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Ion velocities in vacuum arc plasmas have been measured for most conducting elements of the Periodic Table. The method is based on drift time measurements via the delay time between arc current modulation and ion flux modulation. A correlation has been found between the element-specific ion velocity and average ion charge state; however, differently charged ions of the same element have approximately the same velocity. These findings contradict the potential hump model but are in agreement with a gasdynamic model that describes ion acceleration as driven by pressure gradients and electron-ion friction. The differences between elements can be explained by the element-specific power density of the cathode spot plasma which in turn determines the temperature, average charge state, and ion velocity of the expanding vacuum arc plasma. © *2000 American Institute of Physics.* [S0021-8979(00)08723-5]

I. INTRODUCTION

The vacuum arc plasma is produced at nonstationary cathode spots — micro-size, nonstationary locations of very high current density and plasma density.[1] The cathode material is the feedstock material for the plasma. It is well known[2] that the velocity of ions is very high, of order 10^4 m/s, and hence supersonic with respect to the ion sound velocity. Tanberg[3] published first velocity data for copper in 1930. He measured $\overline{v_i}(\mathrm{Cu}) = 1.6\times 10^4$ m/s using two indirect methods: the reaction force of the plasma on the cathode, and the force of the plasma on a suspended vane. His result is surprisingly accurate, as confirmed by later measurements using the same and other methods,[4,5] including the method described in this work. The measurements showed that ions have an energy that, expressed in terms of electron volts, or volts if normalized by ion charge, is greater than the arc burning voltage. This initially surprising result is in fact less remarkable when it is noted that the acceleration of ions occurs away from the cathode, and thus in the ''wrong'' direction, and hence cannot be a simple acceleration by the discharge electric field.

The article by Davis and Miller[5] is considered as one of the most thorough experimental works in the field. Electrostatic and magnetic charge and energy analyzers were used to investigate the following cathode materials: C, Al, Ca, Ni, Cu, Zr, Mo, Ag, and Ta. All velocities were found to be in a relatively narrow range from 0.65×10^4 to 3.7×10^4 m/s, with the low-mass ions being faster than the high-mass ions.

In the late 1990s, a current ''jump'' or ''spike'' method[6,7] was used to directly determine the charge-state-resolved ion velocity without using electrostatic or magnetic energy analyzers. In this method, a sharp current spike is superimposed on the otherwise relatively constant arc current. The current spike increases the mean ion charge state,[6,7] but it also leads to a change in plasma density that can be monitored (with delay) in an extracted ion beam. For velocity measurements, the current spike method has the drawback that the spike itself can cause a change in the ion velocity, and hence what is measured is not necessarily the same ion velocity that is present in the plasma without spike. In this article, the spike method is modified in the sense that only gradual, ''gentle'' modulations are superimposed on the arc current. By parameter variation it can be shown that gentle modulations do not change ion charge states and velocities in any significant way.

II. MEASUREMENT PRINCIPLE AND EXPERIMENTAL DETAILS

The basic configuration of the ''Mevva V''[8] vacuum arc ion source was used for these experiments. The plasma part of the ion source consists of a cathode rod 6.25 mm in diameter, and an annular anode 30 mm inner diameter and 30 mm in length. Plasma generated at the front face of the cathode expands through the anode and enters an expansion region limited by an extractor grid that is also at anode potential (Fig. 1). The distance between the cathode surface and the extractor grid is the plasma drift length $s_{\mathrm{pl}} \approx 145$ mm.

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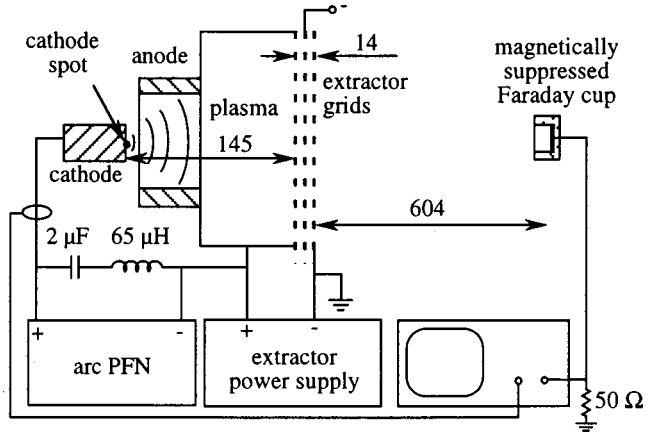

FIG. 1. Schematic of the experimental arrangement, including the plasma drift zone, the ion extractor, and the Faraday cup. A simplified electric schematic shows the pulse-forming network and the modulation LC branch.

