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PRODUCTION OF SIMULTANEOUS, VARIABLE ENERGY BEAMS FROM THE TRIUMF CYCLOTRON

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Summary

An extracted beam at the design energy of 500 MeV was obtained at TRIUMF in December, 1974. Later, beams of varying energies between 180 and 520 MeV were extracted down beam line 4 and further work resulted in the simultaneous extraction of a 506 MeV beam down beam line 1 while variable energy beams were brought down line 4. In order to reduce initial activation of cyclotron components, time average beams have been restricted to 100 nA but 12 µA in a pulsed beam was very easily obtained at 500 MeV. Without much optimization of the injection conditions and without use of the harmonic trim coils an energy spread (full width) of 2.5 - 3.0 MeV has been observed. Ordinarily, the macro-duty factor has been 100% and the micro-duty factor corresponds to a 5 ns pulse every 44 ns. The transmission to 500 MeV is consistent with the expected loss due to gas stripping.

Introduction

TRIUMF is a meson factory[1] based on the acceleration of H^- ions in a sector focusing cyclotron. Actual construction of the facility began in 1971. The year 1973 and three months of 1974 were spent in measuring and tailoring the magnetic field to the precision required as a consequence of the 1200 turns in the acceleration, the large final radius (309 in.) and the fact that the RF is on the fifth harmonic of the ion frequency. The problem was exacerbated by the difference between the fields produced by the 1:10 model and the full scale magnet, as explained previously,[2] but a satisfactory solution was obtained by April 1974. This solution also required the use of most of the 54 circular trim coils either to correct B_z or B_r or both.

In the six months from April through October, 1974 the 80 resonators were installed, the cryolines and cryopanels were installed and tested and the radio-frequency system was gradually worked up in power as the vacuum was improved. The first beam was accelerated to 6 MeV on November 16 and over the next month it was gradually worked out in radius to 277 in. (360 MeV) by careful adjustment of the currents in the circular trim coils on the top and bottom of the vacuum chamber. On December 15 the beam was rapidly accelerated the rest of the way to the design energy of 500 MeV at 309 in., and within the hour it had been extracted and focused on an external beam dump.

Since that time we have verified the variable energy feature of TRIUMF by extracting beams at 50 MeV intervals over the range from 180 to 520 MeV and have transported the beam down several external beam lines of the facility.

The simultaneous extraction of beams of differing energy has been achieved by extracting a beam of over 500 MeV down beam line 1 while at the same time extracting beams of various energies between 500 and 300 MeV down beam line 4.

Beam currents so far have been restricted to tens of nanoamps in order to minimize induced activity. However, a test run has been made at 12 µA peak current in a pulsed mode. The normal macroscopic duty factor is of course 100%; the microscopic duty factor is 11% -- 5 ns pulses every 44 ns.

Diagnostic Probes

Figure 1 is a plan view of the cyclotron showing the relative location of the diagnostic and extraction probes. The large scale of the machine together with the high magnetic fringe fields, the large resonator array and its associated RF fields and the high vacuum of the order of 10^{-7} Torr necessary for an H^- cyclotron presented a number of mechanical problems in the design of the diagnostic probes, but the use of H^- ions simplifies the beam detection at higher energies.

