# THE STATUS OF TRIUMF

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## Abstract

Starting late in 1974, many of the capabilities of TRIUMF have been explored. Beams of varying energies between 180 and 520 MeV have been extracted down beam line IV. Simultaneous beams of differing energies have been extracted down beam lines I and IV and the ratios between the intensities of the two beams have been varied in a controlled manner. Beam currents so far have been restricted to less than 300 nA in order to minimize induced activity, but a test run has been made at 48 μA current in a pulsed mode. The normal macroscopic duty factor is of course 100%; the microscopic duty factor is 12% -- 5 ns pulses every 43 ns. By April, two physics experiments were underway simultaneously on two beams separately extracted from the cyclotron.

## 1. Introduction

A sector-focusing cyclotron accelerating $H^-$ ions was proposed as the basis of a meson factory in 1962.[1] On December 15, 1974 -- twelve years later -- a beam of $H^-$ ions was accelerated to the design energy of 500 MeV at TRIUMF[2] and within the hour extracted and focused down a 15 m beam line. In the meantime, there have been several general progress reports[3-6] on the development of the facility.

Since the acceleration and extraction of the beam in December we have been dividing the time of the facility between an investigation of its capabilities and the provision of beams for the initial work of the experimental groups. Much work has also gone into the completion and tuning up of the three proton beam lines.

The variable energy feature of TRIUMF has been used extensively by experimental groups both in the proton hall and in the meson hall. Meson production research has made use of proton beams at various energies from 350 to 500 MeV while in proton elastic scattering beams of energies from 200 to over 500 MeV have been used. Down the low intensity proton line we have extracted beams of energies from 180 to 520 MeV. Changing the energy has become quite rapid as experience grows, and conditions are so reproducible that it seems quite likely that in the near future we will be able to ask the computer to set up the parameters for any energy at will.

Another feature of TRIUMF which has performed at least as well as expected, is the extraction of simultaneous beams of differing energies. In fact, the two main experimental areas, the Proton Hall and the Meson Hall, are scheduled simultaneously and without regard to each other.

Proton beam currents so far have been restricted to less than 300 nA in the Meson Hall and less than 50 nA in the Proton Hall, in order to minimize the induced radioactivity. However, a test run has been made at 48 μA average current during a macro pulse of 100 μs/10 ms. The normal macroscopic duty factor is of course 100%; the microscopic duty factor is 12% -- 5 ns pulses every 43 ns.

## 2. Magnet

The cyclotron magnet consists of six identical sectors each weighing approximately 680 tons and all excited by a common coil.[7,8] There are 54 concentric and approximately circular trim coils mounted on the top and bottom of the horizontal vacuum chamber. These have been used when powered symmetrically to correct the average value of $B_z$ in order to satisfy the isochronism condition

$$\omega = \frac{qB_z}{m\gamma c} \qquad [1]$$

but also in adjusting the last term in the equation for the axial focusing force on the ions:

$$\nu_z^2 = F^2(1+2\tan^2\varepsilon) - \frac{R}{B_z}\frac{dB_z}{dR} \qquad [2]$$

In practice, a compromise had to be effected between these two requirements at several radii. When differing or even opposing exciting currents are used in the top and bottom components of a coil, corrections are made to the radial component of the magnetic field, $B_R$.

It was found that the outer trim coil, consisting of three turns at 325 in. radius was the best sensor of the overall magnetic field and so it was incorporated with an integrator into the current-regulating system of the power supply. The resulting regulation is 5 parts per $10^6$ over periods of 5 minutes and 1 part per $10^5$ over 8 hours.

There are 13 sets of harmonic coils per sector covering approximately equal intervals in radius. These can be used to correct inequalities in the sectors or to cock the equilibrium orbit by exciting the top and bottom components differently.

The magnet pole-face sectors were made undersized by several inches and studded as shown in Figure 1 so that shim plates of various thicknesses could be bolted on the sides of the poles to vary the profile. In this way the spiral angle and the average magnetic field could be adjusted at a particular radius. Also the deleterious first and second azimuthal harmonics in the magnetic field could be corrected. In addition it was hoped that the pole-face side shims could be used to correct $B_R$ and its harmonics.

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* on leave from UCLA

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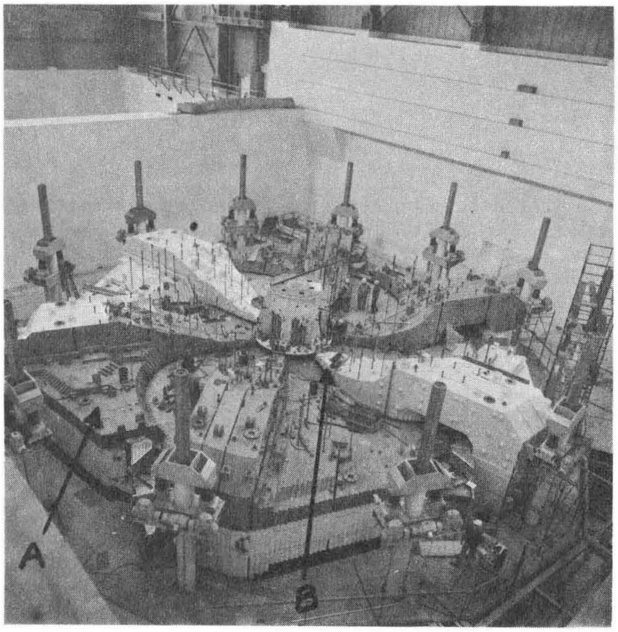

