Off-line ion source terminal for ISAC at TRIUMFa)

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Off line ion source terminal

K. Jayamanna

Abstract The off-line ion source (OLIS) terminal provides beams from stable isotopes to ISAC (see Fig. 1) experiments as well as for accelerator commissioning and for pilot beams for radioactive beam experiments. The OLIS terminal (see Fig. 2) is equipped with a microwave driven cusp source for single and double charge ions, a surface ion source for low energy spread alkali beams, and a multi-charge ion source.

Keywords Ion sources · Ion beams · Highly stripped ion beams · Multi-charge ion beams · Radioactive ion beams · RIB · Stable ion beams · SIB · Plasma sources

1 Introduction

The Off-Line Ion Source [1] (OLIS) facility consists of a high voltage terminal containing (see Figs. 1 and 2b) a microwave cusp ion source [2], a surface ion source [3] or a hybrid surface-arc discharge ion source [3] (which can operate in a hybrid arc-discharge mode) and a multi-charge ion source [4, 5]. The system also includes an electrostatic switch that allows the selection of any one of the sources without mechanical intervention. Figure 1 shows the schematic drawing of the OLIS terminal and the electrostatic switching box. 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 for tuning the beam lines. The primary accelerator RFQ (Radio Frequency Quadrupole) is designed to accept beams at a fixed injection velocity corresponding

ISAC and ARIEL: The TRIUMF Radioactive Beam Facilities and the Scientific Program.

K. Jayamanna (✉)
TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics,
4004, Wesbrook Mall, Vancouver, BC, Canada V6T2A3
e-mail: Keerthi@triumf.ca
URL: olis.triumf.ca

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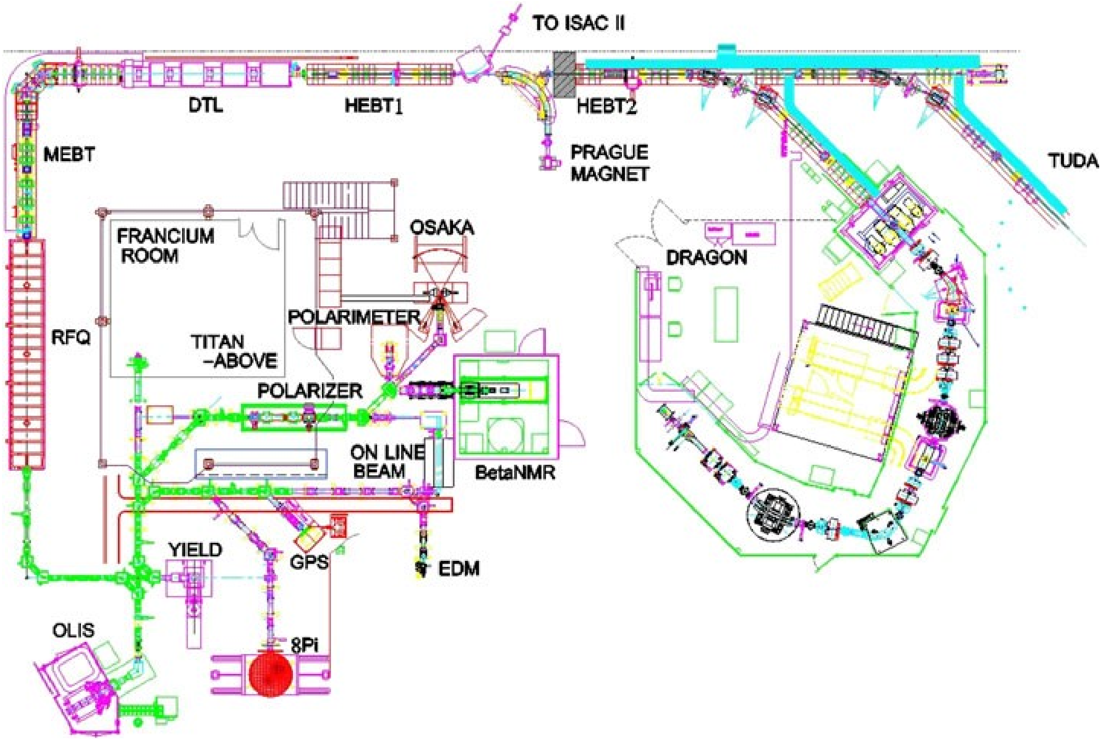

Fig. 1 Technical drawing of ISAC 1 where OLIS supplies beams from stable isotopes to various experiments. The ISAC II experimental hall is not shown in the picture. The stripping foil mechanism is located at the MEBT section before the bending/analyzing magnet

to 2.04 keV/u. Moreover, the secondary accelerator Drift Tube Linac [6] (DTL) requires a mass-over-charge ratio between 3 and 6 (3<A/Q<6). However, the source extraction voltage is limited to 65 kV. The multi-charge ion source was installed to deliver beams above mass 32 and with a A/Q value up to 6, without the need of a stripper foil between the RFQ and DTL. With this addition, OLIS can provide ion beams from all stable elements and satisfy all ISAC demands.

ISAC has two separate high and low energy areas. The online ion source terminal provides beams through a junction cross in order to provide beams simultaneously to high-energy and low-energy beam lines. While radioactive ion beams are delivered from the online terminal to a low-energy area, the stable beams from the offline terminal can be diverted to a high-energy area and vice versa.

