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A MULTI-PINHOLE FARADAY CUP DEVICE FOR MEASUREMENT OF DISCRETE CHARGE DISTRIBUTION OF HEAVY AND LIGHT IONS*

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Abstract

A new multi-pinhole Faraday cup (MPFC) device was designed, fabricated, and tested to measure ion beam uniformity, over a range of centimeters. There are 32 collectors within the device, and each of those is used as an individual Faraday cup to measure a fraction of the beam current. Experimental data show that the device is capable of measuring the charged particles distribution - which is either in the form of a raster scan, or a defocused beam.

INTRODUCTION

Materials degradation due to irradiation is a limiting factor in nuclear reactor lifetimes. Traditionally, materials have been irradiated in test reactors, such as the Fast Flux Test Facility (FFTF) or the BOR-60 fast nuclear reactor. Ion irradiations, using accelerated charged particles, to induce damage at high dose rates have been successful in emulating the microstructural features of materials irradiated in reactor [1, 2]. In ion irradiation experiments, a high energy beam is either raster scanned, in which the beam is scanned at high frequencies [3], or defocused, to distribute charge particles in a nearly uniform manner, over the material specimens. The measurement of the uniform distribution of particles over the sample surface is crucial to quantify the ion dose in these experiments. A Faraday cup, an optical system such as a scintillator and CCD camera, and a beam profile monitor (BPM) are typical devices used to measure distributions of charged particles in space. A Faraday cup measures the total current of a beam for the full aperture geometry of the instrument, resulting in a flux measurement for the cross sectional area of the cup without any additional spatial resolution. The photon conversion efficiency, and damage to the scintillator by the beam bombardment, limit the practicality of a scintillator based imaging system for assessing the spatial resolution over an extended period of time. A BPM has the ability to provide partial or discrete distribution of an integrated beam profile. The BPM measures the current from secondary electrons on a metal shell surrounding a rotating wire. The BPM, however, does not discriminate between ions and electrons, the latter of which can be problematic for assessing the full beam profile. To provide a better description of the beam density in spatial dimensions, we have designed a multi-pinhole Faraday cup (MPFC) device, to overcome some of the limitations of traditional measurement systems. This work serves to present the design and performance of this device under ion irradiation relevant conditions.

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SCIENTIFIC AND TECHNICAL BASIS

In a typical Faraday cup, an electrode, or collector, is used to capture particles. As the Faraday cup measures the electric charge of a beam over time, electrons or ions from outside of the beam are undesirable. A suppressor electrode is used to reduce the entrance of any amount of unwanted particles. To make an effective Faraday cup, there are several guidelines to follow. These are: (1) Charged particles should not physically contact the suppressor. This allows for the suppressor to maintain constant electrical properties. (2) The collector should be relatively deep to minimize secondary electrons loss. (3) The voltage of the suppressor should be negative compared to the collector. (4) The collector may have its own voltage potential applied to minimize the entrance of secondary electrons from the vacuum, or to retain electrons those are generated from within the collector. A beam of scattered or stray particles can create secondary electrons from collisions with the walls of the vacuum system. A negative potential suppresses background electrons, but attracts ions. These low energy ions are rejected using a positive voltage on the collector. If the suppressor is touched by beam particles, especially with an intense or dense beam, the potential of the beam itself can alter the electron suppression. A measured beam current should not be sensitive to the bias voltages once the secondary electrons and plasma ions are properly suppressed [4]. If a Faraday cup functions ideally, the suppressor should not receive any beam current. Since the suppressor is capacitively coupled to the beam charge, a high beam density may result in a temporary spike in the suppressor current (if measured) when the beam strikes. The same scenario may true for a collector.

Based on these criteria, the MPFC was designed and fabricated. Figure 1(a) shows a computer rendering of the multi-pinhole Faraday cup. The device, when viewed at the most basic level, consists of a (1) front plate, (2) suppressor plate, and (3) 32 collectors to satisfy the desirable qualities of a Faraday cup. Table 1 shows parameters of the physical device. Figure 1(b) shows a WARP [5] code simulation to demonstrate equipotential lines and electrical force patterns between the grounded front plate, the suppressor plate held at -150V, and the collectors held at +90V.

The Tantalum front plate has 32 pinholes in line with the collectors to allow the beam to pass. Tantalum was selected because of its high melting temperature, to withstand beam heating, and for its low sputter yield. Because of the relative size of these pinholes to the full beam, the amount of particles passed to the collectors is much less than the number of primary particles. Using a geometric argument, a uniform, evenly distributed beam would have a percentage

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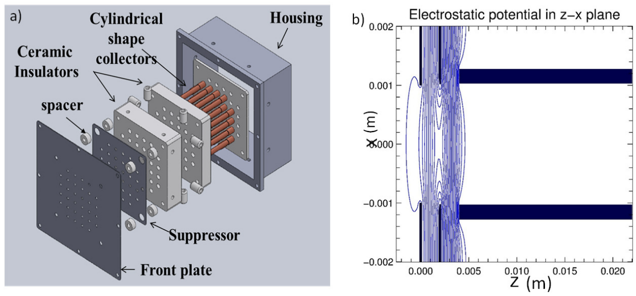

