PROGRESS IN DEVELOPMENT OF ISOL RIB ION SOURCES AND TARGETS FOR HIGH POWER *

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Abstract

The ISAC facility is operational since 1998, we utilize the proton beam from the TRIUMF H- cyclotron to produce the radioactive ion beams (RIB) via the isotopic separation on line (ISOL) method. The ISAC facility is designed to accommodate 100 μA proton beam at 500 MeV.

A new target equipped with fins has been developed that can sustain proton beam up to 100 μA. The RIB intensities depend not only on the target but also on the ability to produce ion beam. The ion sources design for on-line applications are extremely important because of the close contact with the target. They must sustain high radiation field and operate in a large gas pressure range.

A new FEBIAD and ECR ion sources are under development. These two ion sources combine with the actual surface and laser ion sources will allow us to produce a large variety of exotic beam. The FEBIAD ion source has been tested with TiC and SiC target on-line. Development of a LaC and UC targets are in progress using the technique developed for the other carbide targets. The carbide target material is supported onto a carbon sheet that allows a better heat transfer.

INTRODUCTION

The ISAC facility has been designed with the primary goal of producing intense exotic beams, it is described in ref [1,2]. The radioactive nuclei are produced by interaction of a 500 MeV proton beam, up to 100 μA, coming from the TRIUMF's H^- cyclotron impinging onto a thick target material. The fragments produced during the interaction are stopped in the bulk of the target and the atoms diffuse to the grain or foil surface. From there they are released into an ion source. The specific RIB is selected using the isotope separation on line (ISOL) method and delivered to the low energy experiments or to the accelerator complex for nuclear astrophysics and nuclear physics experiments.

The accelerator complex consists of a 4-rod RFQ [3] and a drift tube LINAC (DTL) [4] and a superconducting LINAC [5].

To bombard a thick target with up to 100 μA we had to develop new techniques for the production target and target handling. At the beginning of ISAC the maximum proton beam intensity we were able to utilize for the production was around 2 to 5 μA. Since then, we have developed a high power target that can dissipate nearly 20 kW beam power. In this paper we will discuss the on-line ion sources development occurring at ISAC.

Since we are using intense proton beam to produce our RIB the target/ion source has to be radiation hard. This aspect is very important because changing our target requires between 3 to 4 weeks. This means to be efficient, the target/ion source assembly has to be operational for at least the same amount of time.

ION SOURCES DEVELOPMENT

The requirements for an online ion source are somehow different than the one for an off-line ion source. For efficient transfer of the wanted radioactive species from the target, the on-line ion source is directly coupled to the target oven. The on-line ion source has to operate in a very hostile environment in our case several kRad. We can summarize the on-line ion source requirements as follow:

1. Because the radio nuclides are formed in situ the amount is quite limited we need very efficient ion source,
2. Since the ion source is coupled directly to the target oven, the ion source efficiency has to be independent of the pressure,
3. Ion source must be very stable to avoid instabilities that will degrade the resolving power of the mass separator,
4. Short delay to avoid losses by decay,
5. Ion source has to work at high temperature to avoid condensable elements to stick on the walls,
6. Maintenance free and long lived,
7. Small size to avoid large nuclear waste inventory.

The simplest ion source one can use is the hot surface ion source. The low ionization potential elements, like alkali, can be striped of one electron simply by colliding with a hot surface. Figure 1 shows a sketch of the surface ion source installed at ISAC. The transfer tube is used as the surface ion source by inserting a high work function material such as Re into the tube. For this reason and its simplicity we have mainly used a surface ion source since the beginning of ISAC operation in 1998.

The physics with RIB range from nuclear astrophysics for studying the rapid proton capture (rp-process), the rapid neutron capture (r-process) and the slow proton capture (p-process). The rp-process required RIB from C to Ni. The r-process is more difficult to study since it requires very neutron rich nuclei, which range from ^{8}Li to heavy Pb. The p-process deals with neutron deficient nuclei close to the proton drip-line and it ranges from light Ca to Pb. For those one the mass is the most crucial piece of information one need for network calculations.

