TRIUMF: STATUS AND DEVELOPMENT PLANS

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Cyclotron Description and Operating Experience

Introduction

The TRIUMF accelerator is a single-stage sector-focused isochronous cyclotron accelerating H^- ions from 0.3 MeV at injection to a maximum energy of 520 MeV. Several papers have discussed the design and specifications of the cyclotron/1,2/ and reviewed its operating performance/3,4/ and experimental programme./5/ An H^- ion cyclotron was chosen for the TRIUMF laboratory because of the ease by which several beams of different energy and intensity can be extracted simultaneously using stripper foils at various radii and heights. The consequences of this choice are that the beam must circulate in a vacuum better than 10^{-7} Torr and that the maximum magnetic field seen by an ion must be less than 0.58 T to permit acceleration to 500 MeV with losses, due to stripping by residual gas molecules and by electromagnetic dissociation, less than 15%. The last requirement results in a larqe cyclotron, maximum orbit radius being 7.8 m, and some tight engineering tolerances. A plan view of the cyclotron vacuum tank is given in Fig. 1, and Fig. 2 shows the layout of the cyclotron and experimental areas.

Magnet

The upper portion of the magnet can be raised, together with the lid of the

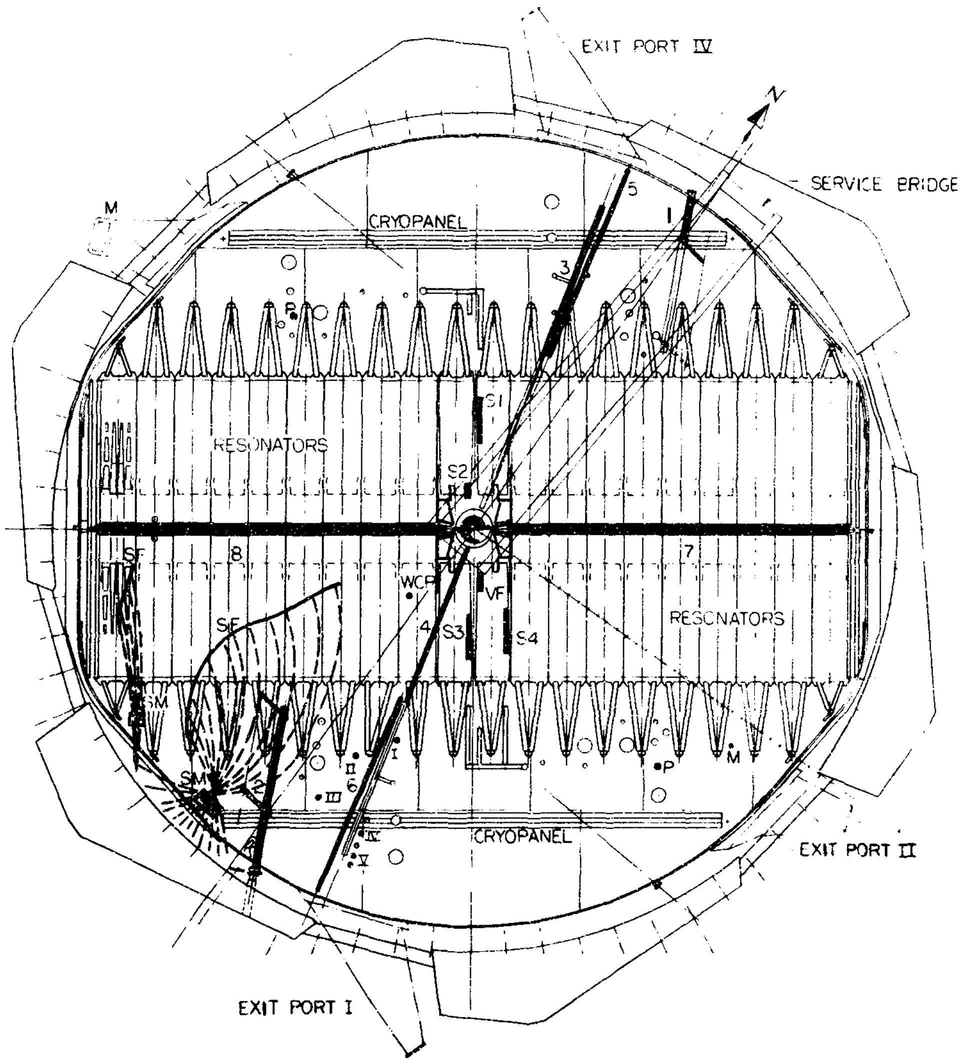


Fig. 1. Plan view of the cyclotron vacuum tank showing the range of movement of the extraction probes (1,2), low energy probes (3,4), high energy probes (5,6), centring probes (7,8) and slits (S1,S2,S3,S4). Also shown are pneumatically actuated pop-in probes (I to V), a water-cooled probe (WCP) and a horizontal flag (VF) which limits the cyclotron acceptance in the vertical plane, scraper foils (SF) and secondary emission spill monitors (SM). Periscopes (P) and mirrors (M) are used for viewing.

