TARGETS AND ION SOURCES DEVELOPMENT AT ISAC-TRIUMF*

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Abstract

The ISAC Radioactive Ion Beams (RIB) facility is operational since November 1998. The facility utilizes the Isotopic Separation On Line (ISOL) method to produce the RIB. The ISAC facility at TRIUMF utilizes up to 100 μA of proton at 500 MeV from the existing H- cyclotron. The science program at ISAC ranges from the nuclear astrophysics to the fundamental symmetry. The facility can deliver RIB to the low energy area and a linear accelerator composed of a 4-rod RFQ and a linear accelerator can provide beam from A = 3 to 30 amu with an energy range from 0.15 to 1.5 A*MeV. An accelerator upgrade is under way and will allow us to extend the mass range to A=150 amu and the energy up to 6.5 A*MeV.

A novel approach for the target/ion source station allows us to bombard the thick target with un-precedent beam intensity without compromising the worker safety. The target/ion source assembly and heavy ion optics components are located in a shield canyon under 2 m of steel shielding allowing high proton beam intensity on thick target.

At the beginning the production targets were operating at 2-5 μA but rapidly the proton beam intensity was raised to 40 μA. Now, we operate up to nearly 100 μA proton beam using the new high-power target design equipped with radial fins. While, the production target capabilities improved quite a lot, from 2 μA to 100 μA, the ion sources development did not follow the same trend.

In order to develop new RIB at ISAC we need to develop new ion sources. A resonant laser ion source (TRILIS) was developed using 3-Ti:Sapphire lasers equipped with the necessary frequency doubling and tripling. We already produced ^{26}Al and ^{62}Ga beams with the new laser ion source. A new FEBIAD ion source is under development, it is being tested in the moment and we are planning to install it on-line next spring. Finally, a new ECRIS is being developed with the goal to obtain higher ionization efficiency and also high gas throughput. Off-line tests are planned to begin mid 2006.

INTRODUCTION

The ISAC facility has been designed for the production of very intense radioactive ion beams (RIB). To achieve that gold we design the facility to take advantage of the intense proton beam available from the TRIUMF 500 MeV H$^-$ cyclotron. A new 100 μA beam line (BL2A) has been built to deliver beam to two target stations, see fig. 1, just north the cyclotron.

The ISAC Facility at TRIUMF is operational since 1998. Since then we have increase the proton beam intensity on our target from 2 μA to 100 μA on refractory foil targets (Ta, Nb), mainly due to the development of a high power target that can dissipate 20 kW of beam power. Furthermore, the development of composite carbide target backed with graphite foil allows us to reach similar proton beam intensity.

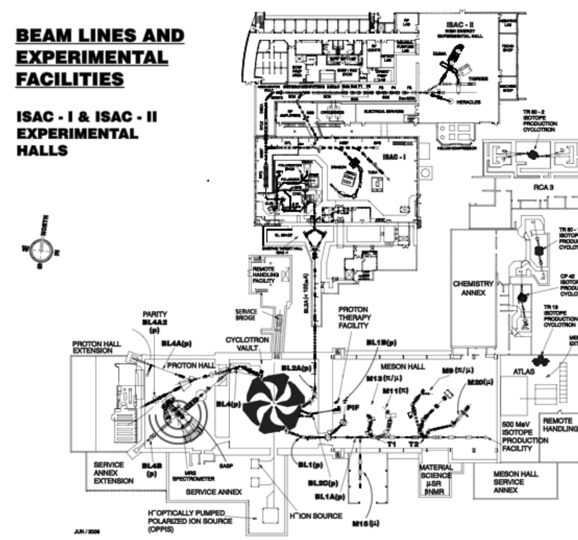

Figure 1: Layout of the TRIUMF site. At the bottom of the figure we can see the H$^-$ cyclotron and the different proton extraction beam lines.

Unfortunately, the development of ion sources did not follow the same trend. The main reason if the difficulty to coupled an ion source with such high power target. The main ion source used at ISAC since the beginning is a hot surface ion source and recently we added a resonant laser ion source.

Development of other type of ion sources (mainly plasma ion source) is under way to increase the number of elements one can produce at ISAC.

PRODUCTION TARGET STATION

The isotopic separation on line (ISOL) method consists of bombarding a thick, heavy Z material target with an intense light ion. The reaction products created by the collision of the proton on the target nucleus are stopped in the bulk of the target material. Once the products are stopped they diffuse to the surface of the foil or granule. The next process involve the desorption from the surface and the effusion from place to place until the atoms reach the ion source where they are ionized to form an ion beam. The target material is usually at high temperature to enhance those processes.

