Arc Plasma Propagation and Arc Current Profiles

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***Abstract*—When electrical arcs occur in space, a plasma expands away from the arc-site, neutralizing adjacent surfaces (a current), and causing a current to be produced at the arc-site (source of neutralization current). The speed of this plasma expansion depends on the plasma species, which in turn depend on the ionizable materials near the initial electrostatic discharge (ESD) site. Based on laboratory experiments undertaken as part of the U.S. round-robin experiments on plasma propagation speed, a scenario for arc plasma propagation and arc current profiles is presented. It is found that the complex arc current profiles invariably seen in laboratory arcs are due to a multicomponent plasma, where each plasma species expands away from the arc-site supersonically and with approximately constant velocity. Apparent slowing of the arc plasma seen in high-speed video cameras is caused by the density depletion of the lightest (most rapid) plasma component first and heavier (slower) plasma components later. Electron currents onto surfaces originate at the arc-site, and the conductive arc plasma is a conduit for these currents. Sudden, simultaneous onset of arc currents at all distances from the arc-site is the result of blowoff currents, making all surfaces more positive, which then attract ambient electrons. Sudden, simultaneous cutoff of arc currents at all distances from the arc-site is the result of collapse of the plasma due to conditions at the arc-site. The ionization at the arc-site during the arc is seen to be rapidly variable, with variations on the nanosecond timescale. This model not only makes the varied plasma velocities reported in the literature understandable, but it also makes predictions about the arc radio-frequency interference (RFI), contamination produced by the arcs, and the total charge in an arc possible. Arc-site materials are suggested which, being hard to ionize and with massive ions, minimize arc currents and maximize arc current rise times.**

***Index Terms*—Arc plasmas, flashover, plasma propagation velocities.**

I. INTRODUCTION

IT IS commonly believed that when a plasma arc occurs, all the electrons and metallic ions are created at the same time, early in the arc [1]–[4]. Thereafter, the plasma expands with the Bohm velocity (the speed-of-sound), neutralizing charged surfaces as it goes, and the neutralized charge is the source of the arc current at the arc-site [1]. Sometimes, the plasma expansion velocity has been reported to be constant, and sometimes, it is reported as decelerating [5]–[7]. Finally, when the entire surface has been neutralized, the arc current goes to zero and the arc is over. Very rapid and simultaneous current rise times at all distances are supposed to be due to some fractions of the rapid blowoff electrons reaching all parts of the surface unimpeded [3], [4] In this picture, the radio-frequency interference (RFI) produced is due to the rapid current rise time, and the arc current at any one time is the product of the speed of plasma expansion and the capacitive charge surface density that is neutralized as soon as the plasma outer edge (perimeter) reaches the surface [1], [8]. This conventional picture of the plasma expansion fails to explain most of the laboratory measurements made to date, as this paper will show in the succeeding sections. While many of the illustrations and examples in this paper are taken from [10], for each assertion, there are numerous other examples in the literature.

II. ARC PLASMA DOES NOT EXPAND WITH THE BOHM VELOCITY

The plasma expansion velocity is important, because it determines how much area of surrounding dielectric can be discharged in a given time interval, and thus what the maximum discharge current can be. To understand the plasma expansion velocity, we must first compare it with the Bohm velocity (the plasma sound speed). Plasma temperatures in arc plasmas measured by optical line strengths in laboratory arcs are not very high and are usually only in the range of 3–5 eV [9]. (See [30] where in a wire-initiated sustained arc plasma, Si I lines are stronger than Si II, even though the ionization potential of Si is only 8.2 eV; and see also [31], where a hypervelocity impact plasma continuum temperature of only about 0.5 eV was measured). A plasma temperature in the 3–5 eV range gives a Bohm velocity on the order of 2–4 km/s, very slow compared with the measured expansion velocities from current peaks, which typically are in the 10–50 km/s range. In addition, measurements made at the U.S. Air Force Research Laboratory (AFRL) show a multicomponent plasma, with expansion velocities from 11.5 to 75 km/s, all well over the Bohm speed [10]. Measurements of plasma expansion speeds taken at The Aerospace Corporation [11] with different arc-site conductors do not show the expected Bohm velocity dependence on atomic mass. Finally, Harris *et al.* [12] and Lee *et al.* [13] (Fig. 1) measurements give multicomponent velocities faster than the Bohm velocity for cool plasmas. We must conclude that in a plasma arc, the plasma expands much faster than the Bohm velocity, perhaps with a large fraction of the acceleration energy.

