HIGH POWER TARGETS FOR ISOL RADIOACTIVE ION BEAM FACILITY

P. G. Bricault, M. Dombsky, P. W. Schmor, TRIUMF, Vancouver, B.C., Canada
A. Dowling, U. of Victoria, Victoria, B.C., Canada

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 new ISAC facility at TRIUMF utilizes up to 100 μA of proton at 500 MeV from the existing H^- cyclotron. In 2000 the laboratory was approved to extend the mass range from 60 to 150 and the energy range from 1.5 to 6.5 A*MeV.

At the beginning of ISAC operation the proton beam intensity was limited 1 to 40 μA on foil targets and to 1 to 15 μA on compound target. The development of new kind of target allows us to run routinely to 50 μA even on compound targets, such as Nb, Ta, SiC, TiC and ZrC.

INTRODUCTION

The ISAC facility is described elsewhere [1], it is a radioactive ion beam (RIB) facility that uses the isotope separation on line (ISOL) technique to produce radioactive ion beams (RIB). The ISOL system consists of a primary production beam, a target/ion source, a mass separator, and a separated beam transport system. These systems together act as the source of radioactive ion beams to be provided to the accelerator or the low-energy experimental areas. We utilize the 500 MeV - 100μA primary proton beam extracted from the H^- cyclotron. A new beam line has been built to transport this beam to one of the two target stations followed immediately by a residual proton beam dump.

A novel approach for the target/ion source station allows us to bombard the thick target with unprecedent 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.

Existing foil targets can accommodate up to 40 μA beam intensities and the available intensities of many radionuclides can be expected to scale with the proton beam currents. But, production targets capable of withstanding proton beam intensities up to 100 μA without compromising the radionuclide yield and the lifetime of the target is a challenge. Several approaches to the dissipation of the power in such targets have been investigated and a realistic solution for the removal of the heat from the target container is proposed.

However, for composite target the heat transfer within the target material itself is highly target dependent. We start investigating the coating of target material with highly conductive carbon foil. First tests with SiC, TiC and ZrC show that we can operates up to 50 μA proton beam intensity for period greater than 10 weeks without compromising the yield significantly. A new target equipped with radial fins was built and tested off-line.

We recognize that target and ion source development is sometime a long process. It interferes with the science program since we use the same target station. It is propose for the next 5-year plan to built a dedicated target station for target/ ion source development.

ISOL METHOD

The ISOL method is well described in Ref. [1] and reference therein, we will just give the basic principles that guide the release of radioactive atoms from a thick target in order to understand the issues we are facing. In the ISOL method a light, energetic beam bombards a high Z target material. The radiogenic elements produced in the collisions are stop into the target material matrix. As we can see the resulting amount of radiogenic elements are in minute quantity with respect to the bulk of the target material. The yield of the wanted specie can be expressed as follow:

$$Yield(/s) = \sigma \Phi_p N_t \varepsilon_d \varepsilon_e \varepsilon_i \varepsilon_t \qquad (1)$$

Where σ is the reaction cross-section, Φ_p the proton flux, N_t the number of target nuclei. The maximum possible rate is attenuated by the efficiencies ε of product diffusion, effusion, ionization and transport respectively.

The release of the exotic atoms from the target to the ion source can be view as two different processes, 1) the diffusion inside the crystal to the surface of the grain or foil, 2) the effusion from place to place until the atom reaches the ion source opening. The two processes can be expressed fairly well using the Fick's laws and are well described by Kirchner [2]. The physics program interested in using radioactive ion beams is mainly interested by nucleus far from stability, where in general the half-life is quite short, few ms to s. To obtain an efficient release of those short-lived nuclei we usually operated the target at high temperature.

