COMMISSIONING RESULTS OF THE 18GHZ FULLY SUPERCONDUCTING ECR ION SOURCE SUSI

G. Machicoane, D. Cole and P. Zavodszky

National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI48824, USA

Abstract

The construction of SUSI the 3rd generation ECR ion source from NSCL/MSU has been completed. After an initial period marked by problems with its coil system, SUSI has now reached stable operation at 18GHz. Excellent performances have been obtained during the commissioning of the ion source for various elements including: ^{40}Ar, ^{129}Xe and ^{208}Bi. Some early results regarding beam transport are also discussed and in particular the choice of not using a focusing element between the ion source and the bending magnet.

INTRODUCTION

The coupled cyclotron at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) can accelerates heavy ion beams up to 200 Mev/u. This primary beam is then used to produce radioactive ion beams by fast fragmentation on a beryllium target. In order to respond to the experimental program in nuclear science, a wide range of primary beam has been developed since 2001 from ^{16}0 to ^{238}U. Beams are initially produced by an ECR ion source and then transported at low energy before injection in the K500. Final acceleration is made into the K1200 and in recent years large gain in beam intensity have been achieved for most beams. In particular more than a 1kW of primary beam power can now be extracted from the K1200 for ^{48}Ca and ^{40}Ar. These gains in beam intensity were not achieved by increasing the ion current extracted from the ECR ion sources but instead reflect a strong effort to improve the beam transport in particular from the ECR to the K500 [1]. However it is clear and in particular for heavier ion beams, that the gains that can be ultimately achieved through the coupled cyclotron largely rely on the choice of the ECR ion source used to inject the beam. SUSI the most recent ECR ion source from NSCL is a fully superconducting ECR source designed to operate primarily at 18GHz. Large gains in beam intensity are therefore expected compare to our 6.4 GHz SC-ECR or 14GHz ARTEMIS. In addition a flexible axial magnetic field described previously [2] provides the capability to modify the length and the position of the resonant zone and also to adjust the gradient of the axial magnetic field near the resonance. Finally, the injection baffle can be moved providing an additional knob that allow for example to adjust the volume of the plasma chamber. These innovative features in the SUSI design should help to not only maximize the intensity of the extracted ion beam current but more generally to optimize the brightness of the extracted ion beam.

MAGNET TESTS AND QUENCHES

However, to achieve an ion source with a flexible axial magnetic field requires the design and construction of a complicated coil system. The axial magnetic field of SUSI is defined using 6 solenoids. Two large solenoids at the injection with an outer diameter of 460mm, and four smaller ones with two at the extraction of the source plus an additional two more in the middle. These fours smaller solenoids have an outside diameter of 400 mm and the two solenoids in the middle are running with opposite polarity. All six solenoids have an inner diameter of 300 mm and a length of 80 mm. A field of 2.6T/1.5T can be reached at the injection/extraction side by powering either coil with 290A/210A. The hexapole coils are also superconducting and are 743 mm long. The ends of the sextupole are far from the central field of the solenoids, to minimize the interaction forces. Based on a similar design developed at LBNL for the construction of VENUS, these coils were wound around a three-piece core, which includes a central piece made of steel to enhance the field. The sextupole coils can provide 1.5T at the plasma chamber walls with 390A.

All coils were wounded at NSCL and then tested individually. During these tests, the solenoids were taken beyond 400A without training. On the other hand the sextupole coils experienced a few training quenches but eventually reached more than 700A each. These current values are well beyond the values needed for operation of the ion source at 18GHz and in fact would correspond to the current needed to operate the ECR ion source with a 28GHz microwave frequency transmitter. After the tests with the individual coils were completed, the assembly of the full coil system took place. The sextupole coils were assembled around the bore of the helium vessel tube, banded together and then inserted into the solenoid bobbin. Bladders installed between each sextupole and inflated with an Indium alloy were used to restraint the sextupole coils from moving radially. A very detailed and complete description of the design, construction and assembly of the coils can be found elsewhere [3]. Once the assembly was complete the coil system was cooled down in a large Dewar and tested. Because the number of current leads on the Dewar was limited, only four solenoids plus the sextupole could be energized at any given time. Additionally, the two large solenoids at the injection were serially connected and depending on the tests either the middle coils or the extraction coils were also connected in series. In this configuration the sextupole was first ramped up and underwent some training quenches. After 10 quenches, the sextupole could reach 567A and was then ramped down to zero without a quench. With no current going to the sextupole, the solenoids were then energized and quenched once at 365A before reaching 400A without any further problems. However it was found that it was not possible to reach a configuration with both the sextupole and the solenoids energized while ramping them sequentially. This situation always resulted in a quench and no improvement was observed over time. Measurements with an oscilloscope showed that the quench always occur first in the sextupole. This behavior did not improve by trying to train the sextupole to higher current or by decreasing the ramp rates of the power supplies used. Also improving the restrain on the leads did not help. Fortunately, a solution was found by ramping together both the solenoids and the sextupole. Although initially, this configuration also resulted in a few quenches, it was found that the coil assembly energized in this way could be trained and in a short time the solenoids reached close to 400A and additional training allowed the sextupole to reach 585A. These tests confirmed earlier findings made with the individual coils that the magnet system can be run with currents high enough to provide a magnetic field suitable for operation at 28GHz. Once done with these tests, the coil system was installed inside the SUSI cryostat. By the end of 2006, the assembly of the ion source was complete and after installation of the injection and extraction hardware the first plasma was ignited.

