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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 a charged particles distribution - either in the form of a raster scanned focused beam or a defocused beam.**

***Index Terms*—Beam diagnostics, beam dosimeter, beam surface uniformity measuring device, Faraday cup, ion beam diagnostics, multi-pinhole Faraday cup.**

I. 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) [1] or the BOR-60 fast nuclear reactor [2]. But even fast reactors are only capable of inducing about 20 dpa of damage in a year. Heavy ion irradiations, in contrast, can achieve damage rates of about 50 dpa per day. Furthermore, 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 [3]–[5]. In ion irradiation experiments, a high energy beam is either raster scanned, in which the beam is scanned at high frequencies [6], or defocused, in which the beam is distributed in a nearly uniform manner, over the 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 (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 explicit spatial resolution. A miniature Faraday cup can be scanned across a beam, or a large cup can be used in combination with a pinhole aperture to provide detailed beam profile information. But it is not a continuous measurement (positioning is required for each point), and uncertainties are involved if there is any beam jitters involved. In an optical system, 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 charge density profile, we have designed a multi-pinhole Faraday cup (MPFC) device. This work serves to present the design and performance of this device under conditions relevant to ion irradiations.

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II. 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 unwanted particles into the cup. 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 electron loss. (3) The voltage of the suppressor should be opposite the potential of the collector. (4) The collector may have its own voltage potential applied to retain the secondary electrons that are generated within the collector. Scattered or stray particles from the beam can create secondary electrons from collisions with the walls of the vacuum system. A negative potential on the suppressor minimizes 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 an intense or dense beam, the potential of the beam itself can alter the electron suppression which should be avoided. A measured beam current should not be sensitive to the bias voltages once the secondary electrons and plasma ions are properly suppressed. In the Faraday cup designed by Sefkow *et al.* [7] a single circular plate

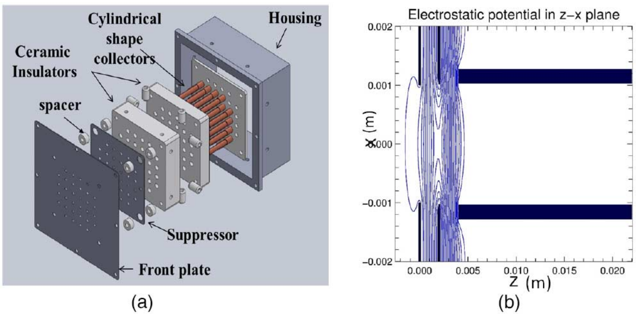

Fig. 1. (a) A sketch of a new multi-pinhole Faraday cup (MPFC) device. The front plate has 32 apertures for a beam pass through, the suppressor has 32 apertures, and there are 32 total numbers of collectors. The electrodes distances were maintained using spacer and insulator made of ceramic; (b) equipotential lines within the electrodes for a single collector. The convex shape equipotential lines show a variation of field gradient at the outer edge (angle).

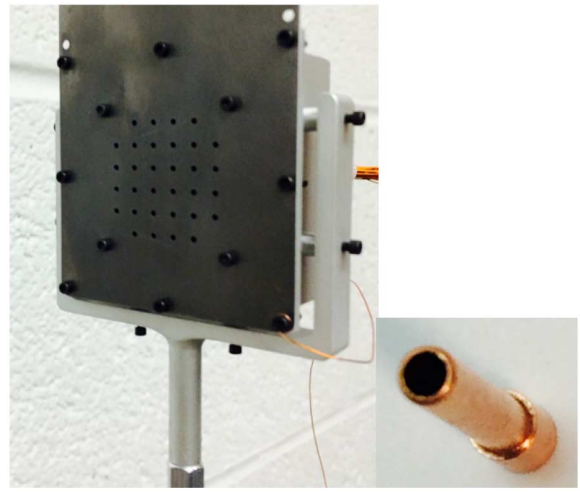

Fig. 2. A fabricated MPFC device, housed in a metal frame (left), and a copper collector (right). The device contains 32 individual copper collectors arranged in a gridded layout. A similar workflow was maintained to achieve a high level of quality control.

