PROPERTIES OF THE TRIUMF CYCLOTRON BEAM

M.K. Craddock

Physics Department, University of British Columbia, Vancouver, Canada

E.W. Blackmore, G. Dutto, C.J. Kost, G.H. Mackenzie, J.R. Richardson,* L.W. Root and P. Schmor

TRIUMF, Vancouver, Canada

Abstract

8% of the 300 keV d.c. beam from the ion source can be transmitted to 500 MeV in the TRIUMF cyclotron, without using the buncher. The beam losses are entirely accounted for by the 40° phase acceptance at injection, 20% gas stripping and 6% Lorentz stripping; there are no significant losses due to orbit dynamic problems during 1500 turns of acceleration. The phase history, like ν_z^2, is in good agreement with predictions based on the magnetic field survey. The effect of the harmonic coils and injection parameters on beam quality has been investigated; they can be used, with a chopper, to reduce the energy resolution of the extracted beam to 0.9 MeV FWHM and the emittance for 90% of the beam to 4π mm.mrad horizontally and 11π mm.mrad vertically.

1. Introduction

In an earlier paper[1] we have described the initial operation of the TRIUMF cyclotron and the simultaneous extraction of two beams with energies variable from 183 to 525 MeV. At that time tuning operations had been aimed only at optimizing the beam transmission to full energy, without regard to the finer points of beam quality. The transmission through the central region was found to be about 10% of the d.c. beam supplied by the external ion source and injection system (ISIS).[2] This is consistent with values of about 40° for the phase acceptance, measured by varying the phase of a chopped beam from ISIS or by observing the shape of the magnet cyclotron resonance; the phase width of the extracted beam was also found to be about 40°. The transmission from 50 to 500 MeV was observed to be about 70%—the loss being only a little larger than that predicted theoretically for stripping H^- ions by the residual gas molecules at the observed pressure of 2.8×10^{-7} Torr. More recently the stripping losses caused by residual air and hydrogen have been measured directly, as described in the status report on TRIUMF appearing elsewhere in these proceedings.[3] The results indicate that at the present operating pressure of 3×10^{-7} Torr (indicated) the gas stripping loss should be 20%. Since an overall transmission to 500 MeV of 8% of the d.c. beam has been achieved (without bunching), it appears that there are no orbit dynamic problems giving rise to significant losses in intensity at intermediate energies. There is circumstancial evidence[3] of Lorentz stripping of the H^- ions at energies above 500 MeV, but up to that energy, where the integrated loss is expected theoretically to be 6%, the experimental evidence is inconclusive.

Although the cyclotron had not been tuned for beam quality initially, we were able to report in our earlier paper that the energy resolution of the extracted beam was no worse than 3 MeV. In the intervening months we have been able to measure the beam properties in more detail and begin tuning for better beam quality; this paper will describe this work. The energy resolution and emittance of the extracted beam have been improved. Some initial measurements of the phase history have been made, and, like the measurements of ν_z^2 reported earlier,[1] are in good agreement with the results of the magnetic field survey. Evidence for radial-vertical coupling in the outer region of the cyclotron is examined.

*on leave from UCLA

2. Diagnostics

The location of the diagnostic and extraction probes in the cyclotron is shown in Fig. 5 of the status report.[3] The low energy probes cover the radial range from the first turn to 145 in. (70 MeV) and the high energy probes extend from 142 in. to 315 in. (525 MeV). A schematic diagram of the probe heads is shown in Fig. 1. The low energy head consists of three horizontal fingers which provide vertical and radial information, together with a

