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EFFICIENT CAPTURE IN AN ACCUMULATOR RING OF 20,000 TURNS OF BEAM INJECTED FROM TRIUMF

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Summary

For the TRIUMF KAON Factory a 450 MeV Accumulator ring is required to match the cw 100 µA beam from the isochronous cyclotron to the first acceleration stage, a 50 Hz 3 GeV Booster Synchrotron. HT ions would be charge exchange injected into the Accumulator through a 250 μ g cm⁻² carbon foil. Approximately 2 A of protons would be accumulated over the 20 ms Booster period and transferred to the Booster in one turn. The first protons injected circulate for about 2×10⁴ turns before extraction. If a substantial fraction of the circulating protons traverse the foil each turn, both the lifetime of the foil and the amount of beam lost would be unacceptable. The proposed acceptances of the Accumulator are 100 π µm horizontally, 30 π µm vertically and 7.6×10⁻² eV-s longitudinally. These are much larger than the TRIUMF emittances of $2~\pi$ mmmrad in each transverse plane and 10^{-3} eV-s longitudinally. It is shown that with simultaneous stacking in the transverse and longitudinal acceptances it is possible to reduce the number of foil traversals per proton to an acceptable number \sim 100.

Introduction

Cyclotrons deliver a high average current by providing a low instantaneous current in a cw mode. This is not suitable for direct injection into accelerators operating in a pulsed manner. Reference l describes the family of rings associated with the TRIUMF KAON Factory Proposal. An accumulation ring (A-ring) will collect cw beam from TRIUMF and transfer it in one turn to a booster synchrotron operating at 50 Hz.

Injection by charge exchange is the most efficient process over many turns and this would require H⁻ ions from TRIUMF. The most suitable TRIUMF extraction energy is ~450 MeV.² The A-ring and Booster rf would be 46 MHz, the second harmonic of the TRIUMF rf, which in turn is a fifth harmonic of the ion rotation frequency in the cyclotron. Beam is injected into stable rf buckets to eliminate losses associated with rebunching. The ring circumference (214 m) is 4.5 times the 450 MeV. Second turn to provide the harmonic doubling.

Each proton extracted from the cyclotron passes once through the stripping foil; in the A-ring the same protons would pass < 20,000 times if a foil were to span the beam pipe aperture. Scattering would increase the emittance of the first beam injected from 2 to ~ 115 π µm. This might be accepted, but the beam power into the foil, the consequent rate of evaporation and radiation damage would lead to an unacceptable short life ~ minutes. The damage caused to the foil by the beam is more important than the deterioration in quality caused by the foil.

TRIUMF and Accumulation Ring Beam Properties

The 135 μ A beam currently extracted by stripping has the properties (presented to the extraction foil) given in Table I. These may be compared with the Aring parameters.¹ A gap is provided for the rise time of an extraction kicker by leaving 5 of the 45 buckets empty.

Table I			
Beam Property	TRIUMF	Accumulator Ring (at end of cycle)	
Horizontal emittance (μm) Vertical " (μm) Longitudinal " (eV-s) ΔΕ (MeV) Δφ (rf MHz) Current {Peak/Mean} (A) Protons/bucket	2 0.003 0.7 ±3° to ±1 {15/1}×10 3×10 ⁷	100 33 0.076 5.8 ±135°(46) 4 {2.8/2.0} 3×10 ¹¹	

The parameters in Table I, a lattice³ with 6 superperiods and tunes $v_{\rm X,y}$ of 5.23 and 6.22 and $\beta_{\rm X,y}$ varying from 4 to 14 m give a space charge tune shift increasing monotonically to 0.15. An rf voltage of 350 kV, greater than the beam-induced voltage, is used to permit straightforward stabilization methods. The growth factor from coupled bunch instabilities is estimated to be 1.4; the change in synchrotron frequency, $w_{\rm g}/w$, during accumulation is 0.00363 to 0.00348 and microwave instabilities are unimportant.¹

Accumulator Stripping Foil

Charge exchange cross sections from Ref. 4 imply that a carbon foil thickness of $250 \ \mu\text{g/cm}^2$ is necessary to convert at least 99% of the HT to protons. Carbon was chosen for the initial study because of its high thermal emissivity, melting point and low vapor pressure which means that the rate of evaporation for a given input power will be low. Energy loss and multiple scattering contributions will also be small compared with the heavy refractory metals.