The extractor grid is the first of the three grids that form a conventional ion extraction system of the accel–decel type. The plasma was kept at $V_{\mathrm{extr}}=30$ kV above ground for ion acceleration, and the center grid was at -3 kV.

The total time an ion needs to move from its ''birthplace,'' the cathode spot, to a downstream Faraday cup is

$$t_{\mathrm{tot}}=t_{\mathrm{pl}}+t_{\mathrm{extr}}+t_{\mathrm{ib}}, \tag{1}$$

where $t_{\mathrm{pl}}=s_{\mathrm{pl}}/v_i$ is the ion drift time from cathode to first extractor grid (distance $s_{\mathrm{pl}}=145$ mm),

$$t_{\mathrm{extr}}\approx \frac{s_{\mathrm{extr}}}{\sqrt{Qe/2m_i}V_{\mathrm{extr}}} \tag{2}$$

is the time the ion spends in the ion extraction system ($s_{\mathrm{extr}}=14$ mm),

$$t_{\mathrm{ib}}=\frac{s_{\mathrm{ib}}}{\sqrt{2Qe/m_i}V_{\mathrm{extr}}} \tag{3}$$

is the flight time an extracted ion of charge Qe and mass m_i needs to cover the distance $s_{\mathrm{ib}}=604$ mm from the third extractor grid to the Faraday cup detector. It is simple to show that $t_{\mathrm{extr}}\sim 0.1$ μs and thus small compared to t_{pl} and t_{ib}, however, we took t_{extr} into account when calculating the ion velocity in the plasma. For the evaluation of Eqs. (2) and (3) we used published ion charge state data.[8] The small uncertainties in the average charge state number Q are not important since $t_{\mathrm{ib}}\sim 0.5-2\,\mu\mathrm{s}\ll t_{\mathrm{pl}}$. We conclude that by far the largest contribution to the total flight time is the time an ion spends moving from the cathode to the extractor, and hence a delay time measurement between arc current modulation and ion beam modulation can be used to determine the plasma drift time. It has been shown[9,10] that ion acceleration in the plasma occurs almost exclusively in the vicinity of the cathode (region smaller than 1 mm from spot center). Therefore, the ion velocity can be treated as constant for the remainder of the drift region to the extractor and the preextraction ion velocity is simply

$$v_i=\frac{s_{\mathrm{pl}}}{t_{\mathrm{total}}-t_{\mathrm{extr}}-t_{\mathrm{ib}}}. \tag{4}$$

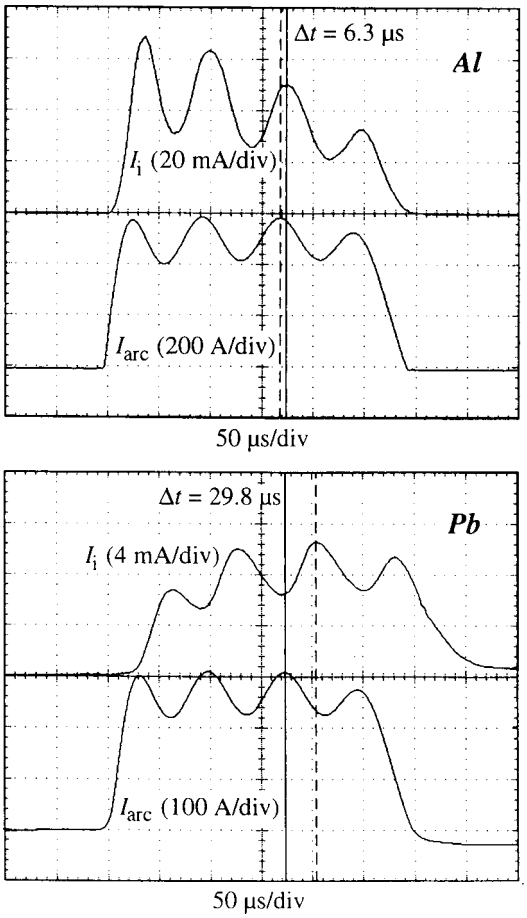

FIG. 2. Example of the modulated arc current and ion beam current.

