VASIMR® VX-CR Experiment: Status, Diagnostics and Plasma Plume Characterization

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Abstract: We report on the status of the VASIMR® VX-CR experiment and present the experimental results of the characterization of the plasma conditions. Our plasma diagnostics include a reciprocating Langmuir probe to measure parameters within the plasma exhaust plume while several temperature sensors are used to monitor the thermal behaviour of the core. We present results of plasma parameters (e.g. ion density profiles, T_e, ion cost) that are relevant to the lifetime issues and steady state of the VASIMR® engine.

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Nomenclature

A_{probe}	=	probe cross sectional area, m^2
$AARC$	=	Ad Astra Rocket Company
e	=	elementary charge, C
f_i	=	ionization fraction
I_e	=	electron current, A
I_{es}	=	electron saturation current, A
I_{is}	=	ion saturation current, A
I_T	=	total ion current, A
J	=	current density, A/m^2
k_B	=	Boltzmann constant, $m^2kg/(s^2K)$
$\dot{m}$	=	mass flow rate, mg/s
m_i	=	ion mass, kg
n_i	=	ion density, m^{-3}
P_{in}	=	input RF power, W
r	=	radial position, m
RF	=	radio frequency
T_e	=	electron temperature, K
V_B	=	bias voltage, V
V_P	=	plasma potential, V
$VASIMR^{®}$	=	Variable Specific-Impulse Magnetoplasma Rocket
$VX-200$	=	VASIMR® Experiment at 200 kW
$VX-200-SS$	=	Steady State VASIMR® Experiment at 200 kW
$VX-CR$	=	VASIMR® Experiment Costa Rica
α_c	=	ion cost, eV/ion

I. Introduction

The Variable Specific Impulse Magnetoplasma Rocket, VASIMR®, engine is a high-power electric propulsion system[1] developed by the Ad Astra Rocket Company (AARC) at two research facilities in Texas (USA) and in Costa Rica. The VASIMR® technology is comprised of a helicon plasma source, followed by an ion cyclotron booster stage, and finalizing in a magnetic nozzle. Figure 1 shows the main stages of the engine, additionally detailing the propellant source, confining magnets and RF generators.

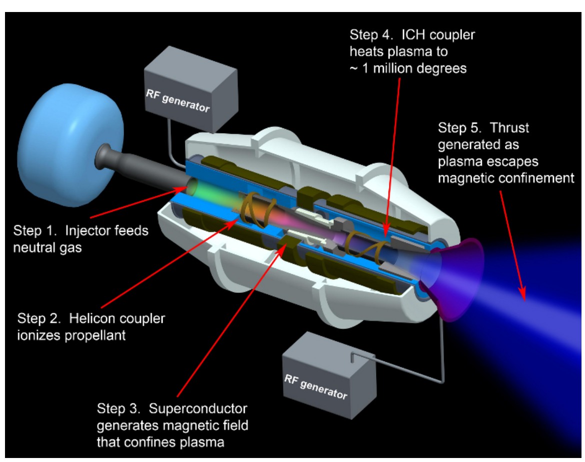

Figure 1. Schematic of the VASIMR® engine detailing its main components.

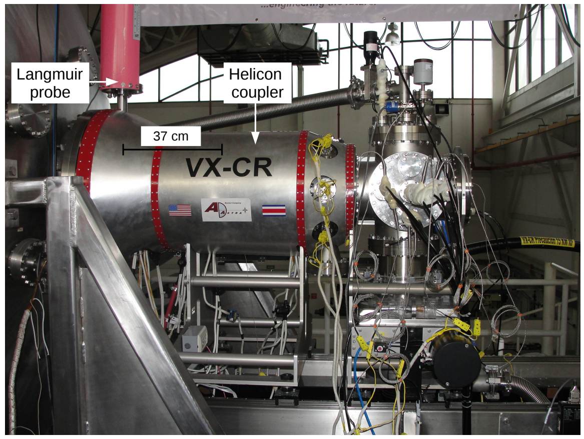

Figure 2. The VX-CR experiment located at Ad Astra Rocket Company Costa Rica. The image shows the location of the reciprocating Langmuir probe and the helicon coupler. The probe is located 37 cm downstream from the edge of the coupler.

