INTENSE BEAM PRODUCTION WITH SUSI

L. T. Sun*, J. Brandon, D. Cole, M. Doleans, D. Morris, G. Machicoane, E. Pozdeyev, T. Ropponen, L. Tobos, National Superconducting Cyclotron Lab, MSU, East Lansing, MI 48824, USA

Abstract

SuSI ion source, a 3rd generation fully superconducting ECR ion source is now used for ion beam injection to the Coupled Cyclotron Facility since September 2009. Initial performances during the commissioning of SuSI (Superconducting Source for Ions) were mainly limited by the microwave power available from a single 18 GHz microwave amplifier, especially for the production of heavier ion beams. The Injection of SuSI was modified to add a second 18 GHz amplifier, to reach a maximum of 3.0 kW of RF power inside the plasma chamber. Production of heavy ion beams, such as Kr^{14+}, Bi^{30+} and U^{33+} is reported, to demonstrate the performance of SuSI. Additional studies were made with various ion source parameters to optimize the beam intensity within a normalized emittance of 0.9pi.mm.mrad as needed for the FRIB project and will be reported in this paper.

INTRODUCTION

As one of the latest developed fully superconducting electron cyclotron resonance ion sources (ECRIS) in the world, SuSI has been used for ion beam injection to the Couple Cyclotron Facility (CCF) since October 2009. Several ECRISs have been used for NSCL cyclotron operation, such as the 6.4 GHz SC-ECR [1] and the 14.5 GHz ARTEMIS [2]. The beam power available from CCF has steadily improved over the last few years due to an ongoing effort to improve both the performances of the ion source and the beam transport in the K500 injection line. But to further improve the performance of the coupled cyclotron facility (CCF), especially for heavy ion beams, a more powerful ion source that can produce more intense heavy ion beams with good beam quality is needed. In order to replace the aging 6.4 GHz ECR ion source, a new fully superconducting ECRIS SuSI was designed [3]. The source was completed and put into commissioning in early 2007 [4]. After some training of the superconducting coils, SuSI commissioning continued using an 18 GHz and a 14 GHz transmitter. Early results with gas and metallic beams showed that SuSI could produce high intensity of medium charge states of light to heavy ion beams [5]. In order to limit the beam transverse emittance propagating into the K500 injection line, a collimation scheme was developed and successfully tested. In the summer 2009, SuSI was successfully connected to the K500 cyclotron and put into operation since then. SuSI has now provided more than 1200 hours of operation to the CCF. Both gaseous and metallic ion beams have been produced, and good reliability and stability has been demonstrated. As a fully superconducting ECRIS with many flexibilities, SuSI has been used for basic ECRIS studies [6], beam developments and FRIB project R&D [7]. After a brief description of the new test setup of SuSI ion source, the latest results from SuSI will be presented.

SUSI ION SOURCE UPGRADES

Several components of SuSI have been upgraded. In particular a New18GHz klystron amplifier has replaced the 14.5GHz klystron amplifier. This configuration provides a maximum 18GHz microwave power of ~3.0 kW. Also, at the outer surface of the plasma chamber, a 2mm thickness tantalum tube has been added to shield the strong bremsstrahlung radiation to protect the high voltage insulator from degradation. The high voltage insulator is a PEEK material tube that has much higher radiation tolerance than the acrylic tube used previously.

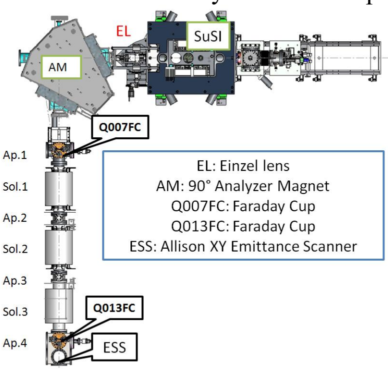

Figure 1: Layout plot of SuSI beam line.

Extracted beam is focused by an EINZEL lens with maximum operational voltage up to -30kV (negative voltage is proved with SuSI to give better ion beam transmission than that positive voltage can do, especially for intense beam transmission) and then analyzed by a 180mm gap 90° double focusing dipole magnet. Analyzed beam is detected by the faraday cup Q007FC with a 4-jaw slit in front of it. Past experience has showed that tuning the ion source for maximum intensity at this location may results in poor transmission through CCF. For example, large transverse emittance can lead to beam losses in the K500 cyclotron. Therefore, after the first analyzing faraday cup Q007FC, the SuSI beam line has been equipped with a setup to provide transverse collimation to the ion beam. The collimation is done by successive sets of apertures that cut the beam in transverse directions. A solenoid between every 2 apertures provides a possibility to do a rotation of the beam in phase space. Due to constraints in the space available, the collimation channel was designed to include four sets of slits and 3 solenoids. A drift space between each solenoid and each aperture is also included. The acceptance of the channel in the transverse direction is set by the size of the apertures. All the beam particles outside the acceptance of the collimation channel will be lost. 2 sets of steering

*sunl@nscl.msu.edu

magnets are placed in front of Q007FC to align the beam through the collimation channel. The collimated beam current is read on a second faraday cup Q013FC situated just after the collimation channel. A set of Allison type XY emittance scanners are also installed to analyze beam quality. Fig. 1 shows the layout of the SuSI beam line.