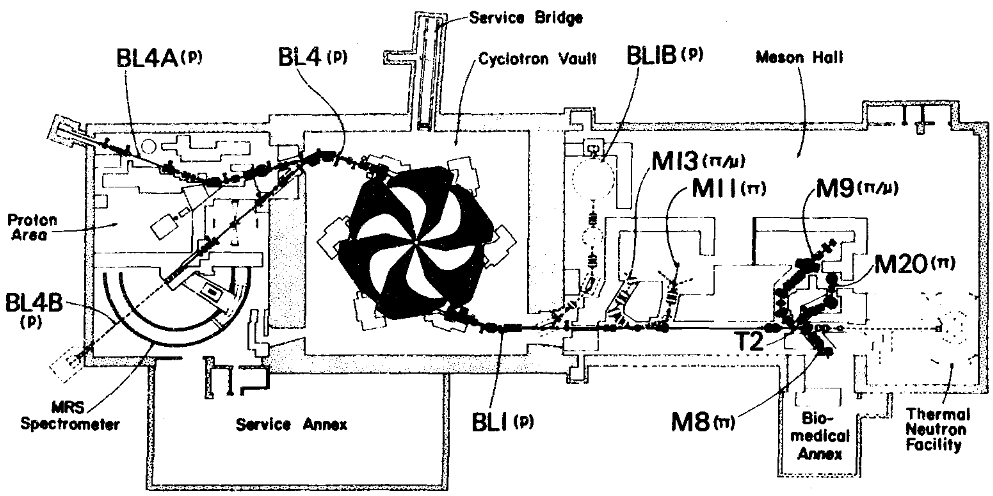


Fig. 2. Beam lines and experimental facilities (—— existing, ---- proposed).

vacuum tank, 1.2 m to permit personnel access into the tank. Measurements of the beam height and phase history show that the field reproduces to better than 0.1 G in $\overline{B}_R$ and in the detailed radial variations of B_z after the lid has been raised and lowered again. Long wavelength (radial) variations in phase have been seen when the previous trim coil settings are restored after a shutdown and are thought due to hysteresis effects; they are easily corrected by coil adjustments. The magnet power supply has a 10 min time constant, and it becomes possible to accelerate a beam one hour after it is turned on; after initial adjustments have been made the trim coils rarely require further attention during a two-week run. The magnet power supply derives a feedback signal from an outer trim coil used as a pick-up loop. Measurements made in the external beam lines of the arrival time of 500 MeV protons with respect to the RF show a magnet stability better than $\pm 1.8 \times 10^{-6}$ over a period of one hour.

Once commissioned the magnet power supply has been trouble free, and perhaps one hour per month is lost to replace one of the over 100 trim and harmonic power supplies.

Ion Sources and Injection System[6] (ISIS)

Two external H^- sources are used, an Ehlers-type unpolarized source, which has delivered 1 mA into an emittance 0.32π mm-mrad, and a polarized source of the Lamb-shift type, which has delivered 900 nA beam. These are mounted in terminals raised to about 300 kV and the ions transported by a beam line with electrostatic elements 40 m to an electrostatic inflector at the cyclotron centre which bends them into the horizontal midplane of the machine and the first accelerating gap. A macropulser placed in the terminal of the Ehlers source operates on the 12 keV beam to give bursts of 10 μsec every 1 msec (1% mode) or the reverse (99% mode); the latter is the normal mode for routine beam delivery. The beam line contains a chopper which can provide beam pulses 10° RF (1 nsec) long and an RF buncher. Mis-steered beam currents can be read from collimators, and in addition several non-intercepting toroid monitors detect the 1% 'hole' in the beam and check the transmission through the injection line. In the past two years there have been no major failures of the ISIS system; however, the source stability is sometimes a problem at high currents. Work is in progress to improve source vacuum and trap electron beams, and transmission monitor interlocks have reduced the amount of sparking. Recently 400 μA dc, adequate for 100 μA extracted at 500 MeV, were run to the inflector entrance for several hours.

