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Discharge characteristics of the DUHOCAMIS with a high magnetic bottle-shaped field [*]

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Abstract: For the purpose of producing high intensity, multiply charged metal ion beams, the dual hollow cathode ion source for metal ions (DUHOCAMIS) was derived from the hot cathode Penning ion source combined with the hollow cathode sputtering experiments in 2007. To investigate the behavior of this discharge geometry in a stronger magnetic bottle-shaped field, a new test bench for DUHOCAMIS with a high magnetic bottle-shaped field up to 0.6 T has been set up at the Peking University. The experiments with magnetic fields from 0.13 T to 0.52 T have indicated that the discharge behavior is very sensitive to the magnetic flux densities. The slope of discharge curves in a very wide range can be controlled by changing the magnetic field as well as regulated by adjusting the cathode heating power; the production of metallic ions would be much greater than gas ions with the increased magnetic flux density; and the magnetic field has a much higher influence on the DHCD mode than on the PIG mode.

Key words: ion source, metal ion beams, Penning discharge, hollow cathode discharge, hollow cathode sputtering, magnetic bottle-shaped field

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1 Introduction

Metal ion beams have been widely used in industrial process such as coating, etching and implantation for material surface modifications, and there has been an ever increasing demand for high intensity, multi-charged metal ions for pure science and accelerator applications [1–4]. Many kinds of ion source can produce metal ions, such as Penning Ion Gauge (PIG), Electron cyclotron resonance (ECR), Metal vapor vacuum arc (MEVVA), Electron beam ion source (EBIS) and Laser ion source (LIS), etc. All of them have their own advantages and limitations in producing metal ion beams in the case of ion species, current density, charge state, beam size, operation mode, and duty cycles and so on. Considering both the high utilization ratio of metal materials and the high universals of a metal ion source, the Dual Hollow Cathode Ion Source for Metal Ion Beams (DUHOCAMIS) was presented in 2007 [5, 6], in which a tubular sputter co-cathode united in a magnetic bottle-shaped field has been developed based on the hot cathode PIG. This kind of ion source would be beneficial to obtain a high metal ion current, high charge state ions, high plasma stability, and high material utilization ratio of various metal species. So this source would be expected as a high universal and very convenient metal ion source to produce metal ion beams in a wide range of ion species, ion energy and ion current; it also can deliver gas ion beams when working in the modified-PIG mode, which is distinguished from the traditional PIG [1, 6] in two aspects: (1) it utilizes a bottle-shaped magnetic field, and (2) the hollow anode consists of three coaxial parts with two gaps. But, there was no more knowledge or experience about this kind of source before. It was much interesting to investigate the behavior of this discharge geometry in a stronger magnetic bottle-shaped field. So a new test bench for DUHOCAMIS with a high magnetic bottle-shaped field up to 0.6 T has been set up at the Institute of Heavy Ion Physics, Peking University. Up to now, we have done a series of experiments related to the discharge properties of the source, which was operated in a wide range of bottle-shaped magnetic field with different cathode heating power, Argon flow, and pulse modes for arc power supply. Some ion spectra were measured

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by an analyzing magnet. To understand the special features of the dual hollow cathode discharge (DHCD) mode, we compared the discharge behavior between the DHCD mode and PIG discharge mode under the same ion source-geometry and comparable discharge conditions.

In this paper, we will describe the ion source structure and the new test bench in detail, and we also present and discuss a series of experimental results in connection with the discharge characteristics of the source, including the effect of the cathode heating power and the magnetic flux density, as well as the ion spectra. On the other hand, it will be much interesting to have a comparison of discharge characteristics between the DHCD and PIG discharge modes. The effect of the magnetic field on the source operating is emphasized and discussed especially. The unique properties of the DUHOCAMIS would be expected and discussed for the DHCD mode operating in a higher magnetic bottle-shaped field higher than about 0.4 T.

2 Experimental setup

2.1 Ion source structure

The discharge chamber of DUHOCAMIS is schematically shown in Fig. 1 together with its outer circuit. The whole structure is coaxially aligned on the axis of a bottle-shaped magnetic field. The H-type magnet (7) was used to generate a magnetic bottle-shaped field with a high flux density in a magnet gap of 20 cm, which was designed by the aid of the Computer Simulation Technology (CST) software package. The maximum of magnetic flux density By can reach to about 0.6 T at the center of the magnet; also, the magnetic mirror ratio, i.e. the ratio of the field near the pole surface to the median plane, can be as high as 2.0. The high magnetic field combined with the high mirror ratio may confine better the electrons in the discharge chamber to increase the ionization probability, the plasma density and the plasma stability, thus to produce high ion current and highly charged ions.