The TRIUMF 5 mg/cm² pyrolytic graphite foils are supported on two adjacent sides and have extracted currents in excess of 200 μ A cw. The proton spot is 2×10 mm², the stripped electrons deposit power over an area somewhat taller than this. No evaporation or simple thermal damage has been seen. A foil is exchanged when operators feel that the extracted beam halo has increased or when the foil is suspected of curling at high intensity. The lifetime between changes is 42±17 mAh and is ascribed to radiation effects. This is equivalent to 5×10²¹ p/cm² and agrees with the values of Livingstone⁵ obtained with low energy heavy ions. This lifetime and that determined by evaporation (10% of thickness) at high temperatures⁵ are combined in Fig. 1 assuming a uniform beam power distribution. The longer, more useful, lifetime is set by the radiation effects.



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Phase Space Manipulation

The ratio of H^- emittance to A-ring acceptance is small and the stripping foil need only occupy a portion of the ring aperture. Assume that the inner vertical edge is set inwards from the edge of the acceptance by an amount equal to the horizontal beam width plus an allowance for ease of operation. For the moment we ignore scattering and energy straggling from beam-foil interactions and concentrate only on geometric effects.

Horizontal Plane

In a phase space with appropriately normalized coordinates, $X = x/\sqrt{\beta}$ and $X' = ((\alpha/\sqrt{\beta})x + x'\sqrt{\beta})$, the betatron motion follows a circular path and matched emittances and acceptances are also circles with radii $\sqrt{\epsilon}$ and \sqrt{A} . Figure 2 shows a matched beam from the cyclotron impinging on the stripper foil displaced from the equilibrium orbit and its position, rotated $2\pi\nu_X$, one turn later. Provided $m\nu_X/n \neq 1$, where m and n are integers, injected turns will be smoothly spread around the annulus (r_1, r_2) . The fraction of turns, f, passing through the foil is the ratio of the shaded area to that of the annulus

$$f = (\theta r_2^2 - r_1^2 \tan \theta) / \pi (r_2^2 - r_1^2)$$
, where $\theta = \cos^{-1} (r_1/r_2)$ (1)

From Table I $r_2 = \sqrt{100}$, $r = \sqrt{2}$ and f = 0.18. After n turns have been injected into the accumulator the first turn has traversed the foil 1+(n-1)f times, while the last turn has traversed the foil once. The average being nf/2.



Fig. 2. The cyclotron beam stripped by a foil located at the edge of the accumulator acceptance precesses $2\pi\nu_{\rm X}$ per turn. Continuous injection over many turns fills an annulus, the fraction interacting with the foil in any turn is indicated by the shaded area. Normalized co-ordinates are used.

At the start of injection bump dipole magnets may be powered to move the ring equilibrium orbit (E.O.) from the beam pipe centre to the foil edge. Here $r_1 = 0$, $r_2 = 2r$ and f = 0.5. As injection proceeds the bump fields slowly fall and the beam first accumulated follows the E.O. adiabatically back to beam pipe axis. When the E.O. displacement is $(r_2 - 4r)$ this beam no longer traverses the foil. The beam now injected has, momentarily, $r_1 = 2r$, $r_2 = 4r$ and f = 0.28. The rate of orbit collapse may be chosen to give a fairly constant power input to the foil or for a desired distribution in phase space. This E.O. sweep reduces the mean fraction of foil traversals a further factor $2\sqrt{\epsilon}/(\sqrt{A} - \sqrt{\epsilon})$ or "0.33. A sweep starting with E.O. coincident with the H⁻ beam produces a somewhat smoother distribution.

