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Flow of multiple charged accelerated metal ions from low-inductance vacuum spark

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Abstract
Results of studies of the short-run beams of multiple charged fast ions that have been found earlier by the authors in a low voltage vacuum spark are presented. The ion emission was due to the formation of micropinches in the cathode plasma jet by the action of the self-magnetic field. A relation between the average velocity of the fast ions and that of the bulk of the ions of the cathode jet was obtained over a wide range of the discharge current amplitudes. The total yield of the multiple charged fast ions per pulse N_f was evaluated from the direct collector measurements with regard to a decrease in ion flow due to several reasons. This value was in satisfactory agreement with evaluation that was obtained from the ballistic pendulum measurements and gave $N_\mathrm{f} \approx 5 \times 10^{13}$–$10^{14}$ ions per pulse at the average ion charge state of +9 at the maximum of the discharge current $I_\mathrm{d} = 12\,\mathrm{kA}$. Evaluation of current density for these ions gave $j_\mathrm{f} \approx 3\,\mathrm{mA\,cm^{-2}}$ at a distance of about 1 m from the anode.

1. Introduction

In recent years, considerable efforts have been made for elaboration of sources of multiple charged metal ions, which are of interest for different purposes and applications, e.g. as the preinjectors of large colliders, for solving material science problems and medical applications. For these applications the intense fluxes of highly charged and high energy ions are desirable. A promising source of ions with suitable characteristics is a vacuum spark, where a high energy density is released in a plasma column. Therewith a spark is also characterized by a relatively low total energy contribution and a simple construction. Indeed, even in early experiments in high current (>50 kA) sparks the bursts of x-rays emitted by hydrogen- or helium-like ions of the cathode material were detected [1, 2]. The ions were evidently produced in the hot plasma of micropinches that were formed in the inter-electrode gap of the spark [3, 4]. The experiments demonstrated that electrons in the plasma of the micropinches were truly heated up to 1–3 keV [5, 6]. Nevertheless, the immediate measurements of ions ejected from plasma of the sparks found that just the low ion charge states were presented [7].

Previously, we found the beams of multiple charged ions of cathode material in experiments with a small size vacuum spark with low values of both the capacitor voltage (up to 2.5 kV) and the stored energy (up to 10 J). It was found that the ions were emitted from the cathode plasma jet at the initial stage of the discharge burning during a short-run time interval of less than 100 ns length. The maximum and the average charge states for copper ions ranged up to $Z_{\max} = +19$ and $\bar{Z} = +9$, respectively, at the discharge current of 10 kA [8]. Maximum energies of the ions reach $E_{\max} \approx 150\,\mathrm{keV}$ [9]. The experiments also showed that there were two groups of ions in the cathode plasma jet of the discharge. They were defined as the 'fast' and the 'slow' ions and some characteristics of the latter, which constituted the bulk of the cathode ion flow, are presented in the paper [10]. The subsequent experiments found that the multiple charged ions of cathode material were produced in micropinches, which were formed within the cathode plasma jet expanding into the vacuum ambient [11]. Note that emission of the high energy ions, which was due to formation of micropinches in the plasma column, has also been found recently in a high current vacuum spark [12].

In this paper, we present results of the detailed measurements of parameters for both types of ions over a wide

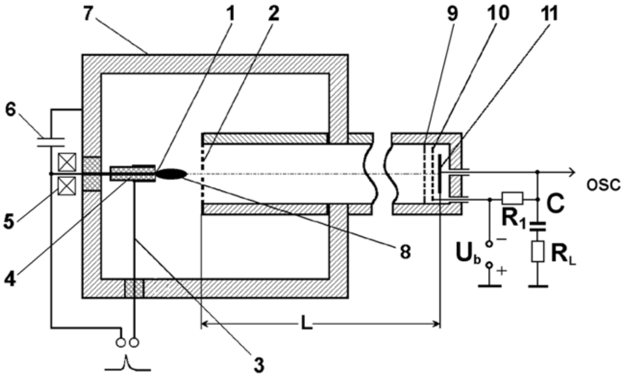

Figure 1. The scheme of experiments: 1, cathode; 2, anode; 3, igniter; 4, dielectric insert; 5, Rogovsky coil; 6, capacitor; 7, vacuum chamber; 8, plasma jet; 9, exit grid of the drift tube; 10, suppressing grid; 11, collector; $R_1 = R_L = 20\,\Omega$; $C = 10\,\mu$F.

range of the discharge current amplitudes. The objectives of these measurements are to establish a relation between velocities and yields of the fast ions and the bulk of the ions of the cathode plasma jet under change of the discharge current and to evaluate a total yield of the multiple charged ions that were produced per shot. These characteristics are important for the estimation of applicability of the discharge as a source of the multiple charged ions for different applications.