Figure 1: a) A sketch of a new multi-pinhole Faraday cup (MPFC) device; (b) equipotential lines within the electrodes for a single collector.

of its particles pass through the plate proportional to the ratio of the total pinhole area and the total beam area. This reduced current to the collectors is perturbed significantly with any additional current of secondary ions or electrons. When a beam with an energy of E, strikes a plate; the beam drift is destructively blocked within a rate of energy loss of the primary ion (dE/dx); and an energy in excitation and ionization process creates secondary particles. In general, a number of emitted secondary particles per incident of ion is defined by,

$$\delta = \left\{ \left(\frac{dE}{dx} \right) \Delta x sec\theta \right\} / \omega \qquad (1)$$

where, Δx is the thickness of the region in which escaping secondary electrons are produced, ω is the work function of the material. The potential of the secondary particles is small, is of around 50 V, but these particles can drift with a beam, if is not suppressed. An ion beam ($I_{primary}$) accompanying with un-suppressed electrons (I_{sec}) is being modified in dimension in a space charge neutralization process [6], and a total current measured (I_{cup}) by a Faraday cup, of radius r, is modified by,

$$\sum I_{cup} = \sum I_{primary} \pm \sum I_{sec}, \qquad (2)$$

which is not desirable. If the suppressor and collector of a Faraday cup are biased with an appropriate electrical potential, the term of secondary electron current is eliminated ($I_{sec} = 0$); so that a beam current density (J_{cup}) measured by a cup, is of $J_{cup} = I_{cup}/\pi r^2$, which is desirable.

Table 1: MPFC Parameters

Item	Scale	
Plate thickness	0.25 mm	Tantalum
Front plate hole size	1 mm	diameter
Middle plate hole size	1.2 mm	diameter
Plates distance	2 mm	
Distance between holes	4 mm	Grid size
Total aperture	32	in each plate
A collector aperture size	1.3 mm	diameter
A collector length	12 mm	

MEASUREMENT OF A BEAM

To make the device operational, the front plate of the device was electrically grounded. The suppression plate was held at -150V, applied using a standard Ortec power supply. The collector bias of +90V was provided by a RBD Instruments 9103 pico-ammeter. Although it would be ideal to have each collector reading simultaneously, there was another setup that functioned well for the purpose of this device. Each collector was connected to a 32-input multiplexer to provide individual circuits from the cups (collectors) to the picoammeter, which is then read by a computer measurement system. The current from an ion beam to a collector is transmitted through 0.25mm diameter Kapton coated copper wire to a connector on the vacuum side of an electrical feedthrough. It passes through an electrical feedthrough, to an air-side-connector, and into 18 AWG conducting wire for approximately 10 meters to a multiplexer. Upon switching to collect the charges with the multiplexer, the current, passes to the pico-ammeter and into a digital recording system designed in National Instruments LabVIEW 2013. Because the system was uses one pico-ammeter, only one collector is read at a given time. The device and measurement system were tested in a controlled manner. Figure 2 shows a sketch of this section of diagnostics. The diagnostics section was placed at the end of a beamline of a Pelletron accelerator at the Michigan Ion Beam Laboratory (MIBL). The devices labeled FC1 and FC2 are two traditional suppressed Faraday cups; BPM is a beam profile monitor, and a slit aperture assembly with an opening of 8mm x 8mm. A beam of 5 MeV, Fe++ ions from a 3 MV Pelletron accelerator, setup with 1.66 MV terminal voltage, was used for this diagnostic testing. The beam was passed through a charge-mass ratio filter towards the downstream end of the accelerator, at an angle of 15 degrees, with respect to the accelerator axis. This high energy ion beam was focused using a quadrupole magnet, and steered to provide an even distribution over the slit aperture opening. Initially, the MPFC device was not placed into the path of the ion beam. The beam current, at upstream and downstream ends of the slit aperture was measured using Faraday cups (diameter 2.54 cm) FC1 and FC2, in Fig. 2, to provide an initial comparison. The beam

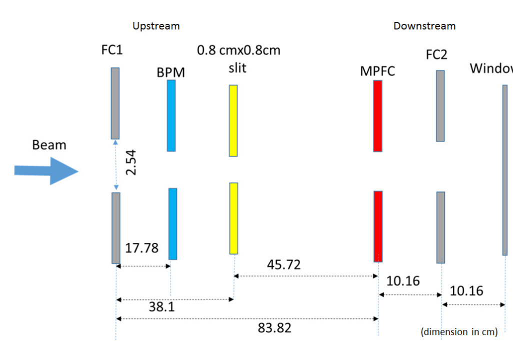

Figure 2: A sketch of a section of diagnostics placement at the downstream end of a beamline.

