

FIRST RESULTS AT 24 GHZ WITH THE SUPERCONDUCTING SOURCE FOR IONS (SUSI)

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Abstract

The first commissioning results at 24 GHz of the Superconducting Source for Ions (SuSI) from Michigan State University (MSU) are reported. Although SuSI has been designed to operate primarily at 18 GHz, the superconducting magnet has been able to reach a field sufficient for operation at 24 GHz. Very exciting new results have been obtained during the commissioning of SuSI at 24 GHz for oxygen and argon. For oxygen 1.4mA of O^{7+} was measured when injecting 5.2 kW of microwave power. For argon, 220euA of Ar^{16+} was measured with 6kW injected. In most cases, the performances don't seem to saturate yet with the injected power. Some surprising observations were also made regarding the coupling of 18 GHz in parallel with the operation of the ion source at 24 GHz as well as the impact of the frequency on performances.

INTRODUCTION

The Electron Cyclotron Resonance (ECR) ion source SuSI is a fully superconducting ion source that has been operated at 18GHz for the last five years for injection into the Coupled Cyclotron Facility (CCF). Excellent performance have been reported with SuSI at this frequency for medium charge state ions of light to heavy ion beams [1] In particular after coupling as much as 3.4 kW using two klystrons, performances were found to be still limited only by the amount of microwave power available. Trying to push further the performances of SUSI a 24GHz gyrotron was installed and tested with the ion source. The choice of 24GHz was solely based on the maximum magnetic field that can be achieved with SuSI. Although, the superconducting magnet structure was initially designed to be compatible with operation up to 28 GHz, quenches of SuSI sextupole magnet have set a limit that in accordance with the field requirement in the high-B mode would correspond to a maximum frequency somewhat above 24 GHz [2]. Even so energizing the SuSI magnet requires a careful ramping of the current. First it is necessary to ramp both solenoids and sextupole coils together to avoid a quench. Second, it is also necessary to first ramp the current in the coils 10 to 15% higher than what is required for a given field configuration before ramping the current down to their nominal values. This procedure has been found to be very important to reach a stable operating point for extended period of time. Therefore to establish a stable field configuration for operation at 24 GHz does require to first push the current in the coils close to the known limits of the magnet. To be safe during the commissioning of the gyrotron, both axial and radial field were kept somewhat below the expected

high-B mode values for 24 GHz operation. For instance the radial field did not exceed 1.5 tesla. Likewise, the injection field was kept around 3 tesla most of the time. As a result, no quench occurred during the commissioning period. Some promising and exciting results at 24GHz have been obtained. After a technical description of the 24 GHz system, the ion source, experimental results will be presented and followed by a discussion.

24 GHZ SYSTEM

A 24 GHz gyrotron system was purchased from GYCOM, a Russia based vendor. Although rated for 10 kW, the maximum output power transmitted from the tube to a water-cooled load during the commissioning tests was 8.8kW which is more than sufficient for operation with the ion source. The high voltage power supply (HVPS) was directly purchased from a domestic supplier and a filter circuit added between the HVPS and the gyrotron. This filter includes a 50 nF capacitance that limits the ripple to less than 2% and a set of four 20 Ohm resistance used to limit the stored energy to a maximum of 5 Joules to protect the gyrotron tube. The 24GHz transmission line and RF coupling system to SuSI is similar to the one developed for the SECRAL source [3]. The 24 GHz microwave propagates in an over-moded circular waveguide. The initial TE02 mode produced by the gyrotron is converted to TE01 using a mode converter because of the low attenuation of this mode. Coupling with the ion source can cause unwanted modes to propagate back in direction of the gyrotron so that a mode filter is also included in the transmission line. Diagnostics at the exit of the gyrotron include an arc detector and a bi-directional coupler. Although the gyrotron tube and the ion source are under vacuum, the transmission line is simply left at atmospheric pressure filled with the air that was trapped during assembly of the waveguide A 10 kW rated, boron nitride window is used at each end to define the vacuum/air interface. Finally, a high voltage break rated for 50 kV was also provided by GYCOM. Because of space limitation, the gyrotron was installed in a room above the ion source and two 90-degree bend were added to the transmission line to connect the gyrotron to the ion source. Figure 1 shows a layout of the gyrotron and ion source together. All components of the transmission line are water cooled. The control system provided with the equipment include a PID loop to regulate the output power using the read-back signal from the bi-directional coupler. A few important features help protect the equipment. First, the circuit used with the arc detector can send a fast signal (<10us) to inhibit the HVPS. Second

should the signal read from the bi-directional fails, the gyrotron control program allows to set a maximum value for the HVPS output voltage which limits the output power available.

