SULI Report: Ionization-enhanced power flow to surface floating downstream from electrostatic double-layer

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Abstract

The purpose of this report is to study power flow in a plasma that is capacitively coupled to an RF power source at 10-30 MHz. The plasma is confined in a three-cell magnetic mirror. This device uses two magnetic nozzles to separate the Source-End-Cell (SEC), Center-Cell (CC), and Far-End-Cell (FEC). We found that power flow from the main chamber depends sensitively on the FEC neutral gas pressure. In particular at low pressure, a negative potential barrier of order -1 kV develops in the FEC. This effectively throttles heat transfer. At high gas pressure in the FEC the potential barrier drops to just tens of volts, and we observe a Tantalum paddle placed directly in the plasma plume obtain temperatures in excess of 900K. It is hypothesized that the large potential is caused by a high temperature low density electron beam, while at high pressure a second population of low temperature high density electrons forms from increased ionization. These two electron populations cooperate to cause the observed effect. We present a tentative model of the phenomenon. This research can be of interest to communities in silicon processing industry (RF plasma source), electric propulsion (magnetic nozzle and double layer), as well as magnetic confinement fusion (power flow from a tandem mirror).

1 Introduction

Recently, NASA funded a proposal to develop a field-reverse configuration (FRC) based rocket engine [1]. The Princeton Field Reverse Configuration (PFRC-II) device is the project's primary experimental facility. This report describes experiments in the Far-End-Cell (FEC) of the PFRC-II. The aim is to characterize the phenomenon of a 20.1 ± 0.1 cm^2 Tantalum paddle. The metallic surface glows red hot at high background gas pressure, and does not glow at low pressure. However, its electrostatic floating potential is high at low pressure and low at high pressure. This phenomenon could be crucial to understanding the behavior of magnetic nozzles or capacitively coupled plasmas.

2 Photography

Our first approach to measuring the phenomenon is using a camera to photograph this phenomenon. A series of images between FEC pressures 0.010 mTorr to 0.090 mTorr captures the spectra from no-glow to peak-glow and later diminished-glow. The RGB value for red in the image is used as a proxy for temperature. Color is a valid proxy for temperature in certain spectra of black body radiation. Since the Tantalum paddle is a metallic surface in vacuum, we believe the thermal isolation is a good reason to assume black body radiation. Therefore color can be used as a measure for temperature. Moreover, the temperature is an indication of power flow from the plasma. It can be seen in the photo that thermal conduction between the Tantalum paddle and the stainless steel clasp which holds it is poor. Thus the power coupled to the paddle form kinetic collisions with the plasma is contained in the solid body of the paddle, until it is radiated away as black-body radiation.

Thus the power flow to a blackbody radiator is justifiably measured by the temperature and color of its metallic surface. Moreover, connecting the Tantalum paddle to an oscilloscope allows one to read electrostatic information from the floating potential.

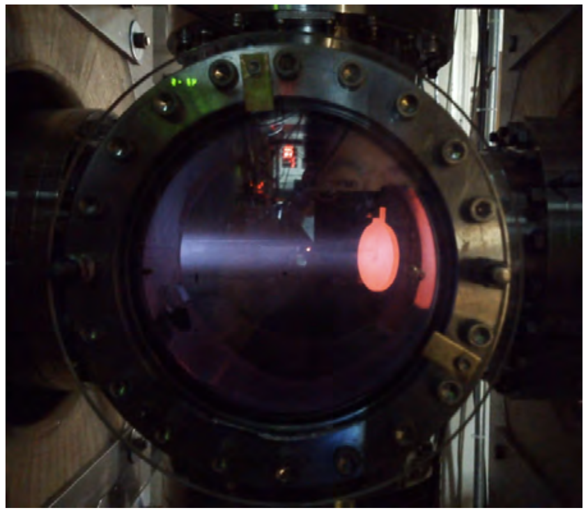

Figure 1: Camera images of paddle glow for various Far-End-Cell neutral gas pressure. Photo made possible by the PhysicsToolKit app developed by Vieyra Software.