When there is a high electric field at an arc-site, the plasma created is accelerated to a high bulk velocity without being heated to a high temperature. So, the accelerated plasma

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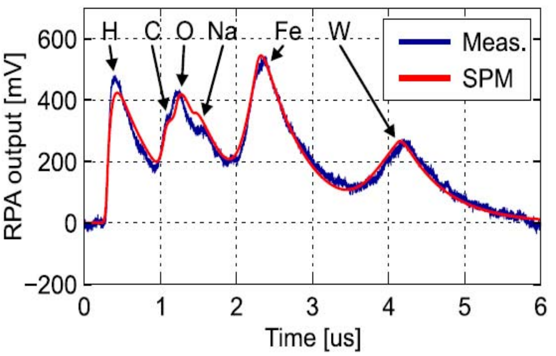

Fig. 1. Multicomponent plasma arrival times with a model fit [13].

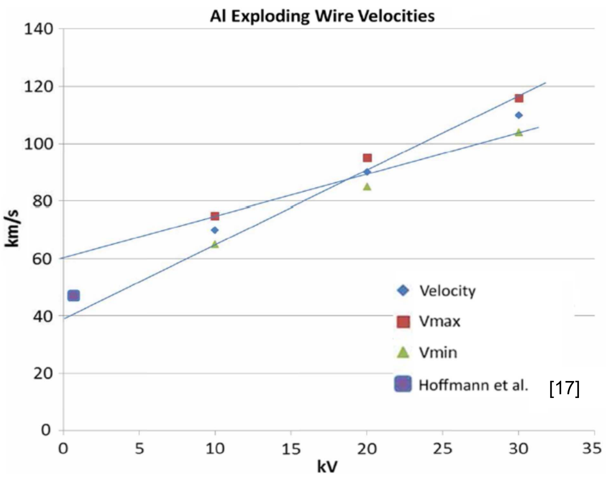

Fig. 2. Exploding aluminum wire velocities [18] with velocity of arc plasma [17].

may expand at a rate much higher than an unaccelerated thermal plasma (which is constrained by the Bohm velocity). An exploding wire is a similar situation [14]–[16]. Here, the high current density leads to very high temperatures, and accelerated electrons ionize the produced gas. Although the electron temperature in the plasma is not very high – 3–5 eV, perhaps, the plasma velocity away from the explosion site is that of the accelerated electron energy, minus the energy needed to pull ions along. Indeed, an AFRL measurement [17] nicely fits velocity extrapolations from exploding aluminum wires [18] (see Fig. 2). So, plasma vacuum arcs act like exploding wires, where the plasma expands at a high velocity, not like stable thermal plasma emitters, with the plasma velocity limited to the sound speed.

III. PEAK CURRENT TIMES OR LIGHT EMISSION PEAK-TIMES VERSUS DISTANCE DO NOT RELIABLY INDICATE PLASMA VELOCITY

Most plasma expansion experimenters assume that the place where the peak currents are happening can be used to find the velocity (from distance/time). That implies that the peak current distances are monotonic in time. If this is not the case, multiple components of the plasma may be inferred (as an example, see Fig. 3 [10]). Here, at the top of Fig. 3 are current traces measured at several distances from the arc-site, which was limited to the center of evenly spaced concentric segments. Segment 5, at the top, is the farthest from the arc-site and has been fit by Gaussians as shown in the bottom of Fig. 3. Three of these Gaussians shown in the intermediate segments 1–4 and have been connected by straight lines back to the origin, each line denoting a different plasma speed (the more vertical the line, the faster the plasma component). As the current trace at each distance is the sum of all the Gaussians at different speeds, the time of peak current need not be monotonic with distance. In fact, AFRL measurements [17] show a “doubling back” (black curve) of arc peak currents, with greater distances showing peak currents at times earlier than shorter distances. It is easy to see that the peak current in segment 2, for instance, is dominated by the slowest velocity component, whereas that in segment 4, the peak is dominated by the middle velocity component. It is not accident that the three derived component velocities correspond to three different expected plasma components.