Radio-frequency System

The RF system operates on the fifth harmonic (23.1 MHz) of the ion rotation frequency. The 'dees' consist of two facing $\lambda/4$ resonators, each being divided into 40 segments 81 cm wide, 20 above the midplane and 20 below. The whole resonator system is contained within the vacuum tank (see Fig. 1), and the beam circulates in the nominally field-free region between upper and lower resonators. The cyclotron is presently operated with a peak voltage difference of about 170 kV between the tips, and 1.8 MW can be provided, sufficient to maintain the accelerating voltage when an additional third harmonic component is eventually introduced to 'flat-top' the waveform. Recent tests at low power levels have shown that the Q for the third harmonic (∿6400) is higher than for the fundamental (∿5500) and that the required 3:1 frequency ratio is within the present tuning capability.

Following modifications[7] the RF amplifiers and combiners have proved quite reliable. Similarly the tuning of the resonator frequency by adjusting water pressure has been quite stable. After a two-day maintenance period, with no tank venting, the RF system can be ready to accelerate beam after a two-hour warm-up period; the natural frequency of the resonators may then drift 10 kHz over the next 24 h and will then be stable during the next weeks of operation.

The major source of unscheduled cyclotron downtime has been thermal damage to parts of the RF structure and beam diagnostic instrumentation. Calculations showed that electrons could be trapped over a large area near the centre and dumped in one location where melting occurred. This problem has been eliminated by introducing field perturbations at several locations to dump the electrons at low power, by replacing aluminum components with copper, and by improved heat transfer. The other source of damage is RF leakage into the nominally field-free regions from the dee gap and the small gaps that separate the resonator sections to reduce cross-modes of oscillation. The RF characteristics of this region are similar to the resonators themselves, and differences of several hundred volts are postulated to exist between top and bottom resonator sets. The power is only a small fraction, about 0.01%, of that fed into the system, but it has been enough to damage probes and other devices in this region. The damage has been alleviated by using copper strips to bridge the gaps between resonators in the vicinity of the probes. However, there is still an RF pick-up problem on many signals, and sets of thermocouples and pick-up loops have been installed to monitor operating temperatures, warn of malfunctions, and help understand behaviour. Resonator segments have been observed to sag, allowing more power to be developed in unwanted modes. Stiffening clamps have been installed but it is still necessary once or twice per year to shim segments to correct for tip misalignments of up to 0.25 in. Measurements of the flight time from ISIS to a beam line target made at several energies, when combined with the phase history, imply that the peak dee voltage falls from 82 kV at 3.7 m radius to 75 kV at 7.9 m. The turn structure indicates a voltage of 85 to 90 kV at the centre. The reasons for this droop are not understood.

Electrostatic correction plates/8/ are installed above and below the beam to compensate for any vertical misalignment of the central segments. Once tuned their values remain constant and are usually only readjusted after a major shutdown. Mechanical oscillations of the segments could also worsen beam quality, and these have successfully been reduced by dampers, consisting of a spring-mounted copper weight bearing against a leaf spring, installed near the tip of each segment.

Vacuum

The 100 m^3 stainless steel vacuum tank is maintained at a typical operating pressure of 8×10^{-8} Torr by two cryopanels cooled with helium at 20°K from a Philips B-20 cryogenerator. Hydrogen is pumped by four 25 cm oil diffusion pumps and five turbomolecular pumps. The system has achieved 2×10^{-8} Torr with the RF off. After a prolonged shutdown with the lid raised, it takes 3 days to arrive at a pressure of 5×10^{-7} Torr at which point it is reasonable to inject a beam and tune the cyclotron; this time includes a 36-hour bakeout using trim coil power and 24 h RF conditioning. A short-term vent is much quicker; the tank has been vented to dry nitrogen, a broken probe device removed, pumped down and the beam restored to experimenters all in 10 h.

Hydrogen is the major component at operating pressures and is estimated to cause half the stripping loss so a liquid helium cryopump is being designed to pump hydrogen. The cryopanels are defrosted every two weeks, and the B-20 is exchanged with a standby for servicing approximately every three months. Several emergency exchanges, taking about 12 h each, have been caused by lead from the heat exchangers appearing in the B-20 cylinders.

Control and Computing/9/

The controls system is responsible for the remote adjustment and readback of several hundred power supplies and for the conditioning and display of analogue signals from diagnostic devices.

Standard settings for a given energy and mode of operation can easily be restored from disc memory, and scanning programs give warning of deviations. Simple algorithms have operated several power supplies in conjunction to produce, for example, a localized deviation in beam phase with a controlled amplitude; however, no 'closed loop' operation is contemplated for the near future. In the last year controls hardware and software has been responsible for about 4% of the unscheduled downtime.

