BEAM QUALITY INVESTIGATIONS FOR H$^-$ EXTRACTION AT TRIUMF

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Abstract

The direct extraction of high intensities of H$^-$ ions from the TRIUMF cyclotron and their injection into an accumulator ring will impose demands on beam quality and thereby on the fields of the added extraction hardware and on the operation of the cyclotron. The fields of each of the extraction devices have been simulated in computer codes to estimate their influence on the final extracted emittance. Parameters controlling vertical emittance have been experimentally investigated to devise an optimum tuning procedure. Results of both computer simulations and experimental beam tests will be given.

I. Introduction

The proposed TRIUMF KAON Factory [1] requires that the cyclotron deliver 150 μA of H$^-$ ions within a longitudinal emittance of 0.003 eV-s ($\pm10°$,±0.6 MeV) and transverse emittances of $3.5\pi\mu$m radially and $2\pi\mu$m vertically. A larger emittance will reduce the efficiency of the injection process leading to greater beam loss in the accumulator and subsequent rings.

The cyclotron must accelerate at least 165 μA to achieve the required intensity. Space charge at the cyclotron center limits the current to about 10 μA/° rf [2]. Measurements show that the majority of particles in a well tuned beam lie within $1\pi\mu$m normalized emittance in both transverse planes. Hence the cyclotron capabilities and KAON requirements are matched but there is little margin. In particular current routine operation demonstrates drifts and jitter in the phase of the extracted beam of $\pm7.5°$ at frequencies slower than the 50 Hz accumulator cycle and $\pm5°$ at frequencies faster than 50 Hz. The former can be tracked by the accumulator rf but may present problems to the H$^-$ extraction system while the latter require stabilization both for cyclotron extraction and KAON injection.

The changeover from extraction by stripping to direct extraction has been discussed elsewhere [3]. In summary nine new pieces of hardware are required, including two electrostatic deflectors (DCD), six channels (MC) and an rf deflecting device (RFD) to generate the large coherent radial oscillation required for precessional extraction. An auxiliary accelerating cavity (AAC) operating at 92 MHz is not strictly necessary for extraction but is available to modify beam behaviour.

II. Computer Simulations

Ensembles of particles have been tracked using the linear motion code COMA. Single particle motion was studied with the ray-tracing program GOBLIN. In COMA transverse emittances of $1\pi\mu$m and a longitudinal emittance of (ΔE,$\Delta\phi$)=$\pm0.2\%$,20° were specified at 380 MeV, well before the extraction resonance at ν_r=3/2 (E=428 MeV). The extraction process was simulated by intercepting those particles with radial positions beyond the septum radius ($\sim$452 MeV) at the azimuth of the first DCD and recording their positions in transverse and longitudinal phase space. Transverse extracted emittances were determined by fitting ellipses enclosing 99% of the particles in the $x-p_x$, $z-p_z$ distributions. These circumscribing ellipses do not necessarily match the cyclotron acceptance. In both codes extraction devices were modelled by including in the calculation either a measured, calculated or analytic representation of the fields.

III. Multi-Turn Extraction

In the TRIUMF cyclotron at peak intensity separated turns are lost within the first few MeV as the large phase band generates energy spread in the turns. At energies above 100 MeV the incoherent radial width $2A_i$ exceeds the radius gain per turn (dR/dn) and turns composed of particles of the same phase (single phase condition) overlap. A wide stripping foil or septum extracts all beam accelerated to its radius with different phases requiring different numbers of turns during acceleration, and extraction of any single phase occuring over two or more turns. A well centred beam matched to the cyclotron acceptance will give an extracted beam whose vertical emittance is that of the circulating beam and whose radial emittance depends largely on A_i and the radius gain per turn (dR/dn). Fluctuations in turn number have little effect.