Intense beam production

The Beam transmission with SuSI to the first analyzing cup Q007FC was found to change significantly with the total extracted drain current, 75 % to 80 % transmission are typically achieved with 1 to 2emA beams while less than 65 % was observed with drain currents exceeding 4 to 5 emA. The flexibility of SuSI axial magnetic field allows the modification of the ECR zone location to achieve more intense medium or low charge state ion beam production. Two experimental configurations have been tested with SuSI to produce intense medium charge state ion beams like 0.5emA Kr^{14+} and 350 eμA Xe^{20+}:

- Keep the radial, injection and minimum magnetic fields fixed, and move the ECR zone to the extraction while the extraction field is lowered when the ECR zone is closer to the extraction side. The ECR length is unchanged during the test. This is similar to the tests on room temperature ECRISs by adjusting the plasma electrode position [8]. (Test 1)
- Keep the radial, injection, extraction and minimum fields constant, and only move the ECR zone to the extraction side. The ECR zone length is kept unchanged. (Test 2)

For the two tests presented, the experimental procedure consisted to adjust the magnetic field configuration by changing the position of the end point of the ECR resonance zone. The magnetic configuration used for reference has the end point at 362mm from the front face of the first injection solenoid and is labelled “Z=0mm” position. The other magnetic field configurations are normalized to it, for example “Z=50mm” means the ECR zone has been moved to the extraction by 50mm. Table 1 shows the results of Test 1. The total drain current and Kr^{14+} beam intensity kept decreasing when moving the ECR zone end point position from 51mm to 72 mm. A possible explanation is that the extraction field kept decreasing for the different positions during the test which has a big impact on the plasma confinement and causes plasma loss. In the second test, where the maximum at extraction was kept the same, a different behaviour was observed. As shown in Fig. 2 and Fig. 3, the variation in the total drain current and Kr^{14+} beam intensity are characterized by successive maxima and minima along the change to the ECR zone position. A possible explanation is that the change of the ECR zone location impacts the coupling of the microwave with the ECR plasma. There is no obvious indication that the closer the ECR zone to the extraction aperture, the more medium charge state ion beam can be extracted. But the change of the ECR zone position modifies the beam extraction significantly, since at certain position more analyzed beam can pass through the collimation channel with the acceptance set at 0.9π.mm.mrad. That means the ECR zone position can not only regulate the ion source microwave cavity but also the intrinsic properties of the emitted ion beams. More investigation with intense beam production will be made in the future.

Table 1: Comparison of the data from Test 1

Z (mm)	Drain Current (emA)	Q007FC (eμA)	Q013FC (eμA)
51	5.20	320	203
55	4.61	279	176
60	4.26	287	205
72	3.72	255	186

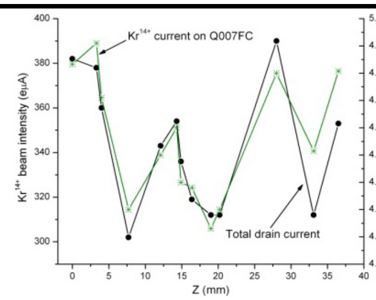

Figure 2: Kr^{14+} beam intensity and total drain current changes as the ECR zone movement (Test 2).

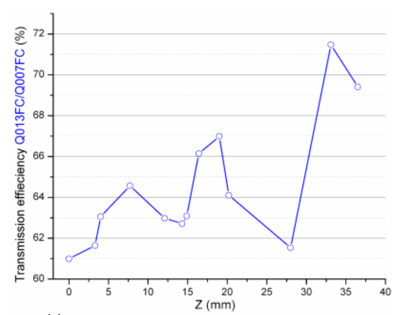

Figure 3: Kr^{14+} beam transmission efficiency through the collimation channel as the ECR zone movement (Test 2).

