DEVELOPMENTS TOWARD SEPARATED TURNS AT TRIUMF

E.W. Blackmore, D.A. Dohan, G.H. Mackenzie and R. Poirier.

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3.

Abstract.- By using a system of internal phase-defining slits, beams with energy resolution $\Delta E/E \approx 1:1000$ have been attained at TRIUMF. The eventual aim of an energy spread of <100 keV implies separated turn extraction over the entire energy range of 200-520 MeV. To achieve this, work has proceeded toward the following three requirements: i) beam phase stability of ±2°, ii) rf voltage stability of $\Delta V/V = 5\times 10^{-5}$ and iii) flat-topping of the rf fundamental with the addition of a third harmonic. Phase stability of ±1.5° has been demonstrated for several hours, using 3 software feedback loops: i) slow magnet drifts measured with an NMR probe to control the magnet power supply; ii) fast fluctuations in the field detected with an outer trim coil provide a correction to the rf frequency; and iii) phase fluctuations measured with the beam itself provide a final rf frequency correction. These loops have been implemented with dedicated CAMAC-based microprocessors.

1. Introduction.- TRIUMF is a fixed field, fixed frequency H^- cyclotron. The major beam lines accept energies between 180 and 520 MeV obtained by altering the radius of the stripping foil. The effective energy gain per turn is in the vicinity of 0.27 MeV/turn and the turn separation varies from 3.5 to 1 mm. Stripping extraction permits more relaxed tolerances on internal beam quality than does an electrostatic or magnetic channel. TRIUMF operates comfortably with a phase acceptance over 45° and a radial betatron amplitude several times larger than the radius gain per turn. Fluctuations in the number of turns made to extraction also do not hamper most modes of operation.

Certain experiments, e.g. nuclear spectroscopy, those involving particle identification by time of flight, beam dynamics and diagnostics, benefit from improved beam quality. As tolerances are made more stringent, improvements can be made on the time width of the beam, energy spread and emittance, the greatest improvements being gained with completely separated turns at extraction. This situation is being gradually achieved at TRIUMF by imposing limits on the phase width of the beam, radial amplitudes, and variations in magnetic field, radio frequency and voltage.

2. Requirements.- Consider a wire stripping foil of negligible width in a "central ray" beam with zero betatron amplitude but with sufficient phase width to provide a homogeneous distribution of beam with radius. The energy and radius of the beam is closely correlated and such a foil will extract a monoenergetic beam. We assume that the stripper mechanism maintains the foil at a given radius, and that there is little coupling between radial and vertical motion, both fairly true in practice.

Small fluctuations in field or frequency will cause the phase to slip but will not affect the extracted energy since the correlation between energy and radius is not destroyed; we can assume for purposes of argument that this type of phase slip does not couple into radial motion. Fluctuations in dee voltage will also not affect the extracted energy. Changes in field large enough to cause a significant change in orbit diameter, and thus the energy at a given radius, would have led to complete loss of beam at an earlier radius.

A foil of finite width W will sample a range of energies. A wire in a "real beam" with incoherent betatron amplitudes ranging up to A_i will also sample a range of energies given by $\pm A_i(dE/dR)$. Both are necessary to provide a reasonable amount of extracted beam and they lead to a trapezoidal distribution in energy spread. The medium energy resolution operation [1] involves restricting A_i and W and reducing coherent oscillations to provide a good correlation between radius and energy. Intensities of 5 to 10% of that obtainable with normal operation can be obtained with $\Delta E/E$ of 10^{-3}. No restrictions are imposed on field, voltage or frequency stability.

Refining this mode to give, for example, ±0.05 MeV at 500 MeV will prove extremely difficult. (dE/dR) is 2.6 MeV/cm, and such a resolution calls for a foil 0.038 cm wide and a betatron amplitude of 0.019 cm. It is possible to make such a foil; emittance selection may yield such a value of A_i and the coherent oscillation amplitude A_c has been kept smaller than the turn separation due to energy gain; however, the intensity transmitted would be reduced by a further factor of ten or more. Table 1 shows the upper limit on foil width and betatron amplitude to yield $\Delta E/E < 10^{-3}$ and for ΔE of ±0.05 MeV FWHM. The former resolution has been achieved over the entire energy range, the latter at 200 MeV [2].

Table 1. Medium resolution operation.

Energy (MeV)	Radius (m)	ΔR/MeV (mm)	Max foil half-width or max betatron amplitude $\Delta E/E < 10^{-3}$ (mm)	±0.05 MeV (mm)
200	5.84	10.9	1.1	0.55
300	6.73	7.4	1.1	0.37
400	7.37	5.4	1.1	0.27
500	7.82	4.3	1.1	0.21

An alternative approach is to limit the energy spread in a turn by restricting the phase width accelerated and extracting all the beam in the turn. If we assume an isochronous machine and that we accelerate on the peak of the rf wave, the phase width of our "central ray" beam to give an energy spread ΔE is $\pm\Delta\phi = (2\Delta E/E)^{\frac{1}{2}}$.