During operations, electrons emitted from the filament (1) will bombard the indirectly heated cathode (2) to form thermal-emission electrons. These thermal electrons will be accelerated and scattered into the discharge chamber. The use of an indirectly heated cathode is essential for multiply charged ion production, since it makes the accurate control and maintaining of the discharge parameters possible [7].

A noticeable feature of this configuration is that the operating mode of the source can be interchanged between the DHCD and PIG discharge modes easily. When switch K is connected to contact D (i.e. the potential of the sputter cathode is the same as the cathode), the source will operate in the DHCD mode [8, 9] ; When switch K is connected to contact P (i.e. the potential of the sputter cathode is the same as the anode), the source will operate in the PIG discharge mode [10, 11].

2.2 Extraction system and test bench

The schematic diagram of the test bench for the ion source is shown in Fig. 2 with a photograph shown in Fig. 3. The extraction system is composed of a triode extraction system (2–4), a magnetic shield (6) and an

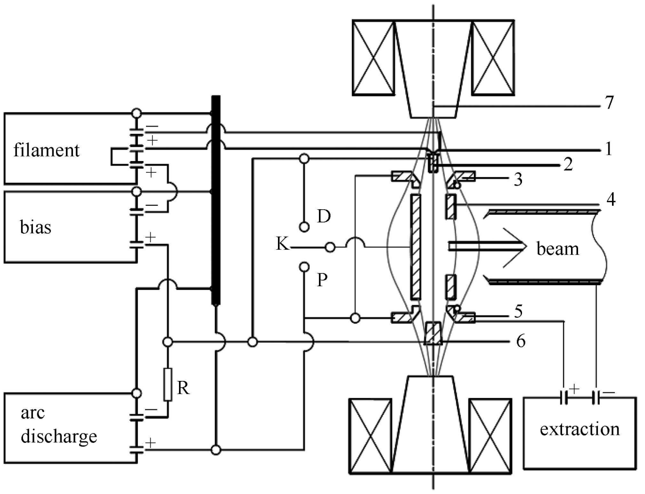

Fig. 1. Scheme of the ion source structure: (1) filament, (2) heated cathode, (3 and 5) anodes, (4) hollow tubular sputter cathode, (6) cold cathode and (7) magnet.

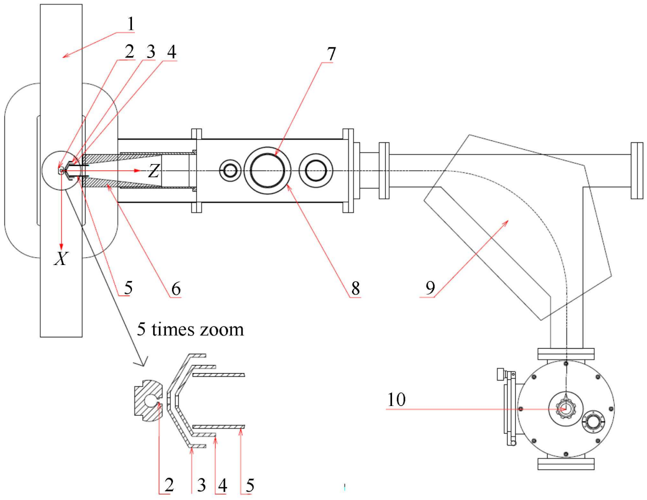

Fig. 2. (color online) Schematic diagram of the test bench for DUHOCAMIS: (1) ion source magnet, (2) plasma electrode, (3) acceleration electrode, (4) deceleration electrode, (5) electrostatic deflector, (6) magnetic shield, (7) Faraday cup, (8) vacuum port, (9) analyzing magnet and (10) target chamber.

electrostatic deflector (5) [12, 13]. The triode extraction system is chosen as usual due to its advantages in the generation of low energy and high current ion beams [14]. The magnetic field of DUHOCAMIS is a high bottle-shaped field with a remote magnetic region in the beam direction. It will result in a serious trajectory deviation of the extracted ions. We thus add a magnetic shield to reduce the edge-field and an electric deflector to minimize the beam deviation [12]. Fig. 4 indicates this magnetic shield can effectively reduce the edge-field and simultaneously keep a high value in the discharge chamber. The analyzing magnet (9) with a bending radius of 0.35 m, is used to sort the ions to get into the target chamber with a desired charge-to-mass ratio. To improve the beam transportability, there will be a focusing lens between the source and the analyzing magnet.

