EXTRACTION EXPLOITING ν_r=3/2: OPTICAL AND TECHNICAL CONSTRAINTS ON PERFORMANCE

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Summary

A demonstration of the feasiblity of directly extracting 100 µA of 450 MeV H^- ions is under way at the TRIUMF cyclotron. The existing turn density must be reduced to achieve an extraction efficiency of ≥90%. The chain of extraction elements consists first of an 11.5 MHz rf deflector placed at the ν_r=3/2 resonance to excite a coherent radial oscillation. Then an electrostatic deflector with a positive voltage is placed at a radius, about 100 turns later, where precession generates a large radius gain per turn. This is followed by a second electrostatic deflector and three or four magnetic channels. A pair of additional 92 MHz rf cavities will triple the radius gain per turn, improving extraction efficiency and reducing electromagnetic stripping loss for proton extraction.

The number and position of the extraction elements is primarily dictated by beam dynamics considerations. Near ν_r=3/2 the orbit of the deflected H^- beam makes three radial oscillations over two turns and the first channel must be placed near a peak in the outward swings. The rf deflector perturbs the circulating orbits reducing and shifting the peaks in separation generated by the electrostatic deflectors. Practical limitations on element strengths and the fringe fields of the magnetic channels impose further restrictions. Finally the location of existing equipment and of existing extraction ports has also to be taken into account. A suitable layout of the extraction elements, as well as experimental testing to date and plans for the future, will all be presented.

Introduction

In many cyclotrons where the beam is extracted directly using electrostatic deflectors and magnetic channels, turn-to-turn spacing is enhanced by employing a precessional extraction technique. The cyclotron field is trimmed to an integer radial tune at the extraction radius and a first harmonic component in the magnetic field creates a large radial coherent oscillation. The subsequent precession causes variations in turn density. In smaller cyclotrons ν_r<1.1 and ν_r=1 is reached naturally at an outer radius where the 'good' field rapidly falls away while still maintaining isochronism.

TRIUMF presently accelerates H^- ions to 500 MeV extracting up to three cw proton beams simultaneously by stripping. Direct H^- extraction would enable charge exchange injection into a higher energy accelerator.[1,2] At the TRIUMF intensity and energy the extraction process must be efficient to reduce power loss and activation. Even at 500 MeV the orbits are still well inside the isochronous field (Fig. 1), so that tuning to ν_r=1 would cause beam loss due to phase slip. Of the several ways available in principle a coherent oscillation could be developed if, near ν_r=3/2, the beam is given radial impulses alternating in direction on every turn to simulate a ν_r=1 situation.

Reducing Turn Density at Extraction

At TRIUMF, separated turns can be maintained to 200 MeV. From 200 MeV to 500 MeV a uniform beam density exists as the turn separation decreases. Despite this, 450 MeV was chosen as the extraction energy since higher energies simplify post-accelerator design and a separated turn condition can be simulated by placing a stripping foil upstream of the first electrostatic deflector to shadow the septum and divert the stripped beam into an existing beam line. Also, beam losses from electromagnetic stripping, which rise rapidly from 400 MeV to 500 MeV to a total of 9%, are only 2% at 450 MeV (Fig. 1).

At this energy the low radius gain per turn (1.5 mm) means that up to half the beam would be intercepted by a 1 mm wide stripping foil. The 450 MeV extraction energy allows precessional enhancement of the turn-to-turn separation by excitation of the ν_r=3/2 resonance. An rf electrode (RFD)[3] produces a radial electric field oscillating at one-half the accelerating frequency. A relatively low voltage (25 kV) generates a large coherent oscillation and the subsequent precession leads to large variations in turn density. In addition, rf accelerating cavities[4] have been designed to increase the energy gain per turn at the extraction radius further diluting the beam density. They offer the additional benefit of reducing losses due to gas and electromagnetic stripping during normal operation. However, in all cases reducing turn density increases the extracted beam size and thus increases the aperture required for extraction components.

