High Charge State Metal Ion Beams from Vacuum Arc Plasma with Gyrotron Heating


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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 magnetic trap under Electron Cyclotron Resonance (ECR) conditions.

Two types of gyrotrons with the following parameters – 37.5 GHz, 1 ms, 100 kW and 75 GHz 0.15 ms, 400 kW have been used for plasma heating. For vacuum arc plasma confinement also two different configurations of the magnetic trap were in consideration. The first one is open magnetic trap with simple mirrors located in ends of trap. Such system was already investigated and provided high charge state ions. The second trap has a cusp B-field configuration with native “minimum-B” magnetic field structure.

Two different ways of metal plasma injection to the open magnetic trap were used. The first one is axial injection from an arc source located out of the trap, and the second – radial injection from four arc sources mounted at the center of the trap. Under the both trap confirmations up 200 e\text{mA} of ion beam current for platinum ions with highest charge state 10+ were successfully extracted from the plasma and accelerated by 20 kV.

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]. A generation of multiply charged ions of non-gaseous ion species is also possible by vaporization of metals [1]. But vaporization is not so suitable for refractory metals and the source lifetime is relatively short.

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 CW modes [2]. The mean charge of the ions of such a source is determined by the cathode material, and typically is in the range of (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 with electron beam injected into the arc 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]. The higher ion charge states were obtained for high current vacuum arcs when power dissipated on the gap reaches 10 MW during a few microseconds pulse duration (Fig. 1) and several amperes 20 µs ion beam was generated [5].

Fig. 1. Time of flight spectrum for short-time vacuum arcs with platinum (top) and gold (bottom) cathodes

Further increasing of ion charge states for hundred microseconds pulsed ion beam requires new approach to a problem. Our idea was to combine vacuum arc produced plasma of metal ions and simple magnetic trap with powerful microwave heating for additional ionization of metal ions under ECR conditions. The paper presents review and analysis of our previous ECR metal ion beams investigation [6–9] as well as discussion of it’s further development.

2. Open linear magnetic traps

The investigations of combining vacuum arc discharge with ECR heating are carried out jointly by research teams from Institute of Applied Physics (IAP) Russian Academy of Sciences, Nizhniy Novgorod and from

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High Current Electronics Institute (HCEI) Siberian Branch of Russian Academy of Sciences. Vacuum arc injection systems were developed at HCEI and they were mounted on the gyrotron-driven mirror-trap test bench at IAP. A number of changes were made to the experimental setup in order to maximize the ion charge states. The main direction of development connects to enhance the gyrotron microwave power together with improvement the microwave cavity in the magnetic mirror trap. Two types of gyrotrons have been used for vacuum arc plasma heating. The first one has frequency 37.5 GHz, pulse duration 1 ms, and microwave power 100 kW. Another gyrotron works with frequency 75 GHz, pulse duration 150 µs, and output power up to 400 kW. Importantly, note that since the resonant $B$-field for 75 GHz is 2.68 T, the microwave heating under ECR conditions has been reached only for 37.5 GHz and not yet for 75 GHz. It was because for 75 GHz experiments increasing of microwave power density in the plasma region and ignition of ECR discharge provoked a huge outgassing from walls and best results for ion charge state increasing were obtained only in the off-resonance mode.

Two different kinds of plasma injection systems are using to feel magnetic trap by the vacuum arc metal plasmas. The first system is based on axial injection from a single plasma gun and shown schematically in Fig. 2. The design of the plasma gun is based to Mevva ion source single cathode unit triggered by flash-over on ceramic surface located [10]. The plasma gun is positioned outside the magnetic mirror trap formed by two coils. The miniature vacuum arc cathode is made from material of the desired ion species. The miniature anode connects electrically to the grounded wall of the discharge chamber. The vacuum arc power supply provides current pulses of more than 100 A and duration of 100 µs or more. The discharge chamber of the mirror trap region has a window through which the gyrotron microwave radiation is delivered into the plasma region.

Fig. 2. Open magnetic trap with axial injection of vacuum arc plasma into the trap. The window for gyrotron microwave radiation and cathode placed before left mirror of the trap

The microwave radiation heats the plasma electrons to high temperature, resulting in additional ionization of the plasma to high charge states. The plasma extends from the magnetic trap into expansion region of 20 cm diameter and 40 cm long. A large cross-section ion beam of 15 cm diameter is extracted from the by a gridded electrode system with accelerating voltage up to +20 kV. Measurement of charge state distribution of the extracted ion beam was done using a time-of-flight spectrometer [11].

In the second injection system the metal plasma is injected radially from the four vacuum arc plasma guns located symmetrically on the mid-plane cycle of the trap between the same field coils (Fig. 2.) The metal plasma penetrates into the trap region from four sides around the mid-plane, and it is partially confined in the mirror magnetic field. It is important to note that due to common anode for all four vacuum arc plasma guns ignition of arc in a single gun stimulates arc triggering on other tree guns with jitter less then 10 µs. Compare with 100–200 µs of arc pulse length such instability of arc triggering in each plasma gun seems rather suitable.

