STATUS REPORT OF SECRAL II ION SOURCE DEVELOPMENT *

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Abstract

For a new injector linac project launched at IMP, a superconducting ECR ion source SECRAL II is now under construction. This ion source is a duplicated one of SECRAL I which is operated routinely for HIRFL facility at the frequency of 18-24 GHz. SECRAL II is designed to be operated at the frequency of 28 GHz, which needs slightly higher radial field at the plasma chamber wall. The fabrication of the cold mass was started at early 2013, and it has been completed in May 2014. The engineering design of the whole superconducting magnet has also been finished and ready for fabrication. After a brief introduction of the recent results obtained with SECRAL I ion source, this paper will present the cold mass test results and the cryogenic system design of SECRAL II magnet. The test bench design will be also discussed.

INTRODUCTION

As an indispensable machine to provide intense highly charged ion beams, ECR ion sources have been used as the ion beam injectors at IMP for over 20 years. At IMP, the national laboratory accelerator facility is HIRFL (Heavy Ion Research Facility in Lanzhou) as shown in Fig. 1, which is mainly composed of one K69 cyclotron SFC, one K450 cyclotron SSC, RIBLL1 for radioactive beam production, cooler storage rings CSRm and CSRe, and the radioactive beam line RIBLL2 to connect the two rings [1, 2]. The HIRFL facility can work with several schemes for experimental researches. The 50 years old K69 cyclotron can work standalone for nuclear, atomic physics and material research purposes with the beam species from H to U. When the K69 and K450 cyclotron work with a coupling scheme, the HIRFL facility can deliver tens of MeV/u CW heavy ion beams. For the operation of HIRFL-CSR, two injection schemes are now available: one is the direct injection of high Q/M heavy ion beam from SFC with the energy of several MeV/u, and the other one is the injection of the beam delivered by SFC + SSC working with a coupling mode. When utilizing the standalone injection scheme with SFC, it is very hard to deliver sufficiently high current with the necessary beam energy, especially in terms of high Z ion beams. By utilizing the coupling scheme of SFC + SSC to do beam injection for CSRm, beam energy is guaranteed, but as a cause of very low coupling efficiency between the cyclotrons, the output beam intensity is far below the injection needs of CSRm, especially for the very heavy ion beams such as Bi, U, and etc. The HIRFL-CSRm is designed to be able to accumulate and accelerate very heavy ion beam such as U with the beam intensity of several 10^9 ppp, which is about 2 orders higher than the present performance. The barrier is the non-optimal injection scheme. A project proposal has been recently issued to build a dedicated injection linac injector for CSRm so as to boost the performance by ~2 orders for heavy ion beams. For this injector linac (called CSR-Linac), a high performance state of the art ECR ion source is needed to provide the needed intense high Q/M heavy ion beams. SECRAL II project is therefore initiated.

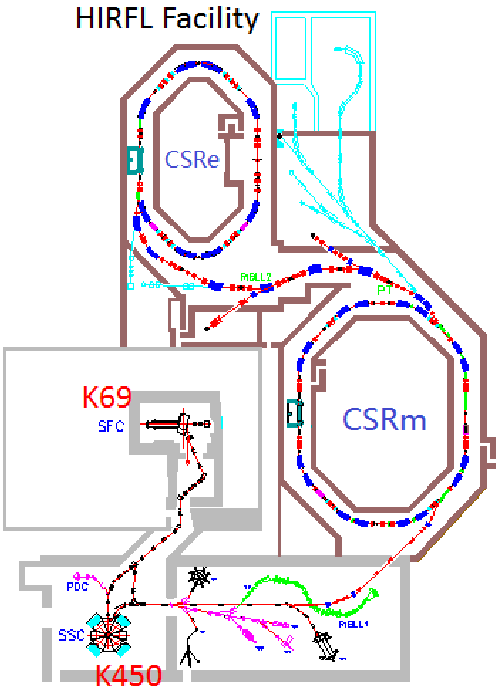

Figure 1: Layout of HIRFL facility.