RF Deflector

TRIUMF accelerates five particle bunches per turn at an rf frequency of 23 MHz. An rf field at 11.5 MHz, 5/2 the particle rotation frequency, will radially deflect each of the particle bunches in alternate

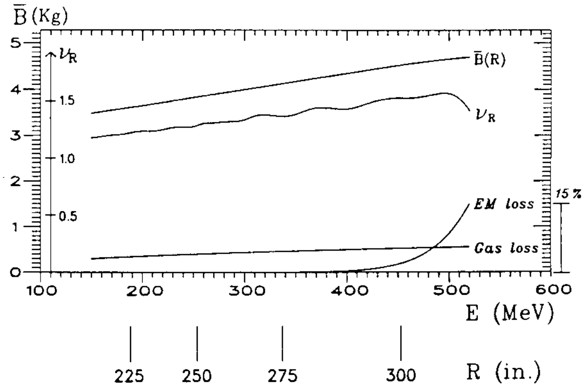

Fig. 1. TRIUMF cyclotron parameters. Shown above are the average magnetic field, the radial betatron oscillation frequency and the cumulative losses from gas and electromagnetic stripping.

directions on each turn. An electric field extending over a ~10 cm radial range is positioned at the $\nu_r=3/2$ resonance. Ions make ~50 turns in the resonance region so a relatively weak rf field will develop a large coherent amplitude (A_c=3.5 cm for 100 V/mm•m). As ν_r grows above $\nu_r=3/2$ the radius gain per turn from precession $\Delta R \sim A_c \cdot \sin 2\pi(\nu_r-1.5)$ can be several times the separation due to the accelerating field. The turn separation due to precession could be doubled if a square wave radial field at 2.3 MHz were employed or if only one bunch per turn were accelerated. However, this enhancement could only be useful if turns are separated; otherwise the beam density is unchanged.

The effect of the rf deflector (RFD) at a relatively low strength is illustrated in the computer simulation shown in Fig. 2. In the lower trace the position of a central particle in a single bunch is tracked in phase space to show the coherent oscillation generated by the RFD (R~297 in.). A particle in an adjacent bunch would follow a similar path in phase space only displaced by a turn. The beam density, given as the amount of beam stripped by a 1 mm protection foil, is plotted as a function of foil position for a beam of emittance $\varepsilon = 1\ \pi$ mm-mrad and phase $\Delta\phi=\pm6°$. The beam density is high where the precession has led to an accumulation of turns and it is low in positions of turn spacing enhancement. The septum protection foil would be positioned in a broad density minimum. For the case shown the RFD has reduced the expected beam loss on a 1 mm foil from 43% entering the RFD to 15% in the third or fourth density minimum, a reduction of 2.9. Computer simulations show that the beam loss reduction is roughly linear to RFD strength and is given by REDUCTION~1+field/(35 V/mm•m).

The RFD strength cannot be increased indiscriminately for several reasons. Firstly, the enlarged turn separation amplifies the radial spread of the beam entering the first deflector adding ~8 mm of width for each 100 V/mm•m of RFD strength. Therefore the gap between septum and shoe (13 mm for TRIUMF) will define an upper limit on the RFD strength. Secondly, the RFD perturbs the central orbit so that at azimuths other than at the protection foil position the orbits of previous turns may overlap the orbits selected for extraction. In this case the separation between the circulating beam and the beam deflected by the electrostatic deflector (DCD) would be reduced. In this case the upper limit on the RFD strength is defined by the maximum stable electric field that can be achieved with the DCD and the separation necessary to enter the first magnetic channel. Finally the number of turns spent near the unstable fixed points of the intrinsic 6/4 resonance increases with the amplitude of the coherent oscillation so that the residual gradient in the third harmonic of the magnetic field could cause beam stretching of the radial ellipse or even beam loss. However, studies indicate that the first two limitations will be far more restrictive.

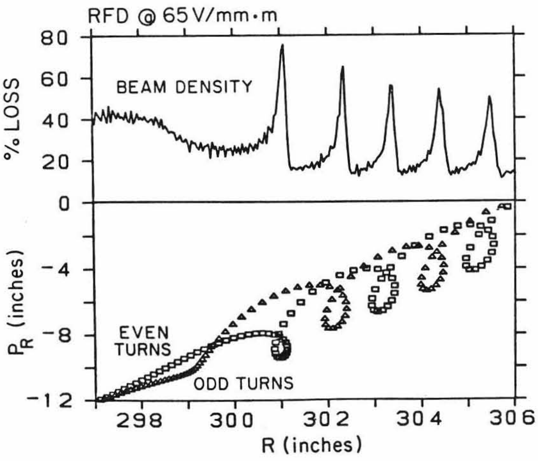

Fig. 2. The bottom plot traces even and odd turns of a central particle in phase space during and subsequent to perturbation by the RFD (R~297 in.). The top trace shows the beam density that results, given as the percentage of the beam that would be lost on a 1 mm foil.

