NEW ACHIEVEMENTS AT TRIUMF AND FUTURE PLANS

P. W. Schmor, TRIUMF, Vancouver, Canada, V6T 2A3

Abstract

The TRIUMF 500 MeV cyclotron continues to operate reliably with a number of simultaneous users and a broad scientific program. The users include condensed matter physicists (μSR, βNMR), Nuclear Physicists (ISAC, TWIST), British Columbia Cancer Agency (eye irradiation), commercial isotope production (Nordion) and commercial electronics manufacturers (proton irradiation facility). The cyclotron reliability has been maintained through a sustained and planned program of component refurbishment.[1] In addition improvements have been made to the solid target facility for commercial isotope production. The proton charge delivered to ISAC charge continues to increase each year as operation with high power targets has become more routine. Modifications are underway to permit safe operation with actinide targets. The laboratory continues to give high priority to acquiring funding for additional ISAC target stations with the goal to have more than one experiment take data simultaneously. A second proton beam line and new target station for target and ion source development have been proposed for ISAC. In the future this new target station could be used as an independent simultaneous source of exotic beams for the experimental program. In addition, a study group is presently evaluating a scheme to compliment the proton produced exotic isotopes by also making rare isotopes through photo fission with a 1 MW class electron beam.

INTRODUCTION

The 500 MeV TRIUMF cyclotron has been in operation for nearly 34 years. Programs have been initiated to both prepare for future requirements and also to ensure continuing reliable beam delivery. The ongoing developments in preparation to achieving the high intensity operation needed for the future ISOL and μSR facility requirements at TRIUMF, were given in a paper to the previous cyclotron conference.[2] In order to ensure continuing reliable operation, a refurbishment program to replace aging and unreliable equipment was initiated a number of years ago. Major items in this program included an upgrade of the cryogenic vacuum pumping system, an upgrade of the rf amplifiers and their controls, upgrades to the diagnostics and cyclotron probes, replacing the vertical injection system, adding a second ion source and replacing radiation damaged cables in the cyclotron vault. This is a major ongoing effort and details can be found in another contribution to this conference.[1]

There are two main techniques being used by radioactive ion beam (RIB) facilities for creating exotic beams, namely, the fragmentation method and the ISOL method. At TRIUMF the ISOL approach is used. ISOL type facilities typically use a light-ion driver-accelerator to produce a variety of isotopes in a target, primarily through spallation. Photo fission of actinide targets has been proposed as an alternate approach for the production of exotic beams in an ISOL facility.[2] At TRIUMF the driver accelerator is the H-, 500 MeV, cyclotron that has been shown to have the capability of accelerating over 400 μA to 500 MeV.[3] The TRIUMF cyclotron can simultaneously extract multiple independent proton beams into different locations. The transport beamline from the cyclotron to the target area in ISAC is shielded for a maximum current of 100 μA of 500 MeV protons on a thick target where the exotic isotopes are created, ionized and extracted for experiments.

The extracted beam is transported through a beamline with electrostatic focusing and steering elements. The electrostatic approach allows isotopes with adequate intensities to be used for tuning purposes and then, to adjust only the mass selecting system to the low-flux exotic isotopes. These fluxes cannot be, in general, observed on the normal beam diagnostic elements. However, with the electrostatic focusing elements, the beamline tune is not sensitive to the mass, only to the beam energy. Therefore the low intensity isotope can be transported through the line without needing to readjust the beam optics elements and requires only a minimum of low intensity diagnostics for optimizing the transport efficiency to the experimental target. An off line ion source (OLIS) is used to provide stable beams for commissioning beamlines, accelerators, setting up tunes and experimental calibrations. The required beam quality, the beam intensity, the beam energy and the momentum spread of the accelerated exotics depend on the particular experiment. For ISAC I the user input led to a continuously variable energy from 0.15 to 1.8 MeV/u for isotopes having an $A/q \leq 30$. Recently ISAC II was added with super conducting linac to increase the energy of the isotopes. The accelerator layout is shown in figure 1.

