INTENSE BEAM ION SOURCES DEVELOPMENT AT IMP *

L Sun#, H. W. Zhao, W. Lu, X. Z. Zhang, Z. M. Zhang, J. Y. Li, Y. C. Feng, Y. Cao, W. H. Zhang, Q. Wu, Y Yang, Z. W. Liu, IMP/CAS, Lanzhou 730000, China
D. Xie, LBNL, Berkeley, CA 94720, USA

Abstract

To satisfy the HIRFL (Heavy Ion Research Facility in Lanzhou) accelerators' requirement and the needs of several other future accelerator facilities, many high beam intensity ion sources have been developed at IMP. The ion sources include intense high charge state ion beam ECR ion sources and high intensity proton beam ECR or microwave sources. This paper will review the high charge state ion sources developed at IMP, especially the recently built fully superconducting ECR ion source SECRAL, and the other classical ion sources and all permanent magnet ion sources will also be discussed. The latest performance of the recently built intense proton ion source which can operate continuously at more than 65emA beam (after LEBT) and 50kV source high voltage for more than 150 hours with very few HV spark intervals will be especially presented in this paper. Recent studies concerning the ion sources for HIAF project are also given.

INTRODUCTION

Particle accelerators are nowadays irreplaceable tool in nuclear physics experimental research and their associated applications. Since ion source is such a unique part of an ion beam accelerator system, which has significant impact on the system's performance, with the development of ion beam accelerator, ion source techniques have been greatly improved in the last several decades. At IMP, researchers had already started heavy ion accelerator studies and development since 1960s. Now a Heavy Ion Accelerator Facility in Lanzhou named HIRFL is fully functional for nuclear physics research activities. This facility is composed of an experimental synchrotron ring, a main storage synchrotron ring, two radioactive ion beam lines, and two cyclotron accelerators which can be either operated as coupled accelerators for experiments or used as ion beam injectors for the main ring [1]. ECR (Electron Cyclotron Resonance) ion sources have been adopted as intense beam pre-injectors for routine operation since the end of 1980s. To further explore the capacity of the facility and also to meet the needs of experimental studies, continuous R&D work has been made to develop higher performance ECR ion sources to enhance the output ion beam intensity and charge state, which will be discussed in this paper. Additionally, heavy ion accelerators can also be used for various application purposes, such as heavy ion cancer therapy. Permanent magnet ECR ion sources have been developed at IMP for a dedicated medical treatment machine HIMM (Heavy Ion Medical Machine).

Hydrogen ion beams have been widely used on accelerators for the purposes of hadron sources. Recently, several 2.45 GHz proton beam sources have been developed successively at IMP. One of them is developed for the CPHS (Compact Pulsed Hadron Source) project in Tsinghua University. Meanwhile, China ADS or C-ADS project has been launched in China for several years. This project needs very reliable and stable intense CW proton beam source. This paper will briefly present the status of the ion sources.

Recently, a very challengeable heavy ion accelerator project HIAF (High Intensity heavy ion Accelerator Facility) has been proposed at IMP. This accelerator complex needs very intense pulsed highly charged ion beams for pre-injection. According to the design, the baseline is to use ECR ion source to produce the wanted ion beams, especially those from heavy elements. However, to reach the designed capacity of the complex, the request for more intense high charge state ion beam injection is much beyond the extrapolated performance of a next generation ECR ion source. But this could be possibly satisfied by the utilizing of LIS (Laser Ion Source), whose techniques have been enormously improved in recent years. This paper will have one section to discuss the according issues.

ECR ION SOURCES

ECR ion sources have been widely used on heavy ion accelerators as pre-injectors of heavy ion beams. Based on the magnet type, they are divided into several types, i.e. conventional or room temperature sources, permanent magnet sources, hybrid superconducting sources and superconducting sources. At IMP, for various purposes, except the hybrid one, the other three types of source have been developed successfully.

Conventional ECR Sources [2]

We have built series of Lanzhou ECR ion sources that have incorporated the latest techniques of ECR ion sources. LECR1 source is the first ion source developed in Lanzhou, on the basis of a 10 GHz Caprice type ECR ion source bought from Grenoble. With a typical source performance of 320 euA Ar^{9+} and 70 euA K^{17+}, LECR1 became fully operational since 1995. High charge state ECR ion source favours higher B field and microwave frequency, which is also the guiding line for the design of the 14.5 GHz LECR2 source. It became fully available for routine operation since 1999. The typical performance demonstrated is 185 euA Ar^{11+}, 50 euA Kr^{19+} and 50 euA Xe^{26+}. With micro-oven and MIVOC techniques, LECR2

*Work supported by China Nature Science Foundation (Contract No. 91126004)
#sunlt@impcas.ac.cn

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enabled the acceleration of metallic ion beams with HIRFL accelerators for the first time. Typical metallic beams are 130 euA Ca^{11+}, 65 euA Fe^{13+} and 50 euA Zn^{13+}. A later upgraded version of this ion source named LECR3 was developed with the similar ions source dimensions, but also incorporated with a higher field hexapole magnet and 2-frequency heating technique. LECR3 was eventually tested with 14.5 and 18 GHz frequencies. The typical performance is 240 euA O^{7+}, 1.0 emA Ar^{8+}, 325 euA Ar^{11+}, 0.4 euA Ar^{17+} and 95 euA Xe^{26+}. It was firstly used as a beam injector for a multi-purpose ion beam experimental platform and latterly put into routine operation for HIRFL since 2006.

