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Study on High Intensity High Charge State Lead Ion Beam Production and Optimize*

HE Wei[1,2;1)] LI Jin-Yu[1] ZHAO Huan-Yu[1,2] CAO Yun[1] SUN Liang-Ting[1] ZHAO Hong-Wei[1] ZHANG Zi-Min[1]

1 (Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China)
2 (Graduate School of the Chinese Academy of Sciences, Beijing 100049, China)

Abstract High charge state metal ion beam is quite effective and essential for new investigations on atomic physics and surface physics. Recently, The high intensity high charge state lead ion beams have been produced with IMP 14.5GHz LECR3, we investigated experimentally influences of some key parameters, such as magnetic field, electrical power on oven, gas mixing etc., on lead ion beam production. Through optimization of the ion source conditions, stable $^{207}Pb^{30+}$ beam of 18eμA and $^{207}Pb^{37+}$ beam of 6.7eμA have been obtained with oven method at 20kV extraction voltage.

Key words ECR ion source, oven method, metallic ion, high charge state ion

1 Introduction

In recent years, the increasing demand for high intensity high charge state metal ion beams supplied for atomic physics, surface physics and application at accelerators has driven the development of various methods to feed solid materials into electron cyclotron resonance (ECR) ion source plasmas. The most important techniques are (1) use of volatile chemical compounds, (2) online chemical synthesis, (3) evaporation from an external or internal furnace, (4) cathode sputtering of the solid, and (5) evaporation by vacuum arc or laser beam[1]. Among all these methods mentioned above, the oven technique is the least intrusive to produce metal ion beams, especially if pure metals can be used. In addition, the evaporation rate of solid sample in the oven is controlled by feed-in power of the oven, assuming that the oven is sufficiently far from the plasma so as to avoid an additional heating by the plasma.

The production methods at the Institute of Modern Physics (IMP) include the use of gaseous compounds, the oven technique, the direct insertion and the metal ions from volatile compounds method (MIVOC). More than ten different metal ion beams have been produced with IMP ECR ion source so far. Typical metallic ion beams such as ^{63}Cu, ^{66}Zn, ^{56}Fe, ^{58}Ni, ^{26}Mg, ^{207}Pb, ^{40}Ca, ^{181}Ta and so on have been successfully produced and delivered to the cyclotron. The production of these ion beams is stable and some of them have been used in atomic physics and surface physics research. A great number of knowledge from tuning highly charged metal ion beams with ECR ion source have also been gained.

To improve the production of high charge state lead ion beam, experiments have been performed with IMP LECR3 (Lanzhou ECR No.3 ion source) to optimize the key parameters, such as magnetic field, electrical power of the oven, gas mixing. After optimizing the parameters, we obtained $^{207}Pb^{30+}$ and $^{207}Pb^{37+}$ ion beam up to 18eμA and 6.7eμA respectively.

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1) E-mail: hewei99@impcas.ac.cn

2 Experimental device

2.1 Experimental setup

Some experiments have been carried out on IMP LECR3 (Fig. 1), an upgrade version of the IMP LECR2, which is devoted to produce highly charged ion beam development and was built in 2001. All possible methods and tricks for improving beam intensity and stability have been used and tested at the ion source, including optimized configuration of the axial mirror magnetic field, efficient rf feeding system, biased electrode, gas mixing effect, aluminum chamber and aluminum plasma electrode, improved cooling of some key components of the ion source, accel-decel extraction electrode, beam line with high transmission efficiency and high resolution[2]. The key parameters of LECR3 are given in Table 1.

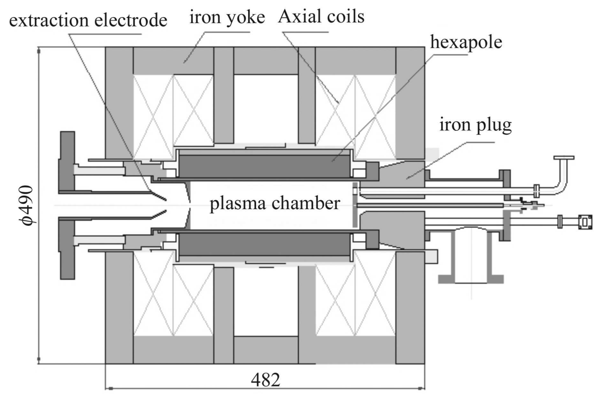

Fig. 1. Mechanic plot of LECR3.

