Generation of the High Charge State Metal Ion Beams by Gyrotron Microwave Heating of Vacuum Arc Plasma[1]

A.G. Nikolaev, K.P. Savkin, E.M. Oks, G.Yu. Yushkov,
A.V. Vodopyanov*, S.V. Golubev*, and D.A. Mansfeld*

Institute of High-Current Electronics SB RAS, 2/3, Academichesky ave., Tomsk, 634055, Russia
Phone: +8(3822) 49-17-76, Fax: +8(3822) 49-24-10, E-mail: nik@opee.hcei.tsc.ru
**Institute of Applied Physics RAS, Nizhniy Novgorod, Russia*

Abstract – The method of generation of the high charge state metal ion beams has been developed. This method is based on microwave heating of vacuum arc plasma in a simple magnetic trap under Electron Cyclotron Resonance (ECR) conditions or under so called off-resonance mode. Two types of gyrotrons with different parameters have been used for heating: one with frequency 37.5 GGz, pulse duration 1 ms, power 100 kW, and another with frequency 75 GGz, pulse duration 0.1 ms, power 400 kW.

Two different ways of metal plasma injection to the magnetic trap were used. The first one is axial injection from a miniature arc source located out of the trap, and the second – radial injection from four cathode units mounted inside the trap just at the center. Both injections ways allowed to decrease background pressure and therefore to avoid microwave breakdowns. Under such experimental conditions about 20 mA, 200 µs of platinum ions with charge state of 10+ were successfully extracted by accelerating voltage as high as 20 kV.

This research was made collaboratively by research groups from High Current Electronics Institute (HCEI) Siberian Branch of Russian Academy of Sciences, Tomsk and Institute of Applied Physics (IAP) Russian Academy of Science, Nizhniy Novgorod.

1. Introduction

Multiply-charged heavy metal ion beams find many applications in fundamental nuclear and atomic physics as well as in applied science such as for ion beam surface modification. Microwave heating of plasma confined in a magnetic mirror trap has been used to produce gaseous ion beams with high current and high charge states [1].

It is possible for the generation of multiply charged ions of non-gaseous ion species; ovens have been used to heat and vaporize the metal [1]. But this method has some disadvantages. For example, vaporization is not so suitable for refractory metals and the source lifetime is relatively short because of surface condensation of metal vapor on the microwave window and other parts of the sources.

For forming plasmas of any metals, the vacuum arc is a more convenient method [2]. Vacuum arc sources can provide metal ion beams with currents of several amperes both in pulsed and dc modes [2].

The mean charge of the ions of such a source is determined by the cathode material, and typically lies in the range 1.5–2.5. Many techniques were used us for increasing of ion charge states of the vacuum arc sources. There are using of a strong magnetic field at the cathode region, application of additional short-time arc current pulses or even “train of spikes”, and additional ionization of metal vacuum arc plasma with electron beam injected into the plasma. For all of those ways the ion charge states can be increased, but by no greater than a factor of about 2.5 [3, 4].

Further increasing of ion charge states requires fresh ideas. Our idea was to combine vacuum arc source produced plasma of metal ions and simple magnetic trap with powerful microwave heating of radiation with dozens kW and millimeters wavelength range of such plasma for additional ionization of metal ions.

It is clear that an electron heating of the mirror-confined vacuum arc metal plasma by high power microwaves (either ECR condition or even non-resonant condition) can provide further increase in the ion charge state of gaseous ions. However, some earlier experiments for metal ions generated with vacuum arc plasma and microwaves in the centimeter range [5, 6] have yielded disappointing results with respect to increasing the ion charge state. We consider that those early experiments have right directions, but no great results were obtained because the confinement parameter $n_e\tau_i$, where n_e is the electron density and τ_i is the lifetime of ions in the trap, was rather low for those cases. Our estimations shown that confinement parameter was about 10^8 cm^{-3} s. When we use of a gyrotron [7] with higher power (up to 100 kW) and higher frequency (37.5 GHz) it is led to considerable progress in this field [8]. Here we describe our further work in the production of producing heavy metal high charge state ion beams.