To improve the efficiency of H$^-$ extraction a large coherent radial oscillation (amplitude A_c) can be introduced. The ensemble of particles is displaced in phase space from the equilibrium orbit (AEO) and precesses about it, increasing dR/dn (often beyond $2A_i$) at the septum. Even though certain ideal phases can be extracted in a single turn other phases with slightly different initial positions entering the resonance region will be split by the septum and require two passes. Particles with phases further removed take up to three passes. The extracted radial emittance of any one phase depends on A_i, the values of dR/dn and dP_r/dn (which are increased due to A_c) and the number of passes necessary for extraction. The extracted vertical emittance is largely the circulating emittance provided the ensemble is centered and matched with respect to the cyclotron acceptance. For any one phase a centred but mismatched ensemble will produce a larger extracted emittance due to rotation between turns.

Both the magnitude of A_c and the rate of motion of the precession center (AEO) can be phase-dependent causing phase-dependence both in the precession paths in radial phase space and in the numbers of turns between resonance and extraction. The former results in an increase in the extracted radial emittance since different phases end up in different regions of phase space. The latter increases the variation in orientation of a stretched ellipse at extraction hence the extracted emittance (see Fig. 4(a)).

IV. RF Deflector

A. Radial Growth

The RFD produces a radial electric rf field at the ν_r = 3/2 resonance. The frequency is 11.5 MHz, 5/2 the particle rotation frequency, so that the radial deflections alternate in sign for successive turns adding to produce the large coherent oscillation (amplitude 5 cm for a field of 110 V/mm·m) required for extraction. The amplitude gained is proportional to the product of the average radial kick and the number of turns in the resonance; this varies as $\cos(\phi/2)/\cos\phi$ while the rate of radial advance of the center of precession (AEO) varies as $\cos\phi$. The phase-dependent precession leads to growth in the extracted ra-

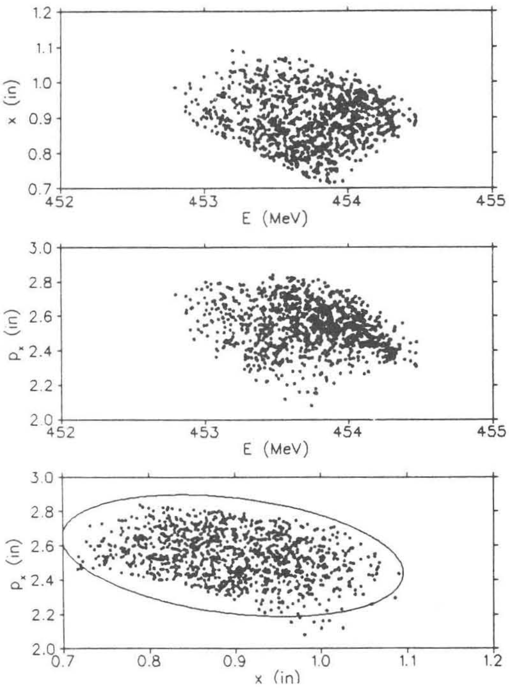

Figure 1: COMA simulation result showing the final position of particles in $E-x$, $E-p_x$ and $x-p_x$ phase spaces for a beam with circulating radial emittance of $1\pi\mu$m, phase band of 40°, and RFD voltage of 110 V/mm·m. An ellipse of $4\pi\mu$m encloses 99% of the extracted particles.

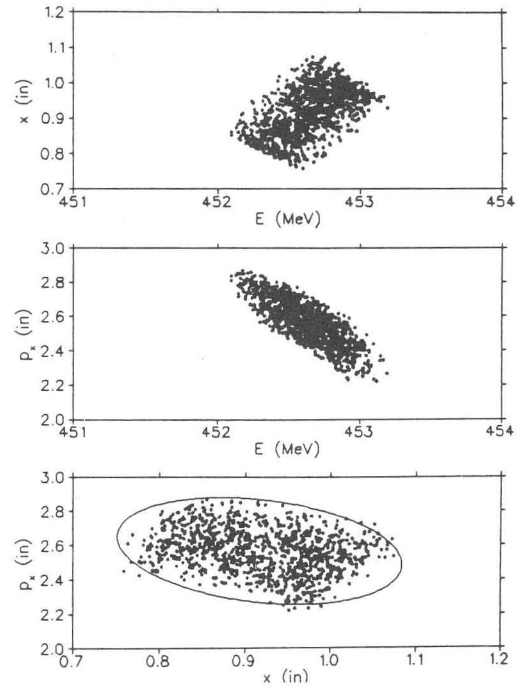

Figure 2: COMA simulation same as for study summarized in Fig. 1 only with flattopping cavity powered (18 kV) to reduce phase dependent effects. An ellipse of $3\pi\mu$m encloses 99% of the extracted particles.

