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ABSTRACT

The effect of ion mass and charge state on plasma transport through a 90°-curved magnetic filter is experimentally investigated using a pulsed cathodic arc source. Graphite, copper, and tungsten were selected as test materials. The filter was a bent copper coil biased via the voltage drop across a low-ohm, "self-bias" resistor. Ion transport is accomplished via a guiding electric field, whose potential forms a "trough" shaped by the magnetic guiding field of the filter coil. Evaluation was done by measuring the filtered ion current and determination of the particle system coefficient, which can be defined as the ratio of filter ion current, divided by the mean ion charge state, to the arc current. It was found that the ion current and particle system coefficient decreased as the mass-to-charge ratio of ions increased. This result can be qualitatively interpreted by a very simply model of ion transport that is based on compensation of the centrifugal force by the electric force associated with the guiding potential trough.

I. INTRODUCTION

Cathodic arc plasma is generated at cathode spots of a low voltage, high current discharge between two metal electrodes in vacuum [1, 2]. Cathodic arc plasmas sources are characterized by high ion flux and high degree of ionization of metal plasma, which make them interesting for film deposition and other applications. Ions are energetic (kinetic energy 20-150 eV [3-6]), therefore films are denser than those obtained by sputtering and evaporation. The major obstacle for broad application of cathodic arc deposition is the presence of macroparticles in the plasma. Macroparticles are liquid or solid particles that are produced at cathode spot along with the plasma, and their formation is intimately related to the explosive plasma generation at arc cathode spots. Macroparticle removal is an issue for high quality coatings, especially when considering semiconductor and optical applications [7, 8].

Curved magnetic filters are commonly used with cathodic vacuum arcs to remove macroparticles from the plasma stream [9-12]. Since pioneering work of Aksenov and co-workers [9, 13] it is known that biasing the filter positively improves plasma throughput and thus deposition rate. For systems operating with pulsed arcs and open filters, it is practical and economical to use the arc current for generation of the magnetic filter field [11, 14, 15]. This approach eliminates the need for a magnet power supply and it also reduces the overall power consumption and cooling needs. This solution has the additional advantage that higher currents can be utilized than one would use for DC systems; higher currents are generally advantageous because they lead to stronger magnetic guiding fields and hence reduced plasma losses.

Until recently, however, it was difficult to supply bias voltage to a pulsed filter because the bias capacitor coupled to the pulse-forming-network (PFN) of the arc supply, i.e., essentially became part of the PFN. In [16] it was proposed to create filter "self-bias" using a low-ohm resistor between the anode of the arc source and the filter entrance. The self-bias obtained from a 50 mΩ resistor, for example, with a current of 300 A will cause a voltage drop of 15 V, which is known to be about the right amount needed to improve transport of plasma. It has been shown [16] that such self-bias of pulsed filters can lead to improvements of plasma transport. This approach also eliminates the need for a separate bias power supply.

In this study, the effect of self-bias on the transport of plasma containing ions of different atomic mass and average charge state was investigated. While it is clear that ion transport is accomplished via guiding electric field, whose potential forms a "valley" or "trough" shaped by the magnetic guiding field [16, 17], little is know about the effect of ion mass and charge state on transport or probability of ion transmission through a curved magnetic filter. The present study aims to address this issue, thereby continuing and extending previous work [16].

II. FIGURE OF MERIT: THE PARTICLE SYSTEM COEFFICIENT

In a relatively recent review [11], a figure of merit called "system coefficient" was introduced, which was defined as the ratio of filtered ion current to arc current,

$$\kappa = I_i / I_{arc} \ . \tag{1}$$

The system coefficient characterizes not only the filter but the coupled source-filter system. For pulsed systems, one may use the charge transported per pulse, rather than current, because sufficiently constant current values may not exist, hence

$$\kappa_p = \int_0^{t_p} I_i(t)\,dt \Bigg/ \int_0^{t_p} I_{arc}(t)\,dt\,, \tag{2}$$