Table 1. The key parameters of LECR3[3].

peak of mirror magnetic field at central axis	1.7T (at injection), 1.05T (at extraction)
central field for mirror configuration	0.42T
field component at the wall of plasma chamber	1.0T
material of hexapole permanent magnet	36 pieces of NdFeB (N45M)
frequent of the microwave	14.5GHz
mode of microwave feeding	waveguide directly-insert
effective length of the plasma chamber	300mm
inner diameter of the plasma chamber	76mm
material of the plasma chamber	aluminum

2.2 Internal oven

An internal oven was developed at IMP for metallic ion beam production. The main part of the oven (Fig. 2) consists of an alumina ceramic wound with a 0.5mm diameter tantalum wire, and its working temperature is from 200°C to 1300°C. A 10A/20V electrical power supply is used to heat the tantalum wire. The relation between oven electric power and its temperature is shown in Fig. 3. The solid sample to be evaporated is placed inside the cavity of the hot alumina ceramic called the "heater". The cavity volume is about 0.1cm^3. An electrical insulator tube is placed between the tantalum wire and the external tantalum tube to avoid electrical short circuit. All these elements are placed inside a tantalum casing which is connected to one end of the heating wire. The casing, which is also a thermal radiation shield, is clamped to a tantalum pod. The other end of the heating wire is connected to a long insulated pushing rod which carries back the heating current[4, 5].

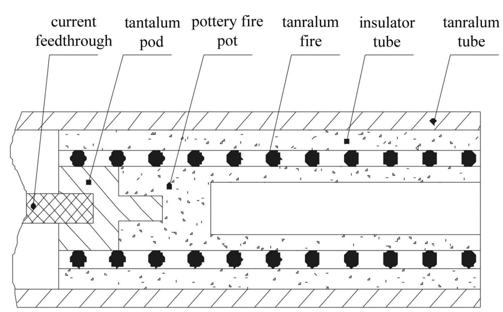

Fig. 2. Schematic of oven in IMP.

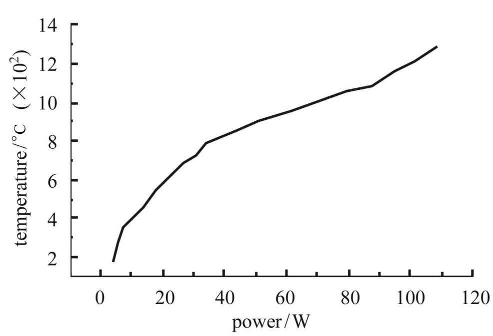

Fig. 3. The relation between oven power and its temperature.

3 Experimental results and discussion

3.1 The influence of some key parameters of the ion source on the highly charged lead ion beam production

We have studied the behavior of the source with sets of variable magnetic fields. Only one parameter was changed each time and the others were kept constant. First, keeping the other magnetic settings constant, the injection magnetic field is varied from 1.5 up to 1.8 T which is not the optimal value, but a safety limit for the coils. Fig. 4 (a) shows the beam intensity obtained at 14.5GHz (in dc mode) as a function of the injection mirror ratio ($R_l = B_{inj}/B_{ECR}$) defined as the ratio between the field value B_{inj} and the resonance value B_{res} (0.52T at 14.5GHz).

Another important ECRIS parameter is the minimum B value, which is directly related to the length of the hot plasma enclosed in the resonance surface. When varying the value of $B_{min}$from 0.4 to 0.6 T, the length of the resonance surface that maps the hot plasma goes from 92mm down to 28mm. The variation of the beam intensity with the ratio B_{min}/B_{rad} is presented in Fig. 4 (b). Experiment performed in dc mode at 14.5GHz shows that $B_{min}$is strongly correlated to the radial magnetic field (B_{rad}) with an optimum value $0.33 < B_{min}/B_{rad} < 0.36$.

The magnetic field at the extraction region is more complicated to handle, since a compromise has to be found between plasma confinement and ion extraction. The extraction magnetic field is dependent to the radial field (B_{rad}) as shown in Fig. 4 (c) The optimum value is $0.81 < B_{ext}/B_{rad} < 0.93$.

