SECRAL II ION SOURCE DEVELOPMENT AND THE FIRST COMMISSIONING AT 28 GHz*

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Abstract

SECRAL II ion source has been successfully designed and developed at IMP. This ion source is a 3^{rd} generation ECR machine optimized for the operation at 28 GHz. As a second superconducting ECR ion source developed at IMP with the identical cold mass design as SECRAL ion source, which has the sextupole coils external to the axial solenoids, the magnet performance is more robust according the training test. After a short time beam test at 18 GHz, SECRAL II has been commissioned at 28 GHz, and some preliminary results have been achieved with high charge state ion beam production. This paper will present the magnet design and test results. The first beam at 28 GHz will also be given.

INTRODUCTION

ECR ion sources have been used in IMP as the heavy ion injectors for over 20 years. Absolutely, the incorporation of ECR ion source to the heavy ion accelerator complex has already improved the machines' performance. The existing facility 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], has 3 injector ion sources, i.e. all permanent magnet ion source LAPECR1 for intense light ion beam beams, room temperature ion source LECR3 for intense medium charge state heavy ion beams (A⩽40), and SECRAL the superconducting ion source for intense highly charged heavy ion beams (A⩾40). SECRAL is now the main working horse of heavy ion beam for HIRFL, therefore in case of any big failure with the ion source, especially the superconducting magnet that has been in operation for over 11 years, the facility would be impossible to run heavy ion beams heavier than Ar, and the performance of the facility will be greatly affected. It has been highly recommend having a second high performance superconducting ECR ion source as the spare one. Additionally, as an upgrade program to boost the performance of the SSC cyclotron and also the storage ring, a project proposal has been issued to build a dedicated injection linac injector for SSC. The most interested ion beam for the design is several puA of U^{34+}, and the more preferred one is U^{37+}. Fundamentally, only with a 3^{rd} generation ECR ion source, the goal could be achieved. Therefore, for a dual-purpose strategy, SECRAL II project was initiated.

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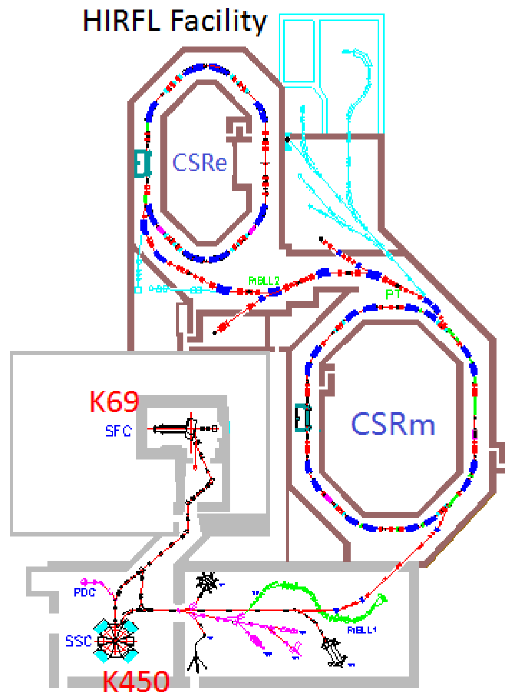

Figure 1: Layout of HIRFL facility.

SECRAL was connected to the injection line of HIRFL complex in 2007 and as of early 2016, more than 24,000 hours' beam time has been accomplished. It has been demonstrated as a very reliable and high performance ECR ion source. Especially, the recent progress with high intensity Ar and Xe beams, such as 1.42 emA Ar^{12+}, 1.1 emA Xe^{26+}, 0.67 emA Ca^{12+}, 0.68 emA Bi^{31+} and etc., has demonstrated its performance and capacity [3]. Logically, SECRAL II will be a duplicated one of SECRAL.

