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IMPROVEMENTS TO THE BEAM PROPERTIES OF THE TRIUMF CYCLOTRON*

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Summary

The behaviour of the internal H^- and external proton beams has been considerably improved during the past year. Better steering near the centre has resulted in the internal vertical emittance being reduced to 1π mm-mrad, while the external beam emittances are now 3π mm-mrad vertically and 3π mm-mrad horizontally, for 90% of the beam. Digitization of probe data together with computer-aided trim coil tuning has enabled the beam to be centred vertically to within ±6 mm; this has been important in simplifying the simultaneous extraction of two beams at independently variable energies (183 to 520 MeV) and intensities (split-ratios from 1/1 to 1/5000). Beam losses in the cyclotron are <20%; direct evidence is presented for gas and electromagnetic stripping, and also for a loss of a few per cent by resonant processes. New techniques have been developed to measure the phase, and have enabled the phase excursions ($\Delta\sin\phi$) to be reduced from ±0.7 to <±0.2 below 400 MeV. At high energies the phase excursions reach ±0.4, as anticipated from the magnetic field survey. However, a method is proposed by which separated turns could still be achieved and the energy spread reduced to 0.1 MeV, just as in a perfectly isochronous field.

Introduction

Initial measurements of the properties of the H^- beam in the TRIUMF cyclotron were reported at the Washington[1] and Zürich[2,3] conferences in 1975. In line with the project's main thrusts since then—towards increased intensity and reliability[4]—development of the beam has centred on

(i) improving beam quality and steering, allowing acceleration of cw beams of up to 50 μA without excessive spill, and

(ii) better isochronism, giving a less critical and more easily recoverable tune, and improving the prospects for separated turn acceleration.

Outside the central orbits the total beam loss in the cyclotron is <20% at present—4→8% by gas stripping, 7% by electromagnetic stripping (from 450-500 MeV), and a few per cent through local beam dynamic problems. In practice the latter means excessive vertical motion, since ions running 90° out of phase get decelerated back to the centre. Several technical improvements have contributed to keeping the localized beam losses at a low level:

(i) Beam 'scrapers' and spill monitors have been installed. The scrapers consist of extended stripping foils mounted 1.4 in. above and below the median plane and so positioned in azimuth that all scraped protons are dumped at one point on the tank wall. This not only localizes the activation but enables the spill from all radii to be monitored simultaneously, and much more sensitively, than by observing the transmitted current.

(ii) The beam quality has been improved both by collimation near the ion source and by better steering in the central region. The internal vertical emittance at 500 MeV is 1π mm-mrad for 90% of the beam; the corresponding vertical width is everywhere <0.6 in.

(iii) Digitized data from the probes can now be transmitted directly to the Computing Centre, allowing any trim coil current adjustments needed to centre the beam vertically to be computed and implemented within minutes rather than hours (the vertical centring is often changed to adjust the relative intensities in the two beam lines, and small changes in centring also occur through hysteresis effects). The beam centroid is normally kept within ±0.25 in. of the desired plane between 70 and 500 MeV.

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Gas and Electromagnetic Stripping

The beam loss due to electrons being stripped from the H^- ions by collisions with residual gas molecules has been determined experimentally to be $8\%/10^{-7}$ Torr (indicated) for air and $4\%/10^{-7}$ Torr (indicated) for hydrogen, to 500 MeV. Over the last two years the residual pressure has dropped from 2×10^{-7} Torr to 6×10^{-8} Torr at best, of which hydrogen is the major component left, so that the present loss is estimated to be 4%.

Both gas and electromagnetic stripping leave characteristic signatures in the distribution of activity around the tank wall. Aluminum activation foils were hung around the interior of the vacuum tank during one shutdown and retrieved the next. The activity associated with ^{22}Na was measured and the activity density per unit angular interval is plotted in Fig. 1 along with the calculated distribution. Electromagnetic stripping occurs at large radii on the hills only, irradiating the neighbouring tank wall in six 40° wide bands. Gas-stripped atoms hit the tank wall at all azimuths, but the distribution is peaked because of orbit scalloping. Good qualitative agreement is found.

