RECENT PROGRESS AT TRIUMF

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ISAC, a new facility for exotic nuclei is under construction at TRIUMF. The radioactive ions will be produced by the ISOL technique with currents up to 100μA of 500 MeV protons impinging on target/ion source stations located in an underground vault. Following mass selection the beam is further transported with up to 60 keV energy to either a low energy area or to an RFQ followed by a DTL. The beam from the DTL will have energy continuously variable from 0.15 to 1.5 MeV/u. A new 480-500 MeV proton beam has already been extracted from the TRIUMF cyclotron simultaneously with three existing variable energy beams. A 5000 m^2 building has now been completed. A 60 keV off-line source, part of the LEBT, a 11.67 MHz prebuncher, an 8 m long RFQ tank, and seven front-end modules of the split ring 4-rod RFQ system have been installed, aligned and are being commissioned. Beam tests through the RFQ front end will be under way at full cw power during summer 1998. Low energy (60 KeV) experiments using exotic ions are planned for year end. Other recent TRIUMF progress, including new records for the OPPIS high intensity polarized beams and highlights of cyclotron applications will also be summarized.

1 Introduction

The TRIUMF facility has been previously described [1] [2]. Since the last ICC in Cape Town, the laboratory has progressed solidly along the following lines as defined by the 1995 Five Year Plan: (1) installation of a new Isotope Separation and Acceleration facility (ISAC); (2) Canadian participation in the CERN LHC construction; (3) continuing cyclotron operation for the basic experimental program; (4) infrastructure support for detector work for intermediate or high energy facilities, and (5) transfer of technology to industry for commercial applications. In this paper we will comment briefly on points (3) and (5) and focus on (1), the design and construction of ISAC.

Cyclotron reliability and beam availability have not been a priority over the last few years because most accelerator resources were diverted to ISAC and CERN-LHC. Nevertheless beam production has been maintained between 5,000 and 6,000 hours per year, with better than 87% beam availability and with typical accelerated beam currents of about 220 μA during high intensity beam production. This includes $\sim$150μA delivered at 500 MeV to beam line 1A, $\sim$70μA used for isotope production between 70 and 120 MeV to 2C4, and up to 1 or 2μA to beam line 4 for TISOL or for a double spectrometer area (Fig. 1). Polarized beam production was scheduled during about one-third of the beam time, typically before shutdowns. Optimization of the Optically Pumped Polarized Ion Source (OPPIS) and of the beam for the parity violation experiment (Fig. 1) has been described elsewhere[3],[4]. At present this experiment is the major user of the polarized beam and has almost completed data taking at 221 MeV[4].

Proton therapy of ocular melanoma using a low intensity, 70 MeV proton beam extracted to beam line 2C1 is now routine. At present the accrual of suitable patients is limited to western Canada and a choice is made between plaque therapy and proton therapy depending on the size and location of the tumour. About 20 patients per year are treated with protons, with the observed level of tumour control and complications as reported by the other treatment centres. The use of negative pions for cancer therapy was discontinued in 1994 after completion of two randomized studies comparing pions with conventional photon radiation. The results have been reported for high-grade brain tumours[5] and the full results of the prostate study are about to be published. In both cases there is no significant advantage for pions.

TRIUMF is also involved in design work, prototyping and commissioning of cyclotron upgrades for axial injection or higher intensities. A proposed scheme of axial injection for the M50 cyclotron at the University of Washington is presented separately at this conference[6]. The Nordion TR30 cyclotron[7] delivering two external proton beams of energy between 15 and 30 MeV is now producing routinely and reliably, for isotope production, a total extracted current of in excess of 1mA, with 1.2mA peak. Other technology transfer highlights include the Contraband Detection System (CDS) being commissioned with beam by Northrop Grumman Corporation in Bethpage, N.Y. Two additonal compact H^- cyclotrons for PET have recently been delivered by Ebco, one to the Seoul Hospital in Korea ($\leq$13 MeV) and the other to the Sherbrooke Hospital in Quebec ($\leq$19 MeV)[8]. Prototype injection studies confirm that a current up to 3mA can be accelerated through the space charge dominated centre region at injection energies of $\sim$28 keV[9].