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Those processes are key to understand the stellar evolution and it has been the main motivation for the construction of the ISAC-I facility. One can see that the range of nuclei is quite large, which means that we have to have efficient on-line ion sources that can cover the most of the periodic table.

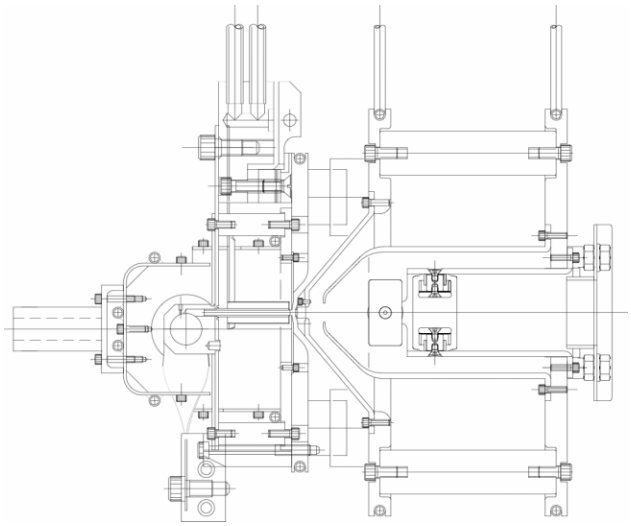


Figure 1: ISAC hot surface ion source. We have on the left hand side the target oven onto which is attached the transfer tube. At the end of the tube we insert a Re foil which has a work function of about 5 eV. This is adequate to ionize alkali elements with high efficiency.

Since there is no universal high efficiency ion source available it means that we have to use a series of specialized ion sources for each type of element. For example, the hot surface ion source is well suitable for alkali elements; the Electron Cyclotron Resonance Ion Source is more suitable for gaseous elements; while the laser ion source work well for the transition elements and finally the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source works well for high ionization potentials. Some models operate at very high temperature and they have been optimized to deal with very refractory elements [6,7].

Resonant Laser Ion Source

The resonant laser ion source (RLIS) is very attractive for the simple reason that it can potentially provide pure beams of only one element. The mass separation of different isotopes of that element only requires unit mass resolution, e.g. a resolving power (R) on the order of $A/\Delta A$, where ΔA is equal to 1. In contrast, ion sources ionising several elements require a resolving power of the order of several ten thousand in order to separate isobars, which in some cases is nearly impossible. There is thus an obvious advantage of ionizing one specific element only, created from the bulk of the target by nuclear reaction, subsequently producing a pure isobaric beam without contamination after mass separation.

Figure 2 shows a number of principal resonant laser ionization schemes. The full lines indicate resonant transitions (tilted arrow) are the ones that can be excited with our Ti:Sa lasers in fundamental, frequency doubled, tripled or quadrupled mode. The transitions indicated by the dashed lines (vertical arrow, indicating non-resonant transition) are excited using a short pulsed, frequency doubled Nd :YAG laser. Scheme number one uses resonant transitions and an auto-ionizing level above the ionization potential (IP). Schemes number 2 and 4 utilize resonant laser excitation followed by direct non-resonant excitation to the continuum. These schemes are less favorable because of the miss match of the phase space for the ionization in the continuum. Scheme 3 utilizes resonant excitation into a high lying Rydberg state, which is very close to the IP. These states are long lived and the electron can be removed either by electric field ionization or by a far infrared laser beam. Schemes 1 and 3 are generally the schemes that yield the highest ionization efficiency.

While we can saturate the resonant steps with laser power of the order of 10 mW, the non-resonant step leading to ionization into the continuum requires larger laser power and this transition is seldom saturated because it will require 10^3 times more power.

