THE HIGH CHARGE STATE ALL-PERMANENT MAGNET ECRIS OPERATED ON 320 KV HV PLATFORM*

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Abstract

An all-permanent magnet ECR ion source named LAPECR2 (Lanzhou All-permanent magnet ECR ion source No. 2) has been built and tested at IMP. This ion source is designed and operated to produce intense ion beams of both low charge states (such as H+, He2+, Xe3+…) and high charge states (such as Ar14+, Xe30+…) for the 320 kV high voltage (HV) platform at IMP. Many good results have been obtained on LAPECR2, such as 1emA O6+, 130 eμA O7+, 166 eμA Ar11+, 2 eμA Ar16+, 0.33eμA Ar17+, 85 eμA Xe20+, 24eμA Xe27+, 2eμA Xe31+. This ion source was designed to fulfill the various requirements of all of the experimental terminals, such as the delivery of metallic ion beams. A high temperature micro-oven has been fabricated and installed on the source to produce stable metal vapor. This HV platform has been successfully biased to 390 kV without ion beam. And ion beams with the energy up to 340 keV/q have already been delivered to the successive experimental terminals. After a brief introduction of the source LAPECR2, the operation status on the HV platform is discussed. The typical performance of the source of both gaseous and some metallic ion beams will be given in this paper.

INTRODUCTION

As the most efficient machine to produce stable intense high duty factor high charge state ion beams, ECR ion sources have been widely adopted as the injectors of multiple charge state ion beams for different purposes [1]. With the development of the techniques of ECRISs, many high performance ECRISs have been built around the world, such as GTS [2], VENUS [3], SECRAL [4], etc. These ion sources can provide very intense high charge state ion beams for the successive accelerators or experimental terminals. Besides the demands of high performance room temperature or superconducting ECRISs, there is great demand of all permanent magnet ECRISs, because of their typical characteristics such as large electricity free, strong cooling water free, easy handling and operation, simple structure, etc. With the advancement of NdFeB techniques, high remanence and high coercivity materials are now comercially available, which enables the realization of high magnetic field with comparably reasonable cost. The Nanogan series [5] and the BIE series [6] are all successful candidates of all permanent magnet ECRISs.

With the development of heavy ion beam associated research, we notice that there is an energy margin between the ion beams delivered by an ordinary ECRIS platform and the ion beams accelerated by SFC accelerator at IMP (K=69), which covers many interesting fields concerning heavy ion beams. To promote the studies in these fields, a 320 kV HV platform had been set up by the end of 2006. Five experimental terminals of this HV platform are dedicated to the research activities of highly charged ion physics, atomic physics, material physics, biophysics, and astrophysics respectively. These research activities inquire the platform to deliver ion beams of both light and heavy elements from low charge states to high charge states. Thus, the project of building a high performance all permanent magnet ECRIS LAPECR2 was started from the beginning of 2004. In this paper, the commissioning results of LAPECR2 and the operation status on the HV platform are presented.

LAPECR2 ION SOURCE

The physical goals of the 320 kV HV platform inquire that LAPECR2 should be a high charge state ECR ion source that can deliver both gaseous and metallic ion beams. This indicates that high B, high rf frequency and high rf power modes should be taken into consideration in this design. However, one of the biggest drawbacks of all permament magnet ECRISs is the inflexibility of the magnetic field and insufficient field strength. Thus, the designed magnetic field configuration should be optimized for the desired operation mode. The latest semiempirical scaling laws of ECRIS [7] can be an important reference in the conceptual design. In our design, three big 24-segmented axial magnetic rings at the source injection side provide the injection magnetic field peak up to about 1.3 T, and three 24-segmented axial magnetic rings at the extraction side provide the extraction field up to about 1.1 T. A single central axial magnetic ring increases the Bmin field up to 0.42 T. And the radial magnet is a 36-segmented Halbach structure hexapole which provides a 1.2 T radial field at the inner wall of a Ø67 mm ID plasma chamber. These key parameters are designed to optimize the operation of the source at 14.5 GHz. To have sufficient radial confinement to the plasma and also to keep the axial field high enough, the hexapole, one of the injection magnetic rings and also one of the extraction magnetic rings are specially shaped to satisfy the physical requirements (as shown in figure

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1). According to the simulation with TOSCA 3D, the total field |B|= 1.05 T= 2Becr contours are well close inside the plasma chamber.

