IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985 2453

BEAM DYNAMICS OF RF DEVICES TO IMPROVE THE EFFICIENCY OF PROPOSED H^- EXTRACTION FROM TRIUMF

R.E. Laxdal and G.H. Mackenzie
TRIUMF, Vancouver, B.C., Canada V6T 2A3

Abstract

Future developments at TRIUMF would benefit from the direct extraction of H^- ions in addition to the present stripping extraction of protons. The radial beam density at the first extractor septum must be reduced to achieve 90% extraction efficiency of a 100 μA, 450 MeV beam. Two methods have been considered. Installation of RF booster cavities could triple the energy gain/turn at the septum radius. Alternatively a radial RF field at ν_r=3/2 could generate a coherent betatron oscillation. The subsequent precession could produce local density minima 20% of the average. The beam dynamics for both methods have been investigated using a simple analytic model and a general orbit code. The booster cavities introduce phase-dependent radial and vertical forces (the former leading to phase compression) that may render the motion of some phases unstable. Large coherent oscillations may be unstable near the resonance. Operating tolerances are specified and successful test results of the second scheme are presented.

Introduction

TRIUMF presently accelerates H^- ions to 500 MeV and can extract up to three cw proton beams of 170 μA total intensity by stripping. This extraction scheme is 99.95% efficient and provides a simple method for changing beam energies. The extraction of H^- ions would be desirable for charge exchange injection into a higher energy accelerator,[1] as well as offering other benefits (e.g. beam splitting, halo removal). At the TRIUMF intensity and energy, the extraction process must be efficient to reduce power loss and induced activation. We are able to maintain separated turns to 200 MeV. From 200-500 MeV a uniform beam density exists as the turn separation decreases. Higher energies are preferred by users, simplify designs of subsequent machines and greatly reduce the radial deflection needed to exit the cyclotron. Electromagnetic stripping losses increase rapidly from 400-500 MeV to a maximum of ~10%. These considerations led to the choice of 450 MeV as optimum extraction energy.

The chief difficulty in extracting efficiently at this energy is the high uniform beam density. Fortunately it is possible to tailor the phase space of an H^- beam before extraction by means of simple foil arrangements.[2-4] The first septum can be protected by a shadowing stripping foil[4] which would divert the stripped beam down an existing beam line. H^- extraction efficiency could be improved by diluting the beam density at this foil. Two 1 m long electro-static deflectors, followed 2-1/4 betatron cycles later by two magnetic channels will deliver the beam to an exit horn.[5]

Beam Characteristics

The rf (23 MHz) phase width of the circulating beam is typically 20° (FWHM). This figure can be reduced at the cost of intensity using a first turn radial flag and a 6th turn slit. Fig. 1 compares the turn width due to incoherent betatron motion (ε_x = 1 πmm mrad) and from a ±5° phase band, with the turn separation for the peak energy gain per turn of 0.32 MeV. The proposed booster synchrotron design demands a phase band of H^- ions of ≤±12°. However, should single turn extraction be necessary a third harmonic[6] must be added to the fundamental rf voltage and the accelerated phase band limited to ±5°, demanding a bright source for 100 μA extraction.

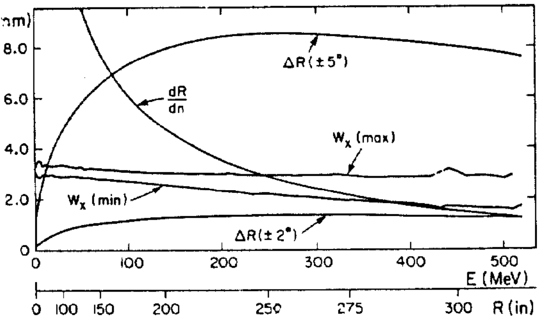

Fig. 1. Present TRIUMF parameters. dR/dn is the radius gain per turn, W_x is the radial incoherent width occupied by 1πmm mrad at the azimuths of maximum and minimum extent. Also shown is the radial width for central ray beams with ±2° and ±5° phase bands.