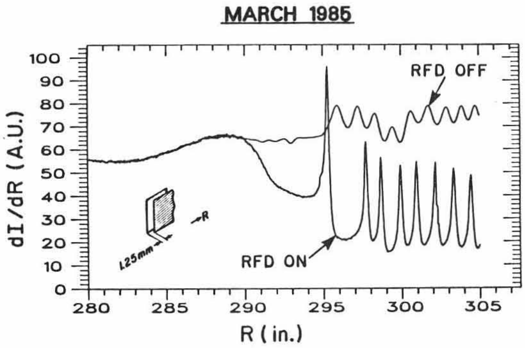

Fig. 3 Beam density measured by a differential probe, 1.25 mm wide for RFD off and RFD on (110 V/mm•m).

In March 1985 a prototype RFD was installed in the cyclotron. RFD fields ranging up to 120 V/mm•m were tested. Turn density reductions matched those of computer simulations to within 5%. In Fig. 3 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. Isochronism changes up to ±35° 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 $\nu_r=3/2$, and depends only on the RFD voltage and the isochronism for E>420 MeV. Therefore, once the septum protection foil is positioned in a beam density minima the stripped current should be quite stable.

RF Cavities

One or two 150 kV cavities, operating at 92 MHz, can be installed inside the cyclotron vacuum chamber to double or triple the existing 300 keV energy gain per turn. The cavities are ~$\lambda/4$ wide in the radial direction and $\beta\lambda/2$ long in the azimuthal direction so that the ion is accelerated twice per passage. The cavities would reduce the beam density while avoiding limitations caused by an off-centred beam. However, the energy spread in the extracted beam would increase and despite the benefits of phase compression,[4] the phase acceptance is much more restrictive.

The dilution could be further enhanced by the simultaneous use of the RFD and one or two booster cavties (RFB). In Fig. 4(a,b) beam density modulations are simulated for no cavity and for one 150 kV cavity for the same effective RFD strength of 110 V/mm•m. (The true RFD strength is increased in the 'on' case to compensate for the reduced number of turns in the resonance region.) Extraction efficiency assuming a 1 mm protection foil increases from 90% to 93% . The final ratio of RFD to RFB strengths will depend on the desired efficiency, energy spread, and separation at the first magnetic channel.

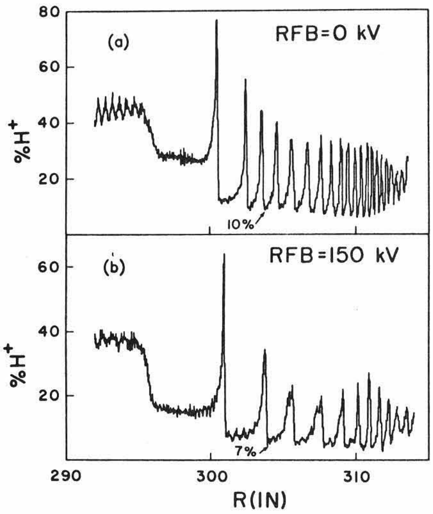

Fig. 4. Comparison of calculated dilution patterns produced by the RFD for: (a) rf booster cavity off, (b) rf booster on for the same effective RFD strength (110 V/mm• m).

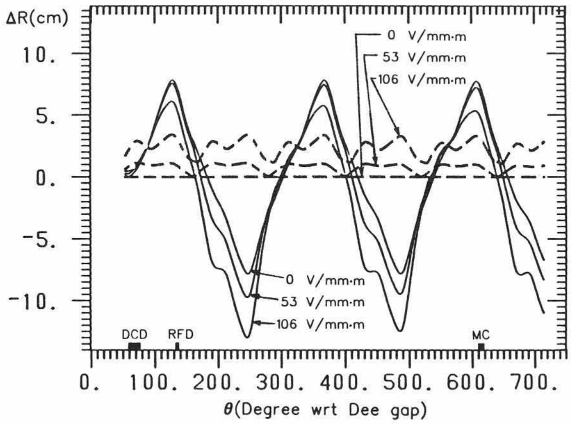

Fig. 6. In one set of plots (solid line) the separation of the DCD deflected beam from the circulating beam is shown for three different RFD settings. In the second set of plots (dashed line) the increase in the radial extent of the circulating beam due to the RFD perturbation is shown.