collector was used with a circular plate suppressor with holes to form a complete measurement device. A similar multi-pinhole Faraday cup design has been fabricated and used in another facility [8]. The key property was the length of the individual pins (1.96 cm) relative to the ID of the pin (0.25 cm). This high aspect ratio provides very effective geometric suppression of secondary electrons. While its performance is not publicly available, a high voltage power supply to the middle electrode was used to investigate cup behavior with various biases [8]. Though a consistent response from -150 V up to -1.5 kV was reported, the voltage required for complete secondary electron suppression was not confirmed [8]. But a significant signal to noise ratio was recorded. 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 first strikes the target [9]. The same scenario may true for a collector.

III. Design of a Multi-Pinhole Faraday Cup Device

Based on the Faraday cup criteria detailed in the previous section, a MPFC device was designed and fabricated at this laboratory (Michigan Ion Beam Laboratory, NERS, UMich). Fig. 1(a) shows a computer rendering of the multi-pinhole Faraday cup. The device consists of a (1) front plate, (2) suppressor plate, and (3) 32 collectors to meet the necessary specifications. Each plate acts in a way similar to a pepper-pot mask. Fig. 1(b) shows a WARP code simulation [10], [11] to demonstrate equipotential lines and electrical force patterns between the grounded front plate, the suppressor plate held at -150 V, while each collector is held at $+90V$. Fig. 2 shows the newly fabricated MPFC device with a single common suppressor plate and 32 collectors. Each of these collectors was aligned to holes in the suppressor and aperture (front) plates. Table I shows parameters of the physical device. Tantalum was selected for use in the plates because of its high melting temperature, its ability to withstand beam heating,and its low sputter yield. Because of the relative size of the pinholes to the full beam, the number of particles entering the collectors is much less than the total number of particles in the beam. Geometrically, a uniform, evenly distributed beam would have a percentage of its particles collected that is proportional to the

TABLE I
MPFC Parameters

Item	Scale	
Plate thickness	0.25 mmm	Tantalum
Front plate hole diameter	1 mm	
Middle plate hole diameter	1.2 mm	
Plates distance	2 mm	
Distance between closest holes	4 mm	
Total aperture number per plate	32	
Single collector diameter	1.3 mm	
Single collector length	12 mm	

ratio of the total pinhole area to the total beam area. For example, if a beam of 87 nA is uniformly distributed, over an area of 12 mm × 12 mm, the total number of projected apertures, N would be $4 \times 4 = 16$. With a hole diameter, r, of 1 mm, the total pinhole area would be $\pi r^2 N = 12.6$ mm. Therefore, the beam transmission is about 11.5 times less than the full beam current. This reduced current to the collectors is perturbed significantly by any additional current from secondary ions or electrons produced when the beam strikes the front plate. In general, when a beam strikes a plate, the number of emitted secondary particles [12]–[14] per incident ion is defined by,

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

where, dE/dx is the energy loss per unit path length by the primary particle, Δx is the thickness of the region in which escaping secondary electrons are produced, ω is the energy required to produce a secondary electron, generally referred to as the work function of the material, and θ is the angle of incidence relative to the normal, in most cases the angle is zero for a straight beam. The potential of the secondary particles is small, about 50 V, but these particles can drift with the beam if they are not suppressed. An ion beam ($I_{primary}$) accompanied by un-suppressed electrons (I_{sec}) is modified in the radial direction through a space charge neutralization process [15], and

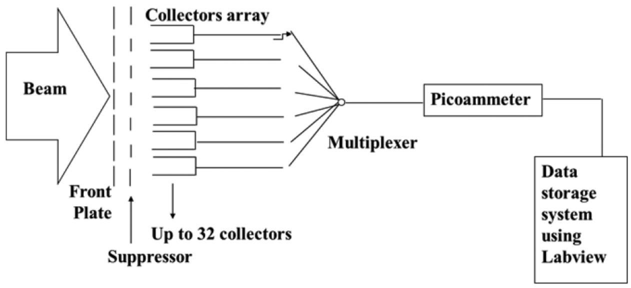

Fig. 3. A schematic of the beam data collection system. A 32 channel multiplexer; and a pico meter, which can detect pico to milli ampere levels of current, were used. The multiplexer completes the circuit between individual collectors and the picoammeter on an electronic control system.