Beam Dilution

Cyclotron physical constraints and anti-septum geometry demand that the first septum lie ~50 cm downstream from the pre-septum foil.[5] A 1 mm wide foil is needed to protect a septum of projected thickness 0.5 mm due to beam divergence of ±0.4 mrad. Consequently, up to half the beam would be intercepted with the present turn separation of 1.5 mm. Two methods have been proposed to locally dilute the turn density at the preseptum foil. Additional accelerating cavities (120 kV) would be added to increase the energy gain per turn by a factor of three. This would have the added benefit of reducing the number of turns, hence the electromagnetic loss, during normal operation. There would also be a proportional reduction in the beam phase spread and average phase excursion due to phase compression.[7] The other scheme uses a radial rf electric field to excite the ν_r=3/2 resonance at 428 MeV. A relatively low voltage (25 kV) generates a large radial coherent oscillation and the subsequent precession leads to large variations in turn density.

Beam Dynamic Models

Theoretical estimations and simple computer calculations were done using a model describing changes in p_θ, p_r, and p_z by an impulse localized at the mid-point of the rf field in a flat (azimuthally constant), isochronous ($B = \gamma B_c$) field. More accurate calculations use the general orbit tracking code, GOBLIN, with both the flat field and the measured TRIUMF field. The linear motion code COMA[8] was used for Monte Carlo type studies of beam distribution and extraction efficiency.

RF Cavities

In the RF Booster option, three booster cavities[9] operating at a harmonic of the 23 MHz fundamental frequency and at 120 kV peak voltage would be used to increase the energy gain per turn from 0.3 to 1.0 MeV. The cavities would be λ/4 wide in the radial direction and βλ/2 long in the azimuthal direction so that the ion receives two comparable energy kicks per passage.

Figure 2 shows median plane fields for two different cavity geometries. The radial gradient in the time varying azimuthal electric field $E_\theta(r) \cdot \cos(h_b\phi)$ generates a magnetic $B_z(r) \cdot \sin(h_b\phi)$ or electric $E_r(r) \cdot \cos(h_b\phi)$ field that gives a radial kick to off-phase particles given by

$$\Delta p_r(\mathrm{eV/c}) = 2/\omega_b \cdot dV/dr \cdot \sin(h_b\phi)$$

0018-9499/85/1000-2453$01.00© 1985 IEEE

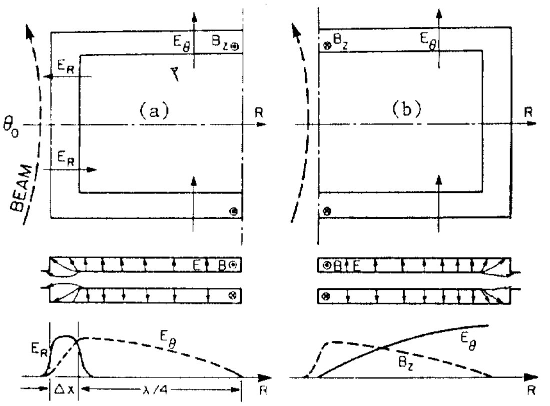

Fig. 2. Two cavity designs with the mid-plane fields as seen by the accelerating particles.

where h_b and ω_b are the harmonic and frequency of the cavity, ϕ is the phase of the particle and V is the accelerating voltage. This is the field responsible for phase compression. Near $\nu_r=3/2$ these kicks can be strong enough to exceed the focussing of the machine, opening the radial stop band over several turns leading to a stretched radial phase space. A simple impulse matrix analysis leads to the stability condition

$$-1 < -\cos 2\pi\delta + G/(2\nu_r\gamma)\cdot\sin 2\pi\delta < 1$$

where $\delta=3/2-\nu_r$, $G=dp_r/dr\ \sin h_b\phi$ and $p_r=R_c/m_oc\cdot\Delta p_r$(eV/c) is the maximum integrated radial momentum kick per passage. For large gradients in the radial momentum perturbation, the stability condition may not be satisfied for positive phases where $\nu_r<3/2$ and for negative phases where $\nu_r>3/2$. GOBLIN results for two values of gradient are shown in Fig. 3a and b. The ellipse shape is plotted at the R,ϕ value of the central orbit particle every 5 turns in case a where $G_{max}=1.5\cdot\sin(5\phi)$ and every 60 turns in case b where $G_{max}=0.22\cdot\sin(5\phi)$. As the particle passes through the cavity the turn separation increases and the phase spread decreases.