2. Experimental set-up

Experiments were carried out with a low-energy vacuum spark (see figure 1). The electrode arrangement was mounted in a 100 mm long and 50 mm diameter stainless steel cylindrical vacuum chamber. The arc was run between a copper cathode as a wire of 1 mm diameter with a cone-like working surface and a grounded grid anode, which was placed at 10 mm distance from the cathode. The discharge was ignited by a high-voltage breakdown at the top surface of a dielectric insert, which separated the cathode and the igniter. A low-inductance capacitor ($C = 2\,\mu$F) sustained the discharge so that the total inductance of the discharge circuit was about 40 nH. The capacitor was loaded up to a voltage that was varied in the range $U_0 = 400$–2500 V. The discharge current was measured by a Rogovsky coil directly in the cathode circuit. The oil-free pump pumped the chamber down to a pressure of (5–8) $\times 10^{-6}$ Torr.

We used vacuum chambers of two designs. The first one was intended for time-of-flight measurements and designed with a grid anode. Plasma was produced at the front face of the cathode, expanded through the anode grid and entered a drift tube 55 mm in diameter that was connected to the chamber. The exit of the tube was also closed with a grid, so that the equipotential drift tube was formed to provide the validity of time-of-flight measurements. After passing the exit grid, the cathode plasma ions were recorded with a collector that was 34 mm in diameter and was biased by a negative potential of −200 V with respect to the ground. An additional grid was placed in front of the collector, it was biased by a negative potential $U_b = -400$ V with respect to the ground. This means that the grid was biased by −200 V with respect to collector to suppress the secondary electron emission from the collector due to the ion bombardment. All three grids were of 60% geometrical transparency, and the distance between exit grid of the drift tube and the suppressing grid was 3 mm. The same was the distance between the suppressing grid and the collector. We used drift tube of three lengths, so that the collector was placed at three distances away from the anode: $L = 10$, 35 and 95 cm. Note that measurements with the collector spaced less than 10 cm from the anode caused a problem because of the possibility of a breakdown between the collector and the anode through the dense plasma of the cathode jet.

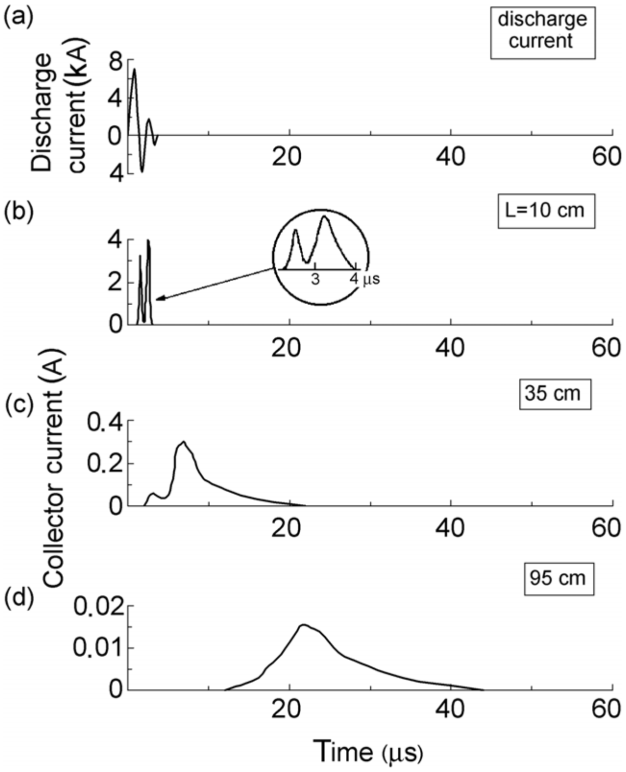

Figure 2. Waveforms of the discharge current (*a*) and corresponding signals of collector current spaced at different distances from the anode (*b*)–(*d*).