dial emittance as outlined above. COMA simulations indicate that for a 40° phase band[1] the extracted emittance will be 2.5 to 4 times that of the circulating emittance for moderate to high RFD voltages respectively. Fig. 1 summarizes one such simulation showing $E-x$, $E-p_x$ and $x-p_x$ distributions of the extracted particles.

The 4^{th} harmonic accelerating cavity (AAC) installed in the TRIUMF cyclotron reduces stripping losses in the radial range corresponding to 370-520 MeV but its performance as a flattopping cavity has also been demonstrated [4]. Simulations show that when the cavity is powered, at low voltage, the phase-dependent emittance broadening can be almost eliminated. The study summarized in Fig. 1 was repeated for an AAC voltage of 18 kV and the extracted radial emittance and energy spread were found to be reduced from $4\pi\mu$m and 1.5 MeV to $3\pi\mu$m and 1 MeV (Fig. 2). In addition, the resulting strong correlation between E and p_x may possibly be used to advantage in the accumulation process.

B. *Vertical Growth*

GOBLIN studies indicate that an initially matched ensemble in vertical phase space is stretched when traversing the RFD, increasing the vertical extent of the beam envelope (Fig. 3). The growth occurs due to vertical fields $\mathcal{E}_z$, associated with the $d\mathcal{E}_r/dr$ gradient in the RFD field. These alternate in sign each turn and drive the ν_z=0.25 resonance at 419 MeV. The magnitude of the stretching is proportional to the RFD strength. Increases in the extracted vertical emittance due to phase-dependent mixing of the elongated ensemble were calculated with COMA. For an RFD voltage of 110 V/mm·m the extracted vertical emittance of a 40° band is three times that of a 5° band, Fig. 4(a). This is primarily due to differences in rotation in phase space between RFD and extraction since $\nu_z \sim 0.25$ once again at extraction, hence only every second turn is extracted ($\nu_r \approx 1.5$) and the ellipse precesses relatively slowly. In this situation flattopping should reduce the emittance growth. This is shown in Fig. 4(b), where the extracted emittance is very nearly the circulating emittance, but, because of stretching at 419 MeV the vertical size of the beam is larger. The ellipse orientation, hence the beam size in the channels, depends on the number of turns made between 419 and 452 MeV and, should it not be possible to redesign the RFD to reduce stretching, the size could be controlled by altering the energy gain/turn.

[1] KAON requirement with allowance for jitter and tuning

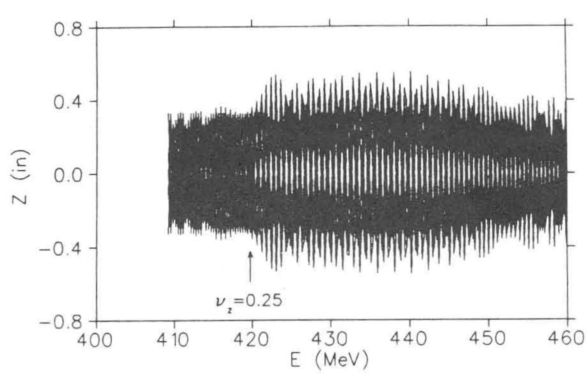

Figure 3: Result of GOBLIN simulation showing the vertical beam envelope at one azimuth while accelerating through the RFD. A growth of 50% occurs as the RFD is entered for an RFD strength of 110 V/mm·m.