The production of exotic isotopes in an ISOL target depends on a number of variables such as driver beam-current & energy, nuclear cross-section for production, target material and target thickness. The observed yield of a particular exotic isotope also depends on the half-life of the isotope, the time that it takes the isotope to leave the target and reach the ion source, and the efficiency for ionization in the ion source. The time required to reach the ion source following production depends on material properties that are temperature dependent. The observed exotic flux from an ISOL target varies non-linearly with the proton beam current because of changes in the target temperature and factors such as radiation induced diffusion. Enhanced variations of the exotic beam flux compared to the proton beam current variations, introduce difficulties for both the experimenter and the accelerator operator. To minimize these problems it is necessary to require beam size, beam position, beam profile and beam current stability tolerances on the proton beam from the driver accelerator. In addition each accelerator event that causes an interruption in beam delivery results in an even longer interruption to the delivery of exotic ions. The target temperature at high beam powers is primarily determined by the driver beam power. The time to restore the equilibrium operating temperature in the target when the beam is restored to the operating level exceeds the time for the temperature to drop to unusable levels when a short beam interruption occurs. Consequently it has become important to monitor, analyze, and take actions to reduce the mechanisms causing the beam interruptions and beam instabilities.

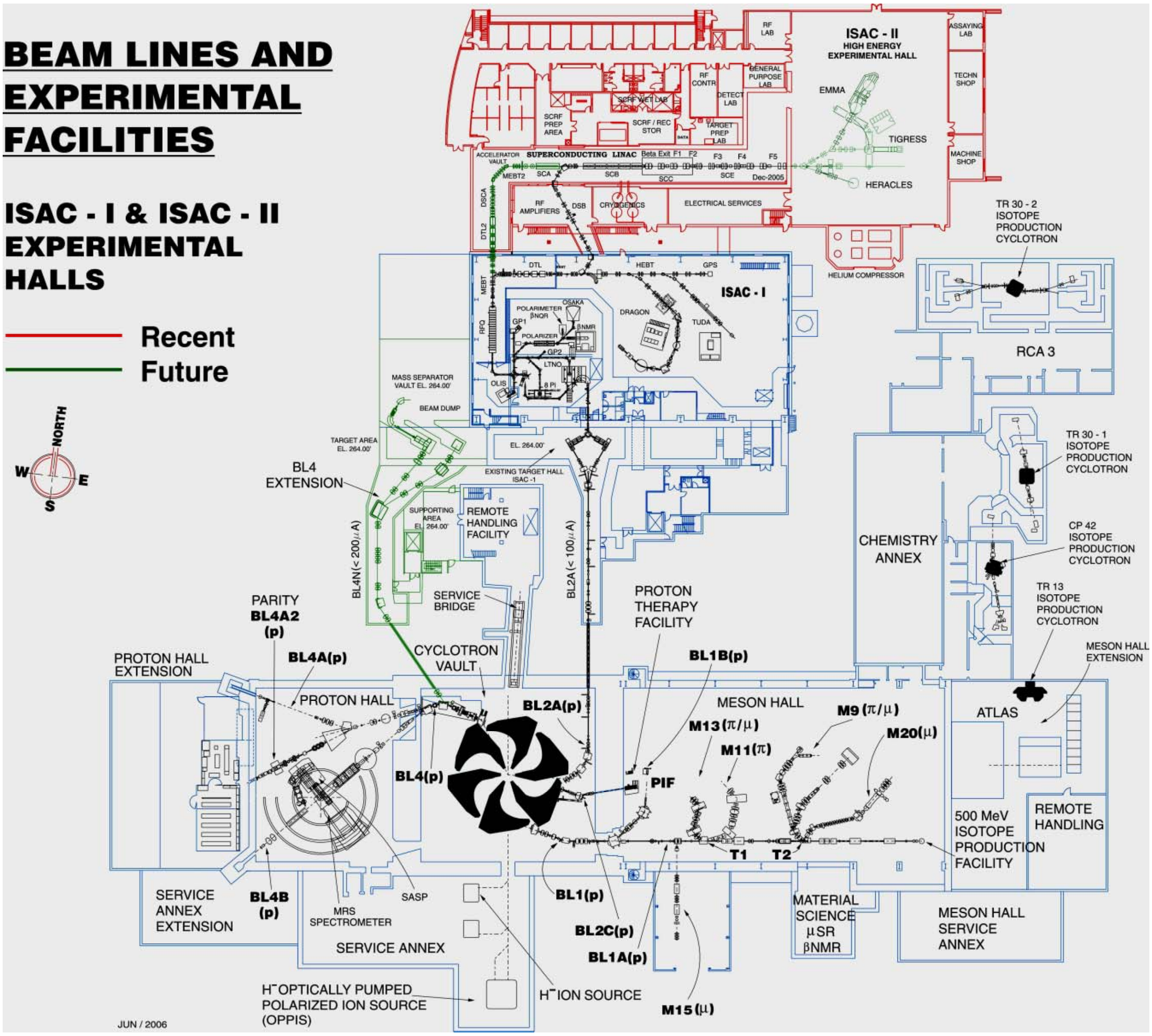

Figure 1. A schematic layout of the TRIUMF facility. The red lines indicate the building envelop for the ISAC II civil construction. The green lines labeled as BL4 extension, indicate the proposed building envelop for the proposed new high power target test facility. The ISAC II high beta cryomodules have been omitted in the schematic. Instead the HEBT beamline to the experimental hall is shown after completion of medium beta cryomodule installation in 2006. The proposed electron linac for photo fission would be located in the location of the MRS spectrometer in the proton hall.

The ISAC (Isotope Separator and Accelerator) at TRIUMF uses the ISOL (On Line Isotope Separator) technique to provide mass-separated isotopes at energies up to 60 keV for low-energy experiments. For higher energies, the ion beam is transported at 2 keV/u, injected into a room temperature RFQ Linac and then into a five-tank drift tube linac that provides variable-energy accelerated exotic-beams from 0.15 to 1.8 MeV/u for nuclear astrophysics experiments. The first stage of a Linac using super conducting rf cavities has been recently commissioned to increase the energy to 4.0 MeV/u for A/q = 7. In January, 2007 a $_{11}$Li beam was accelerated to an energy of 3.6 MeV/u for the first experiment in the ISAC II experimental hall. Additional super conducting rf cavities will be added to the ISAC II linac chain to permit a further increase in the maximum energy of the exotic beams to 6.6 MeV/u by 2010. An ECR-based charge state booster is also being added in front of the RFQ during the winter 2008 shutdown to increase the available mass range of the accelerated isotopes from 30 to about 150.