where the integration is over the pulse duration t_p. These figures of merit make comparison of various filter and source configurations easy because measurements of arc current and ion current of the filtered plasma are simple. In contrast, direct determination of filter efficiency would require to determine the ratio of the ion flux entering the filter to the flux leaving the filter, which is usually impractical to do. The above-defined system coefficients are most useful when different configurations for the *same* cathode material are considered. In this work, however, one configuration is used with *different* cathode materials, each having characteristic ion erosion rates and ion charge state distributions. While the ion charge state distributions and their mean ion charge states are generally known [18, 19], the ion erosion rates may vary not only with material but also depend on the thermal, geometric, and electric specifics of the discharge system, which makes comparison difficult. Therefore, while keeping this issue in mind, we propose to use a "particle system coefficient," which at least eliminates the influence of the various ion charge states from the measurement, by dividing the measured ion flux by the mean ion charge state, $\overline{Q}$, of the material used:

$$\kappa^{part} = I_i \Big/ \left(\overline{Q}\, I_{arc}\right). \tag{3}$$

In analogy to the above we have for pulsed systems

$$\kappa_p^{part} = \int_0^{t_p} I_i(t)\,dt \Bigg/ \left[\overline{Q}\int_0^{t_p} I_{arc}(t)\,dt\right]. \tag{4}$$

In this way we eliminate the "artificial" enhancement in measured ion current caused when the mean ion charge state is greater than unity.

It is generally accepted that the amount of plasma produced is proportional to the arc current. This is indeed a good approximation because the arc voltage is of order 20 V and almost constant [20] as long as the arc current does not exceed about 1 kA. In the future, when refinements become necessary, one should normalize not just to the arc current but to the arc power, $I_{arc}V_{arc}$, or for a pulsed systems to the arc energy per pulse, $\int I_{arc}V_{arc}dt$. In this work, though, we opt to use the particle system coefficient as defined in (4) because it is a dimensionless quantity that is easy to comprehend. In conclusion of this section we would like to stress that values of κ or κ^{part} are usually of order 1%, and values greater than 1% indicate very efficient source-filter systems.

III. EXPERIMENTAL SETUP

A cathodic arc plasma source of the "minigun" type [21] was used, which essentially consisted of a cathode rod of 6.25 mm diameter mounted on axis of a grounded, annular anode cylinder of 2.5 cm inner diameter. The anode opening, where the plasma streams from the source, was 20 mm from the cathode plane (Fig. 1). A detailed description of the experimental set-up was provided in our previous paper [16]. In this work, different cathode materials were used, namely carbon (graphite), copper, and tungsten, to study the effect of atomic mass and charge state on the plasma transport in a biased filter.

The plasma source was operated in pulsed mode fed by a 10-stage PFN of 1-Ω impedance [22]. The arc pulse repetition rate was 1 pulse per second. The amplitude of the arc current depended on the charging voltage of the PFN. The anode of the plasma source was grounded. The vacuum chamber was cryogenically pumped with a base pressure of about 5 x 10^{-5} Pa.

The filter consisted of a quarter-torus solenoid formed by a bent coil of 26 turns of water-cooled copper tubing of 6.25 mm outer diameter. The major and minor radius of the torus were R_t = 150 mm and r_t =36 mm, respectively. The plasma source was placed such as to inject a plasma stream into the filter (Fig. 1).

Filter self-bias was adjusted by using different low-ohm resistors, and the system coefficient was obtained measuring arc current and the ion current leaving the filter. The potential shift at the filter entrance caused by the low-ohm resistor was carefully measured using a fast Tektronix 10:1 voltage divider and a digital storage oscilloscope.

The filtered ion current was determined using an ion collector as shown in Fig. 1. A bias voltage of -90 V was applied to the ion collector to repel plasma electrons. At this collector voltage, secondary electrons can be neglected. Because the system is pulsed, the collector voltage needed to be stabilized by a capacitor; its capacity was 1500 μF. Current measurements were done via wide-band Pearson current transformers (model 1114 with 0.01 V/A for the arc current, and model 110 with 0.1 V/A for the ion collector current). Data acquisition was accomplished using a 500 MHz, 2 Gsample/s, 4-channel digital oscilloscope (TDS 744). Each data point in all measurements represents the average of 50 individual measurements.

Additionally, the radial potential distribution was measured for various conditions (cathode material, self-bias resistor, arc current) in the filter exit plane using a small, movable, floating probe. The probe was carefully positioned in small steps across the filter diameter using a movable feedthrough. The probe was a small cylindrical wire extending 2 mm beyond its ceramic housing. The probe wire was connected to one of the high-impedance input channels of the oscilloscope. The reference potential for all measurements was ground. For these measurements it is assumed that the shape of the distribution of the floating potential is similar to the shape of the distribution of the plasma potential. This assumption implies that electron temperature and mobility do not vary significantly across the filter diameter.