MAGNET DESIGN

The SECRAL II cold mass is almost a duplicated one of SECRAL. In that case, the axial fields inside the plasma chamber wouldn't be different from SECRAL. The radial field gradient would be the same as SECRAL. Therefore, the sextupole field at the same chamber wall would be the same. SECRAL was initially designed with 63 mm inner radius of plasma chamber, but after 1.5 mm thickness Ta shielding cylinder was integrated to do bremsstrahlung X-ray shielding to protect the main insu-

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lator column, the radius was lowered down to ~60 mm with a SS plasma chamber and 58 mm with a Al chamber. And as a result, the radial field on the plasma chamber wall is much lower than designed value of 2.0 T, however it is sufficient for 24 GHz optimization of highly charged ion beams production, but not enough for a 28 GHz plasma, which needs at least ~2.0 T on the inner chamber wall. For this reason, SECRAL II magnet has to find a way to get a higher radial field on the chamber wall. By decreasing the gap between the warm bore and the copper thermal shield, the warm bore size is enlarged to ϕ142 mm. With a ϕ125 mm ID plasma chamber, ~2.0 T field could be achieved. Since SECRAL was designed and built without He recondensation system, the operation efficiency has been greatly affected, especially at high power. Even after the upgrade with an external recondensation system, the continuous operation at high power of 24 GHz is not promising. Therefore, SECRAL II should be designed with integrated LHe recondensation cryogenic system so as to be able to tolerate large dynamic heat load under high microwave power heating conditions. The typical continuous operation of SECRAL II at 28 GHz would be 4-5 kW, and according to the experience with SECRAL [4] and VENUS [5], this will give an approximately 4~5 W heat load to the 4.2 K cold mass. It is quite comfortable to design the cryogenic system with a cooling capacity of over 5 W. For this goal, 5 GM 1.5 W@4.2 K coolers have been utilized in the design. The main design parameters are given in Table 1.

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
Dynamic cooling capacity	> 5 W

MAGNET FABRIATION AND TEST

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 wounded 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. Figure 2 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 coils is situated on the sextupole coils of 7.8 T@191.0 A which corresponds to the loading factor of ~87.5%. The highest field on the injection solenoid is 7.3 T@308.7 A which also corresponds to a loading factor of ~87.6%.

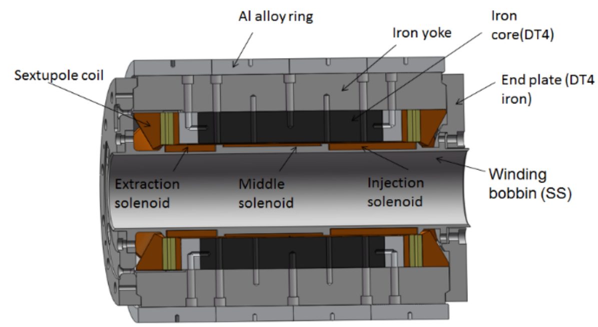

Figure 2: Sketch plot of SECRAL II cold mass.

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 wounded 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 designed to compensate for thermal contraction from room temperature to 4.2 K and two G10 fillers to avoid the localized highest field region. The picture of one of the sextupole coils is given in Fig. 3. 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

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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℃. Figure 4 is the picture of the completed cold mass at the assembly site.

Figure 3: Picture of one of the sextupole coils.

Figure 4: 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 is 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 thermal shield, and 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 2^{nd} stage of five 1.5 W GM coolers individually. To realize quick maintenance of the GM coolers without warming out the whole system, cryocooler sleeves are introduced in the design with the sacrifice of about 0.13 W extra heatload induced by the 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 at 4.2 K is about 1.86 W, which allows a maximum dynamic heat load of 5.64 W. Figure 5 is the sectional plot of SECRAL II magnet with most of the subsystems integrated.

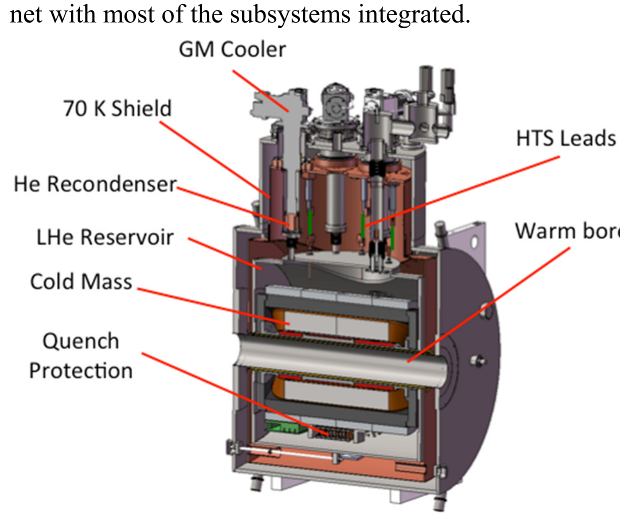

Figure 5: Side view of the magnet sectional plot.

