REDUCING PHASE-DEPENDENT EMITTANCE GROWTH WITH LOCAL FLATTOPPING

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Abstract

The efficiency of the proposed H^- extraction in the TRIUMF cyclotron is improved by inducing a precessional component to the radius gain per turn by exciting a coherent radial betatron oscillation at $\nu_r=3/2$. Beam test and computer simulation results show that accompanying this improvement is a growth in the transverse emittance of the extracted beam. The growth is, in part, due to phase-dependent mixing of the perturbed beam. This phase-dependence can be greatly reduced by flattopping the local energy gain per turn with the addition of a higher harmonic accelerating field in phase opposition to the fundamental. A 92 MHz, 4^{th} harmonic, $\lambda/4$ cavity installed in the TRIUMF cyclotron has been used for such a purpose. Results of both computer simulations and beam tests will be presented.

I. INTRODUCTION

A general description of the method proposed to extract H^- ions from the TRIUMF cyclotron, including a layout of the extraction hardware, has been given previously. [1] An rf deflecting device (RFD), already installed, will improve the extraction efficiency by adding a precessional component to the radius gain per turn. The RFD generates a large coherent oscillation by exciting particles crossing the $\nu_r=3/2$ resonance at 428 MeV (~292 in.) with a radial rf electric field. At higher energies, as ν_r increases, the oscillation precesses generating modulations in beam density. Several precession cycles (~100 turns) later at 452 MeV (~305 in.) an increase in the radius gain per turn of a factor of four is produced. A typical beam density plot from a differential probe is shown in Fig. 3. The extraction point coincides with the third density minimum (304 in. at the azimuth of the probe). An electrostatic deflector, or in the present study, a wide foil is positioned at this point to select the beam for extraction.

The present RFD has been found to stretch the vertical emittance [2]. The growth occurs due to vertical fields $\mathcal{E}_z$, associated with the $d\mathcal{E}_r/dr$ gradient in the RFD field that happen to coincide with the $\nu_z=1/4$ resonance at 419 MeV. The resulting mismatch precesses in vertical phase space.

Both the radial coherent amplitude and the amount of vertical stretching induced by the RFD is proportional to the product of the average radial kick and the number of turns in the resonance region and varies with particle phase as $\cos(\phi/2)/\cos(\phi)$, while the rate of radial advance of the center of precession (accelerated equilibrium orbit) varies as $\cos(\phi)$. This phase-dependence leads to increases in the both the extracted radial and vertical emittances.

II. LOCAL FLATTOPPING

In some cyclotrons a small amplitude of a higher harmonic accelerating field is added for most or all of the acceleration to equalize, or 'flattop' the energy gain for a finite phase band to achieve separated turn extraction. In general all higher harmonic cavities can combine with the fundamental to flattop the energy gain, however as the harmonic m increases, the useful phase width of the flattop is reduced to π/m. In this paper we report how a relatively small fourth harmonic cavity can be used to locally flattop the energy gain per turn and reduce the phase-dependent emittance growth from precessional extraction or from stretching from resonances prior to extraction.

A 4^{th} harmonic $\lambda/4$ auxiliary accelerating cavity [3] [4] (AAC), installed in the TRIUMF cyclotron, spans the energy range from 370–500 MeV (278–310 in.) with the voltage rising sinusoidally from inner to outer radius. The cavity can be used to flattop the local energy gain per turn, initially 340 keV, in the precessional extraction region from 420 MeV to 450 MeV. Simulations show that a voltage of 20 kV is sufficient for this purpose.

III. COMPUTER SIMULATIONS

A. Radial

A computer study was initiated to investigate the benefits of local flattopping. The beam arriving at the RFD was assumed to be homogenous (i.e. lacking turn structure) and matched to the cyclotron acceptance. A set of particles on the boundary of a matched radial phase ellipse were tracked using GOBLIN through the precessional extraction process for various initial particle phases. The results, summarized in Fig. 1(a), show the particle ellipses in radial phase space in the extraction region for two different initial phases, 0° and 20°. Part of the previous precession cycle is also shown, as is an extraction septum to illustrate the details of the extraction process. The radius of the septum corresponds to 452 MeV for the azimuth used in the study. The hatched region represents the area in radial phase space occupied by the extracted beam.