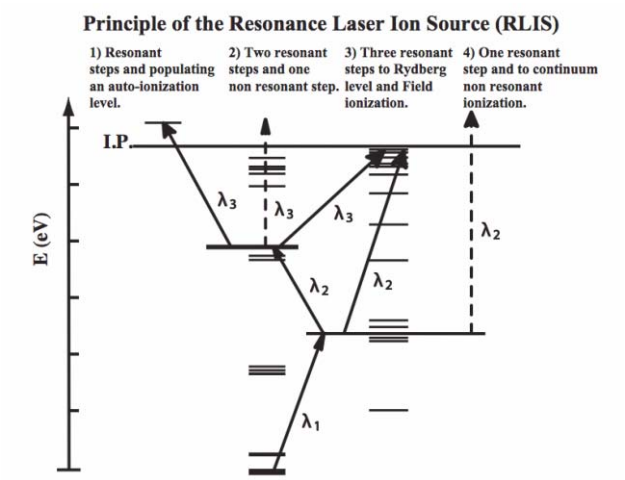


Figure 2: Possible laser ionization scheme using resonant laser ionization. Direct non-resonant ionization is largely suppressed. The best schemes are the one using resonant steps and/or auto-ionization levels.

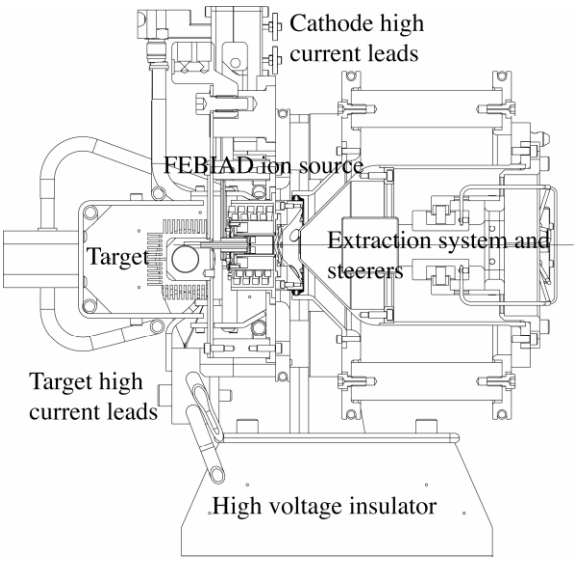
Plasma Ion Source

The hot surface and laser ion sources are not suitable for ionization of elements having a high IP (> 5 eV). It is then desirable to have an ion source that relies on electron bombardment. We are presently developing a forced electron beam induced arc discharge (FEBIAD) to produce the F and Ne isotopes necessary for the study of the proton capture reactions, ^{18}F(p, γ) and ^{18}Ne(p, γ), for nuclear astrophysics.

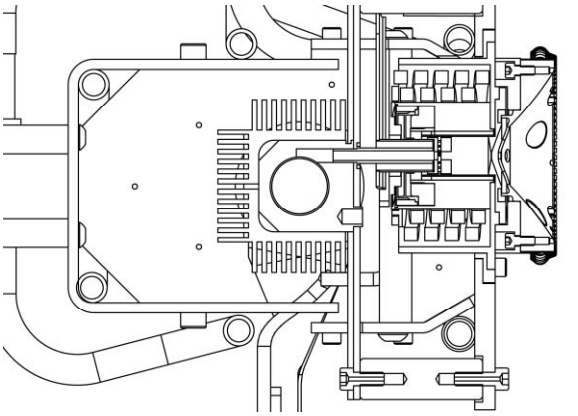
Since we do not have time to change our target module to accommodate a new ion source a compact FEBIAD ion source has been implemented using the same volume envelope used by the hot surface ion source. The design is a combination of the Kirchner [8] and Sundell [9] FEBIAD types that utilized permanent magnet for the axial magnetic field to satisfy the space requirement.

We had two runs for testing the FEBIAD ion source at ISAC, last November using a TiC target and last June using a SiC high power target [10]. In both cases we operated the ion source up to 70 μA proton intensity.

