RECENT PROGRESS AT TRIUMF

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Abstract

ISAC, a new facility for accelerating intense ion beams of unstable nucleii is under construction at TRIUMF. The radioactive nucleii will be produced by up to 100 μA of 500 MeV protons impinging on one of two target/ion-source stations located in an underground vault. Singly-charged ion beams will be transported at energies up to 60 keV to a high-acceptance, high-resolution mass analyser by electrostatic ion optics. Following mass selection the beam is further transported vertically to grade level and then horizontally to either a low-energy experimental area or to a system of linear accelerators consisting of an RFQ and a DTL. The beam out of the DTL, will have energy continuously variable from 0.15 to 1.5 A·MeV. The facility is now being constructed. A new high intensity extraction beam line from the cyclotron is being installed, and the 500 MeV proton beam has already been extracted, simultaneously with the other high intensity proton beam dedicated to meson production. Commissioning of a grade level portion of the LEBT (using a stable off-line ion source), of a prebuncher, and of the front end of the RFQ, has now begun. The schedule calls for first experiments at low energy, using the new target station, to take place before the end of 1998. Other TRIUMF facility progress, including new records for the OPPIS high intensity beams, will also be reported.

1 INTRODUCTION

TRIUMF, the national Canadian laboratory for subatomic physics, has a strong tradition of collaborations and exchanges, in the field of particle accelerators, with several Asian countries, including Japan, China, Korea, Taiwan, India, Russia (BINP), Kazakstan, and Uzbekistan. Its location in Vancouver, on the Canadian west coast, makes communications and exchanges particularly easy and attractive for Asian Pacific Rim countries.

The laboratory (Fig. 1) is based on a 180-500 MeV, variable energy, high intensity H$^-$ cyclotron delivering proton beam simultaneously to a meson production area ($\leq 200\mu$A), a medium resolution two arm spectrometer area ($\leq 1\mu$A), a polarized beam facility for polarized protons and neutrons ($\leq 2\mu$A,p), a low intensity ($\leq 2\mu$A,p) 500 MeV ISOL area for radio-active ion beams up to energy q x 60 keV, and at lower extracted energies, a facility for isotope research and production ($\leq 80\mu$A, 60 to 120 MeV). Elsewhere on site, three high intensity H^- cyclotrons delivering protons of energy between 7 and 42 MeV are routinely used for isotope production for commercial and applied use (e.g. PET research). An ambitious project using the 500 MeV cyclotron as an injector for a 30 GeV hadron facility (KAON) was cancelled in 1994.

In 1995, a five-year plan was approved with a large diversified mandate. This included (1) the design and construction of a new Isotope Separator and ACcelerator (ISAC) for exotic beams; (2) the Canadian participation, through TRIUMF, in the CERN LHC construction; (3) the continuation of the existing basic experimental program with high intensity beams for meson production, and low intensity beams of protons and polarized protons. Protons and muons are also used for material science, life science and medical therapy. The plan also includes (4) infrastructure support to the Canadian sub-atomic physics program with collaboration to major detector work in Canada and abroad; and (5) transfer of technology to industry for commercial applications. Important recent accelerator developments at TRIUMF of interest to this Conference are the ISAC RFQ-DTL linac, now being constructed to accelerate ions with $q/A \geq \frac{1}{30}$ up to 1.5 A·MeV, the intense polarized ion source being developed for several mA of 80% polarized H$^-$, the state-of-the-art compact cyclotrons built in collaboration with industry for isotope production with H$^-$ intensities in excess of 1.2 mA and our recent eye-melanoma proton therapy facility. These will be briefly described below.