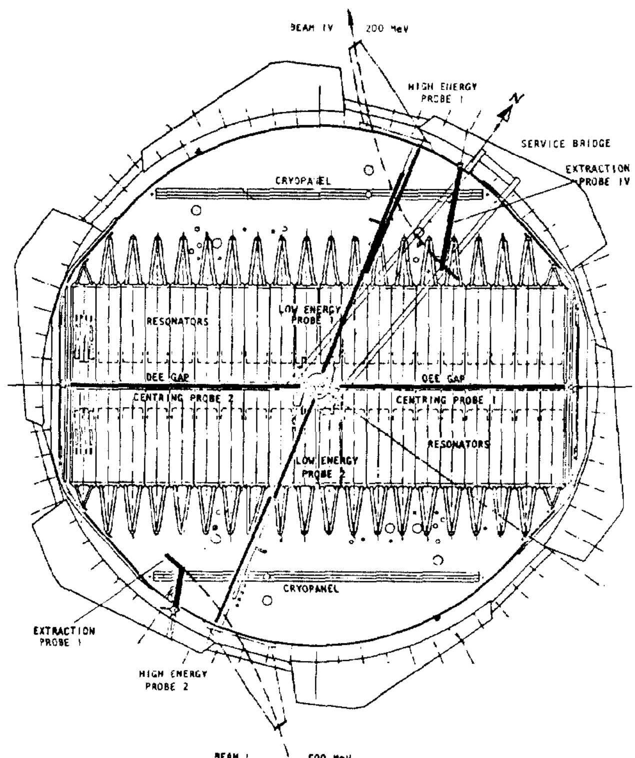

Figure 1. Plan view of the cyclotron vacuum tank showing the various diagnostic and extraction probes.

The full radial range of 315 in. is covered by sets of two current probes, the low energy probe which extends from the first turn to 145 in. (70 MeV) and the high energy probe which extends from 142 in. to 315 in. The probe arms are supported and driven from the lid of the vacuum tank and are lowered into the median plane for beam detection and retracted when not in use. Intercepting phase heads are being developed. The low energy head completely stops the beam and provides both vertical and radial information. The beam is stripped in the thin horizontal foils of the high energy head and the stripped electron current detected. The protons are dumped in a localized region at the tank periphery.

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The five current signals from each head are displayed as histograms on a storage scope, as analogue signals on electrometers or on a six-channel chart recorder driven synchronously with the probe. The vertical centroid and width of the beam are computed from the currents in the horizontal finger probe, and analogue signals are generated for display on the chart recorder. Typical radial beam plots are shown in Figures 4 and 5.

The extraction foils are suspended from a trolley which has three independent motions, a radial and azimuthal motion for positioning the foil for the desired extraction energy (180 to 520 MeV) and for centring the stripped trajectory at the combination magnet, and a vertical motion for partial extraction. Up to six foils are contained in a cartridge on the probe arm, and foil exchange either to replace a spent foil or to insert a special shape of foil is possible under vacuum.

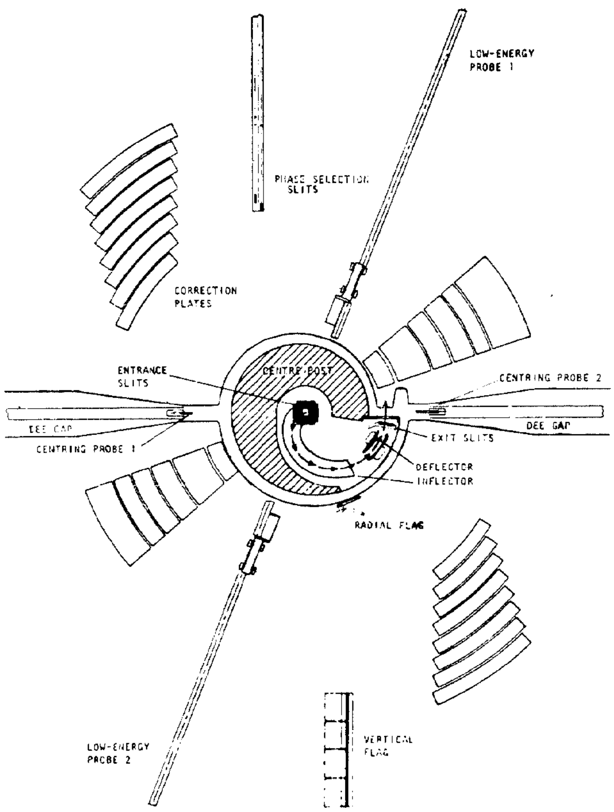

Figure 2. Central region probes, slits and steering elements.

Other diagnostic tools are slits at the inflector entrance and exit, centring probes located along the dee gap, a vertical flag for restricting the beam height at 4 MeV and moveable radial slits between 4 and 30 MeV for phase selection.