IV. RESULTS

Both magnetic field strength and filter bias are known to have an effect on plasma transport through the filter (e.g., [9, 23]). Therefore it is expected that the shift in filter potential caused by the low-ohm self-bias resistor may improve or reduce plasma transport, depending on the bias voltage.

Figure 2 shows the effect of the self-bias resistor on the filtered ion current. A self-bias resistor of zero Ω corresponds to direct serial connection between plasma source anode and filter coil; the connection was made using a copper bar whose nominal resistance was less than 1 mΩ. For the specific conditions of our experiment, increasing the self-bias resistor up to 25 mΩ improved the system coefficient significantly, but higher resistor values caused bias voltages that were too high, which (due to Ohm's law) was more pronounced at higher currents.

Figure 3 shows the potential at the entrance of the filter as measured with the Tektronix voltage probe. Self-bias resistor values greater than 25 mΩ caused the bias voltage to exceed 25 V at high current, i.e. bias voltages were obtained which DC evaluation had qualified as excessive [23]. These measurements confirm that there is an optimum self-bias resistor value for a given arc current range.

The potential “valley” or “trough” was measured using a small movable floating probe. Figure 4 shows the probe floating potential for carbon, copper, and tungsten plasmas at different positions in the filter exit plane, determined for three different low-ohm self-bias resistors. These and previous measurements indicate that the potential trough has two features, namely a dip near the center axis of the filter, and a steep gradient near the physical wall of the filter. The potential gradient near the filter wall becomes steeper and the trough relatively deeper when bias is increased. With all cathode materials, the position of the central potential trough did not move in any radial direction when self-bias was varied.

The floating probe measurements show that the potential at the central position of the potential trough decreases when plasmas with ions of greater mass (or mass-to-charge ratio) are used. This can be quantified by calculating the cross-sectional area integral of the potential trough. The integrated area of the trough is larger for carbon plasma than for copper and tungsten, which have much greater ion mass or mass-to-charge ratio. From previous work one could anticipated that a larger area of the trough may lead to better plasma transport through the filter.

Figure 5 shows the particle system coefficient for carbon, copper and tungsten plasmas as a function self-bias resistor, hence bias voltage, a fixed arc current of 1300 A. The filtered ion current (and, hence, particle system coefficient) of the lightest element, carbon, is clearly greater than the corresponding values of the heavier ions, copper and tungsten. Figure 2 showed examples of the absolute enhancement of ion current by the self-bias resistor, and improvement of system coefficient can be inferred.

V. DISCUSSION

From the literature (e.g. [9, 23, 24]) is it known that filter bias of about 20 V maximizes the system coefficient. Therefore, it was expected that transport improvement could also be achieved when the bias was obtained by the voltage drop across an Ohmic resistor through which all, or a large fraction, of the arc current is flowing. Figure 2 fully confirmed that. Consistent shifts of the system coefficient to higher values were obtained when resistance values of a few mΩ were used. For greater resistance values, the bias voltage exceeded the optimum. Since the bias voltage is directly proportional to the current through the resistor, deterioration of the beneficial effect is seen first at high currents. For a practical application of the self-bias resistor concept, a range of arc current must be selected first, and the optimum self-bias resistor value can easily be estimated knowing the approximate targeted bias (which is typically about 20 V). For the specific conditions of our experiment, a self-bias resistor up to 25 mΩ improved the system coefficient significantly.

Figure 3, besides giving absolute values of self-bias caused by the resistor, indicates by the linearity of the curves that the current flowing through the resistor is proportional to the arc current. Additionally, one can derive from these data that, for the given geometry, about 80% of the arc current goes to the designated anode of the plasma source and hence flows through the self-bias resistor. The remaining about 20% is carried mainly by electron and closes the circuit via the turns of the open copper coil filter.

In the previous paper [16], a simplified model of ion transport in curved filters has been proposed in order to interpret how an electric potential trough, whose "wall height" is typically only 10-20 V ([16, 17] and Fig.4), is able to guide ions having kinetic energies of 20-150 eV.

