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MATCHING AN ISOCHRONOUS CYCLOTRON TO A SYNCHROTRON TO PROVIDE A HIGH INTENSITY INJECTOR

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Summary

Schemes are described for injecting the 23 MHz cw H^- beam from the TRIUMF 500 MeV cyclotron efficiently into a 30 Hz rapid-cycling synchrotron. We have considered extraction of 100-200 turn pulses from TRIUMF followed by multiturn injection into a dc accumulator ring mounted in the synchrotron tunnel. An alternative is to build a small isochronous storage ring to compact several thousand turns. Computer simulations of the various extraction processes will be presented.

Introduction

The TRIUMF cyclotron[1] is a six-sector isochronous machine accelerating H^- ions to a maximum energy of 520 MeV. It routinely produces beams of 130 μA cw within an emittance of 2π mm-mrad. Five H^- bunches per turn (h=5) are accelerated; each bunch separated by 43 ns (23 MHz) and with a bunch width of 5 ns (±20°). This width can be reduced to 2 ns (±8°) with some loss of beam. A 5 mgm/cm^2 carbon foil is used to strip H^- to H^+ for extraction.

We are presently considering using TRIUMF as an injector to a higher-energy machine capable of producing proton beams of the order of 100 μA at energies suitable for the production of kaon, antiproton and neutrino beams of greater intensity than presently available. In this paper we will address the problem of matching the 23 MHz beam from TRIUMF to a 30 Hz fast-cycling synchrotron. To utilize the TRIUMF beam current efficiently, beam must be collected over a large fraction of the synchrotron cycle. At 30 Hz up to 770,000 TRIUMF bunches would be available for each accelerating cycle. One proposal is to collect beam from TRIUMF over ~100 turns (500 bunches) and extract either H^-, H^0 or H^+ particles in 215 ns long packets. Almost 1540 of these would be stored in an accumulator before injection into the synchrotron. Another approach is to extract H^- particles from TRIUMF cw into a separate dc storage ring. From this ring ~60,000 TRIUMF bunches would be extracted in a single packet 215 ns long and injected into an accumulator.

Turn Compaction in TRIUMF

To get the equivalent of 100 turns/pulse from TRIUMF in a usable emittance requires increasing the turn density over the extraction region from 16 turns/inch to >100 turns/inch. This can either be done by driving the ion out of phase with a magnetic perturbation or by reducing the effective dee voltage locally. A vertical kick would drive the dense beam out of the midplane for subsequent extraction.

1. Magnetic Turn Compaction[2]

A small perturbation, δB_z, in the isochronous field, B_{isoch}, over the extraction region causes a deviation from isochronism per turn given by $d\phi/dn = -2\pi h\ \delta B_z/\gamma^2 B_{isoch}$. As ϕ approaches 90° the energy gain/turn ($4eV_d\cos\phi$), where V_d is the dee voltage, decreases until at 90° the ion begins to be decelerated back towards the cyclotron centre. For a single particle maximum turn density is achieved by a slow approach to ϕ=90°. However, for a finite phase spread this results in a large radial spread in the turnaround radii and a greater sensitivity to field, frequency or voltage fluctuations. Therefore a more rapid approach to $\sin\phi$=1 is desired. The optimum compaction occurs when the phase slip gradient $d\sin\phi/dE \simeq 2\Delta\sin\phi/\Delta E_e$ where $\Delta\sin\phi$ is the initial phase spread and ΔE_e the extraction interval.[3] One problem with the magnetic compaction technique is illustrated in Fig. 1. The transition from acceleration to deceleration produces a boomerang-shaped emittance with a turn-front which is elongated in radius and difficult to match efficiently to the 46 MHz synchrotron bucket. A significant trade-off must be made between turns/pulse and total extracted current. For bunches of ±6° initial phase width a phase slip of $d\sin\phi/dE$ = 0.05 MeV^{-1} allows 90 turns/pulse with no losses, or 120 turns/pulse with 10% loss for a 3.8 cm radial extraction interval. Figure 1 also shows how the bunch width has expanded to ±50° (12 ns).

Computer studies show that the existing circular trim coils cannot produce, for the scalloped orbits, a sufficiently rapid approach to $\sin\phi$=1, but new coils following the orbit shape would do so. The coils would be best placed to augment one of the existing phase oscillations such as that at 430 MeV which would also provide a low electromagnetic stripping loss rate. In one case a scalloped triplet ±25 cm from the midplane with 190 At and δB=4 G produced $d\sin\phi/dE$=0.05 MeV^{-1} while $\Delta\nu_z$<0.07.

