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Design of triode extraction system for a dual hollow cathode ion source*

WANG Jing-Hui(王景辉) ZHU Kun(朱昆)1) ZHAO Wei-Jiang(赵渭江) LIU Ke-Xin(刘克新)

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

Abstract: A triode extraction system is designed for a dual hollow cathode ion source being developed at the Institute of Heavy Ion Physics, Peking University. Basic parameters of the plasma are selected after examining the operation principle of the ion source, then the triode extraction system is designed and optimized by using software PBGUNS (for Particle Beam GUN Simulations). The physical design of the system is given in this paper.

Key words: triode extraction system, plasma ion source, magnetic mirror field，PBGUNS

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1 Introduction

In order to obtain low energy high current metallic multi-charged ion beams, a PIG ion source named DUHOCAMIS (Dual Hollow Cathode Ion Source for Metal Ion Beams) is under development at the Institute of Heavy Ion Physics, Peking University [1]. As the properties of the hollow cathode sputter electrode operating under high magnetic mirror field are significant, especially the operation mode and the charge state, we increased the center magnetic field to 0.5 T for DUHOCAMIS.

Most PIG ion sources are working in a homogenous magnetic field with the intensity in the range of 0.02–0.15 T, and the field also serves as a mass analyzer [2]. However, the field of DUHOCAMIS is high (center magnetic field ∼0.5 T) and inhomogeneous (mirror ratio ∼2.0), which will cause heavy trajectory deviations of the extracted ions. Thus a new extraction system has been designed for DUHOCAMIS in which the triode extraction system (also called the three-electrode extraction system or the accel-decel extraction system) is a key component. The other two components are an electrostatic deflector used to compensate the magnetic force and a magnetic shield used to reduce the field strength [3]. Due to the importance of the triode extraction system for a high-current density plasma ion source especially in the case of DUHOCAMIS, the operation principle of the ion source is carefully examined and the triode extraction system is designed and optimized by using software PBGUNS (for Particle Beam GUN Simulations). The detailed simulation process and the key parameters of the system are presented in this paper.

2 Structure of DUHOCAMIS

DUHOCAMIS is derived from GSI hot-cathode PIG sputter ion source [4], the key features are the high intensity inhomogeneous magnetic mirror field (the bottle-magnetic field) as well as the entire sputter electrode (see Fig. 1).

When the central magnetic field is 0.15 T, the primary experimental results of this source in GSI are: 1) A 45 mA Al^{1+} beam and more than 10 mA of other metallic ion beams (mass number<100) were obtained after the mass analyzer, in which the width of the beam pulse is 1 ms, and the pulse repetition interval is 100 ms; 2) The utilization ratio of the sputter electrode material can reach 1% which is 100 times compared with other PIG sputter source operating in GSI; 3) A molybdenum tubular electrode can work for 4 days without interruption; And 4) A 200 μA $^{92}Mo^{3+}$ ion beam has been detected at the entrance of RFQ [1].

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1) E-mail: zhukun@pku.edu.cn

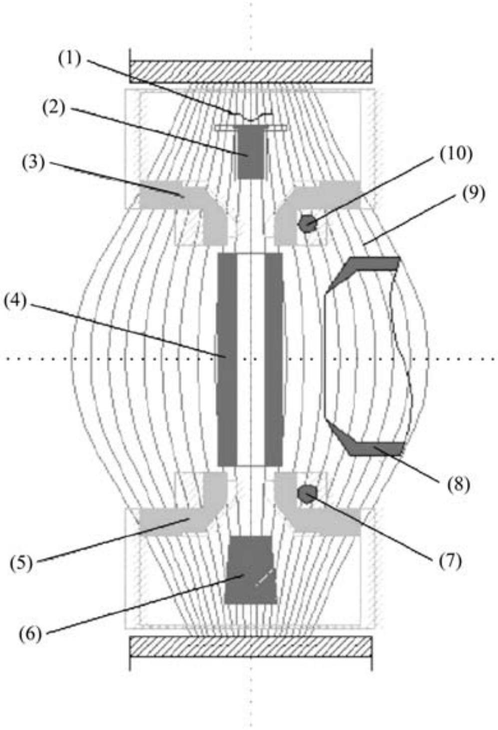


Fig. 1. Sketch of the discharge chamber of DUHOCAMIS: (1) filament, (2) heat-cathode, (3 and 5) anodes, (4) sputter electrode, (6) cold-cathode, (7 and 10) gas inlets, (8) extraction electrode, and (9) bottle-magnetic field.