2 THE ISAC PROJECT

A dedicated new building of $\sim$ 5,000 m^2 of floor space has been built to the north of the original cyclotron complex. A dedicated primary proton beam line is being installed in the cyclotron vault and extends through an underground tunnel towards the north. It will be capable of transporting a 500 MeV proton beam of intensity up to 100 μA to one of two targets and beam dumps in the target area. Initially, only the west target will be used. Beams from both targets will be directed to a $\pm$ 60° pre- separator magnet (Fig. 1& 2). An overhead remotely controlled 20-ton crane links the target area with the area where the target modules storage and hot cell manipulation will take place. Downstream of the pre-separator, a mass separator will be used, with resolving power of $\sim \frac{1}{10000}$ (Fig. 2). After the last defining slits the beam will be deflected and transported through the LEBT, first horizontally, then vertically to grade level in the experimental building and thereafter horizontally either to a low energy experimental area or to the accelerator (see Fig. 3). This consists of an 8 m long RFQ section, a stripper bender rebuncher section (MEBT), a five tank DTL section, and a high energy transport section (HEBT). The DTL includes three bunchers which will allow continuous energy variability from 150 A·keV to 1.5 A·MeV. A recoil mass separator with a rejection factor of 1/10^{15} has been designed and submitted for funding.

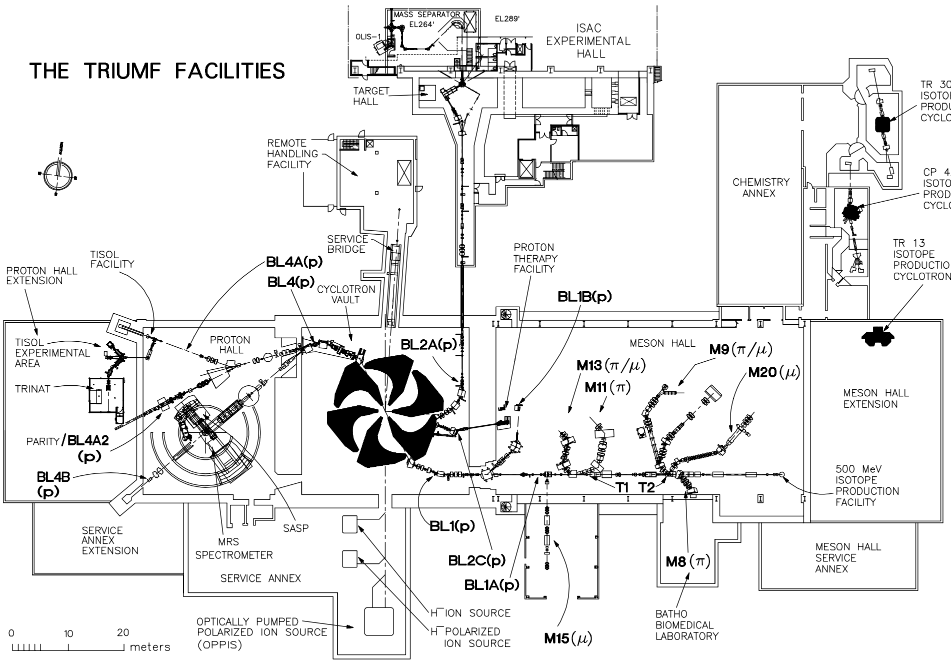

Figure 1: Layout of the TRIUMF facility.

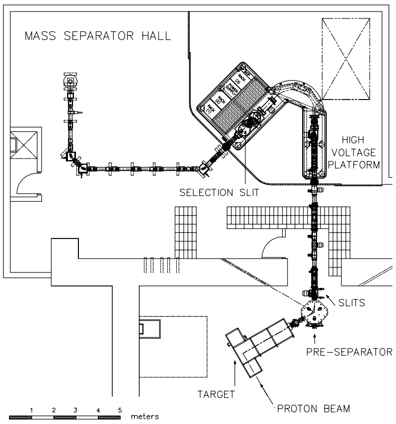

Figure 2: The target mass separator area.

