PROGRESS TOWARDS H$^-$ EXTRACTION AT TRIUMF

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Abstract

A project to prove the feasibiblity of efficient direct extraction of 100 μA of H$^-$ ions from the TRIUMF 500 MeV cyclotron is underway. The cw beam would be extracted by one or more electrostatic deflectors and four magnetic channels. The extraction efficiency would be improved by inducing a precessional component to the radius gain per turn by exciting a radial betatron oscillation at $\nu_r = 3/2$. Further, the energy gain per turn would be doubled at extraction by adding a 150 kV, 92 MHz accelerating cavity. Experiments *in situ* have demonstrated a 90% extraction efficiency for a pulsed beam with an equivalent cw current of 66 μA . A development program has improved the strength of the deflecting field to 50 kV/cm at moderate circulating currents and 32 kV/cm for a time-averaged current of 10 μA. A prototype of the additional accelerating cavity has been tested at low power. A prototype 65 mT iron-free magnetic channel has been designed. Beam optics calculations of the extraction process are being done in parallel. The design concept of a final extraction system will be described.

Introduction

TRIUMF presently accelerates H$^-$ ions to 500 MeV, and up to three cw proton beams of 200 μA total intensity can be extracted by stripping. This extraction scheme is 99.95% efficient and provides simultaneous beams of varying energies. The TRIUMF 100 μA KAON factory design[1] calls for the direct extraction of H$^-$ ions from the cyclotron to permit injection by charge exchange into the first of five proposed rings that would increase the energy to 30 GeV. A program to demonstrate the feasibility of H$^-$ extraction was initiated in 1984.[2]

Direct extraction of an H$^-$ beam requires the use of electrostatic and magnetic channels to peel off the outermost turn. However, at an intensity of 100 μA separated turns cannot be maintained beyond 200 MeV in the TRIUMF cyclotron. Despite this, 460 MeV was chosen as the extraction energy since higher energies simplify the post-accelerator design and the $\nu_r = 3/2$ resonance at 428 MeV may be used to improve the extraction efficiency. As well, the existing beam loss from electromagnetic stripping, which rises rapidly from 400 MeV to 500 MeV to a total of 8% is only 2% at 460 MeV.

At the required beam intensity the extraction process must be efficient to reduce power loss and induced activation. H$^-$ extraction can be made practically loss-free by positioning a thin stripping foil upstream of the first electrostatic deflector to shadow the septum, diverting the stripped proton beam down an existing beamline. The problem then becomes one of raising the efficiency of extraction where the term efficiency describes the percentage of the circulating beam that is extracted as H$^-$ ions. Several TRIUMF beamlines can accomodate 10 μA so that an efficiency of $\geq$ 90% is required to deliver 100 μA to a KAON factory.

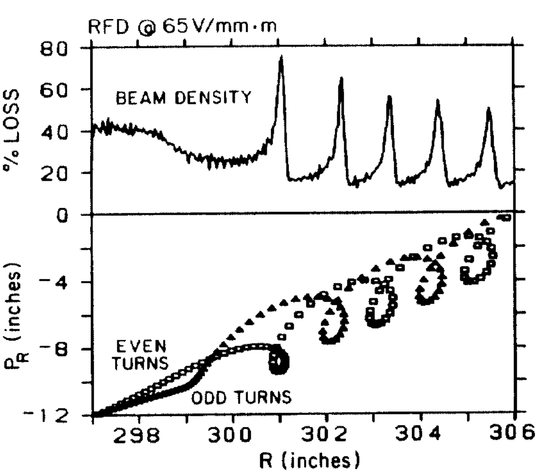

Fig. 1. The bottom plot traces even and odd turns of a central particle in phase space during and subsequent to perturbation by the RFD (R~297 in.). The top trace shows the resulting beam density given as the percentage of the beam that would be intercepted on a 1 mm foil.

Beam Dilution

A septum of effective width 0.5 mm can be safely shadowed with a 1 mm foil for a beam divergence of 0.5 mrad. The low radius gain per turn (1.5 mm) at the extraction energy means that up to half the beam would be intercepted by the stripping foil. The extraction efficiency can be improved by exciting a coherent radial oscillation at the $\nu_r = 3/2$ resonance. The subsequent precession leads to large radial beam density modulation in the 440–470 MeV energy range. The turn-to-turn separation can be further enhanced by increasing the energy gain per turn near extraction.

TRIUMF accelerates five particle bunches per turn at an rf frequency of 23 MHz. An rf electric field at 11.5 MHz, 5/2 the particle rotation frequency, will radially deflect each of the particle bunches in alternate directions on each turn. When the deflecting field is applied in the $\nu_r = 3/2$ resonance region, a coherent amplitude will develop similar to the coherent growth from static deflections at $\nu_r = 1$. As ν_r increases beyond 3/2 the radius gain per turn from precession can be several times the separation due to the accelerating field.[3,4] The effect of the rf deflector (RFD) at a relatively low strength is illustrated in the computer simulation in Fig. 1. The beam density, plotted as a function of foil position, is high where the precession has lead to an accumulation of turns and it is low where turn spacing is increased. The septum protection foil would be positioned in a broad density minimum.