Beam Behaviour in the Cyclotron

Phase Acceptance and Microscopic Duty Factor

The 300 keV dc beam from the H^- ion source and injection system[3] enters the cyclotron vacuum tank axially from above and is then bent into the horizontal median plane by means of a spiral electrostatic inflector (Figure 2). After passing through an electrostatic deflector for radial steering, the ions cross the first RF accelerating gap and gain or lose energy depending on their arrival time. Those arriving when the RF voltage is close to its peak accelerating value (phase ϕ = 0 deg) gain sufficient energy to clear the "centre post" (a structural member supporting a combined magnetic and vacuum load of 2700 tons) and receive further acceleration.

In order to examine the phase acceptance, the chopper[3] in the injection line was used to reduce the phase spread of the injected beam to about 15 deg. The total current on low energy probe LE1 was then measured as the chopper phase was varied (Figure 3).

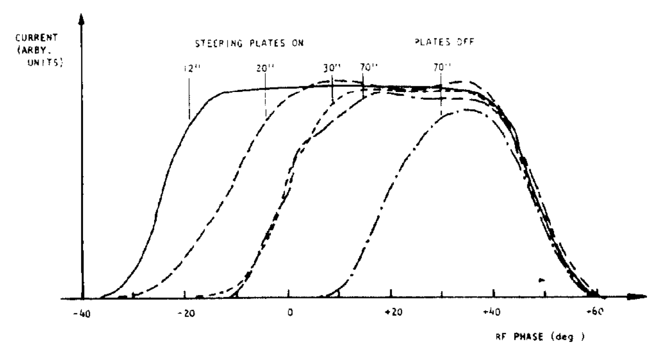

Figure 3. Total current recorded on probe LE1 at various radii as a function of the RF phase of the chopped beam.

At 12 in. radius (1.2 turns) the phase acceptance in the case shown is over 70 deg. As the beam is accelerated to a radius of 30 in. the acceptance falls to 45 deg, but from 30 in. to 70 in. there is no further loss. The ions lost on the first few turns are those with negative (leading) phases, which experience vertically defocusing impulses as they cross the dee gaps. For positive phases the impulses are focusing, though only weakly so for phases close to zero. Any coherent vertical motion induced by radial magnetic field components or dee misalignments will therefore have the largest amplitude for small positive phases. The electrostatic correction plates[4] shown in Figure 2 are used to steer the beam vertically over the first few turns. From Figure 3 we see that when these plates are turned off the phases with the weakest focusing from 0 deg to 20 deg are lost, while the transmission of more positive phases is unaffected, in agreement with expectations. The phases close to zero are potentially the most valuable, since, for a restricted phase acceptance, they are capable of yielding a finer energy resolution.

Three independent observations confirm a phase acceptance of 40-45 deg for the cyclotron:

(i) The total current measured on probe LE1 at a radius of 40 in. (5 MeV) amounts to about 11% of the dc beam from the ion source. Figure 4(a) shows an example where, out of a 1600 nA dc beam, 290 nA are measured on the first turn, corresponding to 65/360 deg, and 180 nA at 40 in. radius, corresponding to 40/360 deg. (The dips in total current at 16 in. and 19 in. radius are due to the width of the probe head being smaller than the radius gain per turn.)

(ii) The magnetic field was scanned through the cyclotron resonance at various radii, producing the characteristic trapezoidal variation in total beam current. The sides of the trapezoid had a width corresponding to $\Delta \sin \phi \simeq 0.65$, i.e. a phase spread of 40 deg.

(iii) Time of flight measurements[5] on the external beam indicated a phase spread of about 40 deg.