In order to study the operation properties of DUHOCAMIS under high intensity magnetic field, a large gap H-type electro-magnet has been constructed at the Institute of Modern Physics, the Chinese Academy of Sciences to provide inhomogeneous magnetic field with the center strength up to 0.5 T and the mirror ratio of 2.0. Because of the special structure as well as the experimental results mentioned above, we can conclude that the advantages of DUHOCAMIS are mainly: 1) With the large area tubular sputter electrode, the unionized atoms sputtered from the wall can adhere to the electrode again, thus the utilization ratio of the sputtering material is increased; 2) The axial high intensity inhomogeneous magnetic field in favor of the formation and stability of the plasma by trapping the electrons and ions in the discharge chamber; 3) The voltage of the sputter electrode can be adjusted in a large scale below the anode voltage, which makes the source work alternatively between the modes of Hollow Cathode Discharge and Penning Discharge, thus different charge states of the ions can be generated; and 4) The lifetime of the source is increased because the anode between the acceleration and sputter electrodes can reduce the rate of ion bombardment to the acceleration electrode like the traditional PIG sources do.

3 Operating principle of DUHOCAMIS

See Fig. 2, the operation principle of DUHOCAMIS is: the electrons emitted from the filament heat the hot-cathode to thermal-electrons emissions, these thermo-electrons become primary electrons (with very small energy spread because of the small collision rate) after acceleration by the potential drop across the cathode double sheath (the thickness is less than 1 mm) near the hot-cathode. Then the primary electrons are scattered by the beam-plasma interaction during which process the excitation and ionization of the neutral atoms occur. After entering the discharge chamber, these scattered electrons become trapped electrons by receiving two kinds of restrictions: First, these electrons will be reflected between the hot-cathode and the cold-cathode, i.e., the Hollow Cathode Discharge mode (both sides of the source are symmetrical hollow cathode structures if the sputter electrode is regarded as the negative electrode, therefore this kind of structure is called a dual hollow cathode structure) [5]; Second, these electrons will simultaneously spiral around the axial magnetic field line which lengthens

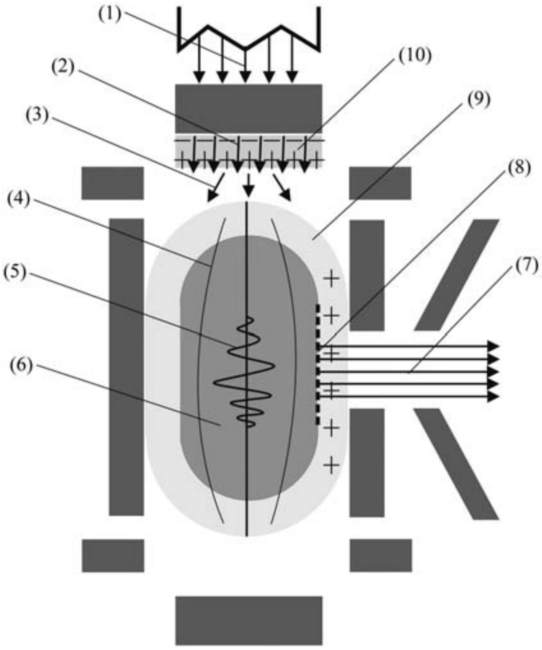


Fig. 2. Operation principle of DUHOCAMIS: (1) thermionic electrons, (2) primary electrons, (3) scattered electrons, (4) magnetic filed lines, (5) trapped electrons, (6) plasma, (7) extracted beam, (8) emission surface, (9) single sheath between the plasma and extractor, and (10) cathode double sheath.

their paths in the chamber, thus the ionizing efficiency is increased by increasing the collision probability between the electrons and the neutral atoms, namely the Penning Discharge mode [6]. Meanwhile, ions in the chamber also receive these two kinds of constrained motions, thus the plasma is formed in the chamber.