Diffusion Process

Solid state diffusion is driven by the concentration gradient of impurities or vacancies. Fick's equation describes well this mechanism.

$$\frac{\partial n}{\partial t} = D\nabla^2 n - n\lambda, \qquad (2)$$

where, D is the diffusion coefficient, which varies with the temperature and the activation energy. It can be expressed as follow,

$$D = D_0 e^{(-E_a/kT)}. \qquad (3)$$

The activation energy is the energy that must be supplied to the atom through the lattice to enable the atom to move from site to site. The diffusion coefficient D_0 depends on the vibration frequency and lattice parameters.

The release efficiency can be found by solving equation 2,

$$\varepsilon_D = \frac{\tanh\sqrt{\lambda\pi^2/4\mu_0}}{\sqrt{\lambda\pi^2/4\mu_0}}, \qquad (4)$$

$$\lambda = \ln 2/T_{1/2}.$$

where, $\lambda = \ln 2/T_{1/2}$, $T_{1/2}$ is the half-live of the nuclei, $\mu_0 = \pi^2 D/d$, d is related to the grain size or foil thickness.

Effusion process

Once the atom has diffused and reach the surface of the granule or foil the next step is governed by the effusion process, which is the equivalent of the evacuation of a volume through an orifice. This process depends on the following parameters:

1) the mean number of collision with the target material surface and container walls,

2) the mean sticking time per collision, which depends on the temperature and absorption enthalpy ΔH_a.

3) the mean flight time between collision, which depend on the mass, temperature and target geometry.

This process can be described using an exponential time dependence with a time constant ν.

$$1/\nu = \chi(\tau_a + \tau_f), \qquad (5)$$

where, τ_a is the mean sticking time and τ_f is the mean flight time between collision. The mean sticking time is given by the Frenkel equation

$$\tau_a = \tau_0 e^{(H_{ad}/kT)}, \qquad (6)$$

where H_{ad} is the absorption enthalpy, T the temperature and τ_0 is the lattice vibration period. H_{ad} depends on the chemistry between the atoms of interest and the target material.

The effusion efficiency is expressed by

$$\varepsilon_e = \upsilon/(\upsilon + \lambda). \qquad (7)$$

From equations 3 and 6 we can optimize the target in order to improve the release of a specific atom. We can select the target material with the minimal grain or foil size that can be made. Selection of a target material that can operate at ultra high temperature will increase the diffusion and the effusion release. The choice of the couple, target material-nuclei of interest can be extremely beneficial by selecting a material, which has the lowest absorption enthalpy. Keeping the volume and thus the surface as small as possible will improve the release of short-lived nuclei by reducing the number of collision.

HOW TO IMPROVE THE YIELD?

Once the target operates at it maximum temperature to increase RIB intensity we can play with the other two available parameters: target thickness, N_t and the incident proton flux, Φ_p. Unfortunately, there very little gain by increasing the target thickness. The effusion process, which depends mainly on the number of collision shows that an increase in volume will result in a larger number of collision. The short-lived nuclei produced far from the evacuation hole in the target container will decay before reaching the orifice. Furthermore, the one produced close to the evacuation hole can effuse away and never reach the orifice. There is a definite advantage to keep the target as short as possible for the short-lived nuclei of interest.

By increasing the flux of incident particle we can hope that the yield of a specific nuclei will increase linearly with the beam intensity. At ISAC we have observed that in fact the yield of ^{74}Rb and ^{11}Li increase faster than the linear proton beam increase. Figure 1 and 2 show the resulting RIB intensities as a function of proton intensity. The non-linear increase may due to radiation diffusion enhancement mechanisms.