The particle ellipses are displaced from, and rotate about, the equilibrium orbit generating an increased radius gain per turn. Since extraction, in most cases[1], takes place over more than one turn the extracted emittance for a narrow phase band is broadened by the rotation of the ensemble . The 20° particles follow a slightly different precession path in phase space than the 0° particles. This will lead to further increases in the extracted radial emittance as different phases are injected into different regions of phase space. In Fig. 1(b) a small fourth harmonic is added in opposition to the main accelerating field in the GOBLIN simulation. In this case different phases follow more closely the same precession trajectory and hence occupy a smaller phase space area once extracted.

Monte-Carlo simulations were done to estimate the extracted radial emittance using the RFD with and without flattop. For an RFD voltage of 110 V/mm·m, a circulating radial emittance of $1\pi\mu$m and a phase band of 40°, the extracted emittance is $4\pi\mu$m. The addition of a fourth harmonic flattop voltage reduced the extracted emittance to $3\pi\mu$m.

B. Vertical

GOBLIN was also used to track particles on the boundary of a matched vertical ellipse through the RFD. The results are

[1]Depending on septum positioning some phases will be extracted in one turn but since the beam density is uniform most will not be extracted cleanly.

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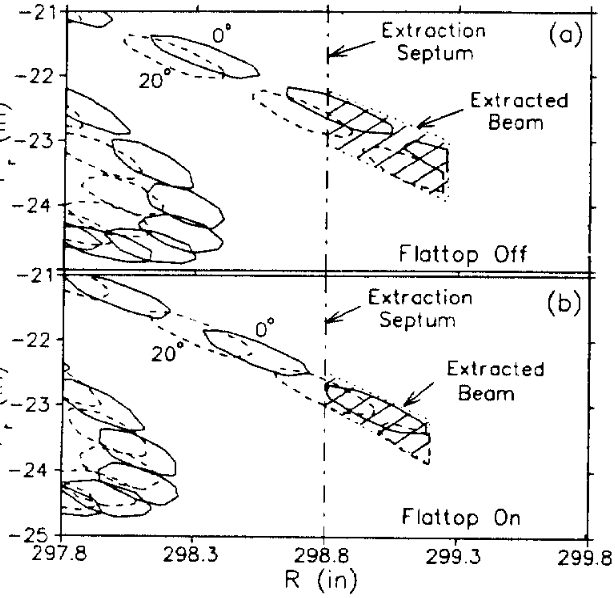

Figure 1: Result from a GOBLIN tracking study. Shown is the position in radial phase space of a matched beam ellipse undergoing precessional extraction for two different starting phases, 0 and 20°. In (b) a 4^{th} harmonic flattopping voltage has been added to the accelerating field reducing the variation in precession between the two phases. The hatched regions represent the area in radial phase space occupied by the extracted, 20° wide, beam.

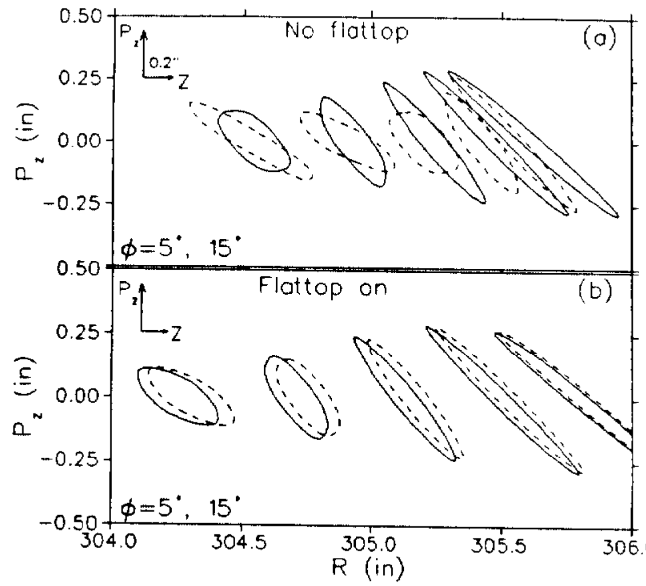

Figure 2: Result of a GOBLIN tracking study showing vertical phase ellipses for turns in the extraction region for rf phases of 5 and 15°. The phase dependence in the orientation of the stretched ellipse evident in (a) is reduced in (b) by the addition of a flattopping voltage.

summarized in Fig. 2(a). The orientations of the stretched vertical ensemble in the extraction region are plotted for two different initial phases, 5 and 15°. For a single phase the orientation changes as the stretched ellipse rotates from turn to turn. At any one radial position the two phases have different orientations. This will increase the extracted vertical emittance for a wide phase band as the various ellipses superimpose in the deflector. In Fig. 2(b) the flattop voltage reduces the phase-dependence in the orientation of the stretched vertical emittance.