SECRAL I was connected to the injection line of HIRFL complex in 2007 and had been in service for more than 17,000 hours for routine operation. It has been the main working horse for the facility, especially in terms of very heavy ion beams operation. In case of any severe problem with the ion source, HIRFL facility would lose most of its performance and capacity. As a contingency plan, SECRAL II project was proposed. Combined with the CSR-Linac project, SECRAL II project serves a dual purpose.

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INTENSE BISMUTH BEAM PRODUCTION WITH SECRAL I

SECRAL I ion source was successfully built and tested at IMP in 2005, and promising performance was obtained in the following years at either 18 GHz or 24 GHz [3, 4]. The research work with such a high performance tool to study advanced ECR ion source has never been stopped, and the highest priority in the research activity list is to explore the ultimate capacity of such a machine in production of highly charged heavy ion beams, especially of those heavier than Xe, such as Bi and U. For the production of uranium ion beams, the oven technique is very challengeable. While for bismuth ion beam production, the oven solution is more straightforward.

Oven Design

3 types of micro-ovens have been designed and tested at IMP, i.e. resistor oven with the highest operating temperature of 1600ºC but moderate material loading capacity, low temperature oven with the highest operating temperature of 650ºC and much larger material loading capacity, and high temperature oven that could reach the temperature of 2000ºC mainly designed for refractory material ion beam production. For the production of intense Bi ion beams, low temperature oven is adopted. The low temperature oven is a design incorporated with a commercial Watt-Flex Cartridge Heater and a large capacity crucible for long term uninterrupted routine operation of intense low melting point metallic ion beams, such as bismuth, calcium, lead beams, and etc. The design concept of this oven was borrowed from LBNL cartridge oven. In 2013, with the help of this oven, 422 eμA Bi^{30+} and 396 eμA Bi^{31+} had been obtained with SECRAL I at 24 GHz [5]. During the test, the oven was found still not powerful enough to yield sufficient Bi vapour for more intense beam production. Several modifications has been made to improve the oven capacity. The cartridge heater power is raised from 150 W to 180 W. Mo replaced the oven furnace material instead of copper, so as to make the oven be more durable under high temperature operation conditions.

Intense Bi Beam Production

In 2013, with a 3.5 kW 24 GHz microwave power heating of the plasma, 422 eμA Bi^{30+} and 396 eμA Bi^{31+} had been obtained on the faraday cup. Since the 24 GHz gyrotron amplifier has the maximum output capacity of 7 kW, there is still big improvement margin of SECRA I to produce more intense Bi ion beams. The major improvement in the 2014 test is the incorporation of a modified cartridge oven with higher power and Mo furnace design, while the loading capacity is conserved. At the highest working temperature of 650 ℃, a nominal vapour pressure of 10^{-2} Torr can be achieved. Actually, heated by the strong plasma radiation, the oven temperature could be higher than the off-line measured values.

During the test of high intensity Bi beam production, 24 GHz microwave is the main power source to heat the plasma, and 18 GHz microwave power is an auxiliary tool to enhance the performance. With 4.74 kW@24 GHz + 1.4 kW@18 GHz, 710 eμA Bi^{30+} and 680 eμA Bi^{31+} have been obtained at the faraday cup. Fig. 2 gives the spectrum when 710 eμA Bi^{30+} produced. The source output of high intensity Bi ion beams is increasing linearly with the microwave power level and oven temperature. Even at the level of 710 eμA Bi^{30+}, there was no indication of beam intensity saturation. The present results seem to be still limited by oven output of Bi vapour and ion source conditioning at high power. A later analysis of the material consumption rate according to the source operation log shows that an average value of 10.91 mg/hr@400 eμA Bi^{31+} and 8.18 mg/hr@300 eμA Bi^{31+} could be expected, which is very close to the value obtained in the 2013 test.