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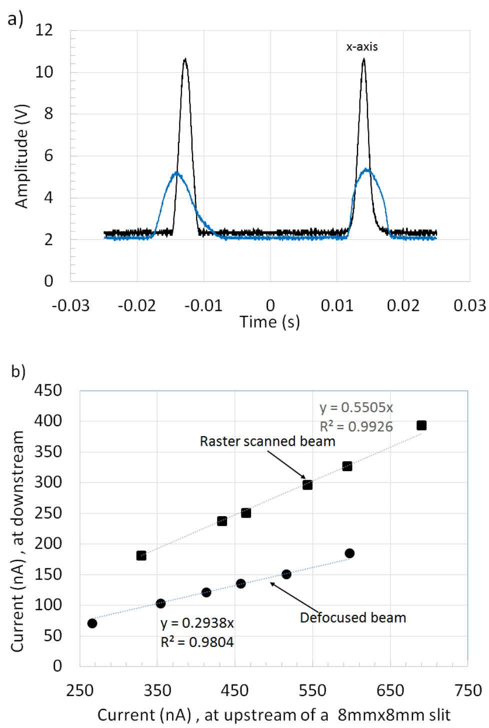

Figure 3: a) Typical BPM profiles of focused (high amplitude peaks shown in black) and defocused (lower amplitude peaks shown in blue) beams; (b) measured beam currents, at the upstream and downstream ends of a 8mm x 8mm slit aperture opening with during raster scanned, and defocused ion beams.

profiles of the focused and defocused beams used in this experiment are shown in Fig. 3(a). An electrostatic scanner provided a flat distribution from the focused beam by scanning the beam over the entire aperture opening once every 3.92 ms. The defocused beam, by changing the quadrupole strength to vary the beam focusing angle, had a uniform area over the slit aperture opening. The current of each beam was measured before and after the slit aperture system. Fig. 3(b) shows several measured beam currents at the upstream (FC1) and downstream (FC2) ends of the slit, for a focused and raster scanned beam, and a defocused beam. Following characterization of the initial beams, the MPFC device placed on the beam axis. The currents were measured using the MPFC, as shown in Fig. 4 in a three dimensional plot for the raster scanned and a defocused beams; highlighting the uniformity of the two beam conditions. The same beams were also measured at FC2 to provide data comparison to the total beam current through the slit apertures. Similar measurements were taken with increasing the beam currents to observe characteristics as shown in Fig. 5. As the slit apertures were set to 8mm x 8mm, only four of the 32 collectors were in the direct path of the beams. The collectors responded proportionally to the increase in beam current with both raster scanned and defocused beams. The slopes for each pin in Fig. 5, ranging between 0.8 to 1.2, demonstrate that the amount of ion flux received for each pin is directly comparable to a traditional suppressed Faraday Cup. The similar pattern was also observed for a defocused beam.

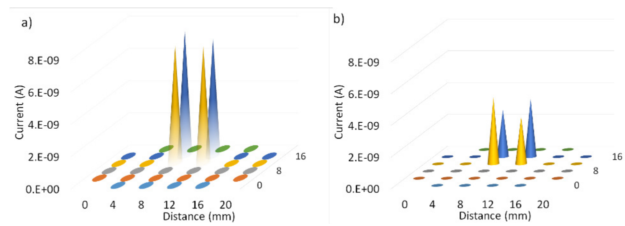

Figure 4: A 5 MeV Fe^{++} beam through a slit of 8mm x 8mm at the highest current measurement for a (a) raster scanned (392 nA at FC2); and (b) a defocused (184 nA at FC2).

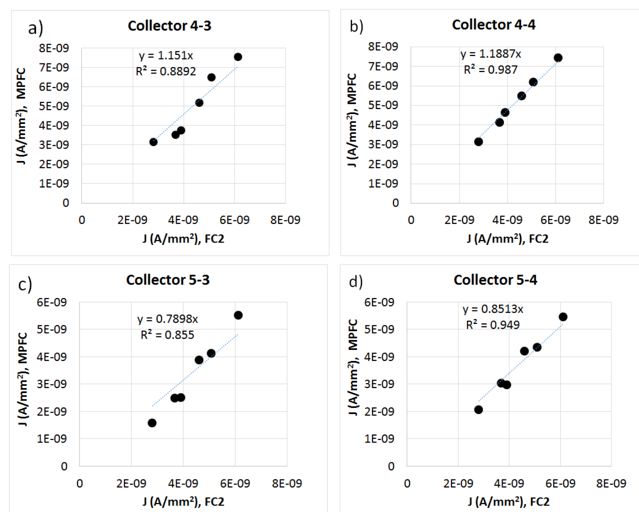

Figure 5: Measurements of current density using FC2 after the slit apertures and the MPFC device for the raster scanned ion beam. The MPFC device collectors (in a given area) responded in a linear pattern to variation in the total beam current, and correlate well to the current density of a traditional suppressed Faraday cup.

CONCLUSION

A prototype multi-pinhole Faraday cup (MPFC) has been designed, manufactured, and tested under controlled conditions. Within the controlled testing environment, four of the collectors (in the direct path of the beam), are able to detect a raster scanned focused ion beam, and a defocused ion beam. The device and its collectors responded well, showing the level of proportionality expected between the measured current on a traditional Faraday cup and this device. Initial results provide a confidence that the collectors are able to sample beam distributions, in a discrete form, at sub-nanoamp currents, within a given geometrical resolution.

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