2 Ion sources

2.1 Microwave ion source

The microwave ion source (see Fig. 3) has been operational since 1995 and provides only singly and some doubly charge ion beams from various stable isotopes. Originally, its prime goal was to provide beams from gaseous elements, but later two ovens and a sputtering system were added in order to provide beams from liquids and from solids. This source terminal is now automated for start up and for mass selection. It is capable of providing positive ions from stable isotopes for months without

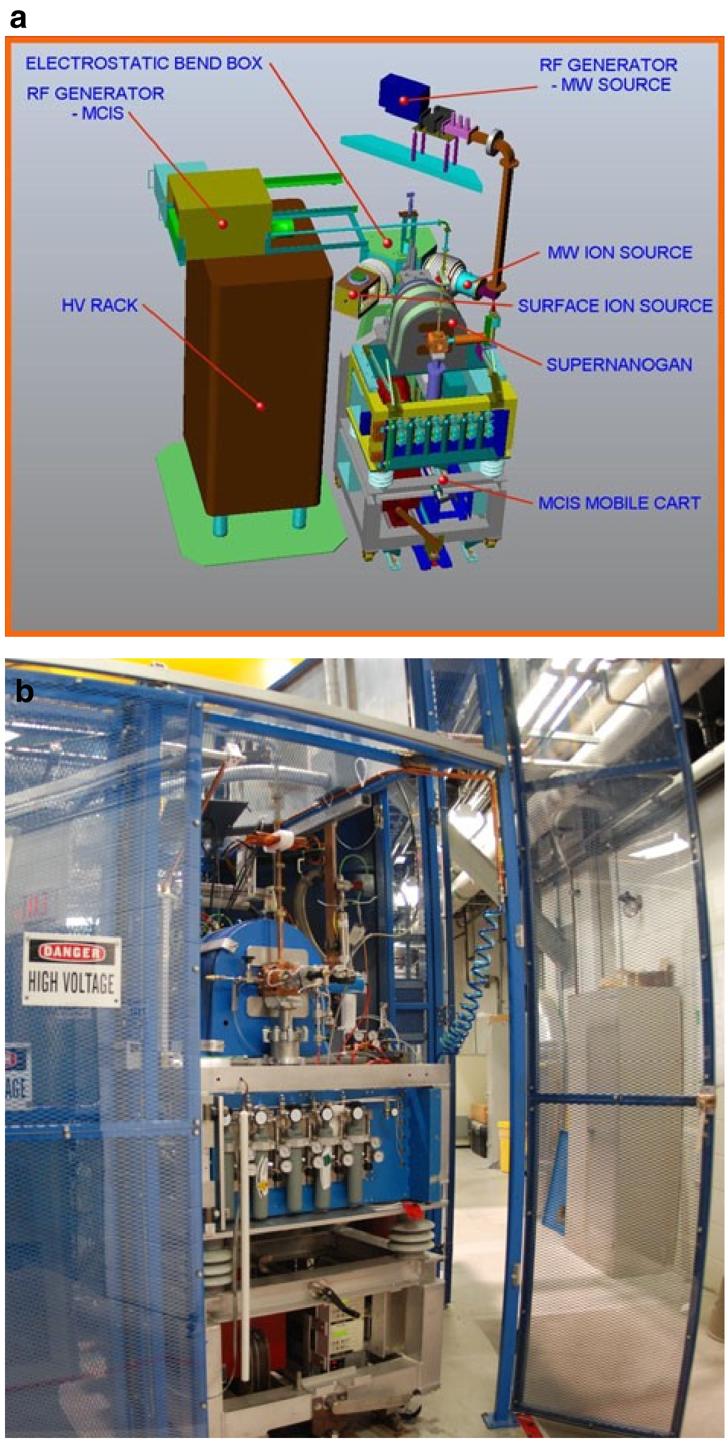

Fig. 2 **a** Engineering model of the OLIS terminal and the electrostatic switching box. **b** Photograph of the OLIS terminal with the high voltage cage

maintenance and even negative ion beams if required. To date, over 40 different isotopes including many rare isotopes have been delivered to various experiments.

The microwave ion source is the most used ion source in the OLIS terminal. It consists of two vacuum chambers. One is a cylindrical cavity with a quartz liner, which serves as a plasma chamber. This chamber is 15 cm in length and 10 cm in diameter. The second chamber consists of two 90° bend wave guide systems as a windowless RF coupling chamber. Ten water-cooled $SmCo_5$ magnetic bars are installed around