According to the simplified model [16], the centrifugal force experienced by the ions going through the curved filter must be compensated by the force of the radial electric field, which leads to [16]

$$\frac{m_i}{2} v_i^2 = \frac{1}{2} QeR \frac{\partial V}{\partial R} \ . \tag{5}$$

The left-hand side is the kinetic energy of ions. The right side can be interpreted as the required minimum energy or electronvolt-equivalent of the potential trough, which must not be confused with the absolute voltage height of the trough. Due to inertia, the radius of path curvature, R, is slightly greater than the major radius of the filter, R_t, and thus only the electric field for $R > R_t$ is important for transport in this simplified model. Taking the average ion energy in the streaming plasma, which is 19 eV, 57 eV, and 117 eV for carbon, copper, and tungsten, respectively [5], one may determine the minimum required radial electric field strength, $\partial V / \partial R$. One can rearrange (5) and obtains

$$\frac{\partial V}{\partial R} = \frac{m_i}{Qe} \frac{v_i^2}{R} = \frac{2}{QeR} E_{kin} , \tag{6}$$

which gives the data shown in Table 1 when using $R \approx R_t$. Conveniently, the simplified model gives a relation that explicitly contains ion mass and charge state, and it appears as mass-to-charge ratio, $m_i / (Qe)$, as it is usual when considering trajectories of charged particles in electric and magnetic fields. From the second part of (6) one can also see that for a filter with given curvature, or major radius, the radial electric field strength of the trough must be at least proportional to the ion kinetic energy divided by the ion charge state. The data shown in Table 1 indicate field strength of 500 V/m or less. If we consider the potential profiles found by probes methods (e.g. [16, 17] and Fig. 4 of this work), we see a voltage drop of order 10 V over a radial distance of about 2 cm, hence the average radial field is indeed about 500 V/m.

Some important qualitative conclusions can be drawn from the simplified model. First, since vacuum arc ions of heavier elements have greater kinetic energy [5, 6], equation (6) shows that the potential gradient must be stronger for heavier ions to obtain comparable plasma transport. That is not necessarily the case. The gradient was approximately equal for the various cathodic arc plasmas, and therefore the plasma with heavier (more energetic) ions will show less confinement and greater losses.

Second, Eq. (6) shows that magnetic filters with tighter curvature will need an inverse-proportionally stronger potential trough, or losses of tighter-curved filters may be greater. Such prediction is in agreement with measurements made by Storer and co-workers [25] who observed that curved filters have greater losses than straight filters of equal length.

Third, from Eq. (6) one would expect that ions of equal mass and similar kinetic energy but higher charge state need less electric field to be guided through by the trough, or, in other words, ions of low charge state are more likely to be lost to the filter wall. Consequently, the plasma leaving filter should have an increased average charge state compared to the plasma entering it. Using a similar 90°-curved filter and a time-of-flight spectrometer, Bilek and co-workers [26] found such increase in the mean charge state for titanium and tantalum plasmas at relatively low magnetic guiding field. At higher magnetic fields and higher plasma density, though, the trend reversed, indicating that other processes such as collisions among ions play a role. Overall, the mean charge state changed but not dramatically. Therefore, the use of the mean ion charge state without magnetic field is retrospectively justified when calculating the particle system coefficient.

Finally, in the simplified model, the electric force of the potential trough compensates the centrifugal force, hence only the potential wall at the *outside* curvature is important, where $R > R_t$. That is in agreement with observations by Bilek and co-workers [24] who found that a biased strip electrode placed along the outside curvature of a filter is sufficient to obtain the full beneficial effect of filter bias.

VI. SUMMARY AND CONCLUSIONS

The effect of ion mass and charge state on the transport of cathodic arc plasmas through a 90°-curved, magnetic filter has been investigated. Carbon, copper, and tungsten have been used as test materials. Selected variables were the arc current and the filter bias obtained by current flow through a self-bias resistor. A clear tendency was found for the three materials used, namely, the greater the mass-to-charge ratio, the smaller the filtered ion current. The ratio of filtered ion current, divided by the mean ion charge state, to the arc current can be used as a figure of merit in order to compare the performance of the filter for different cathodic arc plasmas. Using this figure of merit, plasmas with ions of greater mass show more losses or less transport.