Personnel safety is a hard-wired system involving a PDP-14 computer with a read-only memory; this memory may be redesigned in the next year to accommodate new beam lines and modes of operation.

Beam Lines and Experimental Facilities

At present there are three primary beam lines installed, serving ten experimental stations, Fig. 2. Beam line 1 leads to a meson production target ladder T2 and a temporary water-cooled dump just downstream of the target. The line operates routinely at 10 μA, and the beam spot on target is about 3 mm wide and 14 mm high. Three secondary channels emerge from T2, M8, M9 and M20; their experimental features and meson flux are described in Ref. 5.

Beam line 4A (Fig. 2) is intended for currents up to 10 μA and has operated to date at 1 μA. After emerging from the vault wall the beam passes through a very thin, ∿100 $\mu g/cm^2$, target used for fragmentation studies. A superconducting solenoid, 6 Tm, is placed before a liquid hydrogen or deuterium target and can be used to rotate the spin direction of a polarized beam from vertical to horizontal. Two experiments can be installed between the bending magnet and the dump; the first is an experiment to investigate conversion of the isotopes ^{238}U and ^{232}Th into fissile ^{239}Pu and ^{233}U by proton-induced reactions, and the second is a station investigating proton radiography. Immediately prior to the dump are irradiation facilities for solid targets, a gas jet facility to transport short-lived spallation products to a counting room, and a caesium heat pipe target for the continuous production of ^{123}I.

Standard beam line components are used with the exception of radiation-hard quadrupoles at the front ends of the secondary channels near the meson production target. To reduce beam spills all the windows have been removed from the beam path or placed as close as possible to targets, some are mounted on gate valve bodies and only inserted when necessary, and a carbon stripper ($\lesssim 4$ mg/cm^2) foil is used at high currents to reduce beam halo. Beam spill monitors shut off the beam if a local loss exceeds about 5 nA. Consequently the radiation levels when running 10 μA average a few rad/μA h 10 cm from the beam line, and levels of ∿0.01 rem/h a few hours after turning off a 10 μA beam permit personnel access for maintenance. However, a program of installing quick disconnects is under way to limit personnel exposure.

The beam line is tuned at 5 nA and the results readily scale to 10 μA with minor corrections to reduce spills. Gas-filled multiwire ion chambers are used to give profiles, and the safety spill monitors (scintillators and photomultiplier tubes) are a useful tuning aid at high currents. Timing signals have been obtained from a non-intercepting capacitive monitor and a toroid monitor at beam currents above 1 μA dc (10 μA peak).

Cyclotron Beam Diagnostic Equipment

The diagnostic equipment in the vacuum tank is illustrated in Fig. 1. The low (LE) and high (HE) energy, current-measuring probes have segmented heads to give beam density information in the vertical (LE and HE) and radial (LE) plane. The LE probe operates from the first turn to 70 MeV and has a head thick enough to stop protons; the HE head is made of thin strips of tantalum and records the stripped electron current and operates from 70 to 525 MeV. Since a complete traverse takes at least 3 min, pneumatically actuated pop-in devices have been installed at certain radii to check transmission. A water-cooled probe, able to accept currents in excess of 100 μA, can be inserted at 20 MeV. The extraction probe is also a useful diagnostic tool since its head records the stripped electron current and can be moved radially, azimuthally and vertically. The stripper foils are made of 25 μ aluminum or pyrolytic graphite cut to various shapes, three of which are illustrated in Fig. 3. The shapes depend on whether the foil is to extract all [A], a moderate fraction (0.1% to 30%)[B], or a very small fraction (0.02% to 0.1%) [C] of the circulating beam at that energy. Each probe carries a cartridge of six foils which can be changed remotely. The aluminum stripper foils melt at 10 to 20 μA, in agreement with calculation; the graphite foils should have a thermal lifetime of many days at 400 μA. The centring probes have vertical fingers which cause a reduction in current measured by a stationary probe at larger radius when intercepting beam. The scraper foils are thin strips mounted approximately 3 cm above and below the mechanical midplane to define the vertical aperture and protect equipment in the tank. The azimuthal position is chosen so that the stripped protons are dumped in a well-defined location at the tank wall after passing through secondary emission spill monitors. Inside 70 MeV components are protected by beam stops fitted with thermocouples. A horizontal flag, at approximately 4 MeV, and the vertical slits can be used to restrict the vertical and horizontal beam quality and the phase acceptance.

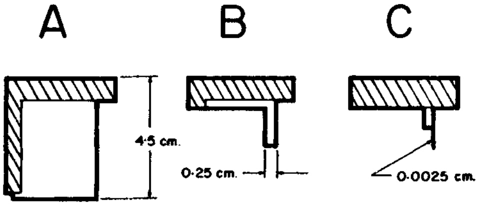


Fig. 3. Extraction foil shapes.