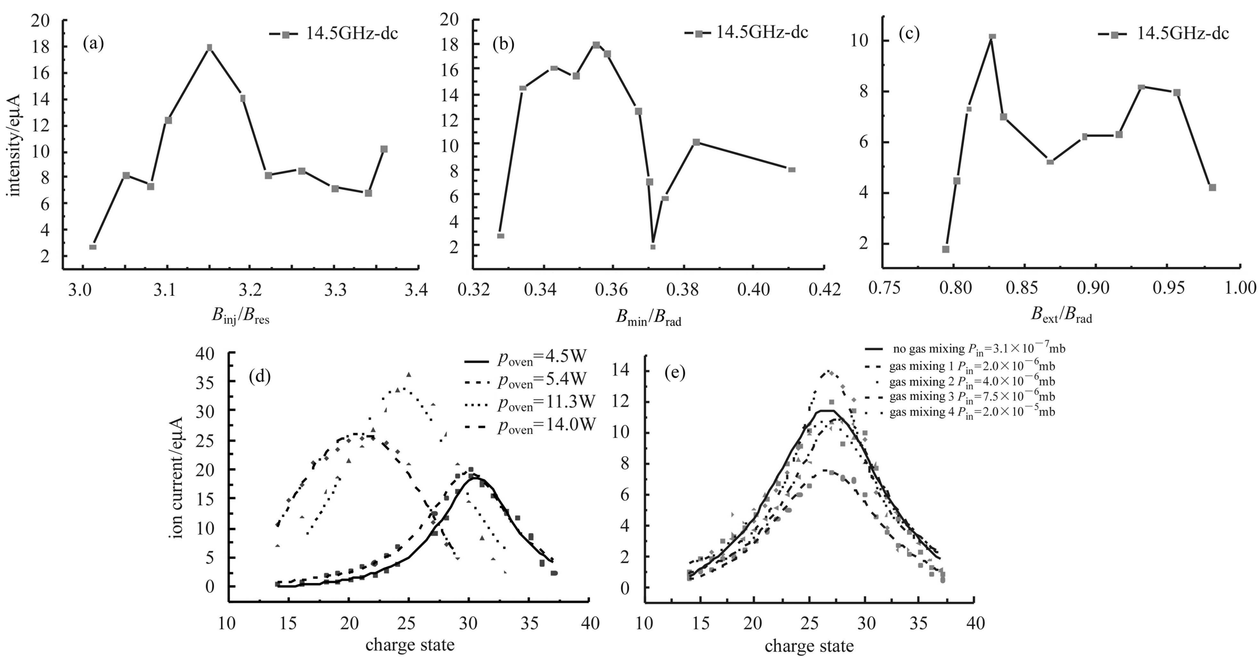

Fig. 4. (a) Evolution of Pb^{30+} intensity with the injection mirror ratio at 14.5GHz in dc mode; (b) Pb^{30+} at 14.5GHz variation of the beam intensity with the ratio B_{min}/B_{rad} (at 20kV extraction); (c) Relation of Pb^{30+} with the extraction magnetic field normalized to the radial magnetic field; (d) Influence of the electrical power on oven on ion current and charge state; (e) Influence of gas mixing on ion current and charge state. For all above experiments, the extraction voltage is 20kV.

For high charge state production, it is important to minimize all ion recombination processes, in particular charge exchange. Therefore neutral pressure control has become an crucial issue. Fig. 4 (d) illustrates the changes of the beam intensity obtained at 14.5GHz (in dc mode) as a function of the electrical power on the oven. With decreasing the electrical power, the spectrum peaks of high charge state lead ion beam will be elevated, meanwhile, those of the medium or low charge state lead ion beam become diminished. The lower the electrical power on oven, the higher intensity of high charge state lead ion beams. The reason is probably that the production of lead vapor reduces with decreasing the electric power of the oven. And decreasing in density of neutral gas would help to minimize the charge exchange and enhances the production of high charge state ions. Unfortunately, excessive gas reduction decreases the first step ionization (which introduces electrons)[6]. This leads to a lack of free electrons in the plasma, which limits the improvement and finally results in a plasma relaxation due to electron starvation. Under these conditions, better electron confinement and artificial electron donors (gas mixing, external electron injection, wall coating, etc.) are generally expected as supplementary improvements.

The gas mixing effect apparently consists in mixing a lighter gas to the main element of the ECR discharge in order to increase the output currents of highly charged ions of that element[7]. Normally about 80% mixing gas is used and it can be up to 95% or higher for very heavy elements. A high ratio of mixing gas increases the neutral pressure inside the ECR plasma and may also limit the production of higher charge states or the maximum intensity of the heavier ions[8]. Experiment performed in dc mode at 14.5GHz shows that the beam intensity is strongly correlated to the flux of mixing gas as show in Fig. 4(e), when the flux of mixing gas exceeds the fixed value, ion current of medium charge state will be elevated evidently. With the flux of mixing gas increasing, the pressure at injection will exceed 2.0×10^{-5}mb, it is observed that the spectrum peaks of O^{+}, O^{2+}, O^{3+} beams clearly rise while those of highly charged lead ion beams fall off. A possible explanation for the gas mixing effect is ion cooling induced from enhanced ion energy losses after dilution[8].