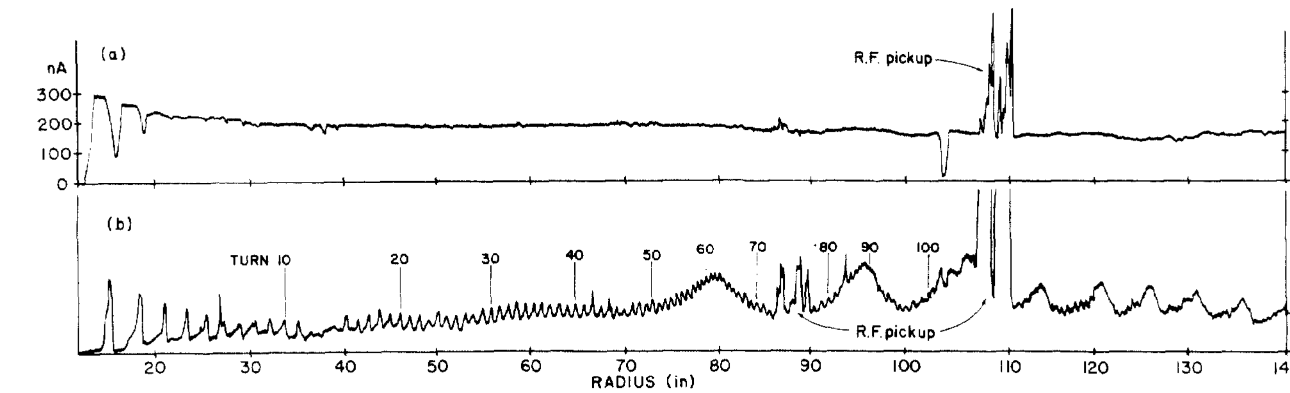

Figure 4. (a) Total current on the 2.0 in. wide x 2.2 in. high probe LE1 as a function of radius; (b) current on the 0.2 in. wide differential section of probe LE1, with the beam steered off-centre to display radial precession patterns and turn structure at large radii. Both traces were taken with unrestricted phase acceptance.

In summary then, it appears that the microscopic duty factor of the beam is at least 11%, consisting of a 5 ns pulse each RF period of 44 ns. The macroscopic duty factor of the beam is of course normally 100%.

Transmission

After selection of the phase acceptance on the first few turns the beam continues to the full energy of 500 MeV with no significant localized losses. There is however a gradual loss with radius which is not inconsistent with stripping of the H^- ions by the residual gas molecules in the vacuum tank. From 40 in. to 140 in. radius (5 - 60 MeV) this gradual loss amounts to about 10%. Thus in Figure 4(a) the current falls from 180 to 160 nA over this region. (The small dips in the total current plot at low radii and the shallow dips at radii of 100 in. and 125 in. are caused by the uppermost segment of the differential probe head being inoperative during this run; the dip at 103 in. radius was caused by a momentary beam trip.)

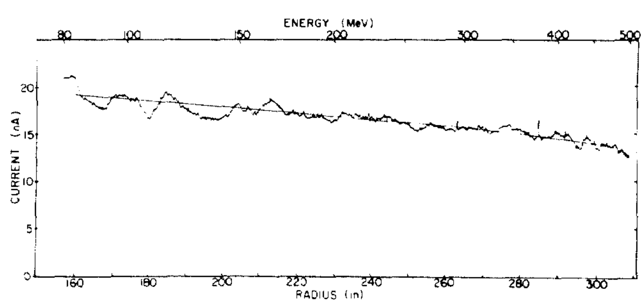

Figure 5. Total current on probe HE1 as a function of radius. The smooth curve illustrates the theoretical fall-off due to gas stripping. No electric stripping is discernable.

An example of the transmission observed in the outer region of the cyclotron, from 160 in. to 309 in. radius (80 to 500 MeV) is shown in Figure 5. The general trend is in good agreement with the smooth curve which represents the theoretical fall-off due to gas stripping[6] for a pressure of 2.8×10^{-7} Torr air equivalent, a dee voltage of 85 kV and a phase of 30 deg. The tank pressure was recorded as 1.7×10^{-7} Torr during this measurement; however, the average pressure seen by the beam will be considerably higher than this, since the orbits pass through the restricted space between the upper and lower RF resonators. The smooth curve represents an overall transmission of 70% over this region.

