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Angularly resolved measurements of ion energy of vacuum arc plasmas

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Abstract

The kinetic energy of ions generated by pulsed vacuum arcs was measured with angular resolution in the interval -90° to +90° with respect to the cathode normal. A current perturbation method in conjunction with drift time measurements was used. Cathode materials included C, Mg, Ti, Cu, Ag, Ta, and Pb with an average arc current of 300 A and 600 µs duration. The measured angular energy distributions are slightly peaked at the cathode normal. Each distribution can be fitted by a superposition of an isotropic component and a cosine function, with the isotropic component dominating. This result is in contrast to plasma jet formation observed by others, which is most likely due to effects of anode geometry and magnetic fields, including the self-field of the current-carrying plasma.

Vacuum arc plasma properties have been investigated in great detail[1] but are still subject to controversial measurements and interpretation due to the small size of cathode spots[2] (~1 μm), very short characteristic times (down to nanosecond timescale), extremely high current density (~10^{12} A/m^2) and associated high power density (~10^{13} W/m^2). Most investigators focus on axial plasma parameters assuming explicitly or implicitly axial symmetry of the cathode-anode geometry. There are also published a number of angularly resolved data on the plasma flux[3-11], electron temperature[6,8], and macroparticle distribution[12]. Summarizing the findings, one may state that the arc plasma plumes preferentially around the surface normal approximately having a cosine distribution[5,9]

$$j_i(\vartheta) = j_i(\vartheta = 0) \cdot \cos\vartheta \qquad (1)$$

for angles up to about 75° with the respect to the surface normal, and greater values than the cosine distribution for $\vartheta > 75°$, where ϑ is the angle between the flux direction and cathode surface normal. In various experiments, not all distributions have been found to be well approximated by a cosine distribution. For instance, some distributions are more peaked thus better approximated by a so-called $\cos^2\vartheta$ distribution[6]

$$j_i(\vartheta) = j_i(\vartheta = 0) \cdot \cos^2\vartheta \qquad (2)$$

In yet other experiments, plasma jets emanating from the cathode have been observed, thus the plasma distribution is even more peaked[13].

It is well known that if an axial magnetic field is present, the plasma flow is greatly influenced by such field, leading to a jet-like plasma profile with a much smaller rate of plasma expansion[5].

Despite several works on angularly resolved density data, only little is known about angularly resolved ion energies[8,11]. Systematic, angularly resolved data could provide important insight in the physics of ion acceleration.

To free the data as much as possible from geometry-specific effects, a special, rotationally symmetric geometry was used. A rotatable vacuum arc cathode assembly was placed in the center of a cylindrical vacuum chamber of 100 cm diameter and 26 cm inner height. A schematic top view is shown in figure 1. The cathode assembly (see insert of figure 1) could be rotated by 180° via rotatable vacuum feedthrough. The cathode was a rod mounted in an alumina sleeve such as to confine the area of cathode spot activity to the rod's front surface of 6.25 mm diameter. The grounded wall of the vacuum chamber served as the anode. Due to symmetry, this arrangement does not change the relative position of cathode and anode even when the cathode-detector angle is varied. No external magnetic field was applied. The chamber was cryogenically pumped to a base pressure of about 1×10^{-4} Pa.

The rectangular arc current pulse was provided by a 0.8 □, 10-stage pulse-forming-network (PFN). Each current pulse had a duration of 600 μs and an amplitude of 300 A. Current oscillations were superimposed in order to obtain a modulation of ion production at cathode spots. This perturbation method has been used to determine ion energies for a very wide rang of materials and is here extended to an angularly resolved technique; details of the original concept are explained in previous publications[14,15]. The basic idea is to measure the time of flight between ion production at cathode spots and ion detection at a collector. From the measured time and the known cathode-detector distance one may infer about the average ion velocity and kinetic energy. The detector was a flat probe of 50 mm diameter at constant bias of –60 V, located 350 mm from the cathode surface and thus operating as a time-resolving ion current collector. For simplicity we chose a current modulation maximum at about 250 μs after the arc pulse started, i.e. we obtain velocity (energy) values close to steady-state conditions[15].

Using the arc and ion current modulation technique, the results compiled in figure 2 have been obtained. The ion velocity or kinetic energy is slightly peaked with maximum at the surface normal. The measured distributions can be fitted by a superposition of an isotropic distribution and a cosine distribution:

$$E_{kin}(\vartheta) = E_{kin}^{0} + E_{kin}^{*}(\vartheta = 0) \cdot \cos\vartheta \qquad (3)$$

where E_{kin}^{0} is the isotropic component and $E_{kin}^{*}(\vartheta = 0)$ is the difference to the maximum energy observed at the surface normal, i.e. trivially $E_{kin}^{*}(\vartheta = 0) = E_{kin}(\vartheta = 0) - E_{kin}^{0}$. Table I shows data for the fit constants of selected materials. One can see that the isotropic component is larger than the angle-dependent component. Ion acceleration is therefore generally isotropic – in agreement with the hydrodynamic model where the electron and ion pressure gradients are the driving forces of the point-like cathode spot plasma.