The VX-CR,[2] shown in Fig. 2, is the flagship experiment at the Costa Rican research facility. It functions as a test-bed of the thermal management and lifetime solutions of the VASIMR® propulsion system while serving as a complement to the VASIMR® VX-200[3] , the engine currently developed at AARC's Texas facility. Compared to the VX-200, the VX-CR presents only the first stage of the VASIMR® engine, i.e. the helicon stage; nonetheless it was designed for longer periods of operation. Previous work on the VX-CR has shown its capability to operate for long periods of time (>15 continuous hours and >100 accumulated hours at 1.25 kW).[2] Earlier campaigns have been mainly focused on plasma production and long-term operations, specifically dealing with helicon design, vacuum improvements, sources of contaminants, and possible cooling methods. The experiment campaigns showcased here, were mainly focused on the characterization of the plasma plume.

II. Experimental Setup

As mentioned above, the VX-CR experiment is a high-power (up to 13 kW) helicon source designed to study the thermal management systems of the VASIMR® first stage, and also to perform component lifetime studies during long periods of time (>100 accumulated hours). All of its subsystems have been described previously,[2] here we will merely summarize the relevant components.

The helicon core and RF coupler of the plasma source are enclosed in high-vacuum chamber (pressure at $\sim 10^{-6}$ torr) which is isolated and separately pumped from the main exhaust chamber. This exhaust chamber consists of a 14 m^3 stainless-steel cylinder, 4 meters long and 2 meters in diameter. During normal operation it has a baseline pressure of approximately 10^{-3} torr.

Figure 3 shows the RF power and the pressure at exhaust for a typical experimental run. As can be seen in Fig. 3, RF power is carefully ramped up and down at the beginning and end of each run. Once the system reaches the target RF power, it is allowed to stabilize prior to any plasma measurements.

Argon is the propellant used in our experiments. During normal operations the gas injection system delivers $\dot{m}$ = 6 mg/s of argon gas flowing into the helicon core. A set of solenoid magnets provide the magnetic field required in order to launch the helicon wave. More over, once the propellant is ionized, the plasma is bound by the solenoid's axial magnetic field thus limiting its interaction with the walls of the helicon source. At its peak, our magnetic field has a value of 0.4 T. Our experimental setup also includes trim coils to optimize the magnetic field configuration. However during these initial experiments these trim coils were not implemented.

To monitor the performance of our plasma source an its components, our plasma diagnostics include a large array of temperature sensors used to monitor the thermal behaviour of the core and a reciprocating Langmuir probe used to diagnose the plasma exhaust plume. In this paper, we will focus on the plasma parameters measured with Langmuir probe.

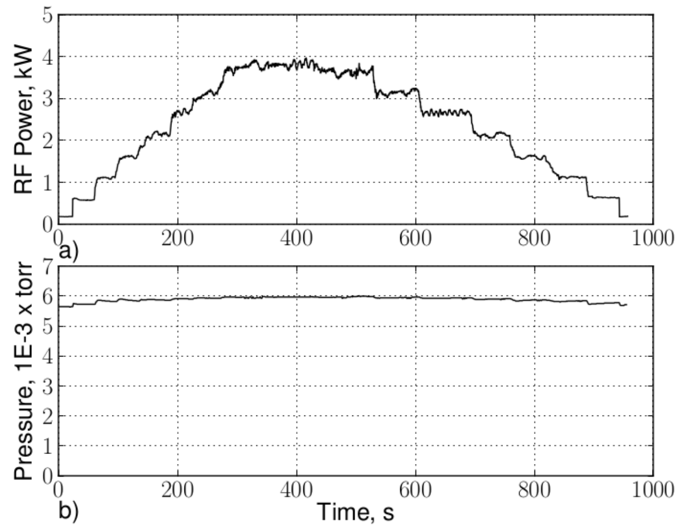

Figure 3. Forward RF power (a) and exhaust pressure (b) profiles for a typical shot.

A. Reciprocating Langmuir Probe

The Langmuir probe consists of an electrode with a 2.5 mm by 5 mm rectangular cross section located at the exhaust, 37 cm downstream from the edge of the helicon coupler (see Fig. 2). A reciprocating motion translates the collector from out of the plasma to the plume axis and is driven by a pneumatic piston. Once exposed to the plasma, it collects a current largely dependent on the potential difference between the electrode and the local plasma. By biasing the probe at various voltages, the collected current varies, thus generating the characteristic I-V curve. This curve is then used to extract various plasma parameters such as electron temperature T_e, ion density n_i and plasma potential V_P.[4]

Our probe uses RF compensation electronics to passively suppress any induced noise caused by the RF of the helicon source. In RF plasmas, the local potential fluctuates with the amplitude and frequency of the perturbing RF waves, thus altering the I-V characteristic of a Langmuir probe.[4] The RF compensation electronics are comprised of two ferrite beads in series with the signal and a 0.1 μF capacitor between signal and ground. The components were chosen to filter noise around the RF frequency (13.56 MHz) and its first harmonic.