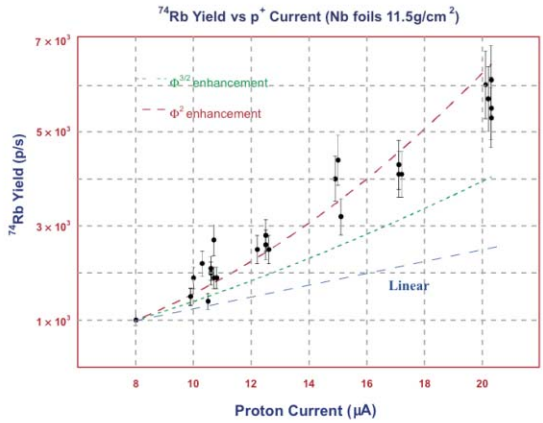

Figure 1: Yield of ^{74}Rb as a function of the incident proton beam. Curves show the projected yield expectations from proton flux dependences of Φ_p, $\Phi^{3/2}$ and Φ^2 applied to the 8 μA yield.

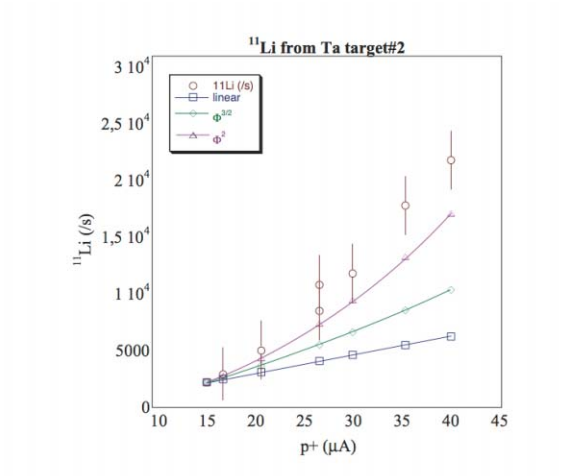

Figure 2: Yield of ^{11}Li as function of the incident proton beam. Curves show the projected yield expectations from proton flux dependences of Φ_p, $\Phi^{3/2}$ and Φ^2 applied to the 15 μA yield.

Radionuclide Yield Enhancements

Since the first ISAC target operated at the 10 μA level, nonlinear increases of both total extracted ion current and yields of specific radionuclides have been observed, [3]. Originally, the nonlinear enhancement was attributed to faster product diffusion resulting from a rising central target temperature; up to the 10 μA level, no power balancing was performed. With target irradiations above 10 μA levels, the Joule heating of targets was reduced to balance the beam power. Initial expectations were, that with a successful balance, the yields would begin to show the expected linear dependence on proton flux. Contrary to expectations, the observed yields continued to display nonlinear enhancements with increasing beam flux. Furthermore, yields of ^{74}Rb from the first niobium foil target operated with 20 μA of proton beam appeared to be essentially independent of applied resistive heating at the maximum proton beam current.

From equation 1) we can say that a nonlinear relation of yield to (Φ_p) likely results from effects buried in one of the efficiency terms. Increased diffusion resulting from radiation effects in materials is well known and the kinetics of radiation enhanced diffusion under steady state equilibrium bombardment conditions have been described in reviews by Dienes & Damask [4] and Sizeman [5]. Under steady irradiation conditions, lattice defects in the form of vacancies and interstitial atoms (Frenkel pairs) are continuously produced in the target matrix. Diffusion is enhanced by increased concentrations of such defects. The defects are mobile and can diffuse and anneal by different mechanisms, either by diffusing to "sinks" in the host lattice (such as dislocations or the matrix surface) or by direct recombination of vacancy and interstitial pairs.

At high temperatures, the diffusion enhancement has a $\Phi_p^{1/2}$ dependence for the recombinant annealing mechanism, while the "sink" annealing mechanism has a linear Φ_p dependence. Combined with the basic linear Φ_p dependence for production, the two cases should display overall correlations to $\Phi_p^{3/2}$ (recombination) and Φ_p^2 (sink). At ISAC, radiation enhanced diffusion effects have been observed with both metal foil and carbide targets.

Figure 1 and 2 show the yield of ^{74}Rb and ^{11}Li from Nb and Ta foil target, respectively. These plots show a clear indication of the non-linearity of the resulting yield as a function of the proton beam intensity.

