Dual Frequency Enhancement of the SuperNanogan Multi-Charged Ion Source at TRIUMF ISAC Facility

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Abstract. In 2008, a Supernanogan ECR ion source from PANTECHNIK was introduced in addition to an in-house developed microwave ion source and a surface ion source to complement the TRIUMF Offline Ion Source (OLIS) facility to provide highly charged ions to ISAC experiments. Originally, it employed a 400 W Travelling Wave Tube Amplifier (TWTA) for RF heating, but less than 50 W was enough to produce all the multi-charged beams required by the experiments. A 50 W solid-state amplifier was added for redundancy purposes but we found a significant improvement when both were switched on at the same time. When properly optimized for the dual frequency, less than ten times the total power is needed to produce the same charge with more current than the single frequency. The beam stability and the ability to extract higher charged ions also improved with the dual frequency enhancement. The simulation studies, operational experience, and results are discussed in this paper.

1. Introduction

OLIS consists of a high-voltage terminal containing three ion sources [1], namely a microwave cusp ion source [2], a surface ion source [3] and a multi-charge ion source [4]. The OLIS terminal also includes an electrostatic switch that allows the selection for beam delivery to accelerators at ISAC from any one of the sources without mechanical intervention with all three sources running simultaneously. The schematic drawing of the OLIS terminal and the electrostatic switching box is shown in Figure 1. These sources provide a variety of 1+ or n+ beams up to A/Q = 32 (A: atomic mass and Q: charge state) for ISAC experiments, commissioning the accelerators, setting up the radioactive experiments, and tuning the beamlines. The primary accelerator Radio Frequency Quadrupole (RFQ) [5] is designed to accept beams at a fixed injection velocity of 2.04 keV/u. Moreover, the secondary accelerator Drift Tube Linac (DTL) [6] requires a mass-over-charge ratio between 3.0 and 6.0. Since the source extraction voltage is limited to 65 kV, a multi-charge ion source MCIS was needed to deliver beams above mass 32. Moreover, a multi-charge ion source capable of producing ions with an A/Q value up to 6, could bypass a stripper foil between the RFQ and DTL, which has limited usage time for higher beam currents. With this addition, OLIS can provide ion beams from all stable elements and satisfy all ISAC, ARIEL and CANREB needs.

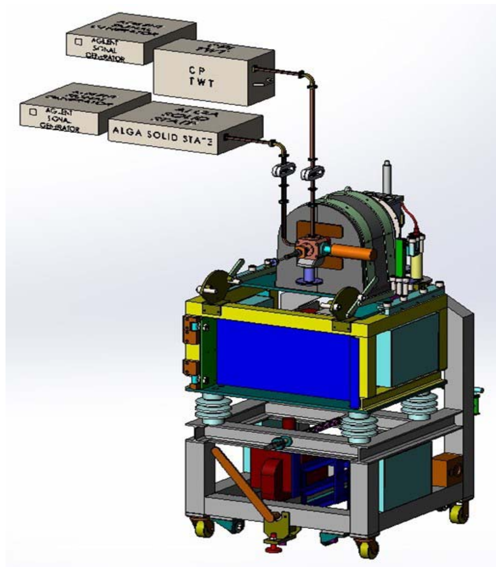

Figure 1: Supernanogan with the dual frequency coupling. Protection systems, including circulators, directional couplers and dummy loads are not shown here.

