PLANS FOR THE EXTRACTION OF INTENSE BEAMS OF H^- IONS FROM THE TRIUMF CYCLOTRON

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Summary

Plans are presented for the cw extraction of H^- ions from TRIUMF for subsequent injection into an accumulation ring. For the injection of thousands of turns only charge changing processes are practicable and H^- ions offer more flexibility than H^0 atoms. The mean radius gain per turn at extraction, 1.5 mm, can be tripled by auxiliary RF cavities which increase the energy gain per turn from 0.3 to 1.0 MeV. The turn separation at a deflector entrance may also be augmented by precessional techniques using the $\nu_r = 3/2$ resonance. The H^- beam will then enter an electrostatic deflector with a positive voltage followed by a second deflector and standard magnetic channels. Our orbit codes have been modified to obtain trajectories in extended regions of time-varying electromagnetic field. Emittance, intensity and efficiency of extraction are discussed together with the tolerances required. The conceptual design of the deflection elements and the RF cavities and amplifiers is described. Alternative schemes for the extraction of H^0 atoms and H^- ions in 200 turn packets are briefly reviewed.

Introduction

TRIUMF presently accelerates H^- ions and extracts 1 to 3 independent cw proton beams of up to 170 μA at variable energies simultaneously by stripping. The RF (23 MHz) phase width of these beams is about 20° (2.5 ns) FWHM. This latter figure can be reduced at the cost of intensity to typical values of 12° and 25 μA, 5° and 10 μA, or 2° and 4 μA.

A task force has been formed with the mandate of extracting beams of different charge states (H^0, H^-) and/or time structures with intensity approaching 100 μA in all cases. A pulsed beam would be obtained by compacting many turns in space and extracting them together as one turn 217 ns long. Several means of compaction are discussed by Laxdal et al.[1]

These beams are useful in their own right; for example compacted beams with the appropriate time structure would improve signal to noise in μSR work and short half-life isotopes studies, and in some experiments using time-of-flight techniques. Unstripped or partially stripped beams offer the possibility of clean, well defined optics and easy beam splitting. They will also be important for efficient injection, by charge exchange, into a following accumulation ring or accelerator.

This paper will emphasize our most recent efforts which are to devise a scheme to extract a beam of H^- ions cw at an energy of 430 MeV, just below significant electromagnetic loss and induced radioactivity. It should be noted that $\nu_r = 3/2$ near this energy.

Beam Preparation and Properties

The phase interval is defined initially by a first-turn radial flag and a ~6th turn slit. Electrostatic correction plates and a vertical flag are used to eliminate coherent vertical oscillations and minimize the vertical emittance. These are followed by a set of radial slits operating at about 30 MeV, just beyond the radial non-adiabatic region, which may be used to define the radial emittance and in so doing also further define the phase acceptance. Centring can easily be achieved to ≤0.5 mm. The subsequent acceleration is mostly adiabatic. The beam passes twice through a weak coupling resonance and later through the $\nu_r = 3/2$ resonance. Table I and Fig. 1 summarize the beam properties. The cw values have been measured and the

Table I. Beam properties at point of extraction.

	Operational	Slit selected (narrowest)	Turn compacted
Intensity (μA)	130	4	100
FWHM phase width deg. (23 MHz)	20°	2°	90°
Turn radial width 90% beam (mm)	34	1.5	25
ΔE/E(450 MeV)(%)	0.2%	0.1%	1.1%
ε_R βγπmm mrad	1.0	0.16	75.0
ε_z βγπmm mrad	2	2	2

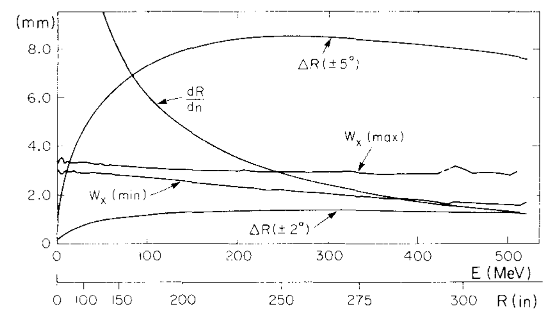

Fig. 1. Present TRIUMF parameters. dR/dn is the radius gain per turn, W_x is the radial incoherent width occupied by 1 πmm mrad at the azimuths of maximum and minimum extent. Also shown is the radial width for central ray beams with ±2° and ±5° phase band.

values for a compacted beam were computed[2] using COMA, a linear motion Monte Carlo code. An intensity distribution may be inferred from Fig. 2.

