First results from the recently developed, high-performance next-generation 18GHz ECRIS-SECRAL

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Abstract. The recently developed SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) ion source is a high-performance next-generation ECR ion source. It is designed to produce high current, high charge state heavy ion beams for HIRFL (Heavy Ion Research Facility in Lanzhou) cyclotrons. In August 2005, the first plasma was obtained at 18 GHz. Preliminary performances of SECRAL on gaseous elements such as oxygen, argon and xenon are quite promising, with many world record ion beams being delivered such as 2.3 emA O^{6+}, 0.81 emA O^{7+}, 0.81 emA Ar^{11+}, 0.5 emA Xe^{20+}, 306 eμA Xe^{27+} and 9 eμA Xe^{36+}. In April 2006, metallic ion beam production was tested on SECRAL. Very preliminary but promising results were obtained. This paper briefly describes the design of the SECRAL ion source, the ion beam analyzing system and also the ion beam detection system. Typical gaseous and metallic performances of SECRAL at 18GHz are presented.

1. Introduction
The ECR (Electron Cyclotron Resonance) ion source has become an indispensable tool in the fields of accelerators and high charge state ion physics [1], because of its high quality multiple charge ion beams production capability. In the past 30 years, development and refinement of ECR ion sources has made some remarkable achievements. Especially with the development of the “high-B” mode sources, namely the 3rd generation ion sources, and the recently developed next-generation sources, the performance of ECR ion sources has been promoted to a very high level for both intense medium charge state ion beams such as 2.0 emA O^{6+} [2], 2.0 emA Ar^{8+} [3] and also very high charge state heavy ion beams such as 0.5 eμA Xe^{42+} [4], 0.5 eμA Bi^{50+} [2].

The main driving aspects for the development of ECR ion sources are the ECR-machine physicists’ ongoing study on this special machine and the higher requirements from highly charged ion physics and nuclear physics research activities. HIRFL (Heavy Ion Research Facility in Lanzhou) is a national laboratory dedicated for heavy ion nuclear physics research and atomic physics research. With the developments of nuclear physics research, atomic physics research and the HIRFL accelerators, especially the recently built heavy ion cooling storage ring (HIRFL-CSR) [5], intense, high charge state ion beams are meant to be delivered by the ECR ion sources. The medium charge state ion source LECR1 and the high charge state ion sources LECR2 and LECR3 have provided multiple charge state ion beams for HIRFL successively for more than 10 years [6, 7], but to satisfy the future need of the
accelerators and other research activities, 20-30 μA stable highly charged beams of $^{40}\text{Ar}^{16+}$, $^{86}\text{Kr}^{25+}$, $^{129}\text{Xe}^{30+}$, $^{40}\text{Ca}^{16+}$ and $^{58}\text{Ni}^{17+}$ are needed. To achieve these goals, a project to build a fully superconducting ECR ion source SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) was launched.

2. Magnetic Design of SECRAL

The design of SECRAL has been optimized for maximum ion source performance at 28 GHz r.f. frequency for very high charge state heavy ion beam production as well as for developing a compact fully superconducting ECR ion source with a magnet structure which is easier to build without great technical challenge [8]. The fully superconducting ECR ion source SERSE [9] and VENUS [10] give many helpful references for design of the next generation of ECR ion sources. To satisfy the requirements of running at 28 GHz, the magnet of SECRAL should be able to excite on the axis the mirror peaks of more than 3.6 T at the injection side and 2.0 T at the extraction side, and a radial sextupole field more than 2.0 T at plasma chamber wall. The mirror to mirror distance is 420 mm. Different from the traditional design, such as the LBNL-VENUS and LNS-SERSE sources, the axial solenoid coils of the SECRAL magnet are located inside of the sextupole. This innovative magnet structure design of SECRAL reduces the strong interaction forces between the sextupole coils and the solenoid coils and makes the source more compact and less expensive. The superconducting coil configuration and the magnet structure are shown in figure 1.

