TRIUMF: ISAC II AND BEYOND

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Abstract

The ISAC (Isotope Separator and Accelerator) facility at TRIUMF uses the ISOL (On Line Isotope Separator) technique to create exotic isotopes in a thick target mainly through spallation from 500 MeV protons. The ISAC target area has been designed to accommodate up to 50 kW of beam power from the TRIUMF 500 MeV H- driver cyclotron. An ion beam formed from these exotic isotopes is transported at energies up to 60 keV through a mass separator either to a linac for further acceleration or to any one of a suite of low energy experimental stations. Isotopes injected into the room temperature RFQ Linac must have an energy of 2 keV/u. The RFQ is followed by 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. Super conducting rf cavities are presently being added to the linac chain to permit a further increase in the maximum energy of the exotic beams to 6.5 MeV/u. An ECR-based charge state booster will be added in front of the RFQ to increase the available mass range of the accelerated isotopes from 30 to about 150. A second proton beam line from the cyclotron 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.

INTRODUCTION

The availability of short-lived exotic beams has become important in the search for solutions to a number of important questions in science. There are two main techniques for creating these exotic beams, namely, the fragmentation method and the ISOL method. In the fragmentation method; high-energy heavy nuclei bombard a thin target, ejected high-energy particles are captured in a beam transport system, then mass separated by a large acceptance magnet system and finally transported to experimental stations. At TRIUMF the ISOL approach is used.

ISAC I

ISOL type facilities typically use a light-ion driver-accelerator to produce a variety of isotopes in a target. These isotopes are transferred by effusion and diffusion processes to an adjacent ion source where the isotopes are ionized, extracted and formed into an ion beam. A particular isotope is then selected by slits at the focal plane of a mass separator and transported to experimental stations either prior to or following further acceleration. The required beam quality, the beam intensity, the beam energy and the momentum spread of the accelerated exotics depend on the particular experiment. In ISAC, the light-ion driver is the 500 MeV H- cyclotron and the extracted 500 MeV protons produce the isotopes in a variety of targets optimized for particular exotics. For the experiments located in the low energy area of ISAC I, the low energy beam transport system (LEBT) and mass separator system have been designed to accommodate ion energies up to 60 keV and masses less than or equal to 240. For the ISAC I accelerated beams, financial constraints and user input led to a continuously variable energy from 0.15 to 1.5 MeV/u for isotopes having an $a/q \leq 30$.

At TRIUMF the driver is an H-, 500 MeV, cyclotron that has been shown to have the capability of accelerating over 400 μA to 500 MeV.[1] The TRIUMF cyclotron can simultaneously extract multiple independent proton beams into different locations. A transport beamline (BL2A) from the cyclotron to the two target stations in ISAC is designed and shielded for a maximum of 100 μA of 500 MeV protons on a thick uranium target.

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. The extracted beam is transported through a beamline with electrostatic focusing and steering elements. This focusing 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 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 and that is kept constant. Therefore the low intensity isotope can be transported through the line without needing to readjust the beam optics elements and a minimum of low intensity diagnostics for optimizing the transport efficiency to the experimental target. Good space charge neutralization is not achievable with electrostatic optics. For many targets and ion sources, as the proton current is increased, space charge effects are indeed observed in the region between the ion source and the preseparator. It is necessary to adjust the electrostatic optics in this region as the ion current increases in order to maintain a good transmission of this relatively slow moving beam that contains all of the ionized exotics. An off line ion source (OLIS) is used to provide stable beams for commissioning beamlines, accelerators, setting up tunes and experimental calibrations. Figure 1 shows the layout of the TRIUMF facility indicating by color coding the existing and planned modifications.