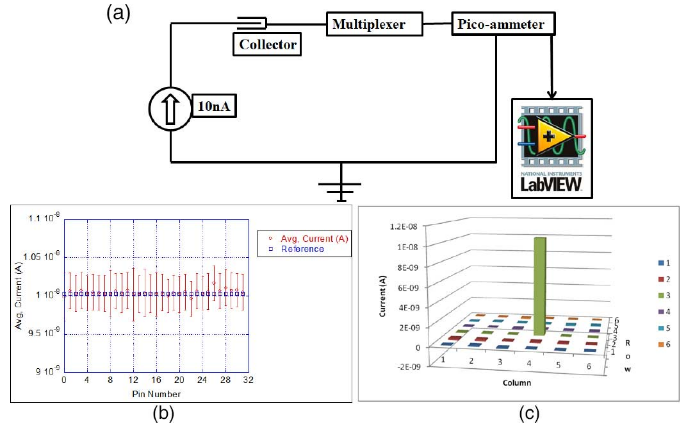

Fig. 4. (a) A schematic of the experimental setup. A 10 nA current from a DC power supply was applied to a collector. The procedure was repeated for the 32 collectors. (b) Results of individual cup measurements on bench-top, each of the collectors receive the same current, within a standard deviation; and (c) an example of a scan in a 3-dimensional plot. If there was an electrical crosstalk, a higher current reading on another pin would be expected.

the total current measured (I_{cup}) by a Faraday cup, of radius r, is modified by,

$$\sum I_{cup} = \sum I_{primary} \pm \sum I_{sec}, \tag{2}$$

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

IV. Data Collection System

The physical MPFC device was coupled with an electric system to collect data. A schematic of data collection system is shown in Fig. 3. The front plate of the device was electrically grounded. The suppression plate was held at -150 V, 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, another setup was used 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 pico-ammeter, which was then read by a computer measurement system. The beam current from a single collector is transmitted through a 0.25 mm 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 a 10 meter, 18 AWG conducting wire to the multiplexer. Upon switching the multiplexer to collect the current from a given collector, the current passes to the pico-ammeter and into a digital recording system designed in National Instruments LabVIEW 2013. Because the system uses only one pico-ammeter, only one collector can be read at a given time. To read all of the collectors in the MPFC, the program scans through the multiplexer, dwelling for 1000 ms on each input before measurement to allow capacitive charge drain from the system to ensure a stable value. This value is output to a file along with the collector number and location. This measurement cycle continues until all 32 collectors have been recorded. The output from the 32 collectors scan data for both the beam profile and a background measurement, using the same settings, are saved to a file which can then be imported into a spreadsheet or other post-processing software.

A. Test of Isolation of the Collectors

If there is any electrical connection between adjacent collectors, the beam current read by a collector can interfere with the measurement in other collectors. To determine if the collectors of the MPFC had any conductive crosstalk, an experiment setup was prepared on the bench-top before testing the new device with a beam. A schematic of the system is shown in Fig. 4(a). A current of 10 nA was applied to a single collector from a Keithley Instruments DC current source. All of the remaining collectors were left in air without any current and compared against a background measurement. This process was repeated with the current applied to each collector. Fig. 4(b) shows the results of individual cup measurements on the bench-top, each of the collectors received approximately the same current. These data also show that resistance of each of the collectors is likely similar. After examining the profiles for all 32 collectors, it was determined that there was no electrical crosstalk between collectors, an example profile is shown in Fig. 4(c).

