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MEASUREMENTS AND CORRECTIONS TO THE BEAM PROPERTIES IN THE TRIUMF CYCLOTRON

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Abstract

The recent commissioning of two centring probes and four pairs of internal slits has for the first time made possible systematic measurements and improvements to the central orbits, and internal selection of beam emittance and phase acceptance. The beam signals are digitized and computer-processed to allow rapid analysis and correction of the centring by means of steering electrodes and harmonic trimming coils. Radial-longitudinal coupling effects agree with theory and are used to optimize the injection conditions for the wide phase acceptance.

With the internal slits it has been possible to improve the incoherent radial betatron oscillation amplitude and to observe isolated turns to 220 MeV and turn structure out to 500 MeV.

Fluctuations in the dee voltage (∿ ±0.1%) and the magnetic field ($\pm 2 \times 10^{-6}$) give rise to fluctuations in the energy and intensity of highly selected beams. Improved stability has been achieved by regulation of both RF voltage and frequency with beam-derived signals.

Introduction

At the previous cyclotron conference, some initial measurements of the properties of the H^- beam in the TRIUMF cyclotron were described.[1] Since then further measurements and improved techniques have reduced the phase excursions ($\Delta \sin \phi$) in the cyclotron to <±0.2 below 400 MeV and ±0.4 to 500 MeV, and improved matching in the injection line and centre region has reduced the beam loss in the cyclotron.[2] These efforts have been important in achieving the primary goal at TRIUMF over the past two years: reliable operation at current levels of 100 μA with minimum loss in the cyclotron. This work is described elsewhere in the proceedings.[3]

However, operation at increased intensities and the recent commissioning of the Medium Resolution Spectrometer (MRS) on one of the extracted beam lines and the eventual aim of separated turn operation have made it necessary to increase the effort to understand the factors determining the emittance, energy resolution and stability of the beam.

This work has been facilitated during the last year by the commissioning of two centring probes, four pairs of internal slits and a "radial flag" (Fig. 1). The centring probes consist of single fingers 0.2 in. wide which can be raised into the beam plane and run along the accelerating gaps between radii of 17 in. and 80 in. The slits consist of pairs of tantalum plates which can be raised into the beam plane and driven independently to define apertures adjustable in both width and radius. One slit runs between 27 in. and 39 in. radius, the remaining three between 72 in. and 112 in.; all run perpendicular to the accelerating gap. The radial flag can be rotated to intercept the innermost ions on the first turn in order to restrict the phase acceptance.

The simultaneous extraction feature of the TRIUMF cyclotron puts very stringent requirements on the stability of the beam both spatially and in intensity. Typical requirements for operation require a split ratio of 1:10000, i.e. currents of a few nanoamperes or less extracted down one beam line (primarily for nuclear physics experiments) while currents of tens of microamperes are extracted down the second beam line to the meson production target. This split is achieved by using as the extraction foil a 0.001 in. diam carbon wire and by inserting it from above into the "halo" of the circulating beam. The success of our efforts to date can be seen in Fig. 2. Further discussion of the factors affecting the beam stability is given later in this paper.

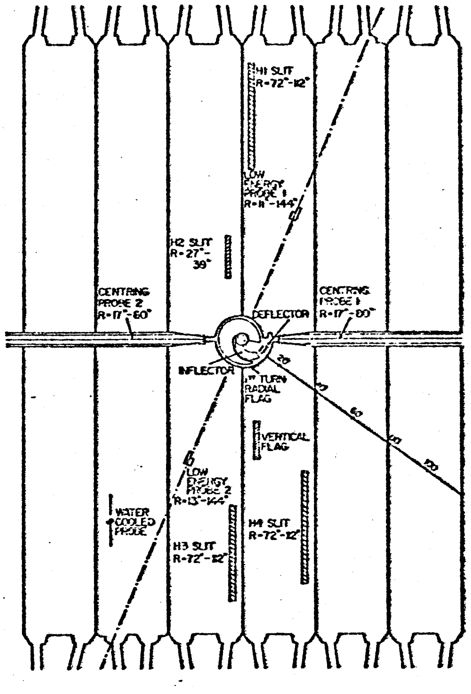

Fig. 1. Layout of diagnostic probe and defining slits in the centre region.