Production of high charge state ion beams

Although high charge state ion beams are not needed for CCF operations, high charge state ion beams of Xenon were produced to study the performance of SuSI. SuSI has many features that enable it to produce good results of high charge state ion beams. SuSI has a fully superconducting magnet to provide sufficient magnetic confinement for the operation at 18GHz, i.e. B_{rad}~1.3T, B_{inj}~2.6T, B_{ext}~1.3T. And the six independent solenoids make it more flexible to optimize the field configuration for high charge state ion production. The aluminium plasma chamber is also a very important part to improve the enhancement of high charge ions production, which has already been proved by many labs. Compared to other latest built fully superconducting ECRISs like VENUS [9], SECRAL [10] and RIKEN SCECRIS [11], SuSI has a more compact plasma chamber with an effective plasma volume typically around 3.6 litres, which makes it easier to reach higher power density with reasonable RF power feeding. An additional 18GHz klystron amplifier was connected to SuSI which increases the available RF power up to ~3.0 kW and increases the power density up to 0.85kW/l. With more power density achievable on SuSI, it is convenient to learn the behaviour of the ion source performances via plasma heating power. The very high vacuum achievable at the source extraction side (low 10^{-8} Torr) helps the extraction and transmission of the high charge state ion beams like Xe^{42+}.

The typical test to produce high charge state ion beams was done with xenon. Fig. 4 gives the typical spectrum optimized for the production of high charge state xenon ion beams. With oxygen as the mixing gas, the charge state distribution can be easily tuned to be peaked on Xe^{31+}, so that higher charge state ion beams such as Xe^{39+}, Xe^{42+} and even Xe^{44+} can be easily distinguished on the spectrum. At lower power level, the high charge xenon beams such as Xe^{38+} can be barely seen in the spectrum, but when the power level is increased beyond 2.0kW, the beam intensity increases very fast. The maximum beam intensity is observed at the full microwave power of 3.0kW, with no indication of saturation. It is very positive that with more power injected into the plasma chamber, more intense xenon high charge state ion beams and even higher charge states are possible.

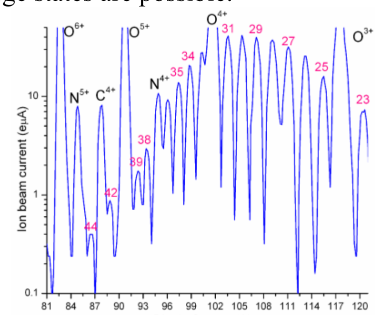

Figure 4: Typical xenon charge state distribution when optimizing for Xe^{38+}.

Production of refractory metal ion beams

The inductive oven developed at NSCL can generate a high temperature up to 2200°C, and has already been used to produce intense refractory metal beams for CCF operation or ECRIS R&D studies. For example, In 2009, more than 200eμA Ni^{12+} and 180eμA Ni^{17+} have been produced with SuSI. In recent years, intense uranium beam has become a worldwide interest. Because of its wide availability and stability even at high temperature, Uranium Oxide (UO_2) is a logical choice to try to produce Uranium ion beams. By design the rhenium tube works both as the recipient (susceptor) of eddy currents generated by the RF power supply and also as the crucible, it is possible to fill the rhenium directly with UO_2 powder. The first test indicated that UO_2 can be used to produce intense uranium ion beams. Although there is plenty of oxygen vapour produced at the same time, some oxygen gas is necessary to sustain the plasma. Fig.5 shows the spectrum when optimizing the production of U^{33+} beam. Within the limit of the inductive oven, 50eμA U^{33+} has been produced. The beam intensity was observed to be stable. Later examination of the experimental setup shows that there is only 100mg UO_2 that has been consumed and no obvious breakdown or burnt-out of the oven during the ~24hrs' real test, which demonstrates that inductive oven is good for the production of intense uranium beam with UO_2. Production of Uranium is limited at the moment by the amount of vapour available from the oven. More studies will be done in the near future to improve the performances of this technique.

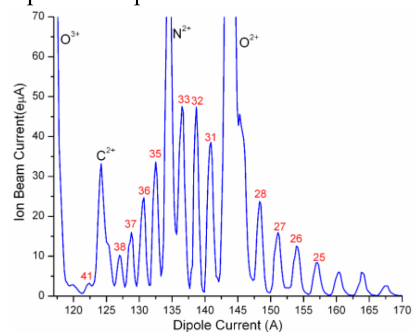

Figure 5: Spectrum obtained with UO_2 to provide uranium vapour.

