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# Ambipolar Ion Acceleration in the Expanding Magnetic Nozzle of the VASIMR® VX-200i

Benjamin W. Longmier[1], Jared P. Squire[2], Mark D. Carter[3], Leonard D. Cassady[4], Tim W. Glover[5], William J. Chancery[6], Chris S. Olsen[7], Andrew V. Ilin[8], Greg E. McCaskill[9], and Franklin R. Chang Díaz[10]
*Ad Astra Rocket Company, Webster, TX 77598, USA*

Edgar A. Bering, III[11]
*University of Houston, Departments of Physics and ECE, Houston, TX 77204, USA*

**An observed 20 eV argon ion energy is attributed to a measured axial plasma potential profile within the expanding magnetic nozzle region of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) VX-200i device, a 10% field version of the VX-200 prototype. The ion acceleration mechanism is identified as an ambipolar flow caused by expanding plasma that follows an idealized electron Boltzmann relation, resulting in a maximum axial speed of $\sim 4.1 c_S$. The VX-200i prototype was operated with 25 mg/s argon propellant, using only the first stage helicon plasma source running at 32 kW, while the engine's second stage was turned off. The size scale and spatial location of the plasma potential structure in the expanding magnetic nozzle region appears to follow the size scale and spatial location of the expanding magnetic field. The thickness of the potential structure was found to be $10^5$ $\lambda_{De}$, many orders of magnitude larger than typical double layer structures. The background plasma density and neutral argon pressure were $10^9$ cm$^{-3}$ and 2x10$^{-5}$ Torr respectively. While the VX-200i results are not indicative of the full engine performance, the ambipolar ion acceleration results have led to more comprehensive efficiency models of VASIMR® performance.**

[1] Research Scientist, Ad Astra Rocket Company, University of Houston. Member
[2] Director of Research, Ad Astra Rocket Company, 141 W. Bay Area Blvd. Member
[3] Director of Technology, Ad Astra Rocket Company, 141 W. Bay Area Blvd.
[4] Lead Project Engineer, Ad Astra Rocket Company, 141 W. Bay Area Blvd. Member
[5] Director of Development, Ad Astra Rocket Company, 141 W. Bay Area Blvd., Member
[6] Research Scientist, Ad Astra Rocket Company, 141 W. Bay Area Blvd.
[7] Research Scientist, Ad Astra Rocket Company, 141 W. Bay Area Blvd.
[8] Computational Research Lead, Ad Astra Rocket Company, 141 W. Bay Area Blvd.
[9] Senior RF Engineer, Ad Astra Rocket Company, 141 W. Bay Area Blvd., Member
[10] Chief Executive Officer, Ad Astra Rocket Company, 141 W. Bay Area Blvd., Associate Fellow
[11] Professor, Physics and ECE, 617 Science & Research Bldg 1, Associate Fellow

## I. Introduction

Single stage helicon sources and Electron Cyclotron Resonance (ECR) plasma sources have previously been proposed as stand-alone electrodeless thrusters for spacecraft propulsion.[1-27] The concept takes advantage of a plasma potential step as a means to accelerate the escaping ions. Charge neutrality of the thruster/spacecraft system is maintained by a population of high energy electrons that overcome the plasma potential step to escape at the same rate as the ions. The plasma potential step is typically described as a Current Free Double Layer (CFDL), ambipolar diffusion/flow, a balance between electron pressure and magnetic pressure, or some combination of these individual processes.[8-34]

The presence of a plasma potential structure was observed during the helicon-only operation of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) VX-200i, and is attributed to an idealized ambipolar flow process that results from a decrease in the plasma density as the plasma escapes from the helicon source's magnetic nozzle. A large downstream vacuum chamber size, >5 m, low background plasma density, <$10^9$ $cm^{-3}$, and low background neutral pressure, <$2x10^{-5}$ Torr, yielded unique and novel operating conditions.

It has been shown that the observed ion energy of ions emitted from double layer thrusters in a laboratory setting exhibit a direct correlation to the neutral gas background pressure[11-15,25-27], which could actually be a result of a large population of electrons in the downstream plasma.[29,30,32] Charles et al. show that the range of gas background pressures that corresponds to the largest potential step in a typical helicon thruster double layer is ~$2x10^{-4}$ to $2x10^{-3}$ Torr for argon.[20,23,35-37] Double layer thruster operation in space will necessarily have a neutral background pressure many orders of magnitude lower than $10^{-4}$ Torr in the far plume region, and may require an extra injection of neutral gas in the nozzle region or a secondary downstream cathode to supply a population of electrons to create and sustain a large amplitude double layer. More experiments are needed to resolve the existence of double layers generated by an expanding plasma source in a laboratory setting at background pressures below $10^{-4}$ and associated low background plasma densities. Hershkowitz et al.[29,30,32] claim that the formation of a laboratory double layer may *require* a low density background population of electrons to flow upstream into the double layer plasma source or double layer thruster. The goal of the experiments presented in this paper is to expand on existing research performed by Charles, Boswell, Lieberman, Chen, Hershkowitz, Scime, Fruchtman, and many others and explore the nature of ion acceleration in an expanding magnetic nozzle in a new parameter space.