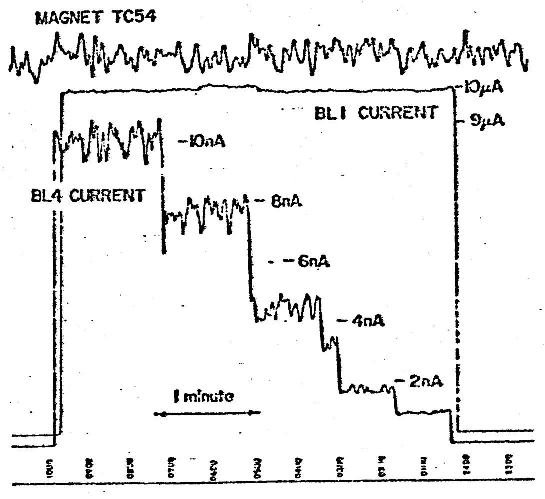

Fig. 2. Stability of the extracted beams at a high split ratio.

Beam Centring Studies

The turn patterns of the central orbits have been studied by moving the centring probes or slits radially while observing the intensity modulation on a fixed current measuring probe at larger radius. The slits yield a positive image of the radial beam profile, while the centring probes provide a shadow scan (Fig. 3). With the phase acceptance restricted to 15-20° by use of the chopper or radial flag it can be seen that the turn separation is virtually complete over the first 60 turns. The usefulness of this data is directly related to the speed with which it can be analysed and the effects of altering machine parameters observed. The beam intensity signals are therefore digitized every 0.050 in. and transmitted to the local university computing centre. The position of the turns are then determined by an automatic peak-finding algorithm, and the data from the two probes (or slits) analysed together to determine the energy gain per turn and the coherent centring error. The former quantity normally gives $V_d \cos \phi = 80 \rightarrow 85$ kV where V_d is dee voltage and ϕ phase.

The (coherent) centring error along the dee gap varies according to the matching between the injection line and the central region (Fig. 4). It can be smaller than 0.1 in. between 40 and 70 in., but always increases from 70 to 78 in. (the cyclotron is most sensitive to first harmonic errors near 60 in.). The recent use of the slits to determine the centring error perpendicular to the dee gap shows that it can be as large as 0.4 in. at large radii. Power supplies are being connected to more of the harmonic coil sets so that it should be possible to reduce the centring errors considerably in the near future.

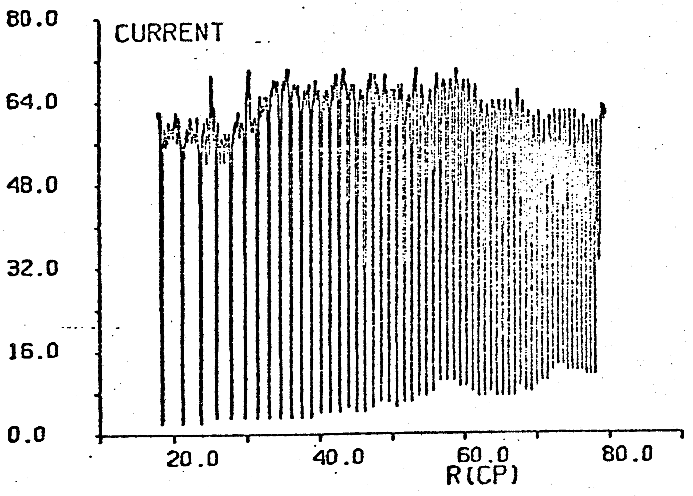

Fig. 3. Centring probe turn pattern obtained by digitizing beam currents at 20 pts/in.

Radial-Longitudinal Coupling Effect

When an ion's centre of curvature is displaced in a direction perpendicular to the dee gap, the ion crosses successive dee gaps at different phases and in general receives a higher energy gain on one side of the dee than on the other side. Simple analytic theory[4] shows that this effect causes the radial width of the beam at 180° azimuth to be nearly independent of the centring error while at the 0° azimuth (the injection gap) the radial width increases as the centring error is increased. Figure 5 shows the radial width obtained from centring probe scans as a function of deflector voltage. Adjusting the deflector voltage displaces the orbit centre normal to the dee gap by 0.12 in./kV. The optimum setting occurs when the radial widths on both sides are equal, in this case about 1 kV from the nominal setting.

Use of Defining Slits to Improve Energy Resolution

Four sets of movable slits are used to restrict and define the radial betatron amplitude of the accelerated beam. Their primary purpose is to provide an extracted beam with an energy spread of less than 500 keV. The radial flag and slit H2 near the centre restrict the phase acceptance of the cyclotron to about 15° and eliminate extreme phases which could be transmitted through the outer slits. Two of the outer slits H1 and H3 are set about turns separated by one quarter of a precession cycle (about 5 turns at 30 MeV). The third slit H4 is also set about the fifth turn but on the opposite side of the dee gap to clean up some particles at the extreme ends of the phase range.

