USING A PULSED DEFLECTOR FOR EXTRACTION OF PULSED BEAMS FROM THE TRIUMF CYCLOTRON

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Abstract

In the normal mode of operation, the TRIUMF cyclotron accelerates H^- ions to produce 500 MeV proton beams of 160 μA with 4 nsec pulses separated by 43 nsec. A proposed experiment ($\mu \rightarrow e$ conversion) requires a 500 MeV beam with 100-200 nsec pulses separated by 1-2 μ sec with an average intensity of 200 μA. Two methods have been investigated to achieve this time structure. Both incorporate a pulsed electric deflector and take advantage of extraction by stripping. In the first case, a deflector with a thin septum deflects radially up to six accumulated turns onto a stripping foil in one turn. In the second, a pair of vertically deflecting plates are pulsed at a frequency to excite a coherent vertical growth, and the particles are eventually intercepted by a stripping foil. Under certain conditions extraction occurs in almost perfect synchronism with the driving pulse. Both methods will be described in detail and results of computer simulations will be presented.

I. INTRODUCTION

The TRlUMF cyclotron accelerates H^- ions at an rf frequency of 23 MHz and an orbit frequency of 4.6 MHz with five bunches per turn. Typically, 160 μA are accelerated to 500 MeV with extraction by stripping. These ions occupy 30-40° of the rf cycle. Hence the time structure of the extracted beam in cw mode consists of 4-5 nsec pulses separated by 43 nsec. The separation between output pulses can be increased five-fold with a corresponding reduction in the average current by cancelling four of the five particle bunches before injection. In addition the macro-duty cycle can be altered by a 1 kHz pulser in the injection line giving pulses of variable length separated by up to 1 msec.

A $\mu \rightarrow e$ conversion experiment [1] [2] requires a pulsed beam with average intensity approaching $200\mu A$ at an energy of 500 MeV. Pulses of 100-200 nsec are desired with a period between pulses of 1-2μsec. The micro-structure of the pulse is not critical. In a cyclotron with separated turns the macro-structure of the beam at the source will maintain itself through to extraction. However, in the TRlUMF cyclotron the energy spread in the turns produced by the phase-dependence in the acceleration and the low radius gain per turn (1.5 mm at 500 MeV) causes overlapping of turns and a uiniform radial beam distribution. For example a single instantaneous pulse of beam at injection would be extracted over a period of 20 μsec. Therefore any intensity fluctuations in the 1 MHz regime created at the source will be effectively washed out during acceleration. In any case the above intensity requirement precludes altering the duty cycle by beam elimination either at injection or extraction since, from space charge considerations, the maximum allowable average intensity in the TR1UMF cyclotron without major development
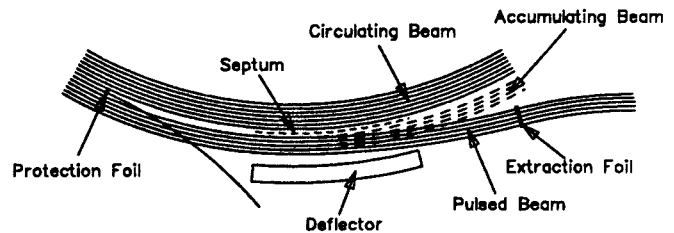

Figure 1. Schematic view of pulsed radial extraction. Here five turns are accumulated, then all are deflected simultaneously onto an extraction foil. A narrow foil lies upstream to protect the septum.

is 10 μA/^{o} of rf or ~400 μA. [3] The specifications set by the experiment can only be met by manipulating the beam near extraction in such a way as not to significantly reduce the average circulating intensity.

II. PULSED EXTRACTION SCHEMES

Two methods were developed to accomplish this. In both cases the full cw beam is injected into TRlUMF and pulsed electrodes near the extraction radius are used to deflect the circulating beam periodically onto an extraction foil.

