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IMPROVED BEAM QUALITY AT TRIUMF

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Abstract

Improved stability, together with the use of beam-defining apertures, have enabled us to obtain separated turns at 200 MeV. This implies an extracted energy spread of 0.25 MeV FWHM and a time width of 0.3 ns FWHM; 0.6 MeV and 0.6 ns, which includes instrumental resolution, have been measured. Mechanical stiffening of the RF resonators has recently reduced the dee voltage fluctuations to ±0.015% while the magnetic field fluctuations are $\pm 2 \times 10^{-6}$. The machine set-up procedure for separated turns will be described. The compensation of the residual magnetic first harmonic has also been improved and should eventually permit lower loss in high-current operation.

Introduction

The uniqueness of TRIUMF as a machine producing simultaneous proton beams with energy easily variable between 180 and 520 MeV[1] has promoted an increased effort towards improved stability, energy resolution and time resolution of the extracted beam. In the proton area a QD-type medium resolution spectrometer with B_ρ of 48.8 kGm and anticipated resolution of 0.1% in $\Delta E/E$ is being commissioned. 0.5 ns is the resolution of the detectors available for time-of-flight experiments. In the meson hall a low-intensity, <10 nA, beam line for more efficient sharing of low-intensity beams has been recently installed.

In normal conditions the beam has an energy spread of about 0.4% in $\Delta E/E$. The 4.5 ns, almost rectangular, pulse length is reduced to ~2 ns FWHM when a sinusoidal buncher is used to increase the current. Techniques that improve quality by restricting phase space and sacrificing beam current are acceptable since most high-quality beam users operate with typical currents of 0.5 to 500 nA. With these techniques separated turns with an intrinsic energy resolution of 0.25 MeV FWHM and time resolution of 0.5 ns have already been achieved for 200 MeV. For 100 keV at 500 MeV, which is the goal of the high-resolution work at TRIUMF, the stability of the magnet has to be improved by only about a factor of three, and the stability of the RF phase and voltage are close to being acceptable. The addition of a third harmonic component to the RF voltage will be necessary if the phase interval accepted is 0.5 ns. Also, the third harmonic will permit the effects of a non-isochronous field to be compensated at various given energies.[2] Work on the production and tuning of the third harmonic is in progress.

For the normal beam with a wide phase interval, on the other hand, an improvement in centring conditions for the various phases should improve the beam quality.[3] The centring improvements are being achieved by compensating with harmonic coils the effect of the residual (0.3 G) first harmonic component in the non-adiabatic region at the machine centre (<30 MeV). Vertical losses (presently 2 to 5% in the high-energy region) caused by radial-to-vertical coupling should also, as a result, be substantially reduced.

Beam Centring

The centring probes, range of motion 17 to 80 in., and the outer slits, motion 72 to 112 in. (see Fig. 1), have been used to provide the differential turn patterns over the non-adiabatic region. The radial flag on the first turn is used to reduce the phase width to 15°, centred around ~0°, so that the turn structure may be observed. The differential turn patterns are automatically digitized, the positions of the peaks determined and the data analysed to determine the coherent centring error. This is shown in Fig. 2. The 'before' data represent the situation achieved after empirically tuning the machine for maximum transmission to 500 MeV. The curves labelled 'after' show the results of the first attempt to improve centring using a computer fitting routine to predict changes in amplitude and phase of harmonic coil sets 2 through 5 lying between 37 in. and 115 in. radius. A significant improvement has been

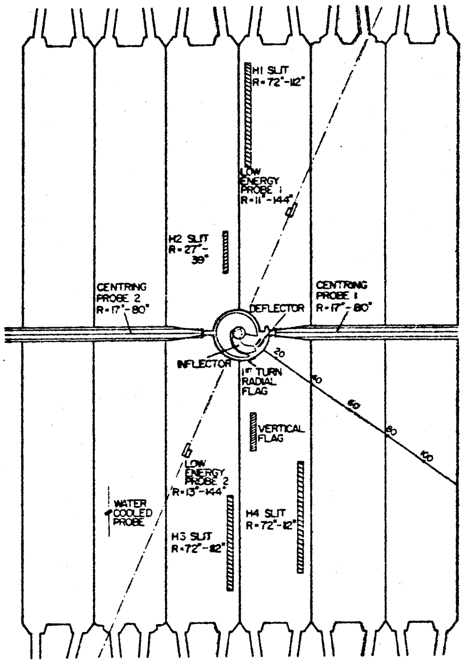

Fig. 1. Layout of diagnostic probes and defining slits in the central region. Two high-energy probes (not shown) operate between 144-320 in. along same azimuths as the low-energy probe.