2. RF Turn Compaction

The second method of stacking beam is to reduce the accelerating voltage thus decreasing the radius gain per turn of all phases. A dee gap voltage decreasing with radius produces a time varying magnetic field $\overline{B}_z=(-dV/dR)\sin\phi/\omega_{rf}$ which expands the bunch longitudinally such that $(d\bar{E}/dn)\Delta\sin\phi$ = constant.[4] The ASTOR code from SIN which simulates this compaction procedure indicates our best case is with 2.5% rf flat-topping and with the fundamental dee voltage dropping from 82 kV to a constant value of 11.5 kV. Under these condition 180 turns with an initial spread of ±6° could be compacted within 7.5 MeV and ±50° (Fig. 2). This is about a factor of two better than magnetic turn compaction, basically due to the better matching of the emittance shape to the synchrotron bucket. For maximum extraction efficiency an isochronous phase history is needed over the region of the voltage gradient so that extra trim coils may have to be added to the cyclotron to flatten out the existing fluctuations of $\Delta\sin\phi$~±0.2.

Two schemes have been proposed to reduce the effective dee voltage at the extraction radius. In one scheme[5] a grounded shielding plate is inserted into the existing dee structure just outside the desired extraction radius. One possibility would be a plate extending from one resonator root to the other (Fig. 3). SUPERFISH[6] calculations show that this geometry will still resonate at the TRIUMF frequency of 23 MHz. In addition experimental tests on a 1:10 rf model of TRIUMF have shown that the plates do not perturb the frequency, reduce the Q-value or seriously increase the rf leakage from the accelerating gap.[7] Alternatively decelerating rf cavities could be installed outside the dees at the extraction radius.[8] λ/4 loaded coaxial transmission lines would be laid back to back in push-push mode (Fig. 4). They would be shaped to match the extraction orbits and would be slotted horizontally to admit the beam. At 23 MHz each would be 4.8 m long.

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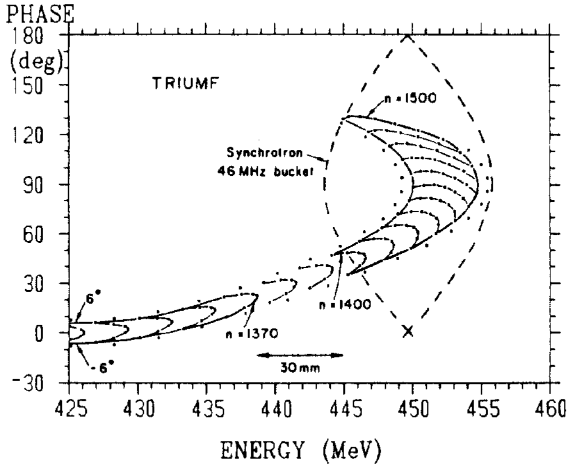

Fig. 1. A beam of ±6° initial phase spread undergoing magnetic turn compaction.

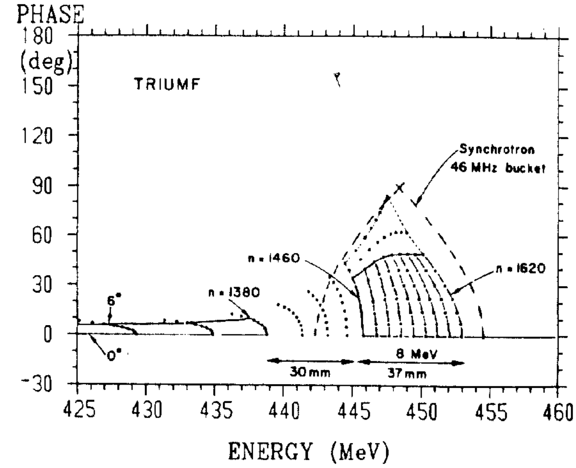

Fig. 2. A beam of ±6° initial phase spread undergoing rf turn compaction.

3. <u>Pulsed Extraction</u>

Pulsed electrostatic plates would deflect the compacted beam vertically so that it would either intercept a stripping foil for H^0 or H^+ extraction or enter a radial electrostatic deflector for H^- extraction. The plates would be pulsed on for one turn to empty the extraction region and then be off for ~100 turns while the extraction region fills up again. A field of 10 kV/cm extending over 10° of azimuth (130 cm) would be adequate. To reduce losses due to the radial fringing field of the plates the beam injected into TRIUMF would have a macro duty cycle of ~75%, say 100 turns on and 30 turns off. The beam quality from both methods of compaction is similar: longitudinal bunch width ±60° (14 ns), ΔE=7.5 MeV, emittances of 8π mm-mrad horizontal and 2π mm-mrad vertical.