Why should there be more than one plasma component? Most arcs occur near “triple points” where a conductor and an insulator come together. In the experiment of Fig. 3, for instance, the arc occurred at the boundary between Kapton tape and anodized aluminum. So, the arc-plasma will normally have at least two components—conductor and insulator. The arc plasma must necessarily then be a mixture of two or more different components (“triple point” components, such as silver and silicon, or aluminum and carbon). In effect, all arc current measurements have several peaks made up of different elemental components that travel at different velocities. These together comprise the total current peak, decoupling the “peak current” distance from a single speed times time relation. So, the nonmonotonic behavior is a proof that the peaks arise from the measurement of a multicomponent plasma. With that understanding, it is unrealistic to expect the arc plasma to have only one ionic component.

Most experiments have only reported one plasma component velocity, even though the current trace has multiple peaks. It must be clear that the correct way to measure velocities is to find current peaks of individual plasma components and to track these peaks (Fig. 3). This explains why (for instance) Ferguson and Vayner [19] inferred different “speeds” even when arcs occurred at the “same spot,” because the percentage mixture of plasma components could vary between arcs.

Finally, some experimenters have used the distance of peak light emission as a plasma tracker and have inferred decelerating plasmas from their results [5]–[7]. However, light emission peaks do not necessarily track plasma density peaks. This is because only the electrons of energy greater than some minimum luminescence energy produce light (as in “snapover” measurements of Ferguson *et al.* [20]), whereas all electrons contribute to the current traces. And, as in Fig. 3, apparent slowing of the arc plasma seen in high-speed video cameras may be caused by the density depletion of the lightest (most rapid) plasma component first and heavier (slower) plasma components later.

IV. PLASMA VELOCITIES CANNOT BE REDEFINED

Some investigators, seeing the difference between their measured plasma velocities and the Bohm velocity, have sought to