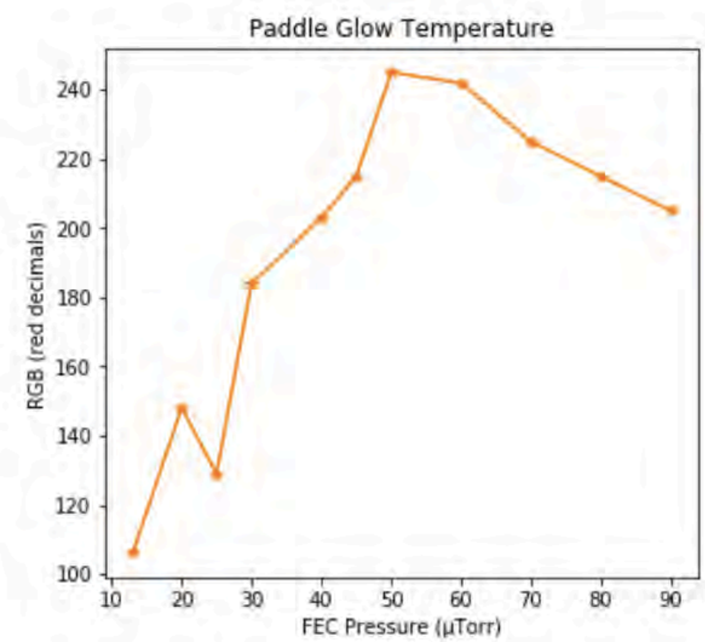

Figure 2: RGB value red from image analysis converted to decimal. We take R to be a proxy for Tantalum paddle temperature. There exists a peak around 0.050 mTorr. This coincides with the floating potential mode transition.

3 Floating Potential

Connecting the Tantalum to an oscilloscope gives information about its floating potential as a function of time. The floating potential is the electrostatic potential of a surface that draws zero current. In a plasma this potential is often non-zero because electrons and ions have equal density but different temperature. Thus a conducting body is expected to charge negative and repel electrons until the positive and negative currents equalize.

The data show that at high neutral gas pressure the magnitude of floating potential is closer to that of low neutral gas pressure Fig 3.

It was taken with the Helicon antennae set to $P_{net} = 300$ Watts. Net power, defined to be forward minus reflected power, is the total power coupled into the plasma. The L_2 coils were set $I_{L_2} = 240$ Amperes of current, and the Nozzle coils $I_{nozzle} = 375$ Amperes. This yields a total $B_{max} = 4000$ Gauss at the center of the magnetic nozzle. The magnetic mirror ratio is about $R = 30$.

Moreover, upon close examination of the time trace from the floating potential, we find that the paddle floating potential is not fixed, but accessing an aperiodic distribution over time. Fig 4 plots a series of histograms to illustrate how this distribution evolves with different neutral gas pressures.

At FEC neutral gas pressure 15 μTorr, the Tantalum paddle floating potential fluctuates around -1100 ± 100 volts. The spread is attributed to natural fluctuations in the plasma. It would be interesting to see whether the frequency of fluctuation matches to either the plasma frequency or the helicon antennae frequency At $P_{FEC} = 31$ μTorr we the spread in floating potential increase to span over 600V. We identify this as the emergence of a second plasma mode. There are two peaks in the histogram. We call the large potential peak 'hot mode' and the small potential peak 'cold mode' after the electrostatic floating potential of the paddle. The plasma stays mostly in hot mode and periodically takes flights up to cold mode. The frequency of these transitions is of order 10 Hz. We attribute this to perturbation from the Langmuir probe which also