Extraction Elements

All schemes require that the beam emerge from the vacuum tank horizontally, in the mid-plane. Even at 430 MeV the low average field of 0.47 T allows the use of traditional electrostatic deflectors and magnetic channels. The latter may also provide focussing if necessary.

The major problem in beam extraction is entry into the first septum separating the extracted turns from neighbours still being accelerated. The projected thickness of a typical electrostatic septum is about 0.5 mm and it can be seen from Fig. 1 that, for the standard cw beam, the turn separation from an energy gain of about 300 keV per turn is only 1.5 mm. The beam half-width can be controlled by the slits but would be ~2.0 mm for reasonable intensity.

At lower energies the situation is easier and in fact TRIUMF has long been able to provide completely separated turns at 200 MeV.[3] At the higher energies a means must be found to separate the turns or at least

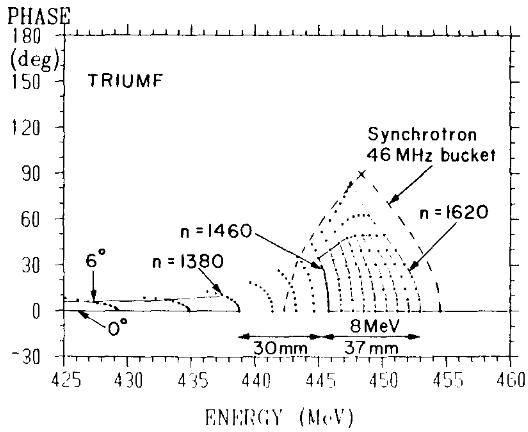

Fig. 2. RF turn compaction in longitudinal phase space (n = turn number in TRIUMF).

dilute the radial beam densities. Fortunately with H^- ions the septum can be protected by a pre-stripper, Fig. 3, which sweeps away the beam that would otherwise

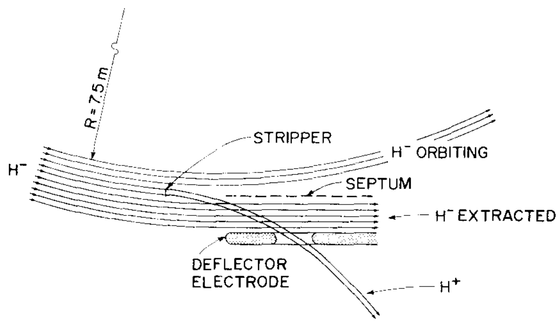

Fig. 3. Deflector with pre-stripper.

hit it. If this swept beam is greater than about 1 μA it cannot easily be dumped in the tank wall. In this case the septum must be positioned so that the swept beam can leave through an exit port. Beams over 10 μA would require use of a major beam line or similar to contain them and of course such a loss may make the achievement of 100 μA more difficult.

Additional radial separation between turns of a central ray may be generated by increasing the energy gain per turn, or by inducing a coherent radial amplitude and adding a precessional contribution. The latter has been achieved elsewhere by accelerating a beam initially off-centre or by inducing a coherent amplitude in a previously centred beam using a field perturbation at an integral resonance, e.g. $\nu_r = 1$. The applicability of these methods to TRIUMF is discussed below.

If an H^- beam of energy much lower than 430 MeV were used for multi-turn charge exchange injection into an accumulator ring then the space charge tune shifts would rise, losses due to multiple and nuclear scattering in the foil would increase and the frequency swing and field excursion of a booster synchrotron of given final energy would be extended. While energies much lower than 430 MeV may just alter the physical aperture, size and cost of a second stage, the use of the alternate beams for TRIUMF experiments would be seriously compromised.