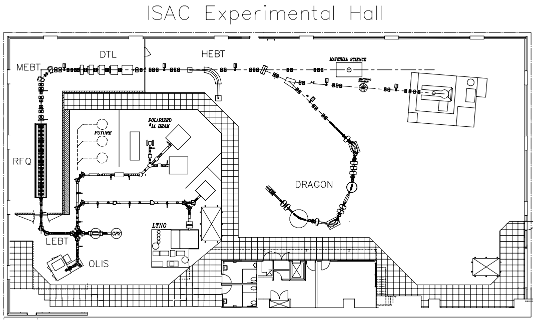

Figure 3: Layout of the ISAC experimental hall.

Initially, low energy experimental activity will include a study of β decay from radio-active atoms in a neutral atom trap to verify symmetries and parity non-conservation in relation to Standard Model predictions. In addition, the half-life and branching ratio of the super allowed Fermi decay wil be measured on ^{74}Rb to verify the intensity of the Cabibbo Kobayashi Maskawa quark coupling matrix. A β NMR station using a polarized ^{8}Li beam is also being set up for material studies. Finally, a dilution refrigerator for low temperature nuclear orientation (LTNO) is being installed. Nuclear astrophysics measurements have been performed for several years at TISOL. They will be continued at higher intensity and higher energy on ISAC.

The schedule calls for a primary proton beam to the target area by April 1998. Exotic ion beams will be delivered to the first low energy experiment by year end. Regarding the accelerator (see Fig. 3), a 60 kV stable off-line Ion Source (OLIS) has been installed in the experimental hall and beam has been tested through a portion of the LEBT to the RFQ entrance. A front end portion (7-ring, $\sim$ 60 A·keV) of the RFQ will be commissioned before summer 1998. The complete 8-m long RFQ (19-ring, 150 A·keV), the MEBT section, and the front end of the DTL (first tank), will be commissioned before the end of 1999. It is planned to install the rest of the DTL and to deliver beam to the $\leq$ 1.5 A·MeV experiments by the end of year 2000.

Design concepts for the various systems of the ISAC project have been reported elsewhere [1–6]. Below we will place emphasis on recent progress highlights.

2.1 Primary proton beam line

With the addition of a fourth extraction beam line the cyclotron will have the unique capability of extracting simultaneously four beams, with a total cyclotron accelerated beam current in excess of 300 μA. Because of the vicinity of BL2A to BL1A, and because of a known vertical displacement of the equilibrium orbit from the median plane at $\sim$ 500 MeV, it was decided to measure the 2A extracted beam characteristics in the vault and to test the compatibility of 2A extraction with simultaneous beam extraction on beam line 1A. The energy was varied from 472 to 510 MeV and measurements were found in agreement with predictions. Both beams were sufficiently well aligned vertically. The installation of the new extraction mechanism, of the extraction chamber, of the combination magnet and of the front end beam line could be achieved with tolerable dose exposure to personnel ($\sim$ 15 mSv) despite the rather high activation level (.2 to 8 mSv/h) at the cyclotron periphery. Remote handling techniques and efficient local shielding for hands-on intervention were employed.

2.2 The target - ion source system

The two target vacuum chambers are ”T” shaped (Fig. 2), about 2 m tall, and fit into two canyons constructed of steel and concrete shielding blocks. They accommodate five modules each. The entrance, target and beam dump modules are positioned along the direction of the proton beam line. These support entrance diagnostics, target and ion source chamber, and a water-cooled copper beam dump, respectively. The two extraction modules are positioned along a direction orthogonal to the primary beam and house the extraction optics directing the beam to the pre-separator. The target-source module is the most complex. It and the exit modules are contained in an independently pumped vacuum box connected to a separate turbomolecular pump. Target proper and source will be biased to give extraction voltages up to 60 kV. The two extraction modules also have boxes with separate vacuum. Special shielding plugs have been designed for each module to fill the 2-meter high space in the vacuum chamber, with allowance for ducts and pumping channels, but such as to reduce the activation on the upper side of the tank to levels compatible with elastomer materials for vacuum seals and services. Modules can be removed remotely and transported to the hot cells without special flasks. The shielding of the target service portion of the building has been designed accordingly.

