

BEAM DEVELOPMENTS AT TRIUMF

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Summary

The cyclotron is routinely operated with three simultaneously extracted beams and more are planned. A double beam has been sent down one line with sufficient separation for magnetic splitting. The extracted beam intensity can now be continuously varied from 10^3 to 10^{15} protons/s (170 μ A). The highest intensities were obtained by the addition of a second harmonic buncher in the injection beam line. Direct measurements of the electromagnetic H^- stripping losses agree with those expected. Beam-defining slits have been used to reduce the energy spread ($\Delta E/E$) of the extracted beam to 10^{-3} at all energies between 200 and 500 MeV. Under certain circumstances the medium resolution spectrometer has measured a resolution a factor of two better. Depolarizing resonances have been located and one of them corrected. A number of new experimental facilities have been commissioned recently. These include a low intensity polarized proton line operating to a polarized target, a high luminosity, low energy π - μ channel, and a clean cloud or surface muon channel using a velocity separator. The influence of the beam size and target shape on the characteristics of secondary particles has been examined.

High Intensity Developments

The maximum intensity extracted from the TRIUMF cyclotron at 500 MeV has been 150 μ A cw for a few hours and 170 μ A in a 70% duty cycle pulsed mode. For regular operation, however, currents are 100 to 120 μ A. Several improvements have aided in achieving better 100 μ A reliability—important for the π^- irradiations of cancer patients which have been undertaken since November 1979.

1) Progress has been made in achieving a brighter source. 2 mA of H^- beam current has been observed on a Faraday cup located immediately downstream of a set of emittance-defining slits. A vertical emittance of 14π mm-mrad has been measured at 15 keV.

2) The percentage of source current accelerated by the cyclotron, as anticipated from calculations, increased from ~30% to ~50% with the installation of a

double-drift bunching system¹ in the 300 keV injection line. Two double-gap sinusoidal bunchers, separated by a 4.6 m drift space, operate at 23 and 46 MHz respectively. Figure 1 shows the calculated velocity modulation for this system (c), compared to the ideal modulation (a) and that for a single buncher at 23 MHz (b). Also shown is the measured velocity acceptance (50% level) of the injection system and cyclotron, a limiting factor which reduces the transmission from a possible 85% to ~50%.

3) Progress has been made toward understanding the beam behaviour along the 40 m long 300 keV injection line. This consists of two 90° bends and a total of 79 quadrupoles—all electrostatic. The beam behaviour was calculated using the computer program SPEAM². This program includes the transverse space charge effect by numerically solving the Kapchinsky-Vladimirsky equations. The initial emittance figures (6π mm-mrad horizontally and 4.5π mm-mrad vertically at 300 keV) were derived by measuring the beam size at four locations at the beginning of the line. The agreement between the envelopes calculated from the actual operational voltage values of all of the quadrupoles and the geometrical restrictions represented by a series of 13 mm x 13 mm collimators and the chopper and 1:5 selector slits is shown in Fig. 2. To achieve this agreement, the electrostatic voltages had to be measured to an accuracy of two percent.

To obtain a more exact knowledge of the gas and electromagnetic stripping loss than can be obtained from transmission measurements two multi-plate secondary emission detectors have been installed at the periphery of the vacuum tank. Stripped neutral atoms leave H^- orbits tangentially and each detector samples a region extending from the highest to the lowest energies. That of the first detector lies on a hill where both gas and electromagnetic stripping occur; the second accepts gas-stripped atoms from a valley. The first detector was calibrated with protons stripped by current measuring probes. Figure 3 compares the cumulative electromagnetic loss with that predicted by numerical integration using the cross section of Scherk³ and the measured energy gain/turn. The latter was obtained as a function of radius by measuring the flight time of a pulsed beam from the injection line to a moveable probe.

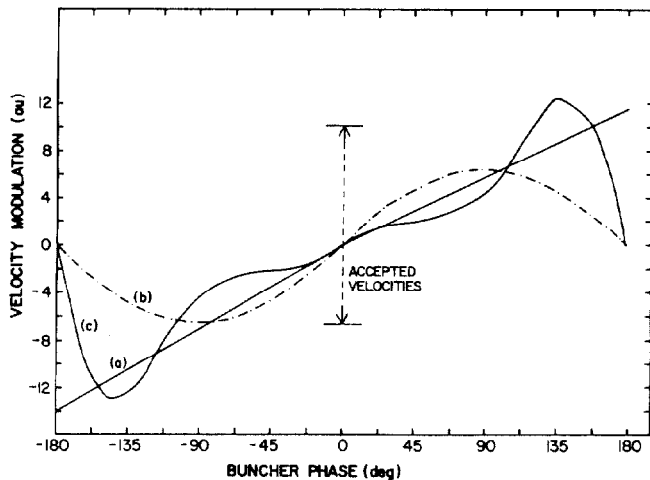


Fig. 1. Velocity modulation due to buncher (see text).