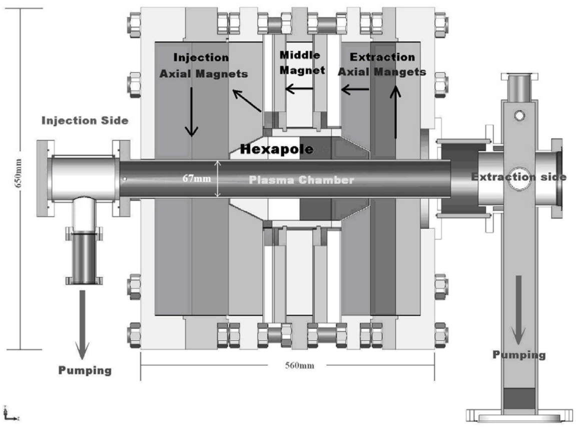

Figure 1: Schematic of LAPECR2 ion source

After about one year's fabrication, the magnetic body was then ready for source commissioning. The measured magnetic field is very close to the designed values. A double wall water-cooling SS plasma chamber is installed to have better cooled chamber in order to avoid thermal demagnetization of the permanent magnet and to minimize the outgassing of the inner surface of the chamber at high rf power injection. 14.5 GHz microwave power is injected into the plasma chamber through a WR62 microwave guide. A simple diode extraction system is adopted to let intense ion beams extraction at HV=25 kV. The total magnetic body and some of the accessorial components are floated at the extraction HV potential.

COMMISSION RESULTS

LAPECR2 was firstly ignited at the middle of 2005 with oxygen plasma at 14.5 GHz with a 350 W TWT microwave generator. But because of HV platform setup, the source could only give the first results at the middle of 2006 [8]. Since LAPECR2 has adopted a plasma chamber whose ID dimension is comparable to that of a room temperature ECRIS, 350 W microwave power feeding is not sufficient to achieve the best performance. A 14.5 GHz klystron microwave generator with the maximum microwave power output of 1.1 kW is adopted as the microwave power generator, with the sacrifice of the alteration of the microwave frequency. RF power coupling, ion beam extraction and transmission are always the spiny aspects in the field of ECRIS. The condition becomes even more severe for an all permanent magnet ECR ion source. For most ECR ion sources, rf power direct feeding through rectangular waveguide is always adopted because of its simple structure and comparably better rf power coupling efficiency. While for a permanent magnet ECR ion source, the injected rf power before being fed into the plasma chamber, it will encounter several parasitic resonances under vacuum (as illustrated in figure 2), which may lead to power absorption inside the waveguide if the vacuum inside the waveguide is not good enough. As for the case of LAPECR2 source, many Ø2 mm holes are drilled at the both H sides of the WR62 waveguide inside the vacuum to help vacuum evacuation inside the waveguide. In this way, the rf power feeding efficiency is improved a lot. The positive and negative magnetic fields (as shown in figure 2) at the ion beam extraction and transmission region of a permanent magnet ECR ion source give much trouble to ion beam extraction and transmission. For LAPECR2, the negative field at the extraction region is -0.87 T, which has the effect of a permanent magnet Glaser lens to the ion beam transmission. Some ion beam mismatching problem might occur during the optical design for the ion beam transmission system. The negative stray field should be considered in the corresponding simulations. For LAPECR2, a solenoidal lens after the source has been adjusted in position to minimize the effect of the negative stray field and also to reduce the magnetic force between the source body and the Glaser lens which is caused by the magnetization of stray field to iron yoke of the Glaser lens. It is worth mentioning that the beam loss caused by ion beam transmission mismatching will be catabatic when the HV platform is biased to hundreds of kV.