Layout of Components

A possible layout of the extraction elements in the vacuum tank of the cyclotron is given in Fig. 5. The septum protection foil (pre-stripper) is positioned to send the intercepted beam down an existing beam line. Since the beam is still well inside the isochronous field, and since $\nu_r \sim 3/2$, the DCD deflected beam will oscillate around the equilibrium orbit reaching maximum separation at ~60°+240°*N downstream from the original deflection (in this case 540°). This is illustrated in Fig. 6 where the separation of the deflected ray from the circulating beam has been plotted for various RFD strengths assuming two DCD's with combined deflecting power of 7.3 kV/mm• m. The separation maxima are reduced and shifted due to the perturbation of the circulating beam by the RFD. The 120° periodicity of the RFD orbit perturbation is shown in a second set of plots.

The extraction elements have, whenever possible been inserted in regions free from existing devices, although modifications to cryopanels, probes and service access ports are possible where necessary. The performance of the rf cavities is not azimuth dependent; however, to permit delivery of power and services, they must be situated in magnet valleys. The performance of the RFD is affected by its azimuthal position. Because the precession takes place near $\nu_r=3/2$ the orbit perturbation is periodic every 120°. Superimposed on this 120° pattern is a pattern periodic in sector structure (60°) due to sector focusing. Figure 7 shows the percentage beam that would be stripped on a 1 mm protection foil at 54° wrt dee gap) as a function of RFD strength and azimuthal position over one 120° cyclotron segment. Plotted on the same figure is the separation produced at 234° (near the position of the first magnetic channel) by the DCD (5 kV/mm• m) also as a function of RFD strength and

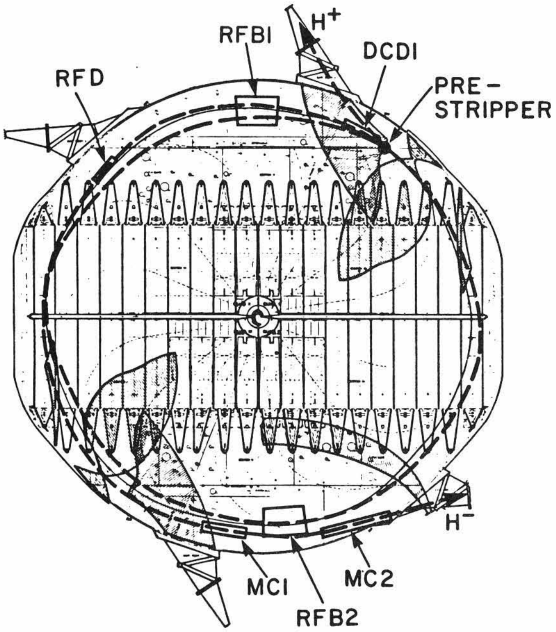

Fig. 5. A schematic layout of a possible H^- extraction scheme composed of an rf deflector (RFD), electrostatic deflector (DCD), rf booster cavities (RFB), and magnetic channels (MC).

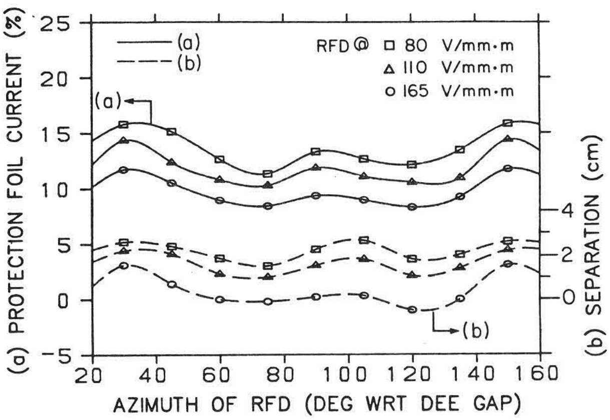

Fig. 7. Computer simulation showing: (a) the dependence of protection foil current (54°) on RFD azimuthal position and (b) the separation produced by the DCD (5 kV/mm• m) at the first magnetic channel (234°) for different RFD strengths.

position. A reduced loss corresponds to a lower separation since both are dependent on the amount of RFD perturbation on the circulating beam. The optimum RFD position depends on the required efficiency, the maximum deflecting power of the DCD, and the separation required at the first magnetic channel.

The first DCD sits in the shadow of the protection foil, ~5° downstream to allow the stripped protons to clear the antiseptum. A total radial deflection of >6 kV/mm•m is needed to provide sufficient separation (>2.5 cm) at the position of the first magnetic channel for a reasonable RFD strength (110 V/mm•m). High positive voltage holding is difficult in the 0.5 T field of the cyclotron. At the moment the maximum voltage held on an 85 cm long test DCD with 13 mm gap is 42 kV so that, barring significant improvement, a second DCD to be placed immediately downstream of the first DCD (allowing for existing radial probes) seems necessary. The existing device consists of a septum made from 120 Mo foils, 5 mm wide and 0.076 m thick, fastened to a template curved to follow the beam orbit, and a gas cooled stainless steel antiseptum.