Localized Beam Spill

The secondary emission monitors recording the spill from scraper foils lose most of their signal when

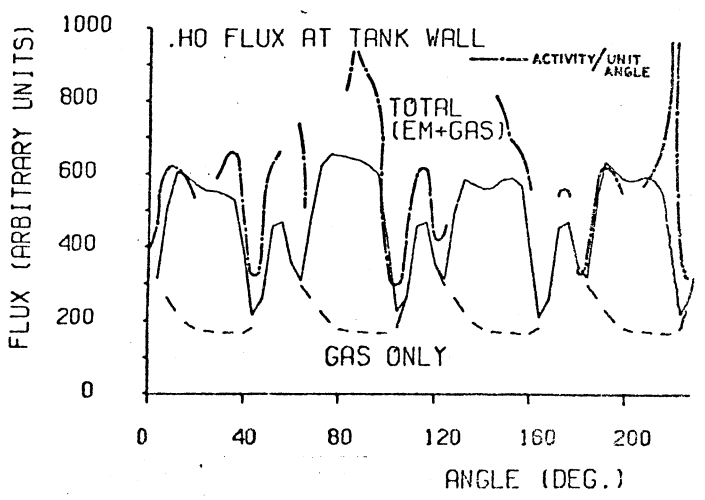


Fig. 1. Distribution of activity at the tank wall due to gas and electromagnetic stripping of H^- ions.

an energy-limiting probe is driven in past radii of 235 and 213 in. Investigation with a chopped beam, 10° FWHM, showed that these losses were associated with the extreme positive phases (a 10° interval out of a total phase acceptance of 40°). Shadow measurements made at 80 MeV for beams of different central phase confirmed that the extreme positive phases are less well centred, having a combined coherent and incoherent amplitude of 0.6 in. The loss radii coincide with the operating point crossing or coming close to $\nu_r-\nu_z=1$; also ν_z^2 is low. There is a smaller loss at 260-270 in. where we are again close to $\nu_r-\nu_z=1$ but ν_z^2 is high. It seems likely that the loss is caused by the resonance converting some large radial amplitudes into large vertical motions. The spill detected under normal operating conditions is 3% of the circulating beam; however, the scrapers are known to be only partially effective at some radii, so the total spill may be higher. The loss could be reduced by eliminating the positive phases with either the chopper/buncher or a radial flag, or by improving the centring for all phases.

Phase Measurements

Two methods have been used to measure the RF phase angle ϕ as the beam crosses the dee gap. The most precise method involves timing external beam bunches relative to the RF wave, using a scintillation counter telescope to detect protons scattered from the 4VM2 beam monitor. Although this involves changing the stripper position and beam line settings, a complete scan from 180 to 520 MeV in 10 MeV steps can be completed in about an hour. The timing is accurate to about 2° RF; however, until recently the technique has only been capable of giving relative results, and has relied on theoretical estimates of the flight-times for different energies. This drawback has now been removed in a novel way by timing protons arising from a decelerating component of the internal beam 'simultaneously' with those from the normal accelerating component. To do this, part of the beam is allowed to bypass the stripping foil and run +90° out of phase at full energy (~525 MeV); it then passes into the decelerating half of the RF cycle and returns to low energy with a mirror image phase history relative to +90°. This reflection symmetry is clearly exhibited in Fig. 2, where the phase histories for the two components have been determined independently by the relative method. Because of this symmetry the absolute phase ϕ_a of the accelerated component can be determined directly from the phase difference $\delta\phi$ between the two components by $\phi_a=90°-\delta\phi/2$. Absolute values of ϕ_a calculated in this way are also plotted in Fig. 2 (crosses); they are in good agreement with the relative values (squares) which have been uniformly phase shifted to better match them. The phase oscillations observed closely match those predicted from the magnetic field measurements.

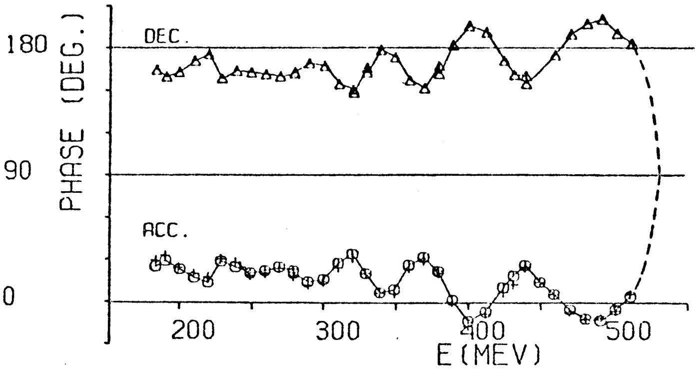


Fig. 2. Phase histories of accelerating and decelerating beams, obtained by timing an external beam.

