Magnetic Trap for Multiple Ionization of Vacuum Arc Plasmas by Electron-Cyclotron Resonance Heating[1]

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Abstract – Multiply charged high-current ion beams of heavy metals find wide technological applications. One way of producing ion beams is to extract ions from the vacuum arc plasma heated by high-power microwaves. A radial plasma injection trap for heating the vacuum arc plasma by gyration microwaves has been developed. A peculiar feature of this method of plasma injection into a trap is low longitudinal velocities of ions in the trap. This lengthens the time for which ions are confined in the trap and, hence, increases the ion charge. This paper discusses the possibilities of additional ionization of the vacuum arc plasma of metals in the magnetic trap through electron-cyclotron resonance microwave heating and considers the parameters of the thus produced ion beams.

1. Introduction

Multiply charged ion beams of heavy metals find application in solving a wide range of fundamental, for example physical experiments to synthesize new chemical elements of the periodic table and applied problems like ion modification of solid surfaces as a novel technological process of up-to-date industry.

In terms of the use of ion sources for solving applied problems of surface modification, an increase in ion charge may provide a possibility of increasing the ion energy without a proportional increase in accelerating voltage. It should be noted that the approximate coast of an ion accelerator with ion energy of hundreds of kiloelectronvolts and the X-ray doze power produced by secondary electrons exhibit a quadratic dependence on the accelerating voltage, all other things being equal. In this connection, the optimal way of increasing the ion energy without a increase in accelerating voltage is to provide multiple ionization in the plasma and, hence, a corresponding increase in the charge of the ions extracted from this plasma.

The use of an electron-cyclotron resonance (ECR) discharge in a magnetic trap in ion sources has made it possible to produce gas ions with reasonably high current and high average charge [1]. For the generation of multiply charged ions of fusible matters, oven can be used in which the working matter is heated and evaporated [1]. Physically, the ECR breakdown in metal vapors under these conditions occurs in much the same manner as that in gases. A shortcoming of this method is that it does not allow generation of ions of refractory metals.

A vacuum arc discharge appears to be the most appropriate way of producing ions of refractory metals [2]. Sources based on a vacuum arc can provide generation of metal ion beams with currents of several amperes both in the pulsed and continuous modes [2]. In such a source, the average charge of ions in the plasma is determined by the cathode material and is 1.5–2.5. With special methods (such as superposition of a magnetic field on the near-cathode region, application of additional arc discharge pulses, electron beam injection into the vacuum arc plasma), one can increase the charge of the ions, but in so doing the average ion charge increases no greater than 2.5 times [3, 4].

It is clear to use a vacuum arc discharge to inject the plasma of refractory metals into an ECR source in order to further increase the ionization ratio of metal ions in the magnetic trap on microwave electron heating. But the earlier such experiments using microwaves of the centimeter range [5, 6], as is done to increase the gas ion charge, have not a great result of ion charge growing. In our viewpoint, this was due to the fact that the confinement parameter $N_e\tau_i$ (N_e is the electron density and τ_i is the lifetime of ions in the trap), which is responsible for the formation of multiply charged ions, was no greater than 10^8 cm^{-3}s. The main reason for this was the small value of τ_i due to high directional velocities of ions of the vacuum arc plasma [9]. The use of a gyrotron with higher power (up to 100 kW) and short-wave radiation (8 mm) [7] has enabled a considerable progress in this field.

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2. Background

Problem of ECR heating of vacuum arc plasma was solved collaboratively by research team represented of two Institutes of Russian Academy of Sciences: Institute of Applied Physics (IAP) and Institute of High Current Electronics (HCEI). Experimental were carried out jointly at the ECR test bench of IAP, where as a compact vacuum arc plasma generator was designed and made by HCEI research group. Join efforts of both research groups provides first experimental evidence of enhancement vacuum arc metal ion charge states by ECR heating [8]. Results of further investigation in such direction were also published in details elsewhere [9].

The general arrangement of the setup used for joint ECR heating of vacuum arc plasma experiments is shown in Fig. 1. Plasma generator 3 was arranged on the system axis near one of the taps of a magnetic trap formed by two coils 6. The magnetic field in the taps ranged to a few Tesla. Plasma generator power supply 4 produced arc discharge pulses of current 100 A and duration longer than 100 μs. Discharge chamber 5 of the magnetic trap had a teflon window through which radiation produced by gyrotron 1 was delivered into the discharge region. The oscillation frequency was 37.5 GHz, the power ranged to 100 kW, and the pulse duration was 1.5 ms.

