THE PRODUCTION TARGET AT ISAC

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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 new ISAC facility at TRIUMF includes: a new building with 5000 m^2 of floor space; a new beam line with adequate shielding to transport up to 100 µA of proton at 500 MeV from the existing H^- cyclotron to two target stations, remote handling facility for the targets services, a high resolution mass separator, a linear accelerator and experimental facilities. A novel approach for the target/ion source station is described. The target/ ion source assembly and heavy ion optics components are located in a shielded canyon under 2 m of steel shielding allowing high proton beam intensity on thick target**s**.

Existing foil targets design can accommodate up to 50 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 will be a future challenge. Several approaches to the dissipation of the power in such targets by the proton beam have been investigated and a realistic solution for the removal of the heat from the target container seems possible. The heat transfer within the target material itself, however, is highly target dependent and it is clear that 100 µA operation will be limited at least initially to only a few target materials that are refractory and have good heat conduction to withstand high power deposition.

1 INTRODUCTION

The TRIUMF‘s ISAC 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 two target stations. The target station contains proton beam monitoring equipment, production target and ion source, a beam dump, and the front-end heavy ion beam optics. A strategy has been adopted in which the target station is contained in a heavily shielded building connected directly to a hot cell facility. This approach is based on the successful experience at TRIUMF of vertically servicing and remote handling of modular components embedded in a close-packed radiation shield, coupled with the requirement for quick access to the production target and of containment of any mobile activity. Careful design of both the modular components and the remote-handling systems was carried out to ensure the operational viability of this system.

The effective operation of the ISOL system is crucial to the overall ISAC facility performance. It is therefore essential that we build in as much flexibility as possible. The target/ion source module is the key component. It must be serviced, or modified and exchanged on a regular basis to satisfy the varying demands of the physics program. Its design addresses many difficult aspects, including high voltage services, containment of radioactivity, and accommodation of different target/ion source combinations, radiation-hard components, and ease of remote handling.

Existing target designs can accommodate up to 10 µA beam intensities and the available intensities of many radio nuclides 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 yield of radioactive isotopes will be a future challenge. Several approaches to the dissipation of the power deposited in such targets by the proton beam have been investigated and a realistic solution for the removal of the heat from the target container seems possible. The heat transfer within the target material itself, however, is highly target dependent and it is clear that 100 µA operation will be limited at least initially to only a few target's materials. Some of the problems may have to be addressed near the 10 µA level but, in general, heat has to be supplied to the target system to maintain the prescribed temperature. The development of high power target is the subject of a development program at TRIUMF.

Ion beams from most ion sources contain many unwanted ion species, in many cases, several orders of magnitude more intense than those of interest. A mass separator is essential in order to produce RIB. The quality of mass separation required will depend on the particular experiment and the production target/ion source system. In some cases, high mass resolution will be required to remove contamination from the beam, while, in others, high acceptance will be of more importance. A mass separator with a mass resolving power m/δm of the order of 10,000 is proposed to satisfy most of the experimental program. It is composed of two stages. The first stage is used as a cleaning device to remove most of the contamination in the heavily shielded building. The second stage is at high potential with respect to the first stage. Most of the particles having the same momentum

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference,* edited by F. Marti

but different mass will be rejected at the second stage. This system will allow a large rejection of cross contamination.

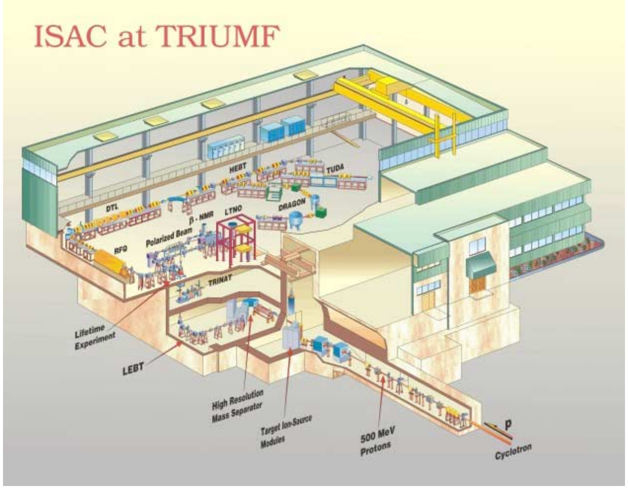

Figure 1. Three dimensional view of the ISAC building showing the target station, remote handling and the experimental hall.