Vertical motion was studied in a similar manner. Particles off the mid plane experience phase dependent vertical kicks proportional to the gradient in the accelerating field. These kicks can be large enough to exceed the natural vertical focussing in the cyclotron leading to vertical beam blow-up. For both motions cavity (b) was satisfactory. If separated turn extraction is required the booster cavities must have positioning stable to within <±0.25 mm and voltage stable to <±0.08%. Also, since h≃20 the isochronism may have to be improved over the accelerating range of the boosters.

RF Deflector

For many years it has been common to use a magnetic imperfection at an integer resonance to develop a coherent radial betatron amplitude and thus add a precessional component to the radius gain per turn to achieve separated turn extraction. It would be difficult even with additional equipment to tune TRIUMF to $\nu_r=1$ at 450 MeV without beam loss due to phase slip. Tuning to $\nu_r=2$ would introduce vertical defocussing. At a half-integer resonance a static magnetic imperfection stretches the radial phase ellipse without displacing the phase ellipse center. However, a coherent oscillation amplitude could be developed if, near $\nu_r=3/2$, the beam is given radial kicks alternating in direction on every turn. This technique is similar to the rf knockout scheme used in cyclotrons and synchrotrons to measure the betatron tune.

A radial rf electric field extending over a 10 cm radial range is tuned to excite the 3/2 resonance which is ~7 cm wide. At a frequency of 11.5 MHz, 5/2 the particle rotation frequency, each of the five particle bunches per turn receive radial kicks that alternate in sign on every turn. (By using a square wave at 2.3 MHz or by accelerating only one bunch per turn we could increase the efficiency of the scheme by a factor of two. However the former is difficult from an engineering viewpoint and the latter reduces our intensity.) Ions make ~80 turns in the resonance region so a relatively weak RF field will develop a large coherent amplitude; ($A_c \simeq 5$ cm for 1 kV/cm•m). For $\nu_r>3/2$ the radius gain per turn from precession can be several times that due to the accelerating field, $\Delta R \sim A_c\cdot\sin 2\pi(\nu_r-1.5)$, where we have included the factor of two reduction when accelerating all bunches. A GOBLIN output is shown in Fig. 4 for an RFD field of 110 V/mm•m. Odd and even turns are joined by different values to show the precession. The effective radius gain per turn is also plotted. The pre-septum foil would be positioned in a broad maximum of this curve. Comparable beam dilution is achieved at less power than with the RF Boosters; however there is no reduction in electromagnetic stripping or in phase spread.

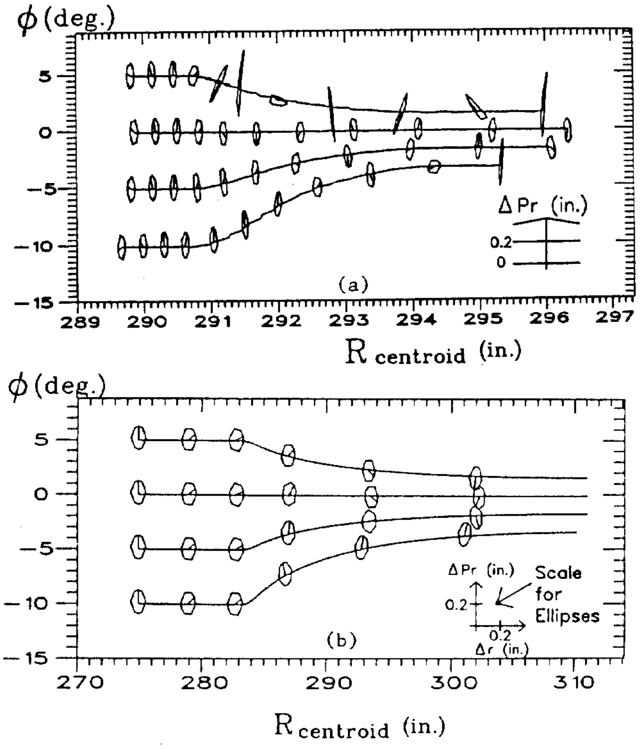

Fig. 3(a,b). Radial ellipses from GOBLIN plotted in R-ϕ space every 5 turns for cavity (a) and every 60 turns for cavity (b). In (a) the steep gradient in the radial momentum kick stretches the emittance.