The construction of the target is now proceeding at a fast pace. The target building is complete and most initial shielding, including iron blocks and concrete forming the canyons, is installed. The T-shaped vacuum chambers have been tested for mechanical precision and vacuum properties.

Ion sources are being studied in a dedicated 60 kV test-stand station in the laboratory. A surface ion source, with a fixed geometry multi-electrode extraction column, was tested first. Emittance measurements performed with ^{85}Rb at 3l.5 keV indicated no significant intensity dependent effect up to 10 μA. Emittances were also measured for several separated mass beams between ^{7}Li and ^{133}Cs. Only the analysing field was changed from one ion species to the next. The results indicated that emittances below 10 π mm mrad could be obtained with small dependence of the beam emittance on the mass. A microwave multicusp source was also tested and gave a satisfactory beam with energy spread of 1.8 eV measured for He^{+1} ions.

2.3 Mass separator and LEBT

The front end (Fig. 2) includes an electrostatic triplet followed by a doublet. Preliminary mass selection will be achieved through the 60° pre-separator magnet having a resolving power around 300. The pre-separator is followed by three matching sections, an acceleration column, a mass analysing section and a deceleration column. It was found practical to use the TASCC 135° mass separator magnet which became available from Chalk River during 1997. The mass separator magnet will be located on a high voltage ($\leq$ 60kV) platform in order to ease magnet tuning and improve the rejection of contaminants. The ion optics were calculated with the computing code GI0S. The separator system will handle beams of ion masses between 6 and 238 amu, source extraction voltages between 12 and 60 kV and emittances of $\sim$ 10 π mm mrad (surface, cusp) or 30 π mm mrad (plasma sources); other parameters are given in Table 1.

Table 1. Parameters of the mass separator system.

Pre-separator stage	
Deflection radius ρ_B	500 mm
Deflection angle θ_B	$\pm 60°$
Air gap	70 mm
n	0.0
Mass separation stage	
Deflection radius ρ_B	1000 mm
Deflection angle θ_B	135 °
Air gap	100 mm
n	0.5

All optics elements of the LEBT between the mass separator and the RFQ accelerator are electrostatic. There are 90° non-dispersive bend sections, a switchyard, several periodic sections, etc. One exception is the 11.7 MHz buncher $\sim$ 5 m upstream of the RFQ, which concentrates the beam in bunches at 86 ns intervals, as requested by experimenters. This made it possible to eliminate in the RFQ the beam shaper and gentle buncher portions at the front end with substantial shortening of the unit. With quasi saw-tooth pulse shaping with 4 harmonics the buncher allows 81% capture by the RFQ acceptance. At present the buncher has been tested and operated with three harmonics below the design voltage of $\pm$200 V. To commission the accelerator, a 60 kV off-line source has been installed in the experimental hall upstream of the main switchyard (Fig.3). Time structure and emittances were measured for a beam of ^{14}N+ at 30 keV (fig 4.). The 4 RMS emittance of $\sim$ 16 π mm mrad and the 5 ns time width of the bunch are well within the calculated acceptance of the RFQ.