If the H⁻ injection beam line were to form a narrow waist on the foil a moderately elongated ellipse would be injected mismatched to the A-ring acceptance. The foil width could be reduced and the E.O. sweep would move the beam off the foil in fewer turns. Too large an eccentricity may require the beam be injected inside $(\sqrt{A} - \sqrt{2})$ or cause scattered particles to fall outside the acceptance, both are undesirable.

Vertical Plane

The foil height would span the vertical acceptance of the Accumulator. The oscillations of a beam with an initial vertical displacement from the E.O. would not reduce the number of beam-foil interactions but would increase the area exposed and extend the lifetime. A programmed steering magnet could be used to give the larger vertical amplitudes to the initial beam i.e. that with smaller horizontal amplitudes.

Longitudinal Plane

A particle displaced from the E.O. in either momentum or phase with respect to the rf will move around a closed path in $(\Delta p/p, \phi)$ space, e.g. Fig. 3. There will be an associated displacement in position $x_s = \eta(\Delta p/p)$, thus the synchrotron motion can move the beam away from, then back to, the foil. Injection with a momentum displacement and $\phi = 0^{\circ}$ minimises the over-lap of foil and acceptance area. In addition the interactions in the foil lower the beam energy thus the fraction of traversals is less when the injected Δp is positive. The longitudinal acceptance may be filled by using an auxillary cavity in the injection line to ramp the H⁻ energy or by tuning the A-ring rf phase and frequency to depress the acceptance buckets with respect to a fixed energy H^- beam as in Fig. 3. The line density may be made to decrease monotonically either side of a central peak. A filled acceptance is less effective in reducing foil traversals than one outer annulus; however the latter may present operational or stability problems.



Fig. 3. Filling the longitudinal acceptance by adjusting the frequency and phase of the 46 MHz rf to lower acceptance buckets with respect to the incoming beam momentum.

Figure 4 adds synchrotron motion (along line MN) to the motion in horizontal phase space. The maximum horizontal displacement due to the synchrotron motion in this representation is $X_{\rm S} = (n_{\rm X}/\sqrt{\beta})(\Delta p/p)$ and the divergence $X_{\rm S}' = (\alpha n_{\rm X}/\sqrt{\beta} + n_{\rm X}'\sqrt{\beta})(\Delta p/p)$. Synchrotron oscillations and a matched (dispersed) beam require a wider foil and this reduces the effect of the original stacking in transverse phase space. That part of the increase, darker shading, due to divergence may be removed by setting $\alpha = 0$ and n' = 0; the situation at the centre of a focusing quadrupole. The A-ring lattice could then be designed with the foil at the midpoint of a focusing quadrupole divided into two sections. Two bump magnets at the focal points would sweep the equilibrium orbit. A combining magnet after the first bump would merge the H⁻ beam and circulating protons.

Following one circuit in $(\Delta p/p, \phi)$ space we see that the momentum falls slowly after injection while



Fig. 4. Stacking in horizontal phase space showing betatron and synchrotron motion. The centre of the injected emittance precesses in synchrotron motion. The centre of the high-ten emittance piecesses in a circular manner about a centre oscillating alowly along line MN. X_g and X_g' depend on lattice parameters n and n' and the difference from central momentum and synchronous phase.

$$X = X_s + X_\beta = (\eta_x/\beta)(\Delta p/p)\cos\omega_s t + \sqrt{\beta}\epsilon \cos\nu_x t$$

many transverse precession cycles occur with the turn factor f above. At some point the associated displacement X_S has decreased sufficiently that the beam leaves the foil. The last traversal is at time t_0 , and the beam next hits after $t = T_s - t_0$. See Fig. 5.

$$t_0/T_s = (1/2\pi) \cos^{-1} \{1 - w/((\eta/\sqrt{\beta})(\Delta p/p \pm \delta p/p))\} (2)$$

 ${\rm T}_{\rm S}$ is one synchrotron period and w is the foil width. For $\eta = 6$ m and $\beta = 14$ m and the maximum momentum offset the turn factor is reduced by ~3. The foil width required may be reduced further by injecting an achromatic beam at the cost of a small reduction in acceptance for the higher momenta.