Entry into the First Radial Deflector

Figures given in the following discussion assume that no third harmonic flat-topping has been added to the fundamental 23 MHz RF frequency. Plans are reported[4] to move a buncher much closer to the point of inflection of the beam into the cyclotron and to make other injection line improvements such that the beam density around the central phase accepted by the cyclotron will be doubled. Improvements to the ion source will increase luminosity and thus one may anticipate 100 μA in ±5°. The radial emittance matched to the cyclotron is 1 π mm mrad^2; use of the radial slits could reduce this.

Pulsed Beams

The compacted beam, Fig. 2., would be kicked vertically into a dc or pulsed radial deflector by means of plates about 40 mm wide. A vertical field of 1.4 kV/mm•m would develop a vertical displacement of 21 mm at this energy. The process would be "clean" in that a pulser in the ion source terminal would be used to prevent population of those turns lying in the fringe field of the vertical kicker. However, this duty factor would mean operating the ion source in a mode equivalent to 150 μA accelerated to obtain 100 μA extracted.

Simple Extraction

It can be seen from Fig. 1 that the turns of a 1 π mm mrad beam with ±5° phase band would overlap above 80 MeV. If a flat-topping third harmonic voltage were applied then turns clearly separated by 0.5 mm could be accelerated to ~340 MeV in a stable machine. The present dee voltage instability of ±160 ppm reduces this limit to ~250 MeV and a stability improvement of a factor of 2 is being sought.[5]

It appears that, for the next few years, 100 μA operation will imply a uniform beam density. Monte Carlo calculation for such a beam indicates that a 0.5 mm wide pre-stripper will intercept about 14% of the circulating beam at 200 MeV and 23% at 500 MeV. These figures scale with pre-stripper width, and an acceptable configuration could probably be found for high current extraction at the lower energies.

RF Booster Cavities

The energy gain per turn contributed by the existing RF may be increased by 25% with the installation of re-designed dees within a few years. Larger increases could be obtained by additional cavities at energies >200 MeV. One example[6] that could triple the present energy gain per turn with cavities of relatively small size and low power is illustrated in Fig. 4. It is a coaxial λ/4 cavity, oscillating at 115 MHz. The azimuthal width corresponds to $c\beta_{ion}\lambda/2$ and the ion receives 2 energy increments per crossing. It is hoped that the peak voltage on each device will be about 110 kV. Four cavities would increase the central ray turn separation by a factor 3 to 4. The ion transit time across the 50 mm gap will be 9.5° (115 MHz). As the beam first enters the cavity the $E_r(t)$ component will give rise to a rapid phase compression, from ±5° to ±1.6°, followed by a slow re-expansion as the beam penetrates further. The cavities are positioned just beyond the radius where $\nu_r = 3/2$.

The rate of increase of energy gain, dEg/dR, is presently 16 keV/mm. GOBLIN calculations, using an azimuthally constant isochronous field $\overline{B}(R) = \gamma B_c$, show the expected phase compression and energy expansion. Although the E-ϕ area is preserved it is not, in general, symmetric about the ϕ axis. Some of the first radial kicks experienced by an incoming particle with a certain phase, $\phi \neq 0$, may be so strong that the displaced orbit misses the cavity on the following turn. Particles with the phase of opposite sign are driven deeper into the rising field. The energy difference developed is never made up but can continue to expand. An example is shown in Fig. 5. A smaller slope dE_g/dR