The general characteristics of this scheme were first investigated using the flat field model. Since $\nu_r=3/2$ the precession patterns observed at one azimuth are periodic every 120°. The optimum turn dilution conditions occur at azimuths 100°+n•120° downstream from the RFD. GOBLIN calculations using the measured TRIUMF field showed that superimposed on this 120° pattern was a pattern periodic in sector structure (60°) due to the aspect ratio of the horizontal acceptance. The resultant pattern defined certain optimum azimuths for positioning the RFD and the pre-stripper of the first septum deflector.

GOBLIN results indicated two limitations on the amplitude of the RFD voltage. Firstly the RFD perturbs the central orbit so that at azimuths other than at the

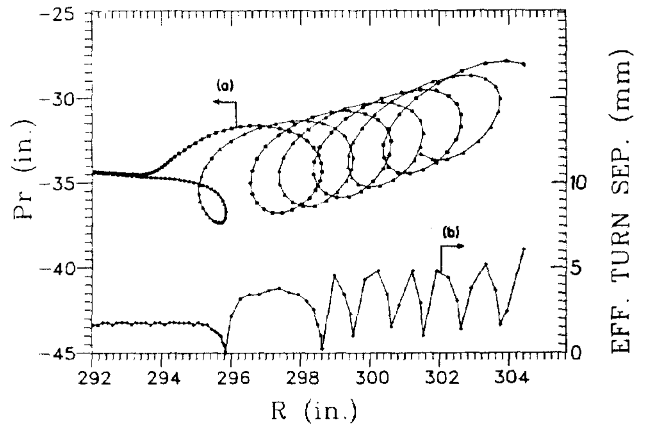

Fig. 4. Curve (a) shows coherent oscillation generated by RFD (110 V/mm·m) for $\nu_r > 3/2$; $p(in) = 4.3 \times 10^{-7} p(eV/c)$. Odd and even turns are joined separately. Curve (b) shows the effective turn separation produced.

pre-septum stripper position the orbits of previous turns may lie outside the orbit selected for extraction. In this case the separation, generated by the electrostatic septum, of the extracted orbit from the circulating beam will be reduced. For RFD fields larger than 200 V/mm·m the pre-extraction orbits begin to overlap the extracted orbit for practical deflector strengths. The second limitation arises from the increase in the number of turns spent near the unstable fixed points of the intrinsic 6/4 resonance as the coherent amplitude is increased. The small residual gradient in the third harmonic of the magnetic field (~0.06 G/cm) can cause beam stretching of the radial ellipse for low fields (100 V/mm·m) while at higher fields (>250 V/mm·m) the beam is lost. In practise higher voltages could be used if additional third harmonic trim coils were added to the cyclotron at the extraction radius to reduce the existing gradient. However it appears that the first limitation on the RFD voltage will be more restrictive.

COMA was used to study extraction efficiency. It was found that for typical values of emmitance (ε_x = 1πmm mrad) and phase spread (±5°), the decrease in beam density at extraction corresponds directly to the increase in the radius gain per turn of the central ray.

Experimental Results

In March 1985 a prototype RFD was installed in the cyclotron.[5] RFD fields ranging up to 120 V/mm·m were tested. The incoherent oscillations and the phase band were limited to 2 mm and ±5° and the coherent amplitude reduced to <1 mm. In Fig. 5 two scans from a 1.25 mm radial differential probe compare the beam density for the RFD off and on (110 V/mm·m). The density modulations with RFD off are due to ellipse stretching and subsequent precession due to the existing gradient in the third harmonic.[10] The gain in the extraction efficiency, that is the ratio of beam with RFD off to RFD on at a density minimum was found to be linear with excitation field over the RFD voltage range tested, and is given by Gain = 1 + field/42.4 V/mm·m. This agrees with GOBLIN results to within 10%.