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Because of the intense proton beam on a thick target we had to develop new techniques to handle and service the target. Contrary to low intensity ISOL facility our target stations are installed into a pit shielded by 2 m of steel and 2 m of concrete. Reference 1 and 2 describe the target station is used at ISAC.

The target stations are located in a sealed building and the target servicing is done using an overhead crane. The target maintenance facility includes two hot-cell for target change and maintenance, an assembly area, a small decontamination facility and a radioactive storage area.

On-Line Target

The target/ion source has to be radiation hard. This aspect is very important since the overhead to change a target takes between 2 to 3 weeks. This means to be effective that the target/ion source assembly has to be operational for at least the same period.

The ISAC target design consists of a 19 mm diameter Ta 2.5% W alloy tube 20 cm long with an integral transfer line/surface ionization source electron beam welded perpendicular to the p beam axis. The design has been described in [3]. The current ISAC target container was originally designed for operation with proton beam intensities of a few μA. For such low intensity beams, the power deposited in the target material is generally of the order of a few Watts. To maintain the high temperatures (2200 ºC) required for efficient diffusion and effusion of the products, targets are heated by a DC current passed through the target container; the Joule heating is regulated by varying the current of the 1000A-10 V heater power supply. Initially, the target containers were wrapped with 3 layers of thin 25 μm Ta foil heat shields to increase the heating efficiency.

To go beyond the 40 μA we need to improve the cooling. An easy way to improve the radiative cooling is to increase the emissivity of the target oven. A bare Ta surface has an emissivity of 0.3 to increase this value we add radial fins on the target oven. Off-line tests using electron beam bombardment show that with such a fin arrangement the emissivity is close to 1. The maximum beam power we can dissipate is then around 20 kW [4].

Since 2004 when the first high power target was installed on-line we ran 8 high power targets. We now operate them at the maximum proton beam intensity we can use at ISAC, say 100 µA. The on-line target is made of several type of material that is packed inside the target oven.

We developed carbide target that is supported onto a carbon sheet that allows a better heat transfer. We have developed a high power target using fins that can dissipate 18 kW of the deposited beam power. This high power target allows us to operate up to 70 A. Now the beam profile limits the beam on target. We are envisaging the installation of an ac magnet to rotate the beam on target.

ION SOURCES

It is a challenge to transpose an ion source for the on-line application. Off-line ion source for accelerator does not have to be very efficient, a few percent most of is sufficient to provide the necessary intensity. Since in the on-line case the available quantity is quite reduced compared to the off-line case the ion source has to be very efficient. Furthermore, the ion source has to operate in a very harsh environment, high radiation field. Since it is impossible to control the outgasing of those targets at high proton flux the ion source has to be efficient over a wide pressure range.

There is no universal ion source that is available in the moment. We have specialized ion source for each chemical group. The surface ion source has high ionization efficiency only for the alkali and some lanthanide elements. It is not suitable for the transition metal and the gaseous elements, where laser and plasma ion sources are more efficient. We started two years ago a program that will permit to equip ISAC with all the necessary on-line ion sources in order to give access to most of the elements in the nuclear chart.

Present On-Line Ion Sources

From 1998 to quite recently we only have a hot surface ion source for the on-line production. An electron cyclotron resonance ion source operating at 2.45 GHz has been installed on-line with not very successful results. Partly, due to the high gas load required to operate the ECR and from the out-gazing of the target under proton bombardment.

Resonant Laser Ion Source

The main advantage of the resonant laser ionization is the fact that we can envisage to produce ion beam of only one element. High selectivity can be achieved by combining the distinctive resonant ionization scheme of a specific element and a large acceptance mass separator. The mass separator acts only as an isotopic separator, select A and A±1 only. Thus reducing the need for high resolving mass separator.

At the design phase of the ISAC facility a laser ion source was already foreseen. The room above the mass separator was built in order to house the laser ion source to minimize the distance between the laser table and the target. In our case the distance is approximately 12 m. At the time only Copper Vapour and dye lasers equipped with frequency doubler and tripler were used for RIB production. In the recent years the Ti doped Sapphire (Ti:Sa) lasers became more available and proven to be a good alternative to the dye laser.

The TRIUMF resonant ionization laser ion source (TRILIS) was designed to use modern, all solid state lasers, more detail can be found in reference [5]. This resulted in a system of up to three simultaneously pumped TiSa lasers with optional frequency doubling and tripling. The pump laser is also a high power, high repetition rate, solid-state laser, thus adding high uptime and low maintenance requirements.