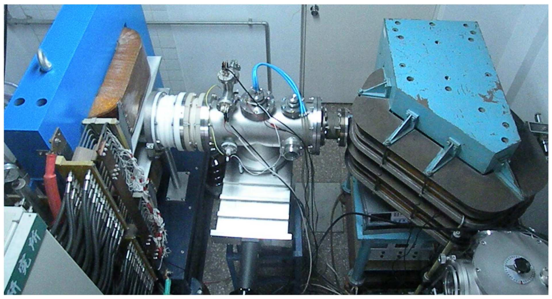

Fig. 3. (color online) Photograph of the test bench for DUHOCAMIS.

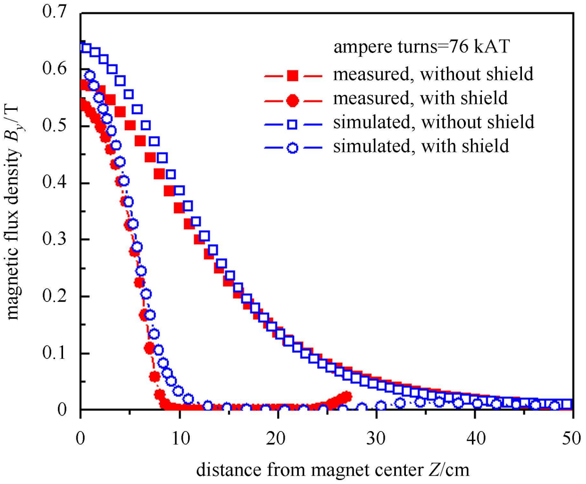

Fig. 4. (color online) Distributions of the magnetic flux density B_y along the beam line.

3 Experimental results and discussions[1)]

3.1 Effect of cathode heating power on arc characteristics

Under the conditions of magnetic flux density of 0.38 T, constant Argon flow of 1.4 cc/min, and pulsed arc power supply with a pulse width of 1 ms and a frequency of 10 Hz, the discharge curve, the voltage-current (V-I) characteristic of the source was measured. Two typical curves corresponding to two cathode heating powers of 0.8 kW and 0.9 kW, respectively, are shown in Fig. 5. The results indicate that different heating powers create different discharge characteristics: higher powers result in a higher arc current with a lower curve slope. It means that the discharge property is sensitive to the cathode heating power： a high heating power is required to obtain a high arc current; in the mean time, the heating power should be stabilized enough. This experiment demonstrates that both the slope of the V-I curve and the discharge current can be adjusted smoothly and stabilized simply by the indirectly heated cathode; it must be better to get multiply charged ions because of the accurate discharge parameters to be guaranteed probably [7].

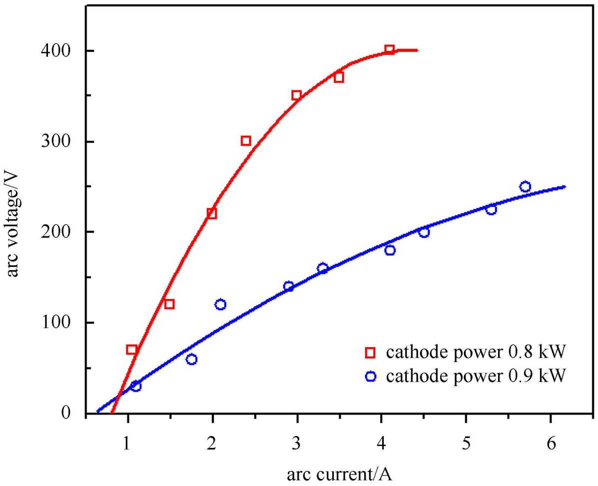

Fig. 5. (color online) Effect of cathode heating power on discharge.

3.2 Effect of magnetic flux density on arc characteristics

Under the conditions of the applied cathode heating power of about 0.8 kW, an Argon flow of 1.4 cc/min, and arc power supply with a pulse width of 1 ms and a frequency of 10 Hz, a series of discharge curves (V-I curves) were measured in a wide range of magnetic flux density from 0.13 T to 0.52 T. The results are shown in Fig. 6.

The results indicate that the discharge current monotonously increases with the increased arc voltage under a constant magnetic flux density; also the discharge current increases with the increased magnetic field under a constant arc voltage. From Fig. 6 we can see that the slope of the V-I curves can be varied in a

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1) In all of the following experiments, the hollow sputter cathode was made of copper (Cu).

wide range by changing the magnetic flux density. In fact, these V-I curves in Fig. 6 could be divided into three kinds of curves or three regions of magnetic flux density: resistance-stabilized (i.e. the slope of the V-I curves is a constant. The V-I curve is a straight line around some magnetic field Bs of about 0.26 T), low-arc-current (i.e. the slope is increased with the increased arc current in the left side of the B_s field) and low-arc-voltage (i.e. in the right side of the B_s field, the slope is decreased with the increased arc current) regions. It demonstrates that there exists a much stronger and sensitive magnetic effect on the DUHOCAMIS. Thus, we can say that the magnetic field is so important for the DUHOCAMIS, not only the field geometry, but also the flux density.