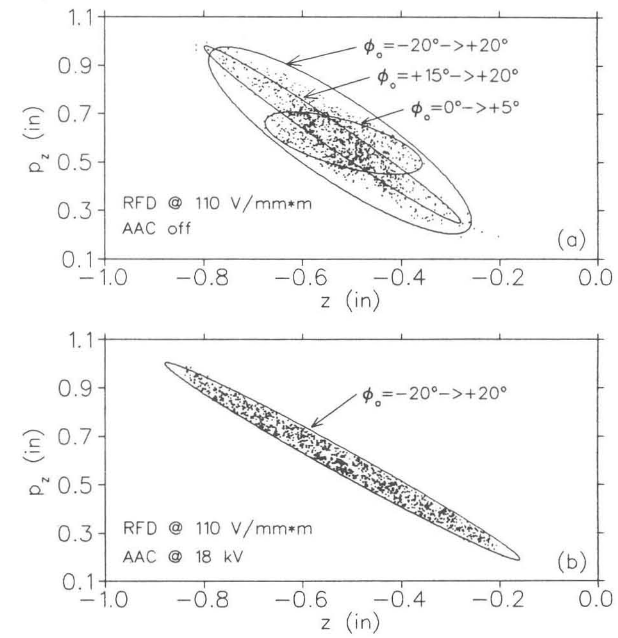

Figure 4: Results of COMA simulations showing the position of extracted particles in vertical phase space for a circulating emittance of $1\pi\mu$m and a phase band of 40°. In both cases the RFD is at 110 V/mm·m but in case (b) a flattopping cavity has been turned on at 18 kV. In (a) phases near 0° and near 20° are grouped separately in the smaller ellipses to show how the phase dependent mismatch increases the extracted emittance.

V. Electrostatic Deflector (DCD)

Two electrostatic deflectors, each contributing 40 kV/cm·m of radial deflection, are required to generate an adequate separation at the first magnetic channel (MC1). Relaxation calculations show a negligible fringe field extending between septum strips into the circulating beam. However the aperture field has non-radial components off the median plane. To avoid vertical distortion the beam must pass within the uniform region which, for an anti-septum of 5 cm full height, is ±1.3 cm from the midplane.

VI. Magnetic Channels

A. *Radial Growth*

A radial gradient in the third harmonic component of B_z will stretch the enfolding ellipse in radial phase space at the ν_r=3/2 resonance. The aperture centers of magnetic channels MC1 and MC2 are only 12.5 and 14 cm respectively from resonances at 419 and 428 MeV. Consequently their fringe fields extend through the resonance region. The channels further downstream are sufficiently distant from the resonance that their fringe fields are of less concern. COMA simulations show that at the azimuth of MC1 and MC2 negative gradients act in phase and augment the existing 3^{rd} harmonic imperfection gradient producing an increase in the extracted radial emittance. Integrated gradients of −0.33 G/cm·m in both MC1 and MC2 yield a 30% increase in the extracted emittance, compared with the gradients off case, for a 20° wide phase band and the RFD powered at moderate strength. Since the gradients cause stretching, the phase-dependent emittance growth at extraction could be reduced or eliminated by applying a small flattop correction; no simulations have been done to date to verify this, however. A conceptual design for additional harmonic gradient coils has been completed should it be necessary to compensate the perturbation.

B. *Vertical Growth*

In general a circulating beam of matched vertical emittance will remain matched when the beam encounters an added gradient as long as the process is adiabatic. If the added gradient is defocussing ν_z will be reduced by an amount proportional to the square root of the gradient change. The vertical width will scale as $1/\sqrt{\nu_z}$. The TRIUMF cyclotron is weakly focussing vertically so that any changes in the vertical focussing by the addition of extra radial field gradients could cause a large proportional change in ν_z and hence a large change in the vertical width of the beam. In the region of interest near 450 MeV ν_z averages 0.24 over the last few turns. To limit the vertical width increase to <15% the existing radial gradient can be reduced by no more than 0.15 G/cm corresponding to $\int dB_z/dr \cdot dl < 7$ G/cm·m for the channels.