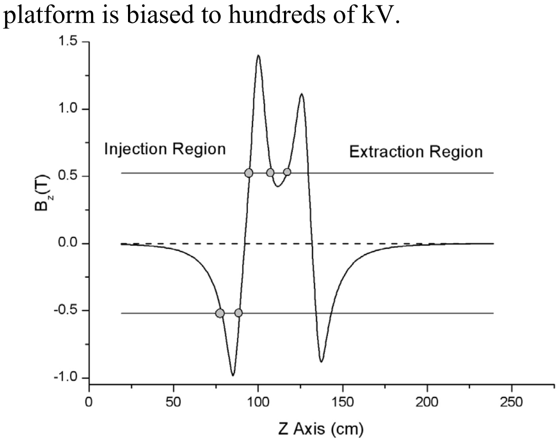

Figure 2: Magnetic field configuration of LAPECR2 and the stray field at injection and extraction sides

By proper solution of the problems of vacuum, extraction HV, microwave power injection efficiency and so on, very promising results of gaseous ion beams have been obtained on LAPECR2 [9]. Figure 3 presents the typical xenon ion beam intensities in comparison with those of other high performance ECRISs. These results are mostly obtained under the condition of 1.1 kW microwave power feeding and an extraction HV of 25 kV. With the power density of about 1.0 kW/l inside the plasma chamber, the typical performance of LAPECR2 is very promising and can even be comparable with those obtained on some room temperature ECR ion sources working at 14.5 GHz, such as LECR2 [10] and 14.5 GHz Caprice [11].

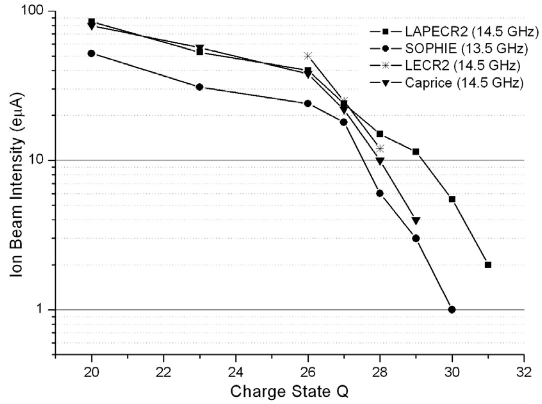

Figure 3: Typical xenon ion beam results in comparison with other high performance ECRISs at 14.5 GHz

METALLIC ION BEAM PRODUCTION

The 320 kV HV platform at IMP is a versatile tool for different physical studies. Gaseous element ion beams are always demanded, however, metallic ion beams are also very important. While the designing of LAPECR2, metallic ion beam production has been taken into consideration. Micro-oven evaporation, plasma sputtering and MIVOC are the possible choices. For low melting point metals, micro-oven is a very suitable method. We have fabricated a medium temperature micro-oven suitable for the accurate handling of the temperature at 300℃~1000℃. Figure 4 illustrates the temperature evolution vs. electric power of the oven. By heating the plasma with a 14.5 GHz TWT microwave generator, the first obvious bismuth spectrum was observed when 9.0 W electric power was applied on the micro-oven, but most of Bi ion beam peaks on the spectrum were very small. By increasing the electric power up to 11.2 W, the beam spectrum peaked at Bi19+. And higher charge state bismuth ion beams such as Bi28+, Bi31+ can be clearly observed in the spectrum as indicated in figure 5. When Poven was enhanced to 12.6 W, 24 eμA Bi21+ was detected. During the tuning, high charge state bismuth ion beams were also detected at the Faraday cup. 17 eμA Bi28+ and 5 eμA Bi31+ are the typical results. As the plasma of LAPECR2 was just recovered from carbon ion beam production, the inner surface of the plasma chamber was severely contaminated. That is why the carbon ion beam peaks are so high in the spectrum when optimizing bismuth ion beam production. For unknown reasons, the bismuth material inside the oven was dissipated very fast. Within about 72 hrs, 900 mg bismuth material was totally evaporated. The possible reason might be that the increment of the temperature in the oven was too fast. And the working condition was not well optimized. This experiment is just a preliminary test. A further experiment with an aluminium chamber is scheduled.