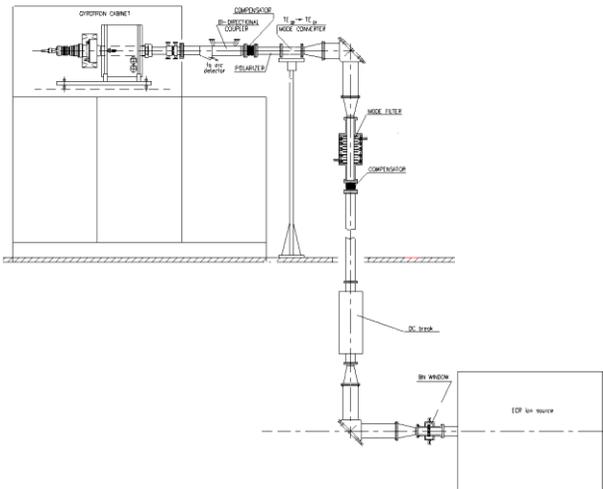


Figure 1: Layout of 24 GHz gyrotron and transmission line to SuSI ECR ion source.

The plasma chamber of SuSI is 101mm in diameter and is made of Aluminum. Because of the small diameter of the chamber, the over-moded waveguide take a significant portion of the injection flange. Figure 2 shows a layout of the baffle at the injection end. Space was made to include an oven, but it was necessary to tilt slightly the tube supporting it in order to maximize the oven diameter.

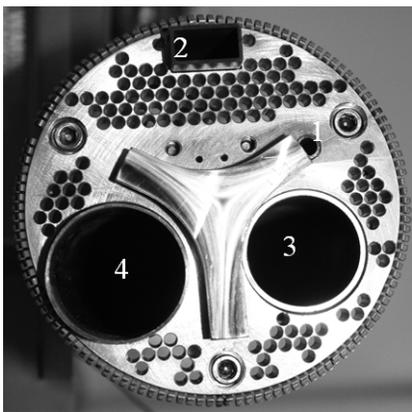


Figure 2: SuSI 24 GHz injection flange (baffle). It includes 1- gas tube; 2-WR62 Waveguide; 3- oven tube; 4-24 GHz circular waveguide.

The baffle also includes a tube for gas injection and a WR62 waveguide. The bias disk, the baffle itself and the WR62 waveguide are all independently cooled. A larger cooling line is used to cool both the 24 GHz waveguide and the oven tube.

SuSI has several interesting features [4]. First the axial magnetic profile is defined using 6 solenoids which provide some flexibility to adjust parameters such as field gradient at the resonance, B-minimum or plasma length.

Second with a diameter of only 101mm, SuSI plasma chamber has a nominal volume of about 3.5 l which raise the possibility to reach power density between 1.5 to 2 kW/l with the gyrotron system. Another interesting feature of SuSI relates to the design of the superconducting magnet cold mass and cryostat. The magnet is directly connected to the laboratory cryoplant so that liquid helium is continuously injected in the cold mass. Recent boil-off measurements have shown that the static heat load at 4.2K is close to 30W. Therefore the ion source magnet is not sensitive to the dynamic heat load generated by the plasma which would only amount to a few watts.

SUSI COMMISSIONING TEST RESULTS AT 24GHZ/5.6KW

Acceptance tests of the 24 GHz system were completed successfully in February 2014 on a water-cooled calorimetric load. Tests included characterization of the tube operational parameters, long term stability at high power (5kW) as well as measurements of the ripple amplitude and frequency. Injection of microwave power started in April 2014 at relatively low power (<1 kW) and lead to a strong outgassing for several weeks. Following this initial conditioning period, commissioning continued using argon gas in May 2014. Finally additional work was done in July 2014 with oxygen and high charge state of argon as detailed below.

