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In this work, the design and construction of a 50 Ω fast Faraday cup and its results in correlation with the Lee Model Code for fast ion beam and ion time of flight measurements for a Deuterium filled plasma focus device are presented. Fast ion beam properties such as ion flux, fluence, speed, and energy at 2–8 Torr Deuterium are studied. The minimum 34 ns full width at half maximum ion signal at 12 kV, 3 Torr Deuterium in INTI PF was captured by a Faraday cup. The maximum ion energy of 67 ± 5 keV at 4 Torr Deuterium was detected by the Faraday cup. Ion time of flight measurements by the Faraday cup show consistent correlation with Lee Code results for Deuterium especially at near to optimum pressures. *Published by AIP Publishing.*
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INTRODUCTION

Dense plasma focus devices are pulsed-sources of neutrons, ions, electrons, and X-ray radiation. The pinch column in a plasma focus device typically produces pulsed ions from a few tens of keV to 100 MeV. Ion energies in plasma focus devices depend on capacitor bank energy, voltage, pinch current, kind of gas, working gas pressure, and the material and geometry of devices. These ions generated by the pinch column can be used for materials science and applications. Most interesting material applications of ions produced by PF are material deposition, nanomaterial fabrication, and nuclear fusion reactor first wall damage studies. Therefore, detecting, measuring, and controlling of ion specifications such as energy, density, and uniformity in a plasma focus device are very useful for material applications. In addition, these ions play an important role in the production of an intense neutron flux in the plasma focus device when using Deuterium gas.[1] For a plasma focus device, the Lee Code is a useful tool for calculating ion energy, density, flux, fluence, and also plasma stream specifications.[2,3] In a recent work based on the Lee Code, the number of D-D neutrons produced by a whole range of plasma focus devices has been simulated. The resulting neutron scaling laws agree with the experimentally developed scaling law in the low to medium energy range of $Y_n \sim E_0^2$ but show considerable deviation (to which the term "deterioration of scaling" has been ascribed) to $Y_n \sim E_0^m$, where m goes below 1 in multi-MJ regimes.[4–6]

For plasma focus devices, a Faraday Cup (FC) is a very useful diagnostic tool for ion current density and ion time of flight measurements.[7–9] The ion energies are predominantly in the tens to hundreds of keV range, the pulse durations are tens of ns, and the currents are typically tens of kA.[10,11] The velocity, energy, and density of nitrogen ions have been estimated using the FC TOF technique in a plasma focus device by Mohanty in 2005.[12] A Faraday cup is a conductive cup designed to catch charged particles in low-pressure gas. The resulting current is measured and used to determine the number of ions or electrons hitting the cup.[10] The design, performance, and calculated error of a FC for absolute beam current measurements of 600-MeV protons were reported by Beck in 1956.[11]

Faraday cups are used to detect bunches of nonrelativistic ions at LINACs up to an energy of 100 MeV and a bunch length down to 1 ns via a 50 Ω matched transmission line to a broadband amplifier. By supplying a negative voltage to the collector electrode, the secondary electrons are repelled back to the collector in connection to the shielding of the advanced electrical field. These devices have a bandwidth limitation of 1 GHz.[12–14]

The FC has been used in several plasma focus experiments to infer the ion spectrum by TOF techniques. However, it has the following demerits: low signal-to-noise ratio and the emission of secondary electrons by the energetic ions impinging on the collector.[15] Sherwin M. Beck has presented "Design, Performance and Calculated error" of a FC for absolute beam current measurements of 600 MeV protons.[11] Specifications and test data are given for a 20 GeV FC, designed to have efficiency better than 0.1% at energies up to 20 GeV.[16] An enhanced MFC (Modified Faraday Cup) has been designed and used to measure the total beam current and power density distribution for high power electron beams used in welding.[17] Beam current measurements for CERN-

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Linac4 have been reported by Hein.[18] "Characterization of Electron Beams in Multiple Welders Using the Enhanced Modified Faraday Cup" has been reported by Palmer in 2006.[19] Developing an external FC for a few nA, 45 MeV proton beam at the MC-50 cyclotron has been reported.[20–22] For plasma focus, the ion pulse characteristics are quite different. In this work, the design and construction of a fast Faraday cup for fast ion beam time of flight measurements is presented. The results have shown good correlation with the numerical experiments based on the Lee Code,[23,24] which is the best observed in the last six decades.

