Multiple Ionization of Metal Ions in SMIS 75

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Abstract A Simple Mirror Ion Source with 75GHz pumping (SMIS 75) has been created. The confinement system is a mirror trap with magnetic field in the plug up to 5T, variable length 15—20cm and mirror ratio 3—5. The plasma of metal ions is injected into the trap by a special vacuum arc minigun. Plasma heating is performed by the microwave radiation of a gyrotron (the frequency of 75GHz, power up to 200kW, pulse duration up to 150μs). The results of the experiment have demonstrated substantial multiple ionization of metal ions. For a metal with high melting temperature (Pt), heating shifts the average ion charge from Pt^{2+} up to Pt^{7+}. Maximum stripped observed ion is Pt^{10+}. Total current of ion beam is about 300mA.

Key words ECR discharge, plasma, multicharge ions, refractory metals

1 Introduction

A method of generating multicharge metal ions, refractory metals including, is developed. Vacuum arc plasma is injected into a mirror trap, the plasma is heated by microwave radiation under ECR conditions. The main advantage of the method is that it allows one to strip ions during one pass through the trap.

A possibility of additional multiple ionization of vacuum arc metal ions injected into a mirror trap was first demonstrated in 2003[1]. Additional ionization was achieved using a gyrotron with radiation frequency 37.5GHz and power 60kW. The early demonstration experiments were carried out with a lead cathode and showed appreciable changes in the average charge of lead ions.

Further research corroborated efficiency of the technique for refractory elements too. The work done in[2, 3] demonstrated that using this method one can obtain ion beams of metal ions, refractory ones including, with high current and high average charge.

The current work is a continuation of the above research. In the present paper we describe experiments in which plasma is heated by a gyrotron radiation with a higher frequency of 75GHz and a larger power density of $100kW/cm^2$.

2 Experimental setup

The experiments were carried out on the experimental stand SMIS 75 at the Institute of Applied Physics of the Russian Academy of Sciences. A special miniature plasma generator fabricated at the High Current Electronics Institute of the Russian Academy of Science was used to study additional ionization of vacuum arc discharge metal ions in the magnetic trap with electron heating by microwave radiation. The design of the minigenerator is shown schematically in Fig. 1.

The vacuum arc discharge initiated by auxiliary discharge on the surface of a dielectric generates a plasma of the cathode 1 material that fills up a hollow molybdenum anode 2. The cathode is made of

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platinum. A thin ceramic tube 4, placed between the cathode 1 and the anode of the auxiliary discharge 3 is used as a dielectric. For the interelectrode distance of the auxiliary discharge of about 1mm, it suffices to apply a voltage impulse of 7kV with duration 10—30μs between the cathode and the trigger rod to excite cathode spots and initiate a vacuum arc..

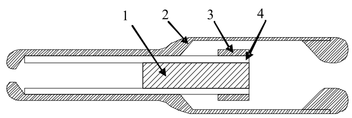

Fig. 1. The design of the vacuum arc plasma minigenerator. 1 – cathode, 2 – anode, 3 – trigger, 4 – ceramic insulator.

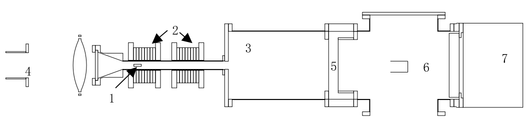

Fig. 2. The schematic of the setup. 1 – vacuum arc plasma minigenerator, 2 – magnetic coils, 3 – plasma chamber, 4 – gyrotron radiation window, 5 – double-grid extractor, 6 – Faraday cup, 7 – time-of-flight ion analyzer.

The schematic of the setup is shown in Fig. 2. The plasma generator 1 was installed along the axis of the system, near one of the plugs of the mirror trap formed by two coils 2. The power source of the plasma generator produced an arc discharge current pulse with duration of about 100μs; the current varied from 80A to 3kA. The power source was placed on a high-voltage platform because the ion-accelerating voltage applied to the plasma generator anode mating the discharge chamber amounted up to 20kV. The discharge vacuum chamber 3 installed inside the mirror trap (16cm long, magnetic field in the plug up to 5T had a teflon window through which radiation from the gyrotron 4 was injected into the plasma with the frequency of 75GHz, power up to 200kW, and pulse duration 150μs. Microwave radiation interacts with plasma electrons increasing their energy, thus leading to additional ionization of ions due to electron impact. A double-grid extractor 5 for ion acceleration was installed at the distance of 55cm behind the second mirror trap plug. At this distance plasma flux density drops down about 1000-fold, which makes it compatible with the extraction system. The formed ion beam was analyzed by means of a movable Faraday cup 6 and time-of-flight mass-analyzer 7, where the ion charge spectrum was measured.