The initial work with argon gas started by optimizing SuSI for Ar^{11+} and Ar^{12+} . After two days spent optimizing the tuning parameters, such as magnetic field, gas, microwave power and biased disc an optimum of 905euA of Ar^{11+} and 860euA of Ar^{12+} were obtained with over 5kW of microwave power injected. Performances were not found to be saturating with the power as shown in figure 3 below.

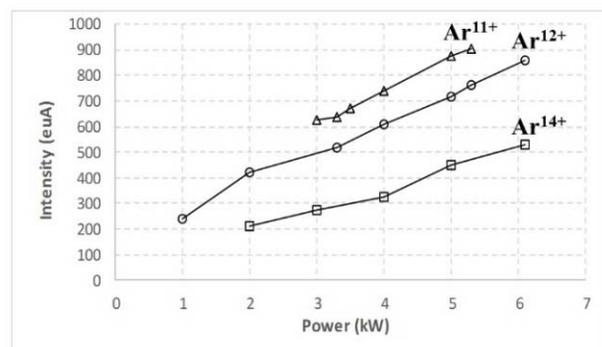


Figure 3: Electrical current of Ar^{11+} , Ar^{12+} and Ar^{14+} for various microwave power level of 24 GHz. None or little 18 GHz used.

It should be noted that the plot above was not obtained while keeping gas and magnetic field constant. Instead gas and field were adjusted for each power level. Power was not initially increased beyond 5.5kW as a safety precaution to protect the plasma chamber. The power density was then about 1.57 kW/l. The corresponding

axial magnetic field profile for Ar¹²⁺ was: B-injection=3.1T and B-extraction=1.56T while B-minimum=0.48T. The field at the plasma chamber wall was B-radial=1.48T. The work continued with Ar¹⁴⁺ and in this case the microwave power was pushed up to 6.1 kW and 530euA of Ar¹⁴⁺ was measured. As observed with Ar¹¹⁺ and Ar¹²⁺ and shown in figure 3, the current was not found to saturate even at this power level which corresponds to a power density 1.74 kW/l. The magnetic field was very similar to the one used with Ar¹²⁺. Optimizing for very high charge states of Argon was however more difficult. Initial tuning on Ar¹⁶⁺ did not yield intensity exceeding 150euA and the intensity was clearly saturating with the microwave power injected beyond 4kW and is shown in figure 4. Also Ar¹⁶⁺ did require large amount of support gas (oxygen). After more conditioning was done for several weeks with the gyrotron system at a power between one and two kilowatt, a noticeable improvement in the current of Ar¹⁶⁺ was observed. Figure 4 shows the difference in the performance of Ar¹⁶⁺ function of the microwave power before and after conditioning the ion source. In both case the radial field was about 1.48T at the plasma chamber wall and the extraction field about 1.57T. The injection peak was higher in the first set of measurements with 3.2 T compare to 3.01 T in the second set. A significant difference also existed for the B-minimum which was at 0.63T initially and in principle more optimized for operation at 24 GHz. In the second set of measurement the B-minimum was adjusted to B=0.50T.

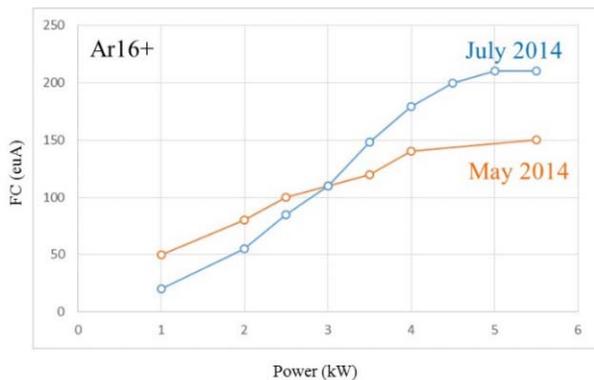


Figure 4: Comparison between two optimization of Ar¹⁶⁺ both done with power injected from 24 GHz gyrotron. The first run (Orange curve) was done in May 2014 and while the second run (Blue curve) was done in July 2014 after further conditioning of the source with the gyrotron.