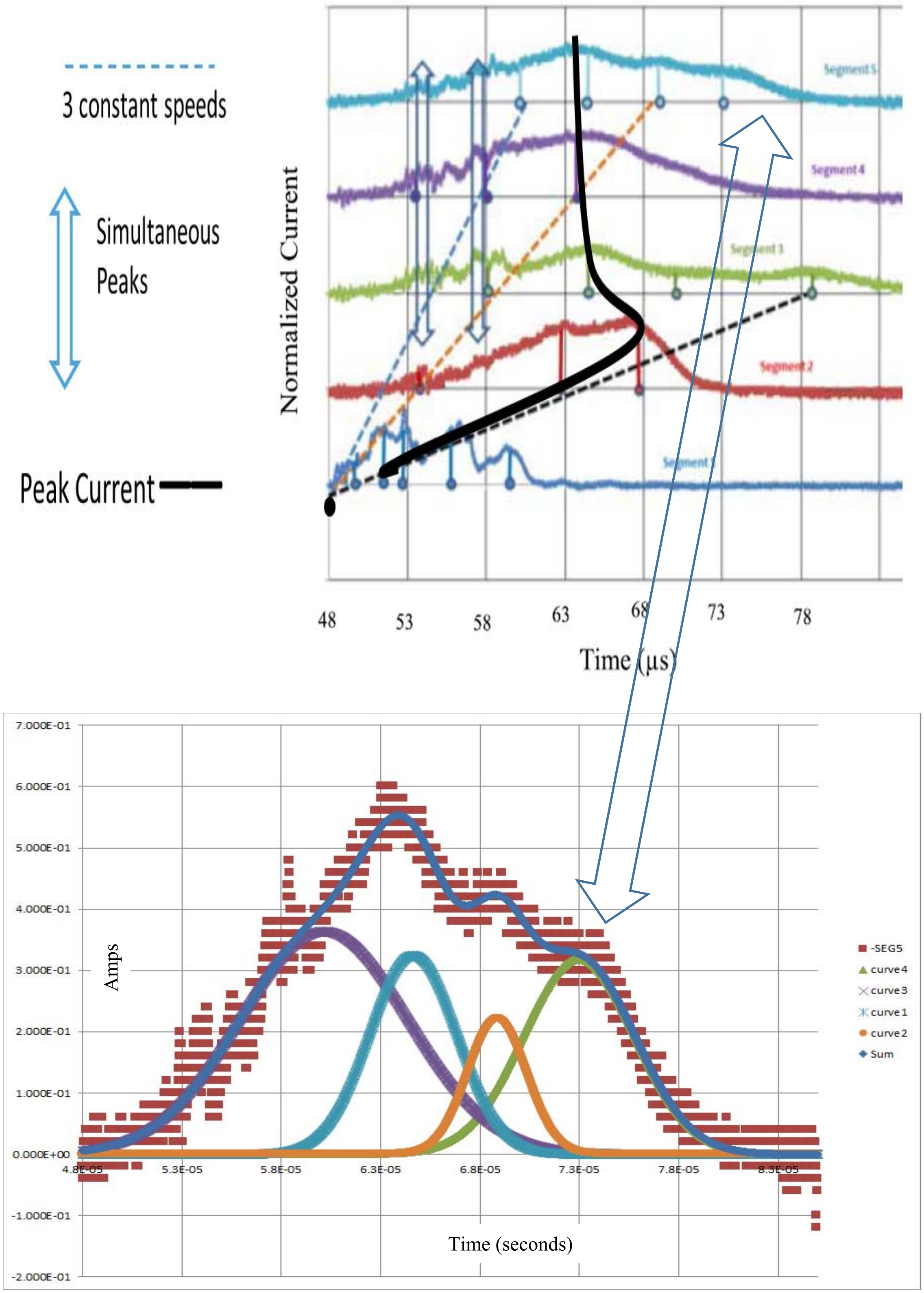

Fig. 3. Multicomponent plasma shows peak current distance not monotonic in time.

redefine the very concept of plasma velocity [3], [21]. They wish to use the time of "full discharge," "peak current," or "current onset" to define plasma velocity at a given distance. In fact, using the "full discharge" time versus distance as a measure of plasma velocity can only underestimate the average ion velocities, as the measurement depends on the slowest ions. (In fact, many arcs do not fully discharge the surface at all, and so, their velocity would remain undefined [22].) "Peak current" velocities measure only the phase velocity of the ion density, not the true average ion propagation speed

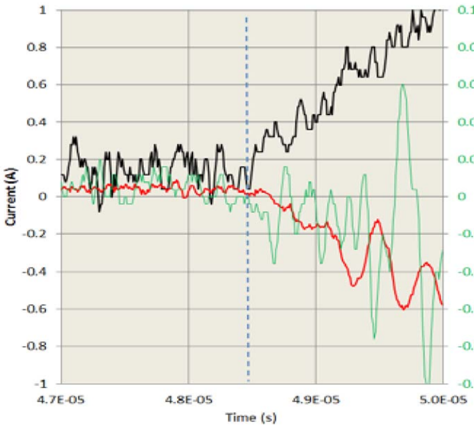

Fig. 4. Simultaneous current onset at different distances [10]. Each curve is a five-point moving average, where each point is 10 ns. Black—arc site. Red—segment 1. Green—segment 5.

(i.e., the speed of a water wave crest versus water molecule speeds). And, a “current onset” velocity measures only the most rapid component velocity and must be an overestimate of the average speed. It may also be confused with current collection from the ambient plasma. It is important to recognize that true plasma velocities are particle velocities only.

Some scientists assume that the high-frequency part of the RF spectrum of arcs comes from the initial rapid rise time of the current waveform (as in [8]). (See also [28], where, as it is typical for arcing measurements, arc onset creates ringing in the circuit.) However, the measurements of the RFI content throughout the arc [23]–[26] show frequency content out to at least 300 MHz. This implies “rise times” of < 3 ns, yet the radiation continues throughout the arc. Even at 20 ns (AFRL measurement [10]), the current rise time would only imply frequency content out to 50 MHz. Also, 300 MHz is much higher than any reasonable plasma frequency in the arc plasma. Something else, such as fluctuations in the vacuum arc-site current at the arc-site throughout the arc duration, must be responsible. These fluctuations are already responsible for simultaneous current variations at all different distances [10] (see vertical arrows in Fig. 3).