Due to its large size and low magnetic field the TRIUMF cyclotron is extremely sensitive to a first harmonic component in the magnetic field and the radial motion is not adiabatic until approximately 30 MeV.[5] A procedure has been developed to adjust the phase and amplitude of harmonic coils between 15 and 30 MeV to centre the narrow phase band produced by the inner slit.

A harmonic coil produces a coherent displacement of the beam in (x,p_x) space with an amplitude and phase linearly related to the amplitude and phase of the first harmonic component of the coil currents. The centring can be determined by observing the turn pattern on a

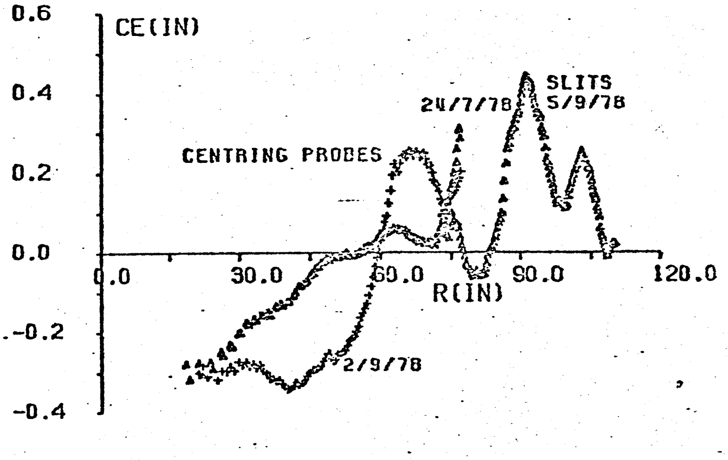

Fig. 4. Centring error to 30 MeV obtained using both centring probes and slits. The curve labelled 2/9/78 was taken with a harmonic coil powered to optimize centring at 70 MeV.

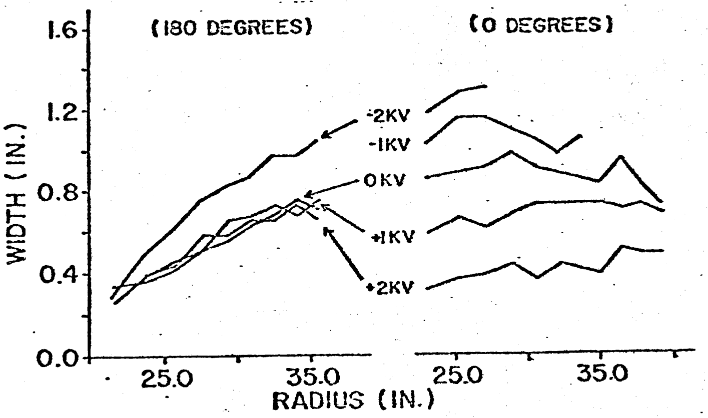

Fig. 5. Radial-longitudinal coupling effect as observed in the radial width of individual turns along the dee gap.

differential probe at 70 MeV. The difference between the maximum and minimum turn separation is noted and the experiment repeated several times with the harmonic coil powered with a fixed amplitude I and different phases. Circles are drawn with radii corresponding to the turn separation difference and on a separate piece of tracing paper lines at angles corresponding to the harmonic coil phases Fig. 6. The origin of the latter figure is moved around the circle corresponding to the coil off until the lines intersect the appropriate circles at points which themselves are on a circle of radius RI centred at P. The optimum setting to centre the beam is then a coil amplitude of (PO/RI)I at the azimuth of vector PO. Typically, after the initial measurements, the procedure centres the beam to 0.020 in. with the predicted settings.

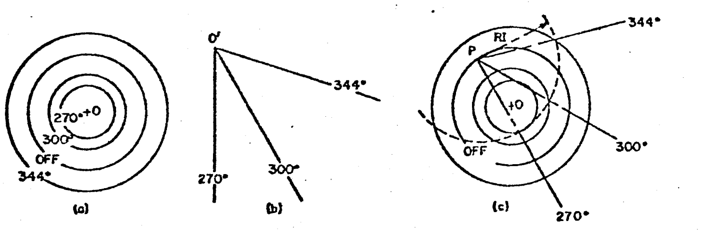

Fig. 6. Technique for optimizing centring with a harmonic coil.