3. Ion Beam Extraction and Analysis

The transmission line is designed to transport 15 emA intense highly charged heavy ion beams with high transmission efficiency and high resolution. Figure 1 illustrates the mechanical layout of the SECRAL source and the beam transport line, which consists of an accel-decel extraction system, a solenoid lens and a 110° analyzing magnet. To reach high transmission efficiency and high resolution, a 110° analyzing magnet with a 120 mm gap and 600 mm bending radius was designed and constructed. Considering larger beam emittance and the beam envelope due to strong space charge, the beam transport line was designed to be as short as possible and the solenoid lens was directly attached on the source body flange at the extraction side so as to focus the beam immediately after extraction.

In order to measure the analyzed beam current accurately, a Faraday cup was designed, particularly to prevent secondary electrons from coming out of the cup. Furthermore, the cup is well shielded and good water-cooling was considered. A suppressor electrode negatively biased to 150-200 V is used to suppress the secondary electrons. A group of horizontal and vertical slits are located at the focus point of the analyzing magnet to help increase the ion beams analyzing resolution. The Faraday cup is located just behind these slits.

Preliminary tests and measurements have demonstrated that the transport line is working well and that it reaches the design goals. During SECRAL commissioning for $^{16}$O$^{6+}$ beam production with the total drain current 10 emA at an extraction voltage of 20 kV, the measured $^{16}$O$^{6+}$ current is about 1.5emA. The later analysis reveals that a transmission efficiency of more than 85% was obtained.

4. SECRAL Magnet test and Measurement

The first test of the magnet in a test cryostat was done in March 2004. Acceptance tests of the magnet at ACCEL were conducted in April 2005. The whole magnet reached 100% of the designed field at ACCEL after 13 quenches. After reassembling, installation, and cooling down in Lanzhou, the whole magnet reached 100% of the designed fields after 5 quenches. The measured typical axial magnetic field parameters at 100% design currents (i.e. $I_{\text{ext}}=138$ A, $I_{\text{inj}}=193$ A, $I_{\text{mid}}=25$ A, and $I_{\text{ext}}=164$ A) on the symmetric axis are $B_{\text{inj}}=3.7$ T, $B_{\text{mid}}=0.82$ T and $B_{\text{ext}}=2.2$ T. Furthermore, at 100% excitation of magnet, the sextupole field at the Ø126 mm plasma chamber wall is more than 2.0 T. The liquid helium consumption rate was measured to be less than 1.0 l/h when the coils are excited. The long-term stability test of the magnet at 95% of the design currents demonstrates that the magnet system is reliable and stable.
5. Commissioning Results of SECRAL at 18GHz

After the final acceptance test of the SECRAL superconducting magnet in Lanzhou, the conventional components of SECRAL ion source were assembled. Unfortunately, the first fabrication of the aluminum plasma chamber failed and a stainless steel chamber of the same dimensions was installed instead. This chamber might depress the performances of SECRAL, especially the performances of very high charge state ions. The first plasma at 18 GHz was ignited on 4th of August 2005 after several days of source conditioning [11].

5.1 Gaseous ion beam performances.

After a long-term conditioning of the SECRAL source, the magnet system was optimized for production of intense high charge state ion beams. Oxygen beams were tested first. With 2.2 kW rf power injection, 2.3 emA O\(^{6+}\) and 810 e\(\mu\)A O\(^{7+}\) were easily obtained during the preliminary test. During the test of xenon beam production, with 3.1 kW rf power injection, 306 e\(\mu\)A Xe\(^{27+}\) beam was obtained, and the corresponding ion beam spectrum was illustrated in figure 2.

![Figure 1. Schematic layout of SECRAL and the ion beam analyzing system.](image)

![Figure 2. Xenon ion beam spectrum optimizing for Xe\(^{27+}\) production.](image)