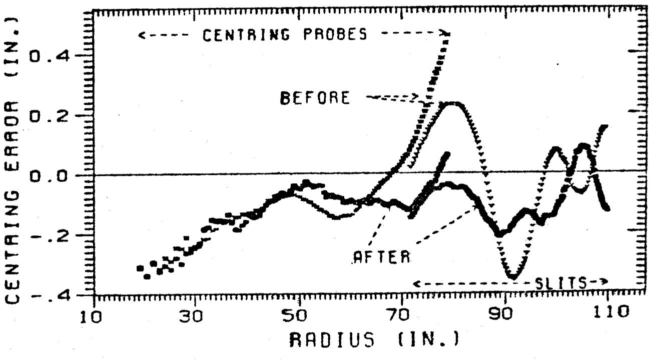

Fig. 2. Centring error along the dee gap (centring probes) and perpendicular to it (slits) before and after harmonic coil fitting.

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obtained over the region 60 to 100 in. The effects of individual harmonic coils on centring, calculated from their measured magnetic field characteristics, agree with the effects directly observed.

Beam Quality Improvement Using Slits and Flags

Beam Preparation

Injection conditions are usually optimized for maximum current transmission and a wide phase acceptance. A typical 40° wide phase acceptance is shown in Fig. 3(a), where the current transmitted to extraction radius is plotted versus the initial phase defined by a $\sim$10° chopper in the injection line. Phases around 0° have optimum radial behaviour[3] and are therefore more convenient for separated turn work. They are vertically more critical. Therefore, correction plates in the central region[4] and the last elements in the injection line are reoptimized for maximum transmission at this phase with chopper on. The vertical flag limiting the size of vertical oscillations between 37 in. and 52 in. is partially raised into the beam to define a 'uniform envelope' vertical acceptance and to eliminate high vertical coherent oscillations.

Radially the centring is optimized by symmetrizing the turn width with small deflector corrections.[5] The radial flag is then inserted to intercept phases more positive than 10 or 15° [Fig. 3(c)]. The inner slit (H2) is adjusted in width and position to select a portion of a turn close to 0° [Fig. 3(d)]. H2 and the radial flag together define a phase width sufficiently narrow that side bands will not pass through the subsequent slits. The chopper is then turned off to eliminate the aberrations introduced by this device.

A differential probe scan is made at 70 MeV, well beyond the non-adiabatic region, and although separated turns may not be seen, gross coherent centring errors yield density modulations. These are removed by empirically adjusting a single harmonic coil set, since we have a narrow phase band. An outer slit [H1, H3 or H4 (Fig. 1)] is then scanned between 15 and 35 MeV; if the turn pattern (as observed on the beam signal recorded on a probe at higher radius) is not distinct, trim coils are adjusted to optimize isochronism in the centre and centring rechecked. At this point we should see turns of almost constant width if the emittance matching and centring are correct. If width modulations are slight, two slits, on opposite sides of the machine, are set about the same turn and the third set one-quarter of a precession cycle (6 to 10 turns) later. The first two select x, the third p_x. A turn pattern at 70 MeV may reveal a coherent oscillation which may be removed empirically or by the method of Ref. 5; this may require a slight adjustment in slit position. While the differential probe is withdrawn to the extraction region slight adjustments in isochronism are made to preserve the turn pattern. In a recent experiment the turn pattern could be easily preserved to 200 MeV.[6]

