EFFICIENT EXTRACTION OF H^- IONS FROM THE TRIUMF CYCLOTRON

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Summary

The TRIUMF cyclotron can produce sufficient cw H^- flux for charge exchange injection into a 100 μA KAON factory but was designed for extraction by H^- stripping. A program at TRIUMF has successfully demonstrated that direct extraction may be achieved by driving a radial resonance with rf electric field and by shielding the deflector septum with a narrow foil. An electrostatic deflector generated a 10 mm wide beam-free region between an extractable H^- beam and the circulating beam at the location of a magnetic channel septum. The average beam power was low (450 W) but the peak intensity equivalent to 20 μA cw. An 85% transmission was measured, the remaining 15% being foil stripped into an existing beam line. Further improvements are expected, especially after the operation of an additional accelerating cavity (2×150 kV at 120 kW) presently under construction. The extracted H^- ions will be accumulated by extended multiturn charge exchange injection into a dedicated ring. The results of recent dynamics simulations and equipment studies are presented.

Introduction

The proposed TRIUMF 100 μA KAON factory is described in Ref. 1. A 50 Hz Booster synchrotron would accelerate 1.25×10^{13} protons, in 40 populated rf buckets, from 0.45 to 3 GeV. A second synchrotron accelerates from 3 to 30 GeV. Bucket-to-bucket transfer would be utilized to reduce beam loss; the population would then be $\sim3\times10^{11}$ protons/bucket in all rings. The TRIUMF cyclotron accelerates H^- ions to 520 MeV, and beams of various energies and intensities are extracted by stripping. The cyclotron has operated at 208 μA cw and at 315 μA peak beam and 10% duty cycle. There is ample flux available for injection into the proposed KAON factory: delivered, however, as a 23 MHz stream of 3 ns wide pulses, 43 ns apart, each containing $\sim3\times10^{7}$ protons. The TRIUMF beam must therefore be accumulated throughout most of the 20 ms Booster cycle to achieve the required bucket population. It is proposed that this be done by extracting H^- ions intact from the cyclotron and continuously injecting by charge exchange over 20,000 turns into an Accumulator, or A-ring, occupying the same tunnel as the Booster synchrotron. The A ring, and initial Booster acceleration frequency, will be 46 MHz, exactly twice that of the cyclotron. The injected beam position and energy and the A-ring closed orbit would be modulated to prepare a stable intense beam for subsequent acceleration. Beam dynamics studies on the extraction process and equipment are reported in Refs. 2,3; hardware and the accumulation process in Refs. 4,5.

Extraction of H^- from TRIUMF

The TRIUMF cyclotron was designed for stripping extraction. The phase width ±10°, emittance (1-2π mm-mrad) required to contain 100 μA together with the present accelerating voltage stability, ΔV/V of 3×10^{-4}, and energy gain per turn are inadequate for separated turns. Consequently a program to demonstrate the feasibility of H^- extraction was initiated in 1984. Two novel techniques have enabled the extractable beam to contain 85% of the ciculating beam. This is in agreement with calculations and an eventual fraction of 95% is expected.

A plan view of the cyclotron, Fig. 1, shows the location of components suitable for the extraction of an H^- beam. The beam which normally would hit the septum of an electrostatic deflector, scatter and cause ionization and activation is removed by a narrow foil placed upstream. This method, applicable to negative ions or partially stripped positive ions, serves to generate a separation between turns. The foil, placed at an appropriate azimuth, can direct the stripped protons down an existing beam line to be used productively. The term efficiency then refers solely to the preservation of H^- ions; the sum of both H^- and H^+ beams can be 100% of the initial H^- beam. The foil required to shadow a septum with an effective width of 0.3 mm would intercept about 50% of the circulating H^- beam. This can be reduced to ~10% by generating a coherent radial oscillation where $\nu_r = 3/2$ and placing the foil where the precession, or oscillation phase advance/turn, augments the radius gain/turn from acceleration. The $\nu_r = 3/2$ resonance occurs at 428 MeV, and suitable extraction points lie between 440 and 460 MeV. While the highest energies simplify post-accelerator design, the electromagnetic stripping of H^- to H^0, which activates the cyclotron circumference, is 9% at 500 MeV and only 2% at 450 MeV. An auxiliary accelerating cavity (AAC) is being manufactured which will double the energy gain per turn beyond 350 MeV. The fraction of ions in the extractable H^- beam will be increased to ~95% and the E-M stripping loss reduced to 3% for routine operation at 500 MeV.