2. MULTI-CHARGE ION SOURCE

The Supernanogan (a commercially available ECR ion source from PANTECHNIK) was chosen to be the multi-charge ion source for stable beams at ISAC. The addition must be accomplished while minimizing the impact on the microwave and surface ion source operations. An ion source system was adopted with all the necessary power supplies, vacuum components, diagnostic devices, and control systems for this functionality. It is a mobile and virtually self-contained mobile ion source station (see Figure 1). This mobile station consists of two main sections, one at ground potential and the other at a high voltage bias of up to 20 kV. The ground section contains a high voltage isolation transformer, two turbo pumps and their controllers, an ion gauge controller, a vacuum box for optics and services, power, PLC, and monitoring. The HV section contains the Supernanogan ion source and shielding, the independent dual frequency RF system, the dry scroll vacuum pump, the gas supply system, DC power supplies for Supernanogan operation, power distribution and computer control and monitoring. The HV section communicates with the ground section controls via an optical link, which then connects to the OLIS control system. The cart rolls into the OLIS HV enclosure and obtains a vacuum-tight connection to the OLIS electrostatic switching box at the central port. The cart is then connected to services such as power, RF, water, air, gas, vacuum roughing system, and controls. The operation of the Supernanogan is then much like the other OLIS ion sources and utilizes the same interlock and safety systems already in use. When the Supernanogan needs servicing, it can be disconnected (from the OLIS terminal) and removed without affecting the integrity of either the OLIS or Supernanogan vacuum. When outside the HV enclosure, the Supernanogan vacuum system can continue to function during maintenance.

3. DUAL FREQUENCY STUDIES

Many laboratories around the world study dual frequency enhancement with various ion sources achieving different degrees of success [7–9]. Extensive studies have been done in the MHz range but GHz range theoretical studies as well as plasma studies are limited. Superimposition of the dual frequency in capacitive and inductive coupling is available in textbooks. However, after plasma ignition capacitive or inductive coupling formulas are no longer accurate and the anisotropic nature of the plasma parameters further complicates the accurate model simulation.

3.1. Experimental test setup

The preferred option is to transfer basic mode TE_{11} from the waveguide to TM_{01} mode through a coaxial coupling to the plasma chamber. Mode TE_{01} provides maximum efficiency of the ECR heating where the electric field is always perpendicular to the magnetic field where ECR resonance occurs. Another option is to transfer the basic mode to TE02 mode for quadrupole magnetic confinement or TE_{03} mode for hexapole magnetic confinement. In these cases, if the multimode matches the magnetic configuration with the right mode rotation, the results will be outstanding since TE_{02} and TE_{03} electric flux density is higher than the TM_{01} near the ECR region. The second frequency with the right tuner position could achieve the preferred mode rotation as well as increased effective ECR volume.

3.2. Frequency and mode simulation studies

It has been demonstrated that the plasma chamber of the ECR ion source exhibits excitation of multiple modes in the presence of none non-magnetized homogeneous plasma. The study reported the generation of different resonant modes upon launching electromagnetic waves into the chamber. Meanwhile, the plasma chamber of the ECR ion source is composed of intricate magnetic field topology resulting from the solenoids and hexapole. As a consequence of these fields, the plasma electrons experience gyromotion, even outside the intended resonance surface. Subsequently, these electrons can be additionally heated if they oscillate at frequencies corresponding to the excited modes within the plasma chamber. Given that the plasma chamber exhibits the creation of multiple modes during single-frequency heating, it is plausible to suspect the excitation of super-multiple modes when operating the ECR ion source under the dual-frequency heating regime. To investigate this phenomenon, the geometry of the plasma chamber in the MCIS was modelled in COMSOL without the plasma to investigate the structure of the launched waves in the chamber. This modelling approach aimed to explore the potential excitation of super-multiple modes, however, due to the limitation of COMSOL to model two different waves of different frequencies simultaneously, for a start, the ports of the two waveguides were simulated for the same frequency 13.785 GHz and found to be exited at TM_{01} mode as predicted 2.