CYCLOTRON DRIVER

A cyclotron refurbishment program was initiated to replace selected unreliable cyclotron components & to allow higher current operation. The cyclotron vacuum is being improved to reduce activation from stripping by residual gas molecules in the cyclotron vacuum chamber. Beam dynamics studies have focused on understanding the sources of the beam instabilities and on increasing the ‘head-room’ for the current of the circulating beam in the cyclotron. The resulting improvements to the beam quality have coincided with the release of Be activity near the strippers in the cyclotron vacuum tank. It is believed that the contamination is due to the higher foil temperatures in the foil. Diagnostics and feedback have been added to monitor and improve the beam stability on the ISAC targets. The cyclotron current extracted for the ISAC target is stabilized, though feedback from a non-intercepting current monitor, by varying the duty cycle with a 1 kHz pulser. Collimators & halo monitors are being used to ensure the beam size is maintained throughout the operation.

SOLID TARGET FACILITY

The beam line 2C4 Solid Target Facility (STF) was first constructed in 1989 to produce radioisotopes from solid targets, and has been in routine operation since 1993. An optimal beam energy of 83 MeV for the production of 82Sr in the previous installation was achieved empirically by measuring the purity of the 82Sr. The STF was upgraded to increase reliability, reduce personnel dose during maintenance and improve the design for higher current running. The proton beam must now pass through more cooling water before reaching the target. Simulations showed that the optimum 82Sr production now requires a 100 MeV proton beam. Commissioning of the upgraded target confirmed that 85Sr/82Sr ration was negligibly small with a 100 MeV beam. The target should now be capable of safely handling at least 100 uA of 100 MeV protons.

ISAC TARGETS & ION SOURCES

The exotic isotopes created in the target material are transferred by effusion and diffusion processes to an adjacent ion source where the isotopes are ionized, extracted and formed into an ion beam. The isotope production target material is located in a tube (2 cm diameter and up to 20 cm long) and the material composition varies depending on the particular isotopes that are being optimized. The target and ion source can be biased up to a voltage of 60 keV. Target configurations have been developed that allow extended operation at the full 50 kW beam power. Novel compounds and enhanced cooling have allowed the proton current to be increased to the full 100 μA on a variety of materials.[4] The rare isotope production facility has seen the integrated proton current delivered to the targets increase by more than 25% during each of the last two years as running of high power targets becomes routine.