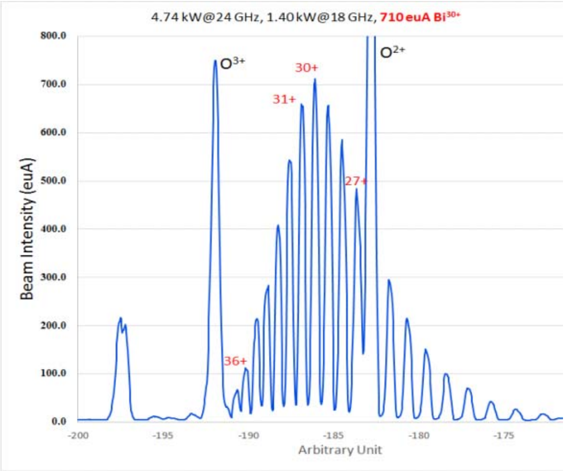

Figure 2: Spectrum optimized for 710 eμA Bi^{30+}.

As the plasma condition was well conditioned for the production of bismuth ion beams, highly charged Bi beams were also tested with lower oven power settings. Different from the production of high intensity Bi ion beams, highly charged ion beams need better plasma stability and less plasma contaminations. At the 24 GHz power level of ~4.0 kW, 100 eμA Bi^{41+} and 10.7 eμA Bi^{50+} have been produced. ~0.05 eμA Bi^{57+} can also be well distinguished from the beam spectrum. Fig. 3 is the spectrum when Bi^{41+} production is optimized.

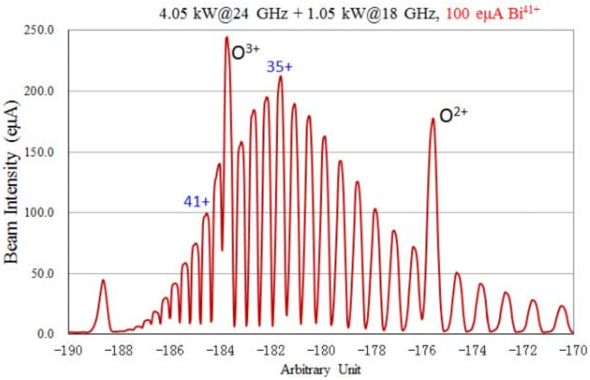

Figure 3: Spectrum obtained when 100 eμA Bi^{41+} produced.

Beam Emittance

In general, two issues are essential for ion beams injected to an accelerator, i.e. beam intensity and beam brightness. High power accelerators need very intense ion beams, while optimal brightness can guarantee the transmission of ion beam with less losses. With the increase of ion beam extracted from an ECR ion source, beam quality will deteriorate as a cause of more severe space charge effect. It is worth checking the beam emittance evolution with the increase of beam intensity. With SECRAL I source, the beam emittance was measured with Alison type scanners. Fig. 4 shows the horizontal and vertical normalized rms emittances measured for Bi^{31+} intensity from 100 eμA to 600 eμA. Error bars are not given here, which should be in the range of ±10% [6]. According to the study, the emittances do not deteriorate dramatically with the beam intensity increase. For high charge state ion beams, provided with the same beam optics, two dominant factors have big impact on beam emittances from an ECR ion source, i.e. plasma conditions and extracted beam intensity. Beam emittances could be optimized through plasma condition manipulation.

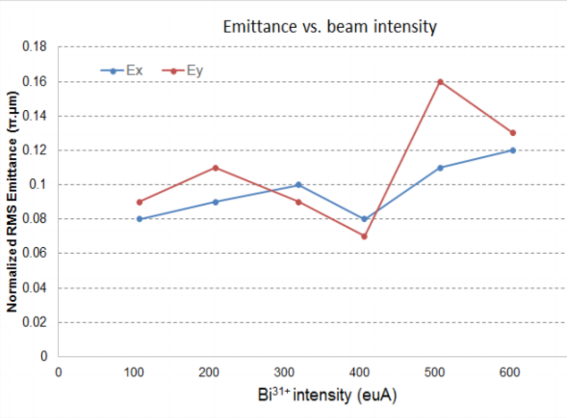

Figure 4: Bi^{31+} beam emittance variation with the increase of beam intensity.