The coherent amplitude has remained quite stable for several hours. A turn pattern taken with a slit H2 aperture of 0.2 in. and the outer slits at 0.1 in. shows identifiable separate turns at 200 MeV (an energy which can be extracted) (Fig. 7). The circulating beam current is reduced by a factor 20. Shadow measurements have shown that the use of the slits produces a factor 3 reduction in the incoherent amplitude. The resulting total betatron amplitude of typically 0.125 in. corresponds to a calculated energy spread of 460 keV. With this slit-selected beam the measured energy spread using the MRS is 900 keV FWHM at 400 MeV and 650 keV FWHM at 200 MeV. However, the spectrometer resolution in its present configuration is calculated to be 450 keV at 400 MeV.[6]

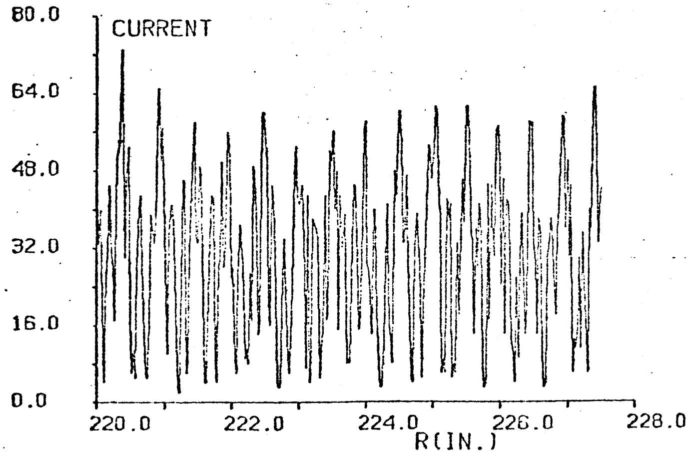

Fig. 7. Differential probe turn pattern obtained using slits. 200 MeV corresponds to a radius of 226 in.

Cyclotron Stability

Measurements of the beam fluctuations in the cyclotron show that there are two main causes, the magnetic field and the dee voltage. These fluctuations are characterized by distinct frequency components, the former at 0.2 to 0.5 Hz and the latter at 5.0 - 7.0 Hz, the mechanical vibration frequency of the resonator structure. One or both of these frequency components can be seen in the intensity fluctuations of an internal slit selected beam, or an extracted beam at high split ratio, in the energy fluctuations of an extracted beam (using a range telescope as the monitor) and in the total time of flight through the cyclotron. This latter quantity, obtained by pulsing the injected beam at 1 ms intervals and measuring the length of time for the beam to arrive at an internal probe at 500 MeV or a capacitive probe along the extracted beam line, is inversely proportional to $\overline{V_d \cos \phi}$ and therefore contains contributions from both dee voltage and magnetic field. Figure 8 shows the correlation between this time-of-flight signal, the magnetic field variations as determined by integrating the voltage induced in the outer of the 54 circular trim coils, and an RF voltage signal. This recording was made with the magnet tuned slightly off resonance to accentuate the effect of the beam phase fluctuations. At present the amplitude of the RF voltage induced fluctuations is about 0.4 μs peak-peak in a 350 μs time-of-flight, corresponding to an effective dee voltage stability of ±0.06%.

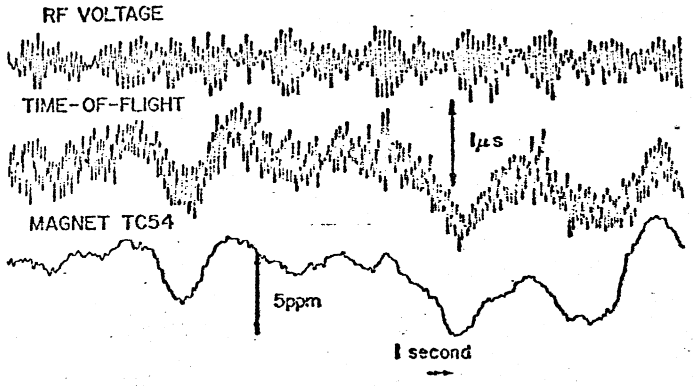

Fig. 8. Time-of-flight to 500 MeV showing components due to RF voltage and magnetic field variations.