HIGH POWER TARGETS

In the Isotope Separation On Line (ISOL) method the element of interest are created during the collision of the proton beam with a target nucleus. The products are stopped into the target material. The target material is normally kept at high temperature (~2000 °C) in order to speed the diffusion of the exotic atoms inside the target material to the surface from which they desorbed. Then the exotic atoms effuse to the transfer tube and the ion source.

Figure 3 shows a photograph of the actual ISAC target. The long cylinder is the oven and contains the target material. It is resistively heated by passing up to 800 Amperes in the leads that we see at both ends. The radioactive atoms are transferred to the ion source by the transfer tube that sticks up perpendicularly to the target tube.

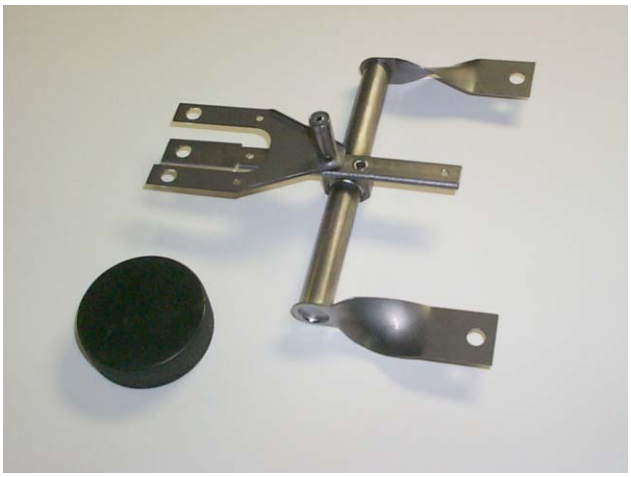

Figure 3 : The ISAC target is composed of a Ta target container and a reentrant transfer tube. The black disk is used as a scale; it is 3 inches in diameter by 1 inch thick.

The current passing though the target is adjusted depending to the target material vapor pressure, and the proton beam intensity. The idea is to keep the centre of the material at a safe temperature. When we are running at low proton intensity a power supply (10 V, 1000 A.) provides the thermal heating in order to speed the release of radioactive atoms to the ion source. In the current design we are limited to proton beam intensity lower than 40 to 50 μA. The main reason being that is the amount of power those targets can radiate at the operating temperature. In order to go beyond this limit we need to modify the target. Several groups had worked and are working on the subject. Even though, this is not a review we will look at the most significant achievements in the field.

High Power Target development

The ISOL target is quite different from any other high power target such as, neutron spallation or projectile fragmentation targets. To obtain the best release efficiency the target has to be uniformly heated to temperature around 1500° C to 2200° C.

The main issue is to provide enough cooling to operate the target at a safe limit. Too much heat will evaporate the target material. Too much cooling will impair the release of exotic atom of interest. They will condensate on the cold region and decay before they can reach the ion source. The trick will be to design a target that can withstand for long period of beam bombardment at high power and provide a quick release of short-lived exotic atoms.

In 1987 Eaton *et al*. [6] had proposed a concept for a high power ISOL target based on the 600 MeV-100 μA SC. The power deposition in the target varies from 3 kW for light Z target to 37 kW for Ta target. For actinide targets an extra 34 W/μA was added to take into account the energy deposition due to fission products. The cooling was done by enhanced radiation cooling using four longitudinal fins for the low power-target. For the high-power target it was done by enhanced radiation conducting cooling. The calculation shows that it will be difficult to take advantage of the full 100 μA using these schemes. For example, the Ta foil target using both enhanced radiation and conductive cooling will only support 84% of a full 100 μA. Such target was never tested on-line with intense proton beam.

In 1992 Talbert *et al*. [7] proposed a new approach based on the addition of an annular gap between the target container and a water-cooled jacket or a heat pipe.