A possible source of uncertainty in current measurements with the high energy probe is the electron capture efficiency. The 0.005 in. tantalum fingers are thick enough to stop the stripped electrons from the H^- ions; however, these electrons could be back-scattered before stopping and re-emerge. Furthermore, the fingers are not thick enough to stop the delta-rays produced by the primary beam. Monte Carlo calculations have therefore been made to determine the histories of the electrons released in the probe, including multiple scattering effects; indications are that the electron capture efficiency is about 80%, the exact value depending on the radius (because of the variation of magnetic field) and which of the five fingers is considered. The larger dips in the plot of total beam current are correlated with vertical excursions of the beam and could be evidence of different capture efficiencies for the different fingers.

There is no clear evidence for electric stripping of the H^- ions by their passage through the magnetic field of the cyclotron at relativistic speeds. From the magnetic field measurements this loss was expected to be virtually zero to 450 MeV, building up to 6% at 500 MeV. In Figure 5 an effect of this size is not distinguishable from the deviations from a smooth curve present at all radii.

Beam Intensity

In order to avoid activation of cyclotron components during the commissioning stage, beam currents so far have been restricted to the 10-100 nA range. To test operation at higher currents without exceeding this current level on average, the beam from the ion source was run in a pulsed mode with beam on for 120 μs every 10 ms. Also the RF buncher[3] in the injection line was used, yielding a gain of a factor 4 in beam intensity at 500 MeV for the normal unrestricted phase acceptance. During the pulses a current of 12 μA was accelerated to 500 MeV and extracted from the cyclotron without any problem.

Indeed a current of 100 μA, the design specifications, has previously been accelerated to 3 MeV in our "central region cyclotron",[7] a full scale model of the parts of TRIUMF which would be most sensitive to space charge problems. We therefore anticipate no serious problems in raising the current in the TRIUMF cyclotron to 100 μA, once the vacuum has been improved and sufficient shielding built around the external beam lines.

Radial Beam Quality

Figure 4(b) illustrates the current density observed with the 0.2 in. wide "differential" section of probe LE1 for a beam of unrestricted phase acceptance. Individual turns are identifiable up to turn 100 or so, and by deliberately steering the beam off centre, as in this example, individual turn structure can also be seen out to 60 MeV (140 in. radius) in the minima of the radial precession patterns.

By restricting the phase acceptance with the chopper to a narrow band near the peak of the RF voltage, completely separated turns have been observed out to turn 60.

Shadowing measurements to investigate the centring and emittance of the accelerated beam have been made using probes HE1 and HE2 at radii of 160 in. (70 MeV) and 309 in. (500 MeV). By 70 MeV the chief effects responsible for worsening the radial beam quality (unoptimized initial centring, radial longitudinal coupling, first harmonic magnetic field components) are expected to have completed their work, so that the radial beam properties measured there should be representative of those over the remainder of the cyclotron. At higher energies ν_r increases from 1.07 to 1.5 and the precession makes it more and more difficult to extract information on the radial emittance using probes 180 deg apart in azimuth.

The 70 MeV measurement indicated that the orbits were centred to 0.15 ± 0.1 in. and that the maximum radial betatron oscillation amplitude $A_r \simeq 0.7$ in. At 500 MeV the centring was 0.1 ± 0.1 in. Assuming no deterioration in A_r as the beam is accelerated beyond 70 MeV, we would expect the energy resolution ΔE of a 500 MeV extracted beam to be about 3.5 MeV; in fact it was observed to be slightly smaller than this (see below).

The observed values of A_r and ΔE are considerably larger than the design specifications of 0.14 in. and 1.2 MeV, but no worse than might have been expected from the residual harmonic components measured at the end of the magnetic field survey. However, the tune-up of the cyclotron has so far been directed entirely at maximizing the transmission; no attempt has yet been made at improving the beam quality. To do this will require careful tuning of the central region (for which the probe LE2 must be installed) and of the harmonic coils.