Isotopes are ionized at ISAC by three different types of ion sources; a thermal (surface) ion source, a resonant laser ion source and a FEBIAD (forced electron beam induced arc discharge) ion source. Each of these ion sources is capable of operating for many weeks with high power targets. An ECRIS (electron cyclotron resonance ion source), based on a 2.45 GHz design from GANIL, has been modified for operation at 2 - 8 GHz and is being tested on a test stand.

Two ion sources (micro wave and thermal) are presently used to provide stable beams from an off line ion source (OLIS). There is a need to add a more universal ion source to meet the needs and a super-nanogan ECRIS has been acquired for this purpose. Proposals have suggested that OLIS might even be useful in the future for longer lived isotopes that might be produced by one of the other four cyclotrons on site and then delivered to the OLIS ion source in containers after chemical separation.

To date ISAC has not produced fission products from actinide targets. This has restricted the range of important exotic isotopes and limited the experimental program. Neutron rich isotopes can be generated through spallation induced fission on actinide targets. The production of these isotopes introduces a need to enhance the containment of potential volatile activity within ISAC. The target modules and radiation monitoring systems in the target hall are being upgraded to permit an actinide target test in the summer of 2008.

ROTATING BEAM

The ISOL target (1.8 cm diameter) must be kept at an elevated and uniform temperature for optimal release of the exotic isotopes. The effusion and diffusion processes, by which the exotic elements leave the target material for the ion source, depend exponentially on the temperature of both the target material and the container walls. The proton beam on the target is approximately guassian in shape. This power distribution leads, in general, to a target with the maximum temperature at the radius centre and lower at the container wall, whereas, one wishes instead a uniform temperature across the target. In an effort to achieve a more uniform temperature, ac dipoles are being installed in front of the target, which will allow a small diameter proton beam to be swept across the target. Initial tests with a small diameter beam have shown that the target yield performance can indeed be improved with small beams near the target edge compared to the yields with small diameter beams at the target centre. These ac dipoles were installed during a mini shutdown in September 2007 and will be evaluated through yield measurements on beam development shifts in October.

ISAC I

Although the ISAC I accelerators were initially designed for a maximum energy of 1.5 Mev/u for beams having a A/q ≤ 30 ratio, isotopes have been accelerated from the injection energy of 2 keV/u up to a maximum energy of 1.8 MeV/u.

The accelerating system consists of a multi-harmonic pre-buncher, a cw RFQ, a medium energy beam transport (MEBT) section, an electron stripper, a re-buncher and a cw drift tube linac. The pre-buncher provides a pseudo saw tooth velocity profile at a fundamental frequency of 11.8 MHz, thereby providing approximately 86 nS between beam buckets. Bunched beam from the pre-buncher fills every third bucket of the 35 MHz, cw, 8 m long, split-ring, RFQ. The singly-charged beam out of the RFQ, at energy 0.15 Mev/u, is focused (transversely and longitudinally) and stripped to a higher charge state in the medium energy beam transport line (MEBT).

The MEBT has a 106 MHz bunch rotator to provide a time focused beam at the stripper and a dual frequency rf chopper to select cleanly separated rf bunches separated by either 85 or 107 ns. The stripped beam is magnetically bent through 90 by two 45 dipoles where silts are used to select only those isotopes having a chosen A/q (3 ≤ A/q ≤ 6) and re-bunched prior to injection into the first tank of the DTL.

The DTL provides a beam that can be continuously varied in energy from 0.15 to 1.8 MeV/u. The DTL is a separated-function structure with five DTL tanks, each operating at 0° synchronous phase, with magnetic triplets located between each tank and three split-ring, three-gap bunchers located between tanks 1, 2, 3, and 4. As the DTL system operates cw at 106 MHz, only 1 in 9 rf buckets are nominally filled (beam bursts are at the pre-buncher fundamental frequency).