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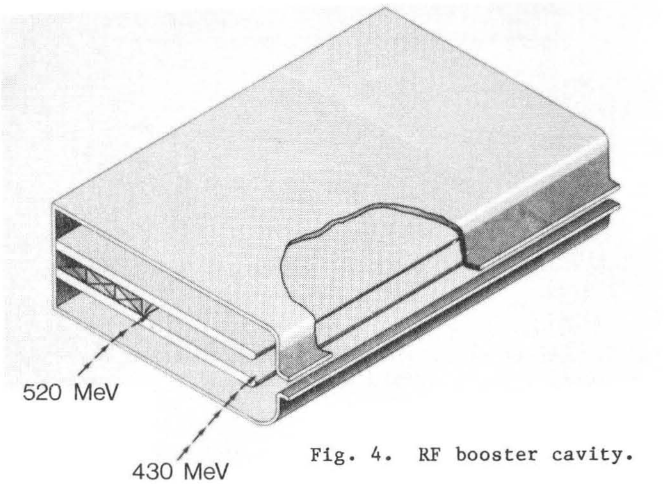

Fig. 4. RF booster cavity.

reduces this non-adiabatic effect. Also, since ν_r is approximately 3/2, three cavities positioned 120° apart at nodes of the induced betatron oscillation should give improved behaviour. The analytic field was used since the measured TRIUMF field is insufficiently isochronous for 115 MHz. The increased energy gain reduces the phase wander but it is possible that the successful operation of cavities at the 25th harmonic of the ion rotation frequency will require special field trimming devices close to the median plane.

Energy expansion results in tight constraints should one wish to locate any beam density structure to ±0.5 mm. The relative position of an incoming beam and the cavities should then be ±0.25 mm, $\Delta V_f/V_f$ < ±80 ppm and the relative phase of a flat-top third harmonic with respect to the dee fundamental frequency is ±0.12° (69 MHz). These tolerances are relaxed should a homogeneous beam distribution be acceptable.[7] The large orbit radius, ~7.5 m, means that a beam compressed to ±2° is still ±5 cm in length for each of five spokes, and 100 μA cw corresponds to a peak pulse current of 2 mA. It has been assumed that longitudinal space charge effects will not alter significantly the radial width of the beam.

Calculations show that the reduced number of turns reduces the total electromagnetic and gas stripping losses by approximately a factor of 2 to 3 between 450 and 500 MeV. Since the cyclotron residual activation is within 85% of the calculated saturation value for beams of 250 mA.h per year these booster cavities would immediately reduce tank activation. On the other hand the increased radius gain per turn would double the beam spot size on the stripper foil.

Generation of Coherent Radial Betatron Amplitudes

An ion with coherent amplitude A_c contributes a radius gain per turn component that alternately adds to

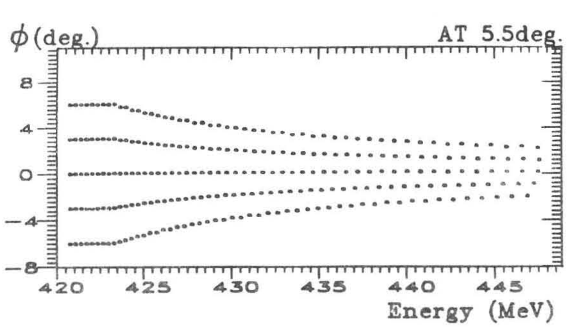

Fig. 5. Asymmetric phase front arising from the rapid onset of booster cavity accelerating field.

or subtracts from that due to the energy gain as the ion precesses. For an upright ellipse the maximum precessional contribution $\Delta R_{p,m}$ is 2 $A_c \sin\pi(\nu_r-1)$ per turn. If $\Delta R_{p,m} > \Delta R_{dee}$ the orbit radius no longer increases monotonically and the true turn clearance depends on the radius of the previous maximum excursion several turns earlier. Small coherent amplitudes of, say 0.5 mm at 30 MeV, have assisted in producing a clearly separated turn at 200 MeV. However, large radial amplitudes, of several mm, cause beam loss at the $\nu_r-\nu_z = 1$ coupling resonances and also vertical excursions in a region where dB_r/dr is large. Measures to compensate these would be necessary should cw extraction require off-centre acceleration through the machine. At the moment large amplitudes must be developed closer to the point of extraction.