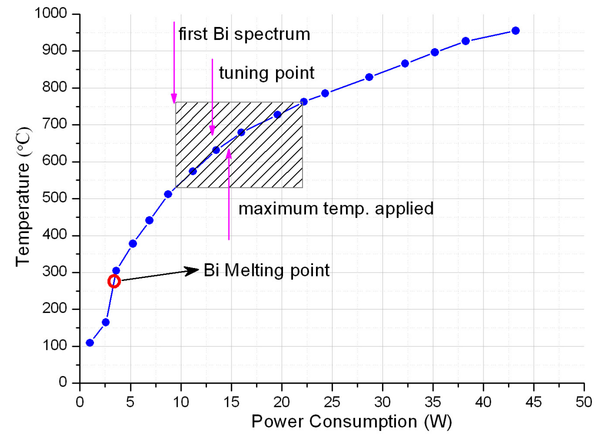

Figure 4: Oven temperature vs. oven electric power

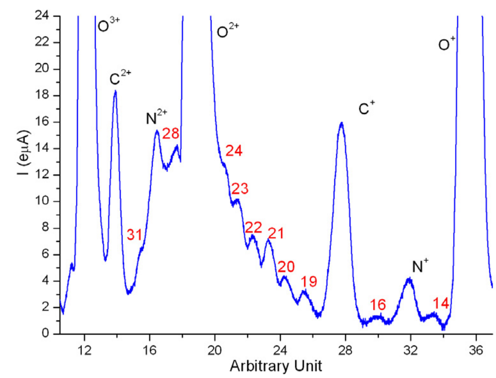

Figure 5: One of the spectra optimized for Bi

THE 320 KV HV PLATFORM

The IMP HV platform is designed to be operated in the energy range of 20~320 kV/q, which covers most of the energy range that interests the researchers of the five experimental terminals. The LAPECR2 ion source, a Glaser lens, a 90º analyzer magnet, a three-column electrostatic lens and the accessories (include power supplies, etc.) are situated on the HV platform. Since many units on the platform need low pressure water cooling, Water pipe with maximum 4.0 kg/cm2 output water pressure is connected to the platform. The maximum drain current of the 400 kV HV power supply is 2.5 emA, which demands that the total drain current from the water pipes should be as low as possible. The electrical resistivity of the cooling water is about 1 MΩ·cm. The single cooling water pipe is about 25 m, which is twisted on an insulator column. During the operation, a 0.8 emA drain current can be observed when ion beam is off. And when ion beams are accelerated, the total drain current increment is around 0.1~0.2 emA. These results are well up to the functioning margin of the HV power supply. All the units on the HV platform are powered through a 400 kV HV insulating transformer. An Ø180 mm ID acceleration column which has a 45-electrode structure has been adopted to connect the HV platform and the vacuum tube at ground potential. In the commissioning procedure of the HV platform, the platform has been biased to 390 kV with the acceleration column installed. The control of all the units on the HV platform is realized by a RF remote control system. According to the more than 3000 hrs operation, this system is quite reliable and stable.

Ion beams extracted from LAPECR2 are analyzed by a 90º double-focusing 67 mm gap analyzer. A Glaser lens mounted between the ion source and the analyzer is a very useful tool for the ion beam transmission adjustment. After been analyzed, ion beam experiences an electrostatic lens which is used to adjust for better ion beam transmission coupling between the HV platform and the acceleration column. At ground potential, the accelerated ion beam is delivered to the straight experimental beam line through a 90º double-focusing deflection magnet. There are totally 5 experimental terminals, which include one straight line terminal and 4 terminals with the ion beam distributed by 120º defection magnets from the straight line. Series of quadrupole magnets are used for ion beam focusing to each terminal. Figure 6 presents the envelope calculation to the first order with Trace 3D [12] for terminal No. 2. And the incident ion beam is 625 keV Xe25+ beam, and the acceleration column voltage is 400 kV.

When the HV platform is at ground potential, the available energy of the ion beams delivered for experiments are normally from 10 keV to 600 keV and the beam intensities vary from pA to μA. Taking Xe beam for example, the ion charge state available is varying from 2+ to 30+ and the extraction HV can be varied from 4.5 kV to 25 kV. Within such a big extraction HV range, it is very important to know how to have very good beam transmission efficiency, stability and beam quality to satisfy the requirements of the experiments. During the tests, we found that the transmitting efficiency of higher charge state heavier ion beams was higher than that of the lower charge state lighter ion beams. For example, at experiment terminal No. 3, the transmission efficiency of Xe22+ beam is 58% and 65 % for Xe27+, but under the same condition, the transmission of He+ is only 5%. It is also found that with lower extraction HV, the quality of the ion beam obtained at the experimental terminal was much worse than that obtained at higher extraction HV.

