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Features of Energy Spectra of the Cathode Material Ions in the Low Current Microsecond Vacuum Arc

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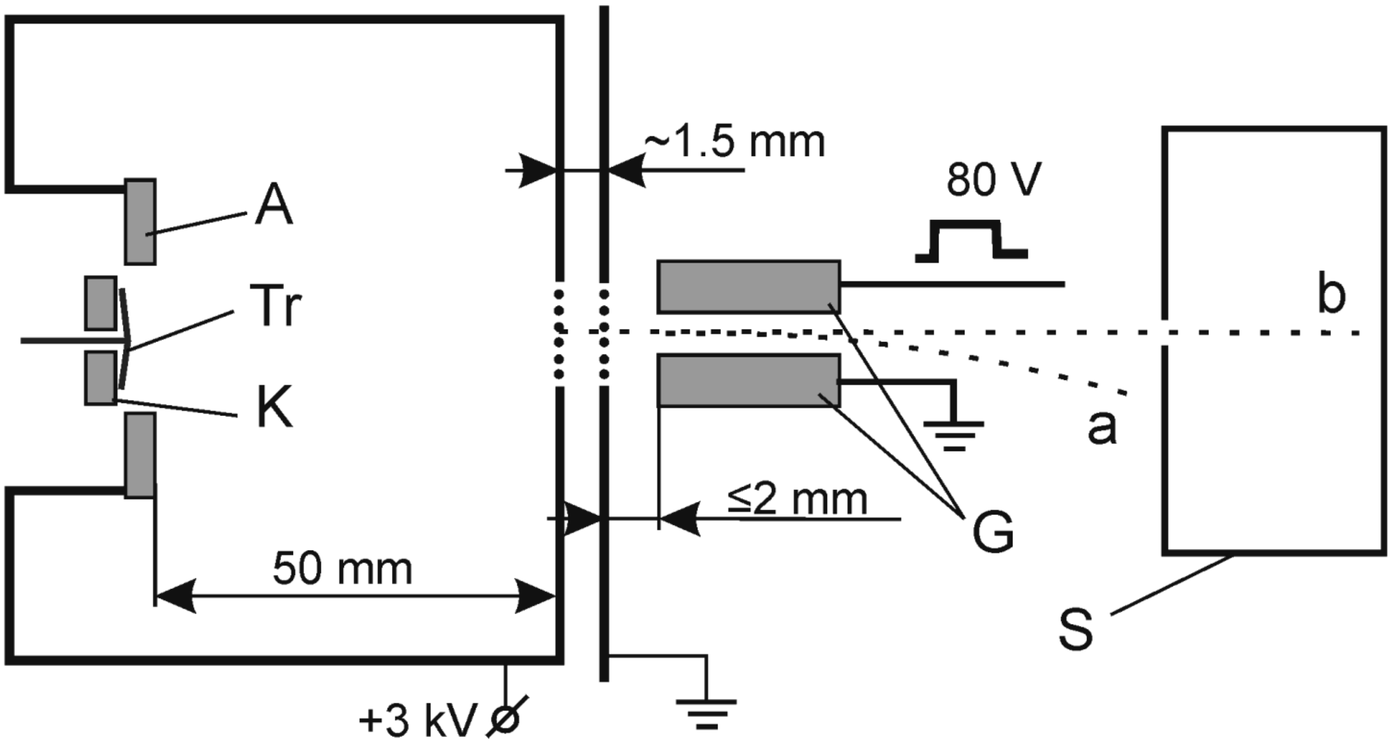
Abstract

Low current vacuum arc discharge was investigated. Pulse source was the LC-line with quasi-rectangular pulse shape. Pulse durations were 2 and 3.5 microseconds. Discharge electrodes were made of copper and CuCr. Ion flow composition and ion energy spectra were obtained via the Thomson spectrometer with automated image recording and digital data processing. Entering of the ion flow to the spectrometer was partially limited by the electrostatic gate with variable duration and delay of the blocking pulse. Therefore the detection of ions depended on the ion velocity and the generation moment of the ion. It was found that the ion spectra have low energy (tens of eV) and high energy (hundreds of eV) parts. High energy ion fraction was sufficiently large, and the high energy ions were apparently generated at the discharge end at the given discharge parameters.