Some electrons and ions will escape from these restrictions and hit the wall of the sputter electrode because strong oscillatory fields exist in the plasma. Atoms of the electrode will be sputtered and then enter the discharge chamber, where these atoms will be ionized by inelastic collisions with the trapped electrons, thus plasma (cold plasma in which the electrons' temperature is higher than the ions') containing ions of the sputter electrode material is generated. The single sheath (several Debye lengths) between the plasma and extractor is formed because of the ambipolar diffusion, which gives the sputter electrode a negative potential compared with the sheath (∼100 V/cm). The boundary of the sheath and the plasma is called a classical sheath edge from where the electric neutrality of plasma is destroyed ($\eta = -e\phi/(kT_e) = 0.8539$). All the ions are assumed to be emitted from this boundary which is also called the emission surface (with a density approximately 100 mA/cm^2). Ions passing through the sheath will receive certain energy from the potential drop in it which is called mean ion drift energy (∼10 eV), these ions will be extracted and accelerated by the extraction system and thus the ion beam is formed. The shape and position of the emission surface are always automatically adjusted according to the electrode geometry and the extraction voltage, so that the beam extraction can be maintained in the space-charge-limit flow, that is, the current density of the extracted beam obeys the Child-Langmuir Law, i.e. the density is proportional to $V^{3/2}$ (V is the acceleration voltage) [7].

4 Design of triode extraction system

Many kinds of ion sources use a triode extraction system for extracting high density or low energy beams [8–12], Fig. 3 shows the geometry of the triode extraction system.

The advantages of the triode extraction system are mainly: 1) The acceleration electrode (negative electrode) will suppress the reversed accelerated electrons back to the source (these electrons partially originate from the ionization between ions and residual gas in the vacuum volume, partially originate from secondary electron emission of the ground electrode because of the ions bombardment), which not only reduces the power consumption and facilitates the stable operation of the source, but also reduces the divergence angle of the beams by assisting in space-charge neutralization in the downstream drift space [13]; 2) According to the Child-Langmuir Law mentioned above, the large acceleration voltage between the plasma electrode and the acceleration electrode can help to gain a high beam current [14].

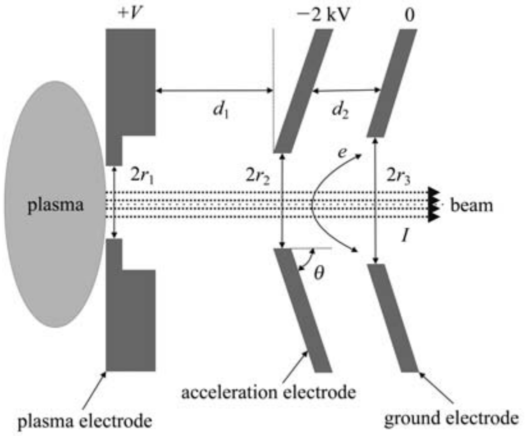


Fig. 3. Key parameters of the triode extraction system: V: acceleration voltage; r_1, r_2 and r_3: half width of the plasma electrode, acceleration electrode and ground electrode, respectively; d_1: acceleration distance; d_2: decelerate distance; θ: the half angle of the electrode; and I: extracted beam current.

The triode extraction system is also applied in DUHOCAMIS. Using software PBGUNS, the influence of the key parameters of the system on the beam quality is evaluated by the root-mean-square emittance (rms emittance) of the extracted beam at a distance of 247.5 mm from the plasma electrode.