It would be difficult, even with additional equipment to tune TRIUMF to ν_r = 1 at 430 MeV without beam loss due to phase slip. Tuning to ν_r = 2 would also introduce vertical defocusing. Magnetic excitation of the ν_r = 3/2 resonance at 438 MeV stretches the ellipse but leaves a central particle unperturbed.[8] A ray initially off-centre may have A_c increased by the stretching factor. A coherent oscillation amplitude could be developed if, near ν_r = 3/2, the beam is given radial kicks alternating in and out e.g. by the electric field illustrated in Fig. 6. If the electric field is flat with radius the stretching should be minor.

Figure 7 shows the results for initial phases −6°, 0°, +6° of a 0.076 kV/mm•m field, starting at 430 MeV (in an attempt to extract the higher energies) using the measured TRIUMF magnetic field. It can be seen that the turn separation of a given central ray is increased to ~1 cm and that the stretching is relatively slight, however, note that the initial emittance corresponded to 0.35 πmm mrad and that all phases started at the same point. In the absence of a third harmonic RF flat-top a continuum of energies will fill in the gaps between the ellipses. Nevertheless a significant dilution factor should be achieved. Gradient components of E_r could enhance the radius gain per turn by opening up the ν_r = 3/2 stop band (regenerative extraction). The resulting stretching may not be deleterious since close to the resonance the ellipses will periodically have a narrow radial projection.[8]

A coherent vertical amplitude could be developed by similar methods. Its utilization would be more difficult due to the smaller vertical acceptance of TRIUMF and the combination of vertical and radial deflectors.

Hydrogen Atom Extraction (H°)

Extraction of neutral atoms is quite feasible at low intensity but problematic at 100 μA. If the stripping device is at the ideal cyclotron azimuth then beam spots of reasonable sizes, up to 5 cm diameter, may be obtained at distances shorter than 100 m. Foil thicknesses of 30 μg/cm^2 C will yield 55% H° atoms but simultaneously give 23% proton contamination. Multiple passes through a much thinner foil will reduce this contamination but not below 4%, a limit set by double charge exchange. All methods to strip the beam must act over an azimuthal width smaller than 0.5 cm of arc so that the divergence of the extracted beam is not significantly increased. This makes it difficult to get sufficient mass in a gas jet; also the use of a localized region of magnetic field would require a 2 T field with a sharp leading edge to strip 99%.

Computer Modelling

To describe the cavities and electrodes discussed above it has been necessary to modify the general orbit

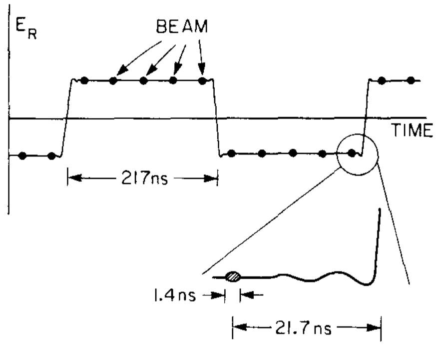

Fig. 6. Alternating radial electric field to induce a coherent radial oscillation near $\nu_r = 3/2$.

code GOBLIN to include extended regions of $E(r,\theta,z,t)$ and $B(r,\theta,z,t)$. The fields studied vary slowly enough in space that the details of the RF current distribution on the surface of the resonator may be neglected and E and H obtained from curlE = -dB/dt. Field propagation times are not included. Monte Carlo calculations are made using our transfer matrix code COMA. COMA, in principle, uses impulse approximations and our new RF fields will have to be parametrized as was the TRIUMF central region field.[9]

Engineering of Extraction Equipment

RF Boosters

Several options for the RF boosters were considered.[10] The selected concept (Fig. 4) calls for four identical cavities built as a shorted $\lambda/4$ long rectangular transmission line capacitively loaded, developing a peak voltage of 110 kV at 115 MHz. The power per unit is expected to be 26 kW of skin losses, and up to 6.5 kW delivered to the beam. The proposal is favoured mainly for simplicity, low RF power, and the fact that the units will not interfere with beam operation at the full energy of 520 MeV. The conceptual design has been completed, and a prototype cavity will be tested within 6 months. The contract for design of a 50 kW amplifier is about to be placed with a local manufacturer and in early 1985 a prototype unit will be tested in a chamber where operating conditions of cyclotron vacuum and magnetic field can be closely simulated.