In 1994 the RIST project [8,9] proposed the development of a Ta foil target that will take advantage of the 800 MeV-100 μA beam from the RAL, UK. The RIST target was developed and tested off-line and on-line [10]. The target is a tube 4 cm in diameter and 20 cm long. It is filled with 25 μm thick Ta foils. The target was designed for power dissipation of 25 kW. The radiative power is absorbed in a water-cooled copper jacket. The target is composed from about 6000 discs and washers. These discs and washers are diffusion bounded together to form a tube. They measured an emissivity between 0,7 and 0,8.

Unfortunately, the test with proton beam never took place, instead the target was move to ISOLDE where it was operated using the 2 μA proton beam from the PS booster [11].

The RIST approach can only be applicable to foil-target which, can be made by diffusion bounding. It limits severely the use of such target for specific beam. This approach eliminates most of the potential target material such as refractory oxides or carbides.

At ISAC we have developed a fin target [12] that can dissipated 25 kW of beam power. Instead of building a target using the diffusion bounded technique we then considered adding radial fins to a Ta tube. The fins are 55 by 55 mm cut out from a Ta foil sheet 380 μm thick. An undersized hole is punched in the centre and extruded using a conical shaped tool to the tube diameter. Then the fins are installed onto the tube from each side of the central block. Once the fins are installed we used a special tool to expand the Ta tube in order to improve the contact between the tube and the fins. We observed an improvement by a factor three in the resistance across the contact area. Contrary to the RIST target the fins are added onto the target container. This allows us to insert any type of target inside at the condition that the heat can be transferred from the target material to the target container wall.

Figure 4 shows a photograph of the fined target. The fins are 55 by 55 mm cut out from a Ta foil sheet 380 μm thick. An undersized hole is punched in the centre and extruded using a conical shaped tool to the tube diameter. Then the fins are installed onto the tube from each side of the central block. Once the fins are installed we used a special tool to expand the Ta tube in order to improve the contact between the tube and the fins. We observed an improvement by a factor three in the resistance across the contact area. The initial test shows that an emissivity of 0.92 is feasible [12].

Figure 4 : ISAC fined target. It is the same target as shown in figure 2 onto which we have installed the fins.

TEST STATION FOR HIGH POWER TARGET

Before going on-line with such a target we need to test the concept off-line using the same amount of power. An electron beam heating system has been developed to test the target behavior under such conditions. A W filament running along the target axis is heated to several thousand degrees and produces the electrons, which are accelerated toward the target container. The filament is biased using a 1.5 kV- 40 Amperes power supply.

The present ISAC facility at TRIUMF is fed by one beam line, beamline 2A that can direct beam to one of the two target stations. One of these targets has been in use since ISAC was commissioned; the second one is currently being commissioned. The numbers of proposals for ISAC experiments are such that we feel the need to deliver more simultaneous RIB to experiments. A proposal has been made for another beamline to ISAC so as to make additional beams available. Through partial extraction by H- stripping, this proposed line would extract a 450-500 MeV beam from extraction port 4 of the TRIUMF cyclotron. A fast switching system would be used to feed an additional two target stations each of them equipped with its own mass separator system. These new target stations will allow target and ions sources development and also allow at least three simultaneous experiments at ISAC [13].

The actual ISAC facility comprises two target stations. They share the same proton and the same mass separator. We can swap from one to the other by reversing the magnetic field in the Y magnet in beam line 2A. This

mode of operation does not permit target and new ion beam development and deliver RIB to experiments at the same time.

Development of new RIB is crucial since each element can take up to 2 years before they can be delivered to experiments. On the other hand ion sources development in the harsh environment of the target is even more crucial.

In order to allow targets and ion sources development for the future program at ISAC we are planning to build new target stations on the new beam line 4. The actual target hall will be expanded to the west to include room for the two new target stations. The idea is to use as much the actual infrastructure we have developed over the last 10 years for the remote handling, nuclear ventilation, waste storage, etc. Furthermore, the new target station will use the same technology we have successfully developed for our actual RIB operation. Figure 5 shows a layout of the actual and proposed target stations. Each of the new stations will have its own mass separator in order to be able to switch from development work to RIB delivery in a very short delay.