B. Bias Voltage Adjustment

In order to find the variation of the ion and electron behavior with the suppressor and the collectors, an experiment was performed where a 5 MeV focused iron ion beam was scanned over an 8 mm by 8 mm area. The aperture area was maintained using 4 plates arranged along the cardinal directions perpendicular to the beam axis. These plates were electrically isolated from each other. The focusing parameters for the beam were held constant across all voltage variations on the suppressor and collector. The suppressor voltage was varied from 0 to -200 V, in steps of -50 V. The pico-ammeter allows for a voltage of either 0 V or $+90V$ to be placed on the measurement circuit. When both the suppressor voltage and the collector voltage were set to 0 V, secondary electrons, generated by both the beam collisions with the slit plates and the front plate of MPFC device, were allowed to enter the collectors. Although it results in a visible full beam profile when analyzed, the measurements were unreliable. When the collector voltage of positive 90 V was applied, keeping the suppression voltage at 0 V, only a small amount of ion beam induced current was discernible above the noise from the secondary electrons. After a change to the suppression voltage (-50 V), energetic secondary electrons were still able to pass through the electric field of the suppressor. With the collector voltage at 0 V (suppressor voltage at $50V$), the electrons from the collectors were allowed to escape, resulting in a noisy beam profile. The individual peaks, for a dwelling time window of the multiplexer operation, from the beam were present, and were barely visible above the electron noise. With the collector voltage increased to $+90V$, the energetic secondary electrons from the front plate were more easily captured in the collector, as were the electrons produced by the ion beam, resulting in a beam profile that did not fit the expected uniform profile. Increasing the suppressor voltage reduced the amount of energetic secondary electrons entering the collectors, but still resulted in a convolution between ion beam produced current and the noise from the secondary electrons, leading to a non-uniform profile. With a suppression voltage of -150 V, however, the secondary electron induced noise was reduced compared to the peaks from the ion beam. The beam distribution became discernible with the collector voltage of 0 V and easily resolved with the addition of $+90V$ to the collector. This beam profile was as expected for a raster scanned iron ion beam that was used in this test. Increasing the suppression voltage to $-200V$ appeared to reduce the clarity of the beam profile with the collector voltage at 0 V. With the collector voltage at $+90V$ though, the beam profile was very similar to the previous voltage setting, in that the beam profile was resolvable and consistent with a raster scanned ion beam. In all cases, the collector bias allowed for an increasd isolation of beam measurements from background scatter. Although the suppressor bias seems to lower the absolute current values, the relative values were consistent. The settings of a suppressor bias of negative 150 V, and collector bias of positive 90 V were chosen as they produced a scan closest to the known beam profile.

C. Characteristics of a Collector with a Beam

Fig. 5 shows the characteristic capacitive behavior of a collector when a 2 MeV Proton beam was introduced to the device. A collector shows a capacitive decay pattern for a short time before reaching an equilibrium (flat) condition. The effect is consistent across all pins. With a scan of all pins, three measurements are taken, following a suitable decay period. As long as the measurement time remained constant for all pins, the relative intensities should be acceptable.

D. Position Variation

Our test was limited to test each of the collectors by moving the device along the vertical axis. This limitation was due to limited hardware which did not permit full motion at that time. To check the performance similarity of the collectors when a beam was applied, the MPFC device was moved downward from the center axis with several measurements recorded at points along the path without altering the beam conditions. A 5 MeV Fe^{++} raster scanned beam was used for the experiment with a slit opening of 8 mm × 8 mm before the device. Fig. 6 shows several measurements from this test. The data show that each of the collectors in a row recorded a similar pattern of the beam signal through the motion path of the device. As the device was moved away out of the beam, the signal disappeared.