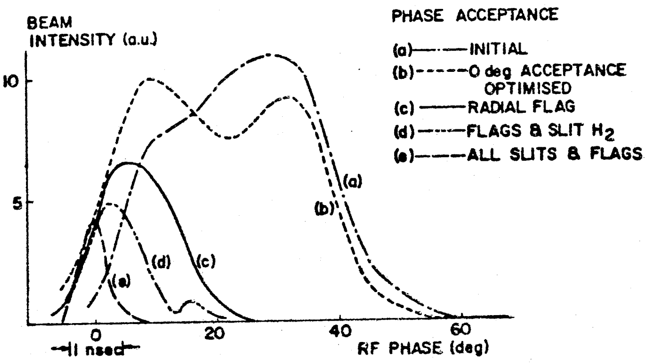
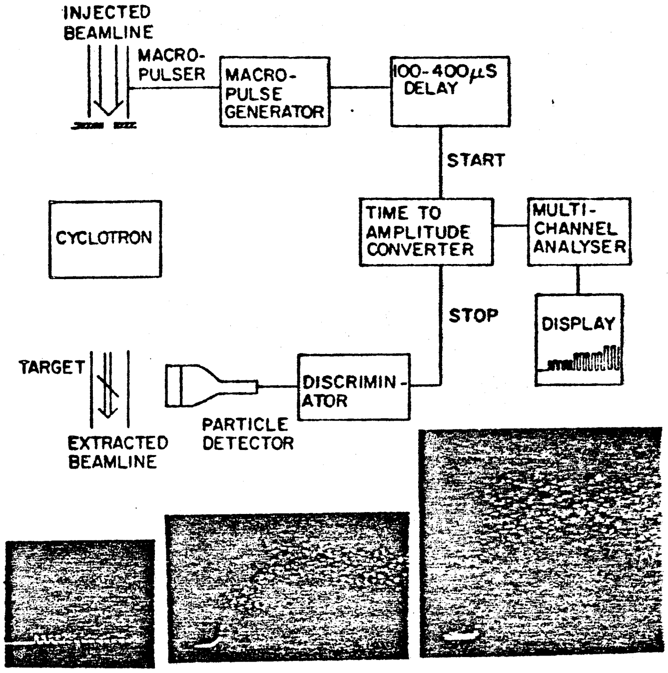


Fig. 3. Cyclotron phase acceptance to 500 MeV, measured by scanning the chopper phase at various stages of setting up for separated turns.



3 turns 2 turns 1 turn

Fig. 4. Time-of-flight system and displays for multiple and single turn extraction.

Beam Extraction and Analysis

A radially narrow (0.03 in.) carbon stripping foil is used for best resolution. A differential trace is made by moving the foil radially and observing the extracted current by means of the stripped electrons or by a secondary emission monitor in the beam line. The relative turn number can be determined by measuring the flight-time between the injection line macropulser and a particle detector adjacent to the extraction line (Fig. 4). The macropulser provides beam bursts every 1 ms with a duty factor variable between 1 and 99%. The rise time is less than 15 ns, much less than the 43 ns spacing of the RF periods. The particles providing the stop signal can arise anywhere in the macropulse, and sufficient events must be accumulated to provide a description of the leading edge. The leading edge is rectangular if the beam extracted comes from a single turn. If several turns are extracted simultaneously the display consists of several macropulses superimposed, the leading edge of each displayed by a time corresponding to one turn (215 ns). The number of steps observed corresponds to the number of turns simultaneously extracted.

A turn pattern and the relative turn number obtained by scanning the stripper foil near 200 MeV are given in Fig. 5(a,b). ν_r is 1.25 and it can be seen that there is a coherent radial oscillation, amplitude about 0.08 in., at this frequency which serves to isolate turns 5 and 10. The turn width is fairly constant indicating a well-matched beam with little phase-dependent coherent oscillation. Lowering the foil and repeating the scan increased the beam current at some turns while making little change at others (1,6 and 7,13). This can be explained by a vertical oscillation; ν_z changes rapidly in this region with 5.5 ± 0.5 turns/precession cycle expected; Fig. 5 implies 6 turns/cycle. Turn patterns such as Fig. 5 have been observed to reproduce to ±0.05 in. over a period of at least 2 h,

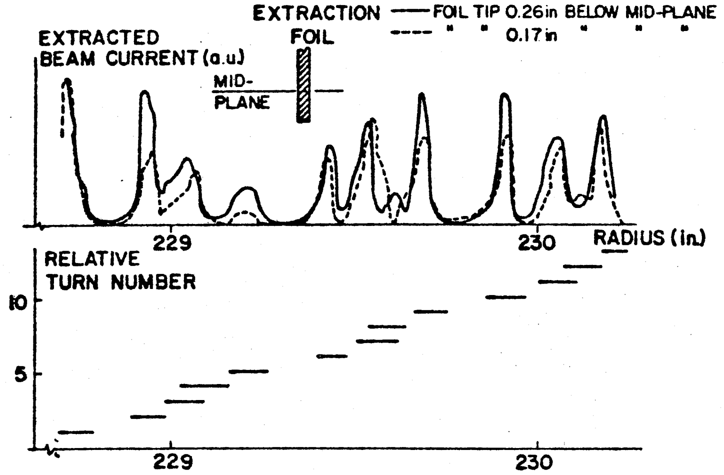


Fig. 5. Turn pattern (a) and the base width versus relative turn number (b) obtained by scanning the stripper foil near 200 MeV.