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2. Experimental setup

The experiments were carried out jointly by research teams from the IAP and the HCEI. A compact vacuum arc plasma gun developed at HCEI was mounted on the gyrotron-driven mirror-plasma test bench at IAP. A number of changes were made to the experimental setup in order to maximize the ion charge states. First, as distinct from our prior work [8], we increased the gyrotron microwave power and improved the microwave cavity in the magnetic mirror trap. In the present work the microwave system can provide pulses of 4 mm (75 GHz) radiation with power up to 200 kW, with pulse length up to 150 μs and a pulse repetition rate up to 25 Hz. Additionally, the microwave power density in the plasma region was increased by reducing the diameter of the discharge chamber (which serves as a high-mode microwave cavity) to 3.2 cm. Another major change was the possibility of increasing the trap magnetic field up to 5 T at the mirror peaks. However, in the work described here the peak mirror field was limited to 2.5 T. Importantly, note that since the resonant field for 75 GHz is 2.68 T, the microwave heating done in this work was not ECR heating. We also point out that the mirror magnetic field was a simple mirror, with no superimposed multipole field.

Two different kinds of plasma injection systems were used to feed the vacuum arc metal plasma into the magnetic trap. The first was axial injection from a single plasma generator located outside the trap and on-axis, as shown schematically in Fig. 1.

The plasma generator was positioned outside the magnetic mirror field formed by the two coils. The vacuum arc cathode was made from material of the desired ion species, and a molybdenum cone cavity of butt diameter 1.8 cm and length 7 cm serves as vacuum arc anode; the anode is held at the same electrical potential as the trap discharge chamber. The vacuum arc power supply produces current pulses of more than 100 A and duration 100 μs. The discharge chamber of the mirror trap region has a teflon window through which the high power microwave radiation produced by gyrotron is delivered into the plasma region.

In the second injection system (Fig. 2) the metal plasma is injected radially from four plasma guns *7* located on the mid-plane of the trap between the mirror field coils *6* and *8*. The magnetic and microwave systems are the same as for axial injection describe above. The four vacuum arc plasma guns are conventional, as used in ion sources of the Mevva type [10], and have high operational stability with lifetime (between needed maintenance) no less than 10^6 pulses.