However, the actual phase width accelerated should be less than this since, as we extract all the beam, a change in dee voltage or slipping in phase will alter the energy gain per turn and hence the extracted energy. We are interested in energy spreads less than the energy gain per turn, and the radial amplitude A_i must be restricted to prevent the overlapping of turns. At lower energies, we have introduced a small coherent amplitude to augment the turn separation at extraction; this is less effective at $\nu_R = 1.5$. We are interested in the FWHM, and it is reasonable to include the effects of the field ($\Delta B/B$), frequency ($\Delta\omega/\omega$) and voltage ($\Delta V/V$) fluctuation in quadrature. Table 2 shows the requirements for 0.1 MeV FWHM; the requirements for separated turns only are somewhat less stringent.

Table 2. Separated turns to yield 0.1 MeV FWHM.

Energy (MeV)	ΔR/turn (cm)	$\Delta\phi$ (deg)	$\Delta V/V$ $\times 10^{-4}$	$\Delta B/B$ $\times 10^{-6}$	$\Delta\omega/\omega$ $\times 10^{-6}$	A_i (cm)
200	0.30	±1.2	±1.2	±0.6	±0.5	±0.05
300	0.21	1.0	0.8	0.3	0.25	0.03
400	0.15	0.9	0.6	0.22	0.16	0.02
500	0.12	0.8	0.5	0.18	0.12	0.02

The intensity is again much reduced; however, the tolerances obtained using the feedback techniques to be described below should enable separated turns to be achieved at 300 MeV. They have already been observed at 200 MeV [3]. Craddock and Richardson [4] show that the field and frequency tolerance may be relaxed by a factor ~7 and the phase acceptance increased 12-fold if the rf wave form were to be flat-topped by the addition of a third harmonic component.

3. Phase stability.- An overall stability of ±1.5° in the phase of the full energy, non-slit selected beam has been demonstrated for several hours. This has been achieved by means of software feedback loops implemented with the TRIUMF control system. Initial tests were conducted on one of the central control system computers [1], with the interaction between the console, the main magnet and the rf system carried out by means of simple FORTRAN calls. After this test phase, the feedback software was transferred to dedicated microprocessors. These auxiliary crate controllers, TRIMACs, were developed at TRIUMF as described in ref. [5]. Since a TRIMAC can only access modules within its local crate, separate TRIMACs were used in the magnet crate and in the rf crate, as shown in figure 1. Control information is passed between the console and the local TRIMAC by means of a shared CAMAC memory or register in the local crate.

The effect of the feedback loops on the beam phase was measured with a non-intercepting capacitive phase probe located in one of the external beam lines, using a detection system similar to that described by Vader and Schreuder [6]. Independent software loops to control the main magnet current and the rf frequency are described below.

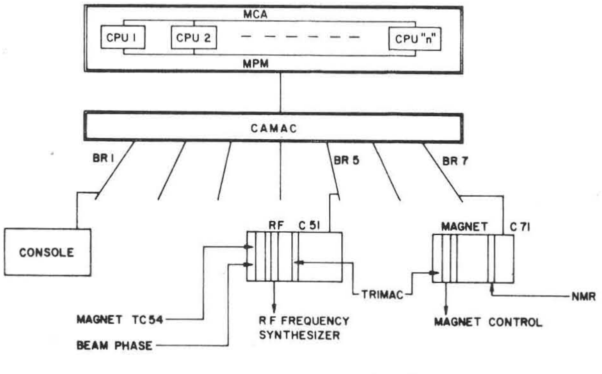

Fig. 1 : TRIUMF control system, showing local TRIMACs.

3.1. Magnetic field stability.- Fluctuations in the cyclotron main magnet field were measured in two ways. The first used an NMR probe located near the centre of the hill of magnet sector #2. The NMR magnetometer, which was developed at CERN [7], had a sensitivity of ±0.01 G, or ±2 ppm of the hill field of 5.6 kG. Although this is not sensitive enough for separated turn requirements, it does provide a measure of the absolute magnetic field and is useful in determining slow drifts. These drifts were measured to be ±10 ppm for periods >10 min and were shown to be correlated with the phase of the extracted beam.

The output of the magnetometer is read by the local TRIMAC, averaged for a period of 1.5 sec, and compared with a set-point value determined by the operator. A feedback correction is then calculated and sent to the main magnet power supply control (figure 1). The results of the feedback are shown in figure 2, in which the overall excursions in the magnetic field are shown to be reduced by a factor of ≈3.