3 Calculations

In this section feasibility of producing in our conditions plasma with high average charge of metal ions will be discussed based on calculations.

It was shown[4] that, ordered plasma flux velocity grows with application of longitudinal magnetic field; for magnetic fields higher than 1T, the velocity increase tends to saturation. Thus, for operating magnetic field values, plasma flux velocity V will be assumed to be 1.5×10^6cm/s.

With such a formulation of the problem, when the ion time-of-flight through the trap is fixed, ion charge state distribution can be calculated in the steady state case, with electron temperature T_e, and plasma flux density from the plasma generator also set to be fixed. The calculations took into account processes of stepwise ionization of ions with the ionization rate constants determined from[5]. The power needed to maintain plasma temperature was calculated as a sum of energy withdrawn by electrons and ionization expenditures. The set of equations is written in the form:

$$\left\{\begin{aligned} \frac{\mathrm{d}N_0}{\mathrm{d}t} &= F_0-k_0\cdot N_0\cdot N_\mathrm{e}-\frac{N_0}{\tau}\\ \frac{\mathrm{d}N_1}{\mathrm{d}t} &= F_1+k_0\cdot N_0\cdot N_\mathrm{e}-k_1\cdot N_1\cdot N_\mathrm{e}-\frac{N_1}{\tau}\\ &\cdots\\ \frac{\mathrm{d}N_i}{\mathrm{d}t} &= F_i+k_{i-1}\cdot N_{i-1}\cdot N_\mathrm{e}-k_i\cdot N_i\cdot N_\mathrm{e}-\frac{N_i}{\tau}\\ N_\mathrm{e} &= \sum_{i=1} i\cdot N_i \end{aligned}\right. .$$

where τ is the plasma time-of-flight through the trap taken to be equal to 1.13×10^{-5}s; F_0, F_1, $F_2\cdots$ are the densities of the flux of platinum atoms and ions injected into the mirror trap by the plasma generator. The average ion charge in the injected flux is 1.5. The problem is solved for zero initial conditions.

Results of the calculations are presented in Fig. 3. Each curve of the plot corresponds to fixed current of a vacuum arc plasma generator. The electron temperature grows from left to right along the curve.

The average ion charge in the stationary discharge and the power density needed for maintaining such a discharge increase simultaneously. The increase of the average charge is accompanied by an increase of plasma density, which introduces additional restrictions for motion along the curve. Evidently, on attaining a critical density, a considerable portion of microwave power starts to reflect from plasma, thus reducing efficiency of its heating. Calculations show that in our experimental conditions it is reasonable to expect ion charge state distribution equal to 8.

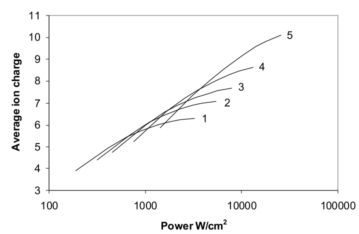

Fig. 3. Calculations of average ion charge of platinum in the plasma. Vacuum arc current: 1 – 100A, 2 – 150A, 3 – 200A, 4 – 300A, 5 – 500A.

4 Results of experiment

Maximal efficiency of additional ionization was achieved for the following basic parameters of the setup: microwave power 200kW; vacuum arc current 120A; density of metal plasma filling up the trap in the absence of heating $3.6\times10^{12}\mathrm{cm}^{-3}$. A histogram of platinum ion charge state distribution is depicted on Fig. 4 under the conditions optimal for average charge. A Pt^{10+} ion signal is well pronounced in the spectrum.

The fraction of impurities in the spectrum has been reduced to less than 10% by increasing the discharge pulse repetition frequency up to 1Hz.

For convenience of analysis of ion charge state distribution the ion beam intensity was reduced 3-fold by decreasing the transparency coefficient of the extractor emitter grid. The total beam current in the experiment was 300mA. Measurements of the ion beam current by means of the movable Faraday cup demonstrated that the current density distribution is homogeneous at the diameter of 150mm to an accuracy of 10%.

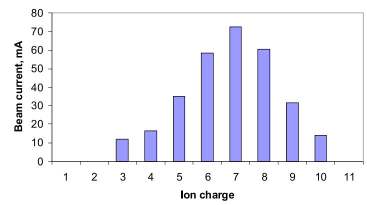

Fig. 4. Platinum ion charge state distribution at the optimal conditions.

5 Conclusion

It has been shown that charge state distribution of vacuum arc plasma ions may be increased by increasing the frequency and power of microwave radiation. Simultaneously, an increase of the frequency and power of the heating field enhances emissive ability of plasma, i.e., it may increase ion beam current. A further increase of average metal ion charge may be achieved by elongating a magnetic trap that is expected to increase ion stripping time and by optimizing conditions of microwave plasma heating.

6 Acknowledgments

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