All of these are in contradistinction to and contradicts the idea that rapid changes in arc current are due to fast electrons. AFRL measurements [10] of the arc current onset (< 20 ns) (see Fig. 4) would require mildly relativistic electrons (1 m/20 ns $= 5\text{x}10^7$ m/s, $v/c = 0.16$, and $E = 7$ keV). There are no such voltages in the system. Furthermore, fast (blowoff) electrons do not come back to surface [27] (there is initially no electric field to bring them back). When the blowoff of fast electrons occurs, the arc-site potential tends toward the local ambient plasma potential, and all potentials on the sample surface are raised positive by capacitive coupling. The start of ambient electron collection will occur then simultaneously at all distances. Thus, discharge by fast electrons is a “red herring”—it is not physical. After contributing to the arc current at the first instant of arc turn-ON, it is expected that the ambient plasma will thereafter contribute very little to the arc current until late in the plasma expansion, since the ambient plasma has such a low density ($4.2\pm2.1 \times 10^{13}$ m^{-3} [17]) compared with the initial arc plasma ($\sim10^{17}$-10^{18} at 1 cm [19]).

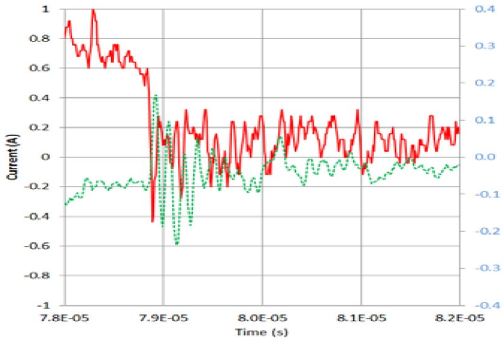

Fig. 5. Simultaneous arc current cutoff at different distances [10]. Five-point moving averages as in Fig.4. Red—arc site. Green—segment 3.

In addition, the rapid simultaneous cutoff in arc current at all distances (see Fig. 5 and [28], [29]) is inconsistent with the ideas of plasma expansion. However, it is consistent with plasma collapse at the arc-site, as will be discussed in the next section.

V. ARC-PLASMA ELECTRONS ARE CREATED THROUGHOUT THE DURATION OF THE ARC

During the initial nanoseconds of the arc, high temperatures at the arc-site boil off gas, which is ionized, and emitted electrons are accelerated by the high electric field at the arc-site. These electrons pull ions along (within a Debye length) to maintain charge density neutrality. In contrast to arc-plasma ions, which are created only at the beginning of the arc and expand outward adiabatically, arc-plasma electrons are not all created simultaneously. As the surface is discharged by the expanding arc-plasma, the electrons lost from the plasma leave a dearth of electrons locally, which sets up a slight electric field, drawing new electrons from the arc-site, like electrons in a wire are conducted from one end to the other. And, like the low resistance in a wire, the low arc-plasma resistance allows current to flow with very little voltage drop. This allows the ions to continue to expand unimpeded, at nearly constant supersonic velocities, since the electron density can remain at the ion density.

AFRL measurements [10] show that different ionic components' distance–time diagrams all go back to the same moment of creation (+/−1 μs). This implies that whatever was in the initially vaporized gas is ionized and that each ionic component expands with its own speed. Arc-plasma ion component bulk velocities point to equipartition. Thus, all ions have about the same energy (~ ½of electron acceleration energy [10]). So, the initial acceleration energy of electrons is shared equally with the ions they drag along.

After the arc-plasma starts expanding, it then acts as an electron conduit from the hot arc-site to the surface-capacitance discharge regions. When the substrate conductor's electrons are released by the discharge of the overlying capacitance, these electrons return to the arc-site, completing the circuit. The round-robin results show that the capacitance-discharge occurs throughout the plasma region [11], not just at the

TABLE I
OLD VERSUS NEW PARADIGMS

Old Plasma Expansion Paradigm	New Plasma Expansion Paradigm
Single Plasma Expansion Velocity	Multi-component Expansion Velocities
Surface Discharge at Perimeter	Surface Discharge Throughout
Expansion at Bohm Velocity (Sound Speed)	Expansion at ~ ½ Acceleration Voltage Energy
Variance in Measured Speeds Due to ???	Variance in Measured Expansion Speeds Due to Component Mix
Multiple Current Peaks Due to ???	Multiple Current Peaks Due to Different Ion Components
Expansion Velocity at Current Peak Velocity	Expansion Velocities are Speeds of Single Ions
Rapid Current Onset Due to Fast Electrons	Rapid Current Onset Due to Ambient Plasma Collection
Rapid Current Cutoff Due to ???	Rapid Current Cutoff Due to Plasma Collapse
RFI Spectrum Up to Inverse Current Risetime	RFI Spectrum Up to Max Fluctuation Frequency