Though nominal VASIMR® operation includes a second stage to accelerate ions through single pass Ion Cyclotron Heating (ICH), the second stage was turned off for the experiments presented in this paper. The recently observed ambipolar potential structure provides an added increase in ion velocity during all phases of VASIMR® operation. The result is likely to be an increase in the overall system efficiency of VASIMR®, especially in the high thrust-low $I_{sp}$ operating range.

## II. VX-200i Device and Supporting Hardware

The VASIMR® VX-200i, Fig. 1, came online in Oct 2008 and was a precursor device to the VX-200, a superconducting device that came online in July 2009. The VX-200i differs from the VX-200 by using water cooled copper electromagnets instead of low temperature superconducting magnets. The VX-200i was operated with a magnetic field of ~1700 G in this set of experiments. However, the VX-200 operates with a peak magnetic field of ~20,000 G.

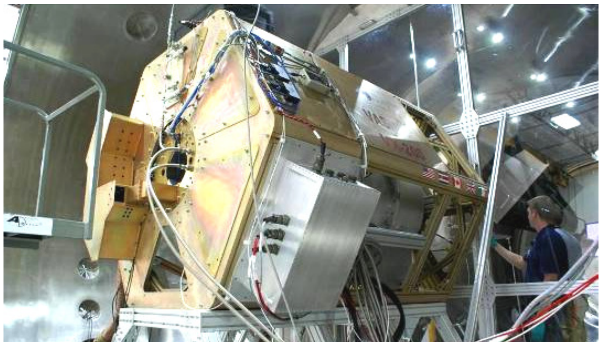


**Fig. 1. VASIMR® VX-200i prototype.**

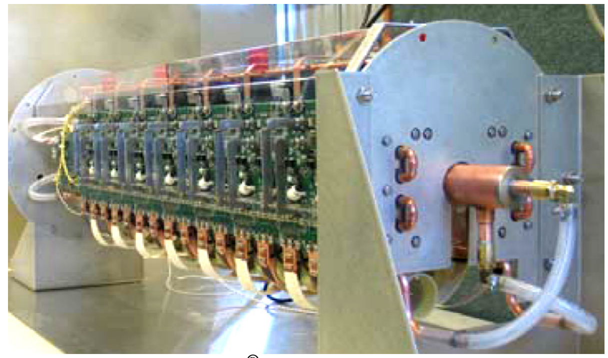


**Fig. 2. VASIMR® VX-200i solid-state RF amplifier, 1m in length.**

Both the VX-200i and the VX-200 have a total RF power capability of 200 kW driven by high-efficiency, as high as 98%, solid-state DC-RF generators, as shown in Fig. 2. For the series of experiments presented in this paper the helicon plasma source of the VX-200i was driven at 30 kW using 25 mg/s of argon gas and the booster stage was unpowered. The magnetic field schematic for the VX-200i is shown in Fig. 3. The helicon source internal structure was electrically floating.

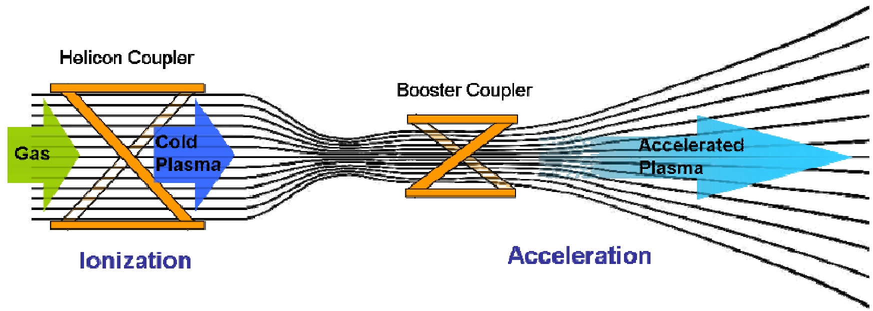



**Fig. 3. Schematic illustration of the VASIMR magnetic field and RF couplers.**

The Ad Astra Rocket Company vacuum chamber is 4.2 m in diameter with a total internal volume of 150 $m^3$, Figs. 4 and 5, and has four 50,000 l/s cryopanels for a total pumping capability of 200,000 l/s. One of the panels was used for the experiments presented in this paper for a total pumping rate of 50,000 l/s and an ultimate base pressure of $1.7x10^{-8}$ Torr. The vacuum chamber is partitioned into two sections, a rocket section and an exhaust section. The rocket section stays at a space-like vacuum pressure which is lower than the exhaust section while the VX-200i is firing. Also shown in Fig. 4 and Fig. 5a) is a 2.5 m by 5 m translation stage that carries a suite of plasma diagnostics for plume characterization. The translation stage uses 2 independent ball screws and is driven by vacuum compatible stepper motors which yield a positional resolution of 0.5 mm. A vertical member mounted to the translation stage holds a mounting table. Each diagnostic is bolted directly to the mounting table for precise alignment and positioning on the translation stage. The red solid line in Fig. 4 depicts the full axial range of plasma potential measurements taken for the data presented in this paper. The red line extends into the VASIMR® VX-200i device, but does not penetrate the helicon source itself, and extends 5 m downstream into the expanding plume region of the vacuum chamber.