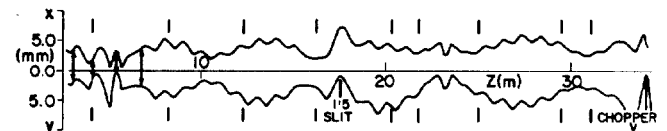


Fig. 2. Beam envelope in the injection line.

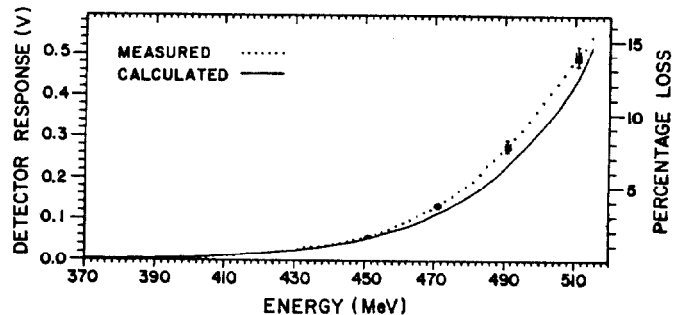


Fig. 3. Cumulative electromagnetic stripping loss.

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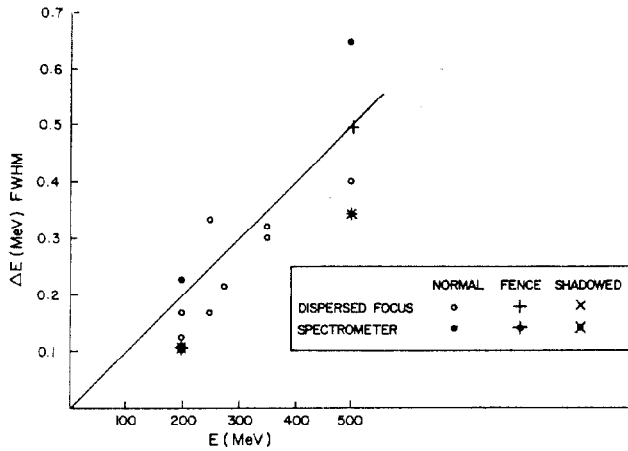


Fig. 4. Energy resolution ΔE observed for external beams of various energies.

Improved Energy Resolution and Magnet Stability

A beam of medium resolution ($\Delta E/E \approx 10^{-3}$) and narrow phase width (0.3 ns) has been produced over the entire available energy range (Fig. 4) by using internal slits to restrict the phase width and horizontal betatron amplitudes and by compensating the magnetic first harmonic to the 0.02 G level. This produces a close correlation between energy and radius, even though turns may not be separated, and a narrow stripping foil selects a narrow energy spread. Computer algorithms can assist and check the set-up which may be carried out by operators.

When the line requiring the medium resolution beam is at the higher energy a further improvement may be made by shadowing the last extraction foil by another probe. The maximum beam current through the slits has been 9.5 μA . We have retracted the slits and replaced the inner extraction foil by one consisting of a series of 7 strips separated by the radius gain/turn. This delivered 30 μA down one beam line while performing a certain amount of emittance selection on the transmitted beam, since $v_r \approx 1.5$. A further selection may be made by placing the narrow second foil at an appropriate radius. The results of this "picket fence" technique are also shown in Fig. 4.

Further improvements in resolution require separated turn operation, up to now limited to ≤ 250 MeV by magnetic field fluctuations. These vary from ± 3 ppm for short time intervals (< 5 min) to as much as ± 10 ppm for longer time periods. These fluctuations are the main source of instability in the phase of the extracted beam. A beam phase stability of $\pm 2^\circ$ (corresponding to a magnetic field stability of ± 1 ppm) is necessary for separated turn operation at full energy. To achieve this stability, three feedback loops have been tested using the Eclipse S-200 control computer. Firstly, NMR probe readings have been used to control the main magnet current. This has removed longer term drifts, maintaining the overall stability in the magnetic field at ± 3 ppm. Secondly, field oscillations between 0.05 and 5 Hz have been measured by digitally integrating the voltage induced in an outer trim coil (#54) and corrections applied to the rf frequency. Finally the beam phase itself has been measured with a capacitive phase probe located in beam line 1A. This signal was used in a third feedback loop to correct for intermediate drifts which may not be field related. The result of combining these feedback corrections is shown in Fig. 5. An overall phase stability of $\pm 1.5^\circ$ was achieved for a period of 1 hour. These feedback loops are being converted to run in dedicated microprocessors.