Unfortunately at that point, new unexplained quenches occurred. These quenches would not appear while ramping the field but instead some period of time after reaching the desired field. The length of time the magnetic field would stay up was found to be extremely random and was measured to be as little as a few minutes or as long as several days. In addition stronger magnetic field did not seem to quench sooner. Careful monitoring of different sources parameters (Power supplies voltage, current and also strain gauges for the support links), showed that the first sign of a quench is always a strong decrease in current in the hexapole then followed by the current in the solenoid at injection. Various tests were made to explain the situation but none provided a satisfactory explanation. At last, the situation improved dramatically in September 2007. Two changes are worth noting that might have caused this sudden change. First the polarity of the sextupole was reversed and also soon after, the forces applied to the support links were adjusted. In a configuration where the magnetic field on the injection side of the ion source is produced by the coil located at the far end, no quenches have occurred since these changes were made. Also, with the same configuration, a magnetic field corresponding to the operation of the ion source at 24 GHz was run continuously for 24 hour without a quench. Finally, the commissioning results shown below correspond to more than 250 hours of operation without any problems. It should be mentioned however that, although the solenoids at the extraction of the source and the ones in the middle have been adjusted over a wide range while tuning the ion source, changes in the magnetic field at the injection of the source by trying to move the peak inward still result in a quench.

COMMISSIONING RESULTS AT 18GHZ

SUSI was directly connected to the 90-degree analyzing magnet without a focusing element in between. An einzel lens was used right after the bending magnet to help reach a smaller beam waist at the analyzing faraday cup. The ion source high voltage was about 24kV. After initial conditioning of the ion source, the base pressure at the injection reached about 6.10^{-9} Torr and about $1.3.\ 10^{-8}$ Torr at the extraction. 2 kW of microwave power was available from an 18GHz klystron. Additional power was used from a 14 GHz transmitter but was not find to help improving the production of Highly charged ions beyond a few hundred watts. Following some uncertainty remaining with the stability of the coil system, no attempt was made to tune the field in the injection region of the ion source and a field of 2.5T was kept constant using the most outward coil. Also, the sextupole during these tests was kept around 370A therefore producing about 1.5T at the plasma chamber walls. However both the current in the middle and extraction coils were adjusted to optimize the intensity of the extracted beam current. Very good performances from SUSI have been obtained for various ions. For Argon, about 550 euA of Ar11+ was reached with more than 1.5kW of microwave power and an additional 300 W from the 14GHz transmitter. For lower charges more than a 1mA was obtained for Ar8+. However a limited time was spent optimizing the charge state distribution for higher charge state and only about 145 euA was obtained for Ar14+.

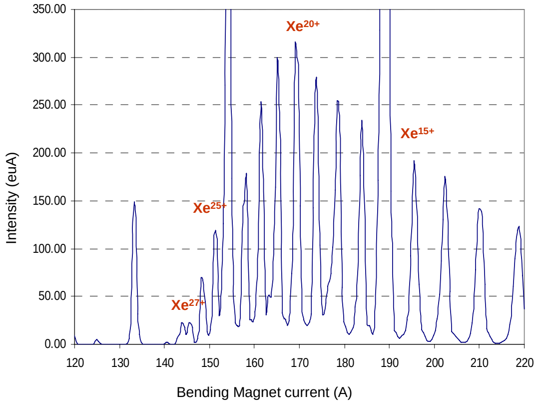

Figure 1: Xenon distribution optimized on Xe^{20+}

Figure 1 shows the distribution optimized for the production of Xe20+. About 335 euA was obtained for this charge state with 1.7kW microwave power. The same distribution but optimized for higher charge state is shown in figure 2 below. About 180 euA was obtained for

Xe27+, with essentially the same microwave power but with a lower Xenon pressure and more Oxygen.