Although the RF voltage stabilization system is capable of achieving 1 part in 10^4 stability,[7] the effective stability depends on how well the reference voltage correlates with the actual accelerating voltage seen by the beam. This is a special problem for the TRIUMF cyclotron where the dee structure consists of 80 separate resonators coupled loosely together mechanically. A number of RF voltage reference signals are available, either from capacitive pickups at the high voltage tip or inductive pickups near the short circuit end. At present the RF control system can average two of these signals to provide the reference for voltage stabilization. Initially the inductive pickups were used for this purpose but measurements of beam stability have shown that the optimum combination of signals, two voltage probes on outer resonators and on opposite corners of the dee structure, results in a factor four improvement in effective dee voltage stability. As the mechanical vibrations of the resonator are water flow-induced, additional improvements have been made by reducing the flow velocity in the cooling channels.

The RF voltage can be further stabilized by an external beam-derived signal. The total time-of-flight signal has been used for this purpose, resulting in a further factor of four improvement in the time-of-flight stability. However as this signal contains beam phase variations due to the main magnet which should not be compensated with dee voltage corrections, this feedback system is not a practical option until the magnet fluctuations have been removed independently.

Magnet Stability

As mentioned previously the magnetic field variations can be measured by integrating the voltage induced in from coil 54. The present field stabilization uses this same signal as part of a slow feedback system (time constant 4 min) to compensate for temperature dependent drifts in the current monitor shunt.[8] With this feedback operational the field is stable to ±2 × 10^{-6} corresponding to a beam phase variation at 500 MeV of ±5° or ±0.6 ns. A phase stability of ±2° is required for separated turn operation. One method being investigated to improve on this stability is to use the beam phase to control the RF frequency. A frequency shift of ±50 Hz in 23 MHz corrects for the observed magnet fluctuations. The block diagram of this arrangement is shown in Fig. 9. Conventional nuclear instrumentation is used except that the time-to-pulse height converter is modified to output a dc voltage rather than a pulse. The cyclotron computer is used to read this voltage and generate the necessary frequency correction. The result of closing this loop is shown in Fig. 10. An intentional magnet adjustment of 15 ppm was made while the feedback was operating. The residual phase variation has been traced to lack of sufficient time response in the loop, a relatively simple improvement to make. In spite of this the stability is close to that required for separated turns.

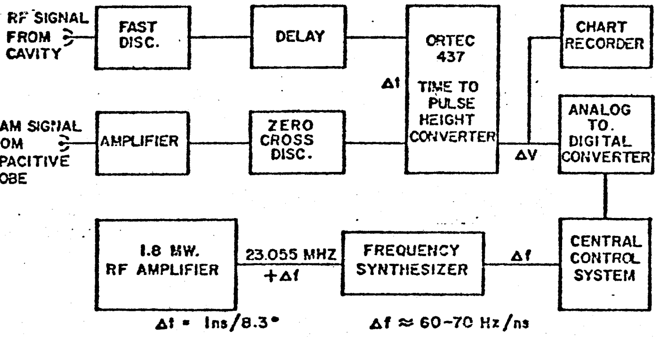

Fig. 9. Block diagram of the beam phase stabilization system.

This solution has the disadvantage that it relies on a beam-derived signal. The RF frequency could also be controlled directly from the magnetic field. The trim coil 54 signal is not satisfactory for this purpose as it is not an absolute measurement, being subject to integrator drift. However an NMR probe capable of better than 1 ppm resolution[9] and with a convenient error signal output is being considered for this purpose.

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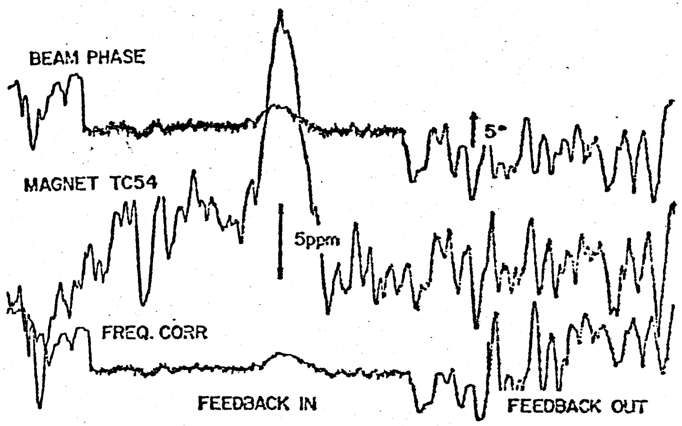

Fig. 10. Beam phase stabilization using the RF frequency to compensate for magnetic field variations.

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