Although the ISAC I accelerators were initially designed for a maximum energy of 1.5 Mev/u for beams having a $m/q \leq 30$ ratio, isotopes have been accelerated from the injection energy of 2 keV/u up to a maximum

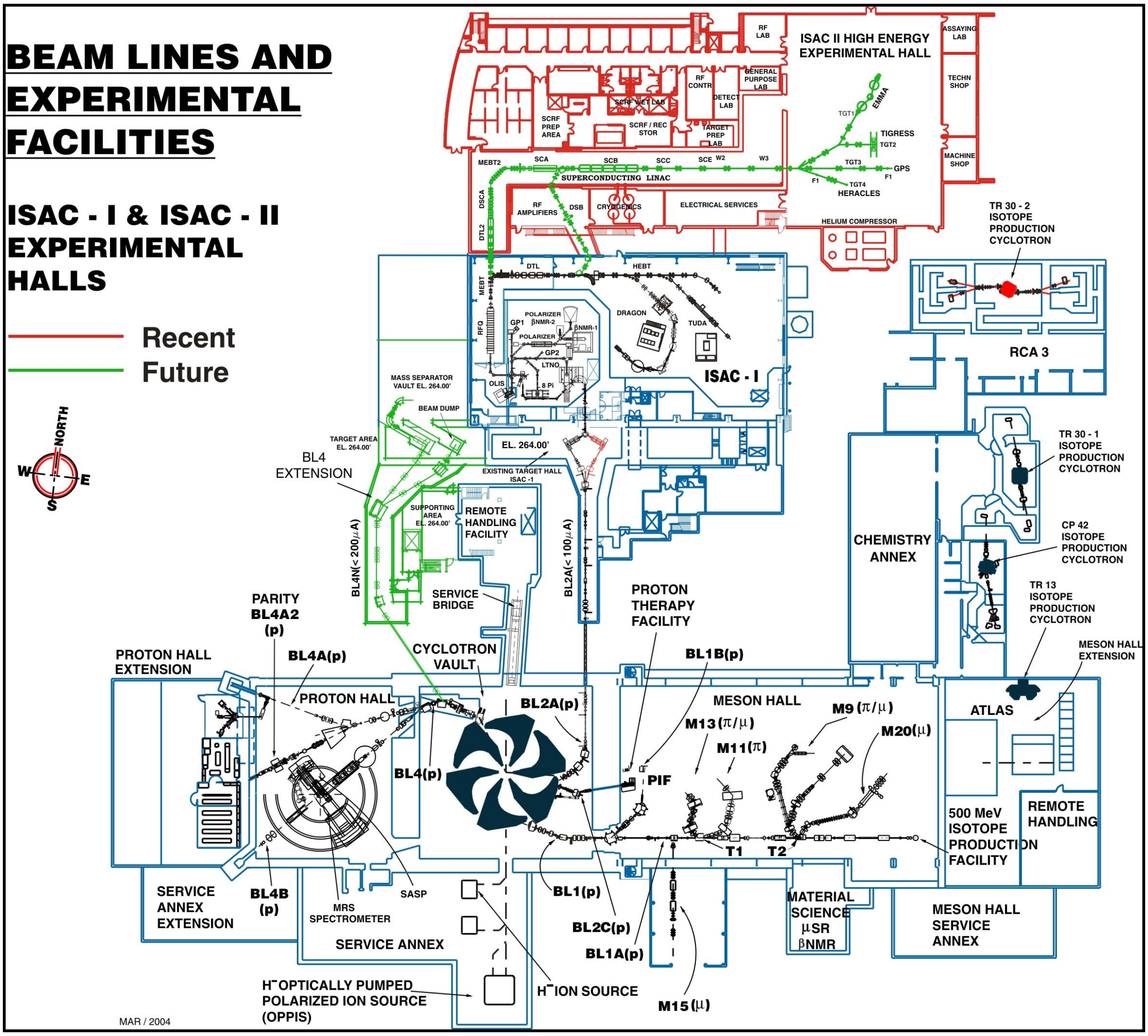

Figure 1. This figure is an overall schematic layout of the TRIUMF facility. The upper building (red lines) indicates the building envelop for the recently completed ISAC II civil construction. The building to the West of the Remote Handling Facility (green lines) labeled as BL4 extension, indicates 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 2005 when the first ISAC II experiments are planned.

energy of 1.8 MeV/u.[2] 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, 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 an 106 MHz bunch rotator to provide a time focused beam at the stripper and a double 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 m/q ($3 \le m/q \le 6$) 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 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 four years. The request for beams of stable isotopes has been greater than initially anticipated. Two ion sources are being presently used to provide the stable beams from the off line ion source (OLIS). There is a need to add a more universal ion source to meet these needs. Proposals have suggested that OLIS might even be useful for longer lived isotopes that were produced by one of the other four cyclotron on site and delivered to the OLIS ion source in gas bottles after chemical separation.