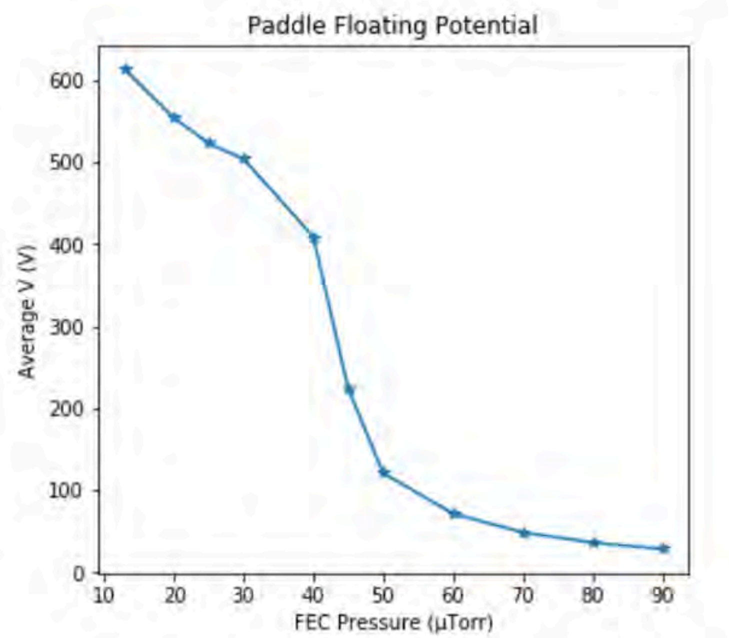

Figure 3: Floating potential measured from back of Tantalum Paddle. Units indicate negative volts. The plotted value is time-averaged by an oscilloscope. The floating potential has large magnitude at low pressure and low magnitude at high pressure. Notice the sharp mode transition from high voltage to low voltage around 0.050 mTorr FEC neutral gas pressure.

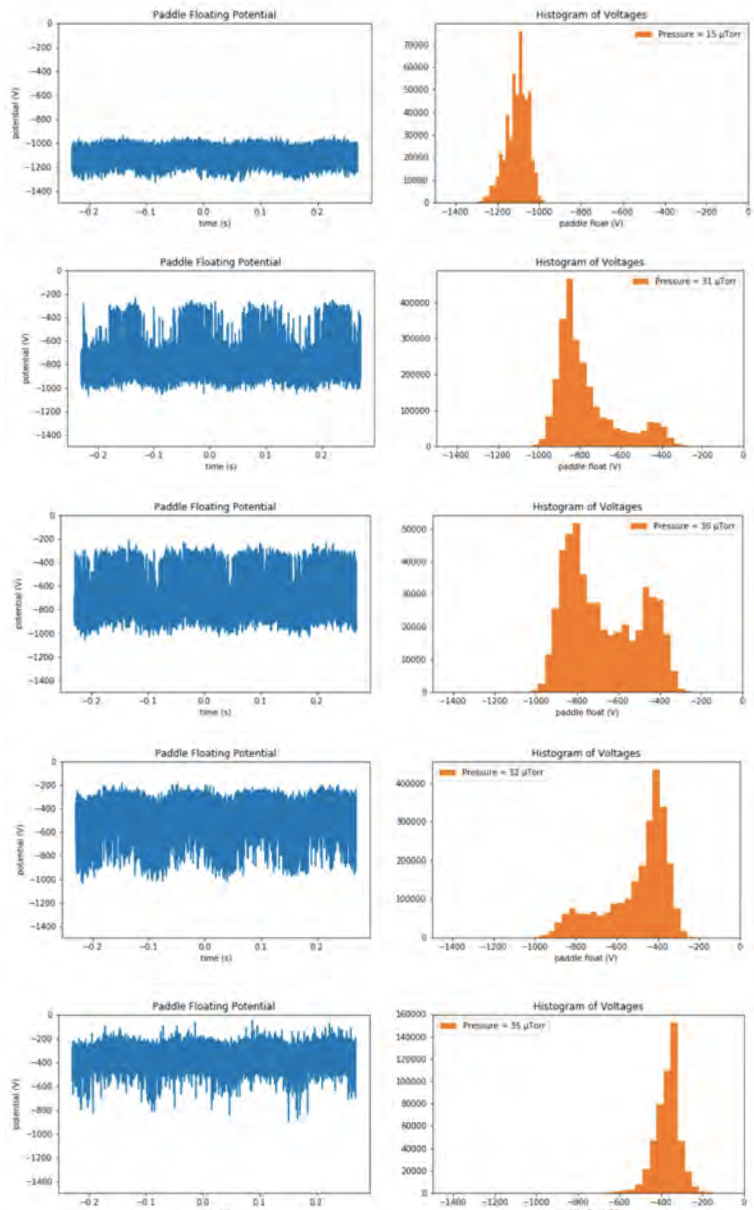

Figure 4: Raw floating potentials are plotted in left column; histogram for each time-series plotted in right column. The pressures displayed are $P = \{15, 30, 31, 32, 35\}$ μTorr. The pressure range for mode transition, just 1-2 μTorr is very thin relatively to the parameter space. This indicates the system's sensitive dependence on pressure.