Electrostatic Deflectors

Two deflectors would be used - one with a positive electrode, the other either positive or negative, depending on its location. Utilizing the SIN experience,[11] radiation cooled, spring loaded Mo strips will be used. Their assembly along the curved beam trajectory with an accuracy of ±0.1 mm over 500 mm, and the holding of ≈60 kV voltage on the positive septum in a magnetic field of up to 0.5 T is considered to be a challenge. An initial study in collaboration with SIN, resulting in a prototype design, is about to begin.

Magnetic Channels

It was found in a feasibility study[12] that a channel of 0.4 T.m with a clearance of 7.5 cm between the channel axis and the last beam turn can be built using iron-free coils. A total weight of ≈200 kg and a power loss of 150 kw are expected. The windings are of radiation resistant pyrotenax and the current is of the order 1000 A. An engineering design of the main and trimmings coils will commence when full requirements are known.

General Engineering

All devices will have to be adjustable in position under operating conditions for achieving the desired

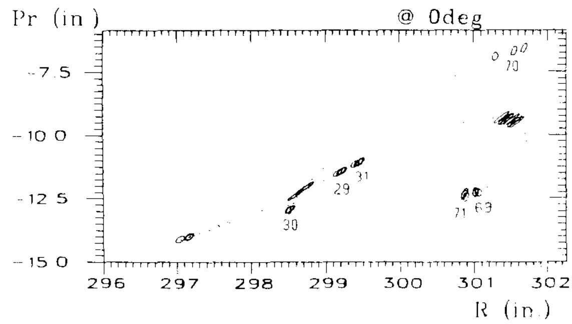

Fig. 7. Effect of a 0.076 kV/mm·m alternating field on three beams with emittance 0.35 πmm mrad and phase -6°, 0° and +6°.

performance and, with the exception of the RF boosters, they must be easily removable from the beam plane for operation at full cyclotron energy. The levels of residual radiation make it necessary to design all hardware for remote installation, servicing and removal.

Status

There appears to be no problem of principle in extracting compacted beams. At present H^- cw beams of 100 µA could be extracted at the lower energies using a simple deflector with 80-90% efficiency. These could be used for injection into a second stage but with an undesirable increase in the latter's cost. The planned improvement program[5] will gradually raise this limiting energy. The RF booster cavities would give similar efficiencies at, say, 430 MeV and have the highly desirable additional feature of reducing cyclotron activation during regular operation. They are considered to be our reference design. The major unanswered question is that of extracted beam quality. Resonant techniques offer a possible alternative route.

The project has the aim of developing the chosen system to the point of demonstrating a beam outside the cyclotron with a charge density equivalent to 100 µA cw at a duty factor of, say, 10%. Equipment common to any system is beginning to be designed and prototypes will be manufactured and tested in a cyclotron simulation chamber. Studies of the less conventional elements are underway together with drafting of models and prototypes for manufacture.

Acknowledgements

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References

1. R. Laxdal et al., IEEE NS-30, 2013 (1983).
2. R. Laxdal et al., TRIUMF report TRI-DN-82-70.
3. E.W. Blackmore et al., IEEE NS-26, 3218 (1979).
4. R. Baartman, G. Dutto and P. Schmor, Paper B39, this conference.
5. R. Baartman et al., Paper C3, this conference.
6. J.R. Richardson, TRIUMF report TRI-DN-83-42.
7. R. Laxdal, TRIUMF report TRI-DN-83-50.
8. R. Baartman, G.H. Mackenzie and M.M. Gordon, Paper B6, this conference.
9. C.J. Kost and G.H. Mackenzie, IEEE NS-22, 1922 (1975).
10. M. Zach, TRIUMF report TRI-DN-83-45.
11. M. Olivo, 7th Int. Cyclotron Conf. (Birkhäusser Verlag, Basel) 292 (1975).
12. E. DeVita, TRIUMF report TRI-DN-84-27.