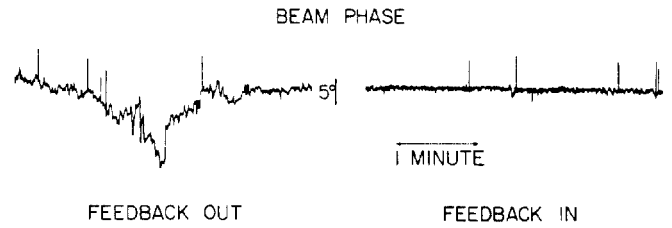


Fig. 5. Effect of feedback loops on beam phase stability.

Depolarization in the Cyclotron

Accurate measurement of the beam polarization at different energies in line 4B has revealed small decreases between 280 and 300 MeV and between 460 and 470 MeV (Fig. 6)—just where depolarizing resonances are expected to occur⁴. The results were normalized by simultaneously observing a fixed 200 MeV beam in line 1B. The resonances expected to cause significant depolarization in the TRIUMF cyclotron are

$$\begin{aligned}
 3.79\gamma &= 4 & (51 \text{ MeV}) \\
 3.79\gamma &= 5 & (298 \text{ MeV}) \\
 3.79\gamma &= 6-\nu_2 & (467 \text{ MeV}),
 \end{aligned}$$

where $3.79 = 1 - g/2$, g being the H^- ion g -factor. The last of these is the most serious, since it depends on the intrinsic sixth harmonic component of the cyclotron's magnetic field and hence cannot be easily corrected. It also depends on the amplitude of the vertical betatron oscillations, but this is difficult to control. The size of the effect ($5 \rightarrow 8\%$) is commensurate with theoretical estimates, although the latter suffer from uncertainties in ν_2 , which varies rapidly with energy in this region.

At 300 MeV there is more direct evidence that the $3.79\gamma = 5$ resonance is implicated, and corrective action has resulted in recovery of the lost polarization. This is an imperfection resonance driven by fifth harmonic horizontal field components. To correct it harmonic coil set #12 was powered in "first harmonic" B_r mode. Each coil set consists of six 60° wide coils, #12 giving a maximum B_r near 300 MeV. In this mode the relative currents are arranged to maximize the first harmonic component and zero harmonics 0, 2 and 3; however, the $(6n \pm 1)$ th higher harmonics—including the fifth—remain non-zero. Scans were made for different current amplitudes at fixed phase and vice-versa. It was found possible to increase the polarization P at 400 MeV by 3% to its 200 MeV value or to lower it by as much as 13%—a much larger effect than has been observed with any other cyclotron control parameter. Moreover the form of the variation agrees well with that expected theoretically⁵ for small changes:

$$\Delta P = A |I - I_0|^2$$

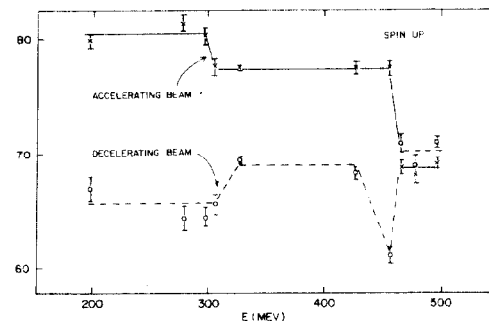


Fig. 6. Extracted beam polarization for various energies. (The lines are drawn to guide the eye.)

where \underline{I} stands for the vector current in H.C. 12 (assumed proportional to the field it produces) and \underline{I}_0 for that needed to correct the existing imperfection.

Proton Beam Lines

The simultaneous transport of two separate beams, originating from separate stripping foils, down a single beam line has been successfully demonstrated. A theoretical simulation indicated that a single stripping foil structure consisting of wide and narrow parts (Fig. 7) would result in well separated beam spots (solid curves) at IAT1 (Fig. 8) with no measurable increase in spill. Figure 7 also shows the beam profile as measured by steering this composite beam across a 1 mm grid of wires. The fraction of the total beam in the "tooth" part could be varied from 0 to 50% by simply adjusting the height of the stripping foil. Further studies have shown that separation >1 cm ($R_{11} \approx 2$) can readily be attained. Figure 8 shows a possible utilization of such beams. The primary beam continues down line 1A while the secondary (tooth) beam (1C) is split off using a magnetic septum to another target.