*Figure 1: Cyclotron magnet during construction*

After the first series of magnetic field surveys it became clear that there was a large deviation from isochronism due to the fact that the field was too high by 100 G over the radial region from 30 to 250 in. This deviation was much larger than the corrections that could be made by the shims on the sides of the poles and it had not been expected because the consistency between the field contours of the 1/20 and 1/10 scale model magnets had been better than 1%. The source of this deviation appears to be due to a difference in the magnetic properties of the steel used in fabricating the model and the full scale magnet as shown in Figure 2. Attempts had been made to ensure similarity of magnetic properties by specifying the steel as AISI 1006 with a mill analysis of carbon content within the tolerances of 0.06 to 0.08%. It is believed that the difference in magnetic properties is probably due to the difference in the thickness of the plates (5 in. vs. 0.5 in. for example).

The major step in correcting the deviation was to add large amounts of iron to each of the sector yokes (both top and bottom) in the position shown by arrow A in Figure 1 and to remove a smaller amount from the yokes near the centre in the position shown by arrow B. In the latter case, flame cutting was involved and care had to be taken not to compromise the structural integrity of the magnet. Over 100 tons of steel were involved in the changes. One fortunate result of the greater permeability of the steel of the full scale magnet was a reduction in the required excitation from a predicted 680,000 to an actual 560,000 ampere turns. This corresponds to a saving in magnet excitation power of over 30%. However, an extra over-size circular trim coil had to be provided with a capacity of 10,000 ampere turns and a radius of 14 in. to reduce the field in the very centre of the magnet.

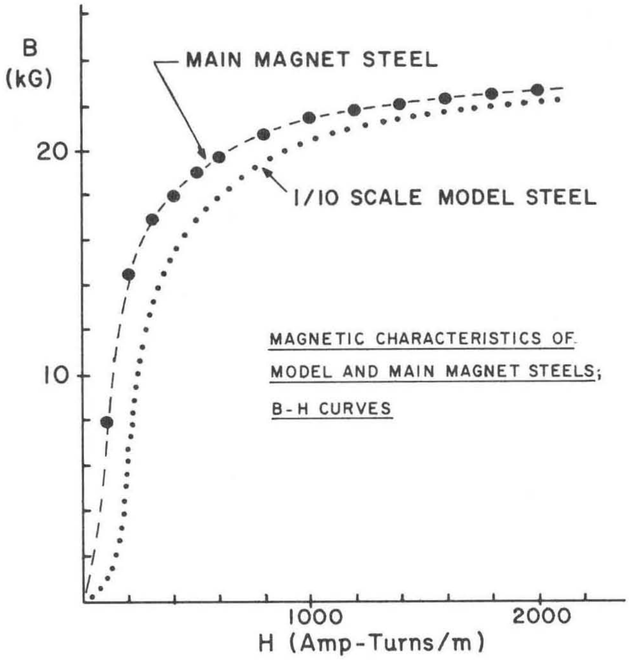

*Figure 2: Difference in B-H curves for model and full scale magnets*

The magnet support structure is asymmetric top and bottom and this produced an undesirable radial field component $B_R$. The reduction of this component required a difference in the treatments of the yoke iron for the top and bottom at arrows A and B in Figure 1.

The effect of the placing of a single shim on the side of one of the sector pole faces was mapped by the magnet survey apparatus[9] and it was found that an appreciable influence on the field extended as far as 15 ft from the point of placement. This made the tailoring of the field a very complex problem which clearly required computer assistance and so an extensive effort was mounted in this area.[10] The first programs were developed to proceed directly from the measured field to the prediction of the required changes in steel shimming to satisfy the requirements on $\nu_z^2$, isochronism, etc. However, these programs were unsuccessful, probably partly because a linear approximation is inadequate and partly because there is no unambiguous solution to the problem. A successful technique was then developed which can be described as follows:

(1) Measure the field as it exists.
(2) Calculate orbit time, $\nu_z^2$, harmonics, beam height, etc.
(3) Estimate shim changes needed to improve all parameters, observing physical constraints on shims.
(4) Repeat if necessary, until desired improvement is predicted.
(5) Make the actual shim changes on the magnet.
(6) Remeasure the field.

As can be seen, this is a time-consuming procedure, but nevertheless it is much faster than doing trial shimming on the magnet itself. The improvement in the field as far as isochronism is concerned is shown in the comparison of the first and last surveys shown in Figure 3.

