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Author
Anders, Georgy, Yu. Yushkov, Andre

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High Charge State Ions Extracted from Metal Plasmas in the Transition Regime from Vacuum Spark to High Current Vacuum Arc

G.Yu. Yushkov[1] and A. Anders[2]

[1] High Current Electronics Institute Russian Academy of Sciences, Tomsk, 634055, Russia

[2] Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA

***Abstract*- Metal ions were extracted from pulsed discharge plasmas operating in the transition region between vacuum spark (transient high voltage of kV) and vacuum arc (arc voltage ~ 20 V). At a peak current of about 4 kA, and with a pulse duration of 8 µs, we observed mean ion charges states of about 6 for several cathode materials. In the case of platinum, the highest average charge state was 6.74 with ions of charge states as high as 10 present. For gold we found traces of charge state 11, with the highest average charge state of 7.25. At currents higher than 5 kA, non-metallic contaminations started to dominate the ion beam, preventing further enhancement of the metal charge states.**

I. Introduction

Metal ions produced in vacuum arcs are often multiply charged, typically involving charges states 1 to 3, and in rare instances 4 and 5 [1-4]. It is recognized that the presence of multiply charged ions has a significant effect on the energy of ions in beams, because their kinetic energy is well approximated by

$$E_i\left(Q, V_{extr}\right) = E_{i0} + QeV_{extr}\,, \qquad (1)$$

where $Q = 1, 2, \ldots Q_{\max}$ is the charge state number, E_{i0} is the "natural" kinetic energy ions have gained by acceleration at the cathode spot [5-7], which scales approximately with the cohesive energy of the cathode material [8]; V_{extr} is the extraction voltage of ion source. From Equ. (1) we see that, for a desired final ion energy, the necessary extraction voltage can be kept lower if the charge state number was higher.

The charge state distributions are a consequence of the cathode material properties and the power density of the discharge. Increasing the current of continuous arc discharges does not lead to higher charge states because the amount of plasma produced is about proportional to the current, and hence the power density per plasma particles is approximately unchanged.

Several schemes have been proposed and explored to shift the charge state distributions to higher values. All of the effective methods have in common that additional energy is dissipated in a given amount of plasma. Among the popular approaches is the use of an axial magnetic field that, at least in part, isolates the cathode region from the anode [9,10]. As a result, a voltage drop, ΔV_{add} appears in the plasma. The additional power dissipation, $I_{arc}\Delta V_{add}$, contributes to electron heating and enhances ionization. It has been demonstrated that the arc voltage, which is typically ~ 20 V, can be greatly enhanced, reaching almost the 100 V level. The mean charge state of ions can be increased by about a factor 1.5-2.5.

Other approaches of pumping energy into the plasma system are by an electron cyclotron resonance discharge [11] or by injecting an electron beam into the plasma region [12]. Another approach was to superimpose current spikes on the otherwise "regular" discharge current: these spikes are not gentle modulations but sharp increases of the current, driven by the applied high voltage spikes [13]. The transient high voltage contributes to an enhancement of power, and this is directly reflected in an enhancement of the mean ion charge state. However, only modest shifts of charge state distributions have been obtained.

More recent investigations focused on the role of neutrals, both metal and gaseous [14]. It was shown that the time dependent mean ion charge state can be well approximated by

$$\overline{Q}\left(t\right) = A\exp\left(-t/\tau\right) + \overline{Q}_{ss}\,, \qquad (2)$$

where A is a parameter describing the importance of the decay after discharge triggering, τ is the characteristic decay time, and $\overline{Q}_{ss}$ is a steady-state value that is approached for continuous arc operation. The extrapolated values $\overline{Q}\left(t \to 0\right)$ indicated surprisingly high mean charge states as produced at cathode spots.

Vacuum *sparks* are characterized by a high, transient voltage between anode and cathode. The current can be quite high, and the magnetic self-field caused by the current pinches and heats the plasma. The pinch develops instabilities which may lead to short-lived "plasma points" containing highly charged (e.g. > 20+) ions [15,16]. Those ions are registered by the X-rays emitted [17]. Extraction of ions from the plasma points to form *beams* of highly charged metal ions is impossible because the highly charged ions are recombined before they arrive at an ion extraction system.

In the mid 1990s, vacuum sparks with peak currents up to 73 kA have been used to extract ions: the maximum extracted ion charge state for copper was 7, short of what was hoped. Ultimately, this effort was terminated because the *non-metal* contribution to the beam was always large (and not fully understood). Another effort was done more recently by Paperny's team [18,19] using a vacuum spark with a copper cathode. One has to deal with the principle difficulty of measuring mass/charge, and so it is not easy, and in some cases impossible, to resolve the peaks of multiply charged metal and light non-metal ions.