A total of three to four magnetic channels will be needed to provide the ~1.4 T•m of deflection required for the H^- to leave the cyclotron along an acceptable trajectory. The first channel will be relatively weak (~0.1 T) with 15 mm water-cooled septum. A prototype is being built[5] and will be tested very soon with the beam. The two or three channels downstream will likely be of a coaxial cos θ distribution design.[6] Such channels require a larger clearance (>7 cm) between deflected and circulating beams but are capable of yielding higher deflecting fields while maintaining acceptable external fringe fields. The computer code GOBLIN was used to determine the strengths, positions and lengths of channels necessary to extract the H^- out beam line II (Fig. 5). These results as well as the clear separation between the circulating and deflected beams at each channel for a total DCD kick of 7.3 kV/mm•m are summarized in Table I. The angles are with respect to the dee gap.

Table I. Magnetic Channel Design Parameters

	B (T)	L (m)	θ (°)	ΔR(cm)
MC1	-0.1	0.93	249.9	3.8
MC2	-0.25	0.93	270.5	6.9
MC3	-0.4	1.07	280.5	15.
MC4	-0.4	1.07	290.5	37.

Experimental Results

H^- extraction tests are carried out in the cyclotron shutdown periods, which occur twice a year and last for several weeks. In March 1986 the prototype DCD and RFD were installed in the cyclotron. The phase width of the beam was reduced by a central slit to ±5° for the test. An extraction stripping foil 1 mm wide was positioned in a minimum of the RFD produced beam dilution pattern. The septum of the DCD was positioned in the shadow cast by the stripping foil. A radial differential probe measured the transmission through the foil and septum to be 82% (Fig. 8) for an RFD strength of 70 V/mm•m and a DCD field of 28 kV/cm. After optimizing the position of the DCD the efficiency was raised to 85% for a circulating current of 1 μA in a 5% duty cycle mode (20 μA equivalent). The result matches the predictions of computer simulations for losses on a 1 mm foil indicating that little or no beam was lost on the septum. This shows that the effective width of the septum is <0.5 mm. The beam deflected by the DCD was measured 1 1/2 turns later to be clearly separated by 1.0 cm from the circulating beam for a DCD field of 34 kV/cm. When the RFD was turned off the separation grew to 1.8 cm and the efficiency dropped well below 50%.

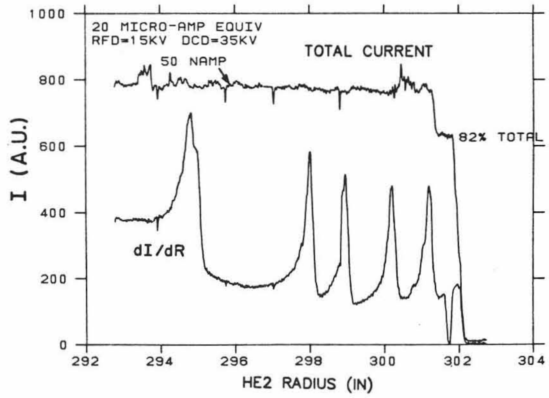

Fig. 8. Experimental result from March 1986. A differential probe immediately downstream from the DCD records the beam density modulations produced by the RFD (70 V/mm•m) and the transmission (82%) through the DCD (28 kV/cm) and a 1 mm protection foil.

Future Plans

Experimental results indicate that computer simulation studies of extraction efficiency and orbit dynamics are very reliable. With a higher RFD voltage, the transmission through the protection foil and DCD should reach 90% for beams of 20 μA. Relaxing the phase restriction at the cyclotron centre should allow 50 to 100 μA H^- to be transmitted with little, if any, deterioration in efficiency. Cyclotron improvements (i.e., brighter ion source, improved bunching) are planned which should allow a routine 100 μA H^- transmission. Adding another 1 m long DCD of the same strength as the existing device will give a total of 6 kV/mm•m deflecting force, sufficient to enter a first magnetic channel. A radiation resistant septum magnetic channel with total deflecting strength 0.065 T•m is presently being designed. A test of a prototype coaxial channel is also being considered. A fourth harmonic rf accelerating cavity has been built for signal level tests. A full power cavity and rf power source are being built for installation in the cyclotron in October 1987. The feasibility of the project and the design of major components will be completely investigated by the end of 1987. An extracted H^- beam could be available one year later.

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