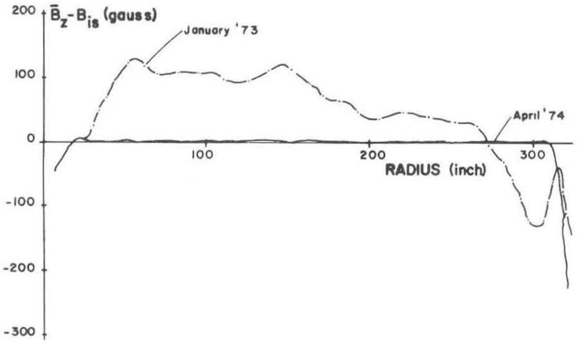

*Figure 3: Comparison of the first and last magnet surveys for $B_z$*

Fortunately, shimming for $B_z$ and $B_R$ turned out to be independent to a first approximation, although the requirements on $B_R$ are quite stringent. This is shown by the relation

$$\frac{\bar{B}_R}{\bar{B}_z} = \frac{\bar{Z}}{R}\,\nu_z^2 \qquad [3]$$

where the bars denote azimuthally averaged values and z is the displacement from the equilibrium orbit at the radius R. Since the axial orbit space is limited to 3 in. it can be seen that the limiting value of $B_R$ can be as low as 0.1 G if $\nu_z$ should fall as low as 0.1 and we wish to limit $\bar{Z}$ to ±0.7 in. or less. This limited value of $B_R$ is almost a factor 10 lower than the 1 G reliability which was achieved in the measurement of $B_R$. However, measurements of the field effects of the trim coils excited asymmetrically (as described above) indicated that the final reduction of $B_R$ to tolerance could be achieved by use of the trim coils, provided the changes in $B_R$ were not too abrupt with radius. Figure 4 shows the results of the $B_R$ survey before and after correction of the magnet and also with the predicted use of the trim coils.

## 3. Radiofrequency and Vacuum Systems

The performance of these two systems is intimately linked and so it is useful to discuss them together. The RF system has been described extensively[11,12] and there are two papers[13,14] at this conference which are concerned with it so reference should be made to those papers for a full description. Figure 5 shows a plan view of the cyclotron vacuum tank with the resonators and cryopanels in place. The resonators act as λ/4 cavities at 23.05 MHz with the voltage loop at the "dee" or accelerating gap. There are 80 resonators altogether, 20 above and 20 below the beam space on each side of the gap.

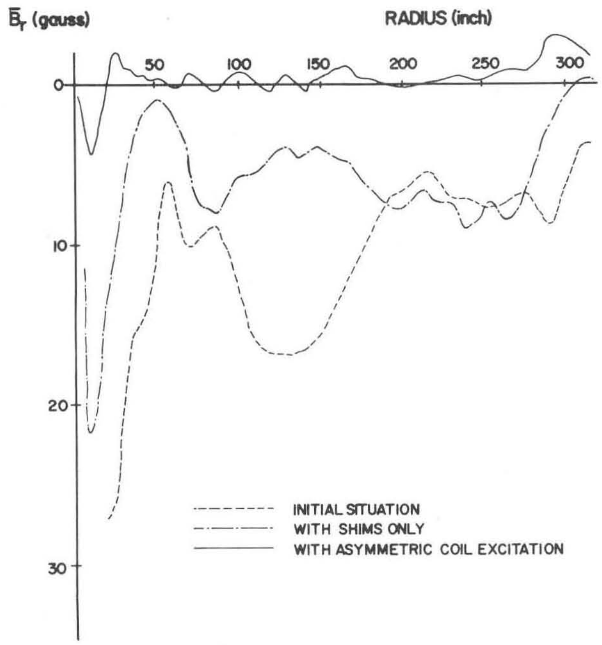

*Figure 4: $B_R$ before and after shimming and the predicted effect of trim coils*

