DESIGN AND ANALYSIS OF A BEAM UNIFORMITY DETECTOR BASED ON FARADAY CUP ARRAY*

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Abstract

Beam uniformity of electron irradiation accelerator has a great impact results for industrial radiation process. In this paper, a beam uniformity detector, based on Faraday cup array, has been designed for a 400KV electron irradiation accelerator in Huazhong University of Science and Technology. Suitable structure has been calculated for the secondary electrons emission. Cooling system is necessary for the detector in the condition of high-intensity ion beams, and it has been designed by thermo-structural analysis. This detector now has been used for experiments successfully.

INTRODUCTION

Electron irradiation accelerator has been widely used in medicine, food, environmental protection and other industrial fields [1]. Uniformity of electron beam has a great influence on the results in the material and life subjects. Measurement of uniformity can provide accurate parameters for experiments, and important evidence for improving the performance of the accelerator.

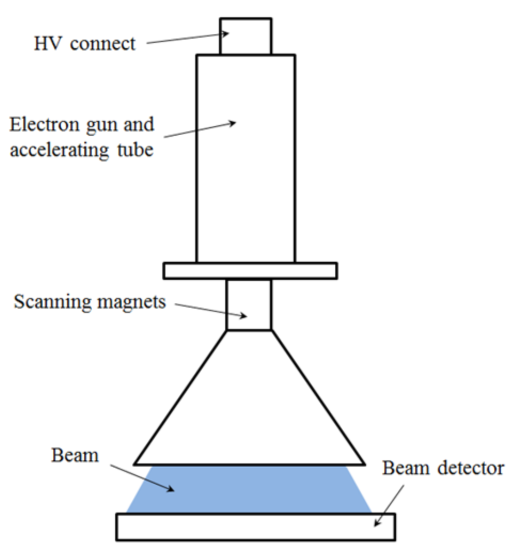

Figure 1: Sketch of a 400kV electron accelerator in HUST.

Faraday cup is a detector designed to measure the intensity of the beam. It is a conductive metal cup hit by a beam of ions or electrons. The metal can then gain a small net charge while the ions are neutralized. By measuring the electrical current in the metal, the number of charges being carried by the ions can be determined. The emission of secondary electrons should been considered, otherwise the result would be less than the actual value. Usually a washer-type metallic electron-suppressor lid, the repeller, is biased at a given voltage to catch the secondary electrons escaped from the metal surface. Faraday cup array is composed of multiple independent Faraday cups arranged in a one (or two) dimension area uniformly. Beam intensity distribution in the area can be obtained by fitting the signals of every Faraday cup. Huazhong University of Science and Technology, HUST, has a 400kV electron irradiation accelerator, as shown in Fig. 1. The length of the beam is about 1000mm. In order to detect the accelerator beam uniformity in the longitudinal direction, a detector based on Faraday cup array has been designed in this paper.

DESIGN DESCRIPTION

Structure

The common structure of Faraday cup is illustrated by Fig. 2 (a). It is composed of a copper cup which collects the electrons and a repeller. The two parts are mounted in an insulated cylinder and they insulate against each other. The metal cup can effectively collect electrons, but the secondary electrons need to be caught again while escaping from the metal surface. For reducing the measurement error, a bias lid mounted on the cup is wildly used. The electric field applied directly on the repeller will reverse and accelerate secondary electrons into the metal cup [2].

As the size of the electron irradiation accelerator's titanium window is 1000mm×100mm, Faraday cup is specially designed to be square, in order to collect more electrons in the beam's longitudinal direction. The inner of the square cup, made up of copper, is 110mm long, 45mm wide and 93mm deep, the surrounding wall is 5mm thick, bottom 7mm thick. The metal square cup is placed into an epoxy square cup with the size of 150mm×75mm× 130mm.The repeller (10mm thick) is mounted on the epoxy cup, so that the distance between bias plate and metal cup is up to 10mm. A square hole (100mm×25mm) is machined in the centre of the lid in order to make the beam enter the Faraday cup directly. A 100V negative bias voltage is given on the electrode.

This beam uniformity detector is composed of a linear array of 10 Faraday cups, as shown in Fig. 2 (b). The distance between each two adjacent is 25mm. Every

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Faraday cup is mounted on a 975mm long grounded copper bar with a 10kΩ resistor.