A. Horizontal Deflection Scheme

In the first case a radial deflector with septum is fed a pulsed voltage. [4] When the field is off the beam is allowed to accelerate in the normal way into the deflecting gap and 5-10 turns corresponding to 1-2 μsec can be accumulated. The device would pulse on for a period equivalent to one turn (200 nsec) to deflect all the accumulated beam onto a stripping foil positioned just outside the circulating beam. (Fig. 1) The rise and fall times of the pulses must be less than the separation of the circulating bunches (40 nsec). Because the beam is homogenous radially, a narrow foil would be placed upstream of the deflector to protect the septum and extract the intercepted beam down a separate beamline. The deflector gap must be large enough to accommodate the extra beam width, and the beamline must be able to accept the increased energy spread of the multi-turn beam.

Near extraction dR/dn is only 1.5 mm, so up to 50% of the beam would be intercepted by a 1 mm protection foil. The efficiency could be improved to 80-85% by employing a precessional extraction technique using an existing rf deflecting device (RFD) at the $\nu_r = 3/2$ resonance at 428 MeV. [5] The RFD alters the time structure so that only every second bunch passes through the extraction region. This doubles the length of the extracted pulse (180 nsec to 360 nsec), and eases by a factor of two the demand on the rise and fall time of the deflector (80 nsec instead of 40 nsec). As well the extraction energy is reduced from the nominal 500 MeV to a value closer to the driving resonance.
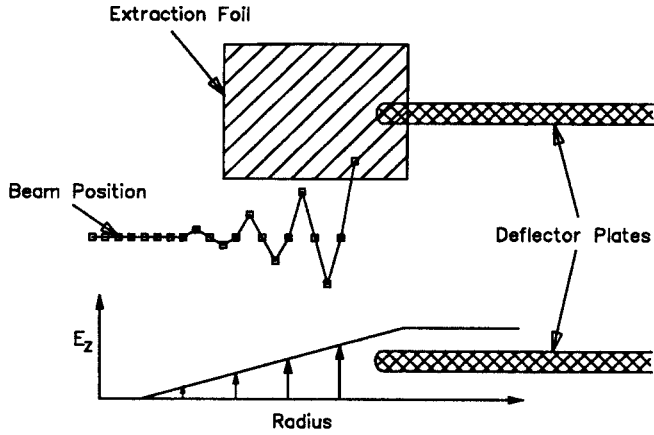
Figure 2. Schematic view of pulsed vertical extraction for the case where $N_s = 4$ and $\nu_z = 0.25$. The small boxes show the vertical beam position once per turn. The darkened boxes correspond to turns when the deflecting field is on. The profile of the fringe field is also shown with arrows indicating the magnitude of the deflections. The particle is intercepted by the extraction foil after a phase advance of $\pi/2$ in vertical phase space from the last deflection.

B. Vertical Deflection Scheme

In this scheme pulsed plates at the extraction radius perturb the beam vertically. [6] As in the previous case the pulse is on for one orbit (200 nsec) with rise and fall times of 40 nsec and a pulse period of N_s turns. With a vertical gap of 30 mm and the dR/dn of 1.5 mm, the beam will spend from 15-20 turns in the fringe field region (Fig. 2). The beam will feel a periodic vertical perturbation of ever-increasing intensity. As long as the deflector strength and pulse period are such that the passage through the fringe field is relatively adiabatic, then the beam will experience a coherent vertical growth. The growth over several pulses will add constructively and thus be maximized when $\nu_z^* = \nu_z \cdot N_s$ is close to an integer and a resonance condition exists. Fig. 2 illustrates the vertical growth in the case where $N_s = 4$ and $\nu_z = 0.25$. The extraction foil would be positioned just above the circulating beam at an azimuth corresponding to a phase advance of $\pi/2$ after the deflector. Whenever the acquired amplitude is sufficient to reach the foil, the particle will be extracted, and this will most generally correspond to a time directly after a pulse. Particles extracted out of synchronism with the pulse could be removed in the extraction beamline by another pulsed deflector.