The local extremes in the beam density can be augmented by increasing the energy gain per turn near the extraction radius at the expense of increasing the energy spread and radial width of the extracted beam. One or two rf cavities, operating at 92 MHz, can be installed inside the cyclotron vacuum chamber to double or triple the existing 340 keV energy gain per turn. The cavities are $\lambda/4$ long in the radial direction and $\beta\lambda/2$ wide in the azimuthal direction so that the ion is accelerated twice per passage. The addition of a single cavity will increase the extraction efficiency from 90% to 93% with the RFD operating at a moderate level.[5] In addition, the expanded precession pattern and reduced beam loss allow extraction at a 10–20 MeV higher energy.

Layout of Components

Several requirements must be considered in choosing an optimal layout. Firstly, beam dynamics considerations, as outlined below, restrict the positioning of the extraction devices. Secondly, the protons from the septum protection foil and the H$^-$ ions will be extracted from TRIUMF through existing exit ports. Thirdly, the extraction elements will be placed to minimize modifications to existing devices. Lastly, the elements will be positioned and designed to minimize restrictions on the existing physics program during the early commissioning of the KAON Factory. To this end, each element will be made either retractable or remotely removeable to allow operation at 500 MeV when desired.

A plan view of the TRIUMF cyclotron illustrating a possible layout of the extraction elements is shown in Fig. 2. The protons stripped by the protection foil are indicated at the top of the figure. The electrostatic deflector (DCD) must be positioned either immediately downstream from the protection foil or in one of the shadows that recur $N * \pi/\nu_r$ revolutions downstream. Since the beam is still well inside the isochronous field and $\nu_r \sim 3/2$, the DCD deflected beam will oscillate around the equilibrium orbit reaching maximum

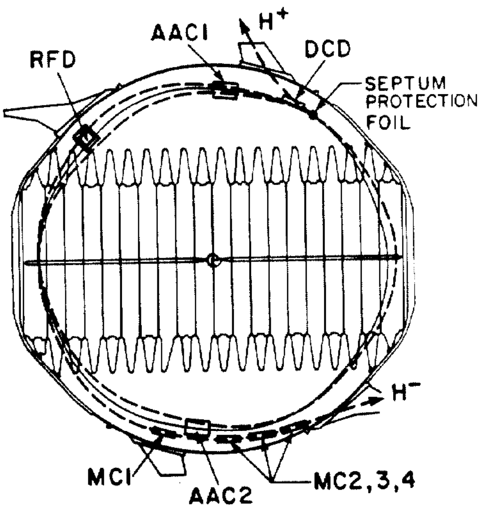

Fig. 2. Plan view of a possible H$^-$ extraction scheme comprised of a $\nu_r = 3/2$ resonance driver (RFD), electrostatic deflector (DCD), magnetic channels (MC1-4) and 92 MHz accelerating cavities (AAC1,2). The beam is extracted 1-2/3 turns after deflection by the DCD.

separation at $\sim 60° + N * 240°$ downstream from the original deflection (in this case 540°). An integrated radial deflecting field of > 5 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. 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 performance of the accelerating cavities is independent of azimuth; however to permit delivery of power and coolant they must be located in magnet valleys. The performance of the rf deflector is dependent somewhat on its azimuthal location due to the 120° periodicity of the precession pattern.[5]

Hardware

Electrostatic Deflector: The prototype 0.85 m long electostatic deflector has been described previously.[6] The septum consists of 5 mm wide and 0.076 mm thick stainless steel foils, attached to a frame contoured to the beam orbits, and separated by 13 mm from the positive stainless steel antiseptum. Nitrogen cooling gas enters and leaves the antiseptum via two hollow Al_2O_3 insulators. The entire device is adjustable in radius and in the pivot angle about the first septum foil. Following an extended development period a voltage of 65 kV was reached. Improvements were achieved by changing the foil material from molybdenum to stainless steel with polished edges, and by installing electron traps at the alumina insulators, now almost completely enclosed in shields. (Fig. 3)

Magnetic Channels: Requirements for the first magnetic channel include a thin septum (18 mm), low fringe field ($\partial B/\partial r \leq 0.08$ T/m), and moderate deflecting strength (0.1 T·m). An engineering design is nearing completion for a prototype of this device.[7] The radiation-resistent, iron-free channel will have a septum width of 15 mm, and generate a peak field reduction of 65 mT, with a mean deflecting power of 57 mT·m. The design, incorporating three independently powered coils, was aided by the use of two and three-dimensional relaxation codes. Computer simulations indicate an acceptable emittance distortion of the circulating beam by the channel fringe field. The two or three channels downstream will likely be of the coaxial $\cos\theta$ distribution design. 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. Fabrication and testing of either channel type is contingent on future funding.