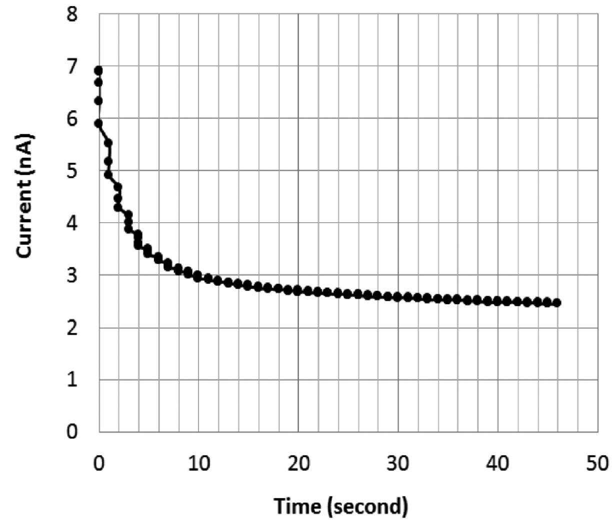

Fig. 5. When a proton beam was introduced, each of the collectors (on the path of a beam trajectory) exhibited a similar capacitive decay at the beginning of the measurement. Similar behavior was observed for an iron ion beam. This measurement provided a guideline of when to measure the beam current after completing the collection circuit.

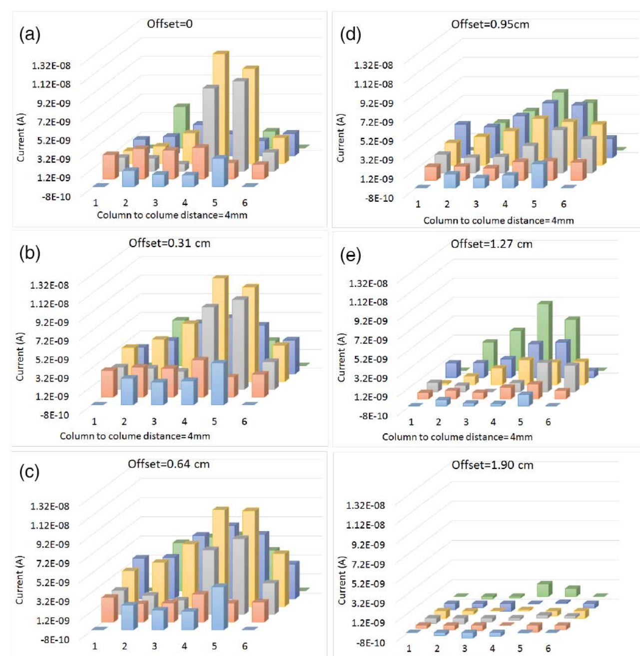

Fig. 6. Results of variation of device location in the y-direction. A 5 MeV Fe^{++} focused ion beam was raster-scanned through an 8 mm × 8 mm aperture opening. These data show that each of the collectors in a row recorded a similar pattern of the beam signal throughout the motion of the device.

V. INITIAL MEASUREMENT OF A BEAM BY MPFC

The new MPFC device has been used to measure several different beam conditions: a focused beam, a raster-scanned focused beam, and a defocused ion beam. In these cases, the beam is in a similar condition used for and actual ion irradiation experiments. A short window of accelerator time was occupied at

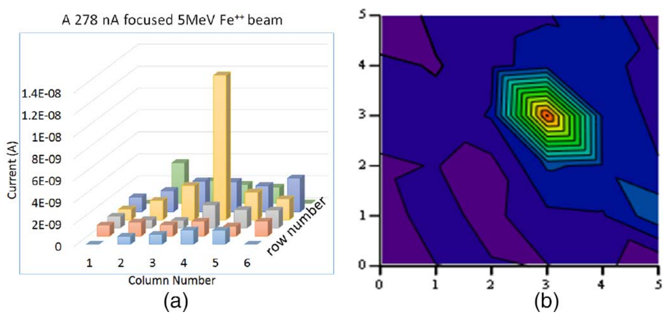

Fig. 7. (a) Measurement of a beam sample using 32 collectors; and (b) a contour plot, which represents a similar profile, similar to an optical image if the resolution were to improve. The central red dot shows the highest intensity - which is the real data through a projected collector. Except for the red dot, the other color lines are contours to background data. The collector near the center received the most signal because the beam with a FWHM of about 3 mm, was focused to the center of the axis. The signal to background noise is about 14:1 in this case.

the end of the experiments to characterize the MPFC. Though the beam parameters vary slightly on a day to day basis, the following information represents the device performance in response to beam measurements.