ISAC II

As mentioned above, the ISAC I facility is currently accelerating radioactive ions (with $q = \pm 1$ and $m \leq 30$) up to 1.8 MeV/u. 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 m/q. In order for experimenters to reach the Coulomb barrier (roughly 6.5 MeV/u) with masses up to 150, it is necessary to increase both the length of the ISAC accelerating system and the maximum mass that can be accelerated.[2] In order to increase the maximum mass of ions accelerated by the RFQ, a 1+ to n+ charge state booster (CSB) is required. Electron-cyclotron-resonance (ECRIS) ion sources have been shown to reach the required $q/A \geq 1/30$ for many elements. The installation of a charge-state-booster in ISAC would allow the acceleration of all masses to 0.15 MeV/u. However, the beam intensities for masses beyond $A \approx 70$ would most likely be too low to be useful if the ions require further stripping at 0.15 MeV/u before injection into the DTL. The stripper, in ISAC I, is located at 0.15 MeV/u and reasonable beam intensities with a q/A of 1/6 cannot be achieved for masses beyond about 70 for beams that require stripping at this low velocity. The optimum stripping energy for $30 \leq A \leq 150$ with $q/A \geq 1/6$ is about 0.4 MeV/u. To accelerate the ion beam from 0.15 to 0.4 MeV/u, requires a new linac (DTL2).

A plan to achieve the ISAC II requirements in a phased approach is being followed that allows experiments to begin prior to completion of the full accelerator capability. The plan is to optimize and install an electron cyclotron resonance ion source (ECRIS), operating in a 1+ to n+ charge state booster (CSB) mode, after the mass separator. Beams from the ECRIS CSB will be transported through the low energy beam transport (LEBT), accelerated to 1.5 MeV/u and then diverted into a new accelerator hall. In the first phase, at the end of 2005, the accelerator would contain only 20 medium-beta superconducting cavities and bring the beam to 4.3 MeV/u for m/q = 6 and, of course, somewhat higher for isotopes that can be charge boosted to a lower m/q. At least one experimental station will be prepared to use the ISAC II beams at this time. By the end of 2007, on completion of the second phase, 20 more cavities will be added to bring the final energy up to 6.5 MeV/u. By the end of 2009, on completion of the third phase, the ISAC I MEBT would be extended from the RFQ to a DTL in ISAC II, that would allow 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 and require additional stripping for acceleration in 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 accelerator layout with respect to each of these three phases is shown in figure 2.

Civil Construction

The ISAC facility has been expanded with the addition of a new building to the north of the existing ISAC I structure. This new building includes floor space for the superconducting linac, the helium cryogenic plant, the experimental stations, a clean room for accelerator assembly and offices. The building was initially occupied in the spring of 2003. The clean room and cryomodule assembly space became operational during the fall of 2003. The first half of the cryogenic system will be installed and commissioned in the fall of 2004. The first medium beta (actually number three in the chain) will be installed in the fall of 2004. Planning has started on evaluating additional ion sources on OLIS in order that the heavier, stable-masses can be accelerated at intensities and charge states suitable for ISAC II needs.

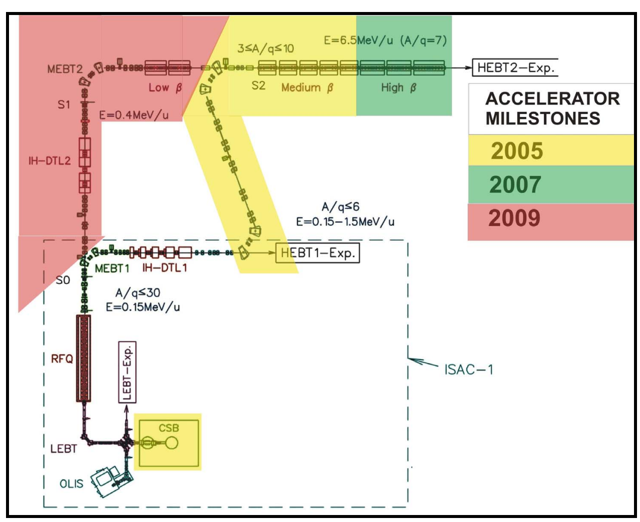

Figure 2. ISAC II accelerator layout with the projected completion dates for the three phases (color-coded).