This laser system with all associated diagnostics and beam transport is located in a quasi clean room environment. For resonant laser ionization the following conditions have to be met:

- Precise wavelength control
- Laser beam overlap (temporal & spatial) in target ion source
- Saturation of optical transitions
- Laser beam overlap monitoring
- Efficient laser excitation/ionization scheme

Figure 2 illustrate the kind of development one have to perform before being able to establish which schemes is the best for resonant laser ionization. The schemes represented on the left hand give approximately the same ionization efficiency, ~ 3 to 5%. The most promising scheme is the one represented in the upper right of figure 2. If one can find a high level Rydberg state close enough to the ionization threshold we will have a better laser pumping efficiency. The loosely bounded electron can then be removed very efficiently using an electric field. To find those high level Rydberg states we need to scan with a third Ti:Sa laser while the two others are locked in frequency.

First beams produced using the laser ion source were ^{62}Ga and ^{26}Al. Recently we developed two other elements using the laser ion source Be and Ag. The preliminary ionization efficiency using the laser ion source is estimated to be between 1% and 5%. As the Ti:Sa laser excitation schemes rely on mostly unknown atomic spectroscopic data one can see that laser ionization development is time consuming, an off-line test stand is under construction that will allow the laser spectroscopy of new elements using the Ti:Sa laser.

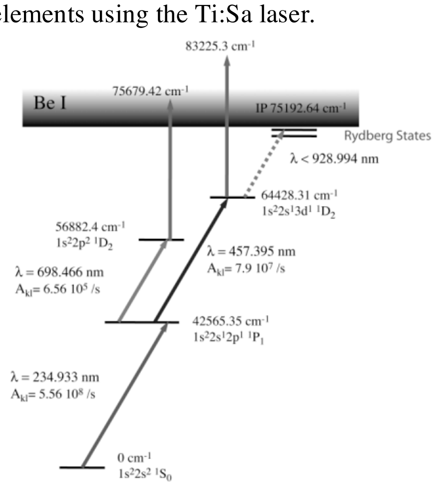

Figure 2: Illustration of the resonant laser ionization schemes we used for the Be ionization.

Plasma Ion Sources

To have access to a larger number of elements we are developing a plasma ion source similar to the one developed at GSI by R. Kirchner and Roekl [6] and at ISOLDE/CERN by Sundell[7]. The FEBIAD (Forced Electron Beam Induced Arc Discharge) ion source is one of the most used ion source for on-line application. The main advantage of this plasma ion source is its ability to operate in a wide pressure range. It makes it suitable for operation with very high proton beam on target. A prototype of this type of ion source has been successfully tested last spring. Figure 3 shows the FEBIAD ion source adapted for the ISAC target. A hollow cathode allows the transfer of the radioactive atoms from the target container to the plasma chamber. The electrons from the cathode are accelerated toward the anode grid and impinge onto the gas. The other endplate facing the cathode can be at different potential depending on the mode of operation. If the endplate is at the anode potential we have the direct mode, if on the contrary the endplate is that the same potential as the cathode we have the oscillating mode, the electron are repelled back and forth from the cathode to the repeller electrode. The ions are extracted through a concentric hole in the endplate facing the cathode endplate.

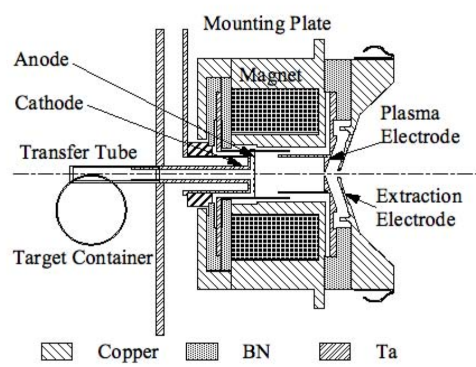

Figure 3: Schematic view of the FEBIAD Ion Source under testing at ISAC.

A new ECRIS for on-line applications is being developed. The main goal is to design an ion source that will be able to stand the high pressure coming from the target material. Since we cannot use permanent magnets close to our target, we are developing a 6 GHz ECRIS similar to the 2.45 GHz constructed at GANIL Ref. 9 where the radial confinement is accomplished using two sets of coils.

CHARGE STATE BOOSTER (CSB) DEVELOPMENT

Most on-line ion sources produce singly charged ions but efficient acceleration requires high charge states. For ISAC at TRIUMF the acceptance of the accelerator is at an A/q value of 30 and if further stripping should be avoided it is at A/q≤6. An ECRIS (14 GHz PHOENIX from Pantechnik) has been set-up at a test bench.