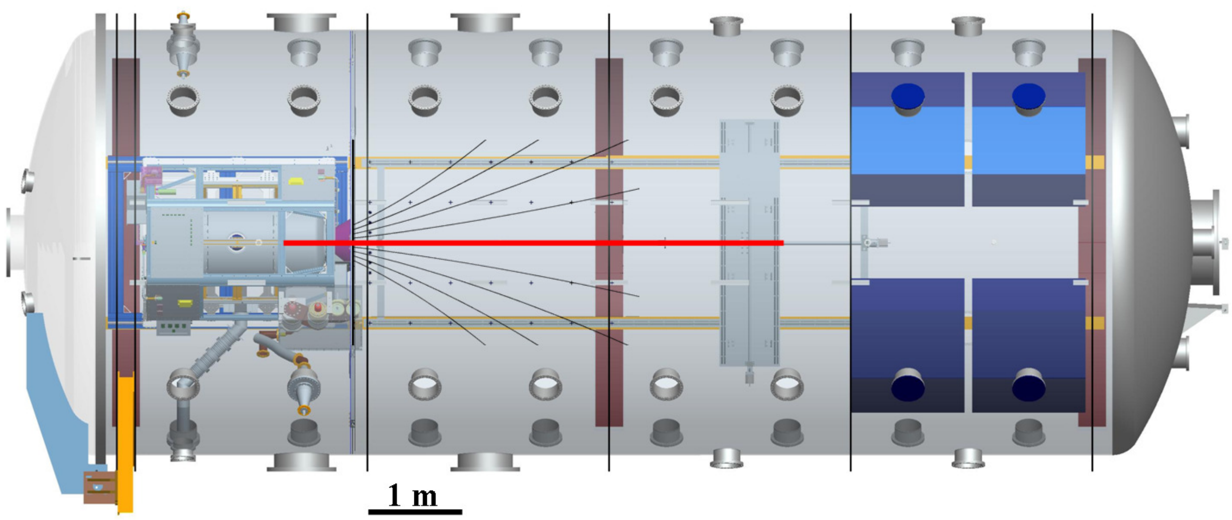
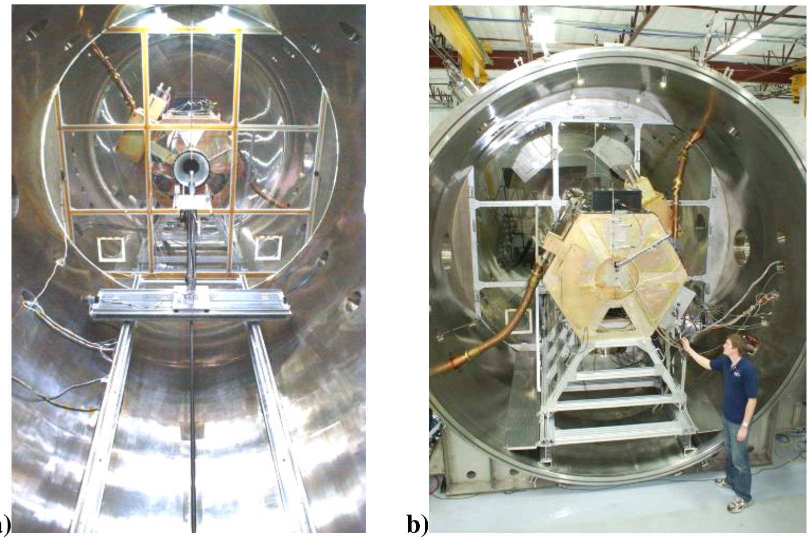



**Fig. 4. Schematic illustration of the Ad Astra Rocket Company vacuum chamber, overhead view.**



a) b)

**Fig. 5. Photograph from within the Ad Astra Rocket Company vacuum chamber showing the translation stage, a), and VX-200i mounted within the vacuum chamber, b).**

