PROGRESS TOWARDS EXTRACTION OF AN INTENSE H^- BEAM FROM TRIUMF

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Abstract

A 150 μA, 452 MeV, H^- beam will be extracted from the TRIUMF cyclotron for injection into the TRIUMF KAON Factory Accumulator ring. As part of the extraction scheme, we will utilize two electrostatic deflectors and a series of electromagnetic channels: 4 dipoles, one quadrupole, and a combined function channel. The first two channels and the quadrupole are iron-free, while the others have iron cores. The channels are of modest strength (85 to 570 mT) but are required to produce a low radial gradient perturbation (< 40 mT/m) in the region of the circulating beam. Designs for the channels have been completed, and prototypes of one iron-free (85 mT) and one iron-cored compensated channel (550 mT) are being constructed. Magnetic and mechanical design features of these channels will be described and results from recent beam tests with an electrostatic deflector will be presented.

Introduction

It is planned to extract a 150 μA, H^- beam at 452 MeV, from the TRIUMF cyclotron for injection into the TRIUMF KAON Factory Accumulator ring[1]. As an intermediate goal, we wish to demonstrate the extraction of a 100 μA H^- beam.

Converting from the present scheme of extraction by stripping, requires the installation of nine new extraction devices in the cyclotron chamber. The scheme for direct extraction of an H^- beam has been reported previously[2]. It employs two electrostatic deflectors (DCDs) to produce the initial beam separation, and then a series of electromagnetic channels: four dipoles, one quadrupole, and a combined function bending magnet, to guide the beam out of the cyclotron (see Fig. 1). The first two channels, and the quadrupole are iron-free, while the others have iron cores. The channels are of modest strength (85 to 570 mT) but are required to produce a low radial gradient perturbation (< 40 mT/m) in the region of the circulating beam.

Since TRIUMF accelerates H^- ions, a 1 mm wide protective stripping foil may be positioned to shadow the septum of the DCD. Protons from the foil are diverted and transported down an existing beam line, without activating the cyclotron. We therefore define extraction efficiency as the percentage of the circulating beam that is extracted as H^- ions. A coherent radial oscillation, driven by an rf deflector (RFD) at $\nu_r = 3/2$, is used to reduce the fraction of beam hitting the protection foil and raise the extraction efficiency[1,2].

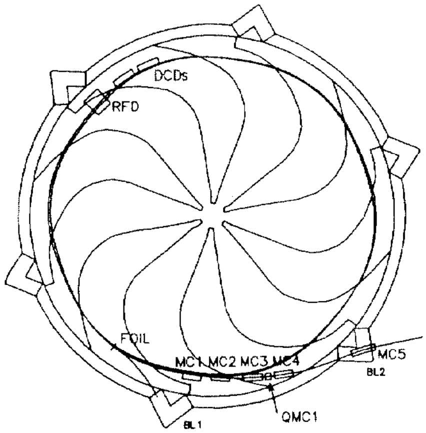

Fig. 1. Reference layout of extraction elements in the cyclotron.

The RFD has been installed and operated in the cyclotron since 1986, while a prototype DCD has been tested with beam several times. During the TRIUMF KAON Factory Project Definition Study (PDS), work has concentrated on building prototypes of one iron-free electromagnetic channel and one iron core, current compensated channel, and on improving the performance of the DCD. The magnetic and mechanical designs of the channels are outlined here, and results from recent beam tests with an improved DCD are presented.

Layout of Extraction Elements

The layout of the extraction components shown in Fig. 1 remains substantially as reported previously[2]. Further beam studies have resulted in a slight reduction in the strength of the first two magnetic channels, while channels 3 and 4 are strengthened. The cyclotron fringe field is strongly radially defocussing, and to achieve sufficient focussing to control the beam size, we have found it necessary to separate the focussing gradient from the dipole field in MC4. A separate, air-cored quadrupole channel (QMC1) has therefore been designed for installation between MC3 and MC4. In addition, to control the beam size in the final bending magnet (MC5), a small gradient (0.7 T/m) has been added to its dipole field. The gradient may be added by shaping the pole tip profile of an otherwise conventional window-frame magnet. The new parameters of all the extraction elements are summarized in Table 1, including the clear separation (ΔR) of the deflected beam from the circulating beam at each channel.

Table 1. Design Specifications for Extraction Devices

Device	$\theta_{entrance} - \theta_{deegap}$	Integrated Strength	Gradient	ΔR(mm)
Foil	233.6°	–	–	–
RFD	131.3°	0.1 MV/m· m	–	–
DCD1	108.6°	3.9 MV/m· m	–	–
DCD2	118.1°	3.9 MV/m· m	–	–
MC1	259.0°	85 mT· m	–	30
MC2	269.0°	128 mT· m	–	50
MC3	280.0°	0.50 T· m	–	140
QMC1	287.5°	–	4.0 T/m	300
MC4	290.5°	0.51 T· m	–	400
MC5	314.5°	0.06 T· m	0.7 T/m	–

Beam Dynamics Tolerances for Magnetic Channels

The tolerances on the magnetic fields of the extraction channels had been obtained from a series of beam dynamics studies[2]. During the PDS these studies were extended and the effects of the channels on the extracted beam properties for the TRIUMF KAON Factory were investigated[3,4].

The channels whether air core or iron compensated will have fringe fields that extend into the circulating beam. The radial gradients in the fringe fields can lower the already weak vertical focussing causing an increase in the vertical amplitude. A total tolerance integrated along the beam trajectory of $\int dB_z/dr \cdot dl$ <70 mT/m·m is required to keep the change in ν_z to less than 0.06 which corresponds to a 25% increase in emittance. In addition, that part of the fringe field which cannot be compensated with the trim coils must not produce more than 10° of phase slip.

The third harmonic component of these radial gradients will stretch the radial emittance at the $\nu_r = \frac{3}{2}$ resonance which lies ~10-15 cm inside the septum of MC1 and MC2. The azimuthal positions and strengths of the added gradients affect the growth of the extracted emittance depending on how the new gradient adds with the existing gradient phasor (13 mT/m·m near MC4). At the position of MC1 and MC2 the phase of the resulting gradient is affected more than the amplitude, while near MC4 the amplitudes add. To limit the increase in radial emittance to no more than 25% above that already occurring at this resonance, tracking studies[3,4] show that a limit of $-10 \leq \int \partial B_{z3}/\partial R \cdot d\ell \leq +30$ mT/m·m