Another typical method to produce refractory metal ion beams is ion beam sputtering and has also been tested with SuSI. A Ø10mm diameter uranium sample has been inserted on the axis of the ion source at the injection end. The large size of the sample provides a large cross section for the ion bombardment ions and the central-positioned sample enables the best acceptance of uranium by the plasma volume. Water cooling to the sample has also been considered. Since SuSI has a ~450mm mirror length and more than 130mm long ECR zone, the cross section to capture the sputtered material is much bigger than conventional ECR ion sources. Different support gases such as $^{16}O_2$, $^{18}O_2$, ^{20}Ne and ^{40}Ar have been tried during the test. Argon gas gives the best efficiency while $^{18}O_2$ gas provides higher charge states. U^{33+} and U^{34+}were the typical charge states optimized, and more than 86eμA $U^{33+}$and 95eμA U^{31+} have been detected on Q013FC. A disadvantage of the SuSI collimation channel is the poor mass resolution that can be achieved. For heavier ion beams such as Uranium, the lack of resolution requires to close the slits and aperture strongly in order to separate charge state effectively. However the transmission then decreases and in the case of the Uranium measurements was around 50 %. More details regarding the sputtering setup and measurements can be found in these proceedings [12].

R&D FOR FRIB

SuSI has been used to do beam studies for FRIB. In particular ion beam brightness has been investigated for high intensity ion beams. For the FRIB project, the ion beam transverse emittance should not exceed 0.9π.mm.mrad (full normalized) For heavy elements that will require transport of two charge states to reach the desired beam current on the production target a smaller emittance is needed, (0.6π.mm.mrad) per charge state. By using the collimation channel set at 0.9π.mm.mrad or 0.6π.mm.mrad, it is possible by measuring the transmitted current through the channel to assess the proportion of beam within the acceptance of the FRIB linac. For FRIB project, 640eμA $^{18}O^{6+}$ and 378eμA $^{40}Ar^{8+}$ are needed and the corresponding full geometric emittance is 200π.mm.mrad and 275π.mm.mrad for 25kV/q energy respectively. Fig. 6 shows the emittance achieved by SuSI for oxygen and argon after the collimation channel. On the other hand for heavier beam such as Krypton 400eμA of $^{86}Kr^{14+}$ was measured on Q007FC, but only 250 eμA $^{86}Kr^{14+}$ can pass through the 0.9π.mm.mrad collimation channel to Q013FC, which means a 62.5% transmission efficiency.

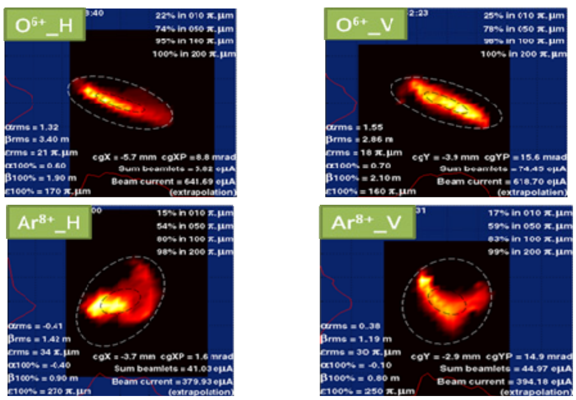

Figure 6: Horizontal and vertical beam emittance plots for 700eμA O^{6+} and 400eμA Ar^{8+} respectively.

CONCLUSION

SuSI ion source can now be operated at more than 3.0 kW at 18GHz and has demonstrated outstanding performances for a wide variety of beams from medium to high charge states. In particular, more than 380eμA Xe26+, 276eμA Xe27+ and 91eμA Xe30+ have been produced. Good intensity of ion beams of high charge states have also been produced with SuSI, such as 22 eμA Xe34+, 3.2eμA Xe38+and 0.35eμA Xe44+. Several other tests on SuSI have also provided solid results. For instance, UO2 was used for the first time with an inductive oven to produce intense uranium ion beams. About 50eμA U33+ has been successfully produced. Also beam sputtering with a uranium sample has provided a beam intensity of 86eμA U33+. As a summary, the latest results from SuSI are listed in Table 2.

A third 18GHz klystron amplifier will increase the value up to 1.3kW/l. SuSI is still on the way to challenging the limit of ECRIS performances at 18GHz. Following the frequency scaling laws, higher frequency ECR heating is also planned with SuSI. A 24GHz/10kW gyrotron amplifier is scheduled to be connected in FY2011.

Table 2: Latest beam results from SuSI

^{86}Kr	Q	I (eμA)	^{58}Ni	Q	I (eμA)
	14	500		12	200
^{129}Xe	20	350		17	180
	26	380	^{209}Bi	27	180
	27	276		28	190
	30	91		29	150
	34	22		31	76
	35	14.5		33	53
	38	3.2		36	9
	39	1.8		41	6
	42	0.95		46	2.5
	44	0.35	^{238}U*	31	95
				32	95
				33	86

* obtained with sputtering method

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