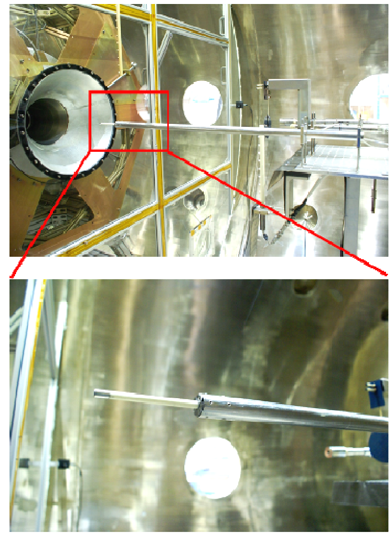


**Fig. 6. Photograph of the Langmuir probe with guard ring on a 70 cm extension shaft.**

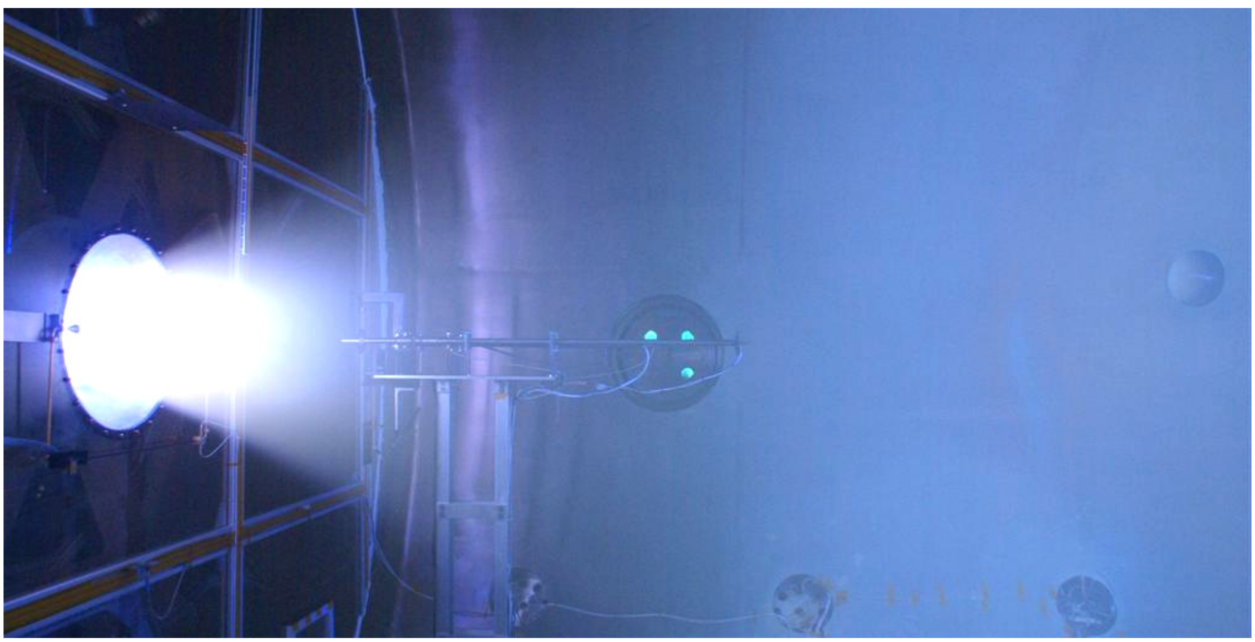


**Fig. 7. Photograph of the VX-200i exhaust plume with the translation stage and plasma diagnostics in the background.**

Measurements of the plasma potential in the rocket core and the plasma plume were made with a ¼" diameter tungsten Langmuir probe with a guard ring, Fig. 6. The probe was swept in voltage from -40 V to +40 V through the entire range of ion saturation and electron saturation regions with a sweep rate of 80 Hz and a sampling rate of 40 kHz. RF compensation was tested, and produced only 0.2 V variations in the measured plasma potential, and 0.1 eV variations in the electron temperature. Floating potential measurements were made with a high impedance oscilloscope from 1 Hz to 100 MHz. Fluctuations in the floating potential were observed to have a maximum peak-to-peak amplitude of 0.4 V at the driving frequency of the helicon plasma source, near the industrial standard 6.78 MHz. Measurements of the ion energy in the downstream section of the plume were made with a 4 grid Retarding Potential Analyzer (RPA). Figure 7 shows a photograph of the argon exhaust plume produced by the helicon source from the VX-200i. The translation stage and plasma diagnostics can be seen in the background of the photograph.

## III. Ambipolar Ion Acceleration

It has long been understood that the electron population in an expanding plasma could be responsible for establishing an electric field that contributes to ion acceleration in the form of a double layer or a more gradual ambipolar potential. The former phenomenon has been extensively studied by Boswell, Charles and others who have characterized the conditions under which laboratory double layers may form. These may be strongly dependent on the parameter space in which the experiment is carried out. The following experiments were performed to expand on the work done by Boswell and Charles et al., and in fact the original goal was to find and characterize a double layer within the VX-200i device.