A third simultaneous beam (2C) for low energies only has been extracted and is currently in use for isotope production. The minimum practical energy, determined by vertical focusing in the cyclotron, is 70 MeV. A multi-use beam line, featuring five target stations has been designed. The line is radiation hardened to accept up to 100 μ A at continuously variable energies from 70 to 110 MeV. A third high energy beam line (2A) is also planned and elements for its front end are under construction.

As reported previously⁶, the TRIUMF cyclotron can produce stable 1nA and 100 μ A beams simultaneously in different beam lines. For experiments using a polarized target, however, beams as low as 10^5 p/s were required in an area of 3×3 mm² and an angular emittance of 5×5 mrad². This was achieved by inserting a 20 cm long, 1 mm diameter copper collimator immediately downstream of the LD₂ target on beam line 4A and by adjusting the optics upstream so that it selected only a small area of the phase space. Currents are typically $\sim 10^8$ p/s upstream of the collimator, where the polarization is continuously monitored, and $10^5 \sim 10^6$ p/s at the polarized target location at the end of the new beam line 4C.

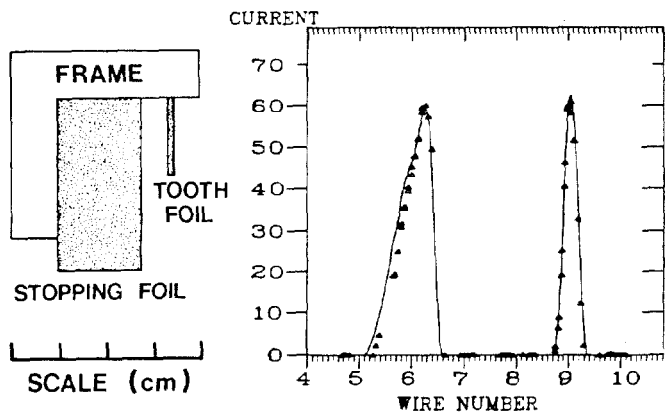


Fig. 7. Two-component stripping foil and the beam profiles produced by it at IAT1 (points—experimental, curves—theoretical).

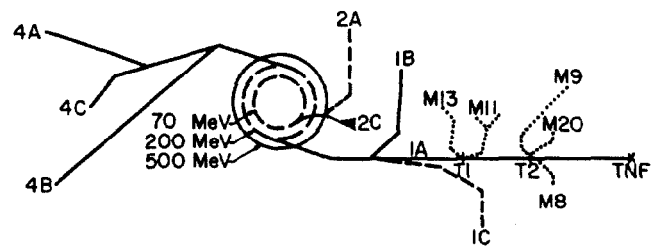


Fig. 8. Beam line layout: — protons, ... pions/muons, --- proposed.

Pion and Muon Beams

The particle fluxes and contaminations in the secondary channels viewing the T2 production target (Fig. 8) have been measured using two target materials, carbon and beryllium, and three proton beam spots—circular, and horizontal and vertical ribbons. The beryllium targets used were encased in stainless steel water cooling jackets with 0.005 in. entrance and exit windows while the carbon target was water cooled only on the side opposite the secondary channels. The results showed:

1. π^- fluxes from the carbon target were 80-85% of those from beryllium (for equal g/cm²)
2. μ^+ and μ^- fluxes from the carbon target were 100-110% of those from beryllium.
3. Electron contaminations were proportional to the amount of material between the production location and the channel. The contamination from the enclosed beryllium target was thus twice that from the carbon target under most usable beam conditions.

An extension to the cloud muon channel M9 incorporating a 3 m long dc crossed field separator with a 10×30 cm² aperture has been in operation since September 1979. The pion and electron contamination is a few percent when the dc voltage over the vertical separator gap is 500 kV. For 100 μ A protons the cloud muon flux $N(\mu^-, 77 \text{ MeV/c}) = 5 \times 10^5/\text{s}$ in a spot of 4 cm diam FWHM. Clean surface muon beams can be obtained with 50 kV over the separator gap. $N(\mu^+, 29 \text{ MeV/c}) = 6.5 \times 10^5/\text{s}$. Transversely polarized surface muon beams have also been achieved.

M13 is a low-energy meson channel⁷ in operation since August 1979. It takes off at an angle of 135° from a 1 cm long carbon production target at location IAT1 and has two 60° rectangular bending magnets. The channel is 9.5 m long, has 30 msr solid angle and momentum acceptance of 8% $\Delta p/p$. The maximum momentum is 130 MeV/c. For 100 μ A protons of 500 MeV on 1 cm C $N(\pi^+) = 2.0 \times 10^7/\text{s}$. $N(\pi^+)/N(\pi^-) = 5.0$. Useful π beams of as low as 15-MeV have been obtained. The surface muon flux = $1.2 \times 10^6/\text{s}$.

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