determined from a five-year plan developed by TRIUMF

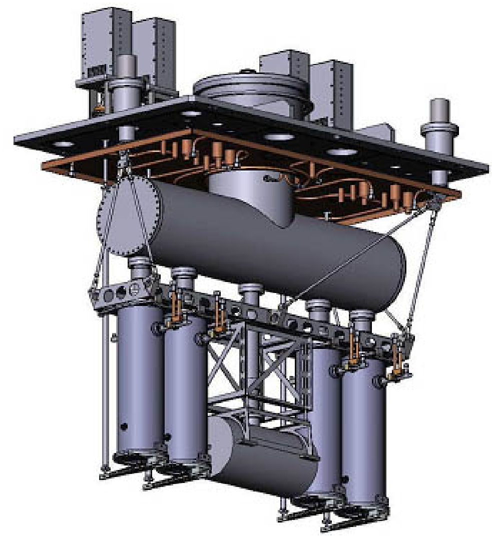

Figure 3. A sketch of the internal components of a medium beta cryomodule. Each of the five medium-beta cryomodules contains two superconducting niobium quarter-wave resonator-cavities on either side of one superconducting solenoid.

and based on submissions to TRIUMF from the Canadian subatomic Physics community. The next five-year plan begins in April 2005 and is being reviewed by the Canadian federal government. In this plan, the ISAC accelerators would be completed, the cyclotron would be upgraded to both improve reliability and increase the proton current and a new proton beam line would be built from the cyclotron to a new target development facility in an extended ISAC building.

High power target development and the experimental program compete for the same beam time from ISAC. Target development scheduling requires a substantial overhead and is inconsistent with the beam reliability 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 build a dedicated target development facility. A rarely used (recently) extraction port will be upgraded for high current operation and a beam line constructed to a new target hall in ISAC, capable of operating at the nominal 50 kW. The facility will include the ISAC style target station modules, a mass separator and yield station. The facility will make use of the existing remote-handling capability, the existing nuclear exhaust system and the existing hot cells. It will operate independently of the other cyclotron beam lines and therefore target development can be carried out simultaneously with the ISAC experimental program. The expansion is being done in such 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

CSB (Charge State Booster)

The CSB is a Phoenix based ECRIS. TRIUMF is collaborating with ISN, Grenoble on its further development. The ECRIS has been assembled on an extension of the existing ion source test stand where its performance will be measured and optimized during the next year. An initial charge state boosted beam has just been observed, using a separate ECR as the 1+ injector. The CSB booster will be installed in the mass separator pit at the target level, downstream of the mass separator, in the January 2006 shutdown. The initial LEBT structure will be installed during the previous year (2005).

LINAC

Briefly the completed ISAC II linac 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 either 141 or 106 MHz). The design fields for these cavities are specified to achieve the ISAC II design energy (6.5 MeV/u) for m/q = 6. Solenoids are located between groups of cavities for transverse focusing and to enhance multi-charge acceleration when strippers are used. The HEBT from the existing 1.5 MeV/u linac to the medium beta cryomodules is currently being installed. The first cryomodule (#3) has been completed and cold tested. The tests have successfully shown that the heat load is within expectations, that solenoid field does not impact the cavity performance, that cavity alignment tolerances are achievable and the rf tuners allow the cavity frequency to be locked. The cryogenic plant has been purchased from Linde and should be commissioned before the end of 2004. The cold distribution system is scheduled to be completed in the fall of 2005, along with all five medium beta cryomodules. By the end of 2005, a 1.5 MeV beam from the ISAC I DTL will be transported to and accelerated by the medium beta section to 4.4 MeV/u. The high beta section will be built and installed with full operation to 6.5 MeV/u to begin at the end of 2007. Finally, the low-beta cryomodule, DTL2 and connection to the RFQ will be completed by the end of 2009.

HEBT

Many of the elements required for the HEBT, both from the existing DTL to the medium beta cryomodules and the HEBT from the cryomodules to the ISAC II experimental stations have already been acquired. The section joining ISAC I to ISAC II is being installed and will be completed by the end of 2004.

FUTURE PLANS

TRIUMF has for the past 10 years been funded in five-year cycles with schedules and resource requirements experimental stations. This would permit the facility to operate multiple RIB experiments simultaneously.