It was observed that the helicon source in the VASIMR® VX-200i produces an acceleration of ions in the expanding magnetic nozzle region downstream of the helicon source. This acceleration is identified as an ambipolar ion acceleration. The thickness of the potential structure observed in the VX-200i device was found to be $10^5\ \lambda_{De}$, many orders of magnitude larger than a double layer structure. A current free double layer, as has been typically defined[11-15, 24], was not observed in the VX-200i device for the described operating conditions. The background plasma density throughout the experiments presented was below $10^9$ cm$^{-3}$, with a neutral gas background pressure below $2\times10^{-5}$ Torr. The argon charge exchange mean-free path was larger than 320 cm for all data presented.

The measured plasma potential, electron temperature, and magnetic field strength as a function of the axial distance in the exhaust plume of the VX-200i device are shown in Fig. 8. The high correlation between the measured axial plasma potential, electron temperature, and magnetic field is more clearly seen if the spatial derivative is taken for $\phi_p$, $T_e$, and $B$, as shown in Fig. 9.

A total drop in the axial plasma potential, $\Delta\phi_p$, of 12 V was measured from location 0 m to 5 m. Plasma potential measurements were only made to an upstream location of 0 m. An additional increase in the magnetic field strength, up to 1700 G, at the magnetic choke of the VX-200i device existed upstream of the 0 m location. Assuming ambipolar ion acceleration from this magnetic choke point of 1700 Gauss, a resulting ion energy equal to 20.4 eV

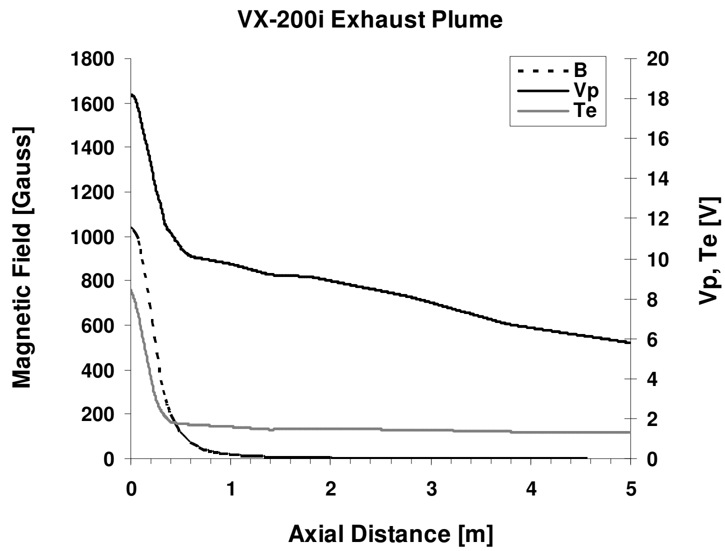



**Fig. 8. Measured plasma potential (solid black), electron temperature (solid gray), and axial magnetic field strength (dashed black) as a function of axial distance. Plasma potential and electron temperature measurements have an error +/- 0.5 V.**

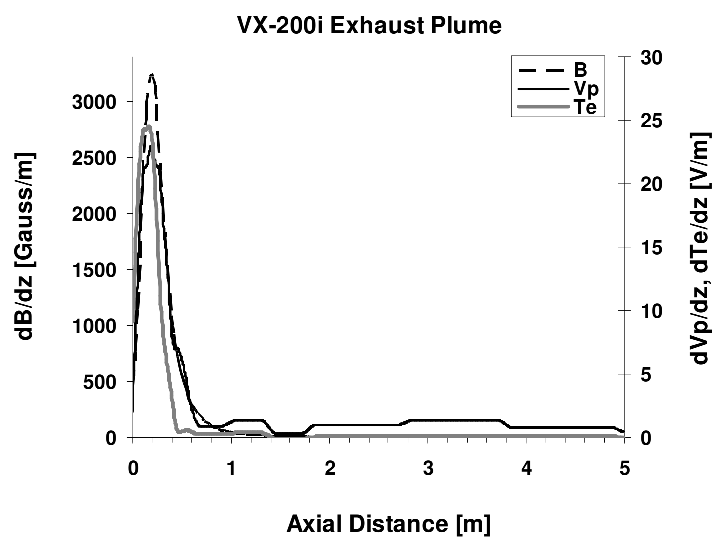



**Fig. 9. Spatial derivative of the measured plasma potential, (solid black) electron temperature (solid gray), and axial magnetic field strength (dashed black) as a function of axial distance. Plasma potential and electron temperature measurements have an error +/- 0.5 V.**

would be expected with an ambipolar ion acceleration. RPA measurements revealed an argon ion energy in the downstream section of the VX-200i device of 22 ± 3 eV. Figure 10 is a representative graph of the I-V characteristic from the RPA (black) and the ion energy distribution function (red) as a function of the RPA retarding potential. The RPA was located downstream of the magnetic nozzle and was able to measure the full ion energy from the VX-200i helicon source. Several retarding potential sweeps are superimposed on top of each other in Fig. 10.