In a very simple model, where the magnetized electrons facilitate shaping an electric potential trough which guides ions, the centrifugal force on ions must be compensated by the electric force resulting from the gradient of the trough potential. This leads to a simple equation, Eq.(6), which correctly predicts a number of features that are observed in experiments, including higher losses for ions of greater mass and lower charge state. Higher losses for tighter-bent filters are predicted, and from the inertia or centrifugal force it is clear that the potential wall at the *outside* curvature of a filter is decisive, which explains the success of using a biased strip electrode at the outside curvature instead of biasing the whole filter, as was demonstrated by Bilek and co-workers.

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TABLES

Table 1. Atomic number, mass in atomic mass units, average kinetic energy in eV, and mean ion charge state number for carbon, copper, and tungsten cathodic arc plasmas (data from [5]). The last column gives the required electric field strength at the larger-curvature side of the trough, as determined by the simplified model, Eq (6), with $R \approx R_t$.

	Atomic number, Z	Atomic mass (m_u)	Average kinetic energy, E_{kin} (eV)	Mean ion charge state number, $\overline{Q}$	Required electric field strength $\partial V/\partial R$, (V/m)
C	6	12.01	18.7	1.0	249
Cu	29	63.5	57.4	2.0	382
W	74	183.8	117	3.1	503

Figure Captions

Fig. 1 Experimental setup showing a pulsed cathode arc source, the self-biased open-coil filter, the movable probe, and the ion collector. The self-bias resistor R was exchangeable.

Fig. 2 Effect of the self-bias resistor on the filtered ion current. Nominally zero Ω corresponds to direct serial connection between plasma source anode and filter coil using a copper bar.

Fig. 3 Electric potential at the filter entrance as a function of arc and filter current (in series) with the self-bias resistor as a parameter.

Fig. 4 Potential of a floating probe in (a) carbon, (b) copper, and (c) tungsten plasmas, measured at different positions in the filter exit plane for three different filter bias. Zero and 72 mm in radial position corresponds to the inner diameter of the filter coil, with zero at the "inner" wall of the curved filter.

Fig. 5 Effect of the self-bias resistor on the particle system coefficient for carbon, copper, and tungsten cathodic arc plasma.

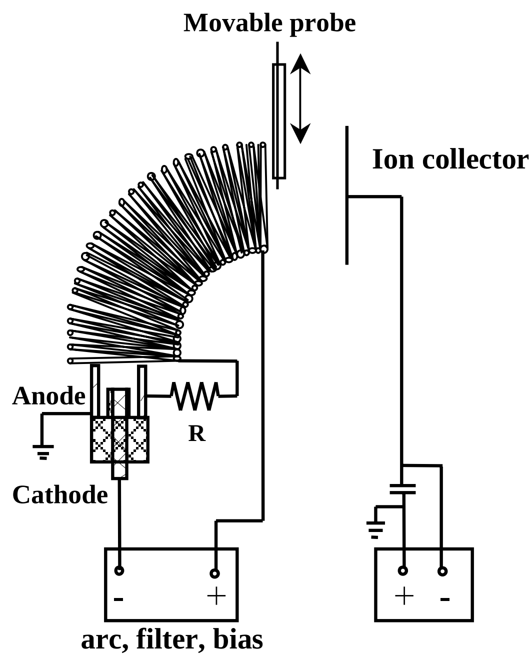
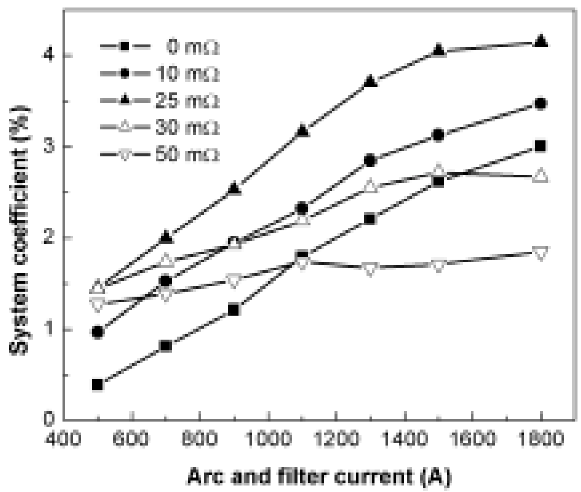


Fig. 1 Byon et al.



