Helium jet ion source in FRIB era

J J Das¹,³*, H K Carter¹, J R Beene², B M Sherrill³

¹UNIRIB, ORISE, Oak Ridge, TN 37830.
²HRIBF, ORNL, Oak Ridge, TN 37830.
³NSCL, MSU, East Lansing MI 48825.

*Corresponding author email: dasjj@ornl.gov, jjdas@msu.edu.

Abstract. Gas stopping of reaction products has a key feature, fixed holdup time independent of element, making it possible to provide ion beams of essentially all element. Two classes of gas stopping have been developed over the last 40+ years, broadly classified as He Jet and Ion guide. A primary difference between these two techniques is the physical separation of the stopping cell and the ionization cell in the He Jet technique. In this paper we point out two applications of current interest where this physical separation is crucial: 1) ionization (ion beam intensity) is independent of primary beam intensity and 2) multiuser capability for accelerator facilities. Specific examples will be described.

1.0 Introduction:

Isotope Separator On Line (ISOL) facilities, like HRIBF, capability to provide beams is strongly dependent on ion source and target chemistry. While many beams are available at high intensities at ISOL facilities many beams, such as refractory and rare-earth elements, have very low efficiencies, approaching zero. For all elements, the efficiency of the ion source depends strongly on the holdup time inside the ion source/target which is described by the average time each atom resides on surface (adsorption enthalpy in the Frenkel equation) times the number of surface encounters. So, efficiency is dependent on hold up time which is element dependent. The fundamental problem in all cases is that the nucleus of interest must be released from surfaces within the target and transported to the ion source through a transfer tube. If one could develop a target/ion source where nucleus of interest has no contacts with surfaces many of the problems of ISOL systems would be significantly improved.

A variety of techniques have been developed since the early 1970s. The first such technique used was Helium Jet in which the reaction products were stopped in a gas cell where the He was mixed with an aerosol [1] and references therein. The aerosol loaded He transported the reaction products to a separate cell (an ion source) where the ionization took place. Difficulties with this technique included the gas load on the ion source and the operation of the ion source. In the 1980s the Ion Guide Isotope Separator Online (IGISOL) Technique [2] was developed in which the products were stopped in pure He gas cell. The basic idea was that the stopped products maintained 1⁺ charge state and was extracted out as beam. So an ion source was not required. More recently, RFIGISOL technique had been developed in which a combination DC and RF fields were used to obtain fast transport and repel the ions away from the walls and direct them to the extraction aperture [3].
Fundamental advantage of IGISOL (including RFGISOL) is faster extraction compared to Helium aerosol Jet.

A main limitation of IGISOL (or RF+DC IGISOL) comes from the drop of efficiency with increasing incident beam flux. Qualitatively this is understood because the incoming energetic, primary beam will produce free charges allowing the ionized reaction products to be neutralized [4]. However, in the He Jet technique stopping and ionization takes place in separate cells therefore one expects no such dependency. In a recent measurement in JAERI using Helium Jet Ion Source, efficiencies close to 20% had been achieved at such intensities [5].

In this paper we point out another application provided by the separation of stopping cell with ionization cell. In this application, for example at a fragmentation facility, we imagine placing the high pressure Helium Jet stopping cell at a beam dump of a fragment separator. That is, the stopping cell accepts one of the secondary beams allowing the primary beam to continue past. In a typical fragmentation reaction, hundreds of nuclei are produced but all except the primary beam are stopped on the slits. The stopped ions in the Helium Jet can be transported by a capillary to a separate cell (ion source) at a faraway place where an independent experiment can be carried out. Not only can a secondary experiment be carried out but the location is quite flexible since the transporting capillary is quite flexible and inexpensive compared to normal ion-optics beam lines. One such idea was proposed to stop fission products (from beam induced fission) in a high pressure Helium Jet cell and transport the radioactive products using a capillary from a ground level driver accelerator to an Ion Source located nearly 40m height above at the top of a vertical tandem and inject ion beams directly to the tandem for re-acceleration [6].

Our original intent was to develop and characterize a He Jet system for use with beams from HRIBF. With the closure of HRIBF our intent was changed to use such a system at NSCL / FRIB. To these ends we have established an offline test facility, Ion source Test Facility 3 (ISTF3). In this paper we will briefly discuss the current status of Helium Jet setup at ORNL and both these applications.