We have tested MC1 *insitu*. Three-dimensional field calculations during design gave the maximum integrated gradient in the circulating beam region to be $\int dB_z/dr \cdot dl \leq$ 1.8 G/cm·m [5]. A direct measurement of ν_z was obtained by introducing a broad ΔB_r bump using 10 trim coils and measuring the resulting average vertical shift in the beam ($\Delta z(R)$) with a 5 finger vertical probe. The value of ν_z can be deduced from

$$\nu_z \simeq \sqrt{\frac{\overline{R}}{\overline{B_z}}\frac{\overline{\Delta B_r}}{\overline{\Delta z}}}.$$

Measurements showed that ν_z was reduced from 0.24 to 0.22 with the channel powered as designed and from 0.24 to 0.15 with the coils powered to increase the gradient by a factor of 4, corresponding to integrated gradients of 2.5 G/cm·m and 10. G/cm·m respectively. Measurements of vertical width using a foil-dip technique (see next section) showed no measurable width increase in the first case and a 30% increase in the second, as predicted.

VII. Cyclotron Tune for KAON

A. *Selection of Longitudinal Phase Band*

Beam pulses of ~4 nsec (35°) are accelerated in the TRIUMF cyclotron to achieve a typical high intensity current of 150 μA with a transmission of ~60%. More intensity is available from the source at the cost of increasing the transverse emittance. In future a CUSP source already developed could be used to achieve brighter beams. With the present source we have achieved an extracted beam of 28μA at 25% duty factor (112 μA equivalent) with 90% of the extracted beam within the required 2.4 nsec (20°). The phase selection was achieved using a radial flag on the centerpost to intercept the more positive phases on the first turn and a radial slit on the 10^{th} turn to trim the tails of the phase band. An overall transmission from injection to extraction of 30% was achieved.

B. *Vertical Emittance*

Beam measurements indicate that the horizontal emittance of the circulating beam is well behaved but the vertical emittance entering the RFD is tune dependent and is larger than at injection. This has hampered extraction tests with the DCD since the resulting large vertical beam size is defocussed in the DCD (Sect. V). A series of experiments were organized to determine the cause of the vertical emittance growth.

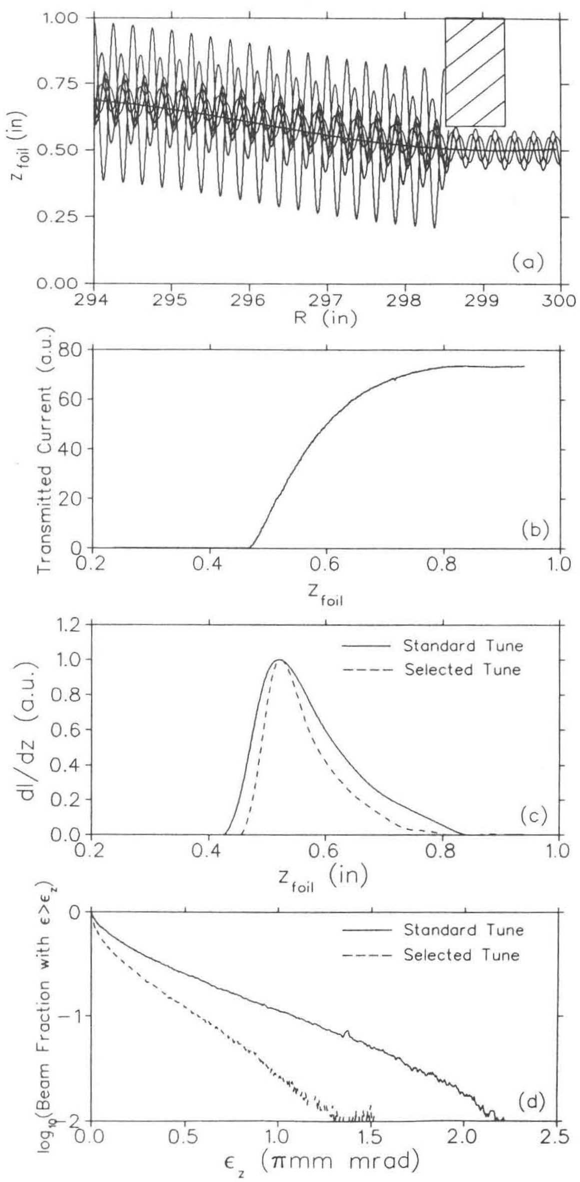

Figure 5: A schematic summarizing the foil dip method for determining vertical beam width and emittance. The beam transmitted (a) past the foil of height z is measured (b) and the result can be differentiated to produce the vertical half width (c) or plotted on a log scale to show the fraction of the beam lying outside a given emittance (d).