The overall efficiency for the production of $^{18}F^{1+}$ and $^{18,19}Ne^{1+}$ compared to Silverberg-Stsao [11] estimation is about 10^{-4}. We are presently investigating the reasons for this low overall efficiency. We noticed a decrease of the ionization efficiency over time. Off-line tests show a deterioration of the permanent ring magnets due to the high temperature of the cathode. The next prototype will incorporate an electromagnet made of 6 mm x 6 mm copper conductor insulated using the same fibre material we used for the MISTIC ion source, see next section. Calculation shows that 100 A in 16 turns coil will produce a 400 Gauss magnetic field in the centre of the plasma chamber. The next tests on-line are scheduled for November 2007. Figure 3a shows a section view of the whole target/ion source assembly and figure 3b show a close-up of the FEBIAD ion source.



a)



b)

Figure 3: Section view of the FEBIAD ion source.

The target is shown on the left hand side, connected directly onto the target oven is the hollow cathode that permits the atoms created in the target to reach the plasma chamber. We have a new design of the grid. This new grid is made from Ta foil 1 mm thick and the slots are machined using a computer-controlled machine. The grid transparency is 75%.

The extraction system is composed of three steps, plasma, extraction and ground electrodes. The new target module in use for the FEBIAD ion source has a new feature, the extraction electrode system allow the removal of the extraction electrode. Contrary to the previous system, the extraction electrode is a part of the target/ion source assembly. The main reason for this change is the fact that the extraction electrode is being coated with material coming from the target

Figure 4 shows a photograph of our extraction electrode after a run. We can notice the large build-up of material onto the face of the electrode. It has to be cleaned on a regular basis to avoid optical distortion of the beam extracted from the ion source. This cleaning process creates huge radioactive air born particulate that contaminate the target module. By making the extraction electrode part of the target/ion source we have a fresh electrode system each time we change the assembly.

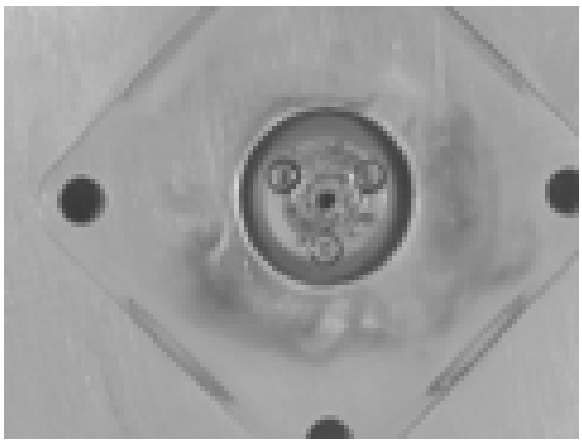


Figure 4: Photograph of the extraction electrode after a run. We can see the build-up facing the other electrode that is attached to the target/ion source assembly.

ECR Ion Source

When TRIUMF started to get involved in exotic beam physics the main drive has been the nuclear astrophysics. The aim is to study proton capture reactions that are representative of the hot burning cycles in the cosmos. In order to satisfy the demand for isotopes for the nuclear astrophysics program we must be able to ionize with high efficiency the gaseous elements, C, N, O, F, Ne. These elements are ionized efficiently with an electron cyclotron resonance ion source (ECRIS).

An early version of an ECRIS operating at 2.45 GHz was tested at ISAC [12]. We discovered that the pressure required to operate the ion source was not compatible with on-line operation. We decided to start a new project with the goal of building a new ECRIS that can operate on-line under the nominal pressure from the target. As a result of the first test we decided to improve the following aspects of the ECRIS;

1) Improvement of the electron confinement,
2) Higher operating frequency, 3 to 6 GHz,
3) Movable extraction electrode.

A new source has been built taking into account these specifications.

To improve the electron confinement we used a design similar to the ECRIS MONOBOB [13] developed at GANIL, where four coils made from hollow copper conductor surrounded by a ferromagnetic structure produce the magnetic field. This magnetic structure creates an axial and radial magnetic well at the centre of the ECRIS.

The coils are made from hollow copper conductors and are water-cooled. They are wrapped with glass insulation to operate under vacuum. The whole ion source is made of radiation resistant material for operation at high proton current.

The magnetic field has an axial symmetry and the last closed equipotential field surface is at 0.4T when the coils operate at 600A for one pair and -600 A for the other pair. The Electron Cyclotron Resonance for 6GHz is at 0.214T and the ECR surface is in the centre of the source.

