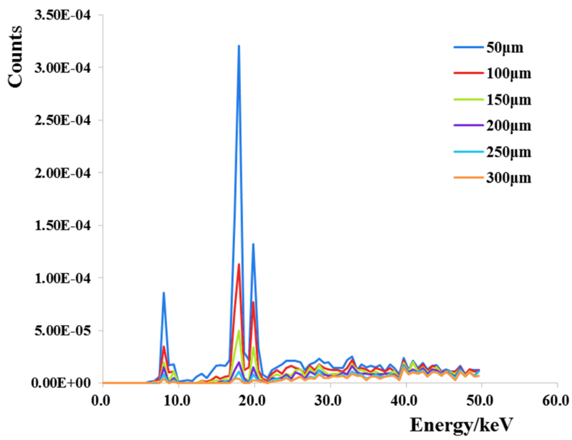

Figure 4: X-ray spectrum produced after Cu(10%)-Al alloy filters of different thickness(energy 70 keV).

As the thickness increasing, the value of the secondary peak decreases, indicating that the filter has occurred. But the intensity of the main peak will decrease, too. There exists an optimal thickness range, which ensuring both the intensity of the main peak and the effect of filter.

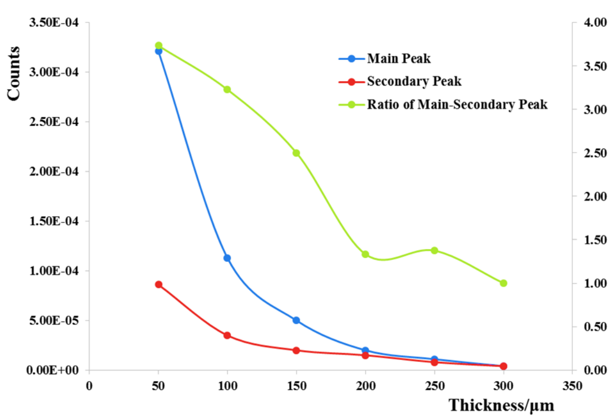

Figure 5: The main peak, the secondary peak intensity and their ratio change with the filter thickness.

Table 2: Filter Effect of Cu(10%)-Al Filter with Different Thickness

Thickness/ μm	50	100	150	200	250	300
Main Peak	3.21 E-04	1.13 E-04	5.00 E-05	2.00 E-05	1.10 E-05	4.00 E-06
Seconary Peak	8.60 E-05	3.50 E-05	2.00 E-05	1.50 E-05	8.00 E-06	4.00 E-06
Ratio	3.73	3.23	2.50	1.33	1.38	1.00

Taking into account both of the peak intensity and filter effect, the best thickness selected is 50-100 μm for Mo target (10 μm). The thickness of the filter causes the secondary peak dropping by half while the ratio of the main-secondary peaks remains at a higher value.

CONCLUSION

This paper theoretically calculate the thickness of the target corresponding to different elements of Mo, Ag, W, etc.. The appropriate thickness for Mo is 10μm. By comparing the emission spectrum of molybdenum and aluminum at different electron energies, it shows that Mo is a good target material when the electron energy increases. Finally we choose Mo as the anode target for MPG to produce x-ray.

The thickness of the filter will have an effect on the final x-ray spectrum. Considering the filting effect and the absorption of the filter, the optimum thickness of Cu (10%)-Al alloy filter is 50-100 μm. This method to study the emitting x-rays can give an optimized design of miniature transmission x-ray tube for MPG.

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