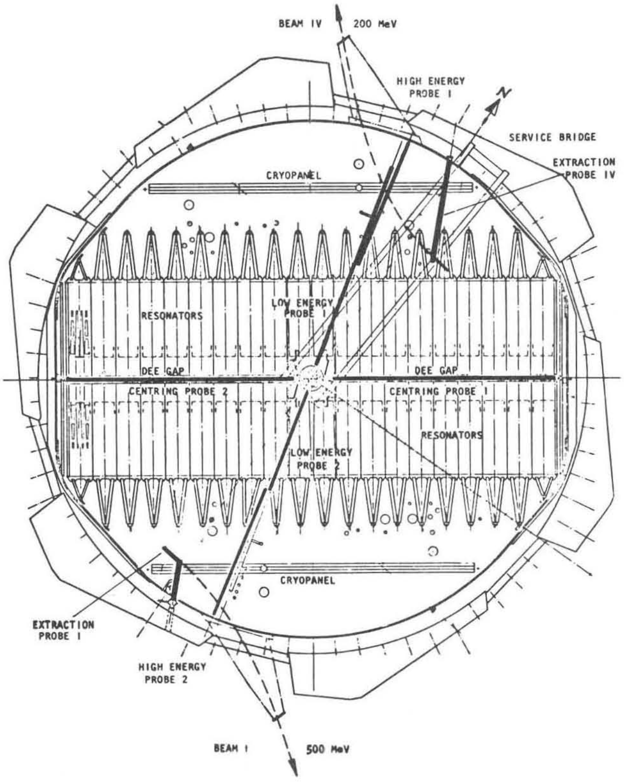

*Figure 5: Plan view of the cyclotron vacuum tank*

The conditioning of the resonators began with an elaborate cleaning and bake-out process after local manufacture. The installation was also performed under carefully controlled clean conditions. The leak testing of the water cooling lines and the pressure control lines was time-consuming as was the alignment of the dee gap to ±0.03 in., but in September, 1974 the system was ready for voltage under vacuum and the final conditioning could begin. It was at this point that some of the limitations in the vacuum system showed up.

As has been described elsewhere, the main high vacuum system consists of two cryopanels maintained at 20°K by a Philips B-20 cryogenerator, with shields at 80°K (Figure 5). This system gives a pumping speed of over a million liters per sec for water and over $10^5 \ell$/sec for air but of course does not pump hydrogen or helium. The hydrogen load was designed to be handled by a separate system of turbo-molecular and titanium sublimation pumps giving a pumping speed of 10,000 ℓ/sec at $10^{-7}$ Torr but only 1,600 ℓ/sec at $5\times10^{-6}$ Torr. This system had had no difficulty in bringing the 60 ft vacuum chamber quickly down to $10^{-7}$ Torr in previous tests. But the presence of the RF fields from the resonators even more than the increased surface to be outgassed made the story now very different. It was virtually impossible to work the resonator voltage above about 60 kV even after long conditioning and the pressure stayed in the range $3\text{-}10\times10^{-6}$ Torr. Mass spectograms indicated an overwhelming presence of hydrogen. It appears that the RF fields were dissociating the outgassed water vapor and hydrocarbons, giving large amounts of hydrogen which when added to that coming directly from the metals presented a total load much too large for the pumps to handle. We solved this problem by installing four 10-inch oil diffusion pumps with LN baffles. This gave a pumping speed for hydrogen of 4000 ℓ/sec (baffled) in the crucial $10^{-6}\text{-}10^{-5}$ Torr range.

Our present operating pressure is $2\text{-}3\times10^{-7}$ Torr, as read on an ionization gauge, usually achieved after accelerating a beam for two or three days. On the basis of mass spectrograms and the relative gauge efficiency for hydrogen, it is believed that the true pressure consists of $1\times10^{-7}$ Torr of air and $4\times10^{-7}$ Torr of hydrogen.[15] These pressures are quite adequate for the operation of the RF system, but are a matter of concern as discussed below when considering the gas stripping of beams of 100 μA or larger. There are still a number of air leaks in the system which can be eliminated.

The usual operating voltage of the resonators has been set at 92 kV as measured by the increase in the radius of the beam in the central region. This is within 10% of the value obtained from a linear extrapolation of measurements at low voltage.

In an ideal, balanced cavity system with the shape of the resonators shown in Figure 5, there would be no RF fields in the beam space far removed from the dee gap. In actual practice, several variations from the ideal were required. For example, in order to have a good quality factor Q for operation at the third harmonic (69.15 MHz), it was necessary to make the central resonator segments about 3 in. shorter than the others. The presence of the probes is a disturbing factor and any slight top-bottom asymmetry will produce some field in the beam space. The effects of these fields are noticeable in RF pick-up and occasional sparking which inhibits the use of some of the probes. It should be emphasized that these RF fields are very small compared to the field across the dee gap. However, efforts are being made to reduce these fields because they do reduce the scope of beam dynamic studies in the central region of the cyclotron.

## 4. Ion Source and Injection System (ISIS)

This system has been described recently[16] and it is shown in Figure 6. It will eventually have three alternative ion sources, but at present only HV1 is used although it is expected that the Lamb shift polarized source will be delivering beam into the cyclotron by September. HV1 employs an Ehlers type source with an emittance of 60 π mm mrad. The average life of the filament has been gradually improved to approximately 300 hours.