Since the December 2006, 320 kV HV platform has been operated for more than 11500 hrs for the commissioning of the HV platform and several physical experiments which covered 9000 hrs. The ion beams of Ar, Xe, Ne, He, O, C, H with various energies and different charge states have been produced. The on-line operation status of the all-permanent magnet source LAPECR2 is quite good. Even with a TWT microwave generator with maximum output rf power of 350 W, very promising ion beam intensities have been produced, such as 200 eμA Ar8+, 60 eμA Ar11+, 50 eμA Ne8+, 70 eμA Xe20+, 17 eμA Xe27+, etc. The operation time with the platform HV biased is up to about 5000 hrs. The highest on-line operation HV applied is 320 kV, which means the HV platform at IMP has the capacity of deliver multiple charge state ion beams with the energy in the range of 4.5 keV/q ~345 keV/q.

CONCLUSION

A high charge state all permanent magnet ECR ion sources have been successfully fabricated at IMP. After more than one years' modification and commissioning, some promising results have been obtained. Typical results like 1.0 emA O6+, 166 eμA Ar11+, 2 eμA Ar16+, 85 eμA Xe20+, 24 eμA Xe27+ and 5.5 eμA Xe30+ are close to or even better than some room temperature ECR ion sources working at 14.5 GHz. The good performances of LAPECR2 owe much to the optimum designed magnetic field configuration, some auxiliary tricks to enhance the plasma density and realize better confinement to higher charge state ions, effective solutions to some intractable problems such as effective rf power feeding, sparking, etc, and also sufficient source conditioning. LAPECR2 has already been dedicated to routine operation for the 320 kV platform. Many MCI beams, such as H+, He+, He2+, O4+, N5+, Ne9+, Ar12+, Xe20+, Xe29+, have already been delivered to the corresponding experimental terminals with the projectile energy in the range of 4.5 keV/q to 345 keV/q. Metallic ion beam production with Bi has also been tested on LAPECR2. Preliminary results show that LAPECR2 has the capability to produce intense high charge state metallic ion beams with the proper methods. More are expected with an aluminium chamber to be installed.

REFERENCES

R. Geller, Electron Cyclotron Resonance Ion Sources and ECR Plasmas (Institute of Physics, Bristol, 1996).
D. Hitz et al., Rev. Sci. Instrum. 75, 1403 (2004).
D. Leitner, M. L. Galloway, T. J. Loew, C. M. Lyneis, I. Castro Rodriguez, and D. S. Todd, Rev. Sci. Instrum. 79, 02C710 (2008).
H. W. Zhao et al., Rev. Sci. Instrum. 79, 02A315 (2008).
C. Bieth, J. L. Bouly, J. C. Curdy, S. Kantas, P. Sortais, P. Sole, and J. L. Vieux-Rochaz, Rev. Sci. Instrum. 71, 899 (2000).
Dan. Z. Xie, Rev. Sci. Instrum. 73, 531 (2002).
S. Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, and G. Melin. Rev. Sci. Instrum. 72, 4090 (2001).
L. T. Sun et al. Rev. Sci. Instrum. 77, 03A319 (2006).
L. T. Sun et al. Nuclear Instruments and Methods in Physics Research B 263 (2007), p. 503–512.
H. W. Zhao, B. W. Wei, Z. W. Liu, Y. F. Wang, and W. J. Zhao, Rev. Sci. Instr. 71 (2000), p. 646-650.
D. Hitz, F. Bourg, P. Ludwig, G. Melin, M. Pontonnier, T.K. Nguyen, Proceedings of the 12th International Workshop on ECR Ion Sources, April 25–27, 1995, RIKEN, Japan, p. 126.
AccelSoft Inc., P. O. Box 2813, Del Mar, CA 92014 USA, 858-677-0133. Available from: accelsoft@ghga.com, www.ghga.com/accelsoft.