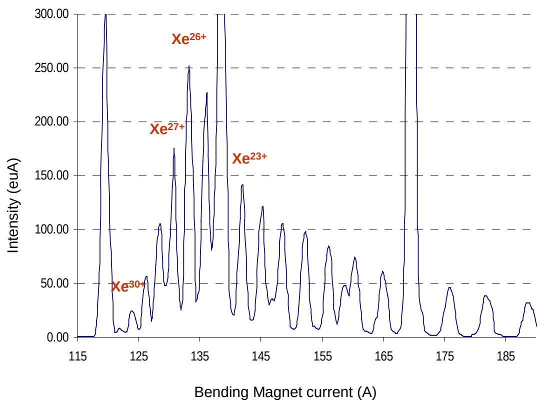

Figure 2: Xenon distribution optimized on Xe^{27+}

The microwave transmitter could not deliver more power reliably and it is expected that better performance could be reached if more microwave power at 18GHz is available. Some commissioning results have been obtained for Bismuth with a resistive oven, which can go up 1300 C. More than 150euA of Bi 28+ was obtained with 1.4kW of microwave power.

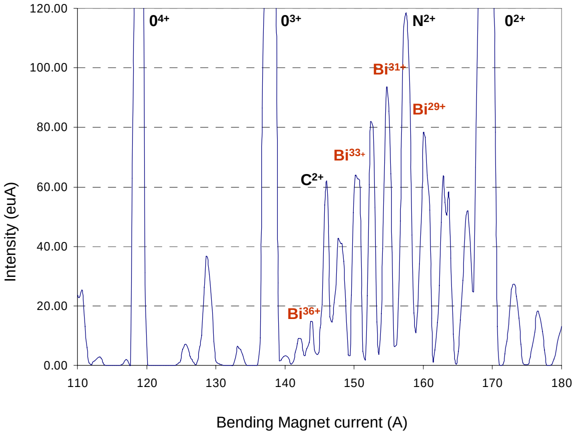

Figure3: 208 Bismuth distribution optimized for Bi^{33+}

Figure 3 shows the bismuth spectra optimized for high charge states. Up to 65 euA of Bi 33+ was produced and 15euA of Bi 36+. This time the microwave power was increased to the maximum available from the transmitter (1.7-1.8kW). It is interesting to note that these results were obtained before complete conditioning of the resistive oven and some significant amount of carbon are still present. It is expected that better results could be obtained if more time is devoted to the production of bismuth. In the present case the ion source was only run for a few days.

BEAM TRANSPORT

Some preliminary studies were made with the beam extracted from SUSI. The beam extraction consists of a plasma electrode (12mm in diameter) followed by an accel-decel system. The gap at extraction can be changed remotely over a range of 5 cm. The bending magnet provides double focusing with pole faces presenting an angle of 27.3 degree. This bending magnet has a large 18 cm gap and actively correct for higher order aberrations. The design was essentially based on the bending magnet developed for the VENUS ion source at LBNL. An initial test was conducted to check the linearity of the bending magnet. First a pencil beam was defined using a very small aperture. Then the beam was deflected horizontally and vertically using a magnetic steerer located 90 cm before the bending magnet and then finally the beam centroid position was recorded on a beam viewer located about 50cm after the magnet for each steerer settings. Provided that the deflection of the steering magnet has been calibrated (in this case 12mrad/A) the position of the beam at the entrance of the bending magnet can be known. The results indicated a central region of the bending magnet extending over 7cm in both directions, which provided an excellent linear response on the beam viewer.