2 TARGET STATION

The ISAC target-handling concept and the ISAC target facility are based on fifteen years of experience at operating meson factories. The meson production target and beam stop areas of these facilities have power dissipation and radiation levels similar to, or greater than, those expected at ISAC. Meson factory experience shows that the correct approach to handle components in high-current and thick-target areas is to place them in tightly shielded canyons. Access to the components is done vertically and repair and service is made in dedicated hot cells.

Three important factors not encountered in the meson factory targets have to be addressed. These are; the containment of large amounts of mobile radioactivity; the high voltage required for beam extraction; and quick routine replacement of short-lived target systems. In the present design these issues are solved by placing the target in a sealed self-contained module, which can be transferred directly to the hot cell facility for maintenance.

The target stations are located in a sealed building serviced by an overhead crane. The target maintenance facility includes a hot cell, warm cell, decontamination facilities and a radioactive storage area. The target area is sufficiently shielded so that the building is accessible during operation at the maximum proton beam current.

Beam-line elements near the target are installed inside a large T-shaped vacuum chamber surrounded by close-packed iron shield. This general design eliminates the air activation problem associated with high current target areas by removing all the air from the surrounding area. The design breaks naturally into modules; an entrance module containing the primary beam diagnostics, an entrance collimator and a pump port; a beam dump module containing a water cooled copper beam dump; a target module containing the target/ion source, extraction electrodes and first steering component and heavy ion diagnostics; and two exit modules containing the optics and the associated diagnostics for the transport of heavy ion beams.

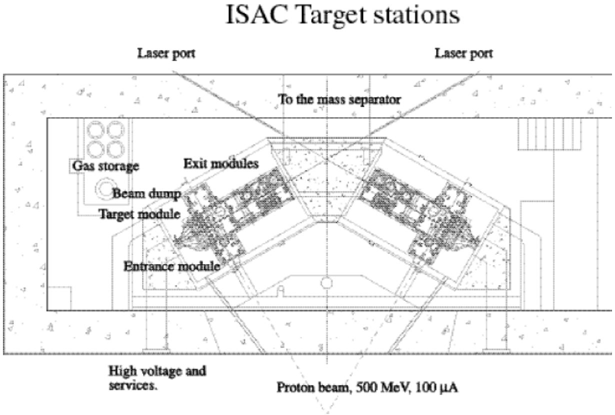

Figure 2. Plan view of the ISAC target stations.

The vacuum design seeks to eliminate the need for radiation-hard vacuum connections at beam level by using a single vessel approach. The front-end components, with their integral shields, are inserted vertically into the T shaped single large vacuum vessel. Most vacuum connections are situated where elastomer seals may be used. Only two beam-level connections exist; one at the proton beam entrance and one at the heavy ion beam exit.

The target stations are shielded by approximately 2 m of steel placed close to the targets. Outside this steel shielding the operating radiation fields will be sufficiently low so that radiation damage to equipment is not a concern. The steel shielding is surrounded by an additional 2-4 m of concrete, which provides the required personnel protection during operation. To service the targets, shielding above the target station is removed giving access to the services at the top of the steel shielding plugs. Residual radiation fields at this level will be low enough to allow hands-on servicing.

3 REMOTE HANDLING

An effective remote handling and servicing system will be required to bring about quick and frequent target changes. All modules in the target area will have high levels of residual activity and will be potentially contaminated with mobile activity. Both aspects are considered in the handling design.

Target component maintenance involves disconnecting services and craning the module to the hot cell. Removing aside the concrete blocks covering the target station gives the overhead crane access to the modules. While the target module is pulled out of the canyon personnel are excluded from the area. Target module transfers to the hot cell must therefore be done completely remotely. The connection and disconnection of the target module services can be done manually since the shielding of the module is thick enough to allow hand-on operation.

4 TARGETS

The ISAC facility at TRIUMF utilizes the 500 MeV proton beam from the existing H^- cyclotron. The two target stations, remote handling facility were built to accommodate beam intensity up to 100 µA. The target/ion source assembly is the heart of the ISOL system. It is there the radio nuclides are produced, transferred to the ion source, ionized and then extracted to form an ion beam. The particular nucleus, which it is desired to study, may be produced by a range of nuclear reactions, depending on how far it is from the valley of stability in the Z-N chart. With high energy proton the three principal reactions used are: spallation, fission and target fragmentation, which cover almost the entire chart of the nuclides.

The spallation reaction is a two-step reaction, which becomes dominant at proton energy of 100 MeV. The emission of charged particles is followed by evaporation of neutrons. The reaction leads to a mixture of a large variety of different product nuclei with cross section in the order of 20 mb.