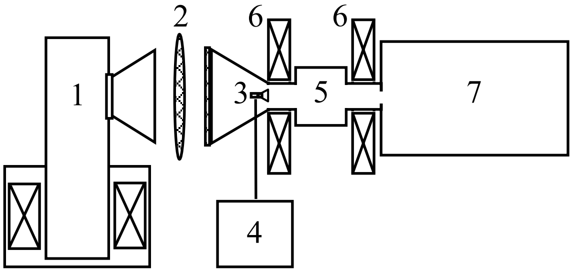

Fig. 1. Magnetic trap for ECR discharge heating of the vacuum arc plasma: 1 – gyrotron, 2 – dielectric lens, 3 – vacuum arc plasma generator, 4 – power supply of the plasma generator, 5 – discharge chamber, 6 – coils of the magnetic field, 7 – ion spectrometer

The interaction of microwaves with plasma electrons under the ECR condition considerably increased the electron energy that, in turn, led to additional ionization of ions by electron impact. A maximum average charge of 4.3 was obtained for platinum ions at a vacuum arc current of 80 A, a magnetic field in the trap taps of 2.6 T and a microwave power input from gyration of 60 kW. Example of such increasing of ion charge state shows on Fig. 2.

Estimates show that the confinement parameter attained in the experiments $N_e\tau_i=3\cdot10^8$ cm^{-3}s closely corresponds to the obtained maximum average ion charge. The current density of an ion beam extractable from such plasma is 1 A/cm^2. At this moment, the obtained experimental results prove to be record-breaking.

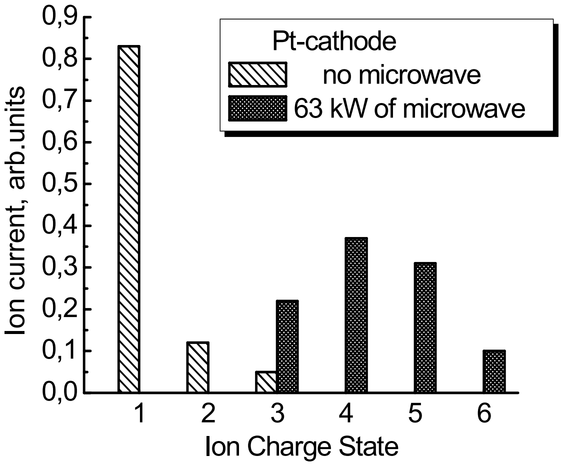

Fig. 2. Charge state distributions of platinum ions with and without microwave heating

One of the main parameters responsible for the efficiency of generation of multiply charged ions in the system under study is the velocity of ions of the vacuum arc discharge plasma, since it is this velocity that affects the time for which ions are confined in the trap and determines finally the value of the confinement parameter. With a fixed size of the magnetic trap, the ion velocity specifies the time of interaction of hot electrons with metal ions and, hence, the ionization ratio of these ions.

It is known that the magnetic field present in the cathode region of a vacuum arc discharge causes an increase in discharge operating voltage and, consequently, in the velocity of ions emitted by cathode spots [10]. Measurements show that the directional ion velocity increases considerably when the magnetic field required for the ECR discharge ignition is superimposed on the discharge plasma which is due to the effect of the magnetic field on the operating discharge voltage. Because of this, the average lifetime of an ion in the trap was no longer than 15 μs. On the other hand, simple estimates demonstrate that with a 60-kW power input into the trap the useful power expended in increasing the ion charge is no greater than 1 kW.

Thus, the key moment in further increasing the ion charge by microwave heating of electrons in the magnetic trap with an ECR discharge is to increase the lifetime of ions in the trap with increasing plasma electron density for the microwave power to be used more efficiently.

3. New magnetic trap with radial injection of metal plasma

To further increase the ion charge, a number of measures have been taken to increase the degree of heating of plasma electrons with simultaneous confinement of ions.

First, we increased the microwave power of the gyrotron and calculated the microwave channel of the new magnetic trap. At present, the microwave system provides application of gyration microwave pulses with a power of up to 400 kW for 4 mm wave-radiation, a duration of up to 100 μs, and a pulse repetition rate of up to 25 Hz into the discharge region of the magnetic trap. Another change taken to confine the plasma was the increase in the magnetic field of the trap taps to 5 T (Fig. 3). To this propose, a special water-cooled low-inductance system was designed. The ordinary coil conductors were replaced by a copper tube with water running through. To increase the microwave power density inside the discharge chamber and the magnetic field, the inner diameter of the discharge chamber of the trap was reduced to 3.2 cm.