Fig. 3. Open magnetic trap with radial injection of vacuum arc plasma into the trap. The four cathodes placed on trap center

3. Heating of plasma into the linear traps

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

Figure 4 shows the measured ion charge state distributions for beams extracted from the vacuum arc plasma heated by gyrotron microwaves with frequency 75 GHz, for both axial and radial injection of plasma into the magnetic trap. For comparison, we also show the distributions for the case without microwave generation, and for the case of ECR microwave heating with power 100 kW and frequency 37.5 GHz but with magnetic trap of diameter 7.3 cm.

The platinum ion charge state distribution without microwave heating has mean charge state value (in particle fraction) about $<Q> = 1.1+$ and contents mainly single charged ions with rather low fractions of double and triple charged particles. This is even lower than typical value for vacuum arc plasma where $<Q> = 1.2+$ [12]. Such difference could be connected
with essential charge exchange processes between ions and neutral molecules in the plasma expansion region under relatively high background gas pressure. As has been shown in our recent publication [13] background gas pressure plays a significant role in the generation (or maintenance) of higher ion charge states in vacuum arc plasmas. However, because the plasma chamber is essentially a long tube with small diameter it is difficult to maintain adequately low vacuum pressure.

For radial injection generation of high charge state ion beams was also possible but 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. However, even though the maximum ion charge state was lower compare with axial injection, for radial injection the mean ion charge state of 6.9+ was incrementally greater.

We estimate that confinement parameter $n_e \tau_i$ has to be about 10$^7$ cm$^2$ s$^{-1}$ for both types of injection, implying generation of charge state about 10$^+$. However, the maximum ion charge state was 6.2+ which is associated with high losing rate of metal ions in the traps. These losses are linked with ion leakage along of the magnetic field lines and with Magneto HydroDynamic (MHD) instabilities which are inherent in such type of the traps. Further elevation of metal ion charge state needs better confinement of vacuum arc plasma into the trap.

For gaseous plasma into an open trap the better confinement can be reached with “minimum-$B$” magnetic field configuration [15]. Such magnetic field is formed by combination of the field of linear trap coils and multipole field of strong permanent magnets. It needs to note that this configuration is analog of trap with “Ioffe’s sticks”, which was proposed at 1970 [16]. This configuration of magnetic field avoids MHD instabilities which lead to better plasma confinement into the trap.

For linear magnetic trap it is clear that increasing of high ion charge state generation requests to elevate a microwave gyrotron frequency and to provide ECR magnetic field (2.68 T for 75 GHz) inside of the trap. Even for off-resonance mode the magnetic field should be about ECR one.
with “minimum-\(B\)” is acceptable for the next step. It is
cusp magnetic field trap, which we propose for future
experiments of metal high charge state ion beam gen-
eration (Fig. 5).

Fig. 5. Cusp magnetic trap: 1 – cathodes for radial injection
and 2 – cathode for axial injection

For injection of vacuum arc plasma into the cusp
trap we propose both methods used in linear trap. For
axial injection a plasma source will be mounted on the
trap axis in opposite to ex-
traction system. For radial
injection single or few cathodes will be mounted on a
ring surface of the cusp. For the cusp trap both meth-
ods provide injection of plasma along magnetic field
lines.

Using of the cusp trap will make possible con-
finement of plasma with density up to \(10^{14}\) \(\text{cm}^{-3}\)
and electron temperature up to hundreds eV. Those plasma
parameters will provide extracted ion beam with cur-
dent density up to tens of Amps per cm sq, and with
higher charge state of metal ions more than 10+. MHD
stability of the cusp trap would help to avoid high
transverse velocity of extracted ions and beam emit-
tance should be acceptable for different applications,
including injectors for heavy ion accelerators.

5. Conclusion

The ion charge state distribution of mirror-confined
vacuum arc platinum plasma can be increased by in-
creasing the frequency and power of the applied mi-
crowave radiation. Use of 200 kW, 75 GHz gyrotron
power allowed the formation of heavy metal ion
beams having a charge state distribution with maxi-
mum charge states up to 10+, and mean charge state
over 6+. Results indicate that the method is suitable
for the generation of ion beams with high current
(ampere range) and high ion charge state (10+).

Further increase in the charge state may be
achieved by using of MHD stable cusp magnetic trap,
where utilization of microwave energy of gyrotron could be higher. We proposed two ways of plasma
filling of the cusp trap as it was done for linear trap.
Those are axial and radial injections. In future cusp
magnetic trap pumped by power high frequency gyro-
tron will be high current source of high charged metal
ions for different applications.

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