The second method of phase measurement is less precise but can be used down to 20 MeV (80 in. radius compared to 220 in. for the method above). It is essentially a development of the traditional techniques based on observing beam loss as the RF or magnet is detuned. For instance, Garren and Smith[5] have used such a technique to determine a phase history consisting of one complete oscillation. For such a large machine as TRIUMF, however, many oscillations are expected (cf. Fig. 2) and hence a much greater radial sensitivity is required. This is provided by ganging together neighbouring circular trim coils to provide local phase bumps. Trim coil doublets are powered nearly equal and opposite, rather like quadrupole doublets; a similar analogy holds for triplets (with which bumps as narrow as 30 in. FWHM can be produced). The procedure is to measure the beam current at full energy as the trim coil currents are varied, the appropriate proportions being maintained by computer control. The phase bumps at various radii which induced a 50% loss in beam current are plotted as dashed lines in Fig. 3. Since the median phase history must touch each of these curves it is defined by the narrow passage between them (solid curve); the wider passage outside 200 in. is consistent with the phase oscillations determined by timing (crosses). The dotted curve shows the estimated result of computer-generated corrections to the 36 trim coil currents. Although tedious to perform and less precise than timing, this method has been effective in reducing errors in $\sin\phi$ from ±0.7 to ±0.1.

Separated Turns Without Isochronism

To achieve separated turns for a finite phase spread $\Delta\phi$, it has generally been assumed that extremely good isochronism is necessary. Thus to achieve an energy resolution $\Delta E/E \approx 10^{-4}$ for TRIUMF, even with the aid of RF third harmonic flat-topping, the phase errors tolerable were determined[6] to be only ±1.1°. In the limited time available for shimming the magnet it was not possible to meet these tolerances everywhere, and

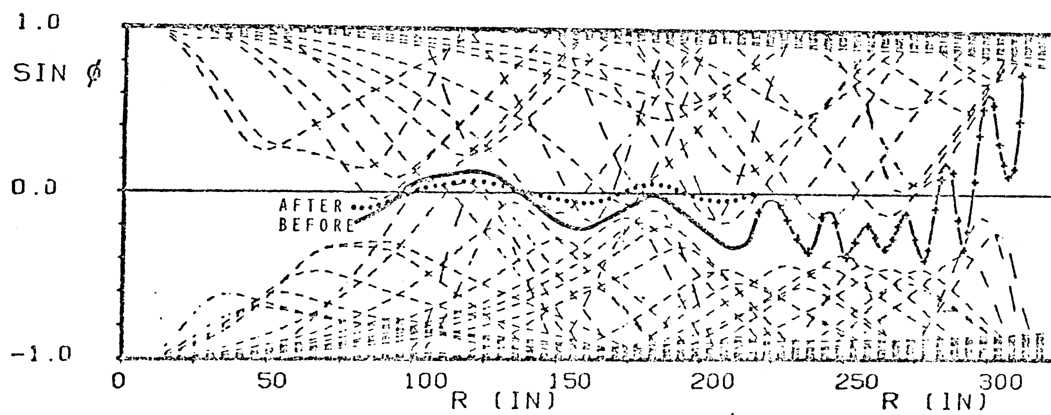


Fig. 3. Phase history determined by trim coil detuning.

phase oscillations of up to ±20° were left, as noted above. However, a technique has now been found which makes such a stringent isochronous requirement unnecessary. In the perfectly isochronous case, for a finite $\Delta\phi$, the optimum fraction of third harmonic $\varepsilon=\varepsilon^*$ is a little greater than the nominal 1/9, creating two humps in the voltage wave at $\phi=\phi_m$, and making $V(\pm\Delta\phi/2)=V(0)$; in this situation the energy resolution $\Delta E_o/E=1-V(0)/V(\pm\phi_m)\approx 3(\Delta\phi)^4/512$. The basis of the new technique is to arrange the phase oscillations symmetrically across the two humps in order to average out the voltage variation. The simplest example to consider is a phase ramp linear in energy from $-\phi_s$ to $+\phi_s$; in this case it can be shown that the energy spread can always be reduced to $\Delta E_o(\Delta\phi)$, independent of ϕ_s, for a suitable choice of ε, viz.

$$\frac{3}{4}\left(1-\frac{1}{9\varepsilon}\right) = \sin^2\phi_m = \sin^2\phi_s + \frac{1}{2}(\Delta\phi)^2.$$

The curves in Fig. 4 illustrate this relation between ϕ_s and ε for 10° steps in $\Delta\phi$. The points, for $\Delta\phi=15°$, indicate the results of a numerical determination of the optimum ϕ_s for a given ε, integrating ΔE turn by turn, and are in good agreement with the curves; the minimum values found for $\Delta E/E$ agree closely with $\Delta E_o/E=2.8\times10^{-5}$, independent of ϕ_s and ε.