Using the ion saturation current measured by the probe, the ion particle flux can be plotted a function of angle as shown in figure 3. The heavy, low-melting point elements lead and bismuth show an almost isotropic distribution for $\vartheta < 50°$. For all other elements, the measurements confirm that a cosine distribution fits well for $\vartheta < 60°$ and the flux is greater for large angles.

The flux is generally less peaked than reported by other researchers[4-6,9]. A broader than cosine distribution is indicative for a high frequency of elastic collisions even outside the vicinity of cathode spot center. It is likely that jet formation observed by others is due to the axial position of the anode in the other experiments. The location and shape of the anode affects the arc current distribution in the plasma and thus the distribution of the magnetic self-field. It has been argued[13] that the magnetic self-field of the arc current could lead to plasma contraction, rather than expansion. For our rotationally symmetric arrangement, we did not find such contraction. The discrepancy could be due to the anode geometry and associated current flow and self-magnetic fields but also to the external axial magnetic field used in the vicinity of the cathode[13]. More research is needed to understand these discrepancies.

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Figure 1. Experimental setup for measuring the angular dependence of ion flux parameters. The rotatable source of plasma (cathode assembly, see insert) is placed in the center of a cylindrically symmetric chamber.

Figure 2. Ion kinetic energy for various cathode materials as a function of angle; 0° corresponds to the cathode surface normal.

Figure 3. Ion particle flux for various cathode materials as function of angle as derived from the ion saturation current of the ion collector.