The section of the copper conductor is 6mm x 6mm with a cooling channel hole of 4mm diameter (and 1mm conductor corner radius). The final width of the conductor including the 0.5mm glass fiber insulation is 7mm x 7mm.

Calculations of the power and cooling requirement show that we will need 15 kW for each coil and 6 l/m with a maximum pressure drop of 35 Bars.

Four 1000A-15V independent power supplies supply the coil. An Agilent® analogue broadband signal generator in conjunction with a CPI® 500W RF amplifier is used to generate the radio frequency necessary to obtain high energy electrons required in the ionisation of the gaseous elements. The RF signal is transported into the ion source by a coaxial cable and injected with the help of a coaxial antenna.

From our first tests it appears that the ECRIS is very stable over a large range of frequency, pressure and magnetic field. The plasma is very easy to ignite at a pressure as low as 2.6 x 10^{-6} mBar. The first results were obtained with a plasma chamber made for Copper and have been published elsewhere [14]. The quartz chamber will allow us to bias the plasma at high voltage while the magnet coils and the steel yoke are at ground potential.

The extraction system is an adjustable, three-electrode system equipped with an Einzel lens. The objectives for this year are to determine the best operating conditions and in order to start the specification for the next ECRIS target module. The design of this target module will take several months to a year. Then the target module fabrication will commence and take typically from 9 to 12 months.

HIGH POWER TARGET DEVELOPMENT

At the beginning of ISAC in 1998, the proton intensity was 1 to 2 μA on the target, which was mainly Ta and Nb foils and oxide pressed power into thin disk. Very soon we realized that if one remove the heat shield layer around the target container we could operate up to 40 μA using Ta and Nb foils targets. We observed at that moment that the release of short-lived radionuclide was non linear. The effect we were seeing was related to the radiation enhanced diffusion [15] that has been observed in the early 1950.

To go higher than the 35-40 μA proton intensity on both metal and composite carbide target, it was necessary to increase the radiative cooling of our standard ISAC target container.

Historically, the development of a target that can withstand high intensity (high power target, HPT) for the ISOL application has been driven by the desire to produce high intensity RIB far from stability and by the nuclear astrophysics research as mentioned previously. For a primary beam impinging a thick target one can express the RIB yield as the following;

$$Y = \Phi_P \, \sigma_X \, N_t \, \varepsilon_{diff} \, \varepsilon_{eff} \, \varepsilon_{ion} \, \varepsilon_{transport} \quad , \qquad 1)$$

where, Φ_P is the primary beam flux per second, σ_X, the product cross section, N_t, the number of target nucleus per cm^2, ε_{diff}, if the efficiency for the diffusion from the crystal matrix to the surface, ε_{eff} is the effusion efficiency from the target material surface to the ion source, ε_{ion} is the ionization efficiency and $\varepsilon_{transport}$ is the transport efficiency from the ion source to the experiment, its includes the stripping and the bunching efficiencies.

From equation 1 we can see that the RIB yield is directly proportional to the primary flux and target size. It is impractical to increase to target size because a larger target volume will reduce the effusion efficiency. The other parameter we can vary to obtain high RIB yield is the primary beam intensity. When increasing the primary beam intensity we must be aware to maintain the target integrity. Since a large fraction of the primary beam power is deposited into the target oven it is imperative to keep this fact in mind when increasing the primary beam intensity onto an ISOL target. If the target container looses its integrity the radioactive atoms will escape from the oven and it will result a lower yield output.

The first paper reporting calculations considering a 100 μA on target was reported at the 11th EMIS conference by Eaton and Ravn [16] in 1986. The first design employed 4 longitudinal fins 90º apart to each other to enhance the radiative cooling. The second design utilizes an extended target surface with additional conductive cooling through water channels. The second attempt at designing a HPT has been reported in 1991 by Talbert, Hsu and Prenger [17]. They proposed an alternative conductive cooling design consisting of an annular solid thermal conductor encasing the target with an outer He-filled gap separating the conductor from a water-cooled outer jacket was proposed. After that a several HPT studies were conducted by Nitschke et al. [18] proposing an active conductive cooling using He gas, Tablert et al. [19] proposing active cooling with thermal barriers and by Bennet et al. [20] proposing a passive radiative cooling approach, referred as the Rutherford Ion Source Test (RIST) target.