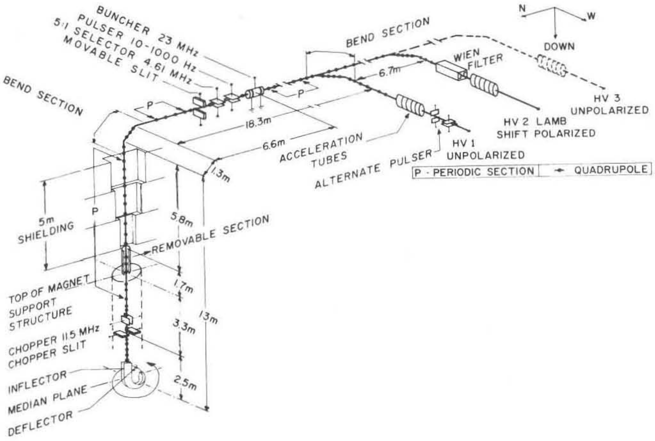

*Figure 6: Ion source and injection system*

The chopper has been useful in analyzing and improving the beam properties of the cyclotron -- it can inject a beam as narrow as 7° full width at half maximum through a 1.2 mm wide chopper slit. The pulser has been used to provide beams from the ion source up to 1 mA for 100 μsec to test the performance of the cyclotron at high beam intensity (1% duty factor) without unduly activating the machine. The buncher has been used primarily in tests. These have shown bunching factors from three for 50° phase width to ten at 15° phase width. The buncher will be particularly useful with the polarized $H^-$ beam. The 5:1 selector at 4.61 MHz shown in Figure 6 will be used in some experiments involving time of flight because it will result in beam pulses every 217 nsec instead of the usual 43 nsec. (The ion frequency is one-fifth of the RF).

The inflector-deflector system has performed well and fulfills its function of injecting the beam into the centre of the cyclotron with the appropriate direction of momentum, both axially and horizontally.

## 5. Beam Development

For a full description of the properties of the cyclotron beam, reference should be made to paper D-24 of this conference.[17]

### 5.1 Central Region

The two low energy probes shown in Figure 5 have been used to investigate the turn structure in the radial region from 12 to 145 in. These measurements have been complicated by the RF fields mentioned above but a typical radial scan is shown in Figure 7. There one can see the successive turns of the beam as the probe is pulled out in radius. Using the injection of a 15° phase spread chopped beam it has been possible to show that 95% transmission is achievable from injection to 20 MeV over a 40° phase range. The turn size in Figure 7, corrected for the finite thickness of the probe, corresponds to $\Delta E/E \simeq 0.4\%$ at 70 in. radius (17 MeV).

### 5.2 Gas Stripping

Rather distant collisions with the residual gas in the acceleration chamber will strip the loosely bound (0.75 eV) second electron from the $H^-$ ion. The fractional loss of beam current as a function of radius can be expressed in the form[18,19]

$$\frac{1}{I}\frac{dI}{dR} = -0.286\,\gamma\,p\,\frac{400}{\Delta T}\ \%\ \text{per inch} \qquad [4]$$

where p is the pressure of air or equivalent expressed in micro Torr and $\Delta T$ is the energy gain per turn in keV. To a first approximation this loss varies with radius only with the total energy $\gamma$, it can be expressed in terms of the survival of beam from $R_1$ to $R_2$ in the form

$$\ln\frac{I(R_2)}{I(R_1)} = -1.16\,\frac{400}{\Delta T}\,p\left[\sin^{-1}\frac{R_2}{R_c} - \sin^{-1}\frac{R_1}{R_c}\right] \qquad [5]$$

where $R_c$ is the cyclotron radius (407 in. for TRIUMF). For example, for the radial interval 12-310 in., $\Delta T$=336 keV and $p=3\times10^{-7}$ Torr of air predicts I(310 in.) = .71 I(12 in.) or a loss of 29% of the beam between the two radii.