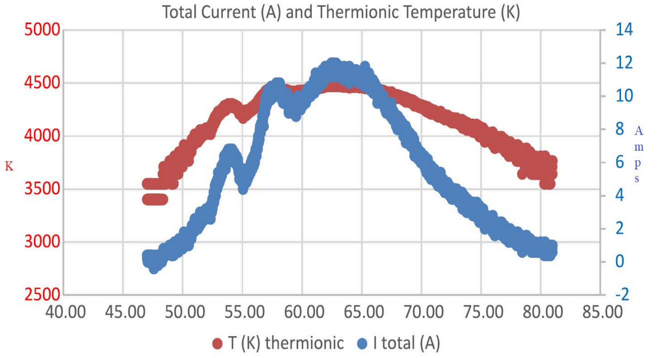

Fig. 6. Total arc current (blue) and thermionic temperature (red) for the arc of Figs. 3–5.

plasma edge, as some models assume. In the picture developed here, conditions at the arc-site are all-important. We rely on the changes in the arc electron current to produce any nearly simultaneous changes in the discharge currents throughout the arc-plasma.

One way of producing electrons at the arc-site is thermionic emission. In this view, as long as the arc currents keep the arc-site hot, electrons will be produced, and when the arc-current decreases, electron emission will stop, the plasma will collapse, and discharge currents will cease everywhere. In Fig. 6 [10], the total arc current is plotted versus time in microseconds. Assuming an arc-site area of 6.3×10^{-8} m^2 (see [10] for justification) and the material properties of aluminum, the temperature can be calculated and is plotted as well. For this choice of parameters, it appears that the arc continues as long as the thermionic temperature is above 3500 K. Why this should be the threshold temperature for this example is not entirely clear, but it should be noted that it is well above the boiling point of aluminum.

There is some evidence that the peak plasma component currents near the arc-site may be inversely proportional to their ionization potential [10]. In the AFRL measurements, the peak Kapton currents are from the fragment with the lowest bond energy, and the other component current amplitudes are roughly inversely proportional to ionization potential. Since arc currents are also proportional to plasma component velocity, which is proportional to the inverse-square root of ion mass, there may be a way to minimize arc currents by a suitable choice of materials. To minimize arc currents, we must maximize the ionization potential while also maximizing the ion mass (see Fig. 7). By these criteria, gold is the best solid conductor (although a gold–mercury amalgam might be better if structurally suitable).

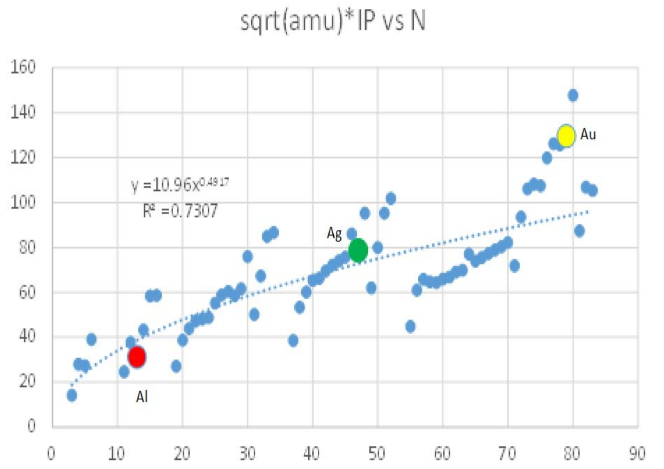

Fig. 7. Minimizing arc currents by choosing high ionization potential and high atomic mass.

VI. CONCLUSION

The new paradigm for arc-plasma expansion presented here is different from the old view in several ways. Some of the differences mentioned in the text are summarized in Table I. Here, "ambient plasma" means that plasma present after the initial blowoff current releases ions from the surface. This will occur even in "GEO" laboratory simulations where only an electron gun is employed.