Singly charged ions produced by several ion sources of the same type as the on-line were used to inject singly charged ion beams into the ECRIS. The goal of the tests has been the optimization of the breeding efficiency and the investigation of the breeding time. The maximum charge breeding efficiencies obtained so far are up to 6 % for noble gas and about 3.5 % for alkaline elements. The breeding time for the highest charge state acceptable for the accelerator system is around 400 ms.

A mass separator that combines magnetic and electrostatic sector fields ensures a good separation. Table 1 summarizes the results obtained for noble gases and alkali metal. For masses larger than 80, we do not obtain the necessary charge states. The ISAC-I linac was designed for A/q ≤ 6. This will force us to upgrade the MEBT bender magnets and the DTL RF system for the last two tanks.

Table 1: Charge State Booster Efficiency for CSB

Element	Mass	Q (A/q)	Efficiency (%)
Ar	40	8+ (5)	5.5
Kr	84	12+ (7)	6.3
Xe	132	17+ (7.8)	4.8
K	39	9+ (4.3)	2.1
Rb	85/87	13+ (6.5)	3
Cs	133	18+ (7.4)	2.7

There some improvements we would like to do before the CSB is installed after the mass separator. We would like to change the extraction from a single gap to a double gap and to add an Einzel lens following the extraction system. This will allow a better adaptation to the beam line. The other improvement we foresee is a better injection scheme from the 1+ ion source to the PHEONIX ion source. In the moment it is a single deceleration gap. We would like to test a new system similar to the one used for the RFQ cooler developed in several laboratories. This deceleration system offers a better adaptation and avoids the creation of large beam divergence when the ions slow down to few eV.

FUTURE DEVELOPMENT AT ISAC

New Target Stations

In the moment only one experiment can receive RNB at the time. This limits greatly the physics output from ISAC. We looked at other possible source for a second RIB source. We investigate several options; a small cyclotron (30 MeV- 200 μA) similar to the Louvain-la-neuve RIB facility [9], a gas-jet system similar to the one developed at Chalk River [10] and an ion guided isotope separation on-line, IGISOL system [11].

But, we came to the conclusion that we can extract another 200 µA from our cyclotron. We can use the currently available BL4 proton beam and bring the beam north to the main cyclotron building and into two new target station located into the ISAC-I target hall west of the currently used target stations.

This will allow us to have two experiments running simultaneously. Furthermore, having another target station will allow us to perform development of targets/ion sources without the slowing down the physics program at ISAC. Figure 4 shows the layout of the ISAC facility with respect to the centre of the cyclotron.

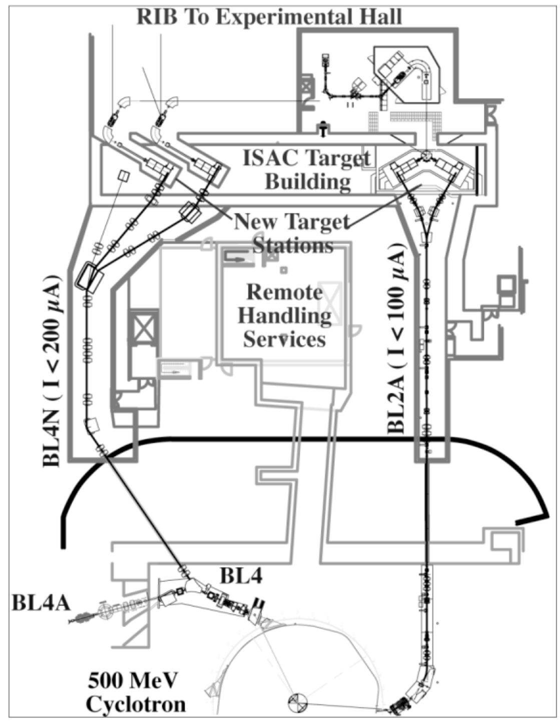

Figure 4: Layout of the 500 MeV proton beam line from the cyclotron that will allow two new target station for the ISAC facility.

New ISOL Front-End Concept

When ISAC was in its design phase we had little experience with high intensity proton beam on a thick ISOL target. We built our target station using a similar approach that is in used for the meson factory, ie, the target is located at the bottom of a plug in a canyon type beam line and heavily shielded with concrete blocks all around. This concept has been transferred to the ISOL system and proved to be adequate for low intensity and the use of non-actinide target. The main issue here is the fact that the containment-box that housed the target/ion source is not hermetically. The other issue with the actual concept is the fact that it takes three weeks turn around when we have to change a target. Further more, since we are operating ISAC at 100 μA the turn around may have to increase to allow some cool-down before someone can disconnect the services.