Two additional bunchers are located in the high-energy beam transport (HEBT) beam line prior to the experimental stations to optimize the longitudinal timing at the experiments. For bunching the lower beta beams an 11.8 MHz triple-gap structure is used and a 35.4 MHz spiral buncher is used for bunching the higher beta beams. This accelerator has provided a wide range of isotopes over the full energy range to the experimental stations for the past seven years.

ISAC II

The ISAC I facility has been accelerating radioactive ions (with q = 1 and m = 30) up to 1.8 MeV/u. ISAC II will increase both the possible mass to at least m = 150 and the energy to 6.5 MeV/u.

The ISAC II LINAC has been described at previous conferences.[5,6,7] Briefly the completed system will include a cw DTL to increase the energy of the beam from the RFQ to 400 keV/u before stripping to a higher charge state. A superconducting linac with cavities designed for β_o = 4.2% (8 low beta cavities at 70.7 MHz), 5.7% (8 medium beta cavities at 106 MHz), 7.1% (12 medium beta cavities at 106MHz) and 10.4% (20 high beta cavities at 141 MHz). The design fields for these cavities are specified to achieve the ISAC II design energy (6.5 MeV/u) for A/q = 6. Solenoids are located between groups of cavities for transverse focusing and to enhance multi-charge acceleration when strippers are used. The medium beta section of the superconducting linac is composed of five cryomodules with each cryomodule consisting of four bulk niobium quarter wave cavities for acceleration and one superconducting solenoid for periodic transverse focusing. The cavities each produce about 1 MV of accelerating voltage. The top assembly of an ISAC II cryomodule is shown in Figure 2.

Although heavier masses are being produced in the targets and extracted from the ion sources, the high-pressure conditions near the ion sources permit only singly ionized ions to be extracted at reasonable intensities. These heavier masses could be accelerated if their charge state was increased to within the required A/q. In order for experimenters to reach the Coulomb barrier for masses up to A = 150, it is necessary to increase both the length of the ISAC accelerating system and the maximum mass that can be accelerated through the RFQ. To increase the maximum mass of ions accelerated by the RFQ, a 1+ to n+ charge state booster (CSB) is required. The installation of an ECR-based charge-state-booster in ISAC, in 2008, will allow the acceleration of all masses to 0.15 MeV/u through the RFQ.

A plan to achieve the ISAC II specifications in a phased approach is being followed in a way that allows experiments to begin prior to completion of the full accelerator capability. In the first phase, at the end of 2006, the accelerator had 20 medium-beta superconducting cavities that bring the beam to 4.0 MeV/u for A/q = 7 and, of course, somewhat higher for isotopes that can be charge-boosted to a lower A/q (9 MeV/u for A/q = 2). At this energy a number of experimenters have approved experimental proposals. By the end of 2009, on completion of the second phase, 20 more cavities (high-beta) will be added to bring the final energy up to 6.6 MeV/u (for A/q = 7). The accelerator layout is shown in figure 3.

In a later addition, ISAC I would be extended from the RFQ to a new DTL in ISAC II, that would allow further acceleration of the beams from the RFQ to 0.4 keV/u. This would provide an alternative for accelerating elements that are not efficiently charge-boosted to A/q = 7 and which would require additional stripping before acceleration in either the room temperature DTL or the superconducting ISAC II linac. A short superconducting low beta section would be added to bring the energy up to the 1.5 MeV/u required for injection into the medium beta superconducting linac.

The first stable beam acceleration through all 20 cavities occurred on April 08, 2006 when 12C3+ was accelerated to 6.3 MeV/u within the accelerator vault during the accelerator commissioning. Subsequently a variety of other stable beams with different A/q values have been commissioned. The measured average gradient is 7.2 MeV/u resulting in final energies of 10.8 MeV/u (4He2+), 6.8 MeV/u (4He1+, 12C3+, 20Ne5+, 40Ca10+) and 5.5 MeV/u (22Ne4+) with transmissions exceeding 90%.[3]