2 The ISAC Project

A layout of the ISAC project is given in Figure 1. An extraction system consisting of a stripping foil, a combination magnet, and the front end of an external beam line have been added to the east of the cyclotron. The radial and azimuthal movement of the stripping foil will allow the proton energy to be varied between 470 and 510 MeV. Two 27.5° benders direct the beam north through a 50m long beam line in a tunnel connecting to the ISAC target building. Beam currents up to 100μA are envisaged. The target building is heavily shielded and will house two T-shaped target-ion source vacuum vessels and remote handling equipment. Exotic ion beams are extracted from the ion sources and will be directed with electrostatic optics to a $\pm 60°$ preseparator magnet Y-shaped followed by a 135° separator system with a resolving power of $\sim$1/10,000. After the analyzing slits of the separator the beam is raised to grade level, through an electrostatic vertical line and two 90° electrostatic bends. A switchyard system will then direct the beam either to the low energy experimental area or to the linear accelerator.

The accelerator consists of (i) an 8m long, 35 MHz cw four-rod RFQ section, accelerating ions with $q/A \geq 1/30$ to 150 A·keV; (ii) a stripper/bender/rebuncher section (MEBT) and (iii) a five-tank IH DTL section resonating at 105 MHz and accelerating particles with $q/A \geq 1/6$ to energies between 0.15 A·MeV to 1.5 A·MeV. Downstream (iv) a HEBT section joins the DTL to a recoil mass separator designed for a rejection factor of $1/10^{15}$. Several buncher units are installed along the accelerator to control the longitudinal phase space. An offline source is installed up front to allow beam tuning using stable ion beams. A plan to expand the facility to ions of mass up to 150 and energies up to 6.5·MeV or higher has recently been developed.

The schedule calls for the western target and the separator to be commissioned during the summer first using stable beam and later for exotic beams to be delivered to the low energy experimental area by November 1998. The accelerated beam is scheduled for experiments by November 2000. A low-intensity primary beam has already reached the beam dump in the west target vessel. Commissioning of the RFQ with beam from the offline ion source is imminent (seven rings out of 19). The RFQ will be completed during the summer of 1999. The first tank of the DTL will be commissioned at RF power in 1998. The entire DTL (five tanks) will be installed and commissioned by fall 2000.

Design concepts for various systems of the ISAC project have been reported elsewhere[10],[11],[12],[13]. Below we will report recent progress highlights.

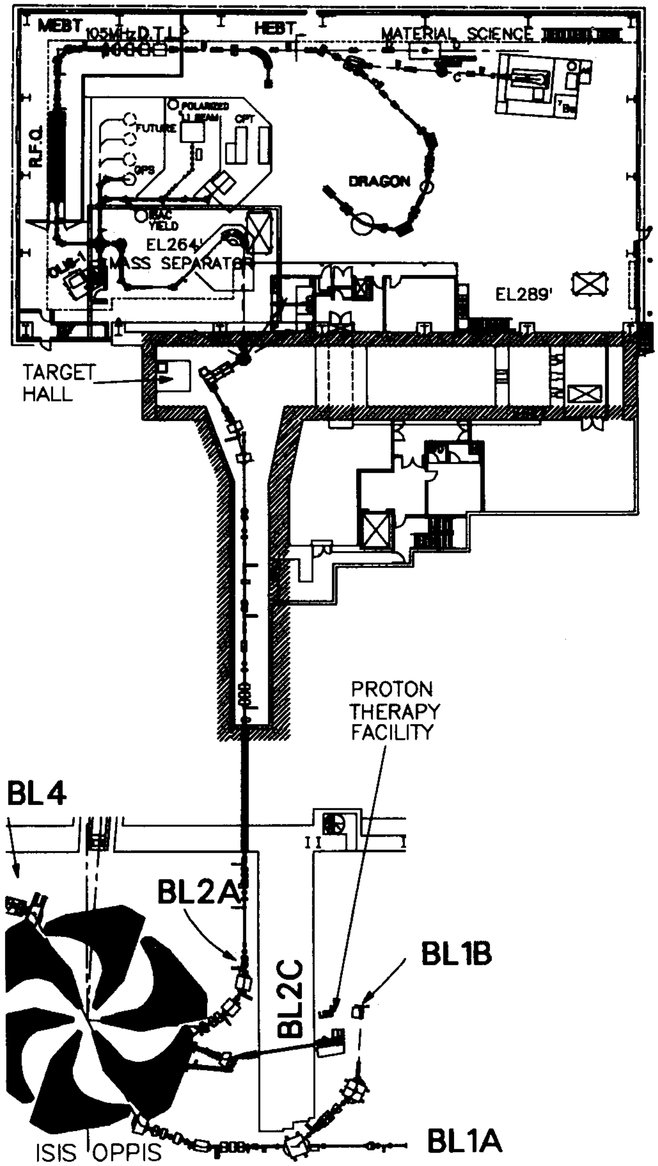

Figure 1: Cyclotron and ISAC Layout.