With the exception of the RIST target none of these designs never yield to a practical high power target. The RIST project developed a prototype target by diffusion bounding of 6000, 0,035 mm thick Ta discs, washers, and spacers of varying internal and external diameter to make a target that is integral to the container. They measured the target container effective emissivity to be of 0,7 – 0,8 at temperatures around 2000ºC. This is a significant improvement compared to 0,3 for a clean Ta surface [21,22]. Even though, the RIST approach shows that an increase of the emissivity of the target container can be obtained by the diffusion bounding technique it is a labor intensive target to produce than very expensive and the technique can only be applied few refractory metals, limiting as a mater of fact the target material that one can use for on-line RIB production.

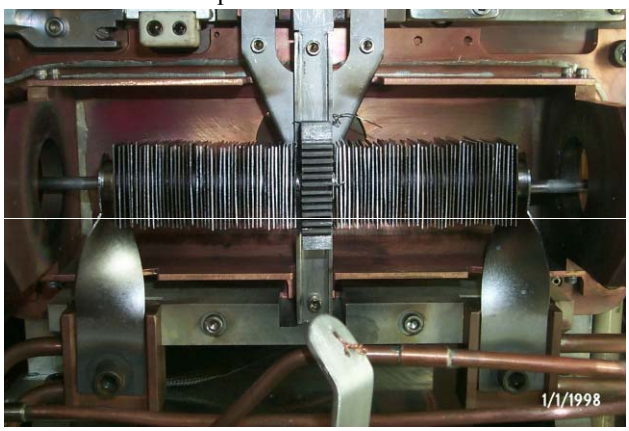


Figure 5: Photograph of the ISAC high power target after the electron bombardment test. The radial fins are diffusion bounded onto the Ta target container. The aspect ration of the gap/height is approximately 1/6 creating a body close to a perfect black body.

Nevertheless, RIST project shows that it is possible to increase the Ta container emissivity and we decided to apply this method for our ISAC HPT. But instead of using diffusion bounding discs and washers we added the radial fins along the target container [23]. The radial fins are diffusion bounded to the target container cylinder by heating under vacuum at 1500ºC to provide a series of annular radial channels along the entire target length surface as shown in figure 5. The ISAC HPT has been tested off-line using and electron bombardment showed that the effective emissivity is 0,92. It is higher than the reported emissivity of the RIST target of 0,7-0,8 because the aspect ratio of the channel is larger in our case, approaching the black body characteristics. The off-line prototype testing using both resistive and electron beam heating shows that it is capable of dissipating > 25 kW of power when operating at 2200ºC.

Using the ISAC HPT containers with resistive and beam power balancing both metal foil (Ta) and composite foil (SiC/C, TiC/C) are routinely operated with 75 μA and 70 μA p^+ beam currents, respectively. In 2007 we demonstrated operation of a high power Ta target at 100 μA continuously for a period of one week. In the moment the limiting factor is the size of our proton beam. We must defocus the primary beam in order to avoid melting the entrance window of the target container and overheating the target central region. Defocusing the proton beam has an unsuspected effect, the target container receives more proton and damage causes by radiation is now visible and the container looses its integrity.