EXPERIMENTAL SET UP

An INTI-PF Faraday cup is a fast 50 Ω impedance FC consisting of two coaxial cylindrical electrodes. Its collector is made of 5 mm diameter, 3 cm long graphite with a 4 mm diameter and 2 cm deep hole for particle collection at the tip of graphite. Graphite was chosen as the inner electrode because of its minimal secondary electron emission. The inner diameter of the outer electrode is 16.8 mm. PTFE is used as an insulating material between inner and outer electrodes. Furthermore, a negative bias voltage of −229 V was applied to the inner electrode, while the outer electrode was grounded. The INTI-PF FC is operated in the biased ion collector (BIC) mode. All physical parameters needed for FC design are given in Table I. Its adjustable entrance pinhole is 200 μm in diameter and made of brass at the standard DN25 vacuum stop-flange body. The schematic of the FC along with the biasing circuit is shown in Fig. 1.

The capacitance and inductance of the cylindrical Faraday Cup are calculated using the following formulas: $C_{FC} = 2\pi\varepsilon_0\varepsilon_r h/\ln\frac{D}{d} \cong 2.8918\,\text{pF}$, $L_{FC} = \frac{\mu_0\mu_r h}{2\pi}\ln\frac{D}{d} \cong 7.2705\,\text{nH}$, and $Z_{FC} = \sqrt{L_{FC}/C_{FC}} \cong 50\,\Omega$.

Keeping radii of the coaxial structure constant ensures that the impedance of the coaxial transmission line is 50 Ω everywhere. This is important to avoid deformation of the signal. The peak voltage of the FC is set by the breakdown voltage of the insulator; $V_p = 0.5Sd_{in}\ln\frac{D}{d} \cong 119\,\text{kV}$, where S (V/m) is the insulator's breakdown voltage and d (m) is the inner diameter of the cylindrical electrode. The cut-off frequency of this Faraday cup is given by $f_c \approx c/\left(\pi\left(\frac{D+d}{2}\right)\sqrt{\mu_r\varepsilon_r}\right) = 18\,\text{GHz}$. The response time for the Faraday Cup is $LC\omega^2 = 1 \rightarrow T^2 = 4\pi^2 CL \rightarrow T = 0.6\,\text{ns}$.

TABLE I. Physical Parameters needed for FC design.

Physical parameter	Quantity
ε_0	$8.854 \times 10^{-12}\ \frac{\text{F}}{\text{m}}$
ε_r	2.1 (For PTFE or Teflon)
D	16.8 mm (Inside diametere of outer electrode–brass)
d	5 mm (Outside diameter of inner electrode–graphite)
h	3 cm (Faraday cup height)
μ_0	$4\pi \times 10^{-7}\ \frac{\text{H}}{\text{m}}$
μ_r	~ 1
$S_{PTFE\ \text{at}\ 3\,\text{GHz}}$	$1000\ \frac{\text{V}}{\text{mil}} = 39.4\ \frac{\text{MV}}{\text{m}}$ (Dielectric strength of insulator–PTFE)

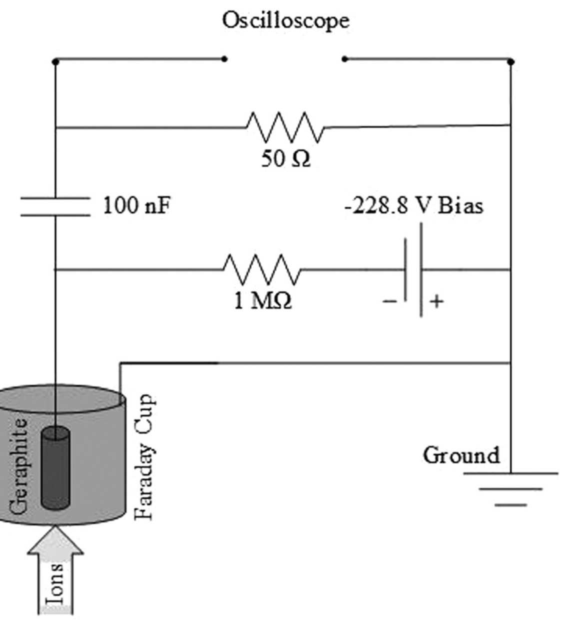

FIG. 1. Biasing circuit for the INTI-PF Faraday Cup.