Monte-Carlo calculations show that for an RFD voltage of 110 V/mm·m and a phase band of 40° the extracted vertical emittance is three times larger than that from a narrow 5° phase band. By adding a fourth harmonic flattop voltage the extracted emittance of the 40° case is only slightly bigger than the small phase band result.

IV. BEAM TESTS

Several experiments were made to investigate the possible benefits of the use of local flattopping in the TRIUMF cyclotron. Flags and slits were used to select a narrow phase band of ~5° FWHM. The small phase band is useful for studying phase dependent effects since the central phase of the bunch can be varied by altering the main rf frequency. A variation of ±200 Hz results in a phase shift of ±20° at the extraction region. In a typical study five different central phases, 0, ±10°, ±20° are each sampled and then the results are compared to test for phase-dependent effects.

The local flattopping condition is found by setting the AAC to the estimated voltage and altering the phase until the RFD induced beam density modulation pattern is stable at the extraction point over the required phase range. A comparison for a ±20° phase variation for flattop off (a) and flattop on (b) is shown in Fig. 3. In practice the differential finger of a radial probe is positioned just beyond the fourth peak of the density plot (at point 'P' in Fig. 3(b)) and the frequency is scanned while noting the stability of the current on the finger.

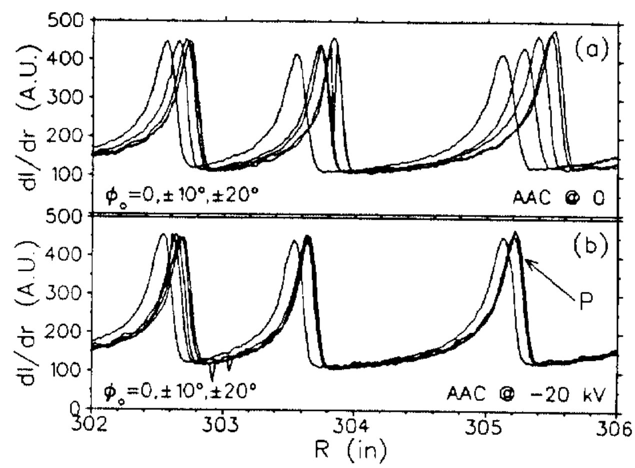

Figure 3: The signal from the differential finger of a radial probe showing the modulation in beam density produced by the RFD for various phases spanning ±20°. In (a) the AAC cavity is off while in (b) the cavity is on and set for local flattopping.

A. *Vertical Measurements*

A probe with five, 6.2 mm tall, horizontal fingers placed one above the other was scanned to measure the vertical width of the beam over the full extraction region for various central phases. A summary of the width scans is shown in Fig. 4. In (a) the AAC is off while in (b) flattopping is used. The scans clearly show evidence of the vertical stretching initiated at the RFD (R=292 in.) and the subsequent precession of the stretched vertical ensemble. At the azimuth of this probe the extraction point occurs near 302 in. The top scans show the phase dependence in the precession of the stretched phase space that develops leading up to this radius. In (b) the phase dependence is eliminated by the addition of the local flattopping.

The vertical width can also be measured by dipping a carbon stripping foil into the beam vertically and measuring the beam

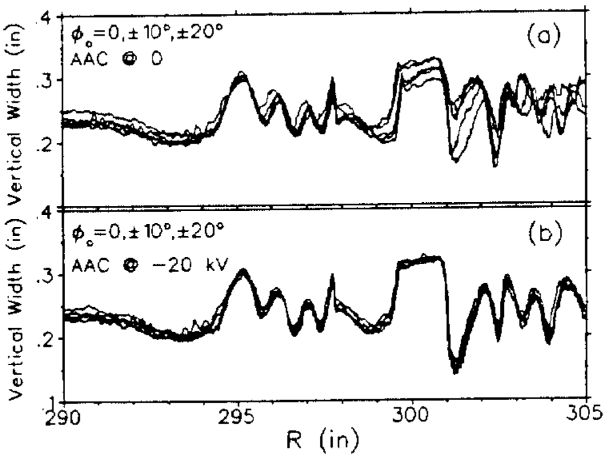

Figure 4: Experimental result showing the vertical beam width in the extraction region for various rf frequencies covering the phase range ±20°. The phase dependence evident in (a) is cancelled in (b) by adding a flattopping voltage to the AAC.