Eventually, we will be able to deliver more beams by the addition of a new switchyard in the diagnostic box like the ISOLDE GPS design [14]. This design allows the selection of three ion beams within the mass range of ± 15% from the central ray. This setup will eventually allow us to serve three experiments at the same time.

DISCUSSION AND CONCLUSION

We have developed a fined target that can dissipate up to 25 kW of beam power. The production of a specific exotic nucleus depends greatly on the target nucleus. There is no universal target material that will produce intense beam of all elements. Contrary to the RIST target technology where the target is made from disk and washer of Ta foil we added the fins onto the target container tube. This allows us to use a large variety of different target material. Foil target materials are inserted into the tube and when the entire target material and container are at high temperature a bound is form between the foil and the wall of the container. For compound target we have developed a technique that allow us to back carbide targets material onto a carbon sheet. The carbon sheet has a high thermal conduction in the transverse plane. The high conductivity of the carbon allows the release of the heat to the target container.

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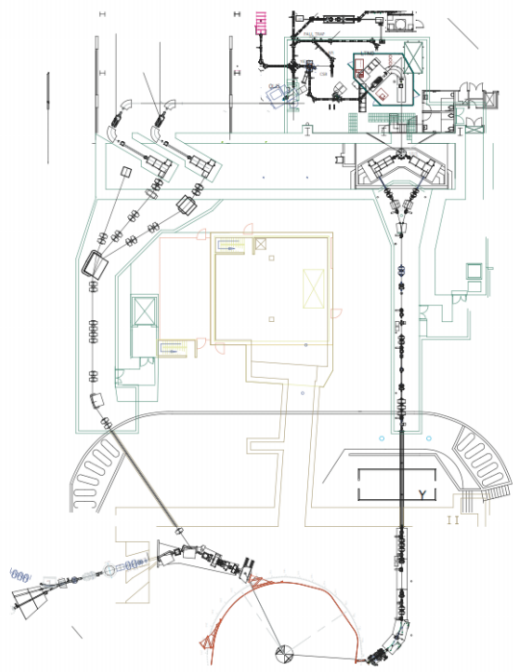

Figure 5: The ISAC new target station for target development.

REFERENCES

[1] P. G. Bricault, M. Dombsky, P. W. Schmor, and G. Stanford, Nuclear Instruments and Methods, B126 (1997) p. 213.
[2] R. Kirchner, NIM B70 (1992) 186.
[3] M. Dombsky, P. Bricault, T. Hodges, A. Hurst & P. Schmor, Nucl. Phys. A701 (2002) 486
[4] G. J. Dienes and A. C. Damask, J. Appl. Phys. 29 (1958) 1716
[5] R. Sizeman, J. Nucl. Mater. 69 & 70 (1978) 386
[6] T. W. Eaton, H. L. Ravn and ISOLDE col., NIM B26 (1987) 190.
[7] W. L. Talbert, H.-H. Hsu and F. C. Prenger, NIM B70 (1992) 175.
[8] J. R. J. Bennett et al., Proc. 4th European Particle Accelerator Conf., London, 1994, p. 1415.
[9] J. R. J. Bennett et al., NIM B126 (1997) 117.
[10] J. R. J Bennett, Nucl. Instr. and Meth. B126 (1997) 105.
[11] J.R.J. Bennett, "Experience with the RIST target, diffusion, effusion delays, etc.", EURISOL meeting, www.ganil.fr/eurisol/targetgroupmeetings
[12] P. Bricault, M. Dombsky, A. Dowling and M. Lane, NIM B204 (2003) 319.
[13] G. Stinson and P. Bricault, "A PROPOSAL FOR AN ADDITIONAL BEAMLINE TO THE TRIUMF ISAC FACILITY",this conference
[14] E. Kugler et al, Nucl. Instr. and Meth. B70 (1992) 41.