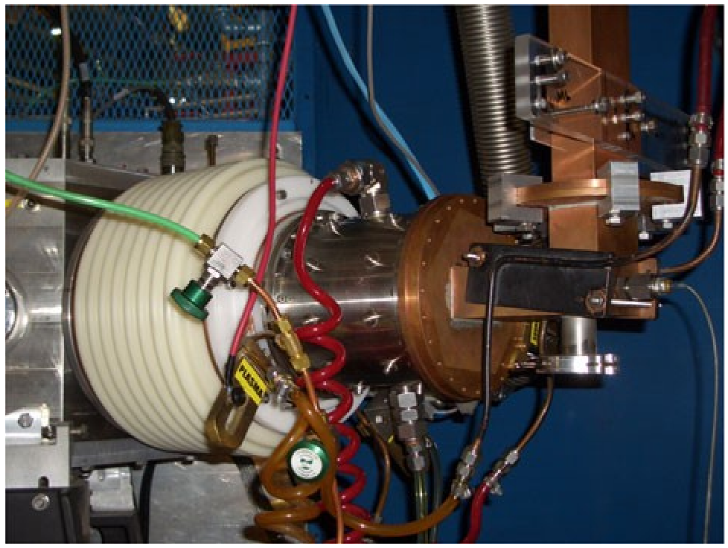

Fig. 3 Microwave ion source with the three electrode extraction system and the RF injection system

the outside of the plasma chamber for confinement. Four more magnetic bars with alternate poles are installed in the side of the back plate to achieve continuous cusp lines. For the positive ion extraction, the magnetic configuration has a cylindrical symmetry. For the negative ion extraction, the magnetic configuration is changed by flipping the polarity of the last magnets in a pair of diametrically opposed rows in order to create a strong virtual filter. This divides the plasma chamber into high and low energy electron regions. Two additional pairs of magnets are placed in the extraction region so that the total integral field is equal to zero.

Microwave power at 2.45GHz is introduced axially to the source in between two back plate magnetic bars through a 10 mm by 72 mm rectangular shape matching diaphragm placed in between two chambers mentioned above. A Teflon™ window with a choke flange in between the microwave generator and the source serves as both a vacuum break and 65 kV electrical isolation. A one meter long waveguide and two 90° bends stop any plasma or particle migration to the Teflon window. An axially symmetric three electrode system was developed to extract beams with an extraction voltage range from 6 kV to 60 kV without significant change in the emittance values.

A gas system equipped with 12 different gases is connected to the source via remotely controllable valves via two high precision gas flow controllers. When the source is used to provide pilot beams or for commissioning the accelerators, a mix of various gases can be injected into the source to provide any mass from the gaseous elements required by the accelerator at any given time. If the source is used only for gaseous elements, it can run with minimal maintenance for years.

Two high temperature ovens are installed in the source, so that high vapor pressure elements could be injected into the source via the back plate. Quartz liners are placed in the source chamber so that, contaminations can be easily removed from the source after each run and before the next run begins.

The source can also be easily converted into a sputter source simply by attaching a standard sputter disk made of required material to the back plate of the ion source and applying 300 V to it with respect to the plasma. DRAGON [6] and TUDA [7] have been the main users of the OLIS microwave ion source for years and H_3^{+1}, $^{12}C^{+}$, $^{20,21,22}Ne^{+}$, $^{16,17,18}O^{+}$, $^{36,40}Ar^{+}$, He^{+}, $^{40}Ca^{+2}$, $^{24,25,26}Mg^{+}$, and $^{27}Al^{+}$ were the common beams delivered to the experiments. Some difficult beams (considering purity), such