2.1 Primary beam line 2A

The restricted energy range of beam line 2A (480-500 MeV) eased the design of the BL2A extraction probe. Vacuum motors simplified the mechanical drives and eliminated the need for ferro-fluidic feed-throughs except on the radial drive. Vertical motion utilizes a worm-gear-driven pantograph to provide a greater vertical range than the other probes. Remote handling techniques and efficient use of local shielding were employed to achieve a tolerable personnel dose during installation.

Because of the proximity of BL2A and BL1A, simultaneous extraction into both lines was verified. Beams between energies of 472 and 500 MeV were extracted into beam line 2A, simultaneously with beam in 1A. Vertical alignment in both lines was good despite a known vertical displacement of the equilibrium orbit from the median plane at 500 MeV.

The north-south portion of the beam line (Fig. 1) operates in a waist-to-waist mode. The first waist is located in the vault downstream of the second of the two 27.5° dipoles. Another lies approximately 7m beyond the outer vault wall. Two remaining waists are in the external tunnel. Beam is directed to the west target by two 15° dipoles. The optics are such as to produce a (nominal) 5mm diameter acromatic beam spot at the targets.

Over a period of less than four hours in April 1998, a 492 MeV beam was extracted and delivered to the target area without problems. Beam profiles along the line were in good agreement with calculations.

2.2 Target and separator

Isotope generating targets proposed at ISAC must withstand bombardment by up to 100 μA of 500 MeV protons. Because this proton bombardment will generate very high operating and residual radiation fields, the target stations are located in a sealed and well shielded building serviced by an overhead crane to access adjacent target maintenance areas including a hot cell, warm cell, decontamination facilities and a radioactive storage area.

The target is installed inside a large T-shaped vacuum chamber surrounded by closed-packed iron shielding. The design aims at eliminating air activation problems by removing all the air from the surrounding volume through a filtered exhaust system. The front-end design breaks naturally into modules; an entrance module containing the primary beam diagnostics, an entrance collimator and a pump port; a beam dump module containing a water-cooled copper beam dump; a target module containing the target/ion source, extraction electrodes and steering plates; two exit modules containing the electrostatic optics and associated diagnostics. Modules are inserted vertically into five rectangular openings at the top of the tank.

The vacuum design seeks to eliminate the need for radiation-hard vacuum connections at beam height by using a single vessel approach. Most vacuum connections are situated at the top where elastomer seals may be used. Only two connections exist at beam heights - the proton beam entrance and the heavy ion beam exit[14].

2.3 Mass Separator

The front end of the mass separator includes an electrostatic triplet followed by a doublet. Preliminary mass selection is achieved using the ±60° pre-separator magnet. The pre-separator is followed by three matching sections that allow enough flexibility to obtain the same mass dispersion from either target station. The main mass separator magnet is the former Chalk River 135° magnet which became available after the laboratory shut down during 1997. The magnet is equipped with so called α and β coils. The α coil permits to correct the magnet index n=0.5 and the β coil permits to adjust the second order correction provided by the pole face curvature. Other details are given elsewhere at this conference.

2.4 LEBT

Installation of the off-line ion source (OLIS) began in July with first beam extracted in early November 97. Commissioning of the low-energy transport line (LEBT) from OLIS to the RFQ followed soon after. The sawtooth prebuncher was installed and commissioned with three harmonics in early Febuary 98. The fourth harmonic will be added following an upgrade to the wide band amplifier. The commissioning results are summarized in Fig. 2.

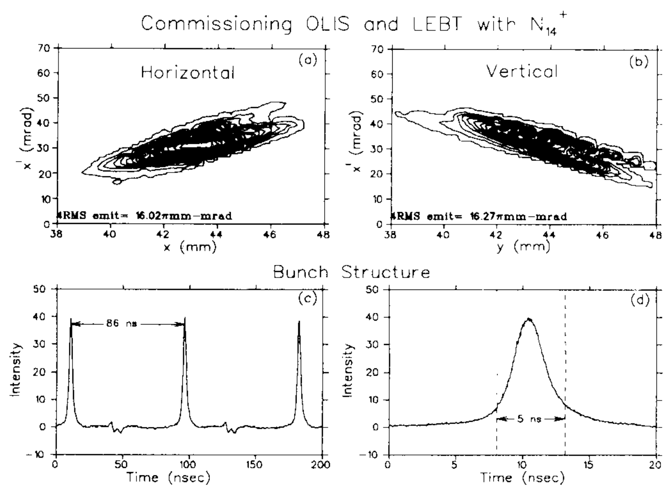

Figure 2: Commissioning results from OLIS/LEBT; the horizontal and vertical emittance of the N_{14}^{+} beam and the bunch structure at the end of LEBT.