This is a position-adjustable Faraday cup. The distance between the FC to the plasma focus anode tip is adjustable by means of a stainless-steel tube from outside of the vacuum chamber. The brass Faraday Cup and its components accompanied by its stainless steel adjustable holder system are shown in Fig. 2.

As mentioned, its collector is biased negatively with respect to the aperture. Current is generated in the circuit by the capture of the ions, and the corresponding voltage (V_R) is developed across the resistor (R). This voltage V_R is proportional to the incoming ion current and is recorded on the oscilloscope. Because of the large ion current emitted from the plasma focus, a small aperture is required to limit the ion current reaching the collector surface and to limit the detected voltage to a manageable level.[15]

After installing the designed Faraday cup, the INTI-PF vacuum vessel was evacuated until 10^{-2} mbar. We fired it using Deuterium in different pressures from 2 Torr to 8 Torr. Ions that pass through the 200 μm aperture hit the graphite. The resulting current is $I = \frac{V}{R}$ from which the current density

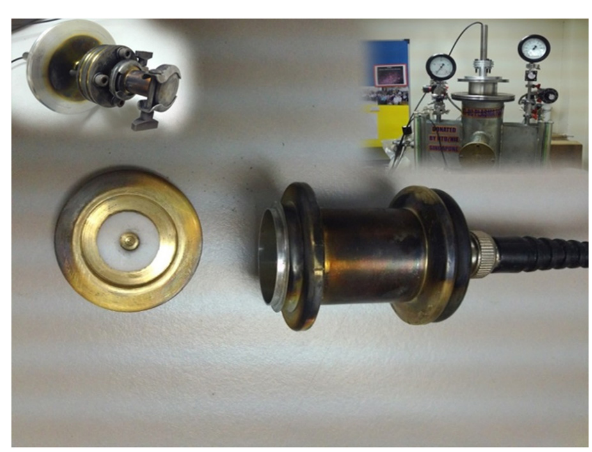

FIG. 2. Assembled INTI-PF Faraday Cup.

TABLE II. Lee Model parameters for different pressures of Deuterium by matching the computed current traces to measured current traces.

Pressure (Torr)	2	2.5	3	4	5	6	8
Axial mass factor	0.0673	0.0646	0.0676	0.06	0.0582	0.0619	0.0601
Axial current factor	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Radial mass factor	0.2	0.16	0.1215	0.06	0.18	0.16	0.7
radial current factor	0.7	0.7	0.7	0.7	0.7	0.7	0.7

is calculated as $J = \frac{I}{A}$, where A refers to the area of the aperture. The number of ions can be calculated by $n = \int I.dt/e$, where e and n refer to the unit electric charge and number of ions, respectively. The number density of ions having velocity v, which hit and are absorbed by FC graphite, can be calculated by $J = n_i ev$, where n_i refers to the number density of ions absorbed by the graphite. The FC signal based on its bias circuit is recorded by using the Scope TDS 3034C with $R = 50\,\Omega$. For all Deuterium experiments, the distance between the anode and FC bottom is 8.5 cm, and the flight length was considered to be from the middle of the pinch length point predicted by the Lee Model Code to the bottom of the FC Graphite cup. Hence, we can calculate the mean velocity of ion beams for every shot and kinetic energy of ions by means of equation: $K = \frac{1}{2}mv^2$, where m is the mass of Deuterium, which is 3.3445×10^{-27} kg.

RESULTS AND DISCUSSION

Faraday cup signals during TOF measurements consist of two peaks. The first peak is due to X-rays emitted from