A. Measurement of a Focus Beam Using the Device

In this experiment, a 5 MeV Fe^{++} focused beam was used with a current of 278 nA. The suppressor (middle plate) of the MPFC was biased with at $-150V$, and the collector bias was $+90V$, as discussed previously. Fig. 7 shows the response of the 32 collectors with a focused beam (3 mm FWHM) directed to the center of the device. A collector close to the center received the highest intensity of the measured beam relative to the other collectors. While several of the collectors received a non negligible signals, this is likely a combination of beam scattering from the aperture before the device and electrical noise. The total integrated current of the 32 collectors was 65.5 nA, corresponding to a transmission ratio between the total beam and the measured current of 0.24. This value is expected for a focused ion beam passing to a single collector.

B. A Raster Scanned Beam Measurement

In order to test a functionality of the MPFC with a raster scanned beam, a full profile, using all 32 collectors was taken following an ion irradiation (5 MeV Fe^{++} ions) on a silicon wafer, Fig. 8(a). Fig. 8(b). No parameters were changed between the ending of this experiment and the measurement of the raster scanned iron ion beam. A full measurement from each of the 32 collectors was performed, as described previously. The measurement shows that the beam was off center to the left compared to the expected profile, which was supported by the observable irradiation area relative to the fiduciaries on the silicon wafer. The center of the measured beam showed 4 collectors higher than the others. Geometrically, these peaks correspond well to the location of the center of the iron implantation area.

C. A Defocused Beam Measurement

In order to test a functionality of the MPFC with a defocused beam, a 181 nA focus beam of 5 MeV Fe^{++} was defocused by varying strength of focusing elements. The beam was allowed to

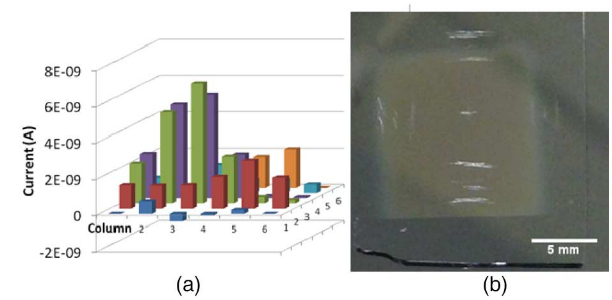

Fig. 8. (a) A full scan of all 32 collectors after an irradiation experiment on a silicon wafer; (b) an irradiated silicon wafer.

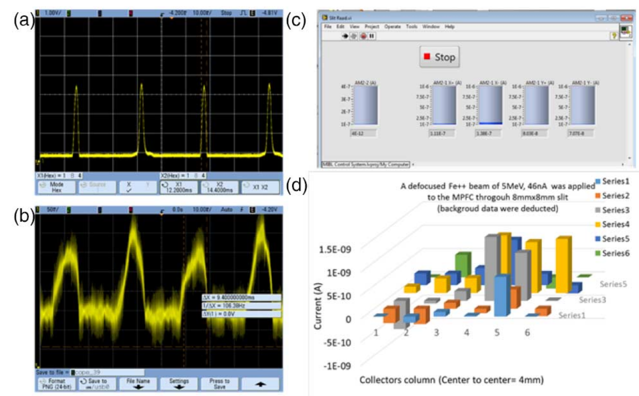

Fig. 9. (a) A profile of a focused 5 MeV, 181 nA, 2.2 mm FWHM beam; (b) the beam was defocused to 9.4 mm FWHM according to a BPM reading, (c) the beam was steered to the center of the aperture, the 4-way slit plates currents represent a condition of the beam placement; and (d) a defocused beam measurement using the MPFC.

pass through an $8mm \times 8mm$ aperture. The beam was steered to center it through this opening by balancing the current measured on each slit. The measured current after the slits was 46 nA, measured using a traditional suppressed Faraday cup. Fig. 9(d) shows the results of a full set of measurements of the defocused beam.

Initial results provide confidence that the collectors are able to sample a beam distribution, at discrete points of an integrated beam. The resolution of these measurements is restricted by the grid spacing between individual collectors. This initial attempt serves to demonstrate that a small collector cup (1 mm diameter) is able to detect a beam current at a nanoampere scale.