The interior of the tank can be viewed through windows and, more recently, retractable mirrors placed in exit horns II and V; a periscope and mirror system has been commissioned for quantitative surveying with the lid closed.

Beam Development

In the past two years the chief aim has been to achieve reliable operation and at higher and higher currents. The improvement of beam quality has been secondary except in so far as it reduced losses causing activity that in turn limited high current operation. The current properties are reviewed in Table I.

Table I. Beam Performance

Property	Achieved	Aim
Energy (extracted) (to exit horn)	183-520 MeV 70 MeV	165-500 MeV
Current (unpolarized)	10 μA (regular) 50 μA (test) 100 μA (@ 2.5 MeV)	100 μA (500 MeV) 300 μA (450 MeV)
Current (polarized)	120 nA	60 nA
Polarization (reversible)	78%	80%
Split Ratio (BL4/BL1)(25% stability)	1/1 to 1/5000	1/1 to 1/2000
Duty Factor - maximum - minimum	11% (5/43 nsec) 4% (chopped)	11% 1% (slits) 20% (3rd harmonic)
Transmission (5-500 MeV) (dc-500 MeV)	80% 8% 30% (bunched)	86% 10%
Vertical Centring	±6 mm	±6 mm
Isochronism (sin ϕ)	±0.1 to ±0.4	±0.02
Energy Spread (@ 10% peak) at 400 MeV	2.0 MeV 1.5 MeV (chopped)	1.8 MeV 0.5 MeV (slits) 0.1 MeV (separated turns)
Emittances (90% beam) - horizontal - vertical (external) (internal)	 3π mm-mrad 3π mm-mrad 1π mm-mrad	 3π mm-mrad 2.4π mm-mrad 1.2π mm-mrad
Spot Size at T2	3 × 14 mm^2	2 × 10 mm^2

Comparisons of the beam properties with predictions from the magnet field survey and other calculations have been reported elsewhere.[10,11] Because of RF leakage problems the detailed and precise measurements made on the working model of the centre region[12] could not be repeated on the main machine, nor has a useful signal been obtained from a phase probe. The centre region is tuned empirically to optimize transmission to maximum energy, and other techniques[13] have been used to measure and adjust the phase history to within ±20° of the central phase.

Shadow measurements at 80 MeV, the beam energy spread and the horizontal emittance all imply a radial amplitude of 7.5 mm. Amplitudes of 5 mm have been measured for a beam restricted by the chopper to a 10° phase interval. The vertical width of the beam immediately before extraction is 1.5 cm, which implies a vertical emittance at the foil of 1π mm-mrad. Multiple scattering in the foil is expected to double this figure, and 3π mm-mrad has been measured in the beam line. Emittances are measured by observing changes in beam profile as one or more quadrupoles are varied./13/ The position of a portion of the beam in phase space and its position on a monitor are related by a linear equation including the known beam transfer matrix. Sufficient measurements are taken so that the problem is overdetermined and the equation solved by an iterative least squares technique to give the density in phase space without any assumptions of an elliptical nature; the 'noise' in the result appears to be a few per cent of the total beam.