In the moment to avoid too much of down time we are forced to operated the same target/ion source assembly for at least three weeks. This is the most restrictive issue, as one knows that the production of RIB using the ISOL method implies operating targets at very high temperature using fragile ion sources and an extraction system that has to stay clean to prevent electric breakdown.

We know now that when operating our facility at 100 μA for only a couple of days that we produce enough material to contaminate the extraction electrode. This means that is has to come out with the target/ion source assembly to be changed on a regular basis.

The proposed new ISOL front end must address the following concerns;

- Must operate at 200 μA -500 MeV proton,
- A quick turn around, ~ 1 day,
- A sealed containment-box to avoid contamination during target/ion source change,
- Disconnection of the target/ion source services remotely.

Figure 5 shows a conceptual drawing of the proposed new front-end system. The target and the ion source are at ground potential inside a vacuum-sealed containment box equipped with a radiation hard gate valve. The extraction system is bias negative with respect to ground that reduce the complexity of the services requirement for the target/ion source operation.

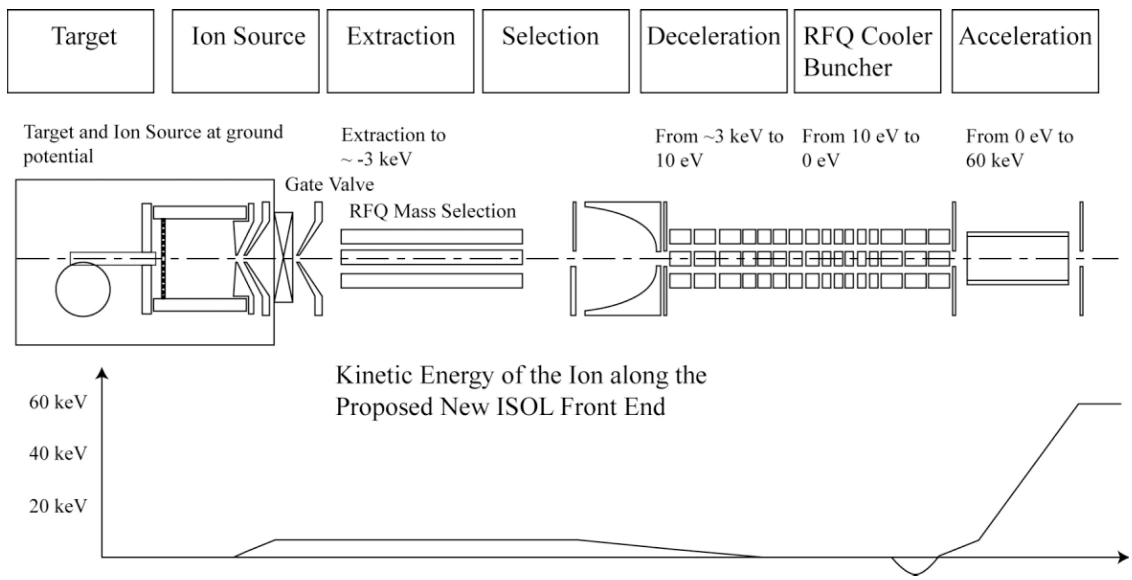

Figure 5: Schematic diagram of the proposed new ISOL front end concept.

A mass selection is done to remove most of the contamination. The RIB is then cooled using a He gas filled RFQ cooler and then the beam is bunched at the end of the RFQ. The ion bunch is then push to the drift tube for the final energy acceleration.

DISCUSSION

The development of carbide targets that is supported onto a carbon sheet that allows a better heat transfer. Combine with the high power target we are now able to operate those carbide and Ta foils targets up to 100 μA.

We have developed a resonant ionization laser ion source that uses all solid-state lasers. After first on-line ^{62}Ga for lifetime and branching ratio measurements in Dec. 2004 we developed ^{26}Al last summer for the nuclear astrophysics determination of the direct proton capture ^{26g}Al(p,γ)^{27}Si. The ^{26g}Al obtained was 6.3 10^9 p/ s with the lasers on and 1.2 10^9 p/ s with the laser off.

It is of prime importance to develop ion sources that can efficiently ionize gas elements for the nuclear astrophysics program. We are developing at a FEBIAD and a new ECRIS in order to increase the number of beams at ISAC.

Two new target stations on a new high-energy proton beam line are envisaged that will permit delivering at least to RNB at the same time. The new target stations will be housed into an extension of the ISAC target hall allowing the use of the same remote handling and air handling capabilities that are in used in the moment.

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