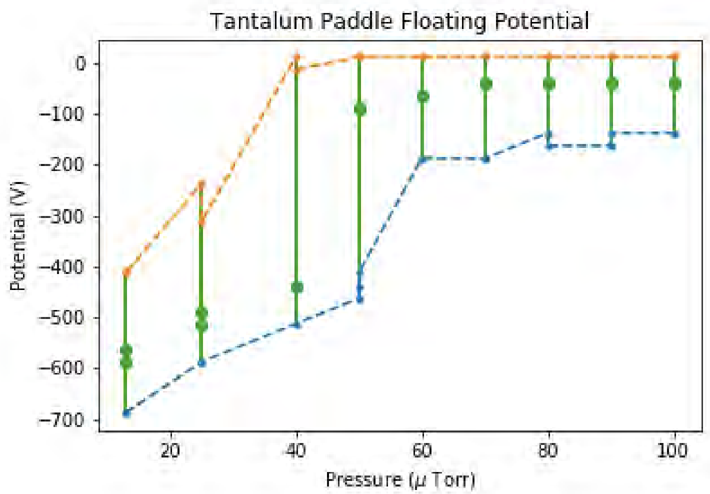

Figure 5: Reduced plot of neutral gas pressure dependent floating potential. Solid point indicates histogram bin with most counts; error bars mark first and last non-empty bin. Notice the discontinuity between 40 and 60 μTorr. This is the thin transition from 'hot mode' to 'cold mode.'

oscillates at around 10 Hz.

4 Langmuir Probe

In addition to taking measurements at the Tantalum paddle, which responds to fluctuations in the plasma, we can probe the plasma directly by using a Langmuir probe. The Langmuir probe is a thin insulated rod with an exposed conducting tip. The tip is inserted into the plasma, and the back end is biased by an electrical power supply. Thus one effectively introduces an electric source or sink into the plasma medium. One can extract several plasma parameters from the plasma by analyzing how current collection varies as a function of probe bias [2]. Fig 6 shows a sample $I(V)$ characteristic.

According to basic Langmuir probe theory [3] the I(V) characteristic looks like an exponential until a certain potential is reached, from there the theoretical

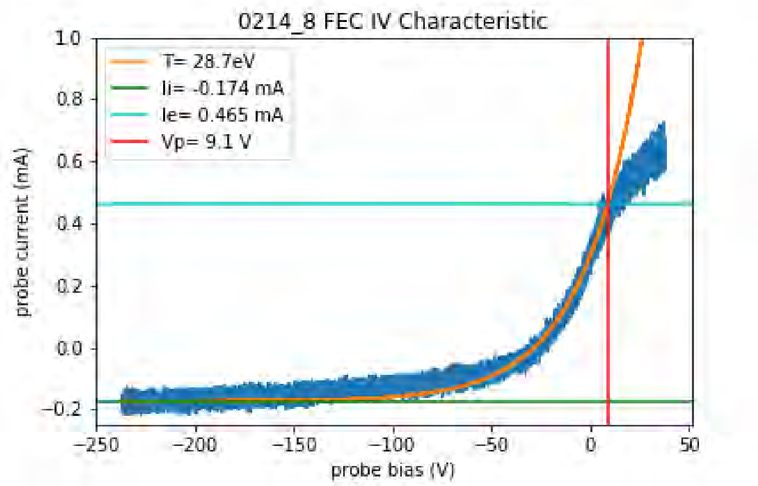

Figure 6: $I(V)$ characteristic measured from the plasma when $P_{FEC} = 65$ μTorr and $P_{CC} = 450$ μTorr. The exponential temperature fit is given in orange, the plasma potential V_p is marked in red, and the electron and ion saturation currents are marked in teal and green respectively.

Langmuir curve tops at a constant saturation current I_s.

$$I(V) = \begin{cases} I_{es} e^{(V-V_p)/T_e} - I_{Ii} & V < V_p \\ I_s & V \geq V_p \end{cases} \tag{1}$$

The plasma potential V_p demarcates a boundary from exponentially increasing electron current to a linear increase. Thus the plasma potential can be identified from the inflection point, and one can compute the electron Temperature by fitting a curve to the exponential region at voltages more negative than the plasma potential.