Permanent Magnet ECR Sources [3]

Permanent magnet ECR ion sources have the virtues like compactness, simplicity, cost saving and high power electricity free and no needs for pressurized LCW cooling, they have been widely adopted by many heavy ion beam HV platforms and industrial applications. 14.5 GHz LAPECR1 is the first permanent magnet ECR ion source built at IMP to produce low charge state intense beams. It features very good compactness with a dimension of only Ø102 mm ×296 mm and 25 kg weight. The typical beam output is more than 1 emA He^{+}, He^{2+} and tens euA of C^{4+} and Ar^{8+}. A much bigger permanent magnet ECR ion source LAPECR2 was successfully built and put into use in 2006. It is designed to be operated at 14.5 GHz to deliver intense high charge state ion beams for a 320 kV multi-discipline HV platform. The obtained performance is very promising, such as 1 emA O^{6+}, 11 euA Xe^{30+}, 15 euA Bi^{33+}, 5 euA Eu^{33+}, and so on. It has been used for the platform's routine operation for more than 37,000 hours since 2007, in which about 31,300 hours are dedicated to physics experiments at the 5 successive experimental terminals of the platform. An Ø450 mm ×380mm sized and ~260 kg weight permanent ECR ion source LAPECR3 has been recently successfully built and commissioned at IMP for the commercial cancer treatment project HIMM. LAPECR3 is designed to be able to deliver more than 100 euA C^{5+} for the beam injection to a compact 7 MeV/u $^{12}C^{5+}$ output cyclotron. In recent test of the ion source with a 14.5 GHz klystron amplifier, ~ 100 euA C^{5+} has been obtained. The source can also deliver more than 360 euA O^{6+}, 125 euA Ar^{9+}, 52 euA Ar^{11+} and 9 euA Ar^{13+}.

Superconducting ECR Sources

A superconducting ECR ion source can provide a full flexibility to tune the axial mirror fields as well as the radial sextupole field inside the plasma chamber, which will enables an optimum tuning of the source parameters for high charge state ion production. Several fully superconducting ECR ion sources have been built globally in recent years, and very promising performance have been demonstrated. SECRAL is one of the advanced ion sources designed to be operational at the frequency of 18~28 GHz. This source is designed with a warm bore size of Ø140 mm which can house a plasma chamber of Ø120 mm diameter with a 1.5 mm tantalum shielding cylinder installed. The maximum axial field is 3.7 T, and a 1.83 T at the inner wall of the Ø120 mm ID plasma chamber. This ion source was successfully built in 2005 and many record beam intensities have been achieved with either 18 GHz or 24 GHz microwave power [4]. Fig. 1 gives the typical xenon beam intensities obtained with SECRAL. Recently, new record beam intensities such as 425 euA Bi^{30+} and 395 euA Bi^{31+} have been obtained with about 4.0 kW 24 GHz microwave heating.

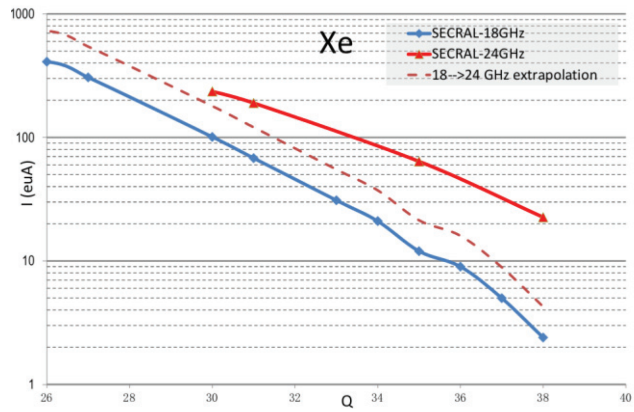

Figure 1: Xenon beam obtained with SECRAL source.

SECRAL was connected to the injection beamline of HIRFL in 2006. Since 2007, it has delivered intense highly charged heavy ion beams for HIRFL accelerators with a beam time of more than 13,000 hours. The typical ion beams for routine operation are Ni^{19+}, Xe^{27+}, Sn^{27+}, Bi^{36+} and U^{32+} with the beam intensity in the range of 50 ~120 euA.