A plot of ν_z as a function of energy calculated from the magnet field survey is shown in Fig. 3. The horizontal dashed lines correspond to ν_z values where the noted pulse period will yield a resonant condition.

III. COMPUTER SIMULATION STUDIES

Computer simulation studies were carried out to calculate the extraction efficiency, the required deflector specifications, and the beam quality (including energy spread and transverse emittance) of the extracted beam. All studies were done using the Monte-Carlo, first order matrix tracking code, COMA. [7] The initial particles occupied a phase band of 40° and a transverse
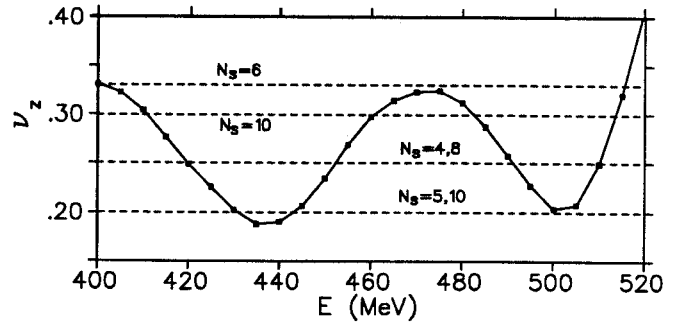

Figure 3. ν_z as a function of energy for the TRIUMF cyclotron. The dotted lines correspond to ν_z values where the noted N_s values would produce resonant conditions.

emittance of $(\epsilon_x, \epsilon_z) = (1.0, 2.4)\pi\mu m$. For normal (unpulsed) extraction the extracted beam characteristics were found to be $\Delta E = 1$ MeV and $(\epsilon_x, \epsilon_z) = (1.3, 2.1)\pi\mu m$.

A. Horizontal Results

Various parameters, including the RFD voltage, the extraction energy and the pulse period were varied in the study. [4] In some cases local flattopping was added to the acceleration to reduce the phase-dependent effects produced in the precessional extraction. [8] Simulation results for a range of RFD voltages are summarized in Table 1 for the case where the pulse period, N_s, is 6 turns and the extraction energy is 465 MeV corresponding to extraction in the fifth precession cycle. Shown are the energy spread and radial emittance of the extracted beam, the deflector voltage and the extraction efficiency. The deflector voltage is determined from two factors: the field strength necessary to generate sufficient deflection and the deflecting gap required to accommodate the beam. The voltage listed in the table provides the field strength required for a 1 m long deflector to separate the pulsed beam by 5 mm from the accumulating beam (Fig. 1), based on a gap 5 mm larger than the radial beam width in the gap. For example, for the case where the RFD is off, a gap of 20 mm is chosen to deflect the 15 mm wide beam. The extraction efficiency corresponds to the fraction of the total beam that would miss the 1 mm protection foil upstream of the septum. The energy spread (2.8 MeV) and beam width in the deflector gap (15 mm) have increased over the unpulsed values (1 MeV and 5 mm respectively) by an amount given by the dE/dn of 0.32 MeV and dR/dn of 1.5 mm each, scaled by the pulse period ($N_s = 6$). As the RFD strength increases, the increased perturbation of the circulating beam means that a higher deflector strength is required for the same separation. The radial emittance is also adversely affected due to the increased rotation in radial phase space from turn to turn. Both the energy spread and the emittance for a moderate RFD setting are improved if local flattopping is used.

As the pulse period increases, the energy spread increases roughly commensurate with the energy gain per turn, and the radial emittance, for cases where the RFD is on, rises dramatically. The deflector voltage increases roughly linearly with pulse period to compensate both for the required larger gap and for the increased kick needed to clear the higher number of accumulated orbits.

Table I

Results of beam simulation showing beam quality (energy spread and radial emittance), extraction efficiency and pulse voltage for various RFD voltages. The pulse period is $N_s = 6$ and the extraction energy is 465 MeV (fifth precession cycle). In one case local flattopping is used.