The second type of vacuum chamber design was intended for measurements of the macroscopic mechanical momentum of the cathode jet immediately beyond the inter-electrode gap. For this purpose, we used an annual anode with hole of 10 mm diameter. Just beyond the anode a ballistic pendulum was placed, which was fabricated as a metal disc of mass 0.35 g and was suspended on a grounded wire [13]. After the cathode jet stroked the disc, the latter deflects from the initial position and from the deviation angle one evaluates a mechanical momentum, which the jet imparted to the disc.

3. Results

Figure 2 presents waveforms of the discharge current and corresponding signals of the collector spaced at different distances from the anode. One can see that there are two peaks in ion current from the collector spaced 10 and 35 cm from the anode. The first peak has a lower delay with respect to the discharge onset and corresponds to the fast ions. The second peak has a larger delay and more amplitude than the first one.

Therefore, it corresponds to slow ions, which represent the bulk of ions of the cathode jet plasma [10]. Characteristics of these groups of ions are as follows. First, one can see from figure 2(*b*) that two peaks in ion signal are distinctly pronounced, amplitudes of the peaks for both ion groups are close to each other and the width of the first ion peak is less than that of the second peak. These results suggest that the total yield of the fast ions constitutes a good fraction of the main ion flow, and the time of production of the fast ions and/or dispersion of their initial velocities are rather less than those of the slow ions.

Second, figures 2(*c*) and (*d*) show that the widths of both peaks in ion current signal increase with length of the drift tube. Apparently, it is due to dispersion of the initial ion velocities. Amplitudes of both ion current peaks decrease with increase in the tube length, but amplitude of the fast ion component decreases markedly sharper than that of the slow ions, so that at length of the tube of 95 cm, this peak drops lower than the record threshold. From this result one can conclude that the relative contribution of the fast ions in the total ion flow also decreases as the cathode jet passes through the drift tube.

From waveforms like those depicted in figure 2, the average velocities and amplitudes of signals of both ion components at the given amplitude of the discharge current were obtained by the procedure as follows. Figure 2 shows that the slow ion component is a bulk of the ion flow and we suggest, in agreement with the known experimental results [14], that flow of ions from the cathode is proportional to the discharge current. Hence, the bulk of ions of the cathode plasma is produced in the first peak of the discharge current oscillations, when amplitude of the current exceeds significantly the subsequent peaks. Our experiments also showed that ion acceleration occurred essentially within the inter-electrode gap, where the discharge current closed the circuit, and after passing of the anode grid the plasma flow expanded freely into the drift tube with the velocity being near hold. The inter-electrode gap is a minor part (<10%) of a full path of the ions from the region of acceleration to the collector. Hence, we took lengths of the drift tube $L = 10$, 35 and 95 cm as the lengths of the ion path for the time-of-flight measurements. The delay between peak of ion signal at the collector and the first peak of the discharge current matches the time-of-flight of the ions for distance L. From this delay and the length of ion path, the mean velocity of bulk of the cathode jet ions could be calculated. In this process, one can see that at $L = 10$ cm the delay of signal corresponding to the bulk of jet ions is comparable to duration of the discharge, i.e. to duration of the ions production. Therefore calculation of the ion velocity at this distance was of insufficient accuracy (about 50%) and this procedure was performed just for $L =$ 35 and 95 cm, where the accuracy was of 20% and 5%, respectively.

We will show below that the fast ions are the multiple charged and accelerated ions, which we have found previously [8, 9]. It was found that the ions were produced during a time interval of less than 100 ns length, which lied approximately at 200–500 ns after the discharge onset. The average velocity of the fast ion component in the *present* experiment was calculated from the delay of the peak of their signal with respect to the middle of this interval (300 ns after the discharge onset).