A 2.4 mm wide foil was inserted into the circulating beam 1.8 m upstream from the differential probe. The resulting probe scan, Fig. 6, clearly shows the absence of beam in the shadow cast by the foil and in several subsequent turns. The fact that existing equipment was used for this test necessitated a foil wider than intended for the future. The figure confirms estimates of beam divergence and turn spacing.

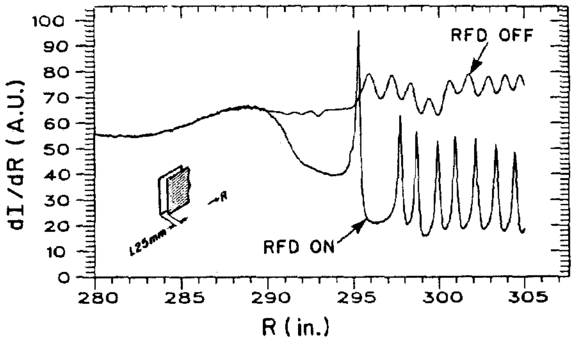

Fig. 5. Beam density measured by a differential probe head, 1.25 mm wide for RFD off and RFD on (110 V/mm·m).

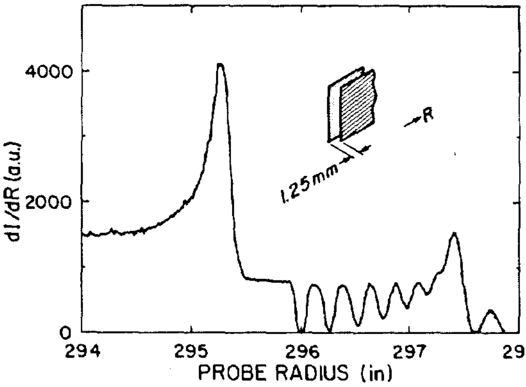

Fig. 6. Beam density on a 1.25 mm differential probe showing the beam free shadow from a 2.4 mm wide foil, 1.8 m upstream. The leading edge of a septum would be placed in the beam free region from such a foil.

A 0.03 mm wide foil positioned in a region of reduced dE/dr gave an energy spread in the extracted 445 MeV beam of 85 kV (FWHM), a factor of three down from the RFD off condition. A 7.6 mm wide foil was inserted to extract the whole beam, simulating the future extracted H^- beam. The energy spread was <450 keV.

De-tuning the isochronism and the centering had little effect on the dilution pattern proving the inherent stability of the RFD extraction scheme. The turn density pattern is virtually independent of cyclotron instabilities that occur before ν_r=3/2, and depends only on the RFD voltage and the isochronism for E>400 MeV. Therefore once the pre-septum stripper is positioned in a beam density minimum the stripped current should be quite stable.

References

[1] M.K. Craddock et al, The TRIUMF Kaon Factory, in these proceedings.
[2] J.R. Richardson and M.K. Craddock, Proc. 5th Int. Cyclotron Conf., 85, 1971.
[3] C.J. Kost and G.H. Mackenzie, Proc. 9th Int. Cyclotron Conf., 493, 1981.
[4] W. Joho, TRIUMF report, TRI-DN-82-13.
[5] M. Zach et al, The H^- High Intensity Beam Extraction System for TRIUMF, in these proceedings.
[6] T. Enegren et al, Development of Flat-topped RF Voltage for TRIUMF, in these proceedings.
[7] W. Joho, Particle Accelerators, 6, 41 (1974).
[8] C.J. Kost and G.H. Mackenzie, IEEE Trans. NS-22(3), 1922 (1975).
[9] J.R. Richardson, TRIUMF report TRI-DN-83-50.
[10] R. Baartman, G.H. Mackenzie and M.M. Gordon, Proc. 10th Int. Cyclotron Conf., 42, 1984.