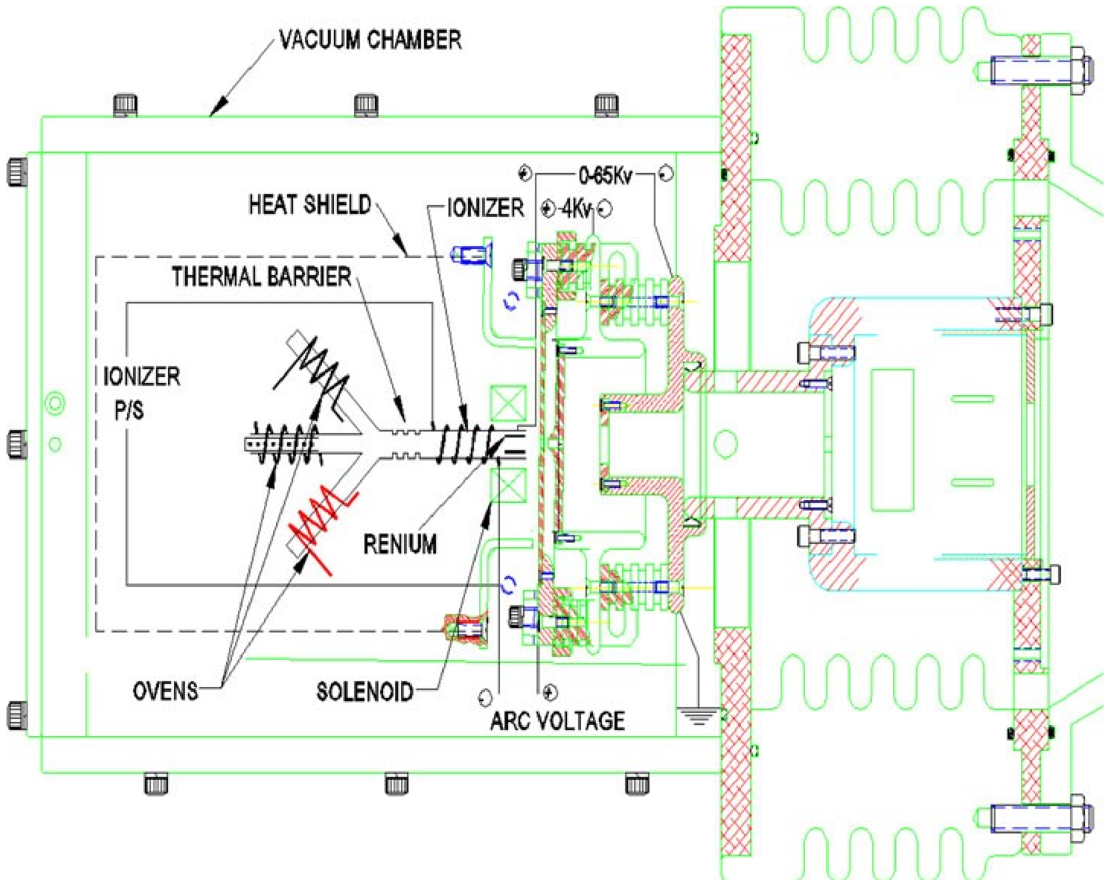

Fig. 4 Surface ion source with three heaters and an ionizer. It is capable of converting to a hybrid surface arc discharge ion source by switching on the arc voltage and axial magnetic field

as $^{10}B^+$, $^{28}Si^+$ and $^{18}O^+$ were also provided for the experiments in the high energy area. During the $^{10}B^+$ beam, boron trifluoride was used as the trace gas. The source needed to produce enough boron beam current so that suppression of the impurities ($^{20}Ne^{+2}$ and $^{40}Ar^{+4}$) was possible. During the $^{28}Si^+$ beam, it was very difficult to suppress $^{28}N_2^{+1}$ completely, therefore $^{28}SiH_3^{+1}$ was extracted from the source and delivered up to the stripping foil as mass 31 for subsequent down stream selection of the pure multi-charge Si^{+7} beam. The SiH_3^+ beam was then delivered to the RFQ for DRAGON at 63.24 kV, which is above the designed upper limit of the OLIS high voltage system. $^{139}La^+$, $^{141}Pr^+$, $^{23}Na^+$, $^{39}K^+$, $^{75,77}Rb^+$ and $^{19}F^+$ from the microwave ion source were also among the other beams delivered to the low energy areas [8].

2.2 Surface ion source (SIS) and arc-discharge mode

2.2.1 Surface ion source

The surface ion source (see Fig. 4) mounted onto the second port of the electrostatic switching box is equipped with an ionizing chamber and three ovens. The three ovens give it the flexibility to run three different temperature regions simultaneously (25–600°C, 600–1200°C, 1200–2000°C). The ionizing chamber is a 5 mm diameter, 5 cm long tantalum tube narrowed down to 3 mm diameter at the extraction side, which is heated by a tungsten filament. For elements with higher ionization potentials, the tantalum tube is replaced with a tungsten tube with rhenium inserts.

All the electrical and water-cooling connections are mounted onto the top single plate for easy removal and maintenance. The special feature of the source is that the extraction system is a removable one-piece unit, which can be replaced easily after contamination with alkali elements. It is designed so that all three electrodes including the ground electrode can be aligned on the bench with higher accuracy before installation to the terminal allowing minimum steering of the extracted beams during the operation.

To date over a dozen alkali and semi-alkali isotopes from lithium to praseodymium were delivered to experiments. A ^{23}Na ion beam of 10 μA in current was delivered to the 8π experimental area and 10 nA was delivered to DRAGON. ^{6,7}Li^{+} and ^{23}Na^{+} beams from SIS also were provided to βNMR and to the polarizer experiments[7]. ^{139}La^{+} and ^{141}Pr^{+} were produced by both MIS and SIS simultaneously and were delivered separately to experimental set-ups for atomic laser spectroscopy [9].

2.2.2 Arc-discharge mode of the surface ion source (HSIS)

To study radioactive capture reactions relevant for astrophysics, the recoil mass spectrometer DRAGON was built in the experimental area. ^{40}Ca(α,γ)^{44}Ti is identified as one of the key reactions in supernovae to produce ^{44}Ti and is given highest priority. For this experiment, an ultra pure Ca^{+2} beam was requested from the off-line ion source. Initial tests showed that when using conventional ion sources, ^{40}Ar and ^{40}K were the impurities that were most difficult to eliminate. In order to overcome this problem, a new concept was needed and the hybrid surface arc discharge ion source (see Fig. 4) was born. This ion source consists of a small surface ionizer and an arc discharge placed in a magnetic field produced by a small solenoid.

During surface ionization ^{40}Ar^{+} can be filtered out since it has a high ionization potential of 15.76 eV. Only ^{40}Ca^{+} and the ^{40}K^{+} is present in the arc discharge chamber since ionization potentials are 6.11eV and 4.34 eV respectively. By carefully selecting the arc voltage and the arc current, ^{40}K^{+2} with an ionization potential of 31.63 eV can be reduced while optimizing ^{40}Ca^{+2}, which has lower ionization potential equal to 11.87 eV.