An isolation circuit was designed to measure the probe current while simultaneously monitoring the bias voltage. Along with the probe position, the bias voltage and the probe current were collected and digitized by the data-acquisition system at sampling rates of 1 kHz.

III. Experimental Results

The reciprocating probe takes roughly 150 ms to move 150 mm from a fully contracted position to the center of the plasma where it dwells for roughly 1300 ms before retracting again in a little over 400 ms.

Figure 4 shows the data collected from the reciprocating probe from a typical experimental run. The top panel, a), shows the position of the reciprocating probe; the middle panel, b), shows the triangular voltage sweep with a peak-to-peak voltage of approximately 60 V and a frequency of 1 Hz; and the bottom panel, c), shows the collected probe current.

Figure 5 shows the IV characteristic extracted from this data. Ion saturation is clearly noticeable at negative voltages. However at the other extreme, the reciprocating probe was not sufficiently biased on the positive voltage side to be able to collect current in electron saturation. Shown in red is a straight line fit to the ion current from where we extract the ion saturation current, I_{is}.

Once the I_{is} is determined, it can be subtracted from the overall probe current to yield the electron

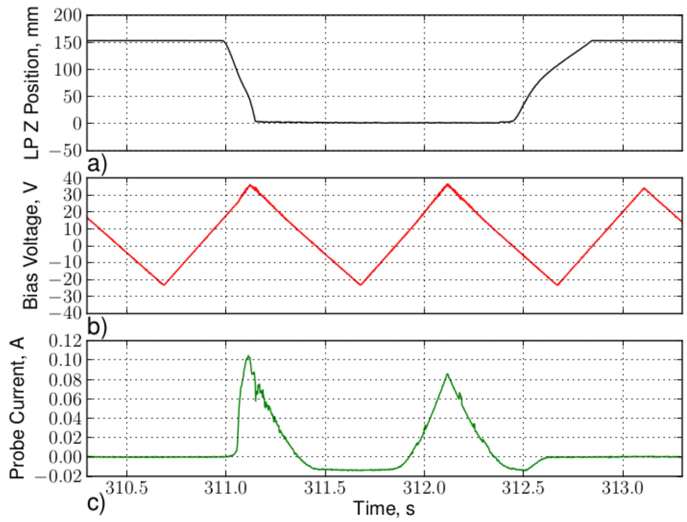

Figure 4. Typical signals obtained from the reciprocating Langmuir probe, featuring probe position from plasma center (a), probe bias voltage (b) and collected current (c). Bias voltage was swept at a frequency of 1 Hz.

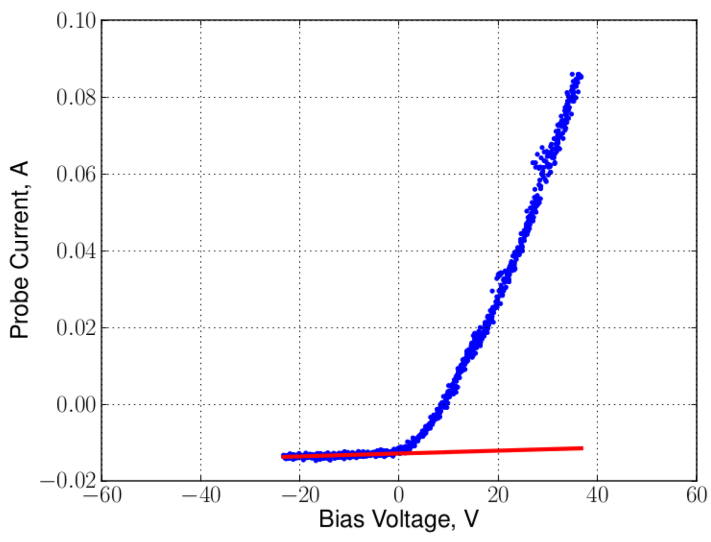

Figure 5. Example of an IV characteristic obtained from the reciprocating probe. The red line shows a straight line fit to determine the ion saturation current, $I_{is} = -13.4 \pm 0.2$ mA. For this particular shot, RF power was set at 3.6 kW. Notice that the range of the bias voltage was not wide enough to reach electron saturation.