We feel that the new paradigm is in much closer agreement with the measurements of arc currents made by the entire community and may make arc-current prediction a possibility, despite very diverse prior results.

REFERENCES

[1] E. Amorim, D. Payan, R. Reulet, and D. Sarrail, “Electrostatic discharges on a 1M2 solar array coupon,” in *Proc. 9th Spacecraft Charg. Technol. Conf.*, Tsukuba, Japan, 2005, p. 16.

[2] D. Sarrail, R. Reulet, V. Inguimbert, L. Levy, F. Boulay, and D. Payan, “Electrostatic discharge and secondary arcing on solar array,” in *Proc. 10th Spacecraft Charg. Technol. Conf.*, Biarritz, France, 2007, p. 13.

[3] V. Inguimbert *et al.*, “Measurements of the flashover expansion on a real solar panel (EMAGS3 project),” *Proc. 12th Spacecraft Charging Technol. Conf.*, Kitakyushu, Japan, May 2012. [Online]. Available: https://repository.exst.jaxa.jp/dspace/handle/a-is/21452

[4] J.-M. Siguier *et al.*, “Parametric study of a physical flashover simulator,” *IEEE Trans. Plasma Sci.*, vol. 40, no. 2, pp. 311–320, Feb. 2012.

[5] T. Okumura, M. Imaizumi, K. Nitta, and M. Takahashi, “Flashover discharge on solar arrays: Analysis of discharge current and image,” *J. Spacecraft Rockets*, vol. 48, no. 2, pp. 326–335, 2011.

[6] H. Masui, K. Toyoda, and M. Cho, “Electrostatic discharge plasma propagation speed on solar panel in simulated geosynchronous environment,” *IEEE Trans. Plasma Sci.*, vol. 36, no. 5, pp. 2387–2394, Oct. 2008.

[7] T. Okumura, K. Nitta, M. Takahashi, T. Suzuki, and K. Toyoda, “Flashover plasma characteristics on $5\mathrm{m}^2$ solar array panels in a simulatedplasma environment of geostationary orbit and low earth orbit,” in *Proc. 48th AIAA Aerosp. Sci. Meeting Including New Horizons Forum Aerosp. Expo.*, 2010, Paper AIAA-2010-1602.

[8] B. V. Vayner, D. C. Ferguson, D. B. Snyder, and C. V. Doreswamy, “Electromagnetic radiation generated by arcing in low density plasma,” in *Proc. 17th Int. Symp. Discharges Elect. Insul. Vac.*, Berkeley, CA, USA, Jul. 1996, pp. 668–672.

[9] B. Vayner, D. C. Ferguson, and J. T. Galofaro, “Emission spectra of arc plasmas,” *IEEE Trans. Plasma Sci.*, vol. 36, no. 5, pp. 2219–2227, Oct. 2008.

[10] D. C. Ferguson, R. C. Hoffmann, E. A. Plis, and D. P. Engelhart, “Considerations of flashover propagation,” *J. Spacecraft Rockets*, vol. 55, no. 1, pp. 1–9, 2018. doi: 10.2514/1.A33812.

[11] J. A. Young and M. W. Crofton, “The effects of material at arc site on ESD propagation,” *IEEE Trans. Plasma Sci.*, vol. 45, no. 12, pp. 3349–3355, Dec. 2017.

[12] J. R. Harris, A. I. Yilmaz, and D. D. Snyder, “Expansion of a surface flashover plasma,” *IEEE Trans. Plasma Sci.*, vol. 41, no. 12, pp. 3624–3633, Dec. 2013.

[13] N. Lee *et al.*, “Theory and experiments characterizing hypervelocity impact plasmas on biased spacecraft materials,” *Phys. Plasmas*, vol. 20, no. 3, Art. no. 032901, Mar. 2013.

[14] G. Y. Yushkov, A. Anders, E. M. Oks, and I. G. Brown, “Ion velocities in vacuum arc plasmas,” *J. Appl. Phys.*, vol. 88, no. 10, pp. 5618–5622, Sep. 2000.

[15] M. Hu and B. R. Kusse, “Optical observations of plasma formation and wire core expansion of Au, Ag, and Cu wires with 0–1 kA per wire,” *Phys. Plasmas*, vol. 11, no. 3, pp. 1145–1150, Feb. 2004.