Beam contamination can only be measured at high energy levels in an ionization chamber at the end of the recoil mass separator since the mass difference between ^{40}Ar and ^{40}Ca is less than 10^{-5} amu. A very low ^{40}Ar/^{40}Ca ratio of 8×10^{-5} for the hybrid surface arc discharge ion source was measured using an the DRAGON ionization chamber whereas the microwave ion source gave much higher values ($>5 \times 10^{-3}$). No indication of ^{40}K contamination was found from either ion sources. The current for the ^{40}Ca^{+2} beam was about 50 nA, enough to successfully perform the ^{40}Ca(α,γ)^{44}Ti experiment [10].

2.3 Multi-charge ion source (MCIS)—supernanogan

The design objective of the Supernanogan (a commercially available multi-charge ECR ion source from PANTECHNIK) addition to the OLIS ion source terminal is to provide multi-charge ion beams from the Supernanogan ion source while minimizing the impact on the microwave and surface ion source operation. The concept adopted

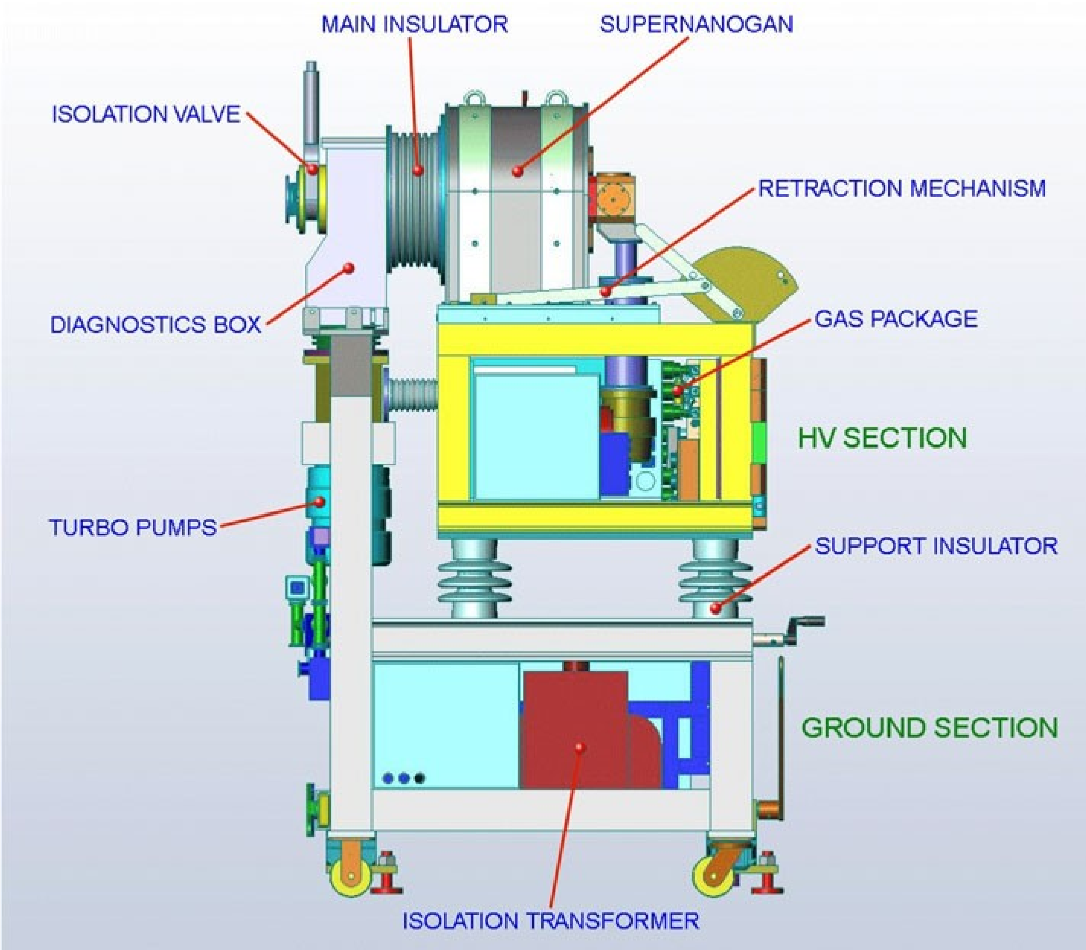

Fig. 5 The mobile station, referred to as the "cart", is a self-contained ion source system that has all the necessary power supplies, vacuum components, diagnostic devices and control systems

for this functionality is a mobile, virtually self-contained ion source station (see Fig. 5). This 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 distribution, computer controls and monitoring. The HV section contains the Supernanogan ion source and shielding, dry scroll vacuum pump, 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, and then the ground section controls connect to the OLIS controls 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 is in need of servicing, it can be disconnected (from the OLIS system) 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