Vertical beam widths and emittances were determined by measuring the beam transmission as a function of foil height for a wide totalling intercepting foil. As long as the foil is wider than $\frac{dR}{dn} \cdot 1/\nu_z$, and $1/\nu_z$ is not an integer, and coherent oscillations are small compared to incoherent then the foil will intercept all particles when it has dipped to the center of the beam. Fig. 5 summarizes the foil dip method. The measured beam (b) can be differentiated to produce the vertical half width (c) or plotted on a log scale to show the fraction of the beam lying outside a given emittance (d). This last plot is useful for displaying halos in the vertical distribution [6]. The emittance is calculated from the vertical width using the relation $z_{\frac{1}{2}} = \sqrt{\epsilon_z \beta}$. The calculation assumes a properly matched centered beam. A stretched or off-centered beam may give misleading emittance results. Off-centered cases are typified by a more symmetric rounded vertical width plot as compared to the asymmetric width plots shown in Fig. 5(c).

All vertical width measurements were taken at the extraction energy of 452 MeV using a 1.9 cm wide by 2.5 cm long foil. In general a narrow phase band was selected in the center region using a first turn radial flag and a radial slit on the 10^{th} turn to decouple phase dependent effects from the results. The central phase of the narrow band was altered by adjusting the slit radius. Phase variations at extraction were achieved by adjusting the rf frequency. Vertical and radial centering errors were either canceled or forced by adjusting vertical deflecting plates and a B_z harmonic coil in the center region while monitoring the oscillation amplitude at 80 MeV where the turns are still monotonic.

Phases between 10-15° gave a slightly smaller vertical emittance at extraction consistent with stronger focussing in the first turns for these phases [7]. A low to moderate buncher setting gave smaller emittances than bunching for optimum intensity. Increasing the source intensity by 50% above the standard increased the emittance proportionally. Forced vertical centering errors of ± 3 mm at 80 MeV increased the emittance by 50%. Forced horizontal centering errors of ± 3 mm coupled vertically at the $\nu_r - \nu_z = 1$ resonance at 165 MeV to increase the vertical emittance by 80%. Vertical growth due to RFD excitation was observed consistent with growth at the ν_z=0.25 resonance. Since the distribution in phase space is stretched the vertical width cannot be used to calculate the emittance. Flattopping coincident with RFD use has been done but only to stabilize the precessional radial density pattern [4]. A comparison of the vertical width measurement for the standard high intensity beam and for a phase selected optimized beam is shown in Fig. 5(c,d). The optimized result corresponds to an intensity equivalent to 60 μA at full duty cycle. The future work will involve achieving the lower emittance result at the required intensity.

VIII. Conclusion

Once beyond the center of the cyclotron almost all emittance stretching effects can be prevented at the point of origin. Magnetic imperfections can be compensated by harmonic coils, vertical stretching at $\nu_z = 0.25$ may be reduced by a redesigned RFD. The coherent radial oscillation, however, is a fundamental feature, nevertheless emittance broadening can be reduced by using the AAC to approach more closely single phase conditions.

IX. References

[1] M.K. Craddock, "The TRIUMF KAON Factory", these proceedings.

[2] R. Baartman, private communication

[3] M. Zach, *et al.*, *Proc. 12th Int. Conf. on Cyc. and Their Applic.*, Berlin, 1989 (World Scientific, 1990) p.368.

[4] R.E. Laxdal, *et al.*, "Beam Test Results using the Auxiliary Accelerating Cavity", these proceedings.

[5] J.B. Pearson, TRIUMF report, TRI-DN-91-K180.

[6] W. Joho, PSI report, SIN-TM-11-14, 1980.

[7] G. Dutto, *et al.*, *Proc. 6th Conf. on Cyc. and Their Applic.*, Vancouver, 1972 (AIP, 1972) p.340.