**Table 1.** Preliminary performances of SECRAL at 18 GHz in comparison with the published results of other high performance ECR ion source, VENUS [2], SERSE[4], GTS [12] and LECR3[13]. (e\(\mu\)A)

| \(f\) (GHz) | SECRAL | VENUS 28 or 28+18 | SERSE 28 | GTS 18 | LECR3 14 |
|-----------|--------|----------------|--------|-------|---------|
| \(^{16}\)O | 6\(^+\) | 2300 | 2000 | 1950 | 780 |
|          | 7\(^+\) | 810 | 600 | 235 | |
| \(^{40}\)Ar | 11\(^+\) | 810 | | 510 | 240 |
|          | 14\(^+\) | 270 | | 174 | 30 |
|          | 16\(^+\) | 73 | | 50 | 10 |
|          | 17\(^+\) | 8.5 | | 4.2 | 0.4 |
| \(^{129}\)(136)Xe | 20\(^+\) | 505 | 320 | 390 | 310 |
|          | 27\(^+\) | 306 | 270 | 110 | 168 |
|          | 30\(^+\) | 101 | 116 | 60 (100\(^+\)) | 60 | 6 |
|          | 34\(^+\) | 21 | 15 | | 8 |

* Results obtained in afterglow mode.

The typical gaseous performances of SECRAL are listed in Table 1. However, since SECRAL has a large plasma chamber volume of about 5 l, the maximum microwave power density available for SECRAL is only 0.64 kW/l at our present power limit of 3.2 kW. At this power density, SECRAL cannot reach its performance peak at 18 GHz. In comparison, the power density used in the AECR-U at peak performance is 1.7 kW/l in double frequency mode and about 1 kW/l in single frequency mode
So, there is still much margin to increase the performances of SECRAL at high 18 GHz rf power. In addition, the plasma chamber used now is a stainless steel one. An aluminium plasma chamber is meant to be installed on SECRAL in the near future and the performance, especially for the high charge state ion beams such as $\text{Ar}^{16+}$-$^{18+}$, $\text{Xe}^{30+}$-$^{40+}$, will be greatly enhanced due to very active effect of $\text{Al}_2\text{O}_3$ on ECR plasmas.

5.2 Metallic ion beam performances.

Intense and stable high charge state metallic ion beam production is another goal for SECRAL. To fulfil the project goal, within 10 days we tested production of calcium, nickel and lead ion beams with a high temperature micro-oven developed for the SECRAL source. During the test, one microwave guide insertion tube was used to install the micro-oven, and then only one r.f. power guide was left to feed at maximum 1.6 kW of power. However, very promising results for instance $287 \mu\text{A} \text{Ca}^{11+}$, $258 \mu\text{A} \text{Ca}^{12+}$, $75 \mu\text{A} \text{Ca}^{16+}$, $18 \mu\text{A} \text{Ca}^{18+}$, $2.25 \mu\text{A} \text{Ca}^{19+}$, $173 \mu\text{A} \text{Pb}^{27+}$, $143 \mu\text{A} \text{Pb}^{28+}$ and $90 \mu\text{A} \text{Pb}^{30+}$ were obtained. Since metallic ion beams are very hard to produce, the 10-day tuning could only give some preliminary performance indicators.

6. Summary

A next-generation fully superconducting ECR ion source, SECRAL, has been successfully developed in IMP/Lanzhou. According to the one-year preliminary test of the source at 18 GHz, very promising intense high charge state ion beams such as $2.2 \text{emA} \text{O}^{6+}$, $0.81 \text{emA} \text{O}^{7+}$, $1.1 \text{emA} \text{Ar}^{9+}$, $0.81 \text{emA} \text{Ar}^{11+}$, $270 \mu\text{A} \text{Ar}^{14+}$, $0.5 \text{emA} \text{Xe}^{20+}$, $31 \mu\text{A} \text{Xe}^{33+}$ and $2.4 \mu\text{A} \text{Xe}^{38+}$ have been extracted easily. The SECRAL source will be moved to the IMP cyclotron basement to be connected with HIRFL accelerators. The source is meant to produce intense high charge state ion beams for HIRFL accelerators by the end of 2006. Some modifications and experiments are going to be done at SECRAL to further enhance its performance. Commissioning of the source at 28 GHz has been taken into consideration, which will enhance the source performance to a much higher level according to the famous empirical frequency scaling laws [15].

Acknowledgement

The work was supported by Knowledge Innovation Program of Chinese Academy of Sciences under contract No. KJCX1-09 and National Natural Science Foundation of China for Young Scientists though the contract No. 10305016. Great thanks to ACCEL Instruments Inc., Germany for the fabrication of the nice superconducting magnet of SECRAL.

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