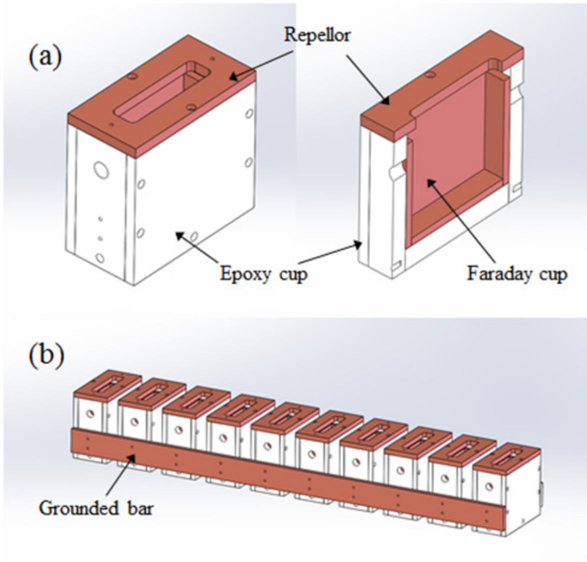

Figure 2: (a)Structure of single Faraday cup (b) Faraday cup array.

Stopping Power in the Bottom

In order to stop the charged particles in the metal, the thickness of Faraday cup's bottom need to be more than the range of particles in copper. The range of electrons for a given material can be approximated by the following expression:

$$R = \int_0^E \left(\frac{dE}{dx}\right)^{-1} dE \tag{1}$$

where R is the range of electrons, E is the initial kinetic energy of the particle.

The ranges of electrons with different energy in different elements is showed in the Atomic Data [3]. As the accelerator beam energy is 400keV, we can found out that the range of electron beam is about 0.8mm, much less than the thickness of the Faraday cup's bottom.

Secondary Electrons Emission

Secondary electrons will be generated by the high power beam hitting the bottom of Faraday cup, it will result in a loss of detection value (see Fig. 3). These electrons escaped from the bottom satisfy the distribution of $cos^2 h$, where h is the angle between reflection line and the bottom surface. If the length of Faraday cup was high enough compared to the inner diameter, the escaped electrons would occur in a lower proportion in all electrons and have little effect on detection value [4].

To simplify we suppose that the beam is just hitting the centre of the bottom, the number of the electrons emitting from the centre is n, and n in the direction along h is in proportion to $cos^2 h$. We can get Equation 2.

$$\theta = \frac{\pi}{2} - h \tag{2}$$

where θ is the angle between secondary electrons emission line and the axis of Faraday cup, so n also satisfy the distribution of $sin^2\theta$. For the angle element $d\theta$,

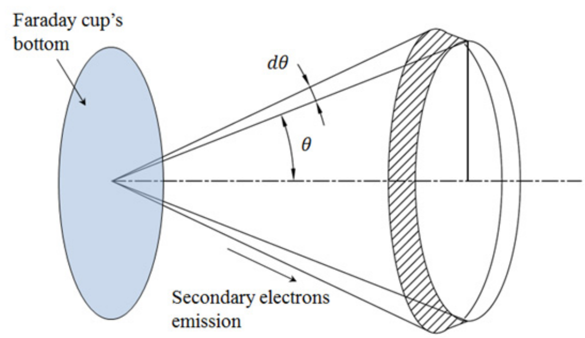

Figure 3: Sketch of secondary electrons emission.

we can get the solid angle dK in the circle face with the radius r.

$$dK = \frac{2\pi r sin\theta \cdot r d\theta}{r^2} = 2\pi sin\theta d\theta \tag{3}$$

$$sin^2\theta dK = sin^2\theta sin\theta d\theta = sin^3\theta d\theta \tag{4}$$

So the number of electrons emitting from dK is in proportion to $sin\theta^3 d\theta$. The rate of the emission electrons can be calculated by the Equation 5.

$$P = \int_0^{\frac{\pi}{2}arctan\frac{b}{a}} 2\pi sin^3\theta d\theta \Big/ \int_0^{\frac{\pi}{2}} 2\pi sin^3\theta d\theta$$
$$= \frac{3}{2}\int_0^{\frac{\pi}{2}arctan\frac{b}{a}} sin^3\theta d\theta \tag{5}$$

where a is the length of Faraday cup, and b is the radius of the bottom. When a=12.5mm, b=103mm, the rate is about 0.5%, and the influence can be ignored.

THERMO-STRUCTURAL ANALYSIS

Faraday Cup without Cooling Channels

The Faraday cup should be considered the thermal deformation, as the heat power of the beam will increase the temperature.

The current of the 400kV electron accelerator is up to 3A, the total power is about 1200kW without regard to the secondary electrons emission, a uniform heat power density was applied on the surface of the repeller and the Faraday cup's bottom: the power on the repeller is about 60W, and 30W on the bottom. It is shown in Fig. 4.

A finite element model was developed for the Faraday cup with surface elements to calculate the thermal radiation to the air at 20 °C. The initial temperature of all Faraday cup is set to 20 °C. The properties of copper have been used for all the analyses.