Beginning at location 0 m the magnetic field decreases monotonically, giving rise to an ambipolar flow of quasineutral plasma. In this monotonically decreasing region of the magnetic field, location 0 m to 1 m, the plasma density scales with the decreasing magnetic field such that $\nabla B \propto \nabla n_e$, as shown in Fig. 11. Others observe similar ion acceleration results from an expanding plasma along a magnetic nozzle.[38-39]

The $\nabla B \propto \nabla n_e$ correlation gives rise to a correlation between $\nabla n_e \propto \nabla \phi_p$ and $\nabla n_e \propto \nabla T_e$. In Fig. 12 $\phi_p$ (solid black line), and plasma density, $n_e$ (solid gray line), are graphed along with a calculated plasma potential, $\phi_{p\_Boltzmann}$ (dashed blue line). The measured values of the local electron temperature and plasma density were used to calculate a plasma potential profile, $\phi_{p\_Boltzmann}$, based on a Boltzmann relation for electrons assuming a diffusive model and a Maxwellian distribution function for the electrons throughout the exhaust plume, where $\phi_{p\_Boltzmann} = T_e \ln(n_e / n_{e\_\max})$.

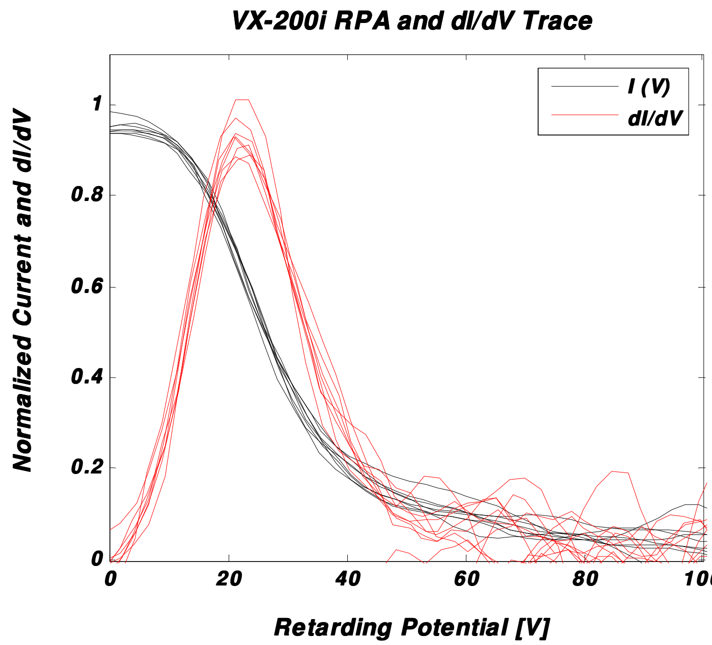



**Fig. 10. Normalized RPA I-V characteristic (black) and normalized ion energy distribution function (red).**

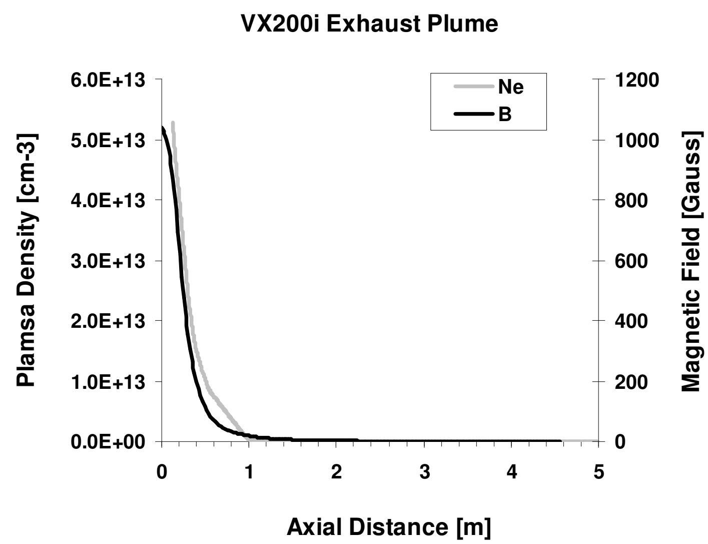



**Fig. 11. Measured plasma density (gray) and axial magnetic field strength (black) as a function of distance.**

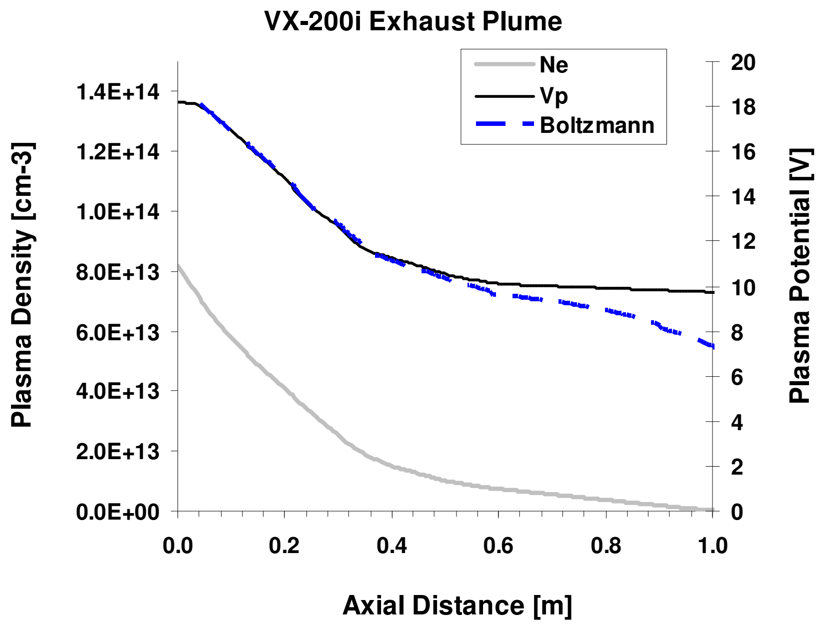



**Fig. 12. Measured plasma potential (solid black) and plasma density (solid gray) compared to the calculated plasma potential (dashed blue) assuming an electron Boltzmann relation.**

## V. Discussion

### A. Ambipolar Acceleration and the Boltzmann Relation

In a helicon plasma source the electron thermal velocity is much greater than the ion thermal velocity and as the electrons start to stream away from the helicon source in the magnetic nozzle, they create a potential step that acts to confine the total electron flux to that of the ion flux. The ions in the upstream section are consequently accelerated down the hill of this potential step, in this case to a velocity equal to $\sim 4.1 c_S$, where $c_S = (k_B T_e / m)^{1/2}$.

In the presence of a large population of electrons in the downstream exhaust plume, the potential step will tend to accelerate these electrons back upstream towards the helicon source. It is possible that the simple presence of a large population of downstream electrons creates the commonly observed Current Free Double Layer, and could explain why CFDLs are only observed for a finite range of downstream neutral pressure levels.[30, 40]

Figure 12 shows a high correlation between the measured and calculated plasma potential profiles at a location between 0 m and 0.6 m. However, the correlation begins to break down at locations farther downstream in the magnetic nozzle, locations greater than 0.6 m. The disagreement between the calculated plasma potential and the measured plasma potential at locations greater than 0.6 m is identified as the result of three effects.