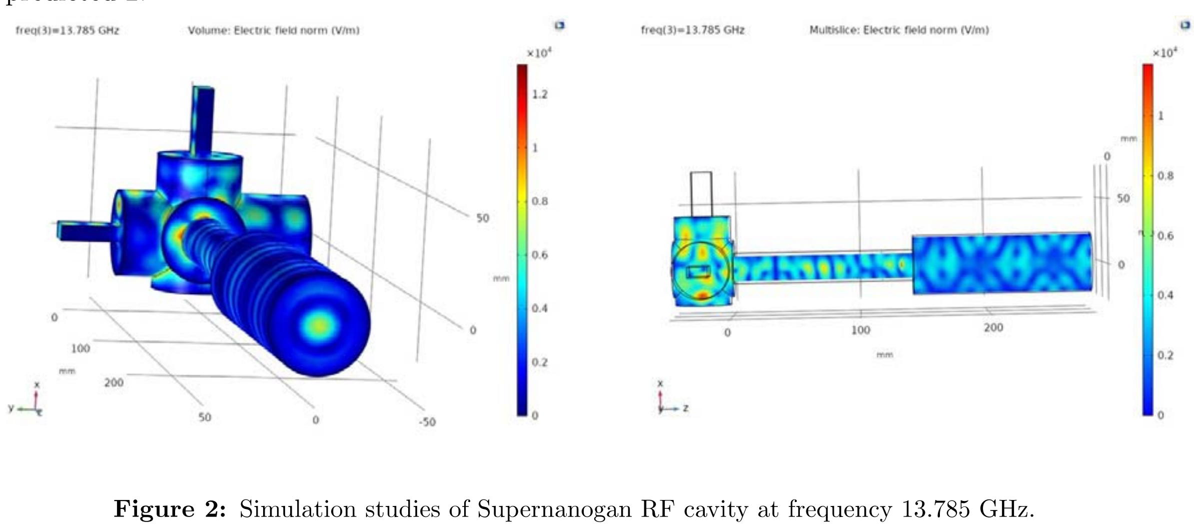

Figure 2: Simulation studies of Supernanogan RF cavity at frequency 13.785 GHz.

4. DUAL FREQUENCY VS. SINGLE FREQUENCY RESULTS

A TWT amplifier capable of delivering 12.75 GHz to 14.5 GHz is connected to one of the RF ports while a solid-state amplifier capable of delivering 13.6 GHz to 14.5 GHz is connected to a second RF port (see Figure 1). Both RF systems are equipped with circulators, dummy loads, and high-voltage isolators. Specialized software was developed to scan frequencies with a 16-bit resolution of each amplifier independently to find optimum frequencies for the maximum current for the required charge state. A $^{78}Kr^{15+}$ was chosen as the charge state for this study even though Supernanogan can produce as high as $^{78}Kr^{32+}$ charge state since +15 has fewer impurities and it can demonstrate the clear advantage of the dual frequency enhancement. A

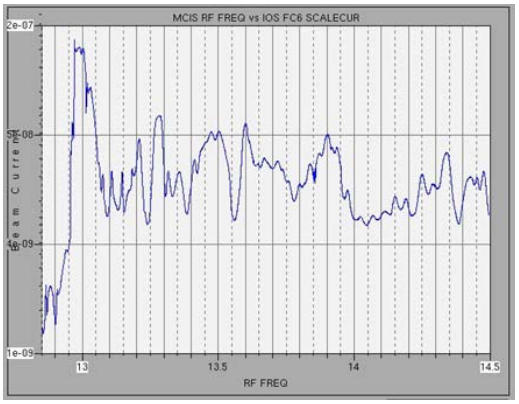

Figure 3: First (basic) frequency full range scan after a few iterations optimized at $^{78}Kr^{15+}$ current.

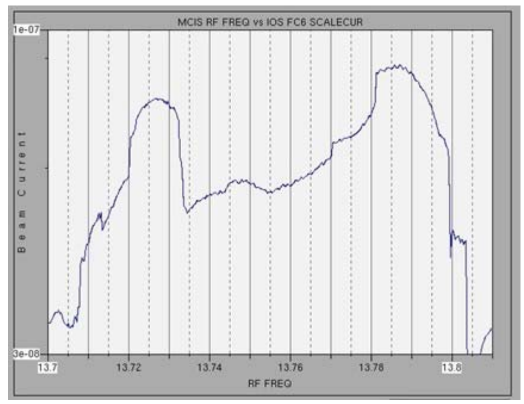

Figure 4: Second frequency scan is done after setting the basic frequency to the maximum $^{78}Kr^{15+}$ current.