transmission as a function of foil position. A foil dip with a foil much narrower than the radius gain per turn will give a measure of the full width of the beam. However, if large coherent radial oscillations are present (eg during precessional extraction), a shadowing probe must be used to eliminate higher energy particles coming back through the foil. We use a wide foil shadowed by a probe one radial betatron cycle upstream, positioned to take 80% of the circulating beam with the foil fully down. Beam width plots for rf frequencies covering the phase range ±20° are shown in Fig. 5(a). Phase dependent variations in the vertical width at the position of the foil are evident. With the local flattopping on (Fig. 5(b)) the phase dependence is eliminated. The width difference between flattop on and flattop off is caused by a change in the number of turns from the onset of the vertical stretching caused by the extra decelerating field.

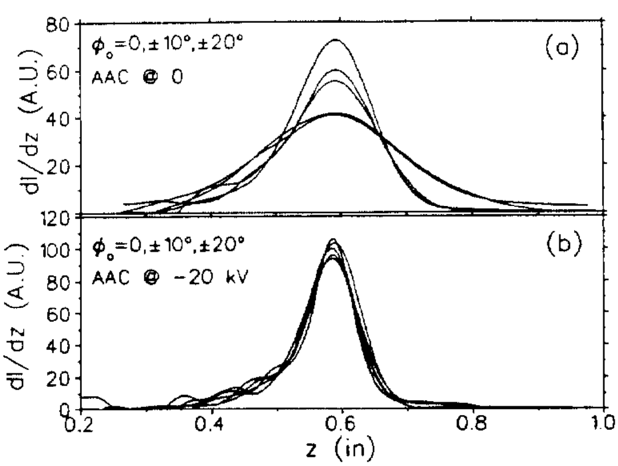

Figure 5: In (a) the vertical beam width at the point of extraction is plotted for beams of central phase 0, ±10° , ±20° indicating a phase dependent behavior. In (b) the phase dependence is eliminated with the addition of a local flattop to the energy gain per turn.

B. *Horizontal Measurements*

One measure of the phase dependence of the radial emittance of the extracted beam is to measure the radial width of the beam on a totally intercepting blocking probe placed at the extraction point for various phases. This can be done by scanning, radially, a shadow probe one betatron cycle upstream from the 'blocker', and measuring the current on the 'blocker' as a function of 'shadow' position. Several scans were taken for different incoming beam phases and the results were differentiated to produce the radial width of the beam on the blocking probe, in this case a wide stripping foil. The variation of the radial width with respect to incoming beam phase is shown in Fig. 6 for no flattopping and for the flattopping turned on. The larger radial width in the 'AAC on' case is due to a slight radial shift in the extraction foil to a position with a higher radius gain per turn.

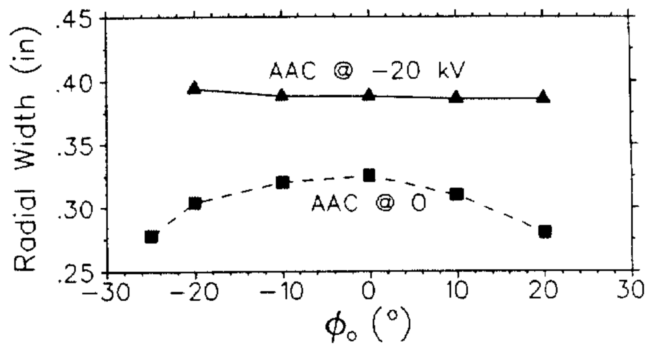

Figure 6: The radial width of the beam on a wide extraction foil as a function of beam phase for flattopping off (dashed curve) and flattopping on (solid curve).

C. *Emittance Measurements*

A wide foil was used to extract the beam into a beam line where three wire monitors separated by drift spaces were used to measure the transverse emittance. The phase dependence in the extracted beam was estimated by measuring the horizontal and vertical beam spot on the monitors for various beam phases. Although the monitors have inadequate resolution to calculate the absolute emittance accurately it was clear that the beam spot on the monitors did vary with beam phase. The addition of the flattopping reduced this phase dependent effect. New scanning wire monitors have been designed which will improve this measurement.

V. REFERENCES

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