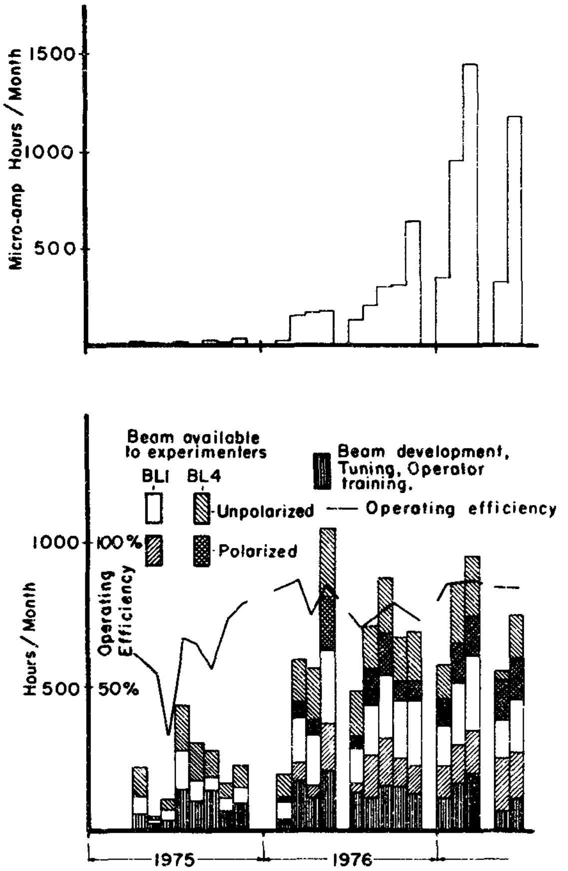
Gas and electromagnetic stripping leave characteristic signatures in the azimuthal distribution of activity around the tank wall. Aluminum activation foils were exposed to this activity between shutdowns, and the profile of the activity density/unit angular interval agreed with that calculated, as did the ratio of gas and electromagnetic stripping peaks. The electromagnetic stripping loss is thus expected to be about 8 to 10% to 500 MeV and is the largest loss mode; it should be reduced to 1% for operation at 450 MeV. Measurements show that gas stripping accounts for 6% loss at 8×10^{-8} Torr. The scraper foil spill monitors show a 3% loss when running with the widest possible phase acceptance; this spill was found to originate at radii where the working point crossed or came close to the $\nu_R - \nu_z = 1$ resonance, not always at radii corresponding to low ν_z^2. Investigations showed that most loss occurred for extreme positive phases which had previously been shown to have the larger radial amplitudes. It is thought that some large radial amplitudes are transformed into large vertical amplitudes at the resonance and these particles hit the scrapers. This loss can be reduced by operating with a slightly reduced duty cycle using the chopper/buncher, or by a radial flag being installed at 270° after injection to intercept beams of extreme phase.

Overall Operation

The accelerator is scheduled for a series of two-week-long periods with two 12 h shifts/day. Two days of maintenance and improvements are followed by six days operation; one shift is then shared between operator training and maintenance essential for successful operation in the following week. Cyclotron and beam line development are usually scheduled one or two shifts, in competition with other users. There are 2 or 3 operators on each shift with a physicist on call as consultant.

The cyclotron has proved remarkably easy to operate. During the two hours taken for the magnet and RF to stabilize, ISIS, cyclotron and beam line elements are restored from the computer memory, and it then usually takes less than one hour to bring the beam from source to T2 target, and perhaps another 30 min to optimize the spot shape, increase the current to full operating value and minimize the spills. The line taking the smaller fraction of beam takes longer to set up, 1 to 2 h, since the split ratio must be carefully set, which may mean making local adjustments in beam height to accommodate constraints imposed on the vertical foil motion, especially at energies inside the resonators. The extracted beam must then be steered to be centred and parallel to the beam line.

The operating experience in the last two years is summarized in Fig. 4(a) and (b), with various milestones recorded in the adjacent table. In the early part of 1975 the beam current was kept below 300 nA to reduce cyclotron activity but also because of losses in the beam line. These were improved and the current rose to 1 μA, the limit being imposed by shielding surrounding the production target. At the beginning of 1976 funds were made available for shielding, and other necessities, for 100 μA operation; the shielding blocks began to arrive in September 1976, and the high current operation has increased steadily since then. The polarized source operated in February 1976, and it is now used about 30-40% of the time.



Milestones

1974	
December	First beam to 500 MeV First extracted beam
1975	
January	First beam to 4B dump
April	First beam to line 1 T2
July	Mesons down secondary channels First 0.3 μA to T2
1976	
February	Polarized beam extracted First 1 μA to T2
April	Commence 24 h/day, 7 day/week operation First 5 μA to T2
July	Licensed for high current operation First 10 μA to T2
September	First 1 μA in line 4A First large shielding blocks arrive for line 1
November	30 μA to T2 for 2 h 50 μA to T2 for several minutes
1977	
January	Regular operation with 10 μA to T2
June	120 nA polarized beam

Fig. 4. Cyclotron operating performance. Note that Fig. 4(b) shows the total hours/month for beam development and tuning, beam line 1 experimental operation and beam line 4 experimental operation plotted above each other.

The operating efficiency, defined as the ratio of cyclotron operating time to scheduled time, has been 80% in the past year.

Since work is still being done in the vacuum tank, the tank radiation levels also can impose a limit on the increase in beam current. The gas and electromagnetically stripped beam emerges from the tank through a specially thin (0.08 cm) median plane portion of the vacuum tank wall into carbon blocks surrounded by boron-gypsum sheets where the protons are stopped before reaching the iron of the return yoke. These blocks also partially shield personnel working in the tank from neutron activation in the yoke, and radiation levels fell by a factor 3 after installation. In addition 5 cm thick lead shields are remotely installed around the inside of the tank periphery at the start of each shutdown and give a further reduction of 3. After prolonged exposure at 10 μA the levels are now 30 mrem/h at the edge of the tank wall and 7 mrem/h near the centre. It is thought that major hands-on maintenance can be carried out in the tank until regular operation at 25 μA. At higher levels items will be serviced by devices attached to trolleys moving radially on the service bridge which rotates azimuthally (Fig. 1). One of the more difficult problems, the removal of a resonator, has been carried out as a test. After prolonged 100 μA operation activation of sodium in the vault walls and cobalt in the magnet iron is estimated to produce general levels ∿150 mrem/h one hour after shutdown and 30 mrem/h ten days later. This shielding problem remains to be solved.