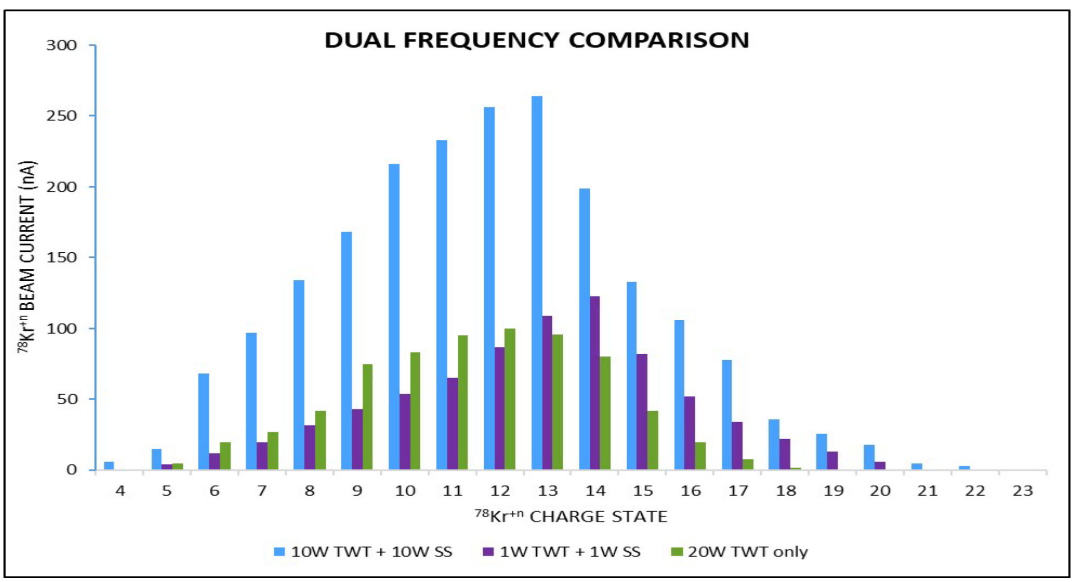

Figure 5: Multi-charge spectrum for $^{78}Kr^{n+}$. Green: Single frequency 12.985 GHz at 20W TWT only, Purple: Dual frequency 12.985 GHz TWT and 13.785 GHz SS at 1 W each, Blue: Dual frequency 12.985 GHz TWT and 13.7625 GHz SS at 10 W each. Both frequencies were kept the same for demonstration purposes even though optimizing both frequencies in the 10 W + 10 W case yielded much higher currents and higher charges.

few iterations are required to find the best two frequencies which give the highest stable current of the given charge state. A comparison of the results for single and dual frequency operation is shown in Figure 6. In this case, $^{78}Kr^{15+}$ TWT frequency was found to be at 12.985 GHz where ECR resonance is at 4638.6 Gauss. The second frequency for the solid-state amplifier was found to be optimal at 13.785 GHz where the ECR resonance is at 4924.5 Gauss. The optimum frequency gap was found to be 800 MHz for the given source parameters. The difference of 296 Gauss is only a few millimetres radially but axially it is more than 20 mm long at some points and creates a complicated and large ECR volume. Frequency multi-factoring could even create much more ECR surfaces explaining why such low power is needed in dual frequency cases. These frequencies vary for different plasma densities and for different tuner positions. A detailed description is beyond this paper's scope and will be published elsewhere. As can be seen in Figure 5 when using optimized dual frequencies, the required power is less than 10 times to achieve the same charge state distribution with the same currents. When the total power of the two frequencies was equal to the single frequency power the higher charges were seen with dual frequency

5. SUMMARY

Many labs around the world have been studying dual frequency enhancement with various ion sources, achieving different degrees of success. MCIS at OLIS with Supernanogan demonstrated a remarkable charge state and current enhancement when the dual frequency was introduced. It is shown that when implementing the dual frequency, less than ten times the amount of power is needed to produce similar charge states and currents. This method could therefore enhance ion thrusters immensely. For the same power, much higher charges are seen with higher currents. Simulations show that precise frequencies are needed to exit desired modes as seen in experimental studies. However, simulation frequencies differ from the empirical frequencies which may be the case when simulation cannot accurately take the anisotropic plasma densities into account. Further detailed studies will definitely enrich the multi-charge ion source community.

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