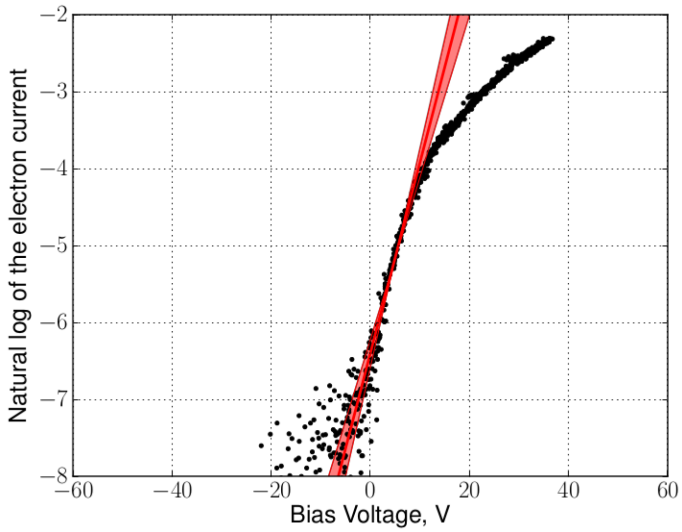

Figure 6. Natural logarithm of the calculated electron current, $\mathbf{I_e}$, obtained by subtracting I_{is} from the probe current. The forward RF power was set at 3.6 kW. The red line shows a straight line fit used to determine the electron temperature, $\mathbf{T_e = 4.0 \pm 0.6}$ eV. The red shaded region shows how the fit varies when adding or subtracting the uncertainty to $\mathbf{T_e}$.

current, I_e, which is given by[4]

$$I_e = I_{es}\exp[-e(V_p - V_B)/(k_B T_e)]. \tag{1}$$

Here I_{es} is the electron saturation current, e is the elementary charge, V_p and V_B are respectively the plasma and bias voltage, T_e is the electron temperature, and k_B is the Boltzmann constant. As will be shown, we determine T_e from measurement of the electron current.

As illustrated in Fig. 6, we fit a straight line to $\ln(I_e)$ in the transition region, i.e. the region where the electron current is increasing prior to saturation.[4] Following Eq. 1, the inverse of the slope provides T_e. The fitted straight line and the calculated T_e vary as one graphically chooses a lower, a wider or a narrower transition region. The red shaded region in Fig. 6 encompasses this range of fitted lines. The uncertainty in T_e captures the range in variation in the fit parameters of these curves.

Figure 7 summarizes the measured electron temperatures obtained at various RF powers. Values range from 3 eV to 4 eV, well within the expected range for a helicon source of this type.[5,6]

Additionally, we also extract ion density with the reciprocating probe. We do so by measuring ion saturation current at various radial positions, with a negatively biased probe at -30 V. It must be noted that at this negative value, we could be emitting secondary electrons at ionizing energies, thus creating extra plasma which will artificially increase our collected ion current. It is then understood that the measurements henceforth represent an upper limit to the ion current.

Using the Bohm formula[7]

$$I_{is} = 0.6 e n_i \sqrt{\frac{k_B T_e}{m_i}} A_{probe}, \tag{2}$$

we calculate ion density with the input of the measured I_{is} and T_e. Here, n_i is the ion density, m_i is the ion mass and A_{probe} is the cross sectional area of the probe.

Figure 8 shows the ion density profile at various RF power settings. Notice the jump in plasma density from 0.6 kW to 1 kW showing the transition of the plasma into helicon mode.[8] Notice also, the flat top distribution of the plasma at higher power settings.