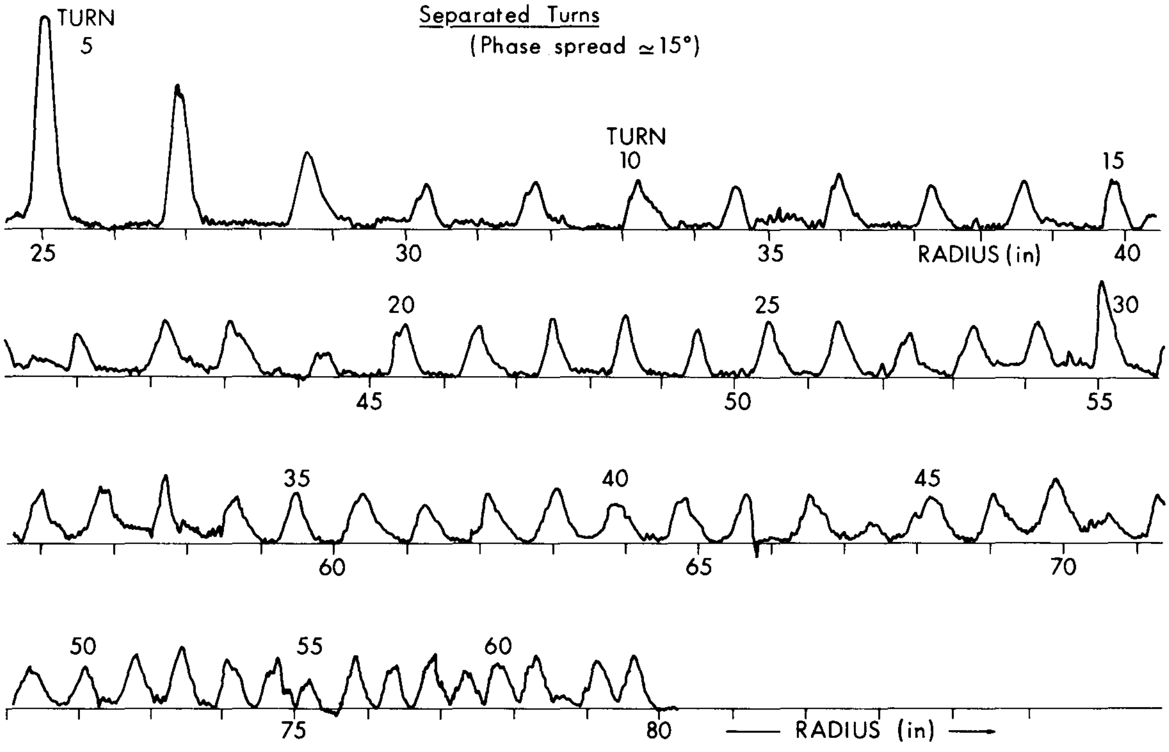

Figure 7: Successive turns of the beam as the probe is pulled out in radius

The results of an experiment to check the validity of these calculations is shown in Figure 8. An increase of pressure as read by an ion gauge of $5\times10^{-7}$ Torr was produced by (a) a controlled air leak from outside and (b) by allowing the cryopanels to warm up, thus releasing air trapped on the 20°K lines. It is assumed in this figure that the pressure and energy gain are uniform and that the calibration of the ion gauge (Bayard-Alpert) is correct. The agreement with the predictions are satisfactory for air, but for hydrogen the points should also extrapolate to the origin. The stripping effect for $H_2$ appears to be a factor of 2 less than for air even though the actual pressure compared to the gauge reading is presumably a factor of 2 greater for hydrogen. Thus the stripping cross-section appears to be a factor of 4 or 5 smaller for hydrogen than for air. Therefore, the gas stripping loss to 500 MeV under the present operating pressure of $2\times10^{-7}$ Torr air equivalent is 20%. However, it should be remembered that this is equivalent to a loss of less than 4% at 500 MeV because most of the gas stripping occurs at lower energy. We expect to reduce our residual gas to $4\times10^{-8}$ Torr air equivalent, which will reduce our total gas stripping loss to 5% and our effective loss to less than 1%.

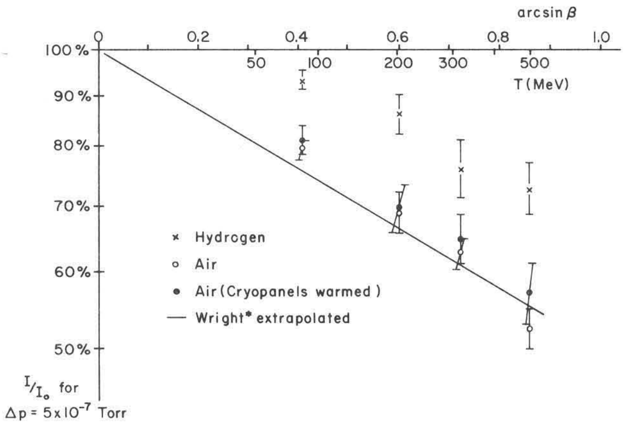

*Figure 8: Beam survival as a function of radius for pressure increase of $5\times10^{-7}$ Torr. Note log scale of ordinate*

### 5.3 Maximum Energy and Electromagnetic Stripping

The high velocity $H^-$ ions in the magnetic field of the cyclotron experience an electric field in their moving frame of $\varepsilon=0.3\ \beta\gamma B$. In TRIUMF, this amounts on the hills to 2 MV/cm, sufficient to facilitate loss of an electron from the ion. The predicted loss is a total due to this cause of 1% at 450 MeV, 7% at 500 MeV, or 17% at 530 MeV. Figure 9 shows an exploration of the outer radii of TRIUMF with a five-fingered high energy probe. The dip in the trace is due to the axial motion which takes the beam from one finger to another one where the capture of the two electrons from the $H^-$ ion is not as efficient. The dashed curve (normalized at 450 MeV) shows the shape of the loss vs. radius to be expected from the electric stripping.[20] The phase history of the ions is shown in Figure 2 of reference 17 and clearly shows that the loss of beam at 525 MeV is due to the ions getting out of phase with the RF. On the basis of our results one can say that the electric stripping is certainly no greater than expected, but we cannot yet say with certainty that we have observed it quantitatively at TRIUMF.