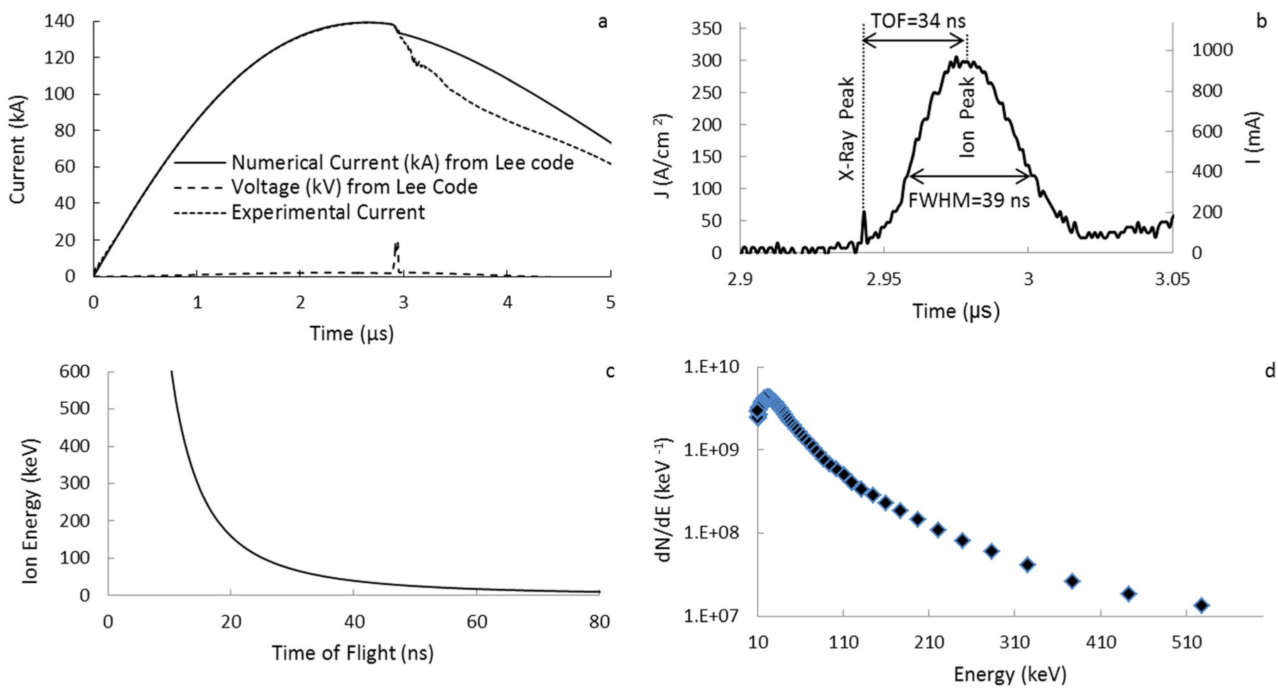

FIG. 3. Experimental current fitted by the Lee Code including the FC signal, 12 kV, 3 Torr Deuterium, and INTI PF: (a) Current fitting, (b) FC signal, (c) Deuterium ion energy versus ion time of flight, and (d) dN/dE versus ion energy.

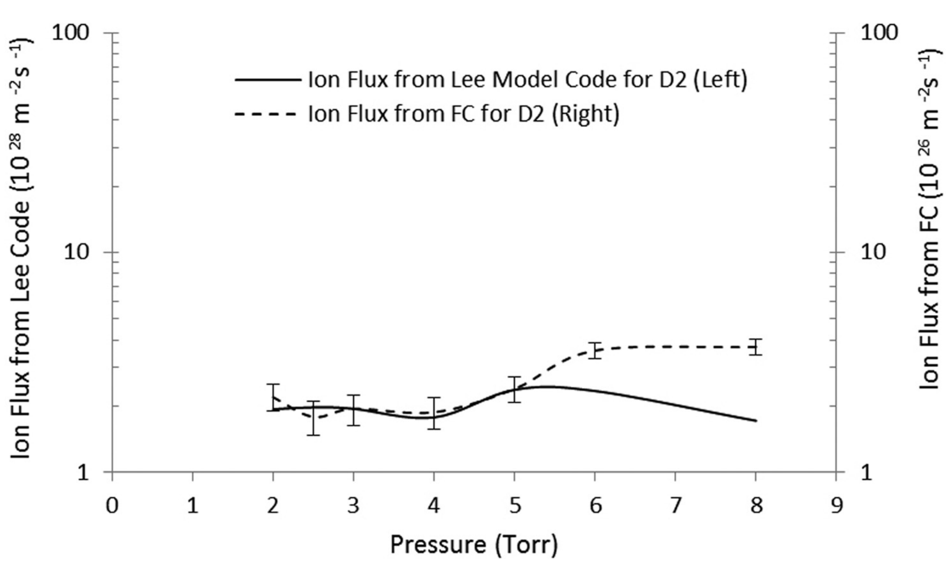

FIG. 4. Ion flux correlation between the Lee Code and Faraday cup.