<u>Accumulation of Compacted Beam</u>

Pulsed extraction yields 100 turn packets consisting of a string of 5 bunches ~14 ns wide at 43 ns intervals. Almost 1540 of these packets, arriving at 22 μs intervals, would then have to be stacked before acceleration by the 30 Hz synchrotron. An accumulator ring could be built in the synchrotron tunnel for this purpose.[9] Synchrotrons of various sizes have been considered but for the purposes of this paper we will assume a radius of ~76 m. This would allow 10 TRIUMF packets to be placed end to end in "boxcar" fashion around the circumference with another 10 packets interleaved in the spaces between bunches. This interleaving of bunches is made possible by running the accumulator rf at 46 MHz, twice the TRIUMF frequency. 77 packets would be stacked in each boxcar. Note that the boxcars in the accumulator make 10 revolutions, while waiting for the next packet, some particles making a total of 15,400 revolutions per synchrotron pulse. Protons, neutral hydrogen atoms and H^- ions have all been considered for transfer of the beam from TRIUMF to the accumulator ring.

1. <u>Proton Transfer</u>

Proton transfer retains the advantages of stripping for the extraction from TRIUMF and offers the convenience of charged particle beam-handling. Injection into the accumulator, however, is more difficult since each packet must enter a separate volume of phase space. A scheme has been investigated in which 5 packets would be stacked in transverse (betatron) phase space and 11 in momentum space using rf stacking.[10] Kicker magnets pulsed at 46 kHz would steer the packets into the appropriate phase space region. One out of five of the TRIUMF bunches would have to be suppressed at the ion source to allow for the kicker rise time. The overall efficiency of this scheme is low (66%) and the kicker magnets and power supply would require a significant development effort.

2. <u>Charge Exchange Injection</u>

H^- or H^0 extraction would allow charge exchange injection into the accumulator thus avoiding the restriction of Liouville's theorem. H^0 extraction may be feasible by passage through very thin foils.[11] A single pass through 30 μgm/cm^2 carbon would yield 55% H^0 and 21% H^+; multiple passage through thinner foils would increase the fraction of H^0 and decrease that

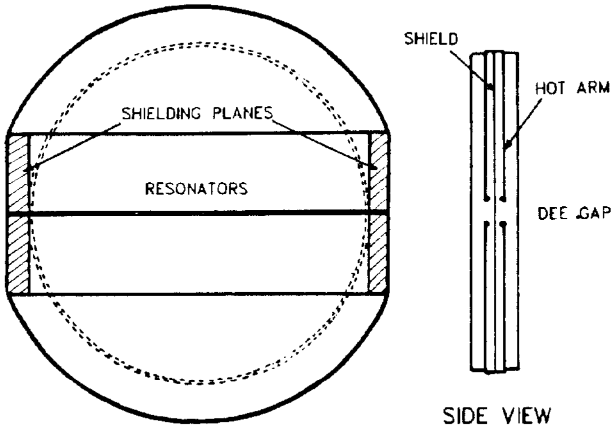

Fig. 3. Rf shielding plates for rf turn compaction.

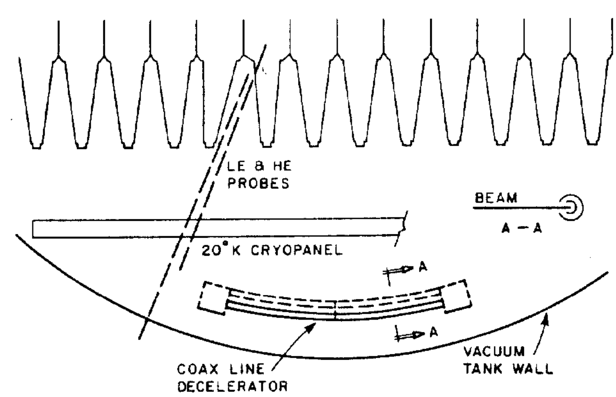

Fig. 4. Auxiliary decelerating cavities for rf turn compaction.

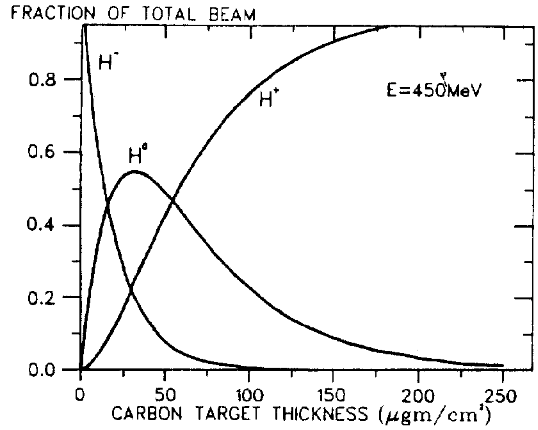

Fig. 5. Charge states emerging from a carbon foil as a function of its thickness.