For the purpose of increasing the discharge plasma density and simultaneously the time of ion confinement in the trap, it was proposed to inject the vacuum arc plasma at the trap center with four plasma generator operating at the same time (Fig. 3). The use of this system of plasma injection into the trap may remove the limitations placed on the one cathode. In the previous design, the one cathode unit located on the trap axis and also its shape was chosen from matching the microwave channel of the trap to minimize the reflected power. The cathode units were standard units which are employed in ion sources of the Mevva type [11] and have a high stability of operation within no less than 10^6 pulses

The arrangement of four cathodes in the trap center at the periphery of the chamber-waveguide ensures another method of heating the plasma. The plasma supplied into the discharge region from four sides drifts around the trap tube in the electric and magnetic fields, forming a "plasma sheath". In the collisionless case, the thickness of the "plasma sheath" must be equal to the Larmor diameter of ions which is estimated to be several millimeters and the configuration of the sheath itself must replicate the force line distribution in the trap, i.e., have a larger diameter in the injection region and a smaller diameter in the tap region. When arrived into the "plasma sheath", the microwave radiation provides heating of electrons to high temperatures, resulting in additional ionization of the cathode material. The radiation flux will be "locked" inside the plasma sheath that must ensure more intense interaction of the microwaves with the plasma

The radial injection of the vacuum arc plasma wherein high directional ion velocities are directed "crosswise" the trap length must lead to an increase in the lifetimes of ions in the trap. With the axial plasma injection used earlier, the longitudinal magnetic field of the trap caused an increase in ion velocity and a corresponding decrease in the time for which they are in the ionization region. Increasing the magnetic field in the system with radial injection involves magnetization of electrons and ions of the plasma, thus contributing to their confinement. So, in the absence of a magnetic field the time of ion confinement in the trap estimated from the shift of the ion current pulses to the Langmuir probe at the trap face with respect to the discharge current pulses was ~10 μs. The occurrence of a magnetic field increased this time. The time in which the ions reached the collector increased to over 30 μs even with relatively small magnetic fields of 1 T (Fig. 4).

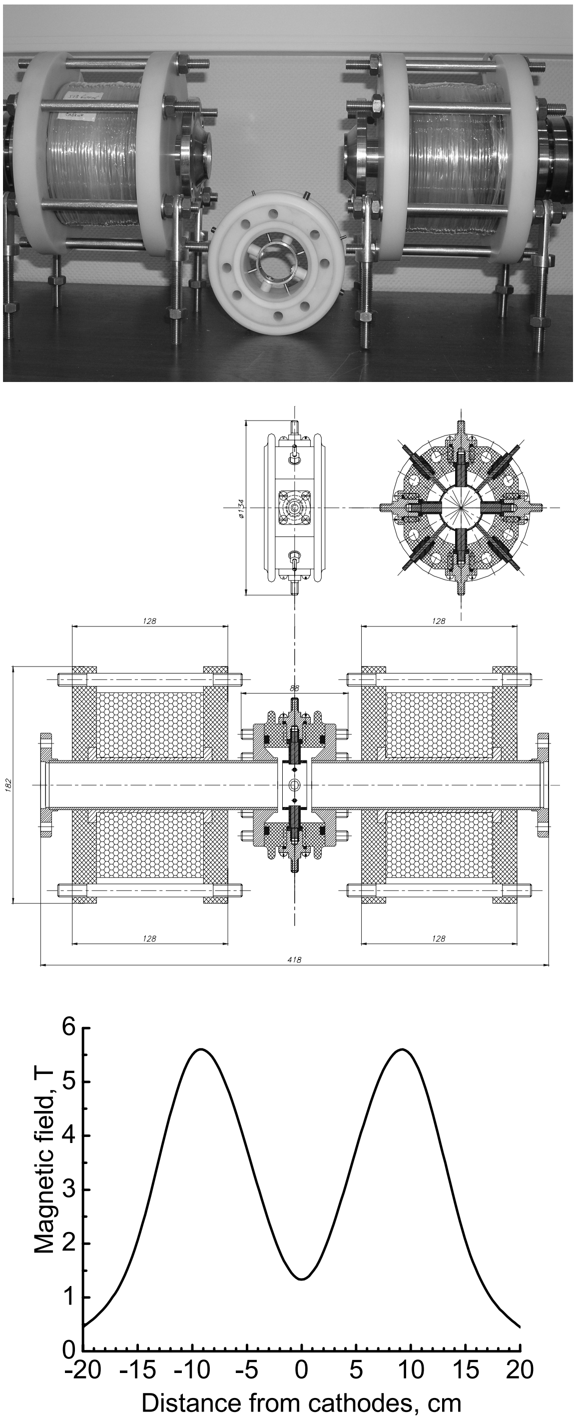

Fig. 3. From top to bottom: picture of magnetic trap with four-cathode unit at center, sketch of the trap, and magnetic field distribution to along of the trap