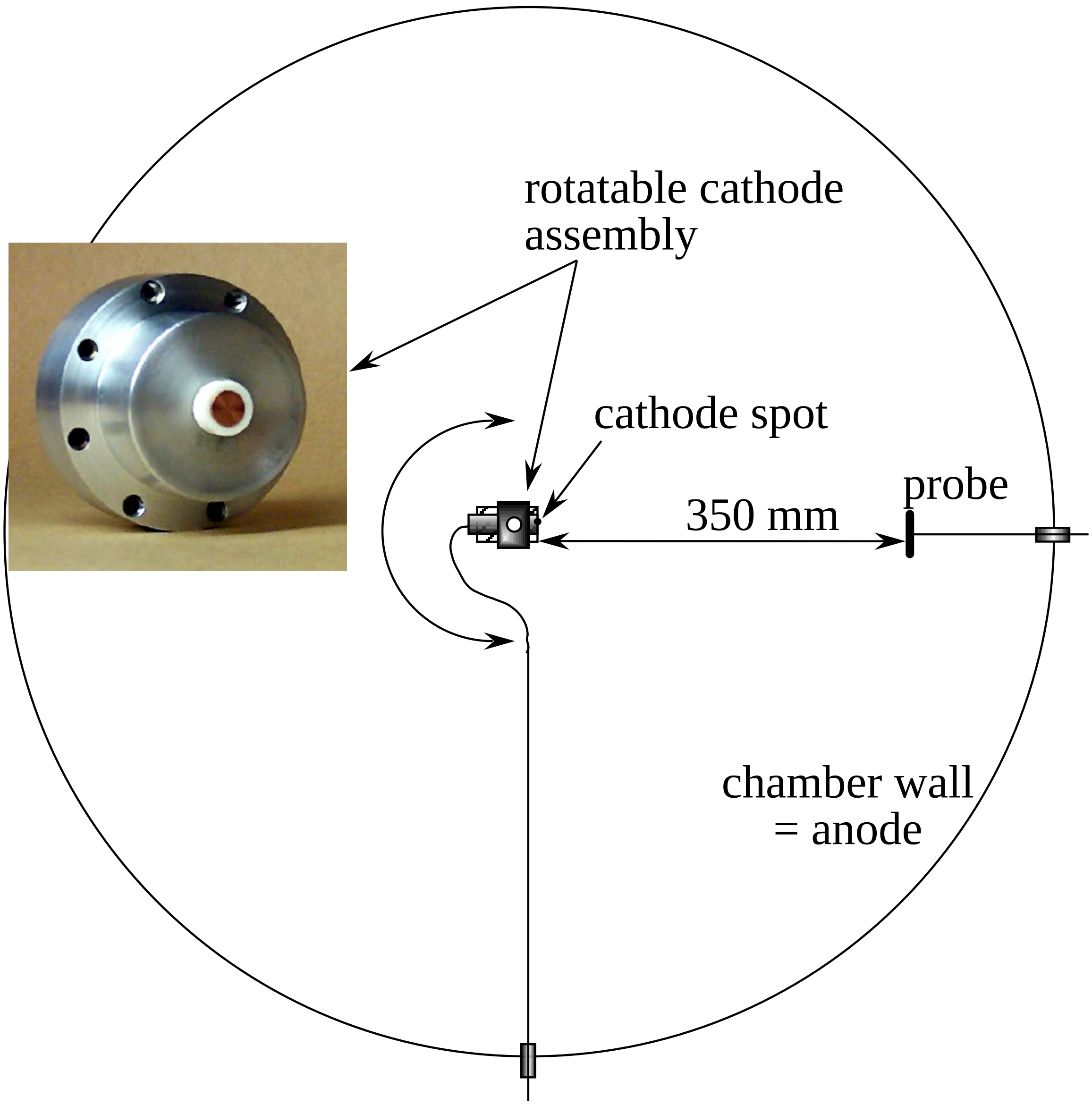

rotatable cathode
assembly
cathode spot
350 mm
probe
chamber wall
= anode

Figure 1

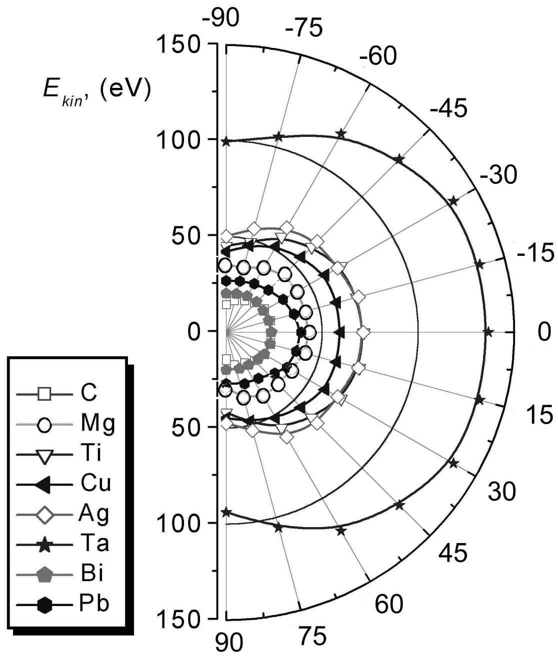
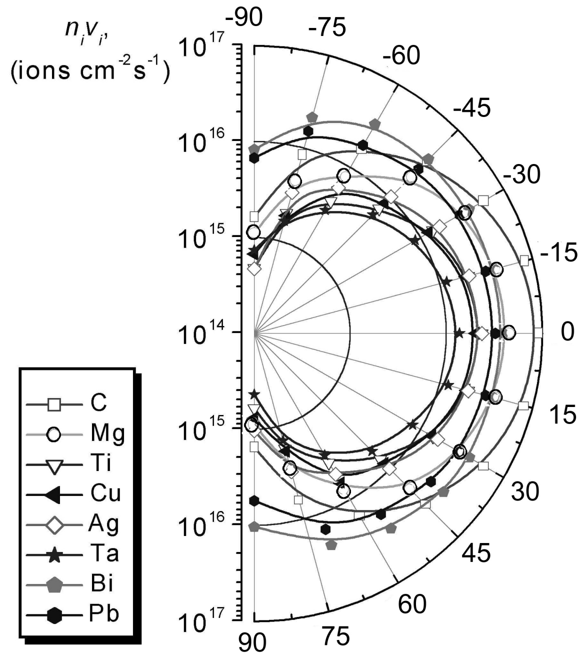

-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90
150
E_{kin}, (eV)
100
50
0
50
100
150
C
Mg
Ti
Cu
Ag
Ta
Bi
Pb

Figure 2



$n_i v_i$,
(ions cm^{-2}s^{-1})
10^{17}
10^{16}
10^{15}
10^{14}
10^{15}
10^{16}
10^{17}
-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90
C
Mg
Ti
Cu
Ag
Ta
Bi
Pb

Figure 3

Table I

Fit constants to be used with Eq. (3), describing the angular dependence of the kinetic ion energy for selected materials.

Ion species	E_{kin}^{0} (eV)	$E_{kin}^{*}(\vartheta = 0)$ (eV)
C	15	4
Mg	32	17
Ti	42	18
Cu	42	15
Ag	48	21
Ta	96	40
Pb	27	12
Bi	20	4