implying a phase stability of ±2° at 200 MeV equivalent to a magnetic field stability of $\pm 2 \times 10^{-6}$. The turn width of 0.09 in. is close to that expected from slit widths of 0.06 in. and an expected phase width of 4° centred close to 0°. The measured time microstructure with all slits in (0.6 ns) is consistent with a calculated time width of 0.3 ns when folding in instrumental resolution and the finite beam width.

The energy spread for a single turn measured by the MRS was 0.8 MeV FWHM; the energy spread when the coherent amplitude was adjusted so that three turns were superimposed was 1.05 MeV. If we assume that the beam energy width was increased by twice the energy gain/turn in the latter case and that the measured energy spread is from the beam and MRS plus beam line resolution added in quadrature, we infer an extracted beam resolution of 0.2 MeV FWHM and an MRS + beam line resolution of 0.7 MeV. Removing a particle detector at the spectrometer entrance reduced multiple scattering, and a resolution of 0.66 MeV was measured on a later occasion. The energy spread expected from linear motion code calculation is 0.25 MeV FWHM in good agreement with the inferred beam resolution of 0.2 MeV FWHM. The observed spot size on target is 0.1 in., and the emittance is expected to be 0.3π mm-mrad for a single turn.

Stripping foils allow a portion of a turn to be extracted. If the coherent amplitude is less than the turn width, the energy resolution and time width should be less than extracting the complete single turn. Figure 6 shows the variation in energy measured by the MRS as a foil was placed at three positions across a single turn. The initial measurement was repeated and the beam found to be quite stable over the 20 min taken for the experiment.

Stability and Future Program

At this time we do not expect separated turns at energies above 300 MeV both because of the magnet instability and because the phase width transmitted through the slits is too large. The two main sources of instability are the magnetic field and the dee voltage, having two distinct frequency components, the former at 0.2 to 0.5 Hz and the latter at 5.0 to 7.0 Hz, the mechanical vibration frequency of the resonator structure. The total time of flight through the cyclotron is a function of both dee voltage and magnetic field. When measured in August 1978 the amplitude of the RF voltage induced fluctuations was about 0.4 μs peak-peak in a 350 μs time of flight, corresponding to an effective dee voltage stability of ±0.06%. Following the shutdown in November 1978 the mechanical coupling between the 80 separate resonators was modified to make the structure stiffer. A recent measurement of the RF voltage induced fluctuations showed that they had been reduced to less than 0.1 μs peak-peak. This result is also confirmed by observing the intensity fluctuations of a slit-selected beam.

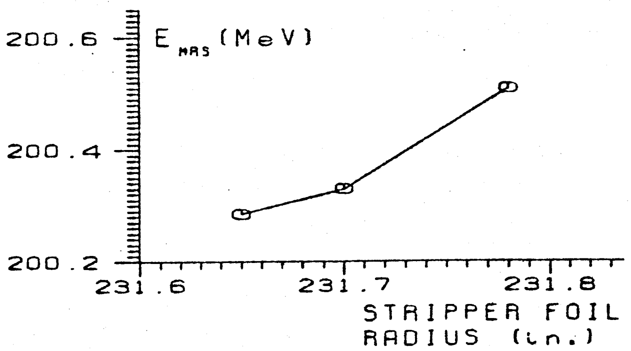


Fig. 6. Measured energy variation over a single turn.

A beam phase stabilization system using the RF frequency to compensate for magnetic field variations has been tried with some success.[5] However, this solution has the disadvantage that it relies on a beam-derived signal, which is not straightforward to obtain for all operating modes. The intention is to use an NMR system[7] capable of better than 1 ppm resolution to provide an error signal to the RF frequency.

The addition of a third harmonic, expected to be operational in about a year, will relieve the tight restriction on acceptable phase range for single turn extraction at 500 MeV.

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