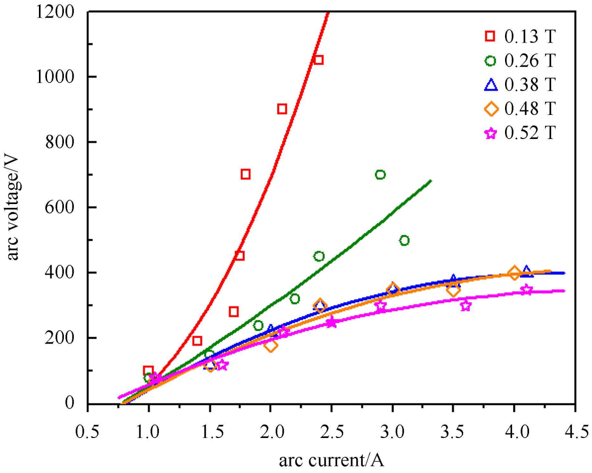

Fig. 6. (color online) Arc characteristics with different magnetic flux densities.

3.3 Ion spectra

With the conditions of extraction voltage of 20 kV, a constant Argon flow of 0.7 cc/min, and a pulsed arc power supply with a pulse width of 1 ms and a frequency of 10 Hz, we measured some ion spectra of the DUHOCAMIS in the target chamber by the analyzing magnet. Fig. 7 presents the Ar-Cu ion spectra of the source operating in two different magnetic flux densities for discharge. It shows that the beam current ratios of Cu^{+}/Ar^{+} and Cu^{2+}/Ar^{2+} increase from 0.3 to 0.7 and 0.1 to 0.8, respectively, when the magnetic flux density of the source increases from 0.13 T to 0.26 T, also the Cu^{+} and Cu^{2+} content becames higher. The primary results confirm that the production of metallic ions would be much increased than gas ions with the increased magnetic flux density of the source.

3.4 Comparison between the DHCD and PIG discharge modes

The DUHOCAMIS can change to the PIG discharge mode from the DHCD mode easily by switch K shown in Fig. 1. With the same geometry and comparable discharge conditions, the discharge experiments for the PIG discharge mode have been done similarly for the DHCD mode shown in Fig. 6. The results are shown in Fig. 8. It shows these V-I curves are similar as in Fig. 6; but no "low-arc-voltage curves" appeared in Fig. 8 in the same range of magnetic flux density from 0.13 T to 0.52 T. On the other side, all kinds of curves in Fig. 8 could be found in the DHCD mode. In addition, the maximal current obtained in the PIG discharge mode (see Fig. 8) is much lower than that in the DHCD mode (see Fig. 6). It means that the magnetic field effect on the DHCD mode is much stronger and more sensitive than that on the PIG discharge mode.

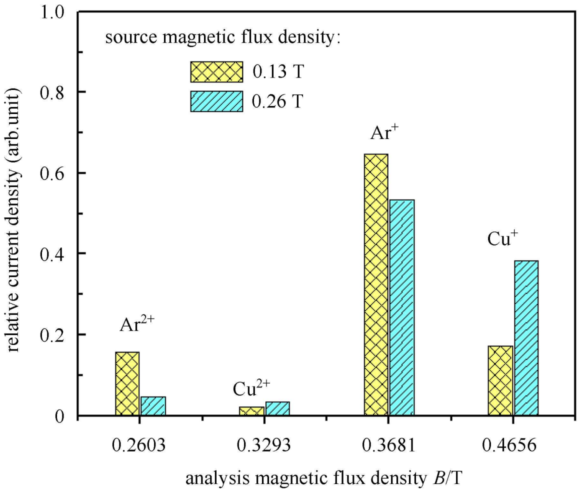

Fig. 7. (color online) Ar-Cu ion spectra.