### 5.4 Simultaneous Extraction

One of the attractive advantages of TRIUMF is the capability of extracting simultaneous proton beams of differing energies. During the first half year of operation this capability has been developed to the extent that our proton lines to the two experimental halls are scheduled independently for simultaneous operation and at independent energies of choice. Extraction probes I and IV (in Figure 5) are in use at the present time, with the beam from probe I going into the proton hall and beam from probe IV going into the meson hall. The extraction foils are at present made of 0.001 in. Al but for higher intensity beams we will use foils of pyrolytic graphite. Whichever beam is of lower energy makes use of an Γ-shaped foil thin in the radial direction for the part of the foil which intercepts the beam. This foil is then raised out of the median plane until the desired ratio of the currents into the two experimental areas is achieved. The same result can be achieved by trim coil changing of $\overline{B}_R$. Reasonably stable ratios of 1 part in 500 to 1 part in 2000 have been achieved for short periods of time, but further development of such high ratios will await demand by the experimental groups. The total current is adjusted by changing the intensity of the injected beam.

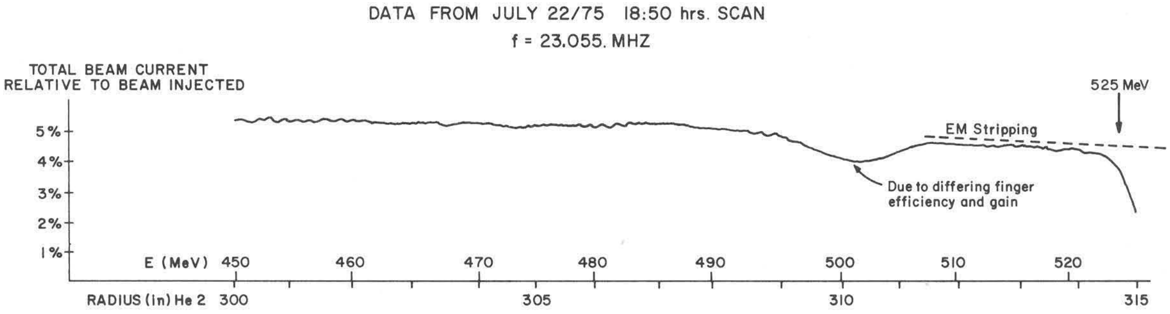

*Figure 9: Beam vs. radius at high energy. Predicted EM stripping normalized at 450 MeV.*

The ratio of extracted currents can also be adjusted by cocking the equilibrium orbit by asymmetrically exciting harmonic coils near the extraction radius as mentioned previously.

The average axial displacement $\overline{Z}$ of the equilibrium orbit from the median plane is dependent upon $\overline{B}_R$ as shown in equation [3] above. It is also of interest to compare the relative axial displacements of the centroid of the beam at different azimuths for the same radius. This has been done experimentally by comparing the beam centroids as measured on High Energy Probe 1 and on High Energy Probe 2 (see Figure 5). The difference is plotted in Figure 10 as a function of radius and is compared with the calculated prediction from the magnetic field measurements. The rapid oscillations in the radial region of 220 to 270 in. are discussed in reference 17 (this conference). The presence of these oscillations has a complicating effect on the extraction of simultaneous beams at differing but close energies, but they do not make it impossible.

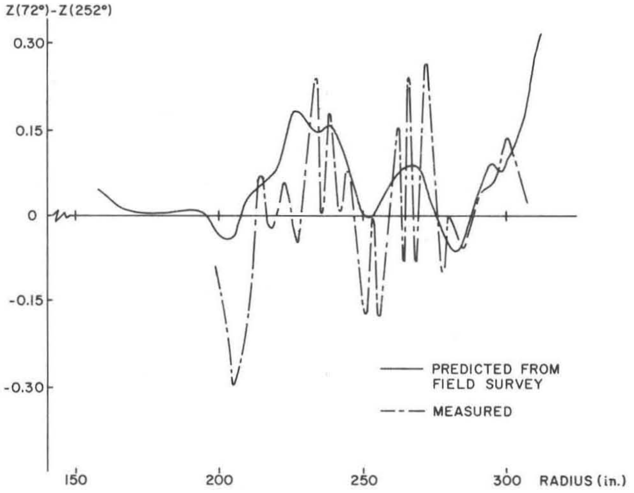

*Figure 10: The difference between the axial positions of the current centroids (in.) on the two high energy probes as a function of radius*

The present energy spread has been measured[21] in one of the experimental beam lines at 400 MeV as 1 MeV FWHM or 2.2 MeV over-all width. With the beam chopped to a phase spread of 15°, the corresponding numbers are 0.7 MeV and 1.2 MeV.

## 6. Experimental Program

Two results from the experimental groups can be shown to indicate the progress which is being made. Figure 11 shows a scatter diagram[22] of the coincidences in elastic scattering of protons by $^4$He at angles down to 3°. Note that the background has not yet been subtracted and so we see that the beam is quite clean to allow measurements at this small angle.