Accelerating Cavity: A prototype of the 92 MHz cavity was constructed and tested under low power operation to peak voltages of

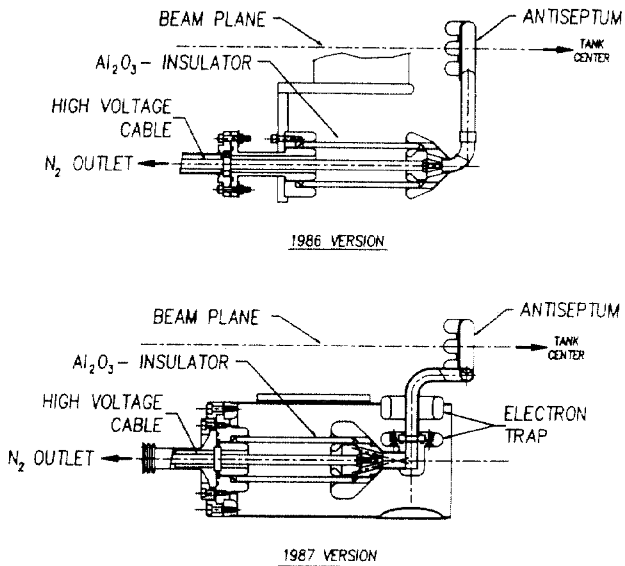

Fig. 3. Comparison of old (upper) and new (lower) DCD insulator designs showing the improved shielding from stray rf fields and electrons. A double ring assembly serves as an electron trap where the high voltage lead to the antiseptum exits the shield.

50 kV cw. The computed Q value of 10000 was verified and the stability from mechanical vibration checked. A matched pair of 15 cm wide tuning tabs on the ground shields at the HV gap enabled tuning over the required range. Direct matching of the loop coupling was staightforward. The design of the final 150 kV cavity is now complete. The cooling of the high power density areas near the shorting plane was designed with a computer code. Construction has begun with installation planned within a year. The ~60 m, 15.5 cm, 50 Ω transmission line installation is being prepared. To generate 150 kW excitation power, the final rf amplifier was designed with a cathode driven Eimac-Y567B tube. In this arrangement an existing 10 kW FM transmitter configured as a linear amplifier can amply supply the driving power required.

RF Deflector: The 11.5 MHz RFD has been operational in the cyclotron since March 1985.[8] The radial electric field is developed across a 12 cm gap between a grounded shield and pair of hot electrodes mounted at the end of a vertical transmission line that extends below the cyclotron. The electrodes are separated vertically by 10 cm and extend for 0.5 m in the azimuthal direction. Presently a power of 2 kW produces a tip voltage of 27 kV corresponding to a peak integrated field of 110 V/mm·m; if desired a higher voltage would be easily possible.

Beam Optics of Extraction

The beam optics associated with the beam crossing the fringe field of the cyclotron and passing into the exit port has been investigated with a ray-tracing code. In one scheme, four magnetic channels were considered to deflect and steer the H$^-$ beam to extraction (Fig. 2). In the initial study the magnetic channels were assumed to add no gradients or B_r components to the existing cyclotron field. Several particles were tracked through the channels and out exit port II. The particles defined a radial and vertical emittance of 2πmm·mrad each. Strong radial defocussing forces were observed as the beam crossed the main magnet exitation coil. (Fig. 4a) The addition of a strong (2 T/m) radially focussing gradient in the fourth magnetic channel precompensates the defocussing force (Fig. 4b). Additional focussing will be required downstream of the exit port to match the beam to the post accelerator transfer line. Further work must now include an engineering design study on the higher strength magnetic channels to determine practical gradient strengths, and a detailed transfer line design.

A preliminary design of a transfer line to the KAON Factory has been completed. It is important to keep the bends moderate enough

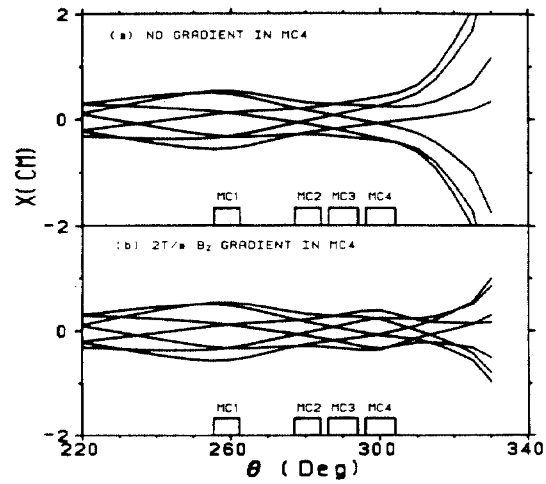

Fig. 4. Shown are two plots of the radial beam envelope as the beam passes through the four magnetic channels and into the exit port. The strong radial defocussing forces from the cyclotron fringe field observed in (a) are precompensated in (b) by a 2 T/m radially focussing gradient in MC4.