At higher energy, say 300 MeV the symmetric fission becomes very probable and it is a very useful mechanism. At even higher energy the target fragmentation become the dominant process. This is the mechanism responsible for light mass formation, $z < 20$ and for nucleus close to the target in the neutron deficient side of the chart of nuclides.

Since the target has to be removed using manipulators in a hot-cell modification were done to the target/ion-source assembly to allow easy access. Figure 3 shows the actual target/ion-source assembly.

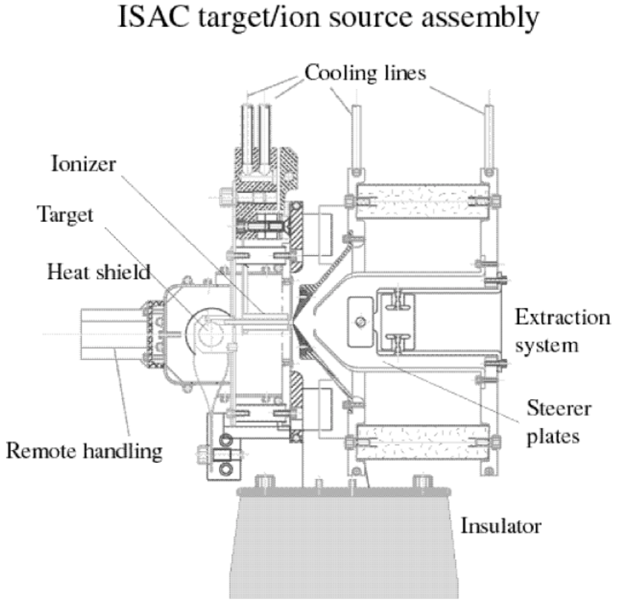

Figure 3. View of the ISAC surface ion source.

In the ISOL method the reaction products are brought to rest before being released from the target material. The main issues are to transfer the desired reaction products to the ion source and to form a suitable ion beam in a timely fashion that decay losses become negligible. The mass transfer from the target material matrix to the ion source cannot suffer long delay due to slow diffusion release or slow effusion due to large number of collisions or/and long sticking time on the container walls. To do this we generally heat a low vapor pressure target material to a sufficiently high temperature at which the nuclei of interest are released by diffusion and effusion process toward the ion source. The atoms are then ionized and extracted to form an ion beam. The separation is obtained by passing the ions through a mass separator.

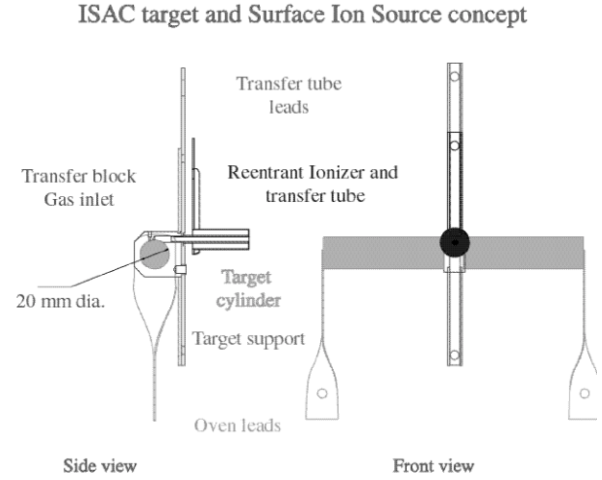

Figure 4. View of the ISAC's target and transfer tube assembly.

So far we have used 5 different target materials, Nb, CaO, $CaZrO_3$, SiC and Ta. The target thickness varies in function of the isotopes we want to extract from the target.

During the year 2000 running period, two ISAC targets were operated using proton currents up to 20 µA. The production of alkali elements from an 11.5 g/cm^2 Nb foil target and a 21.3 g/cm^2 Ta foil target were studied as a function of proton current. For both targets, the proton current was increased in a stepwise fashion and yield measurements of selected products were made at each current level. The central target temperature was kept constant by decreasing the resistive target heating to compensate for beam power deposition. Production of ^{74}Rb was determined from the Nb foil target and ^{8,9,11}Li, ^{26}Na, ^{38g,38m}K and ^{64,74}Ga yields were measured from the Ta foil target. An enhanced nonlinear dependence of yield on proton current was observed for all of the shorter-lived alkali species. For ^{74}Rb, the observed yield increased by ~ 4 when the proton current was doubled from 10 to 20 µA. Corresponding increases for ^{26}Na and the Li species ranged from 3-fold to 6-fold for a doubled proton current.