2.45 GHZ PROTON SOURCES

The development of intense 2.45 GHz proton beam source at IMP could be traced back to 1990s. That ion source was built for a neutron source project at Lanzhou University. With an Ø6 mm diameter extraction aperture, 90 emA beam of H^{+}+H^{2+}+H^{3+} was obtained [5]. Recently, another proton beam source LIPS-1 (Lanzhou Intense Proton Source No.1) with permanent magnet structure has been successfully built and delivered to Tsinghua University for the CPHS project. Table 1 lists the beam quality requirements. Ultimately, more than 85 emA ion beam can be extracted from the ion source with a 50 kV extraction potential, and more than 60 emA proton beam can be detected after a 1.2 meters long LEBT (at the entrance of RFQ) which is mainly composed of two solenoids with corrector coils integrated. A 150-hour long stability and availability test has also been accomplished. In March 2013, the first accelerated beam with a 325.124 MHz RFQ was achieved. 44 emA out of 50 emA proton beam injected was obtained out of the RFQ, which gives a transmission efficiency of 88%.

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Table 1: Beam Requirement of LIPS-1 For CPHS.

Energy	50 keV
Current	≥ 60 emA
Repetition rate	50 Hz
Pulse width	500 μs
Rise time	80 μs
Fall time	40 μs
Reliability	> 120 hrs

The LIPS-1 source design was also used to develop the proton beam sources for C-ADS project. Different from the LIPS-1 source for CPHS, CW proton beam with the energy of 35 keV is needed at the entrance of RFQ. Fig.2 gives the sketch plot of the ion source and LEBT system for C-ADS. The source and the LEBT are still under tight conditioning. Beam intensity has already been reached, and the critical issue now is to minimize the sparking frequency and the source breakdown time.

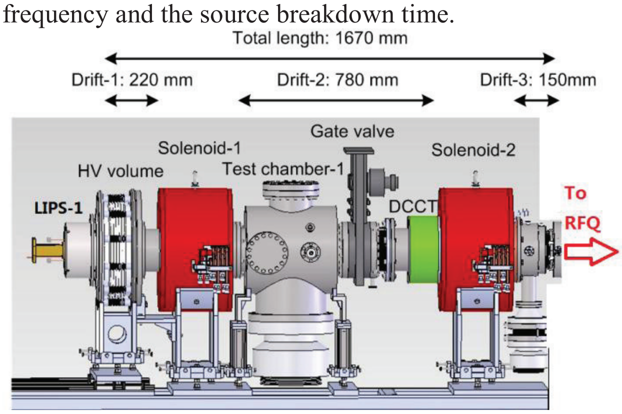

Figure 2: C-ADS ion source and LEBT layout.

NEXT GENERATION ION SOURCES

HIAF project accelerator is composed of intense ion beam sources, injector superconducting LINAC, acceleration and accumulation storage ring, a collection ring and a collider ring. To achieve the ultimate project goal, 0.2 pmA U^{34+} or Pb^{28+} beam with a repetition rate 0.5 Hz and pulse length of ~0.5 ms is needed. No state-of-the-art ion sources can meet the needs. As a baseline of the project, a high performance ECR ion source that can deliver no less than 40 puA U^{34+} or Pb^{28+} will be adopted to produce the pulsed beam of interest for the LINAC accelerator. It's less likely that an ECR ion source has the potential capacity to produce the 0.2 pmA intensity beams, therefore LIS is proposed to be a mostly possible candidate ion source for the application.

The latest results of high charge state uranium beam production with VENUS gave an inspiring result of 400 euA U^{34+} which has doubled the record beam intensity it had made 6 years ago [6], but this result is still 3.4 times lower than the needed current with an ECR ion source for HIAF. According to Geller's scaling laws, we can envision that the so-called 4th Gen. or the next generation ECR ion source can greatly improve the source performance by the factor of frequency scaling. Recent study has shown that neither conventional nor SECRAL structure SC-ECR source can use NbTi wire to meet the field requirements for next generation ECR ion sources, which will be most likely operated at the frequency higher than 40 GHz. Thanks to the recent progress in Nb_3Sn superconductor technique, the fabrication of such a complicated high field magnet is still possible with either VENUS or SECRAL structure. Another very attractive design has been proposed by D. Xie. This is a SC-magnet called MK-I [7] which employs rectangular ends Ioffe-bar design for the sextupole coils, and one Nb_3Sn solenoid coil inside and two other solenoids external the sextupole coils. This design greatly lowered the highest field in the SC-coils and thus lowered the loading line of the SC-wire. The scenario now is to design and build a SC-ECRIS that can be operated at 42 GHz whose microwave generator is already commercial available with more than 10 kW maximum power output.

LIS has got tremendous improvement in last decade. This kind of source features very high beam intensity of highly charged ions within a short beam pulse. For instance, more than 500 emA mixed carbon beam has been extracted with the LIS at IMP when the carbon target is bombarded with a 3 J Nd:YAG laser. But to meet the needs for HIAF, the challenge is still enormous. The output of desired charge state ions should be increased by a factor of ~50, which could possibly be realized by utilizing higher power laser machine and more efficient ion beam injection scheme. As a summary, a LIS that can meet the HIAF project requirements must get the following issues demonstrated: i. the choice of the type of pulsed high energy laser machine, ii. ion beam injection scheme to RFQ, and iii. well controlled produced beam quality.

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