Knowing the electron temperature, one can then calculate the electron density from $I = envA$ where A is the probe area.

$$n_e = \frac{I_{es}}{eAv_e} \tag{2}$$

where the electron velocity can be approximated from temperature $v_e = \sqrt{2T_e/m_e}$. Using this method of fitting an exponential for temperature, the following plasma parameters were computed Fig 7.

A sharp drop in electron temperature appears with the flattening of plasma potential, while the bulk electron temperature continues to increase. If the number of low energy electrons increase, then the number of ions must increase proportionally to preserve quasi-neutrality. We will argue that these are low-energy ions from ionization. The low energy ions will be strongly attracted toward the -1kV paddle. This neutralizes the floating potential and opens the way for high energy electrons to impinge on the Tantalum surface. Collisions from high energy electrons are the main vector for power flow to the paddle. Such collisions only occur when there exists a second low energy electron population to neutralize the paddle floating potential. That is why we call the paddle heating phenomenon ionization-enhanced power flow.

The neutral gas pressure must be sufficiently high to allow low energy ionization electrons to outweigh the high energy electrons from the CC.

5 Ionization Cross-section

In nuclear physics the reactivity rate is defined as a density per time $R = n_\sigma n_e \langle \sigma v_e \rangle_E$ where n_σ is background gas density. In their plasma processing text, Lieberman and Lichtenberg outline a semi-classical derivation for ionization cross-section [4]

$$\sigma_{iz}(\mathcal{E}) = \begin{cases} \sigma_0[\mathcal{E}/\mathcal{E}_{iz} - 1] & \mathcal{E} > \mathcal{E}_{iz} \\ 0 & \mathcal{E} \le \mathcal{E}_{iz} \end{cases} \tag{3}$$

where $\sigma_0 = \pi(e/4\pi\epsilon_0\mathcal{E}_{iz})^2$ in units of area. The energy average can be defined in terms of the electron energy density function (EEDF)

$$R = n_\sigma \int \sigma(\epsilon)F(\epsilon)v(\epsilon)d\epsilon \tag{4}$$

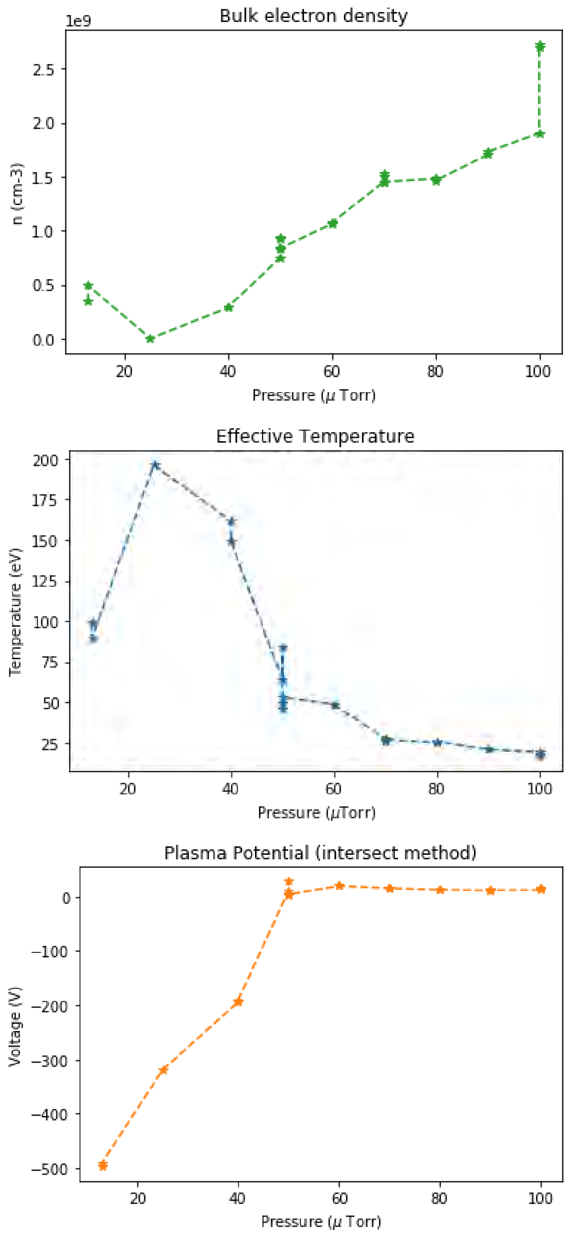

Figure 7: Plasma Parameters from Langmuir probe data. The electron density, electron temperature, and plasma potential all exhibit a phase-transition near $P_{FEC} = 50$ μTorr. A sharp drop in electron temperature appears with the flattening of plasma potential.