The nonlinear yield increases are believed to result from an increased survival of the short-lived products arising from faster mass transport in the target matrix. The faster mass transport results from radiation enhanced diffusion effects caused by the intense proton currents. The signatures of radiation enhanced diffusion have been reviewed by Dienes & Damask [1] and Sizman [2]. Under constant irradiation in the high temperature regime, mass transport is enhanced by the formation of defects (vacancies and interstitials) in the target matrix. The defects are mobile and can annihilate by migration to sinks (such as lattice dislocations or the host matrix surface) or by recombination with each other. For the recombination case, radiation enhanced diffusion is expected to show a square root dependence on the irradiating particle flux ($\Phi^{1/2}$). For the case where defects annihilate at sinks, a linear flux dependence is predicted. Combined with the linear flux dependence for radionuclide production, the overall yield of radionuclides under radiation enhanced diffusion should display a flux dependence between $\Phi^{3/2}$ and Φ^2. This was observed for the alkali product yields measured with 10 to 20 µA proton currents; in most cases the yield dependence was closer to Φ^2. In the case of the ^{38m}K and ^{38g}K species, a Φ^2 dependence was observed for the short-live ^{38m}K ($t_{1/2}$ = 924 ms) while a simple linear dependence on Φ was observed for the long-lived ^{38g}K ($t_{1/2}$ = 7 .63 m). This is consistent with a greater survival of the short-lived species due to faster diffusion enhanced by radiation.

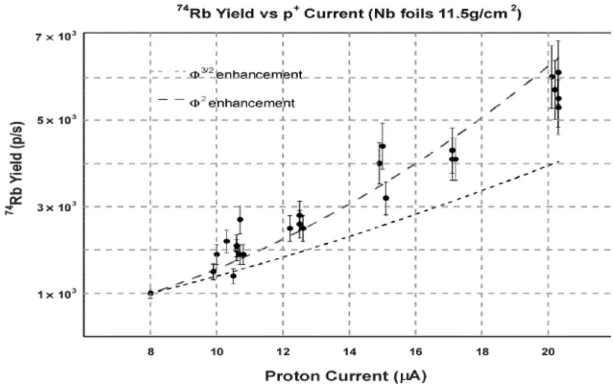

Figure 5. Plot of the ^{74}Rb yield as a function of the incident proton beam intensity.

5 HIGH POWER TARGETS

Targets that can withstand high proton intensity up to several hundred of microamperes are being used in other applications such as the pulsed spallation neutrons sources. The major issues with the ISOL type of target are:

1) Target material must be compatible with the desired radionuclides we want to extract from the target. We just can not used one type of refractory material. The target element is chosen to optimize the yield of the required species.
2) Fast release of the short-lived nuclei of interest in order to avoid decay losses.
3) Temperature uniformity along the target to avoid condensation of the desired species.
4) Target and ion source close-coupled in order to reduce the transportation delay.

Design of a high power target was accomplished and tested by the RIST group[3]. They decided to build a finned target tube and discs by diffusion bounding a stack of many discs and spacer washers. The discs, disc fins and spacer washers were laser cut from tantalum foil sheet. The whole assembly was bounded in a vacuum enclosure within an electrically heated furnace. Pressure was applied to compress the discs for 12h. The RIST target was tested and proved to be successful in increasing the release speed for Li and Na[4].

Even though, the RIST target test was successful it was not done using intense proton beam. A demonstration of an operating target at 100 µA was done at TRIUMF in collaboration with a group from Amparo Corporation [5]. The ISAC facility was used to thermally test a target designed to operate with 100 µA proton beam at 500 MeV. Since the experiment was only a thermal test, no attempt to extract ion beams was made. The target was instrumented with an array of thermocouples to record the target temperature profiles under various conditions of heating by the proton beam. The 15 cm long prototype target was fabricated from 1200 Molybdenum foils and spacers that were diffusion bonded together. The final machining was done using an electrical discharge (EDM) to a specific shape. The target design goal was to provide nearly constant temperature at the center of the 0.95 cm radius target material. In principle the target density has to vary along the length to make the linear energy deposition profile approximately constant by compensating with target mass for beam fluence reduction through the target. The target shaping that resulted from thermal analysis incorporated two longitudinal fins to which the cooling lines were attached, with each fin having a machined thermal constriction with a widening taper along the target length. The experiment was performed last December with the incident proton beam current varied from 10 µA to 100 µA, back down to 10 µA, and cycled up again. The target required only 10 minutes to reach thermal equilibrium. The resulting temperature profiles and the predicted profiles do not agree perfectly. However, the deviation is less than 10 %. Nevertheless, this experiment confirms that it is possible to use appropriate computer analysis to develop reasonable target designs for producing radioactive ion beams under conditions of high power beam heating.