An interesting feature of SUSI is the possibility to bias negatively the beamline between the ion source and the bending magnet to try to take advantage of a higher longitudinal energy when transporting the multi-component beam before charge selection. After a few weeks of conditioning, the beam line could effectively be biased to –20kV while maintaining +24 kV on the ion source reliably. Past experience at NSCL has shown that using a solenoid to provide the initial focusing of a beam extracted from an ECR ion source can lead to significant emittance degradation [4]. To mitigate space charge problem with the beam before charge selection it was decided to try to have the bending magnet right after the ion source without any focusing element in between. Of course, in this situation, the test with the bending magnet described above is important because the beam size is expected to be large inside of it. In this configuration, the distance between the plasma electrode and the edge of the bending magnet pole faces is 90cm. An einzel lens was added right after the bending magnet to improve the beam waist at the faraday cup. This latter was located 75 cm after the bending magnet. Finally an Allison emittance scanner was installed 30 cm after the faraday cup. Two cases were investigated using a ^{40}Ar beam and some preliminary results are shown here: an extracted beam current of about a 1mA obtained with a low microwave power (100W) and a 4mA beam current obtained with higher power (800W) and higher gas pressure. The beam transmission in the first case was close to 85 % and would increase slightly when a -20kV bias was applied on the beamline. In the second case, the transmission would reach 68% with the beamline grounded and increase to 83% with -20kV applied to the beamline. Then the emittance of Ar^{8+} was measured for both cases. Figure 4 shows the phase space distribution for (xx') and (yy') in the case of the 1mA (Top) and 4mA (Bottom) argon beam. The distributions obtained with the 1 mA beam show only little aberrations and mostly in the vertical plane.

Although it is unlikely that the bending magnet produce sextupole aberrations, the test done with the steering magnet needs to be cross check with computer calculations. The other explanation is that these tails originated at the extraction of the source. The emittance measurements for the case with a higher total extracted beam current (Bottom), reflects stronger aberrations due, most likely, to space charge. No improvement was observed when the beam line was biased at –20kV for the 1mA case which would reinforce the idea that the bending magnet is not contributing to the observed tails. On the other hand, some improvement was observed for the case at higher current.

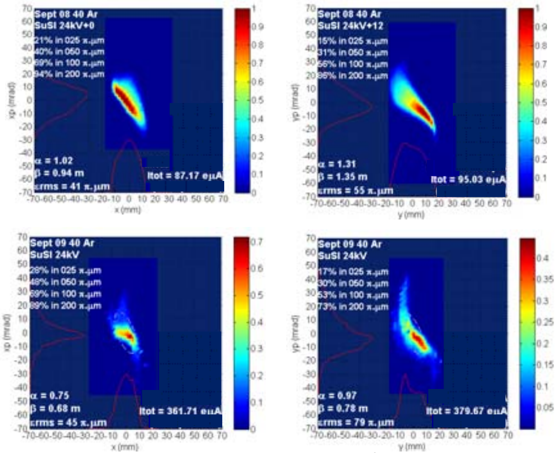

Figure 4: Emittance distribution for ^{40}Ar. Left to right are (xx') and (yy') respectively. Top pictures correspond to a 1mA beam extracted while the distributions at the bottom were obtained with a 4 mA beam current.

CONCLUSION

After a period marked with difficulties with its coil system, SUSI has now reached stable and reliable operation at 18GHz. A stronger magnetic field was also obtained for a short period of time that would make the ion source capable to operate at higher frequency (24GHz). Very good performances have already been obtained with SUSI for the production of high charge state ions of Xenon and Bismuth. Better performance could be obtained with more microwave power. More development will be done with metallic beams such as ^{40}Ca and using our inductively oven: ^{58}Ni, ^{76}Ge and ^{238}U. Also a systematic study needs to be made regarding the flexible axial field and will be reported soon. Finally, although, early results regarding the beam transport without a focusing element between the ion source and the bending magnet are encouraging, more work from both simulations and experiments is needed to validate this configuration. Plans are being made to move SUSI from the development Lab to the ECR area where it will be used for injection into the cyclotron next year.

REFERENCES

[1] M. Doleans "Optics Improvements of the K500 Axial Injection Line", 18th International Conference on Cyclotrons and their Applications, Giardini Naxos, Messina, Italy, September 30-October5, 2007

[2] P.A. Závodszky et al., Rev. Sci. Instr. 77, 03A334 (2006)

[3] P.A. Závodszky et al., Rev. Sci. Instr. **79** 02A302 (2008)

[4] G. Machicoane et al., "Experimental Evidences for Emittance Degradation by Space Charge Effects when using a focusing Solenoid below an ECR ion Source," Proceedings of ICIS2007, Jeju, South Korea, August 2007