VI. Measurement of a Beam in a Controlled Condition, and Verification of Collectors Data

To assess the capabilities of the MPFC fully, a series of controlled tests separate from ion irradiations were conducted to compare the MPFC to known diagnostic equipment. Fig. 10 shows a sketch of the diagnostics at the end of the beamline at the end of a beamline of a Pelletron accelerator at the Michigan Ion Beam Laboratory (MIBL). The diagnostics consist of two traditional suppressed Faraday cups, labeled FC1 and FC2, a BPM, the MPFC device and a slit assembly with an opening of $8mm \times 8mm$. 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 beam filter (separates the ions based on the charge-to-mass

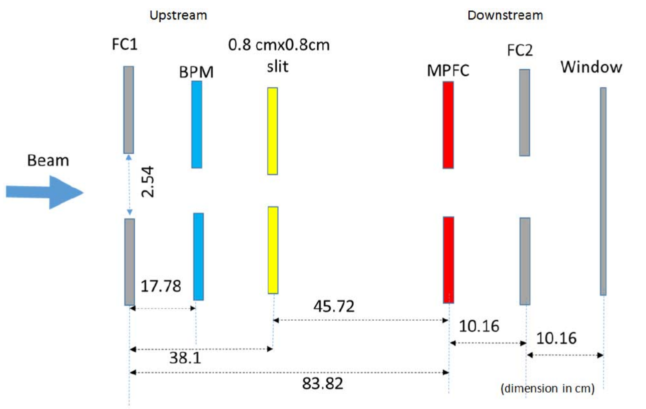

Fig. 10. A sketch of the diagnostics at the downstream end of a beamline. A cross-slit systems, a beam profile monitor device, two traditional Faraday cups, and the new MPFC device were used.

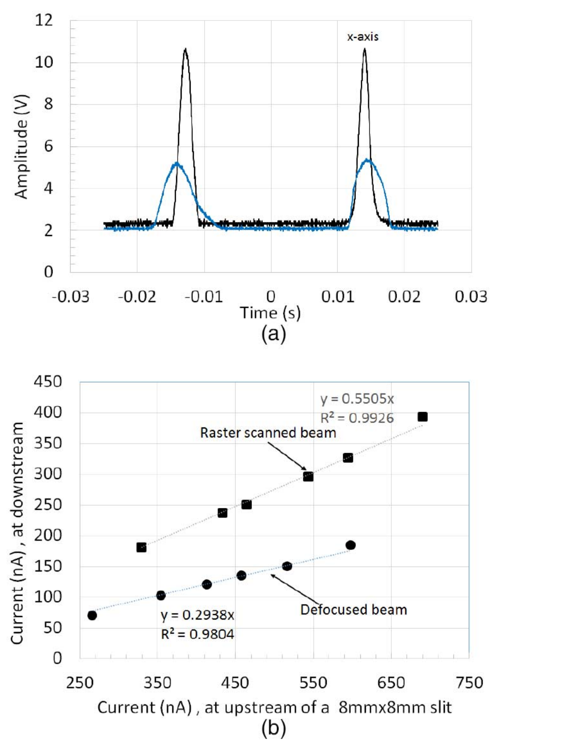

Fig. 11. (a) Typical BPM profiles of focused (high amplitude peaks shown in black) and defocused (lower amplitude peaks shown in blue) beams; (b) measured beam currents, at the upstream and downstream sides of the $8mm \times 8mm$ aperture, during raster scanned and defocused ion beams.

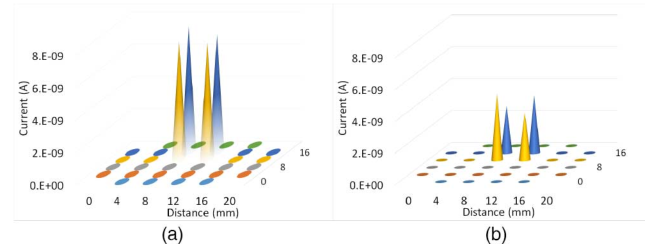

Fig. 12. A 5 MeV Fe^{++} beam through a slit of 8 mm × 8 mm at the highest current measurement for (a) a raster scanned (392 nA at FC2); and (b) a defocused beam (184 nA at FC2). Colors represent collectors row, such as blue for a row, and yellow for a different row.