2.4 The RFQ for 150 A.keV

The RFQ is a split ring 4-rod low β unit resonating at 35 MHz. It is designed to raise the ion energy from 2 A·keV to 150 A·keV for ions of $\frac{q}{A} \geq \frac{1}{30}$. The 8 m long, 1 x 1 m^2 square tank houses the 19 identical split ring structures supporting the four modulated vane-shaped electrodes. Both rings and electrodes are water-cooled. The nominal design voltage across the electrodes is 74 kV, the calculated characteristic radius to pole tip is Ro = 0.74 cm; the focussing strength B = 3.5 and characteristic impedence is calculated to be 313 k Ω m. The challenge of the mechanical design, considering the fact that the cavity has to be operated cw at a 100 kW full power, is the stringent ± 0.08 mm alignment tolerance of the four electrodes. A three-ring full-scale prototype was constructed, full power was achieved, and electrode displacement between power on and off was measured to be below 0.05 mm, within tolerance. Also, the resonating frequency shift between power on and power off is small (less than 20 or 30 kHz). The resonating frequency was found in close agreement (within 200 kHz) with Mafia predictions. The seven-ring front end portion of the RFQ has now been assembled (Fig. 5). An alignment within ± 0.08 mm tolerance has been achieved. A major problem was a slight construction imperfection of the large square vacuum tank, which is split in two halves across the diagonal of the square section for easy access to the rings. The joining surfaces of the upper and lower halves were not exactly on the same plane by one or two mm at the ends. This caused stresses and minor movements of the internal structure when closing the vacuum tank. Securing the bottom portion of the tank to the base and inserting thin spacers between tank surfaces at the ends brought distortions within acceptable limits. Signal level tests have shown a Q of 8200 and a frequency of 35.72 MHz for the seven-ring structure, corresponding to 35.5 MHz when extrapolated for 19 rings; this is within tuning range. Bead pull measurements with non-modulated electrodes confirmed field variations below 1%.

2.5 The variable energy DTL

The Drift Tube Linac was designed [6] to accelerate ions of $\frac{1}{6} \leq \frac{q}{A} \leq \frac{1}{3}$ to energies variable between 150 A·keV to 1.5 A·MeV. It consists of five independent interdigital H mode cavities resonating at 105 MHz, and accelerating beam at 0° synchronous phase, while three split-ring three-gap bunchers and four magnetic quadrupole triplets provide longitudinal and transverse focussing. To lower the 1.5 A·MeV energy the higher energy IH tanks are turned off sequentially and voltage and phase in the last operating tank are varied. The split ring buncher cavities are adjusted to maintain longitudinal bunching. The tank is fabricated from mild steel and copper plated to 0.25 mm thickness. Ridges and stems are fabricated from copper. Cooling is provided for the copper stems through the copper ridges. The first IH tank is being fabricated and will be tested in the summer. A split-ring buncher is being fabricated in Moscow by INR. The design of the triplet is challenging because of space limitation. A maximum gradient of 64 T/m has to be provided with bore aperture of 24 mm. A diagnostic unit will also be added in the congested space between DTL tanks.

2.6 Future Plans

An initial scheme to accelerate ions to mass 240 to 6.5 A·MeV [7] has been developed. Briefly the higher mass is achieved by using a front-end RFQ of much lower frequency (11.67 MHz), and putting it on a high voltage platform. 380kV is required to achieve an injection energy of 2 A·keV for A = 240. The RFQ output energy is 12 A·keV. Ions which have mass larger than 60, will be stripped in a gas stripper, installed at ground potential, to q/A $\geq$ 1/60. Ions are then injected into a 23.33 MHz RFQ extracted at 80 A·keV and then accelerated through two IH linacs to 0.55 A·MeV, to a second stripper. After the stripper, two additional linacs accelerate the ions with q/a $\geq \frac{1}{6}$ to 6.5 A·MeV. A superconducting version would allow 15 A·MeV to be reached for lighter ions.

Other design options are being studied. It is clear that the higher the charge of the ion at injection, the less expensive will be the accelerator. We are therefore presently considering variants which depend upon the development and practicality of ECR or EBlS charge boosting devices. The emphasis will be on a mass range to A $\leq\sim$ 150 and energy to 6.5 A·MeV.

3 THE OPTICALLY PUMPED POLARIZED ION SOURCE

A high intensity optically pumped polarized H$^-$ ion source (OPPIS) developed at TRIUMF, is based on spin-transfer collisions between protons and an optically-pumped Rb metal vapor. The technology involves a superconducting solenoid, a 28 GHz microwave generator, and stable high power solid state tunable lasers. Polarized H$^-$ ion beam current, 2 orders of magnitude higher than from conventional atomic beam sources, has been measured.