The motion of ions is detected by imposing a modulation on the arc current. Plasma production is known to be proportional to arc current. A modulation of plasma density drifts with the plasma flow toward the extractor. This modulation can be detected in the extracted ion beam.

The vacuum arc ion source operated at typical arc parameters of current $I_{\mathrm{arc}}=100-300$ A, pulse duration $t=250$ μs, and repetition rate of 1 pulse/s. The discharge was powered by an eight-stage LC pulse forming network that could be charged in the range 200–600 V. On the otherwise-flat current profile a modulation was imposed simply by adding an LC element as shown in Fig. 1.

III. EXPERIMENTAL RESULTS

Figure 2 shows an example of the modulated arc and ion beam current. Here, the delay can be determined at several points throughout the pulse. That is, not only can the delay time be determined but one can check the constancy of the drift velocity throughout the arc pulse. For instance, one can measure the delays between each arc maximum and its corresponding ion beam maximum. Generally, the values obtained indicate constant ion velocity within the measurement accuracy, with the exception of the very beginning of each arc pulse.

One should expect that ion velocities are higher at the beginning of each pulse. The arc modulation method with ion extraction cannot be applied to the plasma front and be-

ginning of each arc pulse because of the significant time needed to space charge compensate the beam. At the very beginning, when ion extraction starts, the beam ''blows up'' by space charge forces, making the signal at the Faraday cup smaller than it would be without the blowup. Independent measurements showed that, for our conditions, about 50 μs are needed to fully compensate the beam. This space charge problem can be avoided by using a plasma modulation flow measurement with Langmuir probes that operate in the ion saturation regime. Control measurements made this way gave velocity data very similar to the data obtained with ion extraction.

Ion velocity measurements were made for most conducting elements of the Periodic Table. The measured velocity data are compiled in Table I. The data represent the macroscopic plasma flow velocity, i.e., a velocity that represents the average weighted over the charge state distribution. Using the relation $E_i = m_i v_i^2/2$, we can express the velocity as a kinetic energy. The results, presented in the customary unit of eV, are shown in Fig. 3. In the same figure, the average ion charge states are shown as published by Brown.[8] The correlation between ion velocity and charge states will be discussed below.

IV. DISCUSSION

The measurements of the characteristic average ion velocity for each element is important, for instance, for the interpretation of probe measurements of cathodic arc plasmas and sheaths. It is known that the Bohm sheath criterion

$$v_i \geqslant v_{is} = \gamma \sqrt{kT_e/m_i} \tag{5}$$

is oversatisfied for vacuum arc plasmas because the ion flow velocity is larger than the ion sound velocity due to ion acceleration at the cathode [in Eq. (5), $\gamma \approx 1$ for $T_i \ll T_e$ and $\gamma \approx 2$ for $T_i = T_e$, the latter applies to vacuum arc plasmas]. There is no need for the presheath[11] that is usually introduced to ensure ion acceleration to the Bohm velocity, $v_B = \gamma \sqrt{kT_e/m_i}$. In contrast to macroscopically stationary plasmas, the saturation ion current density to a probe or other wall is

$$j_i = \overline{Q} e n_i v_i = \overline{Q} e n_i v_B \mathcal{M}, \tag{6}$$

where $\mathcal{M}$ is the ion Mach number. For calculation of the ion sound velocity we can use the electron temperatures that have been derived from a local Saha equilibrium model inside the charge state ''freezing'' zone.[12] Figure 4 shows the ion sound velocities and Mach numbers for most conductive elements of the Periodic Table.

The correlation seen between ion velocity and average charge state (Fig. 3) could mistakenly be interpreted by the potential hump model.[4] In this model, the electric potential has a distinct maximum (>20 V above the interelectrode plasma potential) near the cathode spot. Vapor ionization occurs in the vicinity of the potential maximum and ions are accelerated towards the anode, falling through the potential drop between the maximum and the anode potential. Although it apparently can explain a number of vacuum arc properties, there is a fundamental problem with this theory, namely it is incompatible with Poisson's equation for the given boundary conditions. A potential hump is equivalent to a potential well for electrons, and electrons whose energy is less than kT_e will very quickly fill the potential well thereby reducing its depth to about $V_h \approx kT_e/e$. Therefore, a potential hump for ions can only exist to a maximum height of about kT_e/e. Even if electrons are accelerated in the poten-

TABLE I. Ion velocity data for most conducting elements of the Periodic Table measured for arc currents 100–200 A at pressure 10^{-4} Pa. The results do not noticeably depend on arc current and are valid for pressures up to about 10^{-2} Pa. Data are valid for $t > 100$ μs after arc initiation. The average charge state numbers were taken from Brown,[a] and electron temperatures from Anders,[b] and all other data are this work.