Simulation Program

The statistical fluctuations in excitation and ionization of carbon are described, for thin foils, by the Landau distribution. For 450 MeV protons and $250 \ \mu\text{g/cm}^2$ carbon the mean energy loss is 640 eV, the most probable loss 350 eV while 0.1% lose between 3.5 and 1200 keV. About 4 angular scattering events occur per traversal and plural scattering theory⁷ is used. The mean rate of emittance growth/traversal is $0.005~\pi$ µm horizontally and $0.01~\pi$ µm vertically. The estimated beam loss from large angle nuclear scattering events in the foil is 0.03%. A vacuum of 10^{-7} cm and nuclear cross section of 230 mb leads to a distributed loss of 0.4%.

The Monte Carlo code BAS populates the 6-dimensional phase space of the H^- beam presented to the foil. Scattering and energy loss effects are added and the revised coordinates are transported to various locations around the ring using linear transfer matrices and a test made at each location to see whether the particles lie outside the beam pipe. At the voltage gaps the energy and phase are modified acording to the usual equations for synchrotron motion. After one turn a test is made to see whether a particle hits or misses the foil. In the former case scattering and energy

loss are incorporated, the phase space co-ordinates $(x,x',y',\Delta p/p)$ updated, and the energy loss added into V the appropriate bin over the foil surface. The incoming distribution is added to the total distribution, any E.O. sweeping adjustments made and the calculation continued. In practice 10 to 100 turns are made between injections of new particles to reduce CPU time. Table II shows the computed efficiency of the methods above, alone and in combination.

Table II Relative Effectiveness of Methods

	nF-mean # of foi traversa	Estimated 1 foil life 1s
a)Horizontal sweep of closed orbit (20 mm ² spot area	740 1)	0.5 h (evapor- ation)T=2260°K
b)Beam focused on stripper (unmatched beam)(20 mm ²)	370	l.5 h (radiation)
<pre>c)(b) + vertical sweep of c.o. (interaction area now 100 mm²)</pre>	370	7 h (radiation)
<pre>d)(c) + programmed sweep + ramping energy</pre>	100	24 h (radiation)

Conditions: injection continuous over 20,000 turns 100 uA beam

foil area 100 mm^2 for (c) and (d).

Conclusion

A solution exists to the problem of matching a cw H cyclotron to pulsed machines of frequency 50 Hz. The mean number of proton passes during accumulation can be reduced to 200 with further reductions possible for optimized conditions. The foil lifetime is acceptable and, although calculations have been made for carbon, it may be that some other metal may be more suitable in radiation dose limited cases. Not all sweeping techniques need to be employed to their full extent for accumulation, however, beam stability and proper matching to the booster may require them. Extended treatments may be found in Ref. 8.

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References

- 1. M.K. Craddock, et al "The TRIUMF KAON Factory" This Conference
- 2. R.E. Laxdal and G.H. Mackenzie, "RF Devices to
- Improve H Extracation Efficiency. This Conference 3. J.I.M. Botman, M.K. Craddock and T. Suzuki, "Magnet Lattices," this conference.
- 4. R.C. Webber and C. Hojvat, IEEE NS-26, 4012, 1979
- 5. A.E. Livingston, et al, Nucl. Instrum. Methods 148, 125 1978.
- 6. M. Hock et al., Journ. Phys. Chem. 59, 97 (1955).
- 7. E. Keil, Z. Naturforsch., <u>15A</u>, 1031, 1960.
 8. J.R. Richardson, TRI-DN-83-30; C.W. Planner,
- TRI-DN-84-63; D. Raparia, MSc Report, University of Manitoba, 1984.