In the present approach, we extract multiply charged ions from a transient vacuum discharge and use a time-of-flight (TOF) spectrometer for species identification.

II. EXPERIMENTAL PROCEDURE

The experiments were carried out at the modified vacuum arc ion source "Mevva V" at Berkeley Lab[4]. The cathode was a 6.25 mm metal rod coaxially placed in a copper tube (anode) of 25 mm inner diameter. The plasma produced at cathode spots at the rod's front face expanded toward a 3-grid extraction system placed 105 mm from the cathode. The current pulse (Fig. 1) was obtained by a low inductance 11 μF capacitor, giving us a peak current of up to 10 kA and a full-width-at-half-maximum (FWHM) of 8 μs. The peak current could be selected simply by adjusting the capacitor's charging voltage (maximum 4 kV). The electrical power dissipated in the gap was up to 10 MW at the end of the first 3 μs, far exceeding typical arc values.

The plasma expanded from the discharge gap and arrived at the extraction grid system, where an extraction voltage of was 30 kV was applied to form the ion beam. The beam current was measured by a Faraday cup (Fig. 2), located on axis 618 mm from plasma grid. The ion collection area was 20 cm^2. Because the Faraday cap collected about 20% of the total ion beam current, the total beam current was about

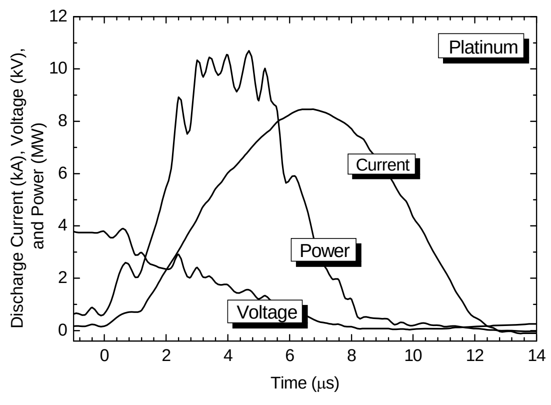

Fig. 1. Discharge current, .discharge voltage, and electrical power dissipated in discharge gap.

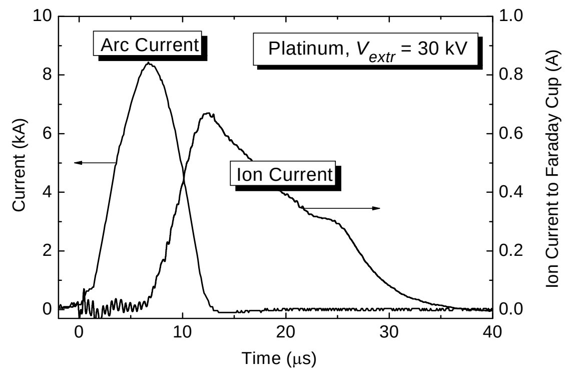

Fig. 2. Discharge current and ion beam current to Faraday cup.

4 A.

The Faraday cup signal was recorded by a fast digital oscilloscope (Tektronix TDS 744) operating in the averaging acquisition mode (100 pulses). Several cathode materials have been used: Ti, Pt, Sb, W, Au, Er, Al and Bi. They all showed similar behavior, and so we can limit the report here by focusing on one element (Pt) and the shortest pulse with 8 μs FWHM. The system was cryogenically pumped with a base pressure of about $1x10^{-4}$ Pa.

III. EXPERIMENTAL RESULTS

Figure 3 shows the charge state distribution of platinum and gold plasmas under conditions that gave the highest values: we observed a mean ion charge state of $\overline{Q} = 6.74$ for Pt and $\overline{Q} = 7.25$ for Au. Those values are significantly greater than the "typical" vacuum arc value of $\overline{Q} = 2.08$ and $\overline{Q} = 1.97$, correspondingly. For platinum we could record charge states 8, 9, and traces of 10. For gold we detected even traces of charge state 11. The corresponding ionization energies are shown in Fig.4. One needs to note that, due to the electronic shell structure, the set of successive ionization energies for platinum shows a big step from 10+ to 11+, whereas but for gold such big step occurs from 11+ to 12+. This contributes to which maximum charge state can be obtained: ionization energies approach about 200 eV for both elements for the highest charge states observed.

It is interesting to solve the 11 coupled Saha equations [20] describing the ratios of charge states 0 to 10 that would apply if we assumed ionization equilibrium. It turns out that a temperature of about 7 eV is sufficient for Pt to approximately generate a CSD with a most likely charge state of 7 and a reasonable amount of 10-fold charged ions.