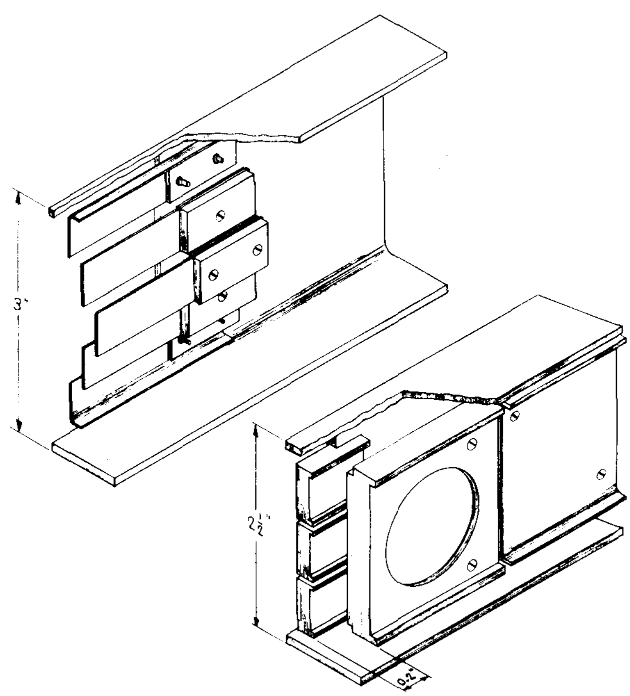

Fig. 1. (above) High energy probe head (below) Low energy probe head

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 240-244

scintillator and total current head. The high energy head has five thin foils which strip the H^- ion and collect the two stripped electrons. This type of probe is useful because the vertical centring of the beam in the outer region is very sensitive to the asymmetric part of the magnetic field.

As the low energy probes operate in the region between the upper and lower resonator arrays their use has been restricted because of RF pick-up problems. The d.c. current signals from the probes are amplified and displayed as histograms on a storage scope, as analog signals on electrometers or on a six-channel chart recorder driven synchronously with the probe. Capacitive pick-up probes are planned but at the present operating currents it is more convenient to measure the time structure of the beam protons scattering from a target in an external beam line. The ease of extraction from 185-530 MeV allows this measurement to be made quickly; the elastically scattered protons are detected with an NE102 scintillator and RCA8575 phototube and processed through a standard time-of-flight system which is stopped by an RF timing signal. This technique is accurate to about 0.25 nsec (2° phase) including the flight time corrections from the stripping foil to the proton monitor.

In the central region there is a vertical flag for restricting the beam height at 4 MeV and movable radial slits for phase selection around 4 MeV and for defining the emittance in the range 15 to 30 MeV.

3. Central Region

Recently the second low energy probe was brought into operation (180° apart from the first) and we were able to make observations on the first few turns using both probes. The indications were that the centres were initially displaced 0.4 in. southwards along the probe axis, 68° from the dee gap. It also appeared that the average radius at the fifth turn, calculated by taking the mean of the two probe readings, was higher than that to be expected for centred conditions, suggesting that the injection energy was too high. The HT supply has indeed indicated an injection energy about 20 keV higher than that expected from central region orbit studies. Recent trials with an injection energy 10 keV lower have led to some improvement in the energy resolution and emittance of the extracted beam; the effect on the centring of the initial orbits has not yet been measured directly, and there are indications that the tuning is less critical than previously in the sensitive region between 200 and 230 in. radius.

4. Phase History

The phase history has been measured over the range of extraction energies by timing the arrival of protons scattered from a monitor in the external beam, relative to an RF signal (see Sec. 2 above). Correction must be made for differences in flight path at different energies, but these do not exceed 1 RF period (43 nsec). With a chopped beam the timing peak had a 2.5 nsec FWHM, making possible a time resolution of 0.25 nsec or 2° in phase. The ease of varying the extraction energy enables the phase history to be measured relatively quickly—a measurement every 10 MeV from 200 to 520 MeV can be made in just over an hour, i.e. 2 min per energy value. The results of such a measurement are shown in Fig. 2; in this example the cyclotron had been tuned for maximum energy (530 MeV), causing a ∿30° shift to leading phases between 300 and 500 MeV (ϕ=0° is chosen arbitrarily). For comparison the dashed curve shows the optimum phase history predicted from the magnetic field survey for a maximum energy of 500 MeV. The two plots are not exactly comparable, since they refer to slightly different trim coil settings; however, there appears to be fairly good agreement between the predicted and observed oscillations, which grow from ±5° at 200 MeV to ±20° at 450 MeV.

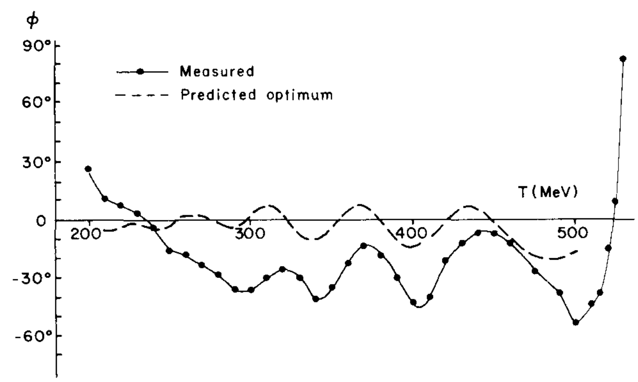

Fig. 2. Phase history measured with the cyclotron tuned for maximum energy, compared with the optimum predicted from the magnetic field survey.