the pinch column, and the second peak belongs to ions. The time difference between the two peaks is the TOF of ions. In our experiments, the filling gas is Deuterium. We have studied FC signals for different pressures of Deuterium as filling gas, at a discharge voltage of 12 kV for INTI PF. All signals have been correlated and fitted by the FIB Lee Model Code. Channels 1–4 of TDS 3034C were used to record dI/dt, XR, FC, and voltage. The Lee Model parameters for each shot

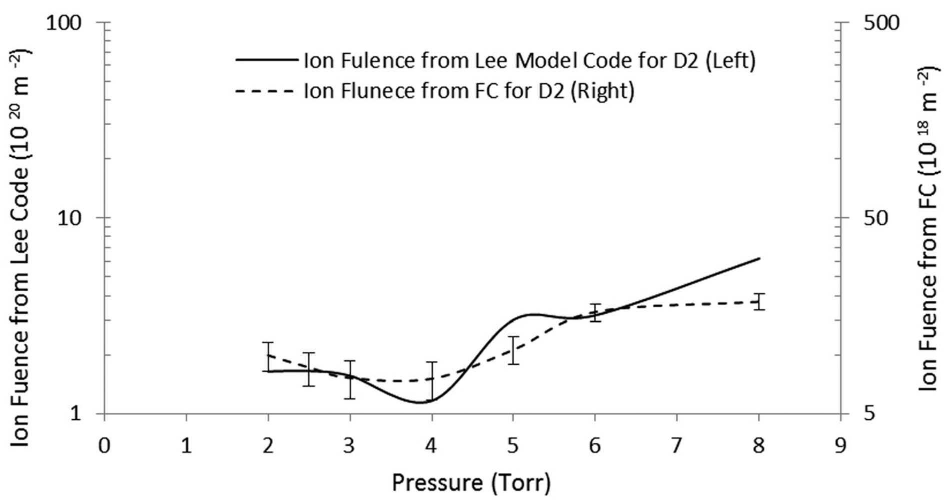

FIG. 5. Ion fluence correlation between the Lee Code and Faraday cup.

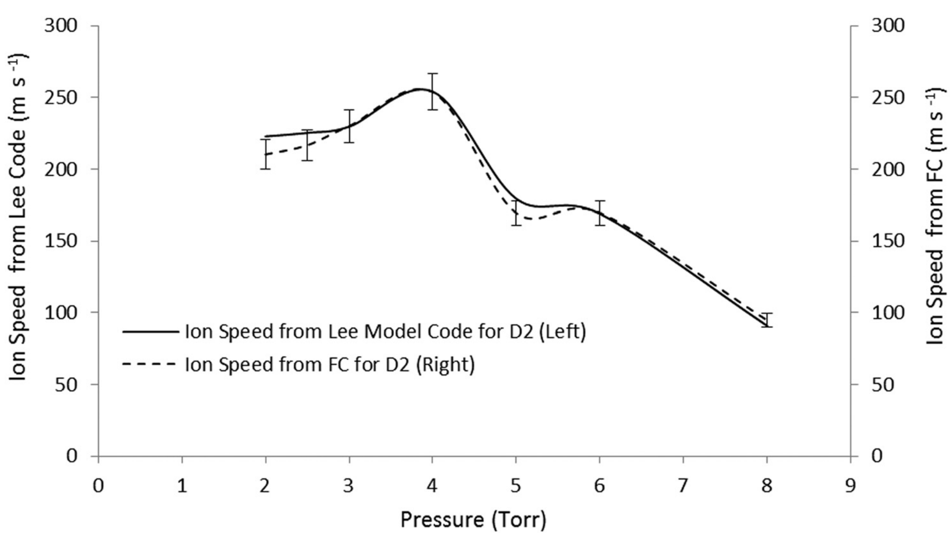

FIG. 6. Correlation between the Lee Code and time of flight measurements for ion speed results at 2–8 Torr Deuterium.