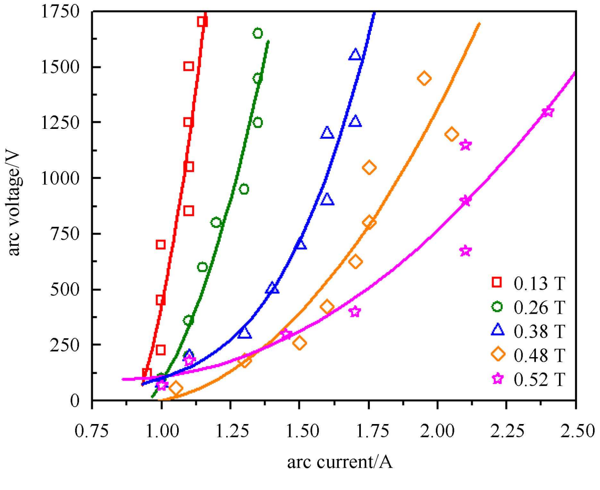

Fig. 8. (color online) Discharge curves for PIG mode.

To understand the differences between the DHCD and PIG discharge modes of the source, we tried to compare their discharge curves in more detail. Let's definite a term of "Factor of DHCD" (F_D in its simplified form): $F_D = I_{DHCD}/I_{PIG}$, in which I_{DHCD} and I_{PIG}

are the arc current in the DHCD and PIG discharge modes, respectively, and they were taken at a discharge condition for the same arc voltage with the same magnetic flux density. The dependence of F_{D} on the "arc voltage" and the magnetic field is shown in Fig. 9, where the trends of curves' slope are very similar as in Fig. 6. It means that there are also three kinds of slope trend: low-arc-voltage, resistance-stabilized, and low-arc-current curves. In Fig. 9 most F_{D} factors are higher than 2 except for the magnetic field 0.13 T. It demonstrates that a higher field causes higher F_{D}, i.e. the magnetic field effect on the DHCD mode is much stronger than that on the PIG discharge mode. Especially, when the field B_y is larger than 0.38 T in the DHCD mode, the discharge will work in the low-arc-voltage region with a high current, i.e. the discharge is much stronger than that in the PIG discharge mode. The reason may be that there was a highly magnetized hollow cathode sputtering metal plasma in the DHCD mode, whereas it did not appear in the PIG discharge mode. It might be true; there is a strong interaction between the sputtering metal plasma and the high magnetic bottle-shaped field. B_y comparison of the discharge curves between the DHCD and PIG discharge modes, the unique properties of the DUHOCAMIS would be prominently demonstrated in operating at a high magnetic bottle-shaped field to deliver high metal ion beams.

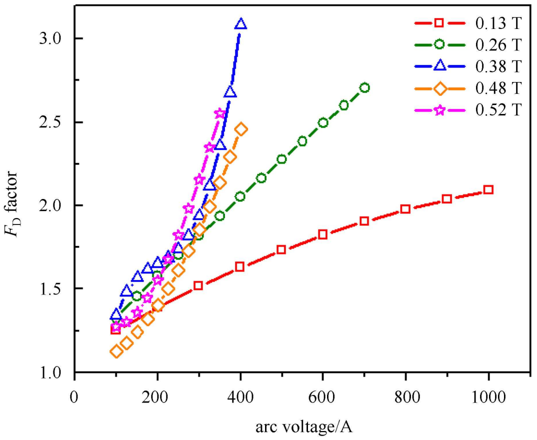

Fig. 9. (color online) Dependences of F_{D} factor on arc voltage and magnetic field.

4 Conclusions

A new test bench for the DUHOCAMIS with a high magnetic bottle-shaped field up to 0.6 T has been built, on which a series of experiments in connection with discharge characteristics in a range of magnetic fields from 0.13 T to 0.52 T have been made.

The experiments with discharge curves have demonstrated that the discharge behavior (discharge curves and ion spectra) is very sensitive to the magnetic flux densities; the slope of discharge curves in a very wide range can be controlled by changing the magnetic field, as well as regulated by adjusting the cathode heating power, independently. In comparison of discharge characteristics between the DHCD and PIG discharge modes, it was found a much stronger magnetic effect occurred on the DHCD mode, especially in a high magnetic field of about up to 0.4 T. It might be true; there is a strong interaction between the sputtering metal plasma and the high magnetic bottle-shaped field.

Thus, the importance of the magnetic field for the DUHOCAMIS may be established not only by its special bottle-shaped structure, but also by its high flux density. The unique property for the DUHOCAMIS would be prominently demonstrated in operating at a high magnetic bottle-shaped field, from that it would be expected to get ion beams with a high current, high charge state and high metal ion content.

Dr. Michael Müller was once one cooperator for this project. He came to PKU three times, contributed his full experience of Dual HCD Ion Source and provided the ion source geometry. The authors wish to express their deep gratitude to Dr. Michael Müller.

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