5. Time-of-Flight Measurements

The flight time of the ions between the ion source and an external target has been measured for a 480 MeV extracted beam. 10 μsec long beam pulses 1 msec apart were produced using a square wave pulse generator.[2] The signal produced by protons scattered from the target hitting a scintillator were compared on an oscilloscope with the trailing edge of the square wave, delayed by a known amount. Initially the total flight time was 327 μsec. After tuning the magnet and a few trimming coils this was reduced to 315 μsec, or 310 μsec after subtracting the 5 μsec spent along the 35 m injection line. This indicates that 1430 turns were taken in reaching 480 MeV, and that the average value $\overline{V_{RF}\cos\phi}$ = 84 kV. If the dee voltage V_{RF} is assumed to be 90 kV, as indicated by the most recent central region orbit measurements, and uniform with radius (see below), then $\overline{\cos\phi}$ = cos21°.

In a separate experiment the time of flight between the ion source and one of the high energy probes[4] was measured between 150 and 500 MeV. The time was found to increase linearly with energy, within 2 or 3 μsec, indicating that the dee voltage does not vary significantly along the dee gap. However, small oscillations were observed around the straight line and these showed promising correlations

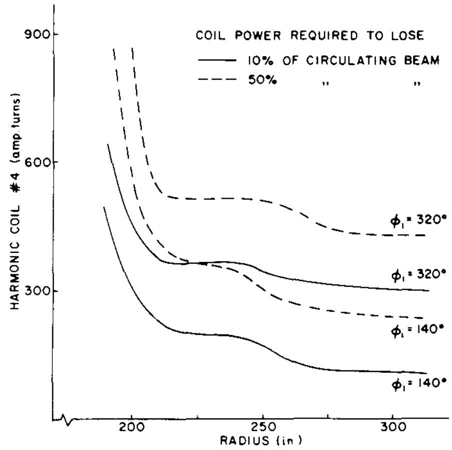

Fig. 3.

Sensitivity of the transmitted beam current to a centring error introduced by a set of first harmonic trim coils at 80 in. (20 MeV).

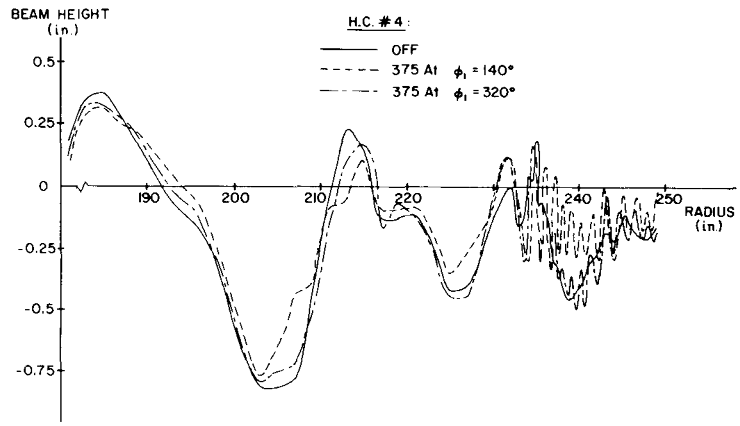

Fig. 4. Effect of a radial centring error on the height of the beam.

with the oscillations in phase illustrated in Fig. 2. We hope to be able to improve the resolution and accuracy of measurement (at present 1-2 μsec) by an order of magnitude in order to explore the possibilities of using the method for tuning purposes.

6. Radial Betatron Amplitudes

Harmonic coil set #4 alters the first harmonic component of the axial field between 15 and 23 MeV. Calculations show that 900 At introduce a change in radial amplitude of about 1 in. and in RF phase of about 10°, depending on the detailed history of a particle, and that this change persists to high energies. When the coil amplitude was increased above a threshold the current transmitted to full energy decreased, the decrease varying sinusoidally with the phase of the first harmonic perturbation. Fig. 3 shows how the coil amplitude required to lose 10% and 50% of the beam varies with radius for the most sensitive and least sensitive phase. Centring-dependent loss can occur at 200 and 250 in. radius; however, since a threshold of at least 50 At exists these loss modes do not reduce transmission for normal operation. Fig. 4 shows the height of the beam centre as a function of radius for these conditions; there is evidence of coupling between radial and vertical motion. This coupling may cause loss at 205 in. where the beam is low; however, the beam is vertically centred at 250 in. and there the loss may be phase related.