SECRAL II MAGNET

SECRAL I ion source has the unique feature of a reversed configuration magnet structure over traditional ECR ion sources. This makes the source magnet body very compact, typically in the magnet length. The success of SECRAL I reveals that The ECR plasma is not affected by the magnet configuration as long as the magnetic confinement is sufficient. SECRAL II ion source will also adopt the unique magnet configuration already demonstrated. SECRAL II magnet is a close copy of the fully superconducting ECR ion source SECRAL I. The main difference is in the cryogenic system design.

SECRAL II is designed to be operated at 28 GHz. Table 1 summarizes the typical parameters. To have sufficiently high radial field at the plasma chamber wall, and also have the 1.5 mm thickness Ta shielding tube incorporated, the warm bore size is slightly increased by optimizing the vacuum and 70 K shield gaps.

Table 1: Main design parameters of SECRAL II

ω_{ecr}	28 GHz
B_{inj}	3.7 T
B_{ext}	2.2 T
Mirror Length	420 mm
Radial field at inner chamber wall	2.0 T
Warmbore ID	Ø142 mm
Coldmass length	810 mm
Plasma volume	> 5 L

Cold Mass Fabrication

Cold mass is the critical part of the magnet, and it is also the most technically challengeable part of the project. SECRAL II magnet cold mass is mainly composed of three axial solenoids wound on a stainless steel bobbin, six sextupole coils rested on the axial coils bound with 0.3 mm×3.3 mm stainless steel strip, cold iron blocks to boost the radial field and also to minimize the stray field, two iron flanges to connect and fix the position of the sextupole coils and axial coils, and the outer most aluminium rings to clamp the sextupole coils. Fig. 5 gives the Solidworks sketch of the cold mass. Both the sexupole coils and axial solenoids are using the same type of NbTi wire from WST (Western Superconducting Technologies Co., Ltd). The typical features of the adopted wire are given in Table 2. The guaranteed superconducting performance is 668.7 A@7 T (4.2 K). Calculation with TOSCA 3D shows that the highest superimposed field on the superconductor is situated on the sextupole coils of 7.8 T@191.0 A which corresponds to the loading factor of ~86%. The highest field on the injection solenoid is 7.3 T@308.7 A which also corresponds to a loading factor of ~86%.

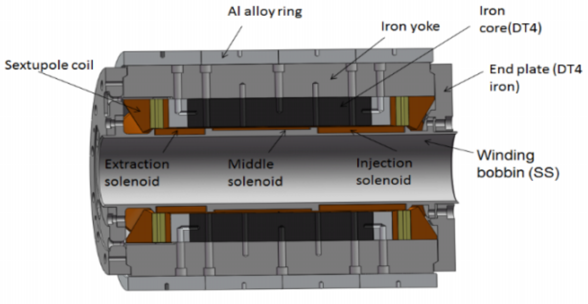

Figure 5: Sketch plot of SECRAL II cold mass.

Table 2: typical features of the rectangular wire from WST used for SECRAL II fabrication

Item	Specs.
Type	Monolith
Insulation	Formvar
Bare size (mm^2)	1.20 × 0.75
Insulated size (mm^2)	1.28× 0.83
Cu/Sc ratio	1.3:1
RRR	>100
No. of Filaments	630
Filament size (μm)	27.6
Pitch size (mm)	15