The EEDF can be derived from measurement through the Godyak-Druyvesteyn method [6]

$$F(\epsilon = eV) = \frac{2\sqrt{2m}}{e^3 A}\sqrt{eV} I''(V) \tag{5}$$

where $I''(V)$ is the second derivative of the experimental Langmuir characteristic.

The calculation in Eq. 4 yields an observable which can be compared with the measured bulk electron densities to validate our model of ionization-enhanced power flow.

6 FLIR Camera

We employed an optical diagnostic to gain a more precise picture of the paddle temperature. The Front Looking Infra Red (FLIR) camera can capture spatially resolved temperature profiles at a high frame rate Fig 8. This image marks a maximum of 440 degrees Kelvin, which does not correspond to known glow temperatures for Tantalum. One explanation is that the infrared signal is attenuated through Tantalum sputter-coating on the vacuum window. One can recalibrate the image by viewing a known temperature source through the sputter-coated window. Alternatively, we can relocate the camera to a position behind the paddle such that the window is shielded from plasma-surface interaction sputtering.

The optical diagnostic is important because it can give us time resolved measurements of paddle temperature. By switching off the heat source, one can measure the radiation rate of the Tantalum paddle. By taking successive images at constant plasma power, one could measure the power flow from the plasma to the paddle. This can be compared to the expected power transfer from the measured EEDF to provide a second test for the model, in addition to checking the density from ionization.

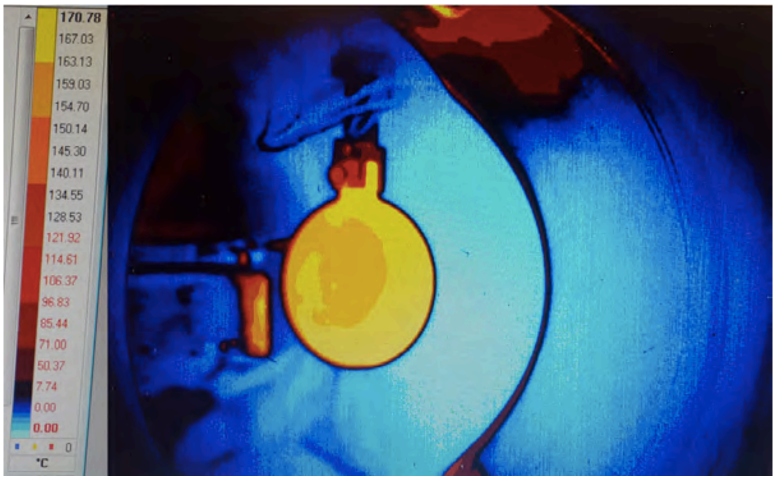

Figure 8: Infrared image of temperature distribution on paddle surface. The false color image is marked in degree Celsius. That values are lower than can be attributed to lost of signal to the vacuum vessel window.

7 Conclusion

The observation is that a Tantalum paddle placed in the FEC glows visibly at high neutral gas pressure. We observe this phenomenon first by taking color photographs at various FEC neutral gas pressure Fig 1. Second we look at the paddle electrically, by connecting its back end to an oscilloscope. This shows the floating potential as a function of time. We found that there exist at least two modes of electrical oscillation. At high neutral gas pressure the paddle floats at low potential (100 V). At low gas pressure the paddle floats at a high potential (1000 V). And in between there is a thin regime of oscillation between modes Fig 4, 5. Third we scanned the plasma parameters such as n_e, T_e, and V_p as a function of neutral gas pressure by inserting a Langmuir probe perpendicularly into the plasma just in front of the Tantalum paddle. Fourth we used a FLIR camera to get a precise measurement of the surface temperature. This optical diagnostic also afforded us spatial resolution on paddle heating Fig 8. Finally we modeled the behavior with theoretical calculation for ionization rate and power flow. Next steps are to complete the ionization calculations and measure power flow through the optical IR diagnostics.