I. Introduction

To study the charge composition of ion flows from the plasma of microsecond vacuum arcs, we use a Thomson spectrometer with automatic signal registration and digital data processing. This spectrometer was modified to detect low-intensity signals of ion flows from the plasma of low-current arcs. An amplifier based on microchannel plates is used to amplify the signal, and an electrostatic ion acceleration system at the output of the plasma source is used to ensure stable secondary electron emission at the amplifier input. The voltage in the acceleration unit is 2 - 3 kV. Generally, the energy spectrum of the detected arc discharge ions is rather narrow, its width does not exceed 100 eV, and the signal of these ions occupies a compact region on the particle detector screen. However, a signal of ions with much higher energy was often recorded. Some of these cases were the consequences of resonant charge exchange. For example, a peak appeared in the spectrum of singly charged ions, twice the voltage at the acceleration site, i.e. with the energy characteristic of doubly charged ions. Nevertheless, additional ion signals were recorded. The energy and spectral width of the signal couldn't be explained by resonant charge exchange. These unusual data were accumulated during a series of experiments and generalized. The obtained observation results are presented in this article.

II. Experimental setup



Scheme of the plasma source with the electrostatic gate.
A - anode entrance ring; Tr - trigger electrode; K - cathode; G - gate;
S - Thomson spectrometer.
Ion path a - with the blocking pulse on the gate, b -without the blocking pulse.

III. Parameters

Cathode – 8 mm diameter disk

Cathode-anode distance - about 800 μm

Anode – hollow, with copper ring entrance (inner diameter 9 mm)

Ignition – copper wire trigger

Trigger discharge gap – about 100 – 200 μm

Current pulse source – LC-line with quasi-rectangular pulse shape

Ion extraction and acceleration – 2-3 kV between the source and the grounded grid.

Drift distance between the arc gap and the anode exit grid – 50 mm.

Distance between the grids – 1.5 mm.

Vacuum conditions – 10^{-6} Pa.

Analyze method – Thomson spectrometer with automatic signal registration and digital data processing, and adjustable electrostatic gate for ion generation moment analysis.

Electrostatic gate – two parallel plates with 2.2 mm spacing. Length along the ion drift axis – 15 mm. The gate was installed between the ion acceleration unit and the input collimator aperture of the Thomson spectrometer. When voltage was applied between the gate plates, the ions acquired a tangential velocity component that did not allow them to pass through the aperture of the collimator.

Closing voltage – 80 V rectangular pulses with adjustable duration and adjustable delay relative to the beginning of the discharge.

IV. Methods

When considering these parameters of the blocking pulse, the distance from the plasma source to the acceleration unit should be taken into account. This distance was about 5 cm, and therefore the characteristic drift times from the moment of generation to the moment of entry into the accelerator will be, for example, for copper ions with an energy of 50 eV - about 4 μs, and with an energy of 1 keV - about 0.9 μs.

If the blocking pulse start is synchronized with the beginning of the discharge, then by changing the pulse duration T_{gp} it is possible to control the cutoff of the fastest ions and ions that appeared at the beginning of the discharge, depending on the ratio of the pulse duration, the time from the beginning of the pulse to the moment of the ion generation T_{gen}, and the ion drift time T_{dr}. Thus, the ion enters the spectrometer if:

$$T_{gen} + T_{dr} > T_{gp} \qquad (1)$$

If the duration of the blocking pulse is large enough to cut off all ions in the previous case, then by changing the delay of this pulse relative to the start of the discharge T_{del}, one can control the cutoff of the slowest ions and ions that appear at the end of the discharge. That is, for registered ions in this case:

$$T_{gen} + T_{dr} < T_{del} \qquad (2)$$

and for cut off ions, respectively:

$$T_{gen} + T_{dr} > T_{del} \qquad (3)$$

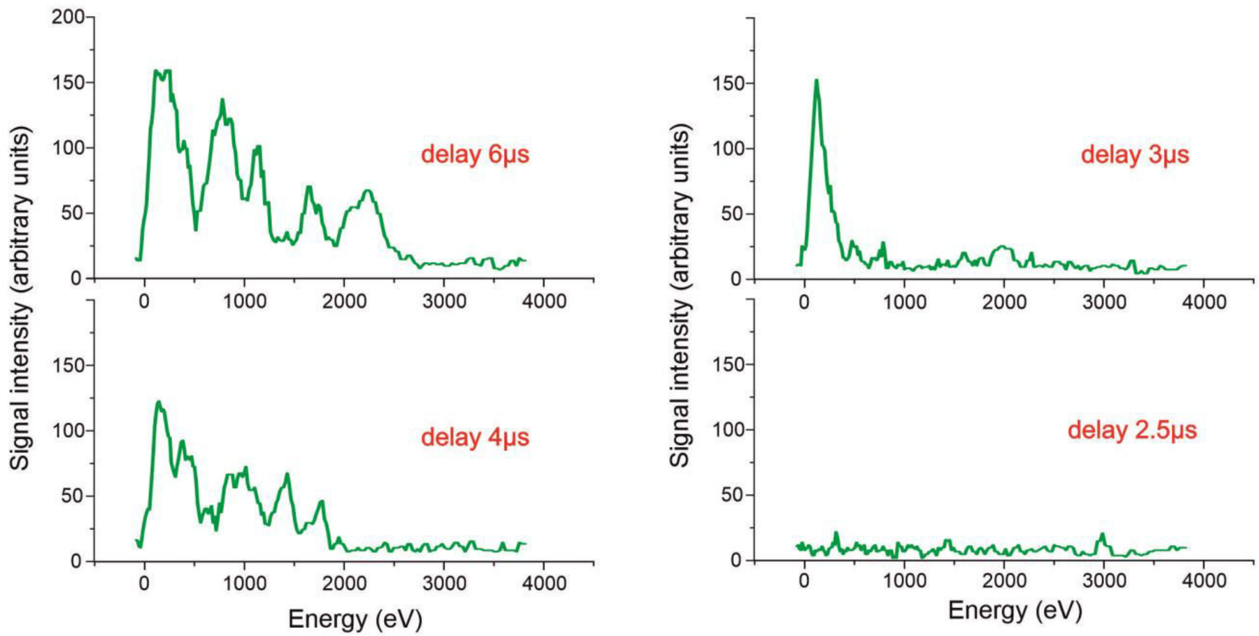
V. Results

The cathode material in the first experiment was copper. In the first experiment with the electrostatic gate, pulse generators based on an LC line with pulse durations of 2 and 3.5 μs were used as the arc source. The time parameters of the blocking pulse operation were varied with a step of 0.5 - 1 μs. The second experiment with a gate was also carried out in the study of ion fluxes from an arc with a cathode made of a CuCr alloy[3]. In this case, only an LC line with a pulse duration of 3.5 μs was used. But the accuracy of the control of the blocking pulse parameters was increased to 0.1 μs.

There were obtained tens of frames with the ion signal. And the data presented here are t he result of averaging of the obtained signals.

We show here examples of ion energy distributions at the several values of the blocking pulse delay for ion species with the most intensive signals, but for the other species of cathode material ions the time-energy behavior is similar.

V. Results



Example of Energy distributions of the copper 2+ ions, obtained at different blocking pulse delay in the first experiment (copper cathode)

Analysis of spectra of all copper ion species showed that the energy of ions in the high-energy component of the ion flux was proportional to the ion charge. And the upper energy limit of the ions was about 500 - 1000 eV per unit of ion charge. This component of the ion flux disappeared from the received signal only when the duration of the blocking pulse exceeded the duration of the discharge by about 1 μs. This time approximately coincided with the drift time for particles with energies of the order of several hundred eV. Thus, the appearance of these particles was not a product of breakdown phenomena in the gap. Otherwise, they would be cut off when the duration of the blocking pulse was not more than 2 μs.