Furthermore, from these ion density profiles we calculate total ion current, I_T, from

$$I_T = 2\pi \int_0^R J(r) r \mathrm{d}r \tag{3}$$

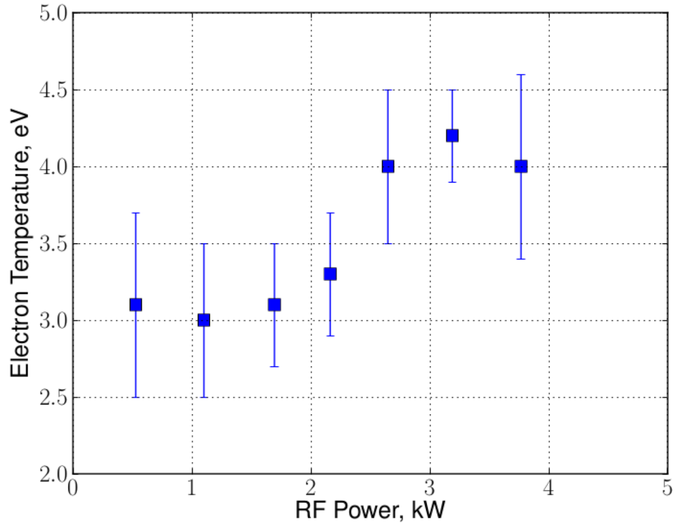

Figure 7. Electron temperature measured at various RF power settings. The uncertainty in T_e captures the range in variation in the fit parameters.

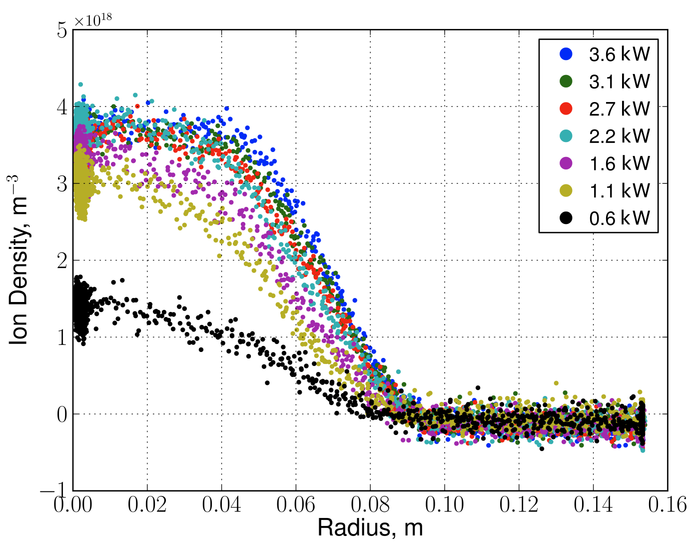

Figure 8. Ion density profiles at various RF power settings. We calculate ion density from the measured I_{is} with a negatively biased probe (-30 V) positioned at various radial positions. Notice the jump in plasma density as the plasma transitions into helicon mode.

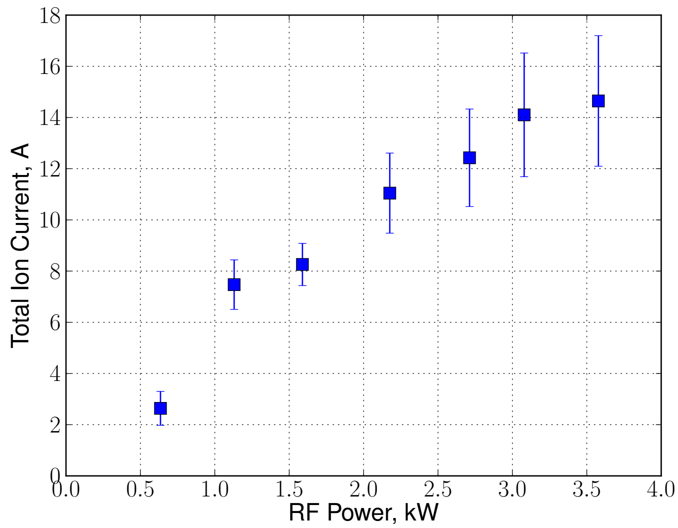

Figure 9. Calculated total ion current, $\mathbf{I_T}$, at various RF power settings and fixed mass flow. The total ion current density was calculated from a numerical integration of the ion density, radial profiles (see Eqs. 3 and 4). Uncertainty in these values originates from the uncertainty in the measurement of current and radial position.

where we are assuming azimuthal symmetry, r is the radial position, and $J(r)$ is the current density given by

$$J(r) = \frac{I(r)}{A_{probe}}. \tag{4}$$

We calculate the total ion current, I_T, by performing a numerical integration and the results are shown in Fig. 9 for various power levels. The uncertainty in these measurements was obtained by propagating the error in $I(r)$ and r. As mentioned previously, these numbers represent top limits to the ion current given the negatively bias probe voltages used to measure I_{is} ($V_B = -30$V).