The precision of the centring allows us to place rather tight error bars on the energy of a beam stripped at a given radius. Thus a nominally 400 MeV beam is expected to have a mean energy 400 ± 3 MeV. The BASQUE experimental group[5] have made an independent measurement of the energy of a nominally 400 MeV external beam by a time of flight technique, with the result 403 ± 10 MeV.

Vertical Motion of the Beam

In the presence of an average radial field component $\overline{B_r}$, the equilibrium orbit at the mean radius R will be displaced from the geometric median plane by

$$\bar{z} = \frac{R\,\overline{B_r}}{\nu_z^2\,\overline{B_z}} \tag{1}$$

where $\overline{B_z}$ is the average axial component of magnetic field and ν_z is the axial tune. Thus the TRIUMF cyclotron, which is designed with relatively low $\overline{B_z}$ (to avoid electric stripping of the H^- ions), low ν_z^2 and large R, is particularly susceptible to vertical excursions caused by B_r components. Because of the scalloping of the orbits, harmonic components of B_r and B_θ can also contribute to the vertical displacement $\bar{z}$, effectively increasing $\overline{B_r}$. At the most sensitive radius, where ν_z^2 is at a minimum of 0.02, a 1 in. excursion can be caused by an effective $\overline{B_r}$ of only 0.3 G. To steer the beam between the 3 in. high gap between the resonators therefore required very careful adjustment of those of the circular trim coils which were powered asymmetrically (i.e. currents flow in opposite directions in upper and lower coils). Nevertheless, it has been possible after careful tuning to keep the mean height of the beam (as computed on-line from the currents on the five fingers of probe HE1) within ±0.3 in. of the median plane from 70 to 500 MeV. To steer the beam to this accuracy in the presence of rapid radial variations in the mean height, manual tuning was supplemented by computer calculations of the current changes required in several neighbouring trim coils together. Under these optimum conditions virtually all the beam was found to be on the three central fingers (total height 1.5 in.) of probe HE1. Where ν_z^2 was large for radii < 170 in. the beam was contained on one finger (height 0.5 in.) only.

The relation (1) above suggests a direct method of measuring the axial tune ν_z by observing the change in mean height of the beam for a given change in $\overline{B_r}$, obtained by adjusting the trim coil currents. In practice, the currents were adjusted in a group of neighbouring coils so as to give a uniform change in $\overline{B_r}$ over a range of radii. The observed change in mean height at the probe azimuth was corrected for the sector modulation of the envelope to give the true change in the azimuthally averaged height. Figure 6 illustrates the results of the measurement, compared to a curve derived from orbit calculations based on the magnetic field survey. The agreement appears to be reasonably good. The accuracy of the measurements was chiefly limited by the requirement that no beam should be driven off the probe head; as a result the permissible displacements were only of the order of the finger width, and sometimes smaller.

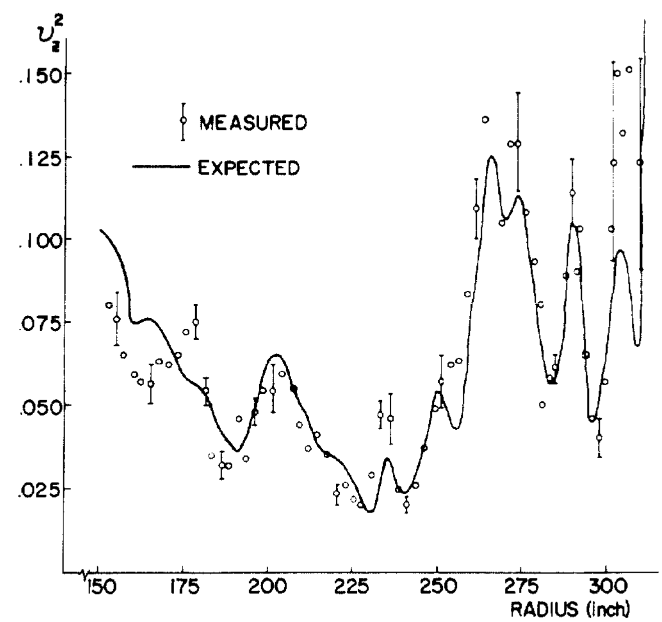

Figure 6. ν_z^2 as a function of radius. The points were obtained from measurements with the beam, the curve from calculations based on a magnetic field survey.