The plasma electrode is already included in DUHOCAMIS donated by Dr. Müller in GSI, and the original structure is kept unchanged with a slit of 2 mm×45 mm for beam extraction (see in Fig. 3). The recessed structure of the electrode is used to form equipotential lines which will reduce the ion divergence angle [15]. The influence of the magnetic field on the beam extraction is neglected because of the relatively short acceleration distance. As ions of Al, Ti, Ta, U, Cu, Mo, Cr, Mn, Fe, Co, Er, and Gd have been extracted in the former experiment, typical ions like Al^+, Mo^+ and Ta^+ are used in the following simulations, and the initial beam angular divergence is added with Maxwell velocity distribution. According to these conditions and the operation principle of DUHOCAMIS mentioned above, the key parameters of the plasma and extraction system are set in Table 1.

Table 1. Main parameters of the plasma and the extraction system for using PBGUNS.

parameters	value
temperature of background electrons/eV	8
temperature of background ions/eV	2
initial energy of the injected ions/eV	18
voltage of the plasma electrode/kV	20–50
voltage of the acceleration electrode/kV	−2
extracted beam current/mA	30–90
neutral ration of the beam(%)	90

In the above conditions, the influences of these parameters like d_1, d_2, r_2, r_3 and θ on the rms emittance of $(x,\ x')$ trace space are simulated and showed in Figs. 4–7 (the extracted current and extraction voltage are 60 mA and 30 kV respectively of a Al^+ beam).

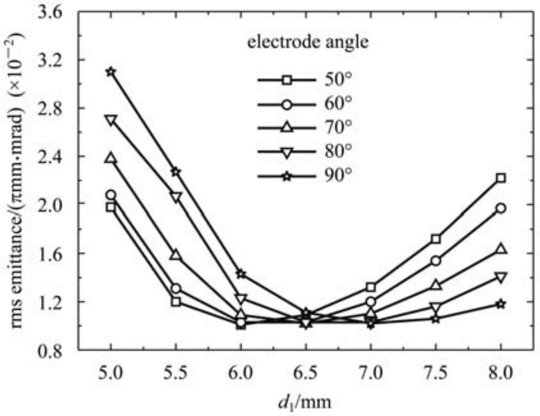


Fig. 4. Influence of the acceleration distance and the electrode angle on the beam rms emittance.

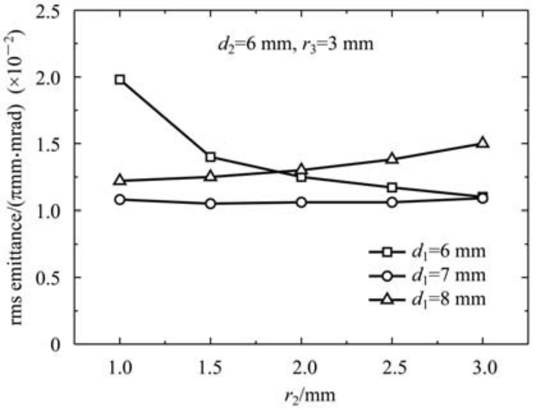


Fig. 5. Influence of the slit width of the acceleration electrode on the beam rms emittance.

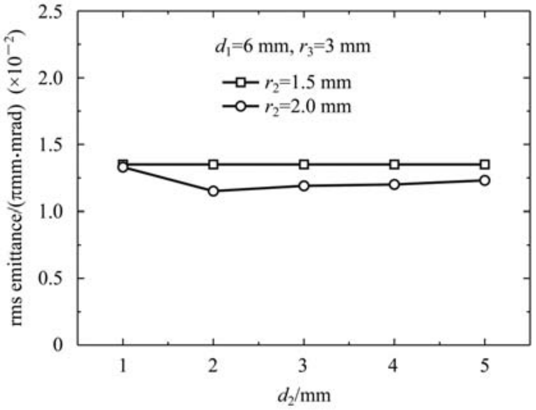


Fig. 6. Influence of the decelerate distance on the beam rms emittance.

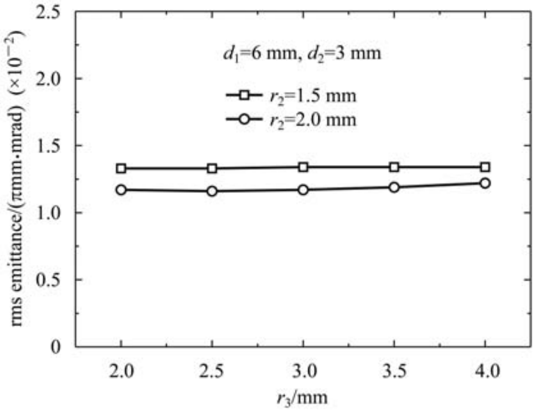


Fig. 7. Influence of the slit width of the ground electrode on the beam rms emittance.