2. Status of Helium Jet at Oak Ridge National Laboratory:

The partnership of UNIRIB, The Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science and ORNL set out to assemble and test a complete He Jet ionization system incorporating key features of existing technology where possible. The Helium Jet system extensively utilized techniques/actual equipment from other laboratories, namely, the Chalk River National Laboratory’s High Temperature Helium cross-jet ion source [7], a Helium recirculation cart from Los Alamos National Laboratory [8] multi-jet target chamber and pumping system from ORNL [9]. The goal being to measure transport / ionization efficiencies of some elements in order to check reproduction of performance data published by Chalk River Laboratories [7].

A new laboratory enclosed space, named ISTF3 (Ion Source Test Facility 3), was complete by the end of 2009. The current layout is shown in Figure. 1. A 75 KVA, 3-phase isolation transformer was installed followed by HV insulated platforms with a distributed power panel and insulated cable trays. Following which, the equipment installed on the platforms at high voltage are: the Roots Blower, the diffusion pump and backing pumps, the Helium recirculation cart, Chalk River ion source, series of filters and the ion source power supplies. At ground potential are a water chiller to cool the ion source and the diffusion pump which is insulated by using de-ionized water as coolant and a resistive loop. The Helium jet target chamber and the shielding required for the Californium source are kept outside the room at ground.

To minimize both, the release of radioactivity contaminated Helium gas and the consumption of Helium, the system is run in a closed loop. The method of operation of the closed loop is as follows: Aerosol loaded Helium flows into target chamber at an appropriate flow rate to attain desired target chamber pressure of 6 atm. From the target chamber, a capillary of about 100 ft length carries the Helium and radioactivity to the side-jet ion source housing. This capillary ends just before the skimmer from where Helium expands out and are pumped by the Roots Blower and aerosol containing
radioactivity enters the side-jet ion source. This Helium then goes out thru the exhaust of Roots Blower and purified using a series of filters and then enter the recirculation cart, where three compressors (Metal Bellows pump) re-pressurize the Helium to 6 atm. Helium is then mixed with evaporated NaCl aerosols in a heated oven and re-enters the target chamber.

A new radioactive exhaust line made of insulating materials was constructed at ISTF3. All the pump exhausts (Roughing and backing pump) and PRVs (pressure relief valves) on the recirculation cart are connected to the exhaust line. The contaminants entering the exhaust line pass through a newly installed HEPA filter system located on the ISTF3 roof before exhausted.

Figure 1: Design layout of equipments for construction of the new laboratory (ISTF3) at Bldg#6010 at ORNL. Briefly, aerosol loaded Helium with radioactive products from the target cell inside the igloo (1) are transported to the ion source by a doubly contained SS capillary (yellow color) and goes over the roof and then enter the ion source through a metal insulator joint (3). Helium is pumped away by the Roots Blower (5) and enter a series of filters (6) and re-pressurized by 3 metal bellows pump on the recirculation cart (6) and then mixed with aerosols in an oven and then goes back to the target cell.
A wire fence containing interlock doors encircle all the equipment at high voltage for personnel safety. For controlling the equipment on the recirculation cart and the Roots blower in a high voltage compatible manner, an Allen Bradley system with optical fibre network made operational. A photograph showing the status of ISTF3 in March 2011 is shown in Figure 2.

Figure 2: Status of Helium Jet system at ISTF3 in ISTF3.

Figure 3 (a): Photograph of the newly assembled Chalk River Helium Jet Source at ISTF3 and Figure 3(b) shows a Photograph taken during off-line operation of the source.
3. Component Testing:

Prior to operating the entire system the individual components were tested. First an important test was to reproduce the performance of the Chalk River side-jet ion source. The newly assembled ion source is seen in Figure 3(a) and its photograph taken during the operation, in Figure 3(b). We have reproduced the published performances of the side-jet of the Chalk River Source [10] as shown in Figure 4. Published temperature profile of the source was also reproduced. We also obtained steady operation of the source continuously for about 40 hrs. The entire system was also operated in closed loop with designed pressure conditions for several hours.