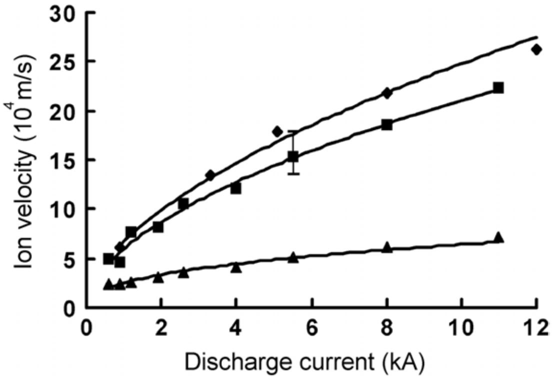

Figure 3. Dependences on the discharge current of velocity of bulk of ions of the cathode jet (—▲—), velocity of the fast ion component (—■—) and velocity of the multiple charged ions found from data of [8, 9] (—◆—).

Note that the procedure also was of insufficient accuracy with the drift tube length $L = 10$ cm, hence velocity of the fast ions was derived just for $L = 35$ cm. Also, to eliminate the shot-to-shot variations, all data were averaged over 10 shots that were run under the fixed amplitude of the discharge current.

To establish a statistically justified dependence of characteristics of ions on the discharge parameters, the measurements were performed throughout the range of variation of the parameters, namely from 0.4 up to 2.5 kV for the capacitor voltage and, respectively, from 0.8 up to 12 kA for peak of the discharge current I_d.

The dependence of velocities of both ion components on I_d are shown in figure 3. Also, in the figure we presented the same dependence for average velocity of the fast and multiple charged ions, which have been found previously in our works [8, 9]. We obtained this dependence from the data of our previous measurements with the energy ion analyser by procedure as follows. First, for the given peak of the discharge current, the energy spectra of ion species at different charge states were built up from a set of signals of the ion energy analyser [8]. Then, the average velocities of individual ion species were obtained from the spectra, these velocities were averaged over all species, so that the average velocity of the fast multiple charged ions was obtained. One can see from figure 3 that the velocity of the fast ions that was obtained from the present collector measurements is close to the average velocity of the multiple charged ions throughout the range of the discharge current variation. This result allows us to conclude that both types of ions are of a unified nature. Also, figure 3 shows that velocities of both the fast ions and the bulk of ions V_f and V_b, respectively, increase with peak of the discharge current I_d, but the V_f increases more sharply than V_b.

Now, let us consider a variation of contents of the fast ions and the bulk of ions in the plasma jet when increase in peak of the discharge current occurs. Dependences of amplitudes of the collector current for both types of ions on peak of the discharge current are presented in figure 4(*a*). It demonstrates the sharp and similar increases in both amplitudes, so that a fraction of the fast ions in the total ion content remains near constant through the range of the discharge current variation. Dependence of the collector current of the bulk of ions I_b on distance of the collector to the anode L is presented in

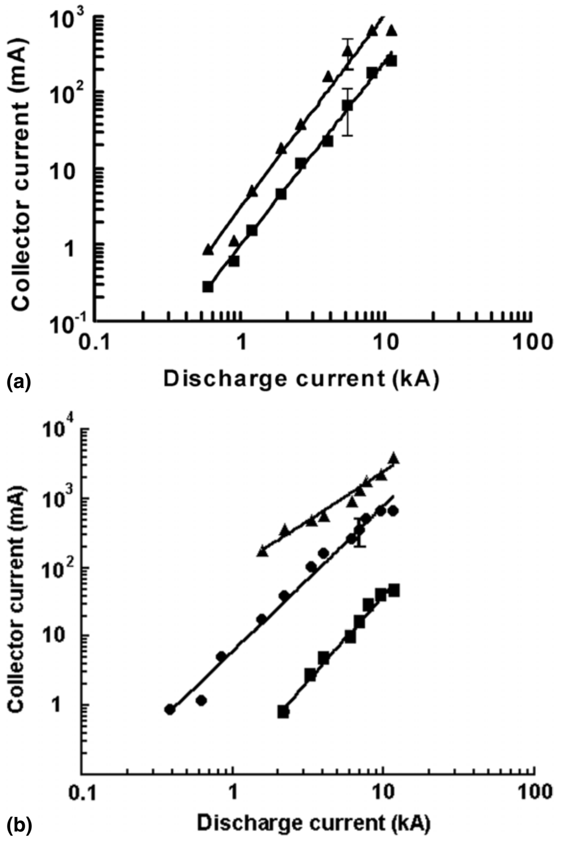

Figure 4. (*a*) Peak of the collector current at $L = 35$ cm from the discharge gap versus peak of the discharge current for the bulk of ions of the cathode jet (—▲—) and for the fast ion component (—■—). (*b*) Peak of the collector current versus peak of the discharge current for the bulk of ions at $L = 10$ cm (—▲—), 35 cm (—●—) and 95 cm (—■—).