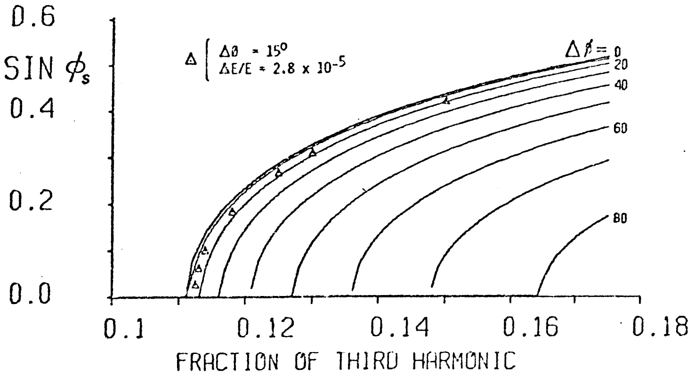


Fig. 4. Relation between phase ramp amplitude ϕ_s and fraction of third harmonic ε to obtain minimum $\Delta E=\Delta E_o$.

If the energy spread can be reduced to ΔE_o for a single ramp, then so it can for a succession of alternating ramps with a common amplitude. The technique also works for purely sinusoidal phase oscillations, bringing ΔE down to ΔE_o at each extreme of the phase. TRIUMF's phase oscillations of course vary in amplitude, so that the optimum value of ε will vary in radius; nevertheless it has been possible to find a value of ε (0.120) which, for $\Delta\phi=20°$, makes $\Delta E < 1.3\ \Delta E_o = 52$ keV between 450 and 500 MeV. Figure 5 illustrates these results. The effect of varying ε by 1% of its value is

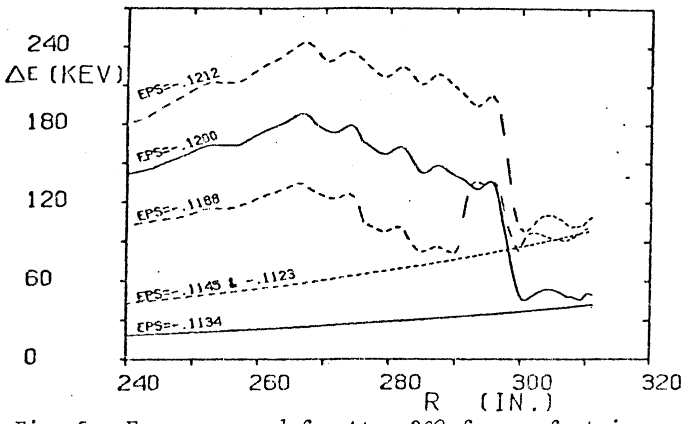


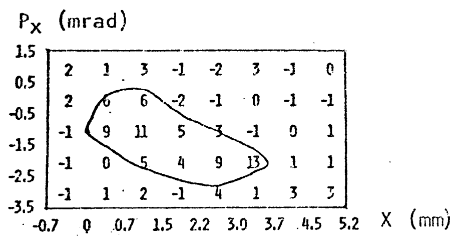
Fig. 5. Energy spread for $\Delta\phi = 20°$ for perfect isochronism (smooth curves) and for actual situation (irregular curves).

also shown; as expected theoretically the sensitivity to ε is independent of isochronism. It should be noted that the discussion above completely neglects the effects of instabilities on ΔE; for TRIUMF these are expected to add an additional 50 keV.

Emittance Density Distribution

It is difficult to measure beam emittance at 500 MeV with the resolution obtained at lower energies using slit systems. A method has been described[3] for measuring an emittance, assumed to be elliptical, using beam profiles measured at various quadrupole strengths. Gray[7] describes a relaxation method using profiles measured at three locations; however, our multi-wire ion chamber monitors do not have sufficient resolution for this, so we have extended our earlier method[3] to use the detail in the profile measurements to give a density distribution in phase space without any assumptions of elliptical shape. At a given quadrupole setting adjacent wires on a monitor define adjacent parallel bands in phase space; the fraction of beam in a particular band is proportional to the signal F_n on the corresponding wire n. Altering the quadrupole strength alters the slope of the bands and the wires sample different slices through the emittance. If the emittance plane is divided into a grid and the beam intensity in the ijth element is I_{ij}, then, summing over i,j, $F_n = \Sigma\, a_{ijn}\, I_{ij}$ where a_{ijn} is the area of the ijth element intercepted by band n. Enough measurements are made that the problem is overdetermined and the I_{ij} are estimated by a least squares method; measurements made in turn with different quadrupoles and using several monitors can be combined to improve the resolution. In practice it is often necessary to alter the quadrupole settings upstream to pre-calculated values to permit a wide range of slopes to be obtained. The measurement is made where the beam line is achromatic. A result is given in Fig. 6; the 'noise' is a few per cent of the total beam. The fitting program has an option to discriminate against negative intensities.

Fig. 6. Intensity distribution of horizontal emittance (B-foil).



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