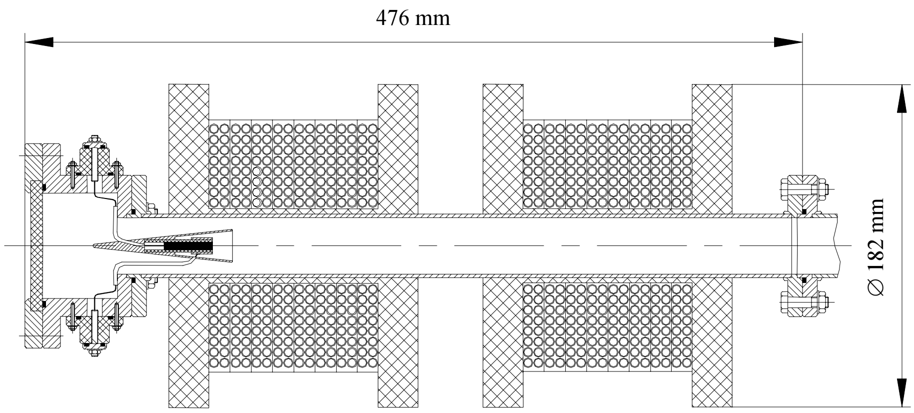

Fig. 1. Magnetic trap with axial injection of vacuum arc plasma

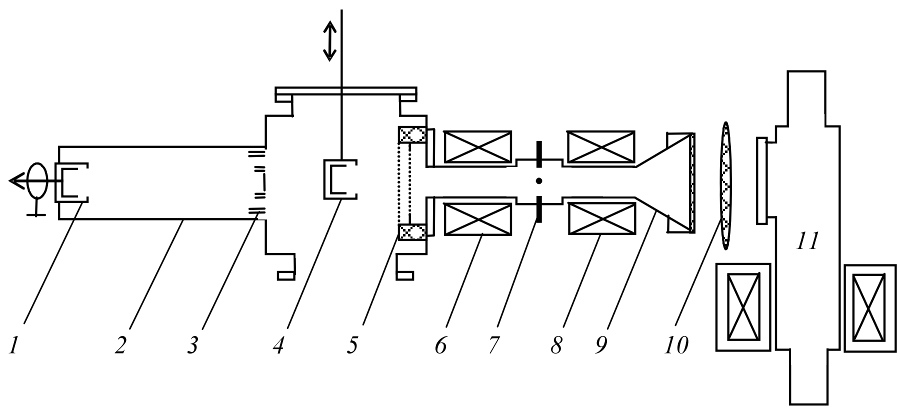

Fig. 2. Magnetic trap with radial injection of plasma from four plasma guns: *1* – TOF Faraday cup; *2* – TOF drift chamber; *3* – TOF gate; *4* – moving Faraday cup; *5* – accelerating grids system; *6*, *8* – magnetic trap coils; *7* – four vacuum arc plasma guns; *9* – discharge chamber of the trap; *10* – teflon lens; *11* – gyrotron

The metal plasma is fed into the trap region symmetrically from four sides around the mid-plane, and is partially confined in the mirror magnetic field. The microwave radiation from gyrotron *11* heats the plasma electrons to high temperature, resulting in additional ionization of the plasma to high charge states. Plasma flows from the confinement region within the magnetic trap into a plasma expansion region 20 cm diameter and 40 cm long. A large cross-section ion beam of 15 cm diameter is extracted from the expanding vacuum arc plasma using a gridded electrode system *5* with accelerating voltage up to +20 kV. Measurement of the ion charge state distribution of the extracted beam was done using a time-of-flight spectrometer *2* of length 1 m [11].

3. Experimental results and discussion

Microwave heating of the vacuum arc plasma resulted in elevation of the ion charge states for all cathode materials (ion species) investigated. Here we describe the results for the case of platinum, since this material typifies refractory heavy metals and has high purity and chemical inertness.

Figure 3 shows the measured ion charge state distributions for beams extracted from the vacuum arc plasma heated by gyrotron microwaves with power 200 kW and frequency 75 GHz, for both axial and radial injection of plasma into the magnetic trap. For comparison, we also show the ion charge state distributions for the case of no microwave heating, and for the case of ECR microwave heating with power 100 kW and frequency 37.5 GHz for a magnetic trap of diameter 7.3 cm.

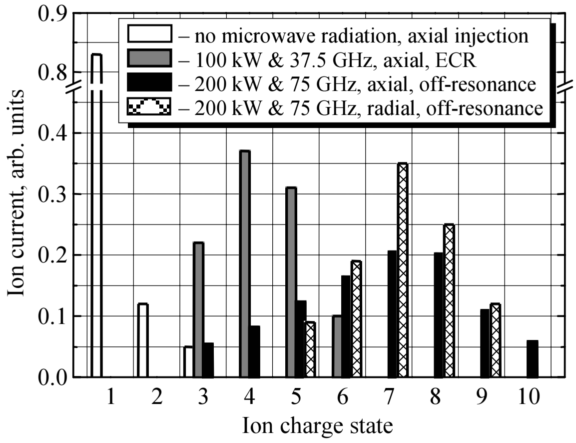

Fig. 3. Charge state distributions of platinum ions with and without microwave heating

The platinum ion charge state distribution without microwave heating has mean charge value (in partical fraction) $<Q_i> = 1.1$ and contents only a low fraction of doubly- and triply-charged ions. This is even lower than typical value for vacuum arc plasma ($<Q_i> = 1.2$) [9]. That could be connected to charge exchange of ions with neutrals within the expansion region. We point out that low background gas pressure can play a significant role in the generation (or maintenance) of higher ion charge states, as shown in a recent publication [12]. Low background gas pressure in the trap region is needed for the formation of very high charge state ions. However, the plasma chamber is essentially a tube with diameter much less than its length, and hence it is difficult to maintain adequately low vacuum pressure. Differential pumping may provide a convenient approach to alleviate this problem.