The oscillations in height at 235 in. are thought to be related to passage through $\nu_r - \nu_z = 1$; this resonance also occurs at 210, 262 and 275 in. where similar oscillations have been seen. Interpretation is complicated by the fact that at large radial amplitudes the radius change/turn due to precession is greater than that due to energy gain. We are preparing experiments to measure more accurately the vertical width of the beam and to excite the resonance by asymmetrically powered harmonic coils.

7. Extracted Beam Quality

Energy Spread

One of the beam lines has been designed to produce a double focus for both an achromatic or momentum dispersed mode of operation. At this focus is installed a gas-filled multi-wire chamber with 2 mm wire spacing in the horizontal (dispersion) plane. The beam optics calculations have been checked in the following manner.

At our extraction energies a change in the first harmonic component of the axial magnetic field moves the position of the equilibrium orbits in the vicinity horizontally, the beam following adiabatically. By powering a set of harmonic coils and choosing the appropriate phase for the first harmonic field produced, it is possible to displace the beam along the stripping foil radius or perpendicular to it, thus altering the energy or angle at which the extracted beam leaves the foil. If the foil is then moved radially the energy is again changed together with beam line object position. By measuring the position of the beam in the beam line during this sequence of operations, it is possible to obtain three elements of the horizontal transfer matrix. The predicted shift in equilibrium orbit was first checked by measuring the position of the shadow cast on one high energy probe by the other as a function of shadowing probe radius and first harmonic amplitude and phase. The technique was then used at 400 MeV for the dispersed mode of operation; the magnification R_{11} was found to be 0.86 ± 0.16, R_{12} was +0.3 ± 0.2 cm/mrad and the momentum dispersion -11.0 ± 1.5 cm/per cent. Calculated values were 0.75, 0.0 cm/mrad and -12.6 cm/per cent.[5]

Fig. 5 shows horizontal profiles measured at three different harmonic coil settings. The FWHM of the standard beam is 0.9 MeV and the width at

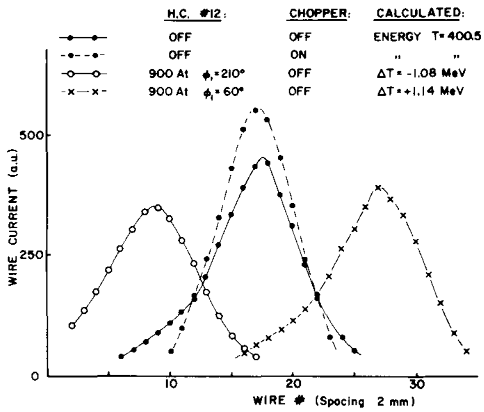

Fig. 5.

Profiles at a momentum dispersed focus measured for three different energies obtained by displacing the equilibrium orbits with respect to the stripping foil using first harmonic coil #12 (284 in.)

10% of the peak height is about 2 ± 0.2 MeV after making an approximate correction for the finite image size. The dashed profile was obtained with the accelerated phase width reduced from 40° to 15° by means of the chopper (Fig. 6 of the status report[3]); this reduced the width at 10% of peak to 1.5 ± 0.2 MeV. The two profiles with harmonic coils off have been normalized to the same beam current.

The absolute energy of an extracted beam was determined to be 348.3 ± 1.7 MeV by momentum analysis of the pions from the (pp→dπ) reaction. The energy expected from the stripping foil location was 348.6 ± 0.8 MeV.