1) The electron distribution becomes non-Maxwellian in the diverging magnetic field as a result of exchange of energy from the high energy electrons to the ions as the ions transition from sub-sonic to super-sonic. This would tend to lower the effective electron temperature that is measured by a swept Langmuir probe.
2) The electron distribution becomes non-Maxwellian in the diverging magnetic field as most of the incident electrons in the upstream section are reflected by the potential step and only the high energy electrons, i.e. those with $E_e \geq \Delta\phi_p$. This would tend to lower the effective electron temperature that is measured by a swept Langmuir probe.

3) At some point downstream, the plasma potential is referenced to the grounded vacuum chamber instead of the floating endplate and floating walls on the helicon source. This effect would tend to flatten out and fix the plasma potential in the downstream section of the magnetic nozzle, this effect is observed in Fig. 8.

If VASIMR® or a double layer thruster were to be operated in a space environment away from voltage reference points in the exhaust plume, it is likely that the axial plasma potential would continue to fall off from the internal floating potential of the thruster at a rate consistent with the Boltzmann relation for electrons, at least until the electron distribution function is severely altered from that of a Maxwellian distribution.

**B. VASIMR® Efficiency**

The net effect of the ambipolar ion acceleration results presented for the helicon stage of VX-200i is an overall increase in the ion velocity of the system. Some early models of the operation of VASIMR® conservatively set the exiting ion energy from the helicon source at 0 eV.[41-47] These efficiency models relied on ICH and ion acceleration from the 1st adiabatic invariant. It is argued that when ICH RF power is applied to the fully functional VX-200 device, the observed axial plasma potential structure will remain intact, acting to enhance the ion velocity distribution function to higher values than previous VASIMR® models took into account.

Based on VX-200i results, an argon ion energy of 20 eV was used for the VASIMR® efficiency model presented in Figs. 12 and 13. Based on recent full magnetic field - full RF power VX-200 helicon results, an ion production cost of 80 eV was assumed for Figs. 12 and 13.[41] Figure 12 shows the calculated power efficiency of VASIMR® as a function of applied ICH power with (red) and without (black) an assumed ion energy of 20 eV from the helicon source. The power efficiency is significantly improved when VASIMR® is operated with a reduced ICH power level due to the 20 eV ion energy that the helicon source produces. This effect may make certain high thrust, low $I_{sp}$ missions possible and more attractive. Figure 13 shows the calculated system power efficiency as a function of Isp with (red) and without (black) an assumed ion energy of 20 eV from the helicon source. The upper curve (red) in Fig. 13 begins at 970 s due to the fact that the VX-200 is unable to produce a lower Isp if the helicon source is operating at a constant 36 kW.