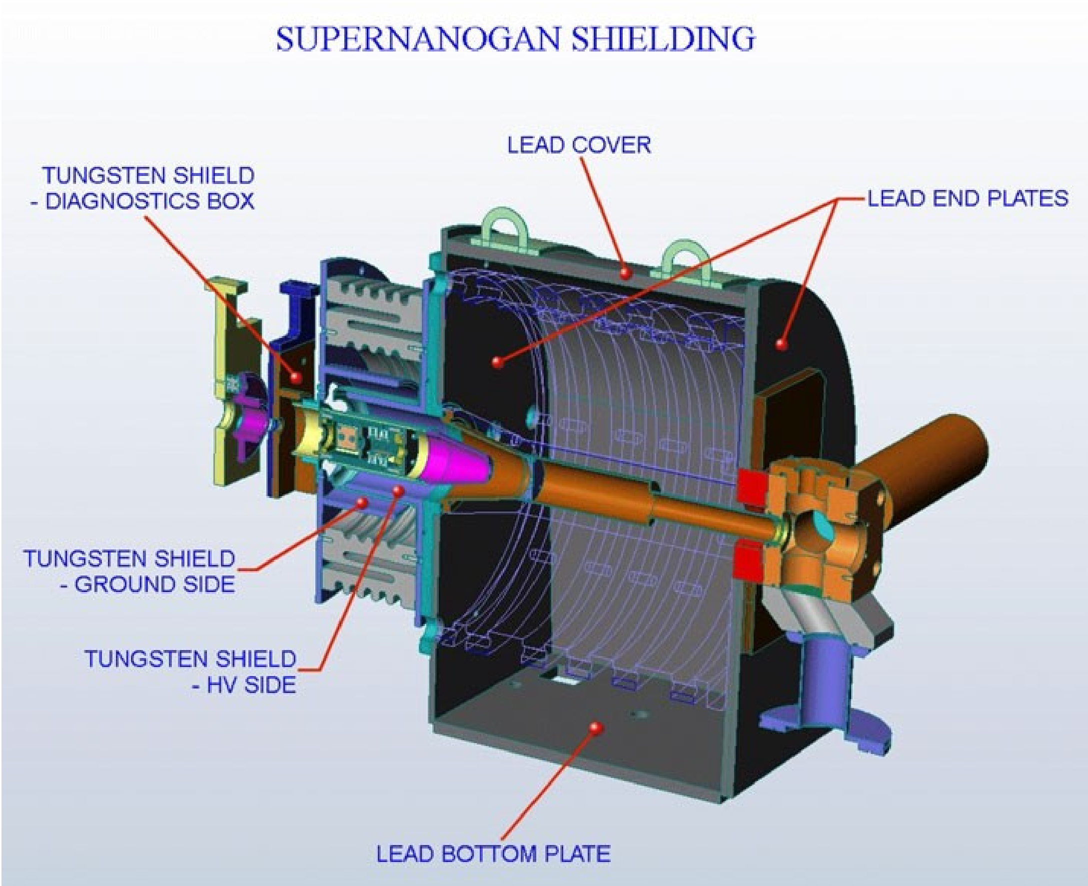

Fig. 6 This cutaway illustration of the ion source shows the extraction region with optical elements, HV insulator and X-ray shielding. Local shielding of the Supernanogan is achieved by a lead shroud with end and bottom plates. Shielding the extraction region is with Elkonite alloy since the X-ray shielding penetrates the vacuum space

operate, and the long conditioning times required for high charge states can be realized. The Supernanogan vacuum conditioning and maintenance time spent outside of the OLIS facility has no impact on the operation of the other ion sources. When the Supernanogan is required to provide beam to ISAC, disruption of OLIS beam operation by introducing the cart into the facility is minimal. Figure 6 is showing the extraction optics of the Supernanogan ECR ion source as well as its x-ray shielding.

2.4 A magnetic stabilization system

A magnetic field stability system was developed for the mass separator magnet at the OLIS. The magnet is connected to a main power supply capable of providing up to 500A. This power supply has a resolution of about 50 mA. The lack of resolution of the main magnet power supply, temperature effects to the magnet material and power supply and various other factors affect the magnetic field produced. This creates an unstable beam over short and long periods of time. Through the use of a PID (proportional-integral-derivative) controller, a small power supply with a better resolution is used to correct for changes in the magnetic field over time. An additional power supply is connected in parallel with the main power supply to provide

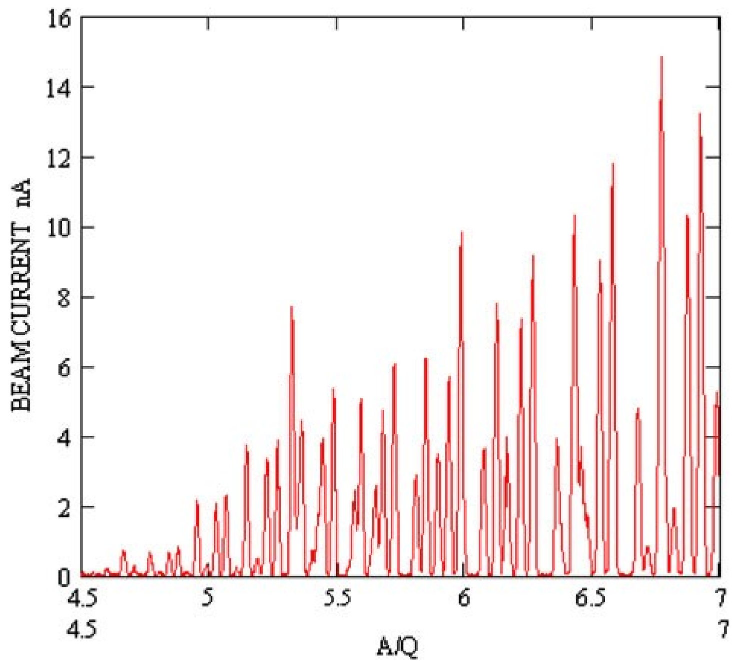

Fig. 7 Xenon multi-charge spectrum with 1 mm object and image slits. Most of the xenon peaks consist of isobaric and different charge xenon peaks. For example the peak at A/Q = 5.6 consist of a $^{128}Xe^{+23}$, $^{134}Xe^{+24}$, $^{129}Xe^{+23}$, $^{130}Xe^{+23}$, $^{136}Xe^{+24}$ and a little bit of $^{132}Xe^{+24}$, $^{131}Xe^{+23}$