Extracted Beams

As mentioned above, following the first acceleration of a beam to 500 MeV on December 15, 1974, a beam was extracted within the hour from a fixed stripping foil down beam line 4 (Figure 7) to a temporary beam stopper in the corner of the cyclotron vault.

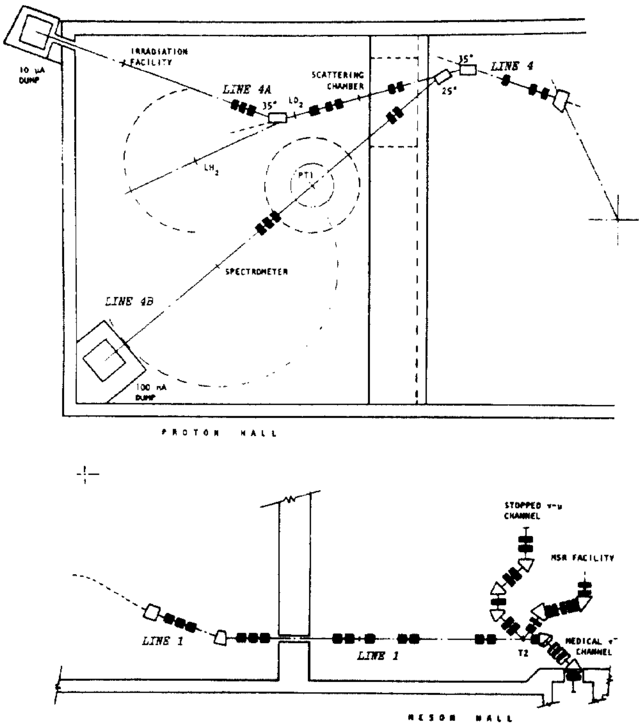

Figure 7. The experimental halls and beam lines.

In January, the moveable extraction probe 4 (Figure 1) was installed and beams were extracted at 50 MeV intervals from 180 MeV to 520 MeV. On average 10 to 15 minutes were required to locate and extract each of the lower energy beams. Subsequently these beams were transported down beam line 4B and, in some cases, down line 4A for the use of the experimental groups.

On February 20 beam was first extracted down beam line 1 to the vault wall from a fixed stripping foil at 506 MeV radius. Extraction probe 4 was then introduced into the circulating beam to produce a simultaneous 506 MeV beam down beam line 4. Subsequently beams of various energies down to 305 MeV were extracted down line 4 simultaneously with the 506 MeV beam in line 1.

Figure 8 shows a CRT display[8] of a 400 MeV beam spot taken on a multiwire chamber stationed at the LD_2 target position on line 4A (Figure 7). The wire spacing is 3 mm, so that the full width of the beam is 6 mm horizontally by 15 mm vertically.

Energy Resolution

The momentum spread Δp in the extracted beam has been measured by running beam line 4B in a dispersive mode and observing the beam width at the PTI target position. The observation was made using a gas filled multiwire chamber with 2 mm wire spacing. The beam line was set up in its normal achromatic mode for a 500 MeV beam and then switched to the theoretical dispersive settings. Calculations lead us to expect that more than 75% of the spot width is attributable to

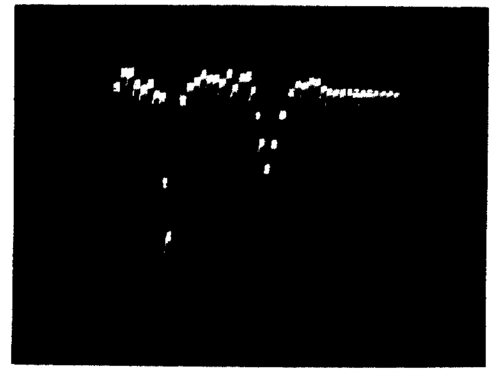

Figure 8. Multiwire chamber display of the beam spot at the line 4A target position. The horizontal and vertical displays are on the left and right respectively; the wire spacing is 3 mm.

dispersion, while the magnification of the achromatic spot is small. The dispersion at the detector was 12 cm/percent ($\Delta p/p$). The momentum spread measured for the 500 MeV beam corresponded to an energy resolution of between 2.5 and 3 MeV (full width), depending on exactly how the cyclotron was tuned.