Some rules and conclusions can be found from the above simulation results:

(1) From Fig. 4 we can see that the beam quality is changing with the acceleration distance when the extraction voltage, beam current, and electrode angle are fixed to constants, and an optimum acceleration distance does exist in certain conditions. At the optimal distance, the influence of the electrode angle can be neglected. As changing the angle of the electrode can reduce the electric field intensity near the axis, thus reducing the discharge rate between electrodes, the half angle of the two electrodes is set to 60°.

(2) From Fig. 5 to Fig. 7 one can see that, the influence of other parameters, like the deceleration distance and the width of the ground electrode over the beam quality can be neglected except the width on the acceleration electrode (the influence of electrode thickness can also be neglected for the relatively high extraction voltage). Thus the width of the acceleration electrode 3 mm or 4 mm, the width of the deceleration electrode 6 mm, the thickness of the

two electrodes 1–2 mm, and the deceleration distance 1–3 mm are adopted.

(3) Figure 4 shows that there is an optimal acceleration distance in the conditions, Fig. 8 shows these distances for different ions with different accelerating voltages and extracted beam currents. From this one can see that most of the distances are falling into the range of 3–10 mm, thus the accelerating distance should be adjustable in this range. At the same time it can be concluded that most metallic ions with different q/m ratios can be extracted from this triode extraction system by regulating the accelerating voltage and the accelerating distance.