RFD Kick (V/mm.m)	ΔE (MeV)	ϵ_x ($\pi\mu$m)	V (kV)	efficiency (%)
0	2.7	1.8	45	50
23	2.7	2.4	44	78
55	2.9	6.0	60	86
$55_{f}lat$	2.2	5.	40	87
110	2.9	13.	120	90

Table II

Optimized deflector voltages and corresponding extracted beam characteristics for various pulse periods, N_s.

N_s (turns)	Voltage (kV)	E (MeV)	ν_z	ΔE (MeV)	ϵ_z ($\pi\mu$m)
4	6	492	0.25	2.9	1.3
5	9	499	0.20	2.7	2.2
6	15	478	0.32	3.8	2.2
7	18	486	0.28	3.7	3.1
8	18	490	0.25	4.3	3.4

B. Vertical Results

In all studies [6] the E_z fringe field was assumed to rise linearly over a 25 mm range approaching the deflector. The position of the extraction foil was optimized for best extraction efficiency. Since $\nu_z \sim 0.25$ in the energy range of interest, the foil azimuths were all in the vicinity of the deflector. In the initial investigation, using $N_s = 6$ and a deflector strength of 1 kV/mm · m (30 kV for a 1 m deflector with 30 mm gap) the position of the deflector was varied to study correlations between ν_z and the extraction efficiency. The efficiency ranged from 80% at $\nu_z^* = 1.4$ to 99% at $\nu_z^* = 1.1$. In a similar study it was found that near the $\nu_z^* = 1$ resonance condition ($N_s = 5, \nu_z = 0.2$ at 500 MeV), the deflector strength could be reduced to 0.4 kV/mm · m while still maintaining 99% efficiency. However the efficiency dropped to 94% at 497 MeV for the same strength, indicating that at lower voltages the results are very ν_z dependent.

For any particular radius and pulse period, the efficiency is optimized at a moderate deflection strength. Too high a strength, and the growth is too non-adiabatic, whereas with too small a strength, the probability of hitting the foil immediately after a kick is reduced. As the deflector voltage is reduced, the vertical emittance drops correspondingly as the maximum vertical extent on the foil is reduced. However, for very low values the energy spread and spot size on the foil increase dramatically, because the variation in the number of pulses needed to achieve extraction increases.

Optimal deflector voltages (for a gap of 30 mm and 1 m length) and the corresponding extracted beam quality are shown in Table 2 for pulse periods ranging from $N_s = 4$ to $N_s = 8$. The efficiencies are all $\geq 99\%$ except at $N_s = 8$ where the efficiency is 97%. Above $N_s = 8$, the energy spread becomes unacceptably large. A higher pulse period demands an increased deflector voltage, since fewer kicks mean stronger voltages for the same amplitude growth. Because of the finite vertical emittance and the adiabatic nature of the extraction, particles of the same rf phase will be extracted over two or three pulses. Therefore the energy spread is larger than in the previous single deflection scheme, and increases with pulse period. The radial extent of the beam on the extraction foil is roughly 5 mm/MeV of energy spread. The increased pulse period also means a reduction in the coherence, since the precession of the vertical phase vector is more rapid and leads to the increased vertical emittance.

IV. CONCLUSION

The amplitude produced by any deflection is inversely proportional to the betatron frequency. Hence vertical deflections are a factor of six more efficient than radial deflections in the TRIUMF cyclotron. As well, the vertical scheme benefits from multiple deflections as opposed to the single pulse deflection in the radial case. The specifications demanded by the radial deflection scheme (≥ 40 kV @ 1 MHz) are beyond present pulsed technology [9]. However at 1 MHz, a 10 kV pulse generator has been designed [10] and fabricated, and is presently being tested in preparation for a beam test of the vertical deflection scheme in the fall of 1995. In a preliminary test 6 kV @ 1 MHz has been reached [11]. Besides the technical development, future work will involve a beamline study to determine if the larger beams can be transported, and a study to estimate the cleanliness of the pulse off condition at the target.

V. ACKNOWLEDGEMENTS

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