GENERAL CONSIDERATIONS

There are several international proposals to build new multi-purpose, high-intensity radioactive ion beam facilities. ISAC experience has shown that successful operation of a RIB ISOL type facility introduces several unique accelerator constraints that need to be preplanned in order to make efficient and cost effective use of the rare exotic beams. The interesting exotic beams are rare and require diagnostics that cannot conveniently be packaged into the space constraints of normal beam diagnostics. The costs and complexity for these low-intensity beam-monitors (using nuclear counting techniques) imply that the accelerators must be initially tuned with a stable higher-intensity beam that is an analog of the beam of interest and then switched to the exotic beam with a minimum of tuning. The facility should include an ion source for stable beams in order to commission the accelerator, provide analog beams for experimental set up and for experimental calibrations. ISAC initially installed a compact microwave ion source for commissioning the accelerators with ions from a range of gases, modified the microwave ion source to also obtain some metallic ions, then added a thermal surface ion source to accommodate experimental requests and is now evaluating how to modify the off-line ion source (OLIS) in order to better satisfy the user community. For a high-intensity ISOL facility, it is essential that the driver linac operate in a cw or near cw mode with a beam stability of a few percent. The intensity of an extracted exotic beam is not solely determined by the production cross section. The temperature of the target is largely determined by the deposited power from the driver beam. The intensity of the exotic beams depends on the diffusion and effusion times from production to ionization. These times are temperature dependent. Consequently for a short-lived isotope the variation of its intensity can be amplified compared to the variation of the intensity of the driver beam. Target development cannot be reliably simulated for high power operation. On line target development has a large time overhead that takes beam time away from the scientific program. However, on line target development is essential. Therefore, it is essential to have a dedicated development facility that can operate simultaneously with the production target used for the scientific program. Moreover, the driver must be capable of varying the power independently two these two areas. The TRIUMF cyclotron, was designed to provide multiple, simultaneously independent beams. The addition of an on line target development facility is a high priority project within the next TRIUMF five-year plan. Figure 2 sows the planned proton beam line and target development facility. The plan also includes a 100 kW beam dump for tuning the cyclotron for reliable high current operation. This project should be complete by 2009.

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.

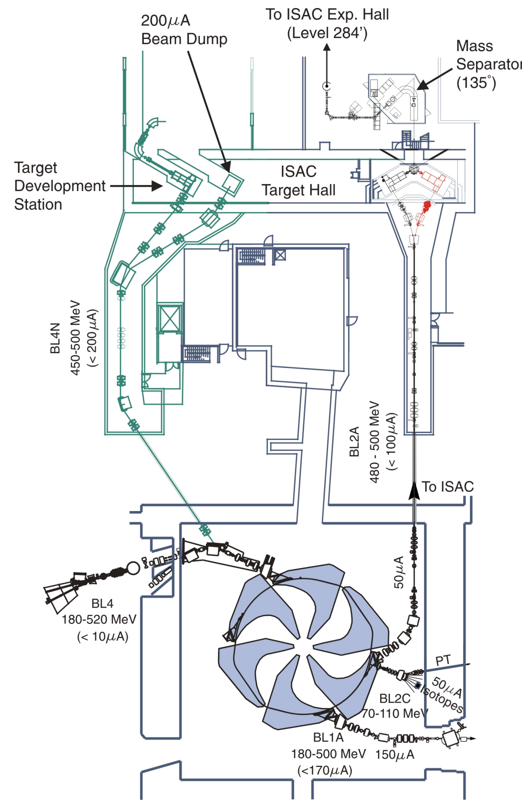

Figure 4. The BL4 cyclotron extraction port will be used to provide beams for high-power target development in an underground expansion of the ISAC target hall (shown in green).

The success of a facility is ultimately measured by its science output. The nuclear astrophysics experimental facility has attracted experimental groups internationally because of its unique capabilities. Experimental groups are already 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), TUDA (a silicon strip detector array), HERACLES, and EMMA (a recoil mass spectrometer).

REFERENCES

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[2] R.E. Laxdal, "ISAC-I and ISAC-II at TRIUMF: Achieved Performance and New Construction", Proceedings of LINAC 2002, Gyeongju, Korea, p. 29