Emittance

The emittance of the extracted beam has been estimated by two methods. In the first method profiles in the horizontal and vertical planes are measured at three locations in the beam line separated by drift spaces. The emittance in each plane is taken to be the ellipse just enclosed in the largest area in phase space that can pass through all these profiles. In the second method profiles are measured at a location 7.8 m downstream from a quadrupole for n different quadrupole strengths. Assuming an elliptical emittance at the entrance to the quadrupole, we can write

$$ay^2 + 2b\,yy' + cy'^2 = \varepsilon^2 \qquad (1)$$

with the normalization ac - b = ε^2 and where y is the displacement in either plane. The n measured envelopes at the wire chamber will be given by

$$\left(y^n_{max}\right)^2 = \left(R^n_{11}\right)^2 c - 2R^n_{11}\,R^n_{12}\,b + \left(R^n_{12}\right)^2 a \qquad (2)$$

where R^n_{ij} are the elements of the transfer matrix from the quadrupole entrance to the chamber. About ten measurements of width y^n_{max} are made and the resulting system of over-determined linear equations solved numerically for a, b and c; these then yield the emittance ε.

Both methods give similar results with an uncertainty of about 20%. The following table gives values obtained before and after the recent change in ISIS energy for emittances enclosing 50% and 90% of the external beam. These values have been normalized by multiplying by (βγ).

	Emittance (π mm.mrad)			
	Horizontal		Vertical	
Original ISIS energy	90%	50%	90%	50%
450 MeV standard beam	20	2.9	17	3.3
450 MeV chopped (15°)	12	2.1	16	3.2
ISIS energy reduced by 10 keV				
500 MeV standard beam	8	1.4	22	4.4
400 MeV chopped (15°)	4	0.7	11	2.8

The vertical width of the beam was measured to be about 0.6 in. at 450 MeV. This would correspond to a vertical emittance at the foil of 11π mm.mrad. The present aluminum stripping foil is 0.001 in. thick and multiple scattering is estimated to increase the emittance for 90% of the beam to 14π mm.mrad, which agrees with that measured externally.

Acknowledgements

The authors wish to acknowledge the efforts of many members of the TRIUMF staff in ensuring the smooth operation of the cyclotron. Mr. P. Bennett, Mr. R. Callon, Jr. and Mr. W. Holmes have provided invaluable assistance with computations and programming. We are also much indebted to Dr. D. Axen and Dr. G. Wait, who kindly made available and set up the equipment for time-of-flight measurements.

References

1. J.R. Richardson, E.W. Blackmore, G. Dutto, C.J. Kost, G.H. Mackenzie, M.K. Craddock, IEEE Trans. NS-22(3), 1402 (1975)
2. J. Beveridge, E.W. Blackmore, P.F. Bosman, G. Dutto, W. Joho, R.D. Riches, V. Rödel, L.W. Root, B.L. White, *ibid.*, 1707
3. J.R. Richardson, 'Status Report on TRIUMF' (these proceedings)
4. J.W. Verba, W. Kundig, A.C. Paul, J.R. Richardson, B.T. Wright, CERN 63-19 (1963)
5. G.M. Stinson, private communication
6. G. Jones, private communication

DISCUSSION

M.P. REISER: What are the major factors other than radioactivity that limit the achievable intensity? What is the intensity achieved so far and how much do you expect to get in the future?

M.K. CRADDOCK: The only significant factor limiting the intensity and not radiation-linked is the tuning of the injection line. This line is 35 m long and contains about 100 electrostatic focusing and steering elements. So far, 90% transmission has been achieved through to the cyclotron and this is quite adequate at the present current levels (∿ 1 μA). However, to accelerate 500 μA d.c. without damaging any elements in the injection line will require careful tuning to reduce the losses to < 1% in any one place and the installation of loss detectors and protective interlocks.

In the full scale model, central region cyclotron (CRC) we have already accelerated a 100 μA H^- beam through a similar injection system and over six cyclotron orbits to an energy of 2.7 MeV in order to demonstrate that a beam of the design intensity can be taken at least through the central region. In the TRIUMF cyclotron the highest current so far accelerated to 500 MeV has been 50 μA during 100 μsec pulses ever 10 msec. On that occasion it was not possible to raise the intensity to the design aim of 100 μA because of adjustments that had been made to the ion source at our regular operating currents to prolong the filament lifetime.

W. FISCHER: At what intensity has your emittance been measured?

M.K. CRADDOCK: The emittance measurements were made with an external beam intensity of about 10 nA.

W. FISCHER: Did you see an appreciable increase of emittance with increasing intensity?

M.K. CRADDOCK: At higher intensities, the emittance has not been measured except at the ion source, but no increase in spot size has been observed, either with 100 μA in the CRC or with 50 μA at 500 MeV in TRIUMF. Nor are space charge effects in the central region expected to enlarge the emittance unless the the intensity exceeds 500 μA.