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8 Appendix: A

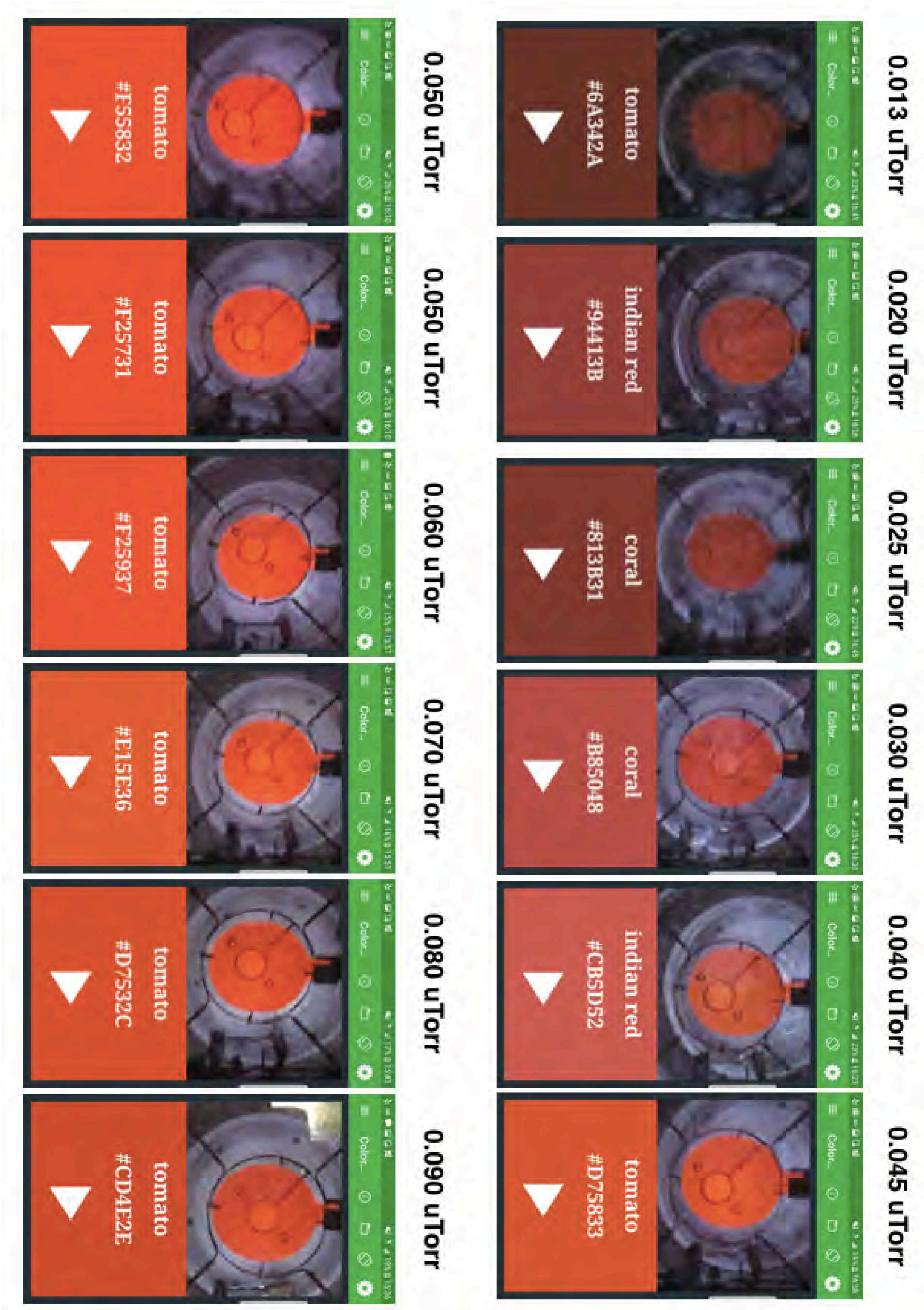

Figure 9: Photographs of Tantalum paddle at 12 FEC pressures. Units are marked in μTorr. Photos made possible by the PhysicsToolKit app developed by Vieyra Software.