All the coils are wound through wet winding with Stycast 2850FT black epoxy. After the solenoids were finished, stainless steel strip is used to do the coil binding. Fiberglass cloth is adopted for insulation purpose. Sextupole coil winding is more complicated and difficult because of the special cross-section configuration and the racetrack layout. Each coil was wound around a 5-piece core, the central portion being an iron pole to enhance the radial field, two aluminium ends to compensate for thermal contraction and two G10 fillers to avoid the localized highest field region. The picture of one of the sextupole coils is given in Fig. 6. After curing, the sextupole coils were also formed to have even external shape for assembly by vacuum impregnation. The finished sextupole coils were bolted to cold iron segments separately, and thus 6 completed sextupole blocks were ready for assembly. The sextupole blocks were positioned around the solenoid bobbin through two end iron plates to fix the position and do pre-clamping. One of the very obvious virtues of SECRAL type configuration is that the Lorentz forces at the sextupole coils ends are all pointing outwards radially instead of being inwards and outwards periodically with traditional configuration magnet, therefore no radial support of the sextupole coil ends were needed provided that the coils are robust enough after curing. Very efficient pre-clamping of the sextupole coils were made by tight fitting installation of the aluminium rings. The negative tolerance designed aluminium rings were installed externally to the cold iron cylinder through hot shrinkage fit at about 150℃. Fig. 7 is the picture of the completed cold mass at the assembly site.

Figure 6: Picture of one of the sextupole coils.

Figure 7: Completed cold mass at the assembly site.

Cold Mass Test

The solenoids were tested in test Dewar separately when they were ready in 2013. Limited by the current power supply, all the three solenoids were only energized to 115% of the design currents without any quenches. 18 months after the fabrication contact being signed, the cold mass was ready for test Dewar training. The magnet system was supported vertically from the top of the magnet test Dewar. A set of quench protection system was installed, which is identical to the final one to be utilized in the real Dewar. The voltage on each coils were monitored to diagnose the quench triggering. Cold mass temperature and LHe depth were also monitored during the training. Since the stored energy of SECRAL is about 0.7 MJ at the designed currents, most of the LHe filled in the test Dewar (~220 liters) were evaporated when a quench happed at ~90% of the designed currents.

Energized separately, the sextupole coils reached 85% of the designed currents with 6 quenches. Then they were energized together with the axial coils. During the whole system training, all the elements were energized evenly together, which was realized by matching the ramping rate of each superconducting coil controllers and going in steps. 8 quenches were detected before the cold mass trained to 90% of the designed currents. It seems that more quenches are predicted if the magnet needs to be further trained to the designed values.

Cryogenics

The cold mass will be housed in a Ø817 mm ID 821 mm long LHe tank. Cold mass, LHe and the helium tank all together weighs about 1.54 tons, which will be supported by 8 support rods. To minimize the heat load to 4.2 K region, G10 material is utilized. 6 auxiliary SUS304 rods are also considered in the design to have redundant supports to ensure transportation safety. External to the 4.2 K reservoir, generally two thermal installation stages are designed. The first one is the 60 K copper shield, and the second one is the vacuum buffer between 60 K and room temperature. MLI solution is also considered in the design. The MLI are used between LHe tank and the 60 K shield, and inside the vacuum vessel. A typical layer density of 25 layers/cm is adopted. Evaporated helium gas will be recondensed to LHe by 5 condensers bolted to the 2nd stages of five 1.5 W GM coolers individually. To realize quick maintenance of the GM coolers without warming up the whole system, cryocooler sleeves are introduced in the design with the sacrifice of about 0.13 W extra heat load induced by each of the sleeves. 5 HTS leads are used to minimize the ohmic and conduction heat load between 60 K and 4.2 K stages. 5 Sumitomo RDK-415 D coolers can provide about 200 W cooling capacity at 60 K that is sufficient for the 60 K thermal shield cooling. The estimated total static heat load to 4.2 K is about 1.86 W, which allows a maximum dynamic heat load of 5.64 W. According to the operation experience with VENUS [7] and SECRAL I [3], this will be equivalent to the bremsstrahlung radiation heat load to 4.2

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K induced by ~3.5 kW 28 GHz microwave heated ECR plasma. But in actual operation condition and for technical reasons, the practical dynamic heat load capacity will be much lower than the nominal value 5.64 W. Fig. 8 is the sectional plot of SECRAL II magnet with most of the subsystems integrated.