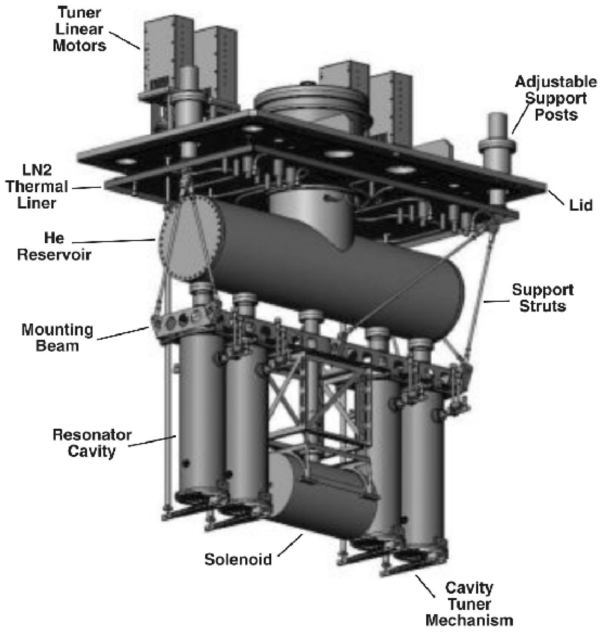

Figure 2. Component layout for each of the five medium beta cryomodules installed and operating in the ISAC II accelerator.

ISAC II OPERATION

A major milestone at TRIUMF was achieved on January 5, 2007 when an accelerated radioactive beam, 11Li was delivered from the ISAC II accelerator to the first experiment in the ISAC II experimental hall. The beam was transported to the MAYA experimental setup and within two hours data taking commenced. The MAYA equipment was brought to TRIUMF from the GANIL laboratory in France to study the outer skin structure of the exotic nucleus 11Li. The medium beta cryomodules in the ISAC II accelerator adds 20 million volts of accelerating voltage to the existing ISAC accelerator chain. For the MAYA experiment, only 11 of the 20 available cavities were needed to accelerate the beam to the required experimental energy of 39.6 MeV.

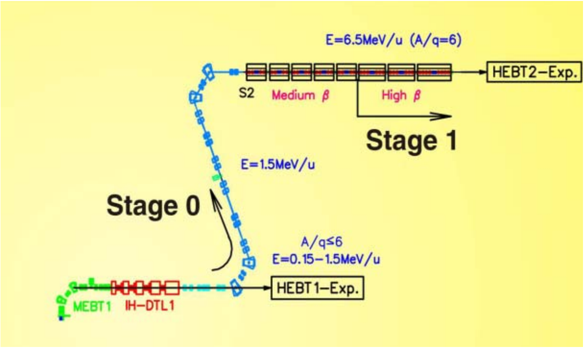

Figure 3. The accelerator layout at ISAC II. Stage 0 which includes the medium beta superconducting section is operational. Stage 1 which adds 20 high beta cavities is scheduled to be completed in 2009.

CSB (CHARGE STATE BOOSTER)

The CSB for ISAC is a Phoenix based ECRIS. TRIUMF has collaborated with ISN, Grenoble on its further development. The ECRIS has been assembled on an extension of an existing ion source test stand where its performance is being measured and optimized with stable beams from various ion sources. The CSB booster will be installed in the mass separator pit at the target level, downstream of the mass separator, in the January 2008 winter shutdown. The low energy beam transport structure to allow the beam to go through the CSB is being installed this year (2007).

FUTURE PLANS

High power target development and the experimental program compete for the same beam time from ISAC. The scheduling of target development requires a substantial overhead and is in competition with the beam avilability demanded by the user community. Experience has shown that high power target development must be done on line with proton beam. Therefore to maintain a viable experimental program, TRIUMF has decided that it is necessary to construct a dedicated target development facility. A rarely used (recently) extraction port (beam line 4) could be upgraded for high current operation and a beam line constructed to a new target hall in ISAC, capable of operating at the nominal 100 kW (figure 4). The facility would include the ISAC style target station modules, a mass separator and yield station. The facility could make use of the existing ISAC remote-handling capability, the existing nuclear exhaust system and the existing hot cells. It could operate independently of the other cyclotron beam lines and therefore target development could be carried out simultaneously with the ISAC experimental program. The expansion would be done in a manner that in the future when the target development facility is not being used for target development, a second RIB beam could be transported to any of the ISAC experimental stations. This would permit the facility to operate multiple RIB experiments simultaneously.