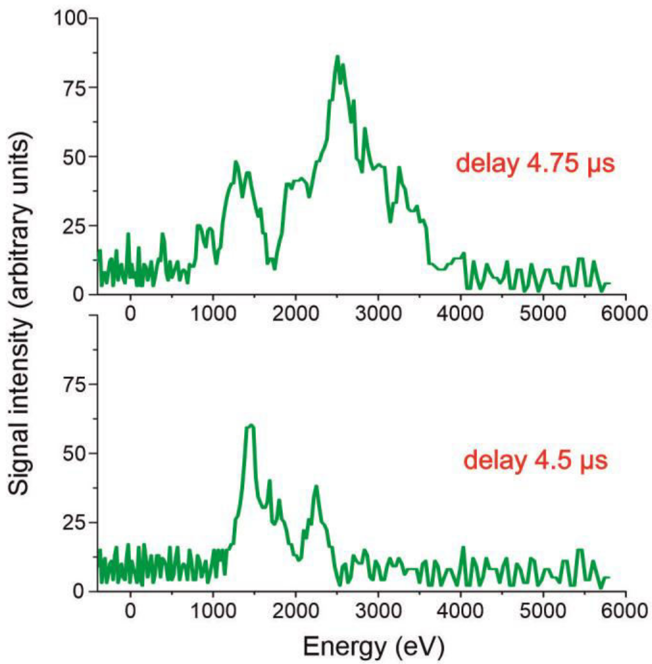
V. Results

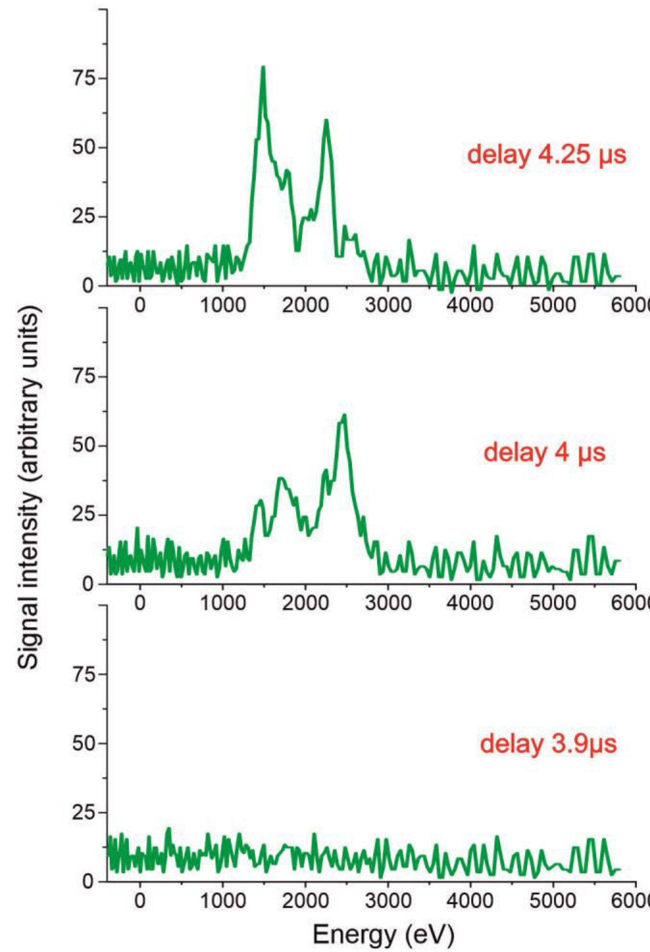
The use of a blocking pulse with a variable start delay showed that the signal of ions with energies of the order of hundreds of eV disappeared when $T_{del} < T_{discharge} + (1 \pm 0.5)$ μs, where $T_{discharge}$ is the arc current pulse duration. The second term of the sum corresponds to the drift time of ions with energies of 400 - 2000 eV. For example, with a discharge pulse duration of 2.3 μs, these ions disappeared with a blocking pulse delay of less than 3 μs, and with a discharge duration of 3.5 μs - with a delay of less than 4-4.5 μs. Thus, the moment of generation of high-energy ions must coincide with the final stage of the discharge. Otherwise, such fast ions would have time to get into the spectrometer before the gate was closed.