3.2. Rf frequency modulation.- A second method of measuring magnetic field fluctuations utilizes the emf induced in a coil surrounding the field region. Voltages induced in outer trim coil #54 (TC54) were sampled, digitized and integrated in software to give a fast measure of these field drifts. To prevent the accumulation of error in this integral due to ADC offsets and digital truncation, a circular buffer of the most recent 8196 TC54 readings was maintained in the TRIMAC memory. The average of this buffer was subtracted from each successive ADC conversion before adding it to the integral, thereby keeping the integral bounded but insensitive to drifts slower than 13.5 min (8196 readings at 10 Hz). The NMR loop described above is designed to take care of these drifts.

A phase slip caused by a drift in the main magnet can be compensated for by applying an equivalent change in the accelerating frequency. This change in frequency is determined by the difference in the above integral and a desired set point. When this correction was applied, the stability of the external beam phase improved considerably. However, a small drift (<0.1 Hz), apparently not correlated with the magnetic field, was still evident. To correct this, a parallel loop in the C51 TRIMAC was implemented, basing the feedback correction on the beam phase itself. Since these drifts are relatively slow, it is possible to use particle counter derived phase signals by averaging

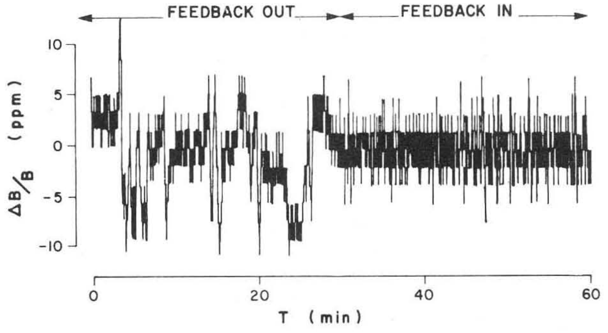

Fig. 2 : Effect of NMR feedback loop on main magnet field.

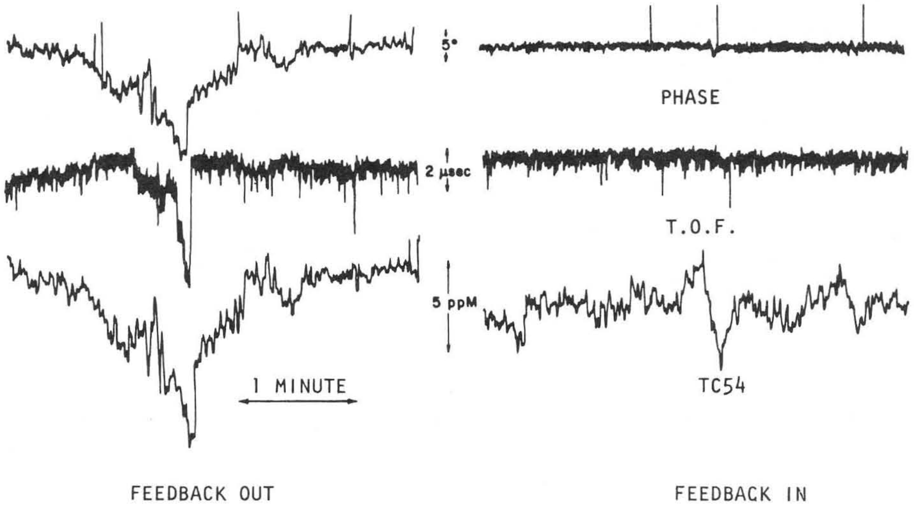

Fig. 3 : Effect of rf feedback loops on extracted beam phase.

out the usually poor statistics. Results of the combined feedback loops are shown in figure 3, in which an overall phase stability of ±1.5° was achieved.

The phototubes and electronics used in many time-of-flight experiments can have a resolution approaching 0.5 nsec, equivalent to a phase spread of 4°. The slits are capable of selecting a phase width narrower than this; however, fluctuations in frequency or field will broaden the average time spread at extraction. At 200 MeV we have measured a FWHM of 0.5 nsec including instrumental resolution. At 500 MeV this is broadened to at least 1 nsec without feedback. Inclusion of feedback loops which stabilise the centroid of the time distribution to ±1.5° should also enable a FWHM of 0.5 nsec at full energy.

Conclusion.- We have shown that a beam of the appropriate radial amplitude and phase width can be selected by internal slits and that the field and frequency are sufficiently stable without feedback to give separated turns, less than 0.5 nsec FWHM and 0.1 MeV FWHM at 200 MeV. With the feedback loops active, the effective phase stability is such that the time spread up to 500 MeV should be ≤ 0.5 nsec, and separated turns should be seen at 300 MeV. The very tight tolerances of table 2 mean that it will be difficult to achieve 0.1 MeV FWHM at all energies in the absence of a third harmonic component of the rf. This option is being actively pursued. To take full advantage of the feedback loops at low currents, for example with polarized beam, work is proceeding towards improving counter-derived phase signals.

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