Observations of the energy spectrum of scattered protons are consistent with these values. The University of Alberta group[9] scattered 400 MeV protons from a polyethylene target and stopped the 150 MeV protons scattered at 49 deg in a 3 in. x 5 in. sodium iodide crystal in coincidence with the recoil proton. The resulting energy spectrum is shown in Figure 9. The full width at half-maximum is 3 MeV; of this 2 - 3 MeV represents instrumental resolution, leaving 0 - 2 MeV for the energy spread of the 150 MeV protons. This corresponds to an energy spread of 3 ± 3 MeV in the primary proton beam.

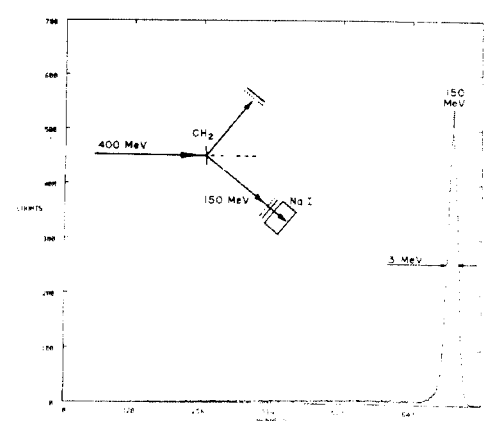

Figure 9. Pulse height spectrum of 150 MeV scattered protons stopped in a sodium iodide crystal.

Operation and Stability

Since mid-November, TRIUMF operation has been on a two-shift per day, 14-shift per week basis. Beam has been accelerated on about 50% of the days with the remaining time primarily for installation of new equipment such as the extraction probes and external beam lines. Since January the available beam time has been divided roughly equally between beam dynamic studies in the cyclotron, commissioning the external beam lines and delivering beam to expimenters' targets. The beam stability on target has been very satisfactory with periods of several hours running with no operator intervention.

Conclusion and Future Developments

The achievements of the first three months of operation of TRIUMF can be listed as follows:

1) Acceleration of an H^- beam to an energy of 500 MeV and above.
2) Variable energy extraction down a 30-meter beam line to a dump has been demonstrated over the energy range 180 - 520 MeV.
3) Simultaneous extraction of beams of differing energies has been demonstrated.
4) Some progress has been made in understanding and improving the performance of the accelerated beam.
5) Some short periods of beam time have been provided to experimental groups for lining up and timing in their counters.

Further work in the development of TRIUMF can be summarized in the following objectives.

1) To improve the vacuum by about a factor of 5 from the present operating pressure of 2×10^{-7} Torr.
2) To improve the reliability and stability of the facility -- although the latter appears to be very good indeed.
3) To improve the energy spread of the raw beam by optimizing the injection conditions and by working with the sets of harmonic coils, the defining slits and eventually with the third harmonic of the RF. It should be possible to achieve an energy spread of much less than 0.1% with these techniques.
4) To further progress in understanding and improving other properties of the accelerated beam.
5) To accelerate H^- ions from a Lamb shift type polarized ion source, which has already been commissioned at 300 nA, 80% polarization.
6) Finally, to start as soon as possible, delivering stable, long-term and simultaneous beam allocations to the various experimental groups.

Acknowledgment

We wish to extend our warmest appreciation to our colleagues at TRIUMF, many of whom have made significant contributions to the success of the project. There are too many to mention by name but without their efforts, this report would not have been possible.

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