As with previous spark experiments, we noticed relatively large quantities of hydrogen, oxygen, and carbon ions. The experiment was not done in ultrahigh but high vacuum, and therefore the anode, grids, and all other surfaces are covered with adsorbed gases that can be desorbed when the energetic plasma particles impact. A mass/charge-selecting bending magnet needs to be employed for those applications that require mass and charge state purity.

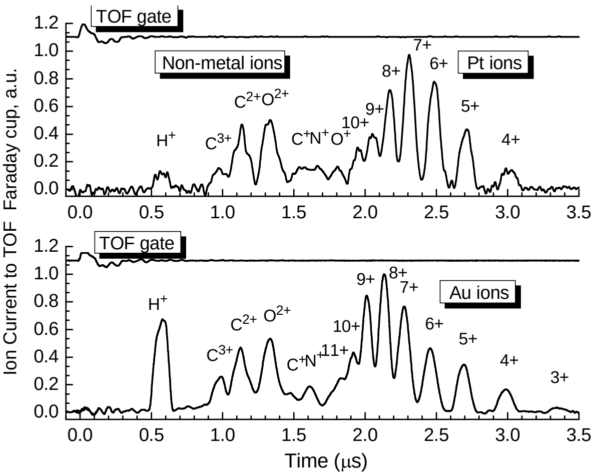

Fig. 3. TOF spectrums of the ion charge state distribution with platinum and gold: the top curves are the gating voltage, and the bottom are the electrical current at the Faraday cup; 4 kA peak, with 3 pulses per second.

The CSD is not constant during the pulse but shows a distinct trend to lower charge stages, indicating the transition from vacuum spark to vacuum arc. Ultimately, on the timescale of ~ 1 ms, the steady state values of DC arcs are observed [14,21].

Figure 5 shows the decay of the CSD for a 3 kA pulse. We see that the highest charge state of 10+ is present only at the beginning of the discharge pulse, and the mean ion charge state is also highest at beginning of the pulse. This is consistent with the observation that the highest power dissipation takes place at this time.

Based on these encouraging results one would assume that by going to higher currents, one might be able to push even further into the territory of higher charged metal ions. The experiments were therefore systematically extended up to 10 kA peak current. The result is shown in Fig. 6: there seems to be an optimum for generating higher charge states at about 5 kA for the given configuration.

This result can be explained when looking at the

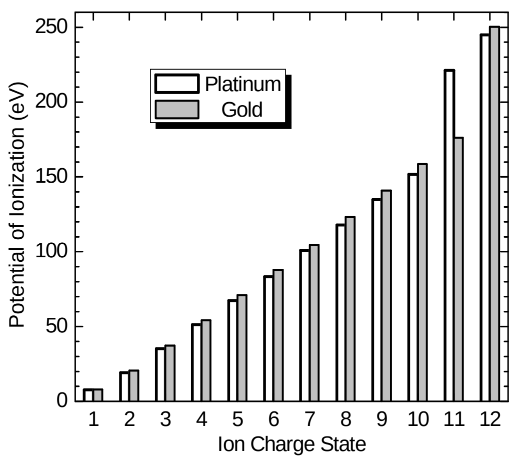

Fig. 4. Ionization energies of platinum and gold from neutral (charge state 0) to singly charged (1), etc. (from [21]).

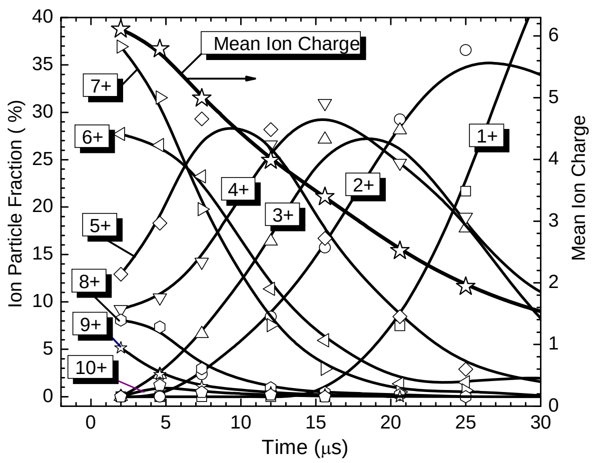

Fig. 5. Evolutions of the platinum ion charge state distribution and mean ion charge state as measured with the time-of-flight method. The time "zero" is defined here as the arrival time of the first (fastest) ions at the Faraday cup detector.

non-metal contamination of the ion beam. As more energy is invested in each discharge pulse, the interaction of the plasma particles with the anode, the first extraction grid and other components becomes more intense. There is an increase in the density of non-metal neutral vapor which leads to charge exchange collisions, which preferably reduce the highest charge states and produce ions like H^{+}, O^{+} and C^{+}.