3.2 Highly charged lead ion beam production

According to experience from above experiments, we optimized $^{207}Pb^{30+}$ and $^{207}Pb^{37+}$ spectrum with the LECR3 working at the following parameters: $B_{\rm inj}$=1.639T, $B_{\rm ext}$=1.071T, $p_{\rm in} = 7.8\times10^{-7}$mb, $P_{\rm oven}$ = 5.7W(for $^{207}Pb^{30+}$); $B_{\rm inj}$=1.645T, $B_{\rm ext}$=1.076T, $p_{\rm in} = 6.2\times10^{-7}$mb, $P_{\rm oven}$ = 5W (for $^{207}Pb^{37+}$), rf power 900W, 20kV extraction voltage and the plasma electrode aperture diameter $\phi=8$mm, 10 mg/h consumption rate for the axial oven. The lead ion beam was stable, the intensity of the extracted ion beams is 18eμA and 6.7eμA respectively. However, due to ion beam output slowly decreasing with time, we had to increase the electrical power of the oven to compensate this decay. Fig. 5 shows optimized $^{207}Pb^{30+}$ and $^{207}Pb^{37+}$ spectrum.

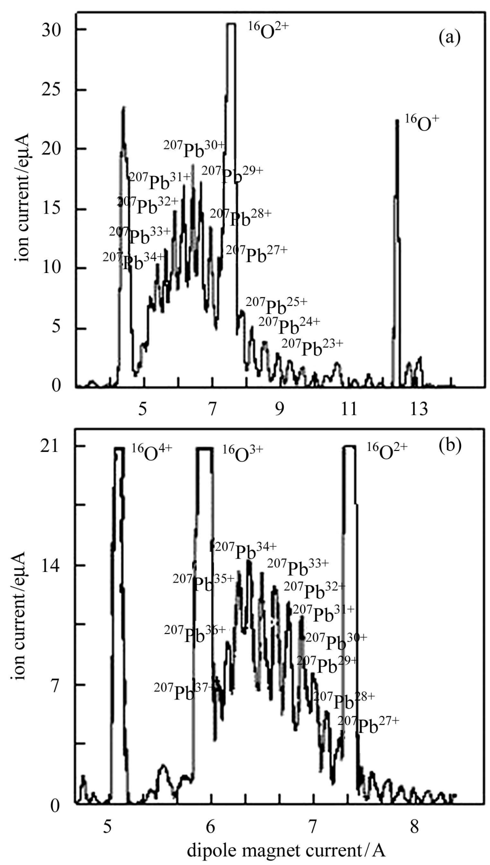

Fig. 5. (a) Ion beam spectrum, optimized for $^{207}Pb^{30+}$; (b) Ion beam spectrum, optimized for $^{207}Pb^{37+}$. For both methods the rf power was 900W, the extraction voltage was 20kV. The electrical power of the oven was 5.1W.

4 Conclusion

Experiments performed with LECR3 give us some guidelines for tuning high charge state lead ion beams:

(1) The injection magnetic field has to correspond to the mirror ratio $R_{\rm l}=B_{\rm inj}/B_{\rm ECR}=3.2$;

(2) The value of minimum B is correlated to the radial field with an optimum value $0.33<B_{\rm min}/B_{\rm rad}<0.36$;

(3) The extraction magnetic field is also correlated to the radial field with an optimum value $0.81 < B_{\rm ext}/B_{\rm rad} < 0.93$;

(4) The lower the electrical power on oven, the higher intensity of high charge state lead ion beams. But the electrical power can not be less than 2W;

(5) The gas mixing has an obvious effect on improving the production of high charge state lead ion beams. The pressure at injection can not exceed 2.0×10^{-5}mb, otherwise the intensity of high charge state lead ion beams will decrease.

In addition, good vacuum condition is very important during the operation of the ion source for the intense highly charged ion beams production. The ion source is baked with high rf power for a long time so that the source internal surface would be "cleaner" through outgasing.

On the other hand, some disadvantages of oven method were also found. (1)The cavity of the oven is so small that have to be refilled after 100—150h runtime. (2)The working temperature is not high enough for some refractory material. The measures will be taken to improve the above disadvantages in the coming work.

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强流高电荷态Pb离子束的产生与优化研究*

何伟[1,2;1)] 李锦钰[1] 赵环昱[1,2] 曹云[1] 孙良亭[1] 赵红卫[1] 张子民[1]

1 (中国科学院近代物理研究所 兰州 730000)

2 (中国科学院研究生院 北京 100049)

摘要 随着原子物理及表面物理研究的发展, 高电荷态金属离子束的需求日益增多. 近来, 在中国科学院近代物理研究所14.5GHz LECR3离子源实验平台上, 以炉子法产生的铅离子束作为研究对象, 进行了一系列ECR离子源关键参数(如: 磁场、炉子功率、掺气等)影响高电荷态铅离子束产额的实验研究, 在此基础上, 调整优化了LECR3离子源的状态参数, 从而获得了强流高电荷态铅离子束18eμA $^{207}Pb^{30+}$和6.7eμA $^{207}Pb^{37+}$.

关键词 ECR离子源 炉子法 金属离子 高电荷态离子

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1) E-mail: hewei99@impcas.ac.cn