Symbol	Atomic number	Ion velocity (10^4 m/s)	Kinetic energy (eV)	Average charge state number	Temperature of electrons (eV)	Ion Mach number
Li	3	2.38	20	1	2	3.2
C	6	2.97	54	1	2	5.2
Mg	12	3.06	117	1.5	2.1	7.5
Al	13	2.76	106	1.7	3.1	5.9
Si	14	2.58	97	1.4	2	7.0
Ca	20	2.59	140	1.9	2.2	8.0
Ti	22	2.22	122	2.1	3.2	6.2
V	23	1.93	97	2.1	3.4	5.4
Cr	24	1.94	101	2.1	3.4	5.5
Mn	25	1.08	33	1.5	2.6	3.6
Fe	26	1.18	40	1.8	3.4	3.4
Co	27	1.18	43	1.7	3	3.8
Ni	28	1.09	36	1.8	3	3.5
Cu	29	1.28	54	2	3.5	4.0
Zn	30	1.04	36	1.4	2	4.3
Ge	32	1.10	45	2	2	4.8
Y	39	1.43	94	2.3	2.4	6.3
Zr	40	1.57	116	2.6	3.7	5.6
Nb	41	1.55	116	3	4	5.4
Mo	42	1.74	151	3.1	4.5	5.8
Rh	45	1.57	131	3	4.5	5.4
Ag	47	1.04	61	2.1	4	3.9
Cd	48	0.68	27	1.3	2.1	3.6
In	49	0.55	18	1.4	2.1	2.9
Sn	50	0.75	34	1.5	2.1	4.0
Sb	51	0.52	17	1	1.4	3.5
Ba	56	0.67	32	2	2.3	3.7
La	57	0.70	35	2.2	1.4	5.0
Ce	58	0.70	36	2.1	1.7	4.6
Pr	59	0.87	55	2.2	2.5	4.7
Sm	62	0.74	43	2.1	2.2	4.4
Eu	63	0.78	48	2.1	1.9	5.0
Gd	64	0.74	45	2.2	1.7	5.1
Tb	65	0.74	45	2.2	2.1	4.6
Dy	66	0.74	46	2.3	2.4	4.4
Ho	67	0.83	58	2.3	2.4	4.9
Er	68	0.82	59	2.4	2	5.4
Tm	69	0.83	61	2	2.6	4.8
Hf	72	0.92	79	2.9	3.6	4.7
Ta	73	1.14	121	2.9	3.7	5.7
W	74	1.05	106	3.1	4.3	5.0
Pt	78	0.68	47	2.1	4	3.4
Au	79	0.58	34	2	4	2.9
Pb	82	0.54	31	1.6	2	4.0
Bi	83	0.42	19	1.2	1.8	3.3
Th	90	0.99	118	2.9	2.4	7.0
U	92	1.14	160	3.2	3.4	6.9

[a]See Ref. 8.
[b]See Ref. 12.

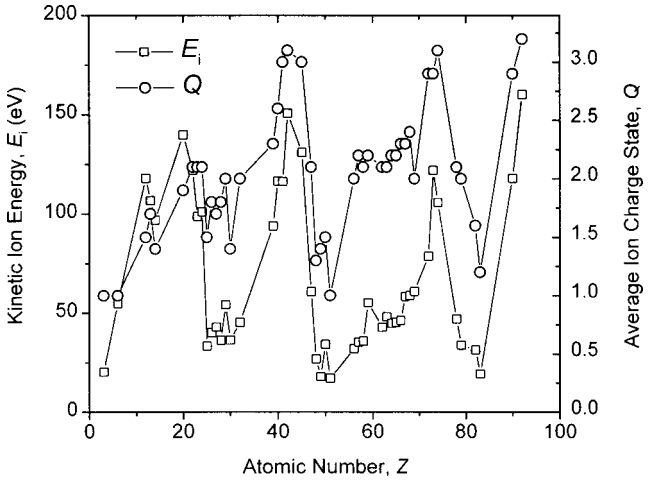

FIG. 3. Kinetic energy of ions (from Table I) and average charge state (from Ref. 8) for most conducting elements.