Since electromagnetic stripping increases rapidly with energy, activation can be reduced by operating at slightly higher currents at 450 or 480 MeV. The flux of high energy mesons would be reduced, however.

Immediate Goals

We are presently able to commit funds and resources to complete the following projects in the next year or two:

High current operation. Our most immediate goal is to achieve 100 μA dc at T2 and to run at least one shift per week at 100 μA during 1978. This is to provide a flux $>10^8$ π^-/sec in channel M8 and permit a useful *in vivo* biomedical program. ISIS has performed adequately, and more than 80 μA dc have been delivered to the water-cooled probe at 20 MeV, 100 μA has been accelerated to 500 MeV in the 1% pulsed mode, and 30 μA dc delivered to T2 for two hours; this is the maximum the temporary dump can accept, although 50 μA was run for a short time interval.

This autumn beam line 1 will be shut down for three months, although experiments will continue in line 4, to extend the line to a permanent beam dump and thermal neutron facility (TNF). At the same time it is necessary to complete the installation of remote handling features to the ends of the secondary channels closest to T2 and desirable to install a second, thin (<4 g/cm^2) meson target at T1 and to install the first dipole and vacuum box of beam line 1B. (See Fig. 2 and below.) The TNF will eventually incorporate a lead target capable of accommodating 300 μA at 450 MeV; since 40% of the beam is lost at T1, T2 and the various collimators, this is equivalent to 500 μA extracted from the machine. These losses mean that all equipment downstream of the meson targets must be remotely handleable.

Experimental facilities. The first spectrum was taken with the medium resolution spectrometer in June, but work still needs to be done to commission the wire chambers and computer programs that correct for aberrations and kinematic effects before achieving the desired resolution. During the first year the spectrometer will be positioned at a fixed angle of 22.5°; later the shielding will be reconfigured to permit motion over 180°.

The septum magnet, to be installed downstream of T1 this autumn, will eventually direct high energy, forward scattered pions into a high resolution channel M11 (up to 350 MeV with $\delta p/p$ of 0.5%), which will be constructed in the spring of 1978. The flux of π^+ from a water target is expected to be extremely high, 5×10^6/sec-μA in an interval $\Delta p/p$ of 5%.

Beam line 1B (see Fig. 2) will also be completed in 1978 or 1979 and enable low current (<100 nA) experiments to be run in both experimental areas and permit more efficient utilization of polarized or high resolution beams.

During the year the neutron channels and an isotope production facility will be commissioned at the TNF. The cyclotron will have a variable duty cycle pulser installed in ISIS for convenient adjustment of the macro-duty cycle and a 5:1 selector should be made operational; this populates only 1 in 5 of the RF phase acceptance periods, giving beam bursts of 1 to 5 nsec every 215 nsec.

Ions stripped to protons at energies much lower than 200 MeV cannot emerge from an exit horn in the same direction as the higher energy beams since they are bent by the cyclotron magnetic field through a larger angle. However, as shown in Fig. 5, they can be brought to a common point on the exit horn and then steered to a desired location. Calculations show reasonable optical properties for energies 65 to 200 MeV, and an experiment has recently confirmed the optics at 70 MeV.[14] There is strong interest in a beam from 70 to 90 MeV to produce certain isotopes by the selective

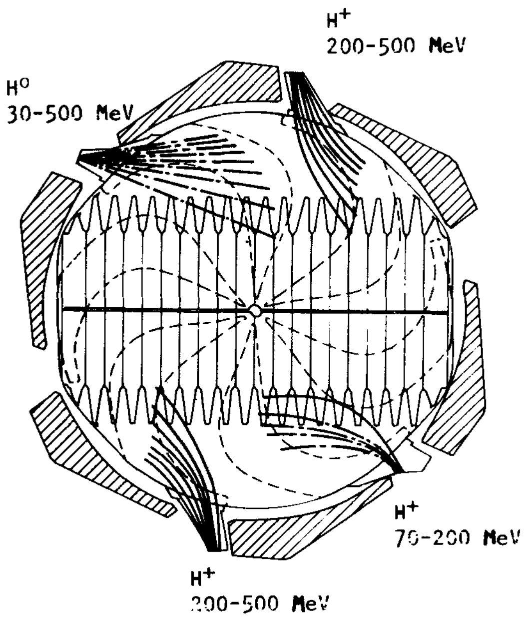


Fig. 5. Exploitation of negative ion extraction.