[16] S. Hohenbild, C. Grubel, G. Y. Yushkov, E. M. Oks, and A. Anders, “A study of vacuum arc ion velocities using a linear set of probes,” *J. Phys. D: Appl. Phys.*, vol. 41, no. 20, Sep. 2008, Art. no. 205210.

[17] R. Hoffmann *et al.*, “AFRL round-robin test results on plasma propagation velocity,” *IEEE Trans. Plasma Sci.*, vol. 43, no. 9, pp. 3006–3013, Sep. 2015.

[18] A. G. Rousskikh, V. I. Oreshkin, A. Zhigalin, I. I. Beilis, and R. B. Baksht, “Expansion of the plasma corona from a wire exploded in vacuum,” *Phys. Plasmas*, vol. 17, no. 3, Jan. 2010, Art. no. 033505.

[19] D. C. Ferguson and B. V. Vayner, “Flashover current pulse formation and the perimeter theory,” *IEEE Trans. Plasma Sci.*, vol. 41, no. 12, pp. 3393–340, Dec. 2013. doi: 10.1109/TPS.2013.2279760.

[20] D. C. Ferguson, G. B. Hillard, D. B. Snyder, and N. Grier, “The inception of snapover on solar arrays—A visualization technique,” in *Proc. 36th AIAA Aerosp. Sci. Meeting Exhibit*, Reno, NV, USA, Jan. 1998.

[21] V. Inguimbert *et al.*, “Influence of different parameters on flashover propagation on a solar panel,” *IEEE Trans. Plasma Sci.*, vol. 45, no. 8, pp. 1864-1870, Aug. 2017. doi: 10.1109/TPS.2017.2686653.

[22] T. Kawasaki, S. Hosoda, J. Kim, K. Toyoda, and M. Cho, “Charge neutralization via arcing on large solar array in GEO plasma environment,” *IEEE Trans. Plasma Sci.*, vol. 34, no. 5, pp. 1979–1985, Oct. 2006.

[23] P. Leung, “Characterization of EMI generated by the discharge of VOLT solar array,” Tech. Rep. NASA-CR-176537, Nov. 1985. doi: 10.1063/1.3325349.

[24] S. Close *et al.*, “Plasma and RF generated by hypervelocity impacts on spacecraft,” *JPL Colloquium*, Mar. 2013.

[25] D. C. Ferguson *et al.*, “Ground-based surveillance campaign to detect global positioning system arcing—First preliminary results,” *J. Spacecraft Rockets*, vol. 54, no. 3, p. 567, May/Jun. 2017.

[26] D. C. Ferguson and B. V. Vayner, “Radiofrequency emissions from satellite solar array arcing,” in *Proc. 15th Spacecraft Charging Technol. Conf.*, Kobe, Japan, 2018.

[27] M. W. Crofton, J. A. Young, and I. D. Boyd, “Computational simulation of inverted gradient vacuum discharges,” in *Proc. 14th Proc. 14th Spacecraft Charging Technol. Conf. (ESA/ESTEC)*, Noordwijk, The Netherlands, Apr. 2016, pp. 1–11.

[28] D. B. Snyder and E. Tyree, “The effect of plasma on solar cell array arc characteristics,” Tech. Rep. NASA-TM-86887, Jan. 1984.

[29] J. Vaughn, T. Schneider, and K. Wright, “Sharp onset and quenching of ESD currents,” in *Proc. Round-Robin Tech. Interchange Meeting*, Albuquerque, NM, USA, 2016.

[30] J.-C. o.-V. Mat lez, V. Inguimbert, K. Toyoda, D. Payan, and N. Balcon, “Time-resolved spectroscopy of electrostatic discharge and secondary arc plasma on solar array in geo environment,” in *Proc. 11th Spacecraft Charging Technol. Conf.*, Albuquerque, NM, USA, Sep. 2010.

[31] I. Linscott, S. Close, M. Hew, and A. Nuttall, “Hypervelocity experiments exploring impact-generated electromagnetic pulse production,” in *Proc. Round-Robin Tech. Interchange Meeting*, Albuquerque, NM, USA, 2016.

Authors’ photographs and biographies not available at the time of publication.