Precessional Extraction

The azimuthal length of the beam-free region downstream from a stripping foil of width w is w/2x', where x' is the radial divergence of the beam. A portion, $(2w\rho_s)^{1/2}$, at the front of the shadow is occupied by the stripped H^+ beam (curvature ρ_s). The length of the remainder must be adequate to accommodate a septum to separate circulating and extractable beams. A 1 mm foil is required for x' of 0.5 m·rad and an effective septum width of 0.3 mm. The beam-free region will recur every π/ν_r (or more perfectly at $2\pi/\nu_r$) with length w/x' and no H^+ beam. A narrower foil may then be used if these secondary shadows are sufficiently stable.

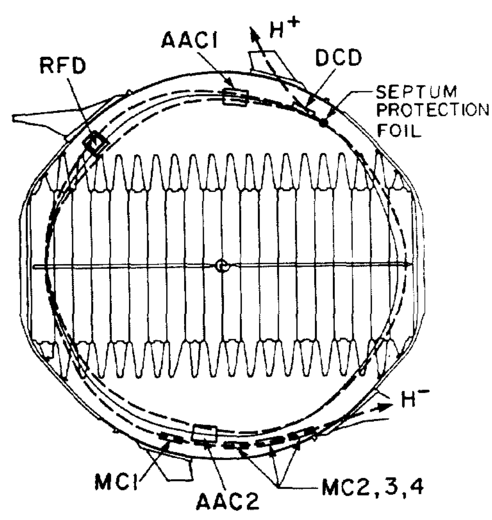

Fig. 1. Plan view of a possible H^- extraction scheme comprised of a ν_r=3/2 resonance driver (RFD), electrostatic deflector (DCD) and magnetic channels (MC1-4). 150 kV auxiliary accelerating cavities (AAC1,2) are also shown.

Precessional extraction involves the generation of a coherent radial betatron oscillation larger than the incoherent amplitude of the beam. This may be done by mismatching a beam at injection or by driving a radial resonance near extraction. Local regions of enhanced radius gain per turn are seen when the phase α of the subsequent oscillation, $\alpha = \arctan(x'/x)$, approaches $\pi/2$. Electrostatic or magnetostatic fields are used to generate coherent oscillations at integer resonances; however, rf fields must be used at non-integer resonances.

The angular extent of one radial oscillation is $2\pi/\nu_r$; when ν_r=1.5 the co-ordinates (x,x') at some azimuth have mirror values (-x,-x') on alternate turns. Figure 2 illustrates how a coherent radial amplitude can be generated and made to grow by applying a radial kick alternating in sign each turn. The effective width of the resonance will be $\{E_0/(dT/dn)\}^{1/2}$ for an isochronous machine. This corresponds to 56 turns or 78 mm for TRIUMF, is much larger than the incoherent betatron amplitude, and all particles acquire the same additional amplitude.

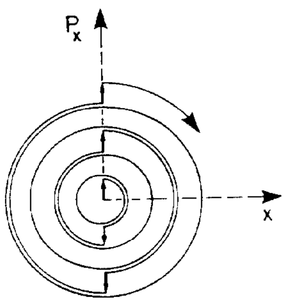

Fig. 2. Generation of a coherent betatron oscillation at ν_r=3/2 by means of alternating (rf) kicks.

The 23 MHz accelerating rf operates at the fifth harmonic of the particle frequency. An 11.5 MHz field will give each of the five bunches a deflection of the same magnitude. The principle is illustrated in Fig. 3(a) and the progression of a pair of particles in the same bunch but arriving one turn apart is shown in Fig. 3(b). The principle can be applied at any value of ν. However, the efficiency of transferring power to the beam is greater near a resonant value. The phase dependence of the acquired amplitude is $(\cos\phi/2)/\cos\phi$ and is constant, to within 8%, over ±25°. The extraction efficiency increases with coherent amplitude A_c but not without limit. One of the following constraints will determine the maximum operational value A_c^{max}. An outward excursion C, see Fig. 3, of an earlier turn may overlap the extracted turn B_e. The detailed shape of Fig. 3 varies with azimuth; an outward excursion of an immediately previous turn may overlap B_e at the location of some equipment. Coupling resonances and non-linear motion are amplitude dependent and affect beam quality. Increased extraction efficiency is correlated with increased beam width within extraction elements and thus may affect design or deflecting power.