However, producing such targets using diffusion bounded discs is very expensive and time consuming when taking into account that a target can be in place for only one specific experiment. The other difficulty comes from the water-cooling of the target, which creates serious design problems to assure that the temperature is uniform over the whole target volume. Our current target design used radiation cooling which is much simpler.

The power dissipated by radiation cooling from a body at temperature T_T is given by

$$P \approx \sigma \varepsilon A \left(T_T^4 - T_E^4 \right)$$

where ε is the emissivity, σ the Stefan's constant, A the surface area and T_E the enclosure temperature.

The emissivity for tantalum is around 0.3. The surface emissivity can be increased by adding fins or by roughening the surface. The tantalum cylinder into which we stack our target foils material can operate up to 40 µA. When we increase the beam intensity, we reduce the oven heater in order to keep the central temperature under the critical temperature, see fig. 6. This temperature is defined such that the vapor pressure is in the low 10^5 mBar. The draw back of this method is that the walls are at lower temperature than the central region of the target.

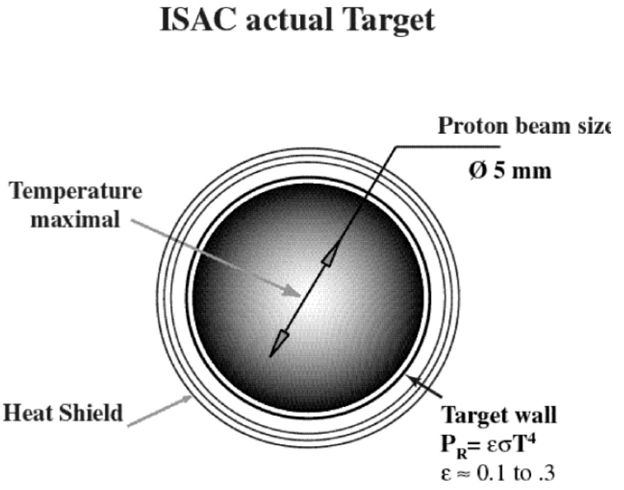

Figure 6. Section of the target showing the radial temperature distribution.

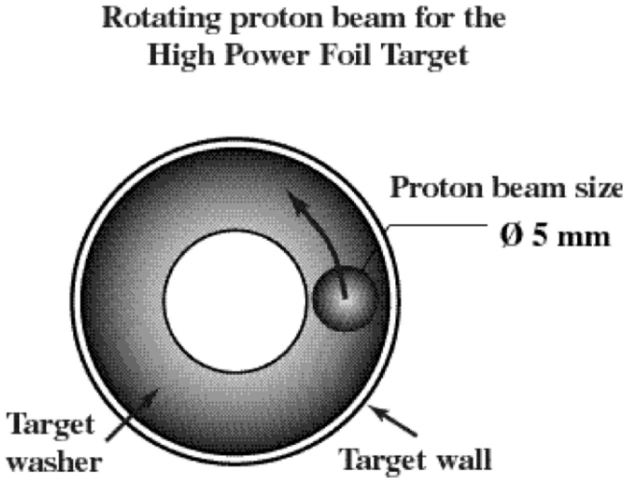

Figure 7. Proposed target for high intensity. The proton beam rotates around the perimeter of the target. The central target material is removed.

Elements with a large surface desorption enthalpy will then experience larger decay losses than alkali elements. To overcome the non uniform temperature distribution we proposed to make a hollow target. To reduce the power deposition density the proton beam rotates around the perimeter of the target, see fig. 7.. The central target material is removed allowing fast effusion inside the target and also avoiding melting the central region. Two steerer magnets powered by a 60 Hz AC supplies installed in front of the target station will bend the beam on a circle around the target periphery.

CONCLUSION

The ISAC target station is operational since end of 1998. The new target station concept was proved to be flexible and reliable. The target itself is an upgrade from the TISOL[6] target oven. The new target fabrication takes advantage of new techniques such as electron beam welding that makes it very robust.

The actual foil target was bombarded by 20 µA proton beam. The production of short-lived ^{74}Rb shows a non-linear dependence with proton beam, which will suggest that we reach a regime where the overall yield of radionuclides under radiation enhanced diffusion displays flux dependence proportional to Φ^2.

ISAC obtained, last May, the license to operate over 10 µA and up to 100 µA. Work is continuing on the target development that will permit to operate those foils target at higher proton flux. A target equipped with radial fins is under fabrication and will be tested over the summer. If successful, it will be used for the fall or next spring runs.

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