tial drop they will interact with each other and thermalize extremely fast. Following Spitzer,[13] the Maxwellization time for electrons is about

$$\tau \approx \frac{12\pi^{3/2}\epsilon_0^2 m_e^{1/2}(kT_e)^{3/2}}{e^4 n_e \ln\Lambda}, \tag{7}$$

where $\ln\Lambda \approx 10$ is the Coulomb logarithm. Using typical experimental data for density and temperature of electrons in the cathode spot, 10^{26} m^{-3} and 4 eV, one finds that τ is less than 1 ps, corresponding to a travel distance of less than 1 μm (a region not accessible to probe measurements). As a result of this consideration, the potential hump, if existent, can only be a few volts in height and cannot account for the high ion energy observed. A few volts is what has been discussed in the early articles.[14,15] Plyutto and co-workers[4] suggested that the potential hump could be as high as 20–40 V. To support their idea, they claimed that Lamar and Compton[14] measured a potential hump for the mercury arc—contrary to the actual data presented by Lamar and Compton.[14] The idea of a potential hump was often used or

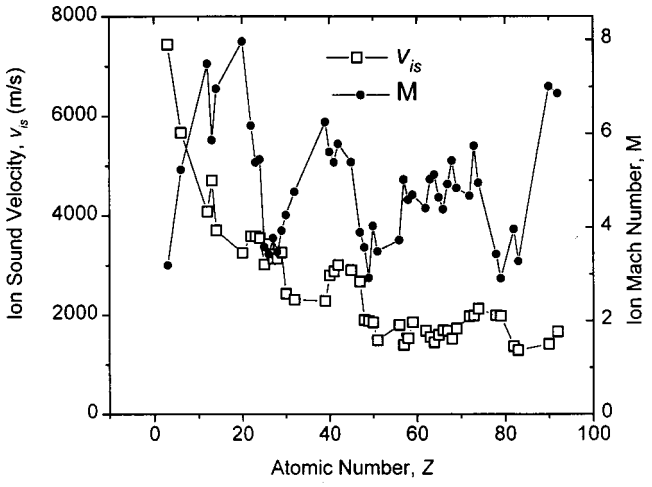

FIG. 4. Ion sound velocities and Mach numbers for most conducting elements of the Periodic Table.

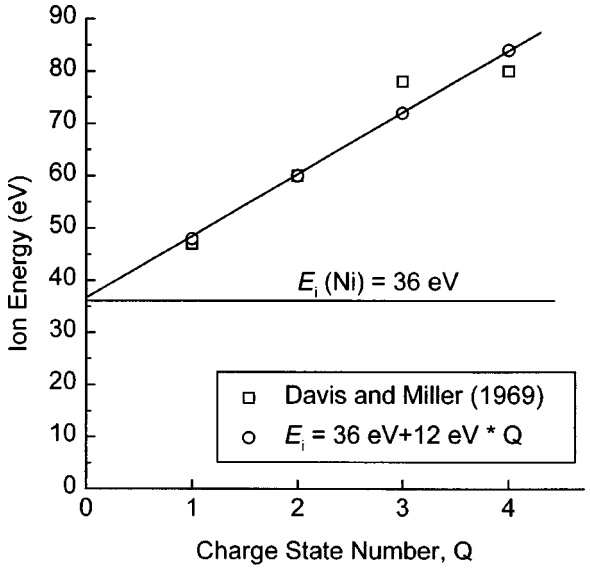

FIG. 5. Energy of nickel ions (90 A arc current) measured by drift time method (horizontal line at 36 eV), data from Fig. 7 of Davis and Miller (see Ref.5) (open squares), and theoretical data assuming a 12 V drop between plasma and analyzer potential (circles).

quoted.[5,16–19] For instance, Harris[17] considered a stationary, quasi-one-dimensional model of the cathode spot based on mass, energy, and momentum conservation, in which he assumed that an ionization zone exists between the cathode surface and the ion acceleration zone. Under these and other simplifying assumptions, he showed that a potential hump may exist with the maximum in the ionization zone. The potential hump was never measured for cold-cathode vacuum arcs; measurements were done only for spotless arcs on *thermionic* cathodes.[20]