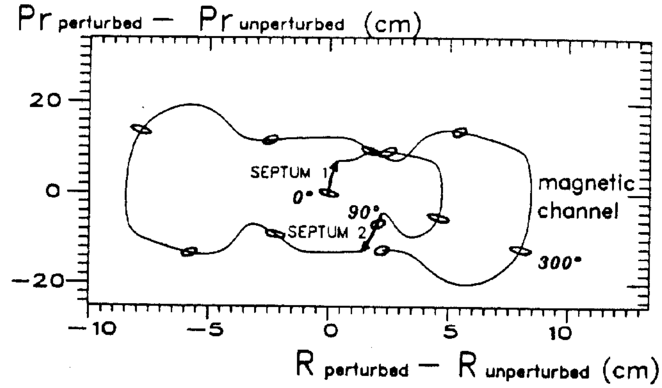

Fig. 6. Extraction without stripping; deviation of the deflected orbit from the unperturbed orbit. The beam ellipse is plotted every 30° of cyclotron azimuth.

of H^+ to a lower limit of ~4% set by double charge exchange (Fig. 5). The H^0 beam size 60 m downstream would be 6×3 cm^2. The H^- option requires an efficient method of extraction to be developed for TRIUMF; no difficulties are foreseen.

If the beam circulating in the accumulator passes constantly through the foil multiple scattering would be excessive; the leading packets of each cycle would make 15,400 passes. Instead an accumulator could be constructed with two closed orbits: a filling orbit which traverses a stripping foil and a storage orbit which does not.[12] A boxcar in the filling orbit would be filled with 154 packets, the first 77 normally and the next 77 interleaved by actuating a 22 ns dogleg in the injection line. A fast rise time kicker would then deflect it to the storage orbit and the TRIUMF extraction plates would delay 215 ns to allow filling of the next boxcar. This scheme reduces the kicker frequency to 300 Hz and the number of foil traversals to a maximum of 1540. The average number of traversals would be <25% of this value increasing the transverse emittance in quadrature by 15 mm-mrad to 17 mm-mrad, still suitable for the 32 mm-mrad acceptance of the accumulator.

External Phase Expansion Ring

1. TRISTOR

An alternative scheme[13] which could compact many more turns into one packet reducing the number of packets and their rate of arrival at the accumulator, would be to build an auxiliary storage and compaction ring. Such a ring (TRISTOR) has been proposed with TRIUMF radius and an operating energy of 430-440 MeV. The energy gain/turn falls from 3.5 kV at 430 MeV to 0.5 kV at extraction to provide phase expansion and turn compaction. The ring would receive H^- cw from TRIUMF and compact 12,000 turns within 7 MeV (33 mm) and ±48° with a 3000 turn gap before the next packet to allow clean extraction. The repetition rate of the accumulator injection kicker would thus be reduced to 300 Hz. Ten proton packets would be injected into the accumulator on each cycle, filling every other 46 MHz bucket and allowing 32 ns between bunches for the kicker rise time. H^- stripping is reserved for injection to the storage ring where it would be essential because of the high turn density. The chief problems with the design are the high degree of isochronism required in the ring (an order of magnitude better than in TRIUMF) and clean extraction from TRIUMF of 125 μA H^- ions within ±6°.

2. Continous H^- Extraction from TRIUMF

In a scheme presently under study the last turn (430 MeV) is perturbed radially with two electrostatic deflectors to deflect the beam into a magnetic channel. Figure 6 shows the deviation from the normal equilibrium orbit of a beam ellipse passing through the two deflectors. The first deflector of 60 kV/cm and 1 m length pushes the beam out radially. At the second deflector 87.5° downstream the orbit is displaced by 2 cm. This deflector, of -60 kV/cm and length 1 m, pushes the beam inward and after revolving ~210° to the magnetic channel (ν_r=1.5) the beam is at its maximum radial displacement of over 8 cm. The large displacements should permit us to reduce the positive voltage on the first deflector which may be more difficult to sustain. The field change from a passive magnetic channel (iron pipe) is too large to be compensated for by the existing TRIUMF trim coils. We would use an active channel with windings arranged to produce only small field changes at inner radii.[14]

Since ν_r=1.5 at 430 MeV a coherent oscillation equal to the normal turn spacing (1.5 mm) would modulate the turn spacing to give a maximum jump of 3 mm. The 6 mm wide 100 μA TRIUMF beam would have to be significantly reduced in order to clear the first septum. A pre-septum stripping foil could direct unacceptable H^- ions to a useful dump or beam line.

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