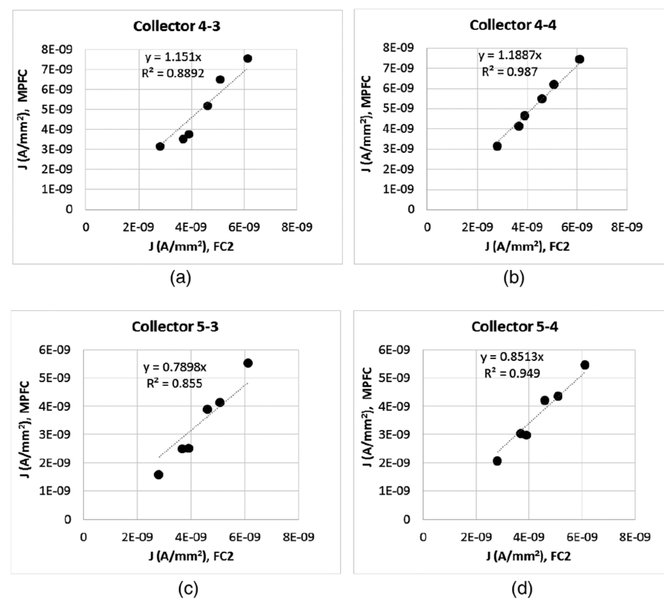

Fig. 13. Measurements of current density using FC2 after the aperture and the MPFC device for the raster scanned ion beam. The MPFC device collectors (in the beam area) responded in a linear fashion to variation in the total beam current, and correlate well to the current density of a traditional suppressed Faraday cup.

ratio) towards the downstream end of the accelerator at an angle of 15 degrees with respect to the accelerator axis. The high energy ion beam was focused using a quadrupole magnet and steered to provide an even distribution across the slits around the aperture. Initially, the MPFC device was not placed in the path of the ion beam. The beam current, at the upstream and downstream ends of the slits, was measured using traditional suppressed Faraday cups (diameter 2.54 cm), FC1 and FC2 in Fig. 10, to provide an initial comparison. The beam profiles of the focused and defocused beams used in this experiment are shown in Fig. 11(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. By changing the quadrupole strength to vary the beam focusing angle, the defocused beam had a uniform area over the slit opening. The current of each beam was measured before and after the slit system. Fig. 11(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 was positioned on the beam axis. The currents were measured using the MPFC, as shown in Fig. 12 in a three dimensional plot for the raster scanned and 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 aperture. Similar measurements were taken with increasing beam currents to observe characteristics (linearity) as shown in Fig. 13. As the slit was set to 8 mm × 8 mm, 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 slope for each pin in Fig. 13, ranging between 0.8 to 1.2, demonstrates that the amount of ion flux received for each pin is directly comparable to a traditional suppressed Faraday Cup. A similar pattern was also observed for a defocused beam.

Within the controlled testing environment, collectors (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.

VII. Conclusion

A prototype multi-pinhole Faraday cup (MPFC) has been designed, manufactured, and tested under controlled conditions. 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 confidence that the collectors are able to sample beam distributions in a discrete form within a given geometrical resolution (The hole diameter is 1 mm, and hole-to-hole spacing is 4 mm.). The experiment was performed for a 5 MeV (300 to 600 nA total current) iron ion beam, and 2 MeV (2 μA to 50 μA) proton beam. The device performance was not tested for a higher current (mA) or a pulsed beam. If a beam of 3 mm was focused to the center of the device, 1/3 of the beam was measured. But for a defocused or raster scanned beam, a beam diameter is not a limiting factor to distribute particles on a desire large area.

Acknowledgment

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