Finally, from I_T we can estimate ionization fraction, f_i, through,

$$f_i = \frac{m_i I_T}{e\dot{m}} \tag{5}$$

and ion cost, α_c, through,

$$\alpha_c = \frac{P_{in}}{I_T}. \tag{6}$$

where $\dot{m}$ is the flow of propellant and P_{in} is the input RF power.

The results of these calculations are shown in Figs. 10 and 11. Figure 10 shows values of $f_i \sim 1$. As previously mentioned, this could be due to an artificially high ion current from a very negatively biased probe. In addition, this could be a result of a high downstream pressure (see Fig.3). If the gas pressure is too high, we could have recirculation of neutrals back into the helicon source and further re-ionization. Further studies will focus on exploring either explanation.

IV. Conclusion

In conclusion, the electron temperatures and ion density profiles measured for the VX-CR are within the expected range for a helicon source experiment.[5,6] On the other hand, the estimated total ion current gives values that seem high, yielding in turn, high ionization fractions and low ion cost.

The magnetic trim coils were not implemented during these experiments. Follow-up experiments will focus on the magnetic field optimization with the trim coils and the possible effect this optimization will have on plasma parameters and density profiles.

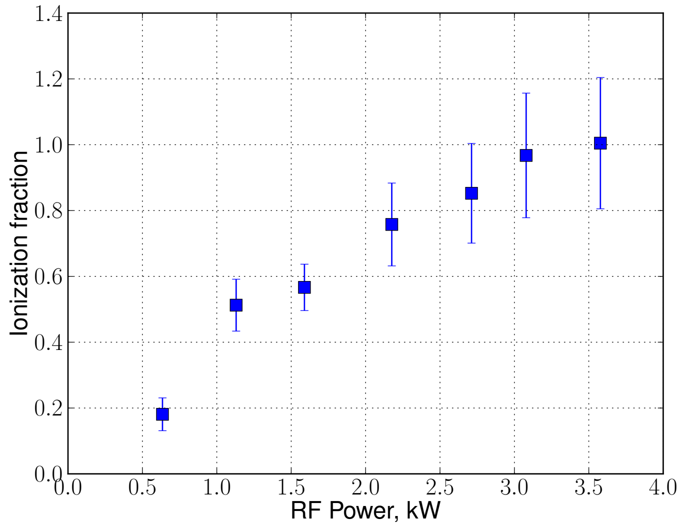

Figure 10. Ionization fraction at various RF power settings and fixed mass flow ($\dot{m} = 6$ mg/s). The errorbars in the graph are calculated from the uncertainty of the total current and mass flow.

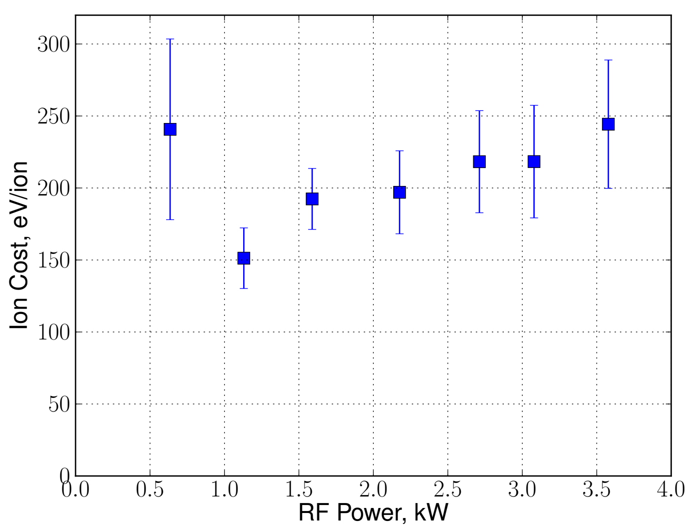

Figure 11. Calculated ion cost at various RF power settings. The uncertainty is calculated by propagating the uncertainties of total current and input RF power.

To finalize, future VX-CR studies will be mainly focused towards measuring potential wall erosion within the core of the helicon source,[9] corresponding with AARC efforts to address the lifetime issues of the engine and the development of the steady state VASIMR® VX-200-SS engine. Due to its design, the VX-CR is suited to measure thermal issues operating at worst-case scenarios. It is therefore crucial to characterize the plasma plume in the VX-CR in order to establish the relevance of the engine test-bed and to allow for scalability in future erosion studies.

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