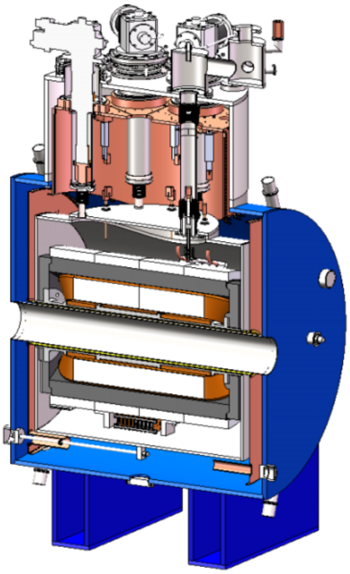

Figure 8: Side view of the magnet sectional plot.

SECRAL II TEST BENCH DESIGN

SECRAL II plasma will be heated by the microwave power from a CPI 10 kW/28 GHz gyrotron amplifier. The plasma chamber will be floated to 25 kV high voltage so as to have efficient beam extraction. A triode extraction system will be adopted to have flexibility on beam extraction optics optimization and suppression of secondary electrons entering the acceleration region. Ion source vacuum is pumped by oil free pumps. A 700 L/s turbo pump is to be installed at source injection tank and a 2000 L/s pump is going to be mounted on the source extraction box. Extracted beam will be focused by a solenoid with aberration correction design. Extracted ion beams will be analysed by a 180 mm gap, 510 mm bending radius, 90 ° double focusing bending magnet. Knowledge from beam line design of VENUS [8] and experimental results from SECRAL [9] indicates that large vertical gap can maximize the beam transmission efficiency through the M/Q analyzer and minimize the high order aberration pickup at the meantime. A set of triplet quadrupole magnets are designed to be mounted after the bending magnet so as to have optimal tuning of the analysed beam twiss parameters and also to improve the beam optical resolution. One 10 cm long solenoid is designed to be installed between the beam slits and the faraday cup or emittance scanner to do beam coupling de-correction compensation, so as to improve the beam quality. The layout of beam line design is given in Fig. 9.

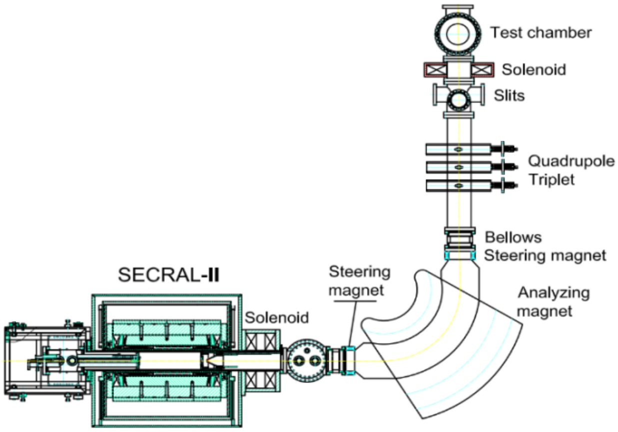

Figure 9: Layout of the SECRAL II test bench.

CONCLUSION

By technical improvement of the cartridge oven technique at IMP, SECRAL I ion source have almost doubled its production performance of intense highly charged bismuth ion beams i.e. 710 eμA Bi^{30+} and 680 eμA Bi^{31+}. Thanks to the fine plasma confinement and efficient ECR heating at 24 GHz + 18 GHz, intense ion beams of very high charge state were also obtained, such as 100 eμA Bi^{41+} and 0.05μA Bi^{57+}. Based on the same conceptual design, a close copy of SECRAL I ion source, SECRAL II is now under construction at IMP. The cold mass was tested in June 2014. The magnet had been successfully trained to 90% of its design currents in the test Dewar. Provided more quenches, the excited currents could be much closer to the designed ones.

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