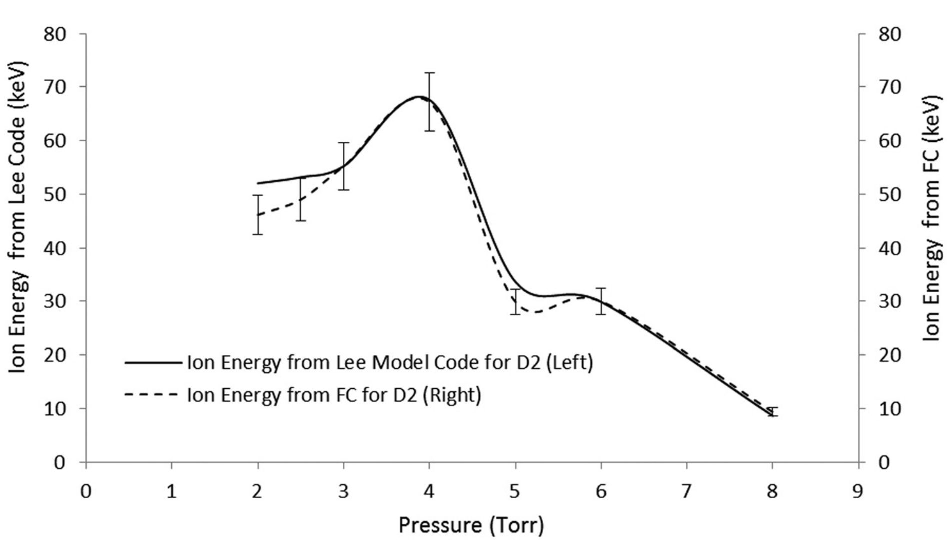

FIG. 7. Correlation between the Lee Code and time of flight measurements for ion energy results at 2–8 Torr Deuterium.

from matching the computed current trace to the measured current trace of the shot are presented in Table II.

For Deuterium experiments at a discharge voltage of 12 kV, 34 ns was the smallest Full Width at Half Maximum (FWHM) of the FC signal recorded for the fast Focus Mode operation of INTI PF at 3 Torr. In the experiments, we measure only the ions passing through a 200 μm (diameter) aperture placed 8.5 cm away from the pinch column (Fig. 3). Thus, not all the ions generated by the pinch column were collected by the FC. So, the number of ions recorded by the FC will be lower than the number of ions emitted by the plasma focus. Figures 4 and 5 present ion flux and ion fluence correlation between numerical experiments by Lee Code and INTI PF FC results, respectively.

The maximum current density for 3 Torr deuterium at 12 kV captured by the Faraday cup was 310 A/cm^2, and most common ion energy for this shot based on FC TOF measurements was 55 keV. Experimental ion flux and ion fluence measured for this shot were $1.95 \times 10^{26}\,\mathrm{m^{-2}\,s^{-1}}$ and $7.6 \times 10^{18}\,\mathrm{m^{-2}}$, respectively.

Fast ion beam time of flight measurements are the most important experiments that can be done by using a Faraday cup, and the correlation between ion TOF results and the Lee Model Code is very interesting. FC TOF measurements and proper current fitting the by Lee Code show an acceptable correlation between FC TOF results and the Lee Model Code. Figures 6 and 7 show the correlation between Lee Model Code and FC TOF results at 2–8 Torr Deuterium in the INTI PF machine. The maximum ion energy of 67 ± 5 keV at 4 Torr Deuterium was detected by the Faraday Cup. Ion time of flight measurements by the Faraday Cup show consistent correlation with Lee Code results for Deuterium especially at near to optimum pressures.

CONCLUSION

The design and construction of a 50 Ω fast Faraday cup and its results in correlation with Lee Model Code for fast ion beam and ion time of flight measurements for a Deuterium filled plasma focus device were presented. Fast ion beam properties such as ion flux, fluence, speed, and energy at 2–8 Torr Deuterium were studied. The minimum 34 ns FWHM ion signal at 12 kV, 3 Torr Deuterium in INTI PF was captured by a Faraday Cup. The maximum current density for 3 Torr deuterium at 12 kV captured by the Faraday cup was 310 A/cm^2, and most common ion energy for this shot based on FC TOF measurements was 55 keV. Experimental ion flux and ion fluence measured for this shot were $1.95 \times 10^{26}\,\mathrm{m^{-2}\,s^{-1}}$ and $7.6 \times 10^{18}\,\mathrm{m^{-2}}$, respectively. The maximum ion energy of 67 ± 5 keV at 4 Torr Deuterium was detected by the Faraday Cup. Ion time of flight measurements by the Faraday Cup show consistent correlation with Lee Code results for Deuterium especially at near to optimum pressures.

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