Magnet Test

The magnet arrived at IMP in October 2015. User's site test had been completed in that December after about one month's preparation. The magnet was eventually ener-

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gized to ~100% design currents after 9 quenches, which announced the success of this magnet fabrication. A comparison between the SECRAL and SECRAL II magnets on user's site test results is given in Fig. 6. SECRAL II magnet indicates more robust coil clamping as it reaches 95% of the design currents via 3 quenches. But it has to overcome the preloading while releasing the stress caused by slight movement during ramping to higher currents, which might be a stepwise process if the preloading is high. The cryogenics system was tested during the system cooling down and static condition at 4.2 K. According to the test with embedded heaters at 4.2 K region, a dynamic heat load capacity of ~6.0 W is estimated.

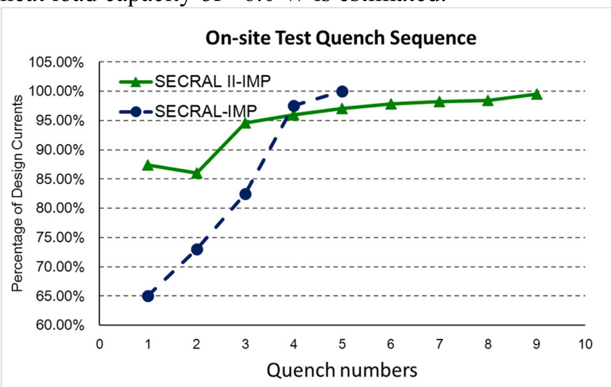

Figure 6: User's site training results of SECRAL and SECRAL II magnets.

SECRAL II TEST BENCH

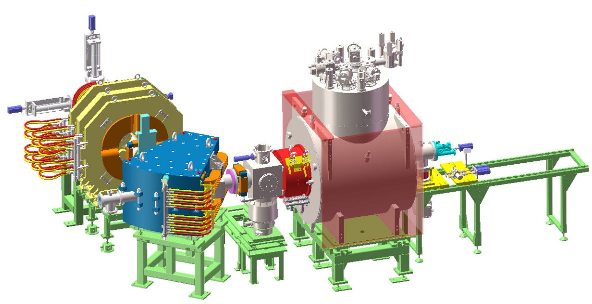

Figure 7: Layout of the SECRAL II test bench.

SECRAL II plasma will be heated by the microwave power from a CPI 10 kW/28 GHz gyrotron amplifier. The plasma chamber is floated to a 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 [6] and experimental results from SECRAL [7] 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 utilized after the bending magnet so as to have optimal tuning of the analysed beam twiss parameters and also to improve the beam optical resolution, especially for high intensity very heavy ion beams, such as Bi and U beams. The layout of the test bench is given in Fig. 7.

FIRST COMMISSIONING RESULTS

SECRAL has been mainly commissioned at 28 GHz with O and Xe plasma. The 1st plasma with beam extraction at 18 GHz has produced 1.75 emA O^{6+}. At 28 GHz, with even 1 kW, about 2.2 emA O^{6+} has been extracted, which is obviously a strong frequency effect against that of 18 GHz. The plasma responds linearly to microwave power input. At 4.5 kW, 5.4 emA O^{6+} has been obtained at the source potential of 25 kV. At 3.5 kW, a 1.57 emA O^{7+} beam has also been extracted. Intense beam production wouldn't be possible without dense plasma having been built. A 20 emA total drain is detected when 5.4 emA O^{6+} created. For Xe^{27+} production, 3.5 kW has been used to give a result of 510 eμA beam intensity. Given more microwave power, this intensity could be further increased according to the beam tuning. Thanks to the high beam acceptance provided by this larger gap dipole. When 8.0 emA drain current of O+He ions transmitting in the system, a 84% transmission efficiency was observed. For 7.0 emA Xe+O ion beams, a transmission efficiency of 86% was also achieved. Since sufficient M/Q separation has been made on the faraday cup, the slits are almost fully open to allow full transmission. The typical Xe spectrum is given Fig 8 when Xe^{27+} is optimized.