(p,mn) reaction and a design study is under way. Fig. 5 also shows beams of neutral atoms from 30 to 500 MeV which will initially be used for diagnostic purposes, but the flux will be in the region of 10^6/deg-turn-circulating A and may be useful for radiography.

Beam quality. The commissioning of the MRS will provide a useful diagnostic tool as well as motivation for improving the cyclotron beam quality. In the near future the operational procedure for setting the slits around a well-centred orbit will need to be developed and tested. Calculations show that these should provide currents of about 0.1 μA with an energy spread of ±0.3 MeV and a pulse width of 0.5 nsec at 500 MeV. This should be further improved to ±0.05 MeV by the addition of a third harmonic component to the RF waveform. The stability requirements in frequency ($\pm 5 \times 10^{-7}$) and magnet current ($\pm 4 \times 10^{-6}$) have been met for periods of 20 min and the third harmonic Q is acceptable. The voltage stability should be $\pm 3 \times 10^{-5}$ but at present is $\pm 1 \times 10^{-3}$; this needs some improvement, and since it fluctuates at a few hertz it may be possible to feed back a signal from the beam. A third harmonic power amplifier has been designed and is in the process of assembly.

The phase oscillations of ±20° vary too quickly with radius to be removed by the concentric trim coils. This precludes separated turns everywhere; however, individual turns may be separated in space at the point of extraction by adding slightly more third harmonic amplitude than the nominal 1/9 so that there are two humps in the voltage wave shape. By programming the phase history between injection and extraction in a simple way, it is possible to ensure that all phases in a 10° wide bundle have acquired almost the same energy, at extraction. [13]

More distant future. In the meson area a slow π/μ channel, M13 in Fig. 2, could be added to T1, and design studies are under way. The TNF structure also contains provision for a third meson production target, T3, which could be installed to feed a possible muon line. The MRS has been constructed in such a manner that it is possible to add a second dipole and convert it into a facility with resolution ±0.06 MeV at 500 MeV, should this be desirable.

Two exit horns (II and V) remain to be utilized; horn II could deliver a beam to the meson area or northward into an open area presently used as a parking lot. There is little difficulty, in principle, in extracting two beams of 100 μA between 450 and 500 MeV, and line 2 could serve future high current targets or a second accelerator or storage ring. Development work will eventually start on a second high current ion source to deliver several milliamperes of H^- ions; space is available in the ISIS area.

The possibility of stacking several turns at the outside of the machine and electrically directing them onto a stripper to provide high density macro-pulses of the beam will be investigated in the future, as will the possibility of exploiting $\nu_R = 3/2$ to extract beams of H^- ions.

Acknowledgements

The author would like to thank all his colleagues at TRIUMF whose work he has had the privilege of reporting.

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Д И С К У С С И Я

Л.А.Саркисян: Рассматривалась ли возможность повышения энергии протонов с помощью каскада из двух циклотронов? Какова возможная конечная энергия? Какой тип частиц (H^+ или H^-) может инжектироваться для ускорения во втором циклотроне?

G.H.Mackenzie: We will consider this and other possibilities in the next few years. The highest energy for protons would be 520 MeV. We may be able to extract H^- ions by exploiting $Q_R = 3/2$ near 435 or 515 MeV.

С.К.Есин: Каков в настоящее время наивысший уровень остаточной активности в районе вакуумной камеры ускорителя?

G.H.Mackenzie: After operating in our regular manner for 6 months with current up to 10 μA we have one or two hot spots of 200 mrem/h. There are very localized regions where, for example, scraper foils dump the beam. One or two meters away the radiation field drops to the ambient level of 30 m rem/h or less. This is with lead shielding installed.

С.К.Есин: Каким образом Вы предполагаете уменьшить потери пучка при переходе к ускорению тока I00 мкА?

G.H.Mackenzie: The majority of the activation comes from electromagnetic stripping. We can reduce this by a factor 5 or so, by operating at 470 MeV or 450 MeV at a somewhat higher current to maintain the meson flux. We would then shedule operation so that only those experiments really requiring high energy mesons would receive a 500 or 520 MeV beam.

We hope to halve the gas stripping by installing a liquid Helium cryopump for hydrogen. The few percent here can be reduced by a factor 3 or so by eliminating the extreme phases.