so that activation due to H^- electromagnetic stripping is minimized. A field of 0.65 T over 4.2 m, giving a bend angle of 45°, will produce a 0.1% loss.[9] Several physical structures complicate the choice of the final beamline path including the cyclotron yoke, the lifting jack posts and the vault wall.

Results of Beam Tests

H^- extraction tests are carried out in cyclotron shutdown periods, which occur twice a year. The results from the April 1987 test are shown in Fig. 5. A radial differential probe positioned just downstream of the DCD measured the transmission through the 1 mm protection foil and the septum to be 90% at a circulating current equivalent to 66 μA at a 1% duty factor for an RFD strength of 100 V/mm·m and a DCD field of 38 kV/cm. During the same test transmission values with no protection foil determined that the effective septum width was < 0.5 mm. In May 1988 a dc current of 10 μA (20 μA equivalent) was circulated to test the ability of the electrostatic deflector to hold voltages at these higher current levels. The beam was deflected by a stable field of 32 kV/cm for 20 minutes onto a wide foil 1-1/2 turns downstream at the position of the first magnetic channel in Fig. 2 and extracted down a beamline to a dump. This represents a significant achievement since 10 μA is the

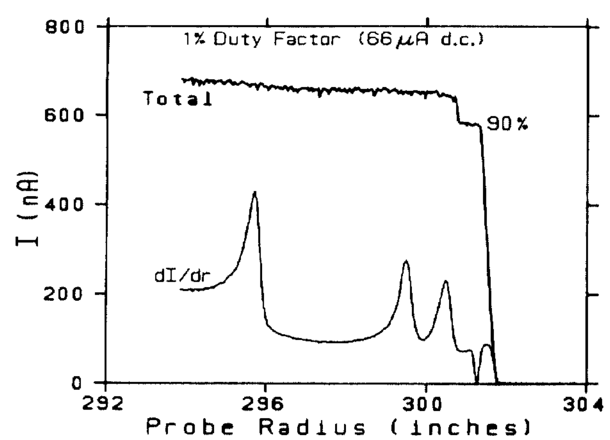

Fig. 5. Experimental result from April 1987. A 1.25 mm differential density probe immediately downstream from the DCD records the modulation in beam density, produced by the RFD (100 V/mm·m), and the separated beamlet, deflected by the DCD (38 kV/cm). A total beam scan indicates a 90% transmission through the 1 mm protection foil and DCD septum for a circulating current equivalent to 66μA dc (1% D.F.).

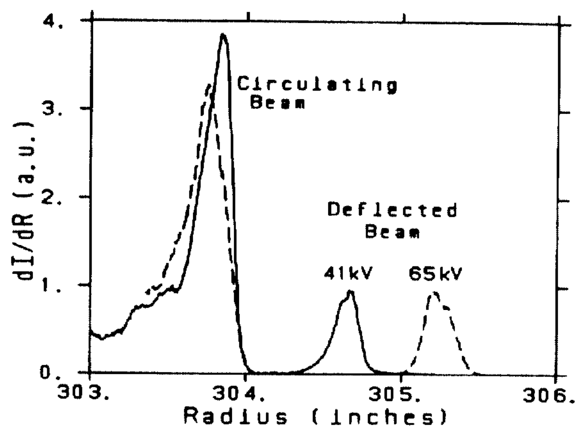

Fig. 6. Experimental result from May 1988. Shown are radial beam densities, 1-1/2 turns after deflection by the DCD at the position of MC1 in Fig. 2, for two different deflector strengths. 32 kV/cm was held at a time averaged beam current of 10μA (50% D.F.) and 50 kV/cm was held with $\sim$ 1 μA circulating.

maximum current that would be needed in the early stages of the KAON Factory commissioning. For lower beam intensities fields of 50 kV/cm were held with a slight increase in the dark current and sparking rate. Fig. 6 shows the separation achieved at the extraction foil for both DCD strengths.

Future Plans

Many of the major design theories and components have been successfully tested. Short term plans include installation and testing of the 92 MHz accelerating cavity, continued development of the DCD in a test vacuum chamber, further studies into optimizing device positions and completion of the transfer line design. Long-term, plans including the fabrication and testing of one or more magnetic channels and the eventual extraction of H^- ions, are contingent on funding.

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