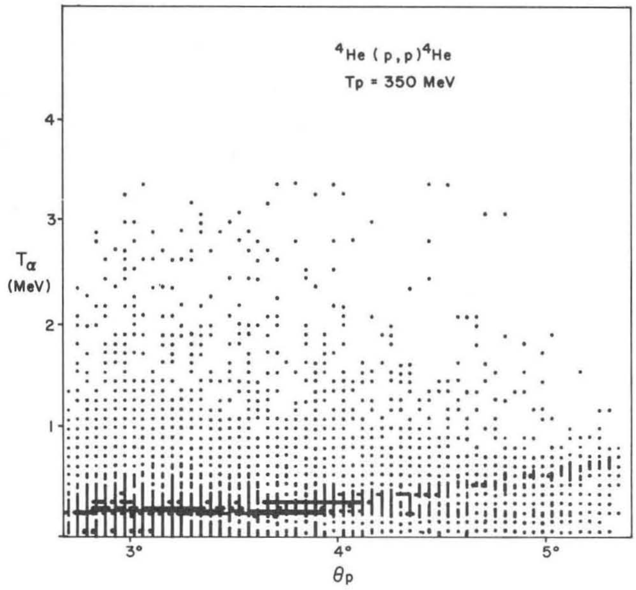

*Figure 11: Scatter diagram from $^4$He(p,p) elastic showing raw data down to 3°. Background not subtracted.*

Figure 12 shows results[23] from the reaction p+p and d+$\pi^+$ where the pions are analyzed in a magnetic spectrometer. Most of the background comes from the carbon in the CH$_2$ target. The energy of the pions can be used to infer the energy of the proton beam -- the result is 348.9±0.5 MeV which confirms the energy of 348.6±0.7 MeV from the BR of the extraction foil.

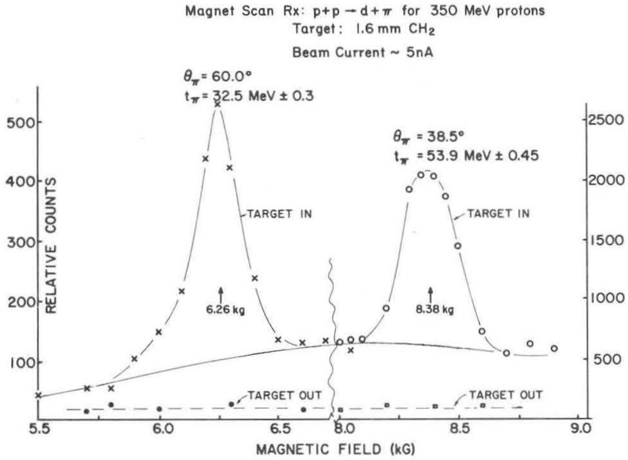

*Figure 12: Pions from H(p,π)d at 350 MeV. Energy agrees with BR to 0.2%.*

Results of preliminary tune-up of the M9 meson channel have indicated a useable flux of pions as low in energy as 20 MeV for $\pi^+$ and 15 MeV for $\pi^-$.

## 7. Conclusion

The first half year of operation at TRIUMF has indeed been very rewarding. The unique features of variable energy and simultaneous beam extraction have shown their worth in the experimental program and the ease with which these features can be employed has been pleasing to the operating staff.

The main objectives for the immediate future can be listed as follows:

(a) Reduce the emittance by a factor of 5 from the present value of 10 π mm mrad.

(b) Improve the vacuum by a factor of 5 from the present operating pressure of $2\times10^{-7}$ Torr effective.

(c) Accelerate $H^-$ ions from the Lamb shift type polarized ion source, which has already been commissioned at 300 nA, 80% polarization.

(d) Install the third harmonic RF amplifier and achieve separated turn acceleration with 100 keV energy spread at 500 MeV.

(e) Increase the beam intensity by slow stages to 100 μA.

## 8. Acknowledgement

It is obvious that this report summarizes the work of a large number of individuals. Those mentioned in the list of references have made particularly valuable contributions to the project.

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## DISCUSSION

Y. JONGEN: From actual data on beam losses, what induced activity do you expect for a 100 μA beam?

J.R. RICHARDSON: The residual activity in the machine itself will be in the order of 5 R/hour, or something in that order, after a day of cooling time. It will be a serious problem; we have a program on remote-handling and the objective is to be able to remove the resonators, if necessary, by remote-handling. We have a service bridge which goes in the vacuum chamber but is not equiped yet for remote-handling due to lack of money, but it will be.

R.E. POLLOCK: When you run simultaneous beams, one of which has a low intensity, do you have a number for the microscopic duty factor of the low intensity component?

J.R. RICHARDSON: It depends on the way in which we get the lower energy. If we have an extraction foil like an upside-down capital L, we can either bring it down so it intercepts the beam at the bottom; or if it is thin in the radial direction, we can take the beam over the whole area. The phase spread depends upon the method used. I cannot answer your question with precision, but in general our microscopic duty factor is about 12%. Now I would expect under some circumstances that it might be reduced to 8%, but I do not think less than that. We can on the other hand, with the chopper, have a microscopic duty factor which is much smaller than that: we can get 7° out of 360, which is 2%.