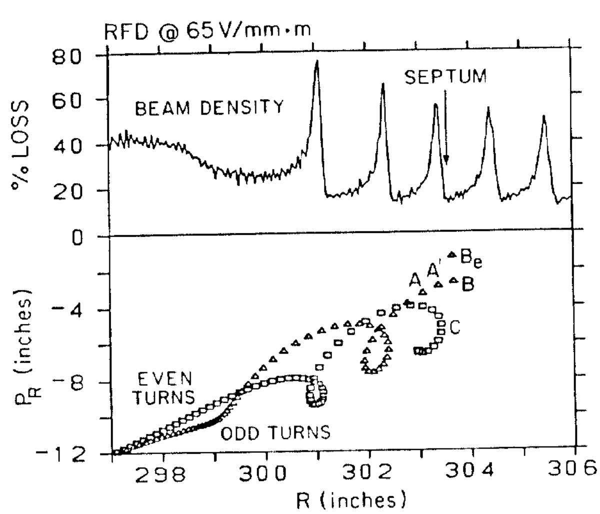

Fig. 3. Motion in radial phase space of the two phases of coherent oscillation generated by the resonance driver and the resulting beam density. B is an extractable turn, displaced to B_e by an electrostatic deflector. A, A' and C are turns referred to in the text.

The resonance driver consists of a hollow flat U-shaped electrode mounted at the end of the inner conductor of a capacitively foreshortened vertical transmission line. The 11.5 MHz electric field E_R is developed between the tip of the U and a grounded structure enclosing it. The mid-point of the gap lies on the ν_r=3/2 resonance at 428 MeV. A field integral $E_R \cdot \ell$ of 100 (V/mm)m increases the radial gain per turn from 1.5 mm to 5 mm. The electrode structure is open to a radius beyond 520 MeV. This allows acceleration into the field free region to develop precession when the device is energized, and to permit normal cyclotron operation when off. The 5 kW rf tranmitter generates 25 kV in the cyclotron, sufficient to produce A_c^{max}.

Beam Deflection

The 450 MeV orbit lies 1 m from the field fall-off with radius and extensive deflection is required. Complete extraction within one of the two clear areas in Fig. 1 would require a 60 (kV/mm)·m electrostatic deflector followed immediately by 6 T·m magnetic channel. A more practical system, illustrated in Fig. 1, locates a series of weaker elements over 1.5 turns.

The initial deflection of the H^- beam has been produced by an 0.85 m long electrostatic deflector with a nitrogen gas cooled stainless steel antiseptum separated by 13 mm from a grounded septum made from 5 mm wide, 0.07 mm thick molybdenum strips. The cooling gas enters and leaves the antiseptum via two hollow $A\ell_2O_3$ insulators. The electrical connection to the positive bias supply is also via the insulators and gas feed pipes. The entire device is adjustable in radius and in the pivot angle about the first septum foil. The initial voltage was limited by field emission to 40 kV, 2.6 (kV/mm)·m. An improvement program, utilizing a chamber simulating the cyclotron vacuum and magnetic field, is under way. Stainless steel foils with polished edges have already shown promise.

An engineering design is nearing completion for a magnetic channel with a 15 mm wide septum coil.[6] All features which might pertain to an operating version have been included. Limitations of length and height imposed by the present standard remote handling equipment dictate a septum coil that is asymmetric about the mid-plane. The field components have been calculated by GFUN(3D) and introduced into the orbit code GOBLIN. Central ray and emittance calculations indicate an acceptable emittance distortion and a compensatable closed orbit displacement.

The separation generated at the next channel by this initial, magnetic channel is 35 mm. Several, stronger, channels (totalling 1.4 T·m) are needed to bring the H^- beam into the exit port. A conceptual design has been made for coaxial channels whose windings, varying in a $\cos n\theta$ manner, produce a central field of 0.3 T and a low leakage field of 1 mT.

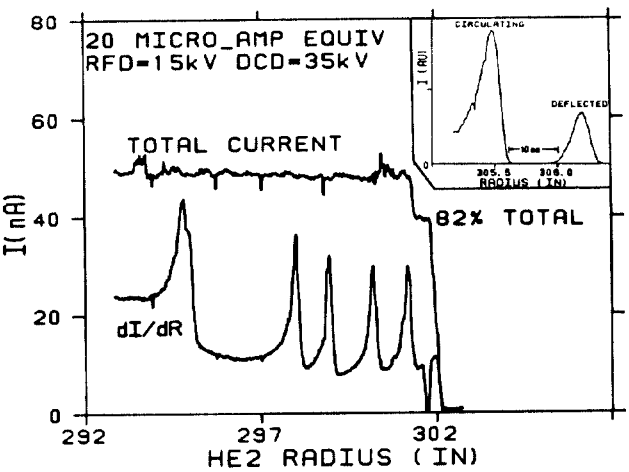

Fig. 4. Beam intensity and density measured by a differential probe immediately downstream of the E-S deflector. For driver field 70 (V/mm)•m, deflector 2.8 kV/mm and 1 mm foil the measured transmission was 82%. The insert shows a density measurement 1.5 turns later; the extracted beam is separated by 10 mm.