Composite Ceramic for High Power Targets

In order to dissipate higher beam power deposited in the compound target materials such as SiC, a means of fabricating composite target foils (analogous to the metal foil materials) was developed. Instead of pressing SiC into pellets, the SiC was mixed with small quantities of organic binders and plasticizers in an aqueous solvent system and slip cast onto thin sheets (0.13 mm) of flexible exfoliated graphite foil. After solvent evaporation, the result is a thin flexible composite foil of ceramic powder bonded to graphite sheet. The ceramic layers are typically ~ 0.25 mm thick, much thinner than can be routinely achieved by pressing powders (~ 1-2 mm). Slip casting produces green ceramic layers with typically 50-60% theoretical compound density, comparable to that previously achieved for ISAC pressed pellet targets. Details of the fabrication techniques are available in [24]. To achieve good thermal contact with the inner target container wall, the flexible composite materials are cut oversize (as with the metal foils) prior to loading into the target. Burnout of organic components and sintering of the ceramic layer is achieved by heating the target in an off-line vacuum chamber before installation for on-line irradiation. With composite target foils in bare target containers with resistive/beam power balancing, p^+ currents of 35 μA for SiC/C, TiC/C and ZrC/C materials have been achieved at ISAC. Furthermore, using the HPT we are routinely operating the composite target up to 70 μA.

TARGET FUTURE DEVELOPMENT

Uranium carbide target is the next step for high mass online targets for ISAC. Since Lanthanum carbide is analog for Uranium carbide it has been chosen for the target development, so that the target material processing can be practiced without the risk of radiation contamination. As uranium carbide cannot be bought commercially, it will have to be manufactured in house. A carburization process was developed for manufacturing lanthanum carbide. The starting materials are La_2O_3 and carbon powder. The powders were prepared using the slip casting technique and cast onto a glass surface. The dried green cast (organic polymers present) was placed in a graphite coated tantalum boat and heated slowly up 1600 °C through resistive heating with a 1000 amp power supply. The organics are burnt off slowly. After the carburization temperature is reached, it is held there for 72 hours to complete the reaction. The chemistry of the reaction is with slightly less than the stoichiometric amount of 7 moles of carbon (graphite powder -

conducting grade; -325 mesh) to one mole of lanthanum oxide, as there is additional carbon provided through the incomplete burnout of the binder.

$$La2O3 + 7C \rightarrow 2LaC2 + 3CO$$

Typical yields from the reaction are 85 - 90%, with material losses due to the incomplete transferal of the slurry from the milling jars to the glass plate. Once the reaction is completed the Lanthanum carbide is moved out from the evaporator under argon and placed inside a glove box with an argon atmosphere that contains less then 3 ppm of water and oxygen. Slip casts have been prepared in the glove box using a non-aqueous based solvent. The organic material is burnt off by heating the material between 200 °C and 650 °C. Binder burnout goes to completion under oxidizing conditions, however, it generally does not go to completion under vacuum and a certain amount of carbon remain. Sintering effectively takes place around 50% of the ceramic's melting point. Handling of lanthanum carbide slip cast is also done in a glove box under argon atmosphere. Tests of the LaC on a graphite sheet on line are scheduled for spring 2008.

In order to have access to a larger RIB inventory we are looking at developing oxide target that can sustain the same high intensity as the carbide target. For example, the $^{18,19}Ne^{+}$ beams required for the nuclear astrophysics program can benefit from the development of an oxide target.

In this case we are binding the oxide onto a Nb foil. The Nb foil will be in contact with the tantalum tube and will provide most of the heat transfer for cooling.

CONCLUSION

The recent development of the HPT allows us to operate at proton beam current up to 100μA. This is obtained by widening the proton beam on target. However, widening the proton beam profile results in loosing beam on the target container, which in the long term create damage that impair the target container integrity and result in RIB looses. We are in the process to install a rotating beam that will allow the use of a narrow beam. Beam power deposited close to the target wall container would be more efficiently dissipated and a higher beam power density may also enhance product release through increased RED effects.

RIB development at TRIUMF is only possible using the on-line target stations. This sometime limit the progress we can make during our on-line test. Further more, the competition for beam time is such that it is sometimes difficult to allocate a proper beam time for on-line development. To satisfy the increased demand for beam at ISAC we are looking at other options to add at least two more target stations that will allow development and RIB delivery to other experiments. Among the possibilities we can extract 200 to 300 μA protons out of an unused port (BLA) on the H^{-} cyclotron at 460 MeV to bombard two new target stations similar to the actual ISAC target stations.

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