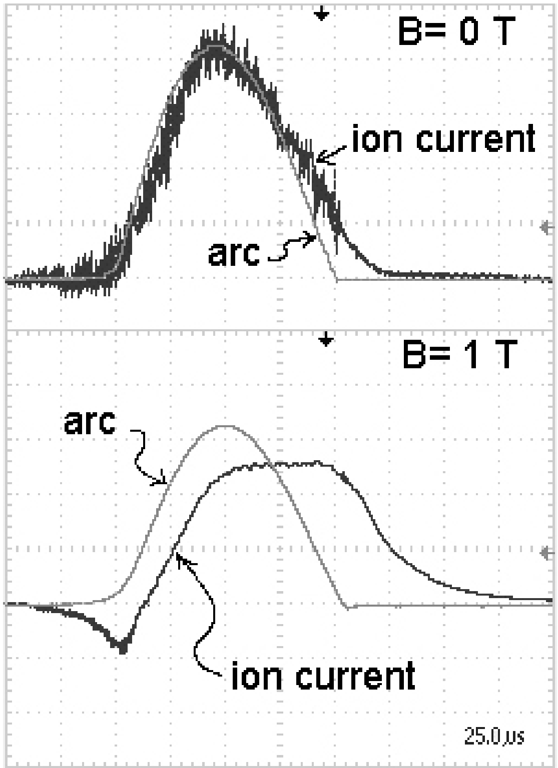

Fig. 4. Vacuum arc current and ion current from trap without (top) and with (bottom) magnetic field. Arc currents are 120 Amps per div. Ion currents are 2 mA per div. (top) and 1 A per div. (bottom)

Thus, it can be stated that the radial injection of the vacuum arc plasma increases the time for which ions reside in it at least threefold. Taking into account that four vacuum arc discharge ignited at a time ensure a high plasma density, the confinement parameter $N_e\tau_i$ is expected to be greater than 10^9 cm^{-3}s^{-1} which, at high electron temperature, means production of ions of heavy metals with a charge of 10+ and over.

4. Conclusion

The increase in the charge of metal ions allows an increase in ion beam energy without a corresponding increase in accelerating voltage. This makes an ion source cheaper and decreases the power of spurious bremsstrahlung. The use of 100-kW gyrotron microwave radiation has made it possible to generate ions of heavy metals with a charge of up to 6+. The proposed magnetic trap with radial injection of the arc discharge plasma has allowed us to produce ion beams with a charge of 10+.

Acknowledgment

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References

[1] Thuillier T., Bouly J., Curdy J., et al., *Proceedings of the 15th International Workshop on ECR ion sources*, 2002. Jyvaskyla, Finland. P. 13–16.

[2] G.A. Mesyats, S.A. Barengolts, Uspekh. Fiz. Nauk, 2002, V. 172, No. 10, p. 1113–1130.

[3] Oks E.M., IEEE Transaction on Plasma Science. 2002. Vol. 30, N 1. P. 202–207.

[4] Batalin V.A., Bugaev A.S., Gushenets V. I., et al., Journal of Applied Physics. 2002. Vol. 92. No. 5. P. 2884–2889.

[5] Cavenago M., Kulevoy T., Vassiliev A., Rev. Sci. Instrum. 1998. V. 69, N 2. P. 795–797.

[6] Spadtke P. GSI-Darmstadt. Unpublished private communication.

[7] Goldenberg A.L. and Litvak A.G., Physics of Plasmas. 1995. V. 2, N 6. Pt. 2. P. 2562–2572.

[8] A.V. Vodopyanov, S.V. Golubev, V.G. Zorin, S.V. Razin, A.V. Vizir, A.G. Nikolaev, E.M. Oks and G.Yu. Yushkov, Rev. Sci. Instrum, 2004, V.75, N.5, P.1888–1890.

[9] Vodopyanov A.V., Golubev S.B. Mansfeld D.A. Nikolaev A.G., Oks E.M., Razin S.V., Savkin K.P, Yushkov G.Yu., Zhurnal Tekhnicheskoi Fiziki, 2005, V.50, N.9, P.101–105. (Translated source: Technical Physics, 2005).

[10] Anders A., Yushkov G.Yu., Journal of Applied Physics. 2002. V. 91, N 8. P. 4824–4832.

[11] Nikolaev A.G., Oks E.M., Savkin K.P, Yushkov G.Yu., Brown I., MacGill R., *Patent of the Russian Federation 11.04.05, RU No. 48105.*