More accurate measurements of the estimated moment of high-energy ion generation were carried out in the second experiment with the CuCr cathode. The discharge duration, in this case, was 3.5 μs. Preliminary coarse measurements showed that ions with high energies were not detected by the spectrometer when the delay of the blocking pulse was less than 4 μs. Therefore, special attention in this experiment was paid to the range of blocking pulse delays from 3 to 5 μs. The delay time of the blocking pulse was changed in increments of 250 ns, and then 100 ns.

V. Results

Energy distributions of the copper 2+ ions, obtained at different blocking pulse delay in the second experiment (CuCr cathode).

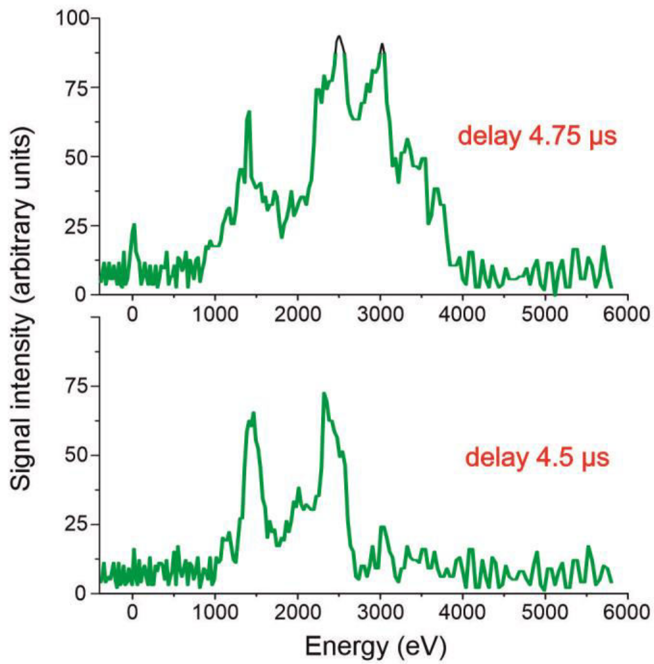


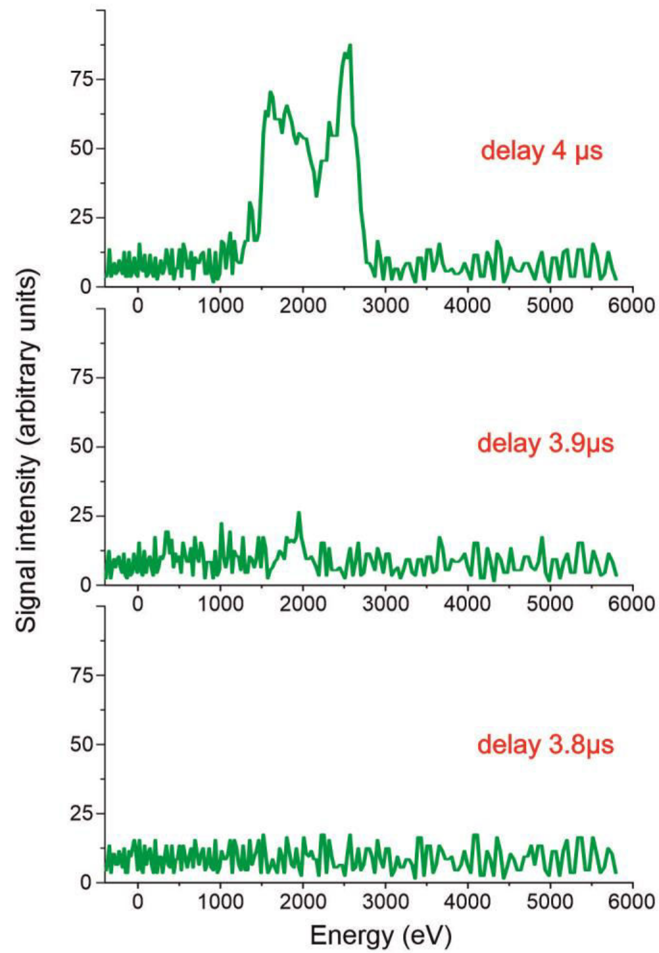


Examples of energy distribution are shown in this slide and the next slide. The Cu^{2+} and Cr^{2+} energy distributions are presented here since the ions had the highest signal intensity. Changes in energy distributions for these ion fractions were almost identical.