As discussed by Kutzner and Miller,[21] an alternative model of ion acceleration at cathode spots is the gasdynamic model.[22,23] This model predicts that ions of different charge states have practically the same velocity due to electron-ion coupling and expansion cooling (thermal energy is transformed in kinetic energy of directed flow). However, neither the potential hump theory nor the gasdynamic theory seemed to fully explain experimental observations. Ion energy measurements using charge state and energy analyzers showed that ion velocities of one element are neither proportional to the square root of the ion charge state (potential hump model) nor practically identical (gasdynamic model). Adjustments to both models have been made. Most noticeable, Wieckert[9,24] developed a multifluid model in which the electron and ion pressure gradients drive the expansion. Higher charged ions are somewhat more accelerated due to the Q^2 dependence of electron-ion coupling and to the Q dependence of the electric field contribution. Wieckert[9,24] and Hantzsche[10,25,26] pointed out that ion acceleration to supersonic speeds does not need the potential hump hypothesis. The greatest contribution to ion acceleration results from the pressure gradient in conjunction with electron-ion friction. A small potential hump may exist (<10 V) but, as Beilis (Ref. 27 p. 255) puts it, this hump is a consequence of plasma acceleration, not its cause.

One may ask the question: if a significant potential hump

does not exist, why is there a clear correlation between ion velocity and ion charge states for the different elements? Can Wieckert's and Hantzsche's model explain the present observations? A qualitative answer can be found by some straightforward energy considerations. Besides element-specific shell effects, the ion charge state of an element is determined by the power input per particle, i.e., by

$$\tilde{P} = I_{\mathrm{arc}} V_c / n_i , \tag{8}$$

where I_{arc} is the arc current, and V_c is the cathode drop voltage. At equal current (e.g., 100 A), the different elements have slightly different cathode voltage drops which are correlated with the electron temperature deduced from charge state measurements.[12] High melting-point materials tend to have smaller erosion rates and cathode craters, hence the power $I_{\mathrm{arc}} V_c$ is distributed over less particles, leading to higher temperature. Higher temperature implies greater local ion and electron pressure gradients, which are the main driving forces for ion acceleration.

If this picture is correct, different ion charge states of the *same* element should have only slightly different velocities because all ions experience practically the same pressure gradient, while ions of different elements should have an average velocity that is correlated to their average charge state because both velocity and average charge state are functions of temperature. This is indeed the case, as recent experimental data show. Tsuruta, Skiya, and Watanabe[28] investigated vacuum arc silver and copper ion velocities using the time-of-flight principle. They found that the ion velocities for each of the two elements do not depend on the charge state. Yushkov[29] used two charge-state-resolving time-of-flight methods for the investigation of a representative selection of light and heavy ions (Mg, Al, Ni, Ti, Zr, Nb, Cu, Pb, and Bi). Both the current perturbation method and the current-zero method showed that ions of the same element have a velocity almost independent of their charge state while ions of different elements have different velocities.

We note that drift time measurements generally give slightly different results from measurements using energy analyzers. One might suspect that a different between the plasma potential and analyzer potential gives rise to an additional charge-state-dependent ion acceleration. This interpretation is supported by quantitative evaluation of data. For instance, taking the velocity data for nickel from Fig. 7 of Davis and Miller's article,[5] one can show that they are consistent with our measurements provided a -12 V potential drop existed between plasma and analyzer potential (Fig. 5). Our measured ion velocity corresponds to 36 eV (Table I) and the ion energies for one-, two-, three-, and fourfold ionized nickel going through a 12 V acceleration should be 48, 60, 72, and 84 eV, respectively, in good agreement with Davis and Miller's data.

V. CONCLUSIONS

Drift time measurements based on the delay between arc current modulation and ion beam modulation are well suited for the measurement of vacuum arc ion velocities. By performing measurements for most of the conducting elements of the Periodic Table, a correlation between the element-dependent ion velocity and average charge state has been found. This correlation can be understood by energy consideration of the cathode spot, specifically taking the element-dependent arc burning voltage into account. From theoretical considerations and other recent measurements one can conclude that the ion acceleration is based on a pressure gradient force coupled with electron-ion friction. The potential hump model is not consistent with Poisson's equation for the given boundary conditions and makes predictions that contradict recent ion drift time measurements.

ACKNOWLEDGMENTS

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