The TRIUMF OPPIS [8] provides a high-quality beam for precision measurement of parity non-conservation in proton-proton scattering at 221 MeV. To minimize helicity-correlated modulations and obtain required accelerated beam stability, most of the beam intensity must be sacrificed for beam quality. Therefore, high-brightness source performance is required. This implies optimizing the core of the high intensity beam. Therefore these OPPIS developments are also conducive to the development of higher intensity sources with larger emittance.

TRIUMF is presently involved in a collaboration with KEK and BNL on polarized source development for polarization facilities at RHIC. The world's first operational OPPIS developed at KEK was moved to TRIUMF for upgrade to RHIC specifications. A 0.5 mA pulsed H^- current is required for the RHIC injector, with normalized emittance of 2.0 π mm mrad at 7.5 Hz repetition rate and 300 μs pulse duration. A preliminary 1.64 mA of 60% polarization dc H^- ion current was obtained [2]. Higher than 80% polarization is aimed for in the pulsed operation. Another ongoing study at TRIUMF is the feasibility of a 10-20 mA pulsed OPPIS for proposed high energy polarized proton facilities at the HERA proton collider.

4 APPLIED TECHNOLOGY AND MEDICAL FACILITIES

TRIUMF has now more than thirty years experience in the production, acceleration and use of H^- beams with cyclotrons. This has lead not only to a very efficient and reliable 500 MeV H^- cyclotron, but also to the design and implementation, in collaboration with Ebco Industries, of a series of compact cyclotrons mostly for medical diagnostics below 13 MeV, 19 MeV, or 30 MeV respectively, with variable proton energy; or below 15 MeV with variable deuteron energy. Five machines have been built so far. Two are installed at the TRIUMF laboratory. The first one, delivering 15 to 30 MeV protons, has now been upgraded to deliver routinely a total of 1.2 mA (two 600 μA beams) to two isotope production targets. Elsewhere on site a 13 MeV H^- cyclotron is routinely used for production of PET isotopes for the UBC hospital, linked to TRIUMF via a 2 km pneumatic link for rapid isotope transmission. Both machines are very reliable.

Another important project for transfer of technology is the explosive or contraband detector developed in collaboration with Grumman Co. [10]. This is based on a high intensity 10 mA proton beam from a 1.8 MeV tandem. To detect nitrogen 9.17 MeV γ are produced through a (p,γ) reaction on ^{13}C and are absorbed by resonant absorption in N^{14}. The re-emitted γ are then monitored with standard tomographic techniques. Other technology transfer activities are being pursued.

On the medical front, in addition to the isotope work above, irradiation with π^- meson has been suspended, because of insufficient proven advantages of this type of therapy. However, ocular melanoma therapy with protons of energy around 70 MeV is now routine and is providing local ophthalmologists with a very successful tool.

5 REFERENCES

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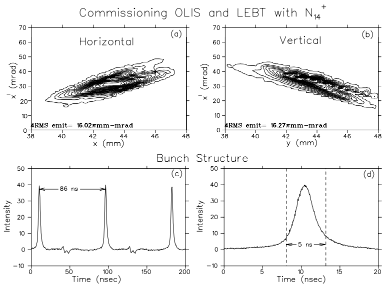

Figure 4: Measurement of beam characteristics at the RFQ input.

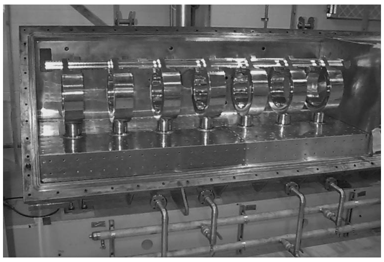

Figure 5: Assembly of seven rings on the ISAC RFQ for front-end beam tests.

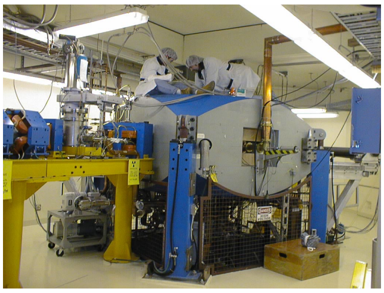

Figure 6: The TR30 cyclotron.

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