2.5 RFQ

The 8 m long, 1m×1m^2 ISAC RFQ tank houses 19 split ring structures each feeding 40 cm lengths of modulated electrode.[11] Both rings and electrodes are water cooled. The design peak voltage between electrodes is 74 kV, with a bore radius of R_o=7.4 mm.

The buncher and shaper sections of the RFQ have been completely eliminated from the design in favour of a four-harmonic sawtooth pre-buncher located 5 m upstream. This not only has the benefit of shortening the

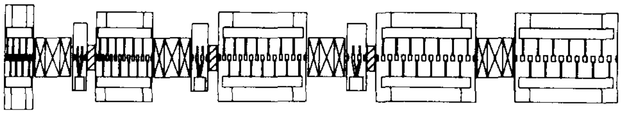

Figure 3: Schematic drawing of the ISAC variable energy DTL. Five IH tanks (A) provide acceleration at 0° synchronous phase, three triple gap spiral resonators (B) provide longitudinal focus ($\phi_s \sim -60°$) and quadrupole triplets (C) provide transverse focus.

structure but also reduces the output longitudinal emittance. These gains are made at the expense of a slightly lower beam capture. We expect 81% of the beam will be accelerated in bunches with a time spread of 86 nsec (11.7 MHz).

The RFQ tank arrived in late summer 1997. Presently the initial seven ring segment of the RFQ has been installed in preparation for an interim beam test.

Signal level measurements of the RFQ have determined a frequency of 35.7 MHz, a shunt impedance of 300 kΩ·m and $Q = 8700$. The frequency is expected to be slightly lower with the addition of the remainder of the rings. Bead pull measurements show that the average field along the electrode length varies by no more than ±1% and that quadrupole symmetry is maintained to ±1%. The electrodes themselves are aligned to the ideal beam axis to within the tolerance of $\pm 80\mu$.

2.6 Drift tube linac

The drift tube linac is required to accelerate, in cw mode, ions with a charge to mass ratio ≥1/6 from an injection energy of 0.15 MeV/nucleon to a final energy variable from 0.15 to 1.5 MeV/nucleon. A *separated function* DTL concept has been adopted. Five independently phased IH (Interdigital H-mode) tanks operating at $\phi_s = 0°$ provide the main acceleration. Longitudinal focussing is provided by independently phased triple gap spiral resonator structures positioned before the second, third and fourth IH tanks. Quadrupole triplets placed after each IH tank maintain transverse focussing. A schematic drawing of the DTL is shown in Fig. 3.

To achieve a reduced final energy the higher energy IH tanks are turned off and the voltage and phase in the last operating tank are varied. The spiral resonator cavities are adjusted to maintain longitudinal bunching. In this way the whole energy range can be covered with 100% transmission and no longitudinal emittance growth.

Fabrication of the first IH tank and the first DTL buncher are proceeding well in advance of the bulk of the DTL in order to get an idea of the fabrication difficulties and techniques. The stems and ridge of the first tank are made of copper. The tank has been received at TRIUMF for leak testing prior to copper plating. Signal and power level tests of tank 1 are scheduled for summer 1998.

The first DTL buncher has been designed and is being fabricated at INR Troitsk. The buncher is scheduled to arrive at TRIUMF in June 1998 for testing. The fabrication of the remainder of the components will proceed after the acceptance tests are complete. Commissioning of the DTL is expected in the first half of 2000.

Position	Transverse		Longitudinal	
	$\epsilon_{x,y}$	$\beta\epsilon_{x,y}$	ϵ_z	ϵ_z
	($\pi\mu$m)	($\pi\mu$m)	(π% ns)	(πkeV ns)
LEBT	50	0.1	DC	DC
After RFQ	5	0.1	0.33	0.5
After Foil	10	0.2	0.45	0.67
Before DTL	11	0.22	0.50	0.74
After DTL	$11\cdot(\frac{0.018}{\beta_{fin}})$	0.22	$0.5\cdot(\frac{0.15}{E_{fin}})$	0.74

Table 1: Beam simulation results showing the transverse and longitudinal emittance at various locations in the ISAC accelerator chain. The values quoted enclose 98% of the particles.

2.7 Beam quality

The beam from the source is expected to have a transverse emittance no larger than $\epsilon_{x,y} \leq 50\pi$ mm mrad corresponding at 2 keV/u to a normalized emittance of $\epsilon_n = \beta\gamma\epsilon = 0.1\pi$ mm mrad. The expected transverse and longitudinal emittances at various locations in the accelerator chain are shown in Table 1. Note the effect of multiple scattering and energy straggling in the stripping foil and the small emittance growth in the MEBT rebuncher.