The charge state distribution (CSD) of Ar¹⁶⁺ obtained after further conditioning of the ion source is shown in figure 5. The distribution is peaked on Ar¹⁴⁺ and large amount of oxygen were used to optimize the current. It is difficult to evaluate the amount of Ar¹⁷⁺ is present next to the peak of 0⁷⁺.

After working with Argon, the ion source was then switched to oxygen and optimized for the production of 0⁶⁺ and 0⁷⁺. As for Argon, the current did not saturate with

the microwave power injected but it was difficult to optimize the current of 0⁶⁺ beyond 2.3 emA partly because SuSI beamline is not optimized for the transmission of high current but to inject low emittance beam into the coupled cyclotron. The optimized charge state distribution for 0⁶⁺ and 0⁷⁺ is shown in figure 6 below. The characteristic magnetic field is very similar between the two charge states and is detailed in figure 6. Mostly the optimization of the ion source on 0⁷⁺ was done by reducing the gas load.

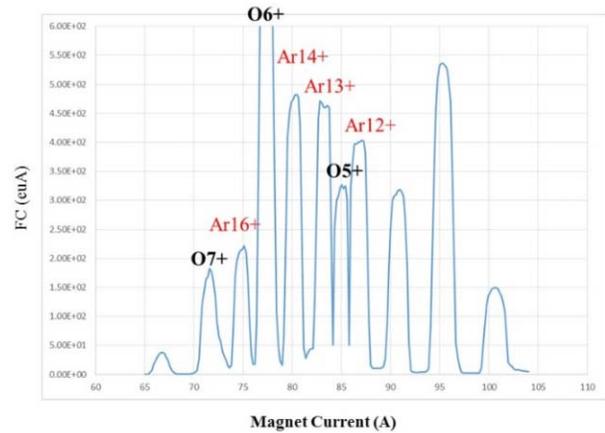


Figure 5: Argon distribution optimized for Ar¹⁶⁺. Power 24GHz=5.7kW; Power 18GHz=500W; Drain current=4.5emA. Pressure extraction=2.5 E-8 Torr. B-radial=1.46T; B-injection=3.01T; B-minimum=0.49T; B-extraction=1.54T.

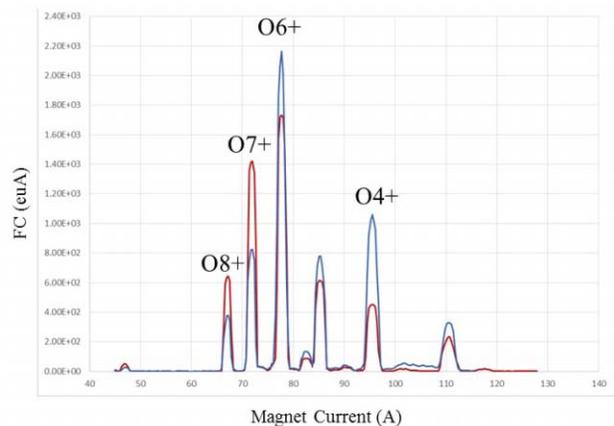


Figure 6: Oxygen distribution optimized for 0⁷⁺/0⁶⁺. Power 24GHz=5.2/5.2kW; Power 18GHz=0/300W; Drain current=3.9/7.3emA. Pressure injection =7E-8/3E-7 Torr. Pressure extraction=3.3E-8/3.7E-8 Torr. B-radial=1.46/1.49 T; B-injection=3.05/2.97T; B-minimum=0.52/0.46T; B-extraction=1.57/1.53.

DISCUSSION

First it is important to note that the commissioning results shown in the previous section have been obtained over a short period of time and that operation of SuSI at 24 GHz did require significant amount of conditioning as was also previously noted for SECRAL [3]. However a