The application of microwaves of frequency 37.5 GHz and power 100 kW with plasma electrons at the ECR condition in a trap with diameter 7.3 cm results in significant electron heating, which in turn leads to additional ionization of ions by electron impact. A mean ion charge state of 4.3+ was obtained. Estimates show that the confinement parameter obtained in the experiments, $n_e\tau_i = 3 \cdot 10^8$ cm^{-3} s, corresponds closely to the mean ion charge state obtained. Nevertheless, the current density of the extracted ion beam was 1 A/cm^2, which is a world record value for high-charge-state metal ion beams. The key to further increase of the ion charge state is to increase the electron density as well as the microwave power density. A simple approach to this is to use a yet more powerful gyrotron and a smaller diameter trap – as we have done in the present work with a 3.2 cm diameter trap and a 200 kW, 75 GHz gyrotron.

Axial injection of platinum plasma into the trap and heating by a 200 kW, 75 GHz gyrotron provides microwave power flow density up to 100 kW/cm^2. Estimates [13] show that under these conditions it should be possible to increase the mean ion charge state to greater than 10+, where as the mean ion charge state which was achieved in the experiments was 6.2+. We ascribe this result to the fact that in these experiments the microwave heating was not ECR-heating – the peak magnetic field was always less than 2.68 T as required for ECR at 75 GHz, only off-resonance heating was employed. Attempts to increase the magnetic field up to ECR conditions for 75 GHz were limited by the generation of some kind of gas discharge in the trap. In this case, the plasma density in the trap increased sharply and a high fraction of gaseous ions appeared in the extracted beam. This could be because of gas evolution from the trap walls and elsewhere, and higher gas pressure in the trap that reduces the ion charge state. Differential pumping of the trap may prevent this negative feature. Another contributing reason for the lower-than-expected ion charge states could be the substantial axial ion velocity for plasma injected axially from the vacuum arc plasma gun [9], leading to a shorter ion lifetime in the trap. Nevertheless, an ion beam with more that 5% of Pt^{10+} ions and a total beam current of about 1 A was achieved. This suggests the possibility of forming high current (ampere range) metal ion beams with MeV energy using an accelerating voltage of just ~ 100 kV.

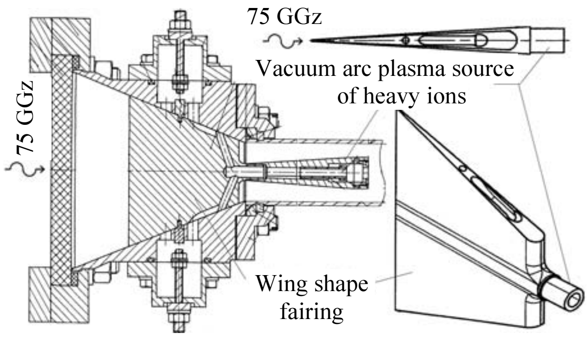

Fig. 4. New matched waveguide wing-shaped design of vacuum arc plasma generator

As for axial injection, for radial injection a generation of high charge state ion beams was possible only for magnetic field strengths lower than the ECR field. The highest ion charge states achieved was 9+, which is comparable to that for axial injection. We hypothesize that radial injection may lead to higher release of gas from the trap wall because plasma bombardment of the wall. However, even though the maximum ion charge state was lower with radial injection than with axial injection, the mean ion charge state of 6.9+ was incrementally greater with radial injection than with axial injection. We estimate the confinement parameter $n_e\tau_i$ to be about 10^9 cm^{-3} s^{-1} for both types of injection, implying generation of charge state about 10+ as observed in the experiments.

The experiments show that the ion charge state distribution of mirror-confined vacuum arc platinum plasma can be increased by increasing the frequency and power of the applied microwave radiation. The use of 200 kW, 75 GHz gyrotron power allowed the formation of heavy metal ion beams having a charge state distribution with maximum charge states up to 10+, and mean charge state over 6+. The results indicate that the method is suitable for the generation of ion beams with high current (ampere range) and high ion charge state (10+ range). Further increase in the charge state may be achieved by reduction of gas pressure in the plasma trap and heating of the vacuum arc metal plasma at the ECR condition.

Other problem for further increasing of ion charge states of metal ions related with maxima of microwave radiation injected into magnetic trap and then heated electrons of vacuum arc plasma which produced additional ionization of ions. For prevent reflection of part microwave flow from plasma source construction we developed a new design of plasma generator (Fig. 4).

This generator has matched waveguide wing shaped design of plasma generator. We estimated that with such improvement system ion charge state would be elevated up to 15+. New results will be presented future.

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