**Figure 4:** We reproduced the published performances of the side-jet of the Chalk River Ion Source at ISTF3 [10]. A reduction in the ion source pressure to 1/6 is seen as the Helium flow starts into the side-jet. In Figure 5, reproduction of data from Los Alamos [8 and references there in] are shown. The linearity of data demonstrate the steady efficiency for a Helium Jet systems at high intensities for heavy ion fission products produced by U(p,F) reactions @ 800 MeV.

4. Transport Efficiency Measurements:

For measuring transport efficiency of the system, a $^{252}$Cf source will be used in the target chamber. Fission products will be stopped in high pressure aerosol loaded Helium and transported using the same capillary to the ion source location. For this test, a moving tape replaces the ion source with identical geometry of, side-jet, skimmer and the ion source.

Fission products will be directly stopped on the tape and carried to a newly installed HPGE detection system where decay gamma rays will be measured in $\gamma-\gamma$ coincidence. A coincidence data acquisition system using ORPHAS (Oak Ridge Physics Acquisition System) had been installed, tested and found to be operating satisfactorily. With these developments, the entire system can be operated with minimum personnel and also avoiding the need to be inside the cage even during non-HV operations. Transport efficiencies >80% has been measured using a Cf source and Helium Jet at Idaho National Engineering Laboratory [11]. In Figure 6, the photograph of the igloo constructed for shielding the radiation from Cf source is shown.
Figure 6: A photograph of the Igloo to house the stopping cell [9] with a 2 mCi Cf source inside. The green colored shield material is made of recycled sheets of 5% Boron doped polyethylene (BPE). The central recess tightly fits to the stopping cell. The Helium supply line enters from left and the main capillary leaves the cell through top to the ion source. The sheets outside are to be inserted after the stopping cell is secured in position and all gas connections are completed. Physically the Igloo is located north of ISTF3 laboratory (See Figure 1).

5. Application of Helium Jet for High Primary Beam Intensities:

No dependency of Helium Jet efficiency with respect to the primary beam intensity is expected. This is because the primary beam impinges the stopping cell which is physically separated from the cell. In Figure 5, we see linear increase of rates of reaction products as incident proton beam intensity was increased [8]. Bai et. al. used 800 MeV proton beam on a target of ~15 mg/cm² ²³⁵U₂O₃ with a total Uranium weight of ~4 gm. The estimated beam power on the target was approximately 5 kW and rates of fission and spallation products exceeded 10¹³/s [12]. Figure 7 is a simplified picture of a Helium Jet system where we show the stopping cell, transport capillary and the ion source all separated in space. Thus the events in the stopping cell does not affect the ion source functioning.

Figure 7: A schematic of a Helium Jet system to illustrate the concept of separation of stopping and ionization region.
Figure 8: (a) Chart of nuclei shown to explain the multiuser concept for FRIB. Typically at a fragmentation facility, prime interest is decay of exotic nuclei. However, the same reaction also produces numerous other nuclei. ISOL beams of many of these species are intense for ISOL beam experiments. As an example, \(^{48}\text{Ni},^{56}\text{Ni}\), \(^{132}\text{Sn},^{58}\text{Ni}\) are produced from same primary beam of \(^{58}\text{Ni}\) and \(^{235}\text{U}\) respectively. In Figure 8(b), specific case of Sn isotopes produced simultaneously with \(^{100}\text{Sn}\) beam is illustrated.

6. Helium Jet and FRIB:

Here the basic idea is to perform a parallel experiment at FRIB when the main experiment is in progress, which is named as multiuser mode in this paper. We explain the concept behind this application with the aid of Figure 8(a), showing the chart of nuclei.

Figure 9: Probable location(s) of the Helium Jet stopping cell inside FRIB pre-separator shown by vertical arrows (red colour). The entrance of the cell will have a thin window and the cell is approximately 10 cm in length and 3 cm in diameter, operated at 6 atm. The space required is a cube of about 6 inch x 4 inch x 2 inch. For operation of the stopping cell, upstream of S1A dump slits, a Ar/Xe wedge discussed in following section may be used for efficient momentum compression.
When a particular experiment is being carried out, e.g. $^{48}$Ni decay, $^{58}$Ni is used as primary beam. The same beam also produces numerous other nuclei including e.g. $^{56}$Ni, which is a good ISOL beam. While details of the fragment separator settings will determine exact rates and the species available, conceptually, a second species can be stopped in a Helium Jet gas stopping cell. The rates for $^{56}$Ni is $\sim 10^{11}/s$.