few surprising observations were made during the measurements. First, although an 18 GHz/2kW klystron was also available during commissioning, it was observed that injecting even low level of power at 18 GHz did not help improve the ion source performance and mostly led to the current falling down by a few percent. The only noticeable exception was Ar^{16+} where 500 W of 18 GHz was used and helped improve the current by 10 to 15%. To dispel any doubts regarding the 18 GHz system, the ion source was then operated at a lower field and injected with microwave power from the klystron only. In this configuration, the performance of SuSI were similar to previous results. Factoring the transmission through the waveguide, the forward power at 18 GHz read at the bi-directional coupler at the injection of the ion source was in good agreement with the output power generated at the klystron while the reflected power stayed very low in all cases (< 10 Watt). Also it is unlikely that it is due to a critical density effect because the situation was the same for lower level of 24 GHz power injected. May be the fact that the radial and the peak values of the axial magnetic field were not optimized yet for operations at 24 GHz impacted the coupling of the 18 GHz. However, the minimum of the magnetic field was slightly below 0.5T in most cases, which is a value commonly used when injecting microwave power at 18 GHz. More work is needed to understand the conditions to optimize dual injection heating of 18 and 24 GHz. The second surprising observations was that the performances of the ion source at 18 GHz and 24 GHz appear equivalent for a similar level of microwave power injected into the ion source. A good example is shown for Ar^{14+} in figure 7. It is clear from the figure that for a range of microwave power extending from 2 to 3 kW the performance are very similar for both 18 GHz and 24 GHz. A clear advantage of the 24 GHz system is that it can provide much larger amount of microwave power to the ion source.

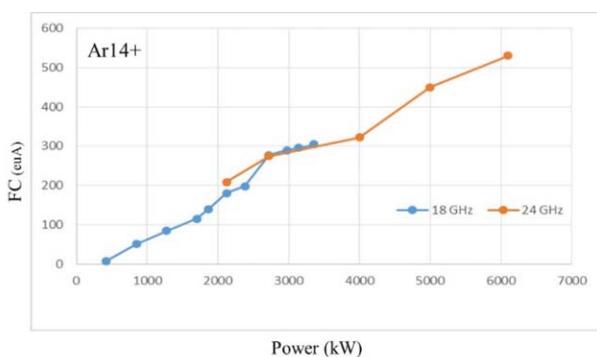


Figure 7: Comparison between 2010 run when only 18 GHz was used (Blue) and 2014 with only 24 GHz injected. Performances are very similar for equivalent amount of power injected in the source.

This observation was also true for Ar^{11+} and Ar^{12+} . However for Ar^{16+} the current obtained at 24 GHz was higher than the one at 18 GHz for similar power injected. Of course it could be that the source need more conditioning before the scaling of the performances with the frequency can be observed clearly. Finally, as it is difficult to know how much power is injected in the ion source with the gyrotron, we monitored the return temperature of the plasma chamber cooling water. Although it does not provide a precise calibration of the forward power, it was at least observed that the temperature of the water did increase for each increase of the output power of the gyrotron demonstrating that more power get coupled into the ion source. Interestingly, we compared the return temperature of the plasma chamber cooling water for 1kW of 18 GHz as measured at the ion source bi-directional coupler with the return temperature for also 1kW of power injected from the 24 GHz gyrotron. Surprisingly, the increase in temperature was measured to be about 1 degree Fahrenheit with the 24 GHz system while it was only about 0.66 degree with the 18 GHz. Although this effect is not at present completely understood one possible explanation would be to consider that operation of an ECR ion source at higher frequency results in higher radial losses due to the more energetic electrons present in the plasma.

CONCLUSION

The first commissioning results at 24 GHz of SuSI were presented. Very good performances have been obtained for oxygen and argon and it was possible to couple very high level of microwave power to SuSI without problems. The magnet structure also was able to operate at a higher field without triggering any quenches. Work will continue in the future with SuSI to investigate the performances for heavier elements such as Xenon and Bismuth. Conditioning at 24 GHz takes time and better results are expected in the future. A Systematic study of the magnetic field need to be conducted to better understand the source behavior. Future work will also address measurements of the beam stability and emittance.

REFERENCES

- [1] L.T. Sun et al., proceedings of the 19th international workshop on ECR ion source, Grenoble, France (2010).
- [2] G.Machicoane, D.Cole, P.A.Zavodszky, proceedings of the 18th international workshop on ECR ion source, Chicago, USA (2008).
- [3] H.W. Zhao et al. proceedings of the 19th international workshop on ECR ion source, Grenoble, France (2010).
- [4] P.A. Závodszky et al., Rev. Sci. Instr.79 02A302 (2008).