TRIUMF is currently formulating an ambitious new five-year plan for the period 2010 - 2015. One part of this plan is the second proton beam to the ISAC target hall. Another part of this plan is to further enhance the availability and range of isotopes at ISAC through photo fission by adding a 1 MW class electron accelerator.[2] The proposed 50 MeV electron accelerator would be located in the currently vacant experimental proton hall and use the beam line 4 tunnel to also transport the electron beams to targets in the ISAC target hall. If approved, this could potentially allow for three simultaneous exotic beam experiments in the future.

SUMMARY

The accomplishments described in this paper were realized by a team effort. Without presenting the many names individually, I must nevertheless acknowledge them for these achievements.

The success of a facility is ultimately measured by its science output. The nuclear physics experimental facility has attracted experimental groups internationally because of its unique capabilities. Experimental groups are acquiring and setting up the apparatus needed for the ISAC II science program. The three major facilities will include TIGRESS (a high efficiency gamma array), HERACLES, EMMA (a recoil mass spectrometer) and a general purpose station which presently accommodates the MAYA detector.

REFERENCES

[1] I. Bylinskii et al, “TRIUMF 500 MeV Cyclotron Refurbishment”, These proceedings.

[2] W. T. Diamond, “A radioactive ion beam facility using photofission”, Nucl. Instr. and Meth. A 432 (1999 p. 471.

[3] G. Dutto et al, “TRIUMF High Intensity Cyclotron Development for ISAC”, Proceedings of Cyclotrons 2004, Tokyo, Japan, p. 82

[4] P Bricault, “Progress in Development of ISOL RIB Ion Sources and Targets for High Power”, These Proceedings

[5] R.E. Laxdal, “ISAC-I and ISAC-II at TRIUMF: Achieved Performance and New Construction”, Proceedings of LINAC 2002, Gyeongju, Korea, p. 296.

[6] R.E. Laxdal et al; “Commissioning of the ISAC-II heavy Ion Linac at TRIUMF”, Proceedings of EPAC06, Edinburgh, Scotland, p. 1556

[7] R. E. Laxdal, “Commissioning and Early Experiments with ISAC II”, PAC07 Proceedings of PAC07, 2007, Albuquerque, p. 2593

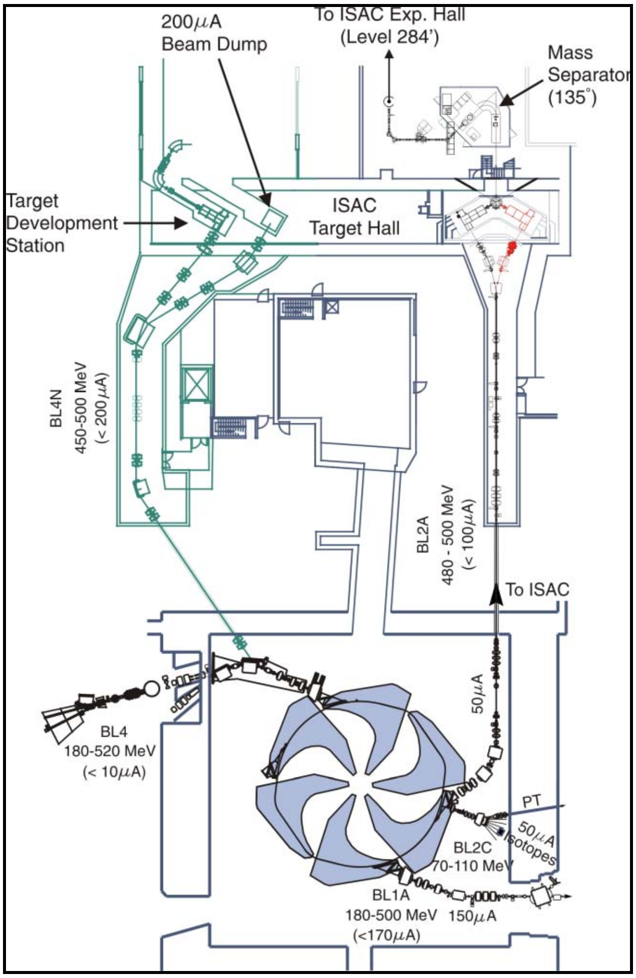

Figure 4. The BL4 cyclotron extraction port will be used to provide beams for high target development in an underground expansion of the ISAC target hall (shown in green).