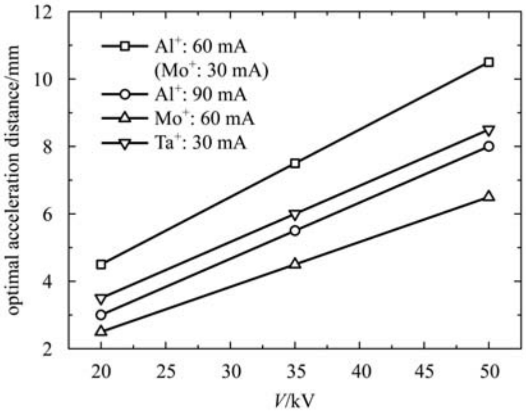


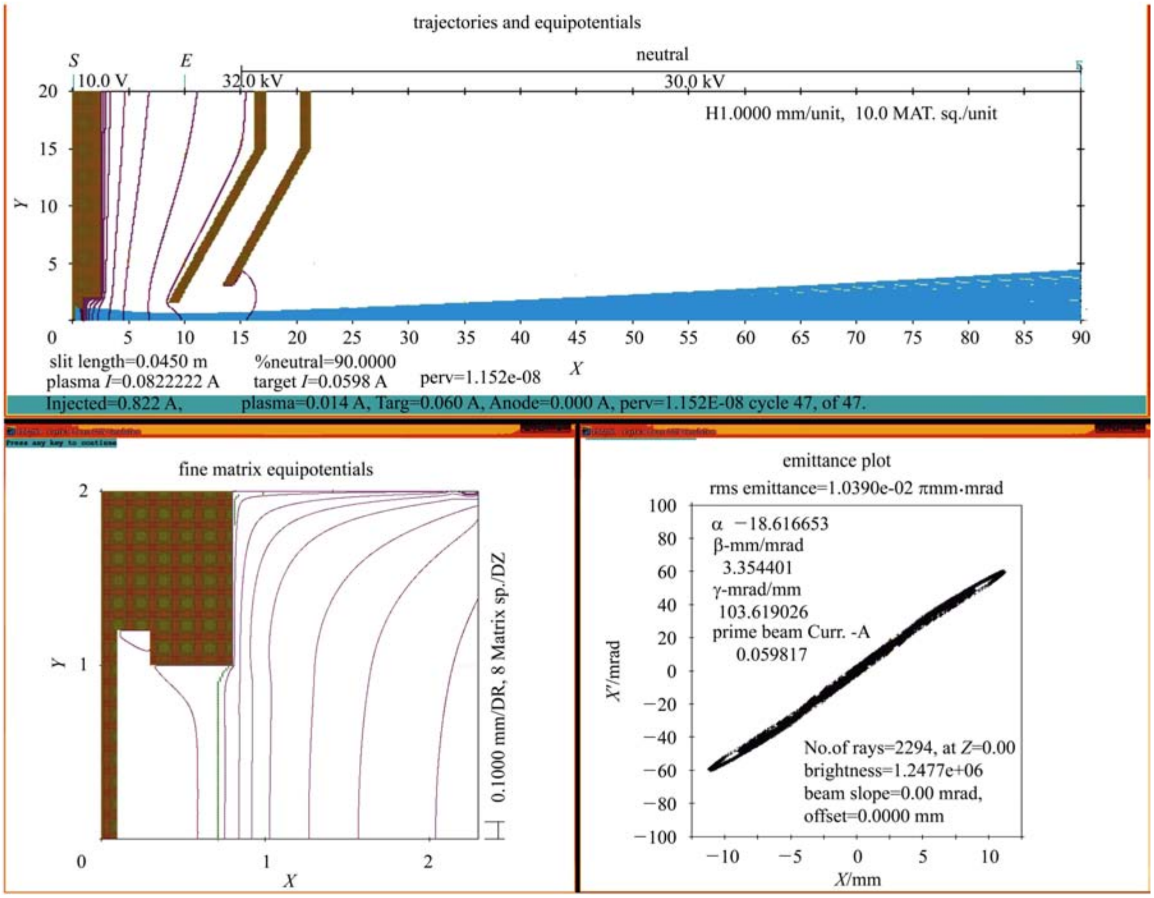
Fig. 8. Optimal acceleration distance for different ions with different accelerating voltages and extracted beam currents.

Based on the above simulation results and discussions, and considering the parameters in another direction, the key parameters of the triode extraction system are summarized in Table 2.

Table 2. Key parameters of the triode extraction system.

parameters	value
slit of plasma electrode/(mm×mm)	2×45
slit of acceleration electrode/(mm×mm)	3×50 or 4×50
slit of ground electrode/(mm×mm)	6×50
acceleration distance/mm	3–10
deceleration distance/mm	1–3
thickness of the electrodes /mm	1–2
half angle of the electrodes/(°)	60

Keeping the configuration of the above extraction system and the plasma condition, Fig. 9 shows a typical simulation result for an Al$^+$ ion beam.



```
slit length=0.0450 m      %neutral=90.0000
plasma I=0.0822222 A      target I=0.0598 A      perv=1.152e-08
Injected=0.822 A,         plasma=0.014 A, Targ=0.060 A, Anode=0.000 A, perv=1.152E-08 cycle 47, of 47.
```

```
rms emittance=1.0390e-02 πmm·mrad
α −18.616653
β-mm/mrad
  3.354401
γ-mrad/mm
  103.619026
prime beam Curr. -A
    0.059817
No.of rays=2294, at Z=0.00
brightness=1.2477e+06
beam slope=0.00 mrad,
offset=0.0000 mm
```

Fig. 9. PBGUNS simulation results of beam envelope, plasma boundary and rms emittance for a 60 mA Al$^+$ ion beam (the extraction voltage is 30 kV, the extracted beam current is 60 mA, the acceleration electrode is 3 mm and the acceleration distance is 6 mm).

5 Conclusions

Using PBGUNS software a triode extraction system for a plasma ion source named DUHOCAMIS has been designed and is under development at the Institute of Heavy Ion Physics, Peking University. With this extraction system, the simulation results show that by regulating the extraction voltage below 50 kV and the accelerating distance in the range of 3–10 mm, most of the metallic ions with different q/m ratios can be extracted with a beam current up to several tens of mA. The simulation results will help to direct the experimental setup and the validity of the extraction system will be verified.

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