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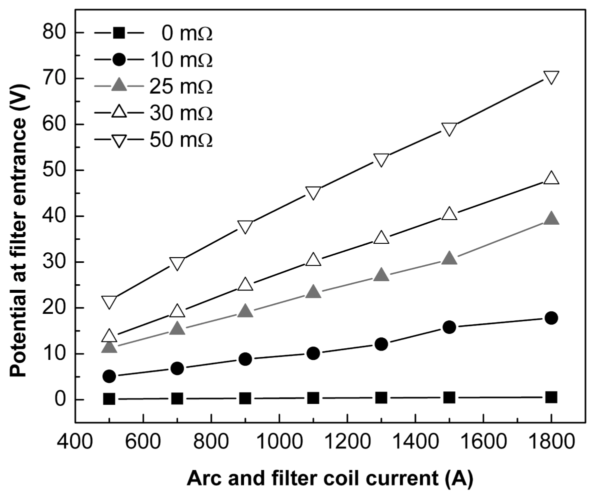

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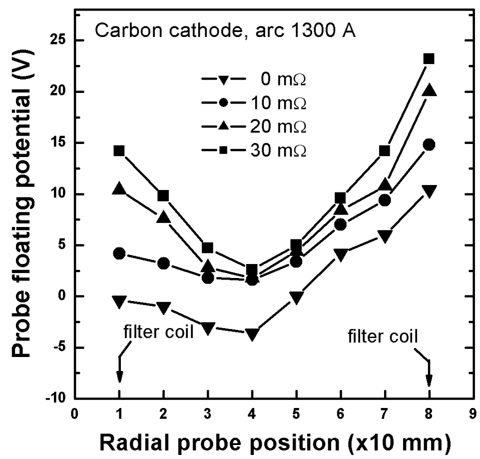
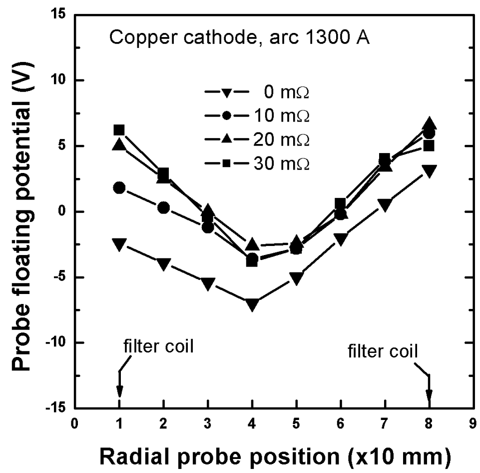


(a)



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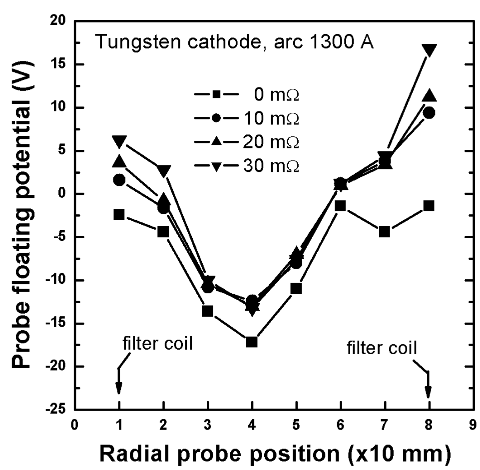

(c)

Fig. 4 Byon et al.

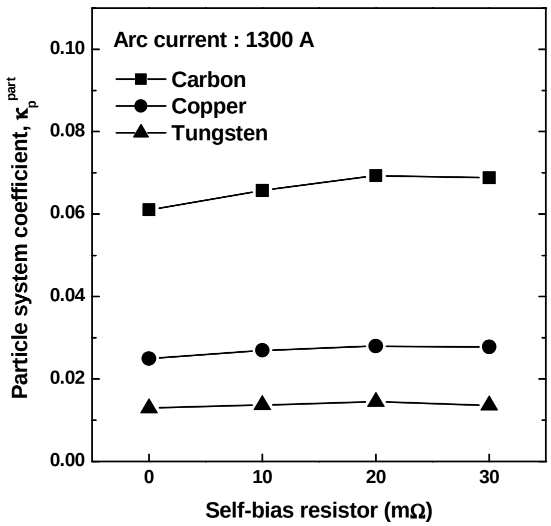

Fig. 5 Byon et al.