In Fig. 5 the temperature distribution and the thermal deformation in the copper are shown. Obviously, the deformation is too high for normal operation and the high

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temperature would influence the cooper electrical conductivity. Water-cooling channels are necessary for both the repeller and the bottom.

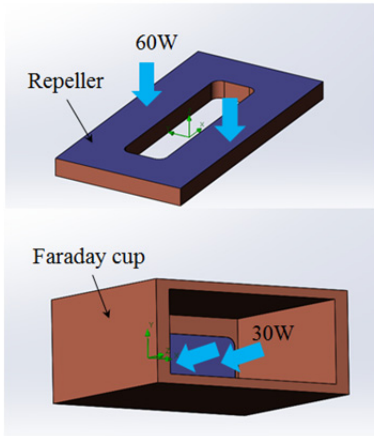

Figure 4: Heat power on the repeller and the bottom.

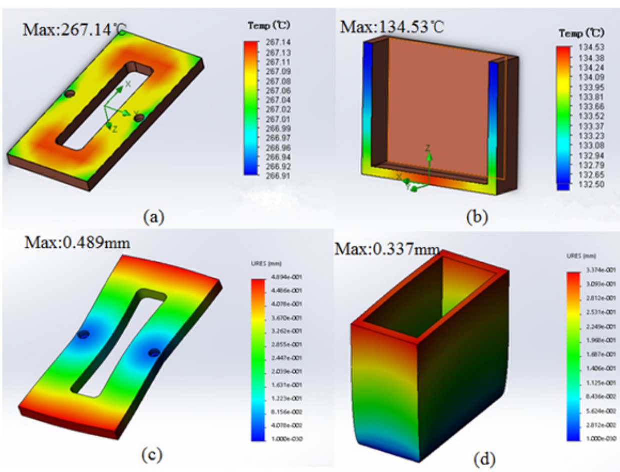

Figure 5: (a)&(b)Temperature (°C) distribution ,(c)&(d) Thermal deformation(mm) in the repeller and the Faraday cup without cooling channels.

Faraday Cup with Cooling Channels

Water-cooling circuits with $\phi 3$ mm inner diameter are processed separately in the repeller and the bottom. Coolant inlet temperature was always set to 20°C. Water velocity was set to 3m/s, water maximum temperature within values that do not influence electrical conductivity (<60-70 ℃), while stress distribution should be preliminarily kept under 107MPa.

The heat transfer process inside the cooling channels in ruled by forced convection in single-phase flow. Fluid-thermal and thermo-structural analyses were carried out to investigate the effect of various parameters (heat flux, water flow, model geometry), in term of temperature of the water and of the cooling channels walls, temperature and stresses in the copper.

In Fig. 6 the max temperature of the repeller and the Faraday cup with water-cooling channels inside is about 22 °C, as the influence on the thermal deformation could became negligible.

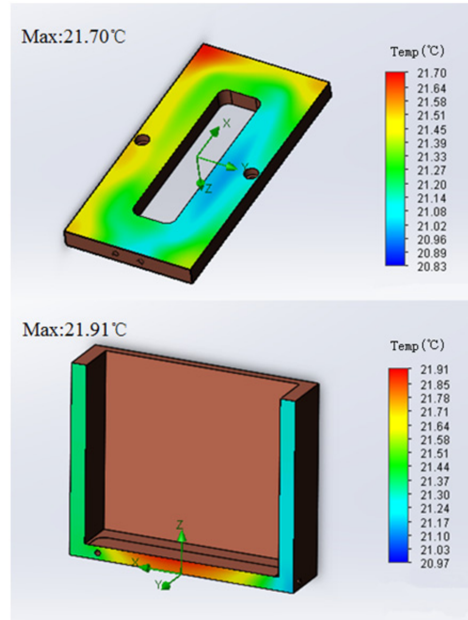

Figure 6: Temperature (°C) distribution in the repeller and the Faraday cup with water-cooling.

CONCLUSION

The beam uniformity detector based on Faraday cup array for electron irradiation accelerator has been designed and used successfully. Compared with other detector, Faraday cup array is simply processed and installed, the matched electric circuit and data processing are both uncomplicated.

The secondary electrons emission is the key of the design. The size of the Faraday cup has been confirmed, by means of numerical calculations: the range of high energy electrons in the copper bottom and the rate of the emitting secondary electrons' number, that was found to be the most critical component.

The water-cooling channels in the repeller and the bottom were found necessary to limit the temperature and thermal deformation in the Faraday cup.

The next step in this work would be to design another detector based on a movable Faraday cup in one or two dimensions. It will help detect the beam uniformity continuously.

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