a current resolution in the magnet of about 1 mA. The magnetic field was measured with a Group 3 MPT-141 Hall probe with a Group 3 DTM-151 digital Gauss meter. The second power supply is capable of correcting for as much as 40 Gauss in changes to the magnetic field with a minimum of 0.01G with 1 mA resolution in this particular set up. The PID controller is run continuously to correct for changes in the magnetic field as read by the magnetic field probe. It was found that, over a period of a week of operation, the magnetic field was kept steady to within +/− 0.2G using the PID controller to stabilize the magnetic field. This stabilizing system is paramount hold the exact A/Q for a prolong periods. For example holding at the $^{18}O^{+1}$ within the tail of the H_2O^{+1} peak and away from the maximum H_2O^{+1} peak is only possible with this stability method.

3 Results and discussion

3.1 Multi-charge ions and their efficiency studies

Multi-charge ionization can be achieved by either step-by-step ionization or by Auger transition. ECR plasma at higher frequencies is able to deliver enough energetic electrons (T_e) and electron densities (n_e) high enough to produce highly charge ions. Most importantly, the Golovanivsky's boundary condition [11] ($n_0/n_e \leq 7 \times 10^3 \xi T_e^{-3/2} A^{1/2}/Z$) must be fulfilled in order to increase the population of the given charge state, where Z: desired charge state, A = atom mass number and ξ = total number of electrons in the outer shell. Since ISAC needs A/Q ∼ 6, the background neutral density must reach 10^7 cm^{-3} or below, if the electron density is to be in the range of 10^{11} cm^{-3}. A very delicate balance of electron temperature versus electron density must be maintained in order to produce significant amount of higher charge ions in the range over mass 100 and A/Q<6.

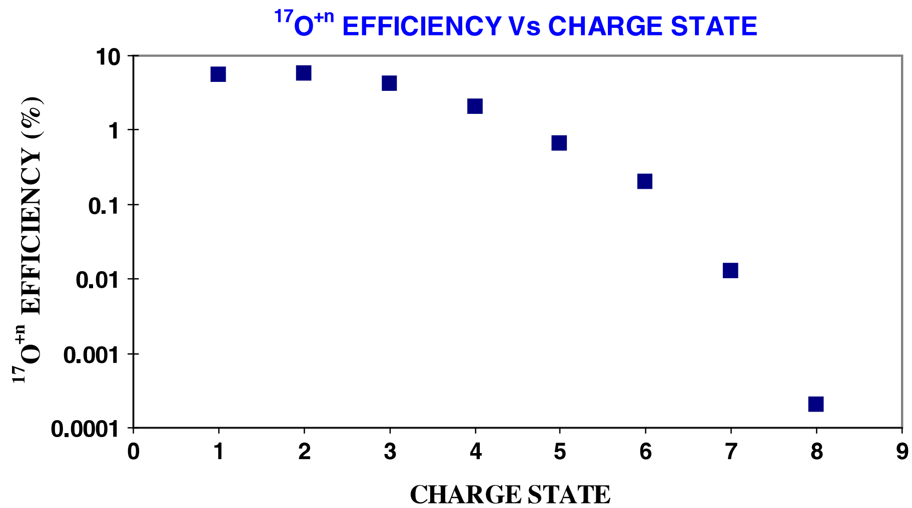

Fig. 8 ^{17}O efficiency vs. charge state was measured at 18 kV extraction with 2 mm diameter plasma aperture. For this measurement, the source was tuned for minimum emittance of charge state +3. The source pressure with the ^{17}O flow and when the high voltage is on and off are 4×10^{-8} Torr and 5.5×10^{-8} Torr respectively. Beam current is significant enough to affect the pressure

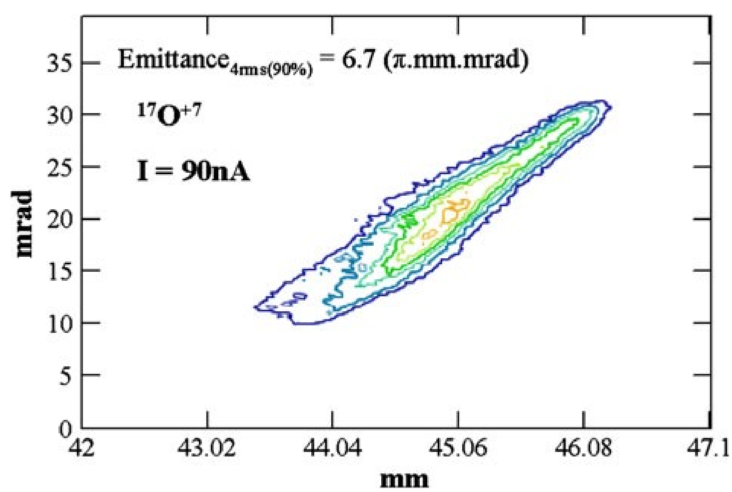

Fig. 9 Emittance of the $^{17}O^{+7}$ beam measured with a 2 mm diameter plasma aperture