V. Results

Energy distributions of the chromium 2+ ions, obtained at different blocking pulse delay in the second experiment (CuCr cathode)





It is noticeable that with a delay of the blocking pulse of 4.75 µs, there were detected ions with energies from 500 to 2000 eV per charge unit. And at a delay of 4.25 µs, ions with energies above 1300 eV per charge unit disappeared. The blocking pulse with the 3.8 µs delay cut off all ions, and 3.9 µs almost everything except a small amount of Cr^{2+} with an energy of about 2000 eV.

V. Results

Ion, and its energy, eV	T_{delay}, at which the ions were not registered, μs	Estimate of the generation time T_{gen}, μs
Cr^{2+}; 2400	3.9	> 3.31
Cu^{2+}; 2400	3.9	> 3.37
Cr^{2+}; 1000	4.25	> 3.43
Cu^{2+}; 1000	4.25	> 3.35
Cr^{2+}; 3600	4.5	> 4.06
Cu^{2+}; 3600	4.5	> 4.02
Cr^{2+}; 2000	3.8	> 3.2

Estimates of the ion generation time for several ion fractions with characteristic energies

For the generation time estimation, there were chosen characteristic energies of 1800, 1200, and 500 eV per charge unit. Drift times to the distance from the discharge region to the ion accelerator grids were from 0.435 μs for the 3600 eV Cr^{2+} ions to 0.9 μs for the 1000 eV Cu^{2+} ions. Therefore, using formula (3), knowing the blocking pulse delay at which the ions disappeared from the detector, we can determine the lower limit of the generation moment for the ions. The estimations for the ions with characteristic energies are presented in the Table.

V. Results

The results obtained for ions with charges +1 and +3 not contradicted the Cu^{2+} and Cr^{2+} values, and with a delay of the blocking pulse of 3.8 μs or less, it was not possible to obtain any ion signal that was distinguished on the background noise. Taking into account the duration of the discharge pulse in the gap not exceeding 3.5 μs, it can be assumed that ion flows with energies of 500 - 1200 eV per unit of charge are formed at the end of arc burning, and with energies up to 2000 eV per unit of charge - even after its extinction.

Ions from the arc plasma with energies in the range of tens of eV had a drift time from 4 to 9 μs in this experimental setup (for copper ions with energies from 50 to 10 eV, respectively). Such ions were detected at the sufficiently large delay of the blocking pulse. In the first experiment, the appearance of a peak in the energy distribution of copper ions at 100-150 eV and the 3 μs delay can probably be associated with breakdown processes in the gap with the copper trigger electrode. And the absence of such a peak in the second experiment, when the trigger electrode was made of tungsten, indirectly confirms this assumption. Nevertheless, ions with energies in the range of 500–1000 eV per charge unit were detected only in plasma associated with the final stages of arc burning.

VI. Conclusion

The appearance of a high-energy component in the ion flux from the plasma of microsecond arcs is regular. The contribution of this component to the total ion signal can be quite high.

The use of an electrostatic gate with variable time parameters showed that the generation of these ions apparently occurs at the end of the discharge. An analysis of the energy distributions of ions shows that their acceleration mechanism is of a field type. The ion energy of the cathode material does not exceed several hundred eV per unit charge of the ion. Such ions can be recorded in the hollow anode - electrostatic extractor system even though the arc burning area is located away from the collimator axis. This effect must be taken into account in a course of investigations of an ion flows from the plasma of low-current microsecond vacuum arcs.

Acknowledgment

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References

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