In Figure 8(b), we illustrate a specific case at FRIB pre-separator with $^{100}$Sn study. Using $^{112}$Sn as the primary beam @ 220 MeV/A, the fields of fragment pre-separator of FRIB is set for $^{100}$Sn products. Rates of other p-rich Sn isotopes upstream of the S1A slits are shown in this figure.

There will be numerous other nuclei produced in the target and if these can be stopped and ionized, then a parallel experiment can be performed. In Figure 9, we show the schematics of locations of the Helium jet stopping cell (red arrows pointing up) inside the FRIB pre-separator. It could be located upstream of slits or even a wedge. Because of its compact shape, demand for space inside the separator will be less and might be possible to placed in most effective locations.

8. Momentum compression of relativistic fragments:

Stopping of relativistic fragments using a compact Helium Jet cell, will not be at all efficient using momentum compression. Therefore, for using the Helium Jet stopping cell upstream of a wedge, a simple Ar/Xe wedge may be used. The conceptual scheme of the wedge is shown in Figure 10(a).

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**Figure 10:** (a) shows the stopping and bunching schematics (details in text) for relativistic heavy ions using Helium Jet stopping cell shown in previous figure. In Figure 10(b) the energy bunching achieved using this setup for entire mass range of A=50-230 are shown. Due to the good bunching capability, about 80% stopping efficiency can be achieved with a compact cell.

As an example, stopping of about 10-20 GeV, Sn fragments are required. In the dispersive plane, the energy spread of fragments is assumed to be about $\sim$8% from 9.1-9.9 GeV. After retarded by a suitable solid degrader, the fragmentation products enter the wedge filled with Ar/Xe @ 6 atm. For a typical energy dispersion of 4 mm/% at this focal plane, an entrance cell dimension of 40 mm in
diameter of the wedge is adequate. Degrading gas thickness of 0-30 atm.cm of Ar or Xe can be easily obtained with a cell of length up to 50 mm.

The residual energy of the fragments downstream of the wedge is green circle, blue diamond and red triangle for incident energy of 9.1, 9.5 and 9.9 GeV Sn isotopes respectively. We also studied the quality of the energy bunching of this wedge for a wide mass range from A=50 to A=230. Results are shown in Figure. 10(b). In this, we plot the residual energy, $E_{\text{res}}$, as a function of A(amu) and the quality of energy bunching is adequate for the proposed application.

9. Expected performances of the HeJet system at FRIB:

A Helium jet capillary can transport these stopped ions with high efficiency to an ion source. As mentioned earlier, stopping and transport efficiencies >80% have been achieved [11]. The combined efficiency of the ion source and separator for mass separated beam had been measured earlier [7] and is shown in Table 1 below.

The initial rates of Sn fragments incident on the stopping cell for a particular location (upstream of S1A dump slits) can be estimated from Figure. 8(b) when FRIB pre-separator is set for $^{106}$Sn. Assuming a stopping/transport efficiency for Helium Jet as 50%, and using ion source efficiency of 5% for Sn isotopes, we get the rates of low energy mass separated Sn beam. This is shown in Table 2. For comparison, we also show rates of ISAC @ TRIUMF. This clearly illustrates the difficulties associated with production of p-rich ISOL beams and advantages of FRIB+HeJet for these beams. Our study tends to indicate that this could be valid for a wide variety of p-rich species.

10. Summary and conclusions:

We discussed the status of a Helium Jet ion source system being developed and tested at ISTF3, ORNL. The project had started in early 2009 and almost halted in spring 2011 following closure of HRIBF, ORNL. During this period, a new laboratory was built, equipments were installed and tests reported in this paper were performed. We also described the unique capabilities of this version of gas stopping technique to FRIB: ionization efficiency dependence on primary beam intensity and multiuser capability. From our simulations, it appears the concept may be competitive to produce
ISOL beams, especially of p-rich nuclei. We believe this would justify the need to complete the commissioning of ISTF3 and bring it to NSCL for further tests.

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