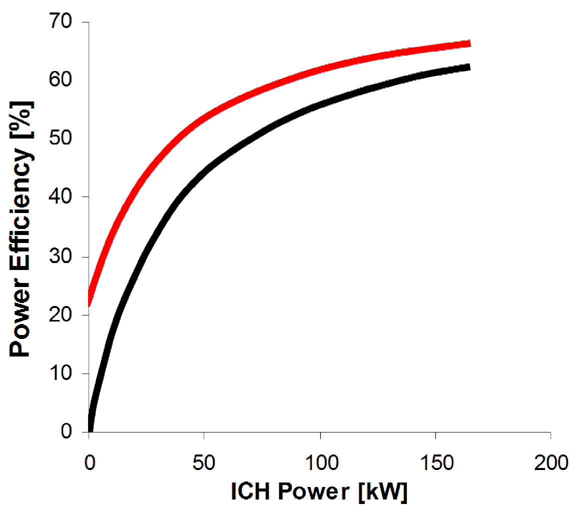



**Fig. 12. Calculated VASIMR® power efficiency as a function of applied ICH power. The model assumes a constant 36 kW helicon power with (red) and without (black) 20 eV ions from the helicon source.**

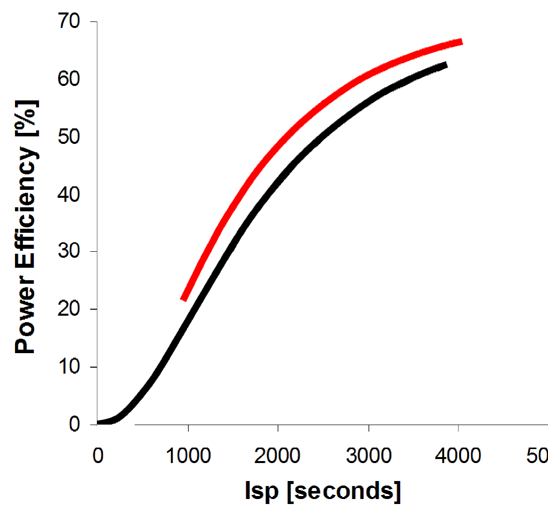



**Fig. 13. Calculated VASIMR® power efficiency as a function of Isp The model assumes a constant 36 kW helicon power with (red) and without (black) 20 eV ions from the helicon source.**

If the ambipolar ion acceleration found in the VX-200i continues to scale proportional to $\nabla n_e$, then the VX-200 device should produce a resulting ion energy that similarly scales with $\nabla n_e$. Recent VX-200 results using 32 kW RF power and 130 mg/s argon have revealed a total ion current that is ~7x larger than the VX-200i, which operated at an RF power level of 32 kW and an argon flow rate of 25 mg/s. The total strength of the peak magnetic field of the VX-200 is also ~20x larger that of the VX-200i. The enhanced ion flux and increased magnetic field should act to significantly increase the maximum plasma density within the helicon stage of VX-200 and increase the total $\nabla n_e$ that can be expected with the new full power VX-200 device. Future experiments are planned to look at the total ambipolar ion acceleration in the new VX-200 device with and without ICH power in an effort to find scaling laws and/or a saturation in the ambipolar ion acceleration mechanisms described in this paper.

## V. Conclusion

Using a one dimensional idealized electron Boltzmann relation, it was possible to describe the observed plasma potential profiles and the resulting ambipolar ion acceleration seen during the operation of the helicon stage of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) VX-200i device. The measured plasma potential was observed to differ from calculated plasma potential only in the far-plume region of the VX-200i magnetic nozzle, and agreed closely within the first meter of the magnetic nozzle. A double layer plasma potential-like structure as reported by others was not observed. The background plasma density and background argon neutral pressure were below $10^9$ $cm^{-3}$ and $2x10^{-5}$ Torr respectively. It is argued that the existence of a double layer may in fact require a substantial population of downstream electrons, which may be unphysical in a space environment. A 20 eV argon ion energy was inferred by plasma potential measurements and directly measured with a retarding potential analyzer (RPA) in the magnetic nozzle of the VX-200i device. A downstream argon ion velocity equal to 410% of the ion sound speed was observed in the far-plume region of the VX-200i device. Previous VASIMR® power efficiency models conservatively neglected the added ion velocity from ambipolar ion acceleration. The present results support the inclusion of this effect in the current model.

## Acknowledgements

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