3 Future Project

TRIUMF is currently preparing a new five year plan requesting additional funding from the Canadian Government for the period begining in April 2000. A major element of this plan includes an upgrade of the ISAC facility (called ISAC2) to permit acceleration of radio-active ion beams up to energies of at least 6.5 MeV/u for masses up to 150. Studies have concluded that the optimum accelerator satisfying user requests and budget constraints is a superconducting linac. The proposed acceleration scheme would use the existing RFQ with the addition of an ECR charge state booster to achieve the required charge to mass ratio ($q/A \geq 1/30$) for masses up to 150. A new drift tube linac would accelerate the beam from the RFQ to 400 keV/u where the beam could be more efficiently stripped to give a charge to mass ratio greater than 1/7 for the full mass range. This beam would then

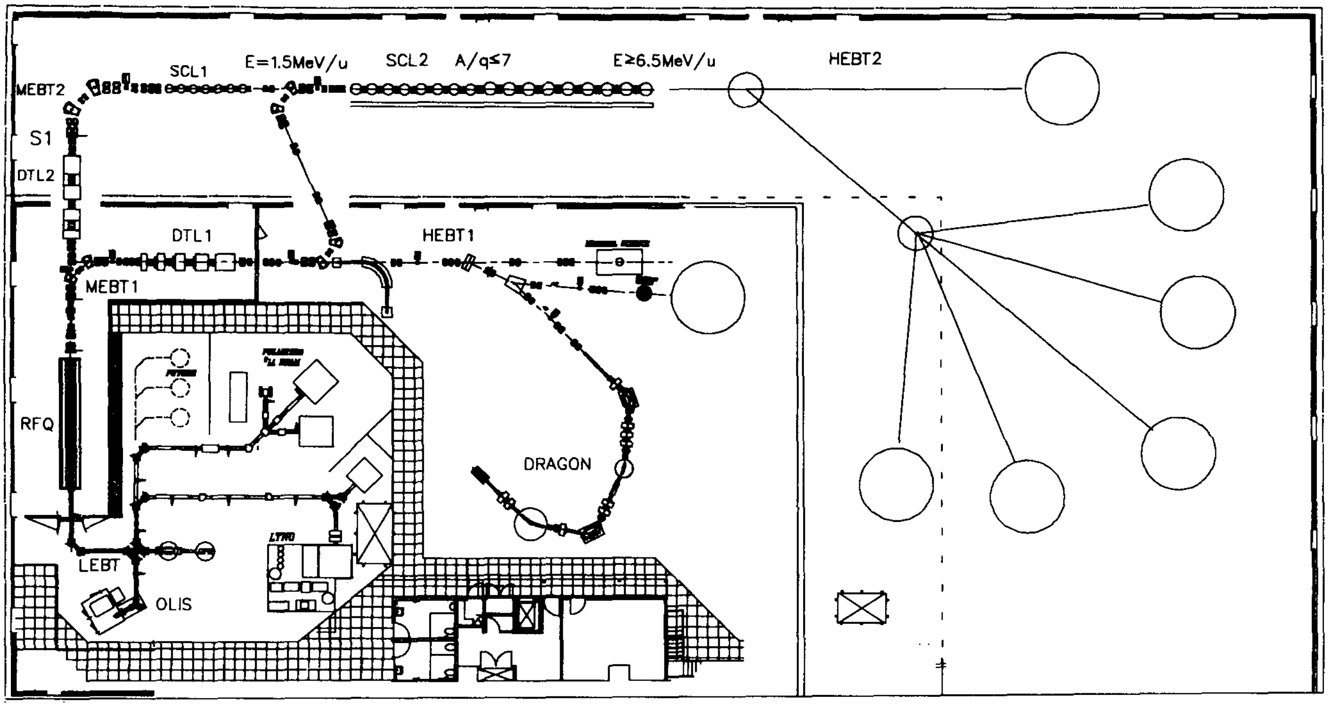

Figure 4: Layout of the proposed ISAC2 facility.

be accelerated by a linac consisting of many short superconducting cavities. The flexibility inherent in the superconducting option means that lighter ions with higher q/A are accelerated to energies beyond 6.5 MeV/u. To achieve higher energies two years in advance of the final configuration some superconducting cavities will be initially placed directly after the existing 1.5 MeV/u DTL. An additional stripper would be positioned between the DTL and the first superconducting cavity. This would allow an energy up to about 5 MeV/u for masses up to 60 to be reached as early as 2003 within the existing building, albeit with reduced ion beam intensity compared to the completed ISAC2 facility shown in Fig. 4.

4 References

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