Results of Beam Tests

H^- extraction tests are carried out in cyclotron shutdown periods, which occur twice a year. During the most recent run in March 1986 the phase width of the beam was reduced by a central slit to ±5°. Ideally an extraction stripping foil 1 mm wide would be positioned in a minimum of the driver-produced beam density pattern. The septum of the E-S deflector would then be positioned in the shadow cast by the foil. However, mechanical difficulties prevented this and the driver strength had to be lowered to 15 kV to generate a pattern matching the deflector location. A radial differential probe measured the transmission through the foil and septum to be 85% (Fig. 4) with a circulating current of 1 μA at a 5% duty cycle. That is, for a 450 W beam with ion source and space charge conditions equivalent to 20 μA. The result matches the computer simulation for losses on a 1 mm foil, indicating that little or no beam was lost on the septum whose effective width would then be <0.5 mm, see Fig. 5. One and one-half turns later the deflected beam was clearly separated by 10 mm from the circulating beam.

Turning the driver off reduced the efficiency below 50%. The separation increased to 18 mm because the encroachment, Fig. 3, was reduced. The voltage holding performance and leakage current of the E-S deflector were unaffected by the presence or absence of this 0.45 kW beam. Trim coils were adjusted to move the particle phase at extraction to values between -30° and +30°, which exceeds the phase band required. The coherent amplitude was unchanged but the radial width of an oscillation decreased with larger $|\phi|$. Extraction of a beam with large phase width would be restricted to the first, wider, minima in Fig. 3. Increased energy gain from AACs will expand the width of these minima.

Immediate Plans

The extraction experiment will first be repeated with a circulating beam power of 4.5 kW (10 μA) to test the ability of the E-S deflector to maintain higher voltage in the presence of beam. The beam phase width

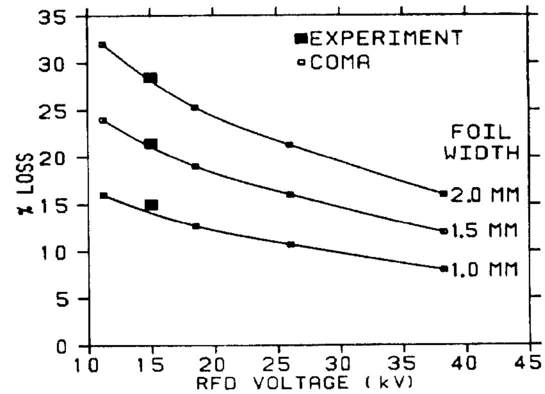

Fig. 5. Fraction of beam intercepted by 1.0, 1.5 and 2.0 mm wide protection foils placed at density minima produced by different driver fields. The measurements are in good agreement with Monte Carlo (COMA) simulations.

will be close to the ±9° required to contain 100 μA. The next experiment is planned to follow the manufacture, laboratory measurements and installation of the septum magnetic channel. Tight tolerances are required from this channel to avoid perturbing the cyclotron beam before extraction and during deflection.

The AAC concepts were discussed in Refs. 2 and 4. The azimuthal length is $\beta\lambda/2$, ions are accelerated entering and leaving. The radial length is approximately $\lambda/4$. A fourth harmonic of 23 MHz was chosen to keep the cavities small and the power low. The maximum voltage is at the outer cyclotron radius to provide an adiabatic acceleration. Phase compression arises from the $B(t)$ in the accelerating gap. The size, and consequently the harmonic, must provide both adequate increase in acceleration at 450 MeV and continued acceleration to beyond 500 MeV when the extraction system is not in use. A medium power AAC has been built and Q (10^4) and tuning measurements performed. The intermediate stage transmitter should shortly permit laboratory tests at 10-20 kW while the final stage (120 kW) nears completion. After successful tests at moderate power, the final cavity will be prepared for installation in the cyclotron during 1988.

Acknowledgements

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