The non-metal ion current fraction for different discharge currents is shown in Fig. 7. An increase of the discharge current leads to a dramatic decrease of the platinum ion current fraction. For example, for a peak current of 4 kA, the ratio between platinum and non-metal ion current was about 3 to 2. When the peak current is set to 10 kA or more, the ratio is amazingly small, namely 1 to 70. Clearly, for further enhancements of the metal ion charge states one should go to ultrahigh vacuum systems.

We emphasize that is not just the high current that leads to high ion charge states but

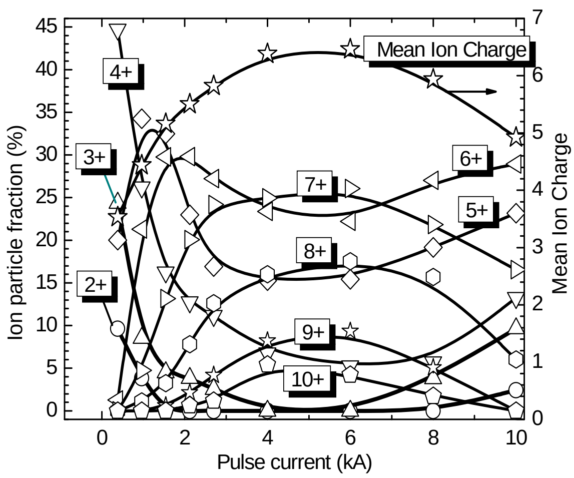

Fig. 6. Ion charge state distribution and mean ion charge state of platinum plasma for different discharge current.

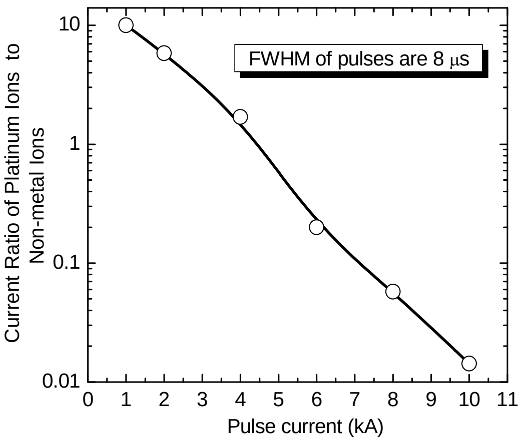

Fig. 7. Ratio of ion currents of platinum ions to non-metal ions for different discharge current.

the power density and therefore the voltage should be high. This can be done by using short pulses: the transient voltage is much higher than in the typical arc situation as long the plasma had not time to establish a steady-state distribution (Fig. 1). For pulses with FWHM more then 50 μs, the discharge voltage reached about 30 V and therefore the mean ion charge state is reduced to the typical vacuum arc values. Clearly, for further increasing of the metal ion charge states one should go to even shorter pulse duration utilizing a very low inductivity circuit.

V. CONCLUSSIONS

In summary, we have shown that extractable high ion charge states can be obtained from a simple high voltage, high current (low inductance) capacitor discharge in vacuum. Operating in high vacuum of about 10^{-4} Pa, mean ion charge states of about 7 have been observed when using different cathode materials and a peak current of about 4 kA, with the highest charge state of 10 in the case of platinum, and 11 for gold. At higher peak currents, the non-metallic contaminations (H, O, C) become large and eventually dominate the beam, and no further increase in metal ion charge states was observed.

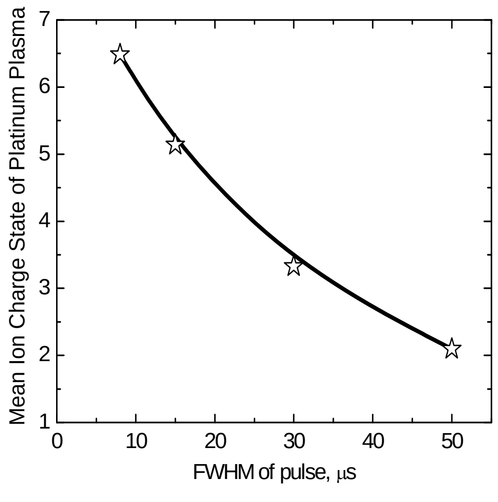

Fig. 8. Mean ion charge state of platinum plasma for different pulse duration. Peak currents for all pulses were 4 kA.

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E-mail of authors:

GYushkov@opee.HCEI.tsc.ru

AAnders@lbl.gov