Efficiency of the source was measured using calibrated leaks from oxygen and neon isotopes. In order to achieve maximum efficiency, the gases were sent directly into the source chamber through the hollow coaxial antenna of the source. The efficiency of each charge vs. mass is shown in Fig. 7. In order to match the acceptance of the ISAC RFQ, the plasma aperture was reduced to a 2 mm diameter.

3.2 Emittance vs. charge state studies

For emittance measurements, an improved version of the electric sweep scanner, originally proposed by Allison [12], was used. The emittance figure for $^{17}O^{+7}$ is shown in Fig. 8. It was found that the emittance of the extracted multi-charge ions varies with different charge states of the same element. Since the variation was very little, a new and more accurate data processing method had to be developed in order to minimize the noise reduction and emittance calculation error to ≤ 1 %. Figures 9

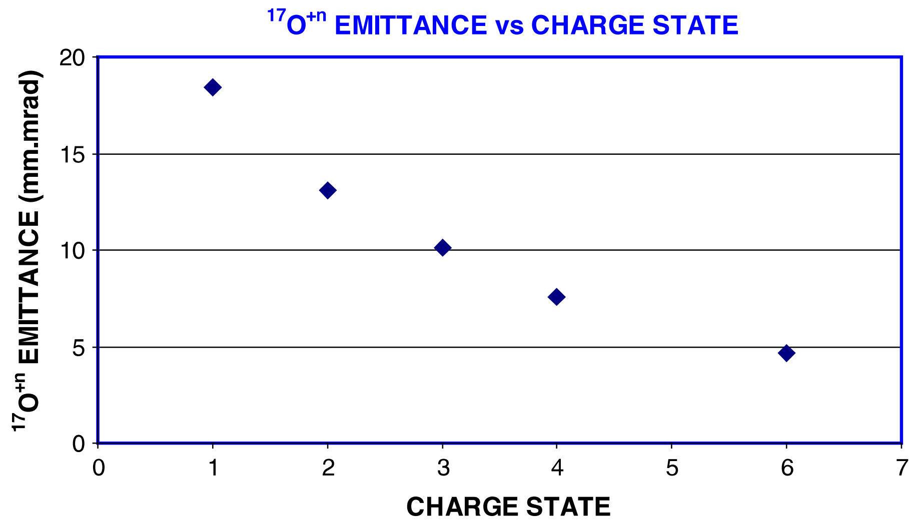

Fig. 10 ^{17}O emittance vs. charge state was measured at 18 kV extraction. The concentration of higher charge states near the centre of the plasma may explain the observed lower emittance of higher charge states

and 10 show the variation of the emittance values for different charges of ^{17}O isotope. Detailed analysis of the data is beyond the scope of this paper and will be published elsewhere.

4 Discussion and summary

The OLIS Terminal (with three ion sources, a microwave ion source, a surface ion source and multi-charge ion source) is capable of delivering from virtually any stable isotope close to A/Q = 6 or higher. Each ion source can be serviced outside the OLIS terminal while other sources provide the beam to the ISAC. To date a large number of isotopes have been delivered (see OLIS web page for details) to ISAC experiments including exotic isotopic beams such as $^{13}C^{+1}$, $^{17}O^{+3}$, $^{18}O^{+4}$, $^{33}S^{+6}$, $^{15}N^{+2}$, $^{21}Ne^{+5}$, $^{36}Ar^{+7}$, $^{74}Se^{+14}$, $^{80}Kr^{+15}$ and $^{130}Xe^{+24}$ from the multi-charge ion source, $^{17}Be^{+1}$, $^{18}O^{+2}$, $^{19}F^{+1}$, $^{15}N^{+1}$, $^{21}Ne^{+1}$, $^{24,25,26}Mg^{+1}$, $^{28,29}Si^{+1}$, $^{36}Ar^{+1}$, $^{35,37}Cl^{+1}$, $^{48}Ti^{+1}$, $^{58,60}Ni^{+1}$, Kr^{+1}, $^{139}La^{+1}$, $^{141}Pr^{+1}$ from the microwave ion source and most of the alkali beams from the surface ion source.

Regarding the multi-charge ion source, the ability to vary the frequency with very fine intervals has led to a significant enhancement of source performance. A few watts of RF power can be sufficient to provide the necessary multi-charge beams to ISAC. The emittance of multi-charge ions was measured. Observed lower emittance for higher charges can be explained by the concentration of higher charges towards the center of the plasma. With the installation of the Supernanogan a stripping foil is no longer necessary and the ISAC beam current capability for nonradioactive beams has increased by more than ten folds. Recently ISAC achieved one of it's milestones 1 GeV using $^{131}Xe^{+24}$ beam from OLIS. There are some discussions about using OLIS terminal for radioactive isotopes since it can produce large amounts from pre-prepared samples.

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