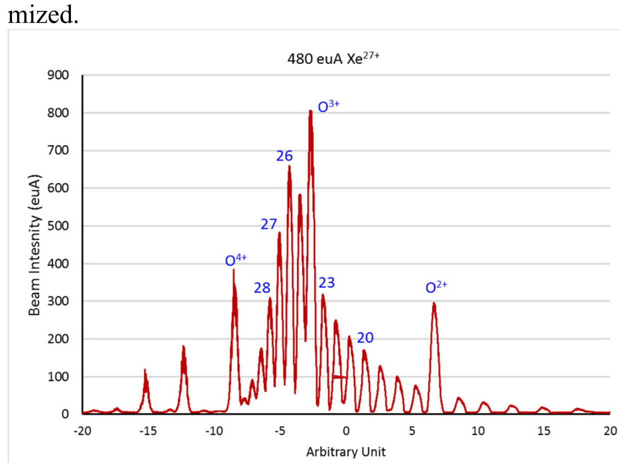

Figure 8: Typical spectrum optimized for 480 eμA Xe $^{27+}$ beam production.

During the commission at 28 GHz, the SS plasma chamber was burnt by the plasma twice at the locations of lowest |B| inside the plasma chamber wall (Fig. 9), i.e. one at the source extraction and the other one at the source injection (for the same plasma chamber). SECRAL had been tested at even much higher microwave power for several years without any burnt holes in the plasma chamber. And the field mapping of SECRAL II is quite consistent with the design value. Under those conditions,

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plasma chamber cooling was doubted. A later water flow rate test of the plasma chamber showed that the water channels of the damaged chamber are not functioning well as a possible cause of fabrication mistake. Just before this workshop, a newly fabricated plasma chamber has been installed.

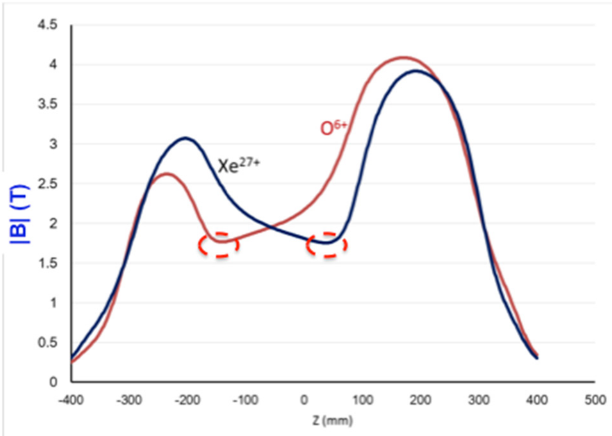

Figure 9: Two burnt holes' locations, one at the extraction side for O^{6+} plasma and one at the injection side for Xe^{27+} plasma.

CONCLUSION

SECRAL II ion source has been successfully developed after 3.5 years. The preliminary test of this ion source at 28 GHz has given quite promising results with 5.4 emA O^{6+}, 1.57 O^{7+} and 510 euA Xe^{27+}. But a malfunctioning plasma chamber gives trouble during high microwave power test with burnt holes. Here listed the key milestones of this project:

- 2013.01: Project contract
- 2014.07: Cold mass successfully tested
- 2015.08: Cryostat and magnet integration
- 2015.09: Factory test and acceptance
- 2016.01: 1st plasma at 18 GHz
- 2016.06: First oxygen plasma at 28 GHz and a plasma burnt hole at 5 kW

This project indicates that SECRAL structure is reliable and also reproducible with proper design and engineering.

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