figure 4(*b*) for three values of L. The figure shows that with increase in L, the current decreases and the estimations showed that the decrease can be roughly approximated with a relation, as follows, $I_b \propto L^{-n}$, where parameter n is varied from 2.0 to 2.5 in the range of the discharge current variation. This means that the motion of the cathode plasma inside of the drift tube is close to a free expansion.

Now let us evaluate the total yields of both ion components as per a specified discharge pulse, which we denote as N_f for the fast ions and N_b for the bulk of ions. The evaluations were obtained from the collector measurements for $L = 10$ cm by the procedure as follows. Initially, one calculated the total charge of each ion component per pulse by integrating the corresponding peak in collector current signal over the peak length (see figure 2(*b*)). Then, by dividing the obtained values by the corresponding mean charge state Ze of the ions, the yield of the ions was derived. The value of Z for the bulk of ions was taken as the standard one for vacuum arcs with a copper cathode, $Z \approx 2$ [15] and that for the fast ion component was taken from our previous measurements, where it was established that Z increases from $Z = +4.5$ at peak discharge current of 1.2 kA up to $Z = +9.3$ at current of 12 kA [8]. The results of estimation of the yields of the ion components N_f and N_b are presented in figure 5. It is seen that the yields rise with the discharge current so that N_f attains about 2×10^{12} ions per pulse for the fast component.

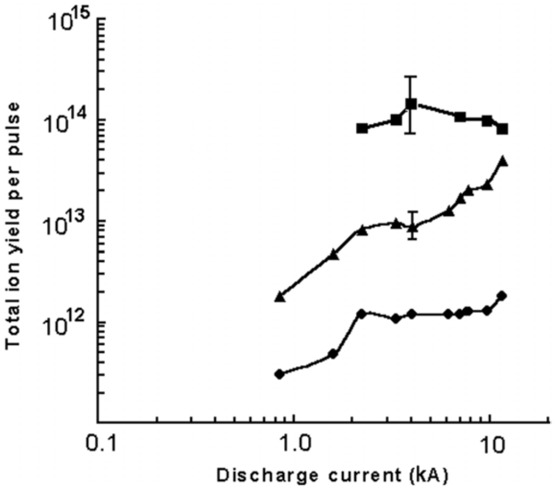

Figure 5. Dependence on the peak of the discharge current of the total yield per pulse of the fast multiple charged ions obtained from the collector measurements (—◆—), the same for the bulk of ions (—▲—) and evaluation of the yield of the multiple charged ions derived from the ballistic pendulum measurements (—■—).

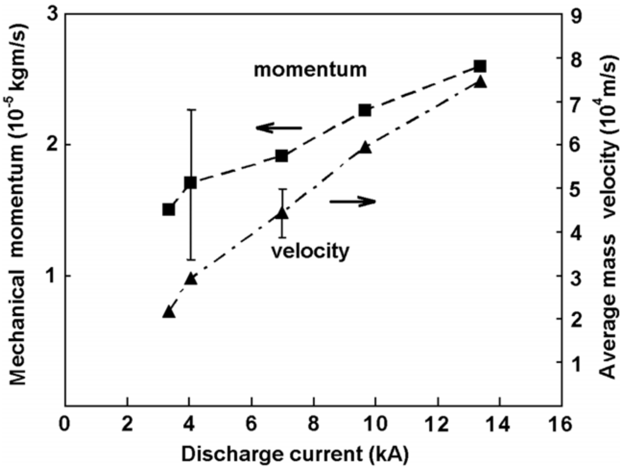

Figure 6. Mechanical momentum of the plasma jet derived from the ballistic pendulum measurements (—■—) and the average mass velocity of the jet (—▲—) versus peak of the discharge current.

To justify this result, the yield of the multiple charged fast ions in cathode jet in the immediate vicinity of the inter-electrode gap was estimated by means of the other method that was based on measurements of the total mechanical momentum of the jet by a ballistic pendulum. Dependence of the momentum P on peak of the discharge current is presented in figure 6. The similar dependence for the average mass velocity V_m of the jet is depicted in figure 6, as well. The velocity was derived from the data presented in figure 3 taking into account the contributions of both ion components in the mass velocity by the formula as follows:

$$V_m = \frac{V_f N_f + V_b N_b}{N_f + N_b} = \frac{V_f + (N_b/N_f)\ V_b}{1 + N_b/N_f}. \tag{1}$$

Here V_f and V_b were obtained from figure 3. To derive the ratio of yields of both ion components N_f/N_b, we used the data obtained at length of the drift tube $L = 10$ cm. We believe that it is a signal of the collector minimum spaced away from anode (like that depicted in figure 2(*b*)), which presents the relation between collector currents of the ion components close to the true one because the charge-exchange distorts the relation when the plasma jet is passing through the drift tube.

From the measured momentum and average mass velocity, the total ion mass of the plasma jet M was calculated as $M = P/V_m$, and the total yield of ions in the jet was estimated as $N_i = N_f + N_b = M/m_i$ (m_i is the ion mass). Finally, from this value and the ratio N_f/N_b the yield of the fast ions N_f was obtained for a range of amplitudes of the discharge current. The dependence of N_f on I_d that was evaluated from the pendulum measurements is also presented in figure 5, which shows that this value attains 10^{14} ions per pulse and is near hold under changes of the discharge current within a wide range of values.

Also, one can evaluate from figures 2(*b*) and 4(*b*) the underestimated maximum current density j_f of the fast multiple charged ions at the distance of 10 cm from the anode, namely $j_f \geqslant 0.3\,\mathrm{A\,cm^{-2}}$. The estimations presented above showed that the ion current density decreases as the plasma jet expands into the drift tube by the relation $j_f \propto L^{-n}$ where the parameter n is close to 2, hence we conclude that at 1 m distance from the anode $j_f \geqslant 3\,\mathrm{mA\,cm^{-2}}$.

4. Discussion

Let us discuss the significant difference between the total yields per pulse of the fast highly charged ions that were obtained from the pendulum and from the collector measurements (see figure 5). We suggested that the latter is underestimated substantially for two reasons. First, the ion flow decays when expanding inside of the drift tube because of charge exchange of ions with atoms of the residue gases that results in a decrease in the mean ion charge state. Really, the paper [16] shows that as the residue gases pressure in a vacuum chamber exceeds 10^{-6} Torr, the content of the multiple charged ions with $Z = +(3\text{–}5)$ in the cathode jet of a vacuum arc decreases more than the order of value at the distance of about 50 cm from the anode with the corresponding increases in content of ions with $Z = +1$. In the given experiment, as the collector was distanced from the anode, this effect should decrease in the mean ion charge state of the fast multiple charged ion component with $Z = +4.5$ to $+9.3$ sharper than that of the bulk of ions, which has $Z \approx +2$. This, in turn, results in a more sharp decrease in collector current for the fast ion component. Figures 2(*b*)–(*d*) exhibit that this effect apparently takes place in our experiment. Also, note that in our first experiments, which were performed at the relatively high pressure of the residue gases, of about 2×10^{-4} Torr, we observed just ions of the cathode material at low charge states, namely Cu^+, Cu^{+2} at the same discharge parameters [17]. It was decrease in the pressure down to $(5\text{–}7) \times 10^{-6}$ Torr in subsequent experiments that permits us to observe the ions at high charge states, up to Cu^{+19} [9]. These results support our suggestion that decrease in charge states of ions of the cathode jet in the given experiment also takes place due to the jet propagation inside of the drift tube and the decrease is due just to charge exchange at the residue gases atoms.

The second reason for underestimation of the ion yield per pulse with the collector measurements is due to expansion of the jet plasma beyond the anode grid in the drift tube; because of this, the recorded collector current did not take into account the total jet even if the collector was spaced 10 cm from the anode. To evaluate the effect, we extrapolated the data presented in figure 4(*b*) towards the near anode region by using the approximate relation presented above, $I_b \propto L^{-2}$. Also, taking into account the effect discussed above, we obtain the rough estimation of the total yield of the fast and multiple charged ions in the plasma jet in the immediate vicinity of the anode that is 1.5–2 order more as compared with the values presented by the corresponding curve in figure 5. Hence, we estimate the ion yield of the order of 5×10^{13}–10^{14} particles per pulse with the mean charge state $Z = +9.3$ at the discharge current of about 12 kA. It is evident that we should also enhance by the same factor, i.e. by 1.5–2 orders of magnitude, the current of these ions, which attains, approximately, 10^2 A for this discharge current. The satisfactory agreement between estimations of the total yield of the fast multiple charged ions in the cathode plasma jet that were obtained by two independent methods supports a validity of these estimations.

Now let us consider a possible nature of those ions and compare their characteristics with those in laser produced plasma. The latter is widely used now as a source of the multiple charged and accelerated metal ions for distinct purposes (see, for instance, [18]). It is well known that, like in our experiment, there are the fast and slow, thermal, ion components in the laser produced plasma flow expanding into the vacuum ambient [19]. The fast ion component corresponds to the multiple charged ions of material of the irradiated target, which are accelerated up to high energies because of carrying away by the ambipolar electric field. The field arises as a consequence of emission of a beam of accelerated electrons from the boundary of the current-free laser plasma flow [20]. On the other hand, it is a well-known fact that in plasma of a high current vacuum spark at the discharge current exceeding 50 kA a micropinch develops, which results in the emission of a beam of high energy electrons moving along the discharge axis towards the anode [21]. Our model calculations and experiments demonstrated that in the cathode jet of the discharge under consideration, a micropinch was also produced at a rather less peak of the discharge current $I_d > 1$ kA [11]. Plasma electrons in these micropinches were heated up to temperature $T_e \approx 0.1$–0.3 keV. It is natural to suppose that in this case the micropinch formation also results in the emission of an electron beam moving towards the anode, therewith ambipolar field of the electron beam carries away the multiple charged ions, which have been produced in the micropinches, and accelerates these ions up to high energies. Recent experiments in a laser-induced vacuum discharge found that in fact a micropinch was produced in the cathode jet at the discharge current of just a few kiloamperes and this causes the emission of a beam of the accelerated electrons towards the anode [23].

Now let us compare the quantitative parameters of beams of the multiple charged ions under investigation and those of the laser produced plasma. We take for comparison the data of the rather advanced experiments at high power laser facilities, where the highest charge states of metal ions have been attained. The energy of the laser pulse in these experiments is of 60–250 J and maximum laser intensity is about 6×10^{16} W cm^{-2} [22]. For instance, parameters of ions of the nickel were as follows: the maximum charge state is $Z_{\max} = +26$, the maximum energy is $E_{\max} = 2.5$ MeV, the ion current density is $j = 20$ mA cm^{-2} (at 100 cm distance collector to the target) and the ion yield ranges from about 1×10^{12}–1×10^{13} ions sr^{-1}. When comparing the data with those presented above, one can see that both $Z_{\max}$ and ion yields obtained in [22] are comparable with those in our studies and $E_{\max}$ and j exceed ours, approximately, just by the order of value. Note also that one should expect significant increase in both the mean charge state and current of the multiple charged metal ions when the experiments are being performed in the high current low-inductance vacuum spark like that in [5] at the current amplitude of about 100 kA.

5. Conclusions

We have established in a low voltage vacuum spark a relation between velocity of the fast ion component and that of the bulk of ions of the cathode plasma jet under change of the discharge current over a wide range. We obtained the approximate evaluations of a total yield of the fast and multiple charged ions that were produced per shot with two independent methods and these evaluations were in reasonable agreement. A comparison of the presented data and parameters of the laser produced plasma showed that:

- there are a few common characteristics between the process of acceleration of beams of the multiple charged ions that are emitted from the cathode plasma jet of a vacuum discharge and those emitted from the laser produced plasma, hence we suppose the similar nature of production and acceleration of the ions in both cases,
- the main parameters of beams of the accelerated multiple charged ions yielded from the given plasma source and those yielded from the laser produced plasma are comparable, therewith the laser facilities are of incomparably bigger sizes, cost and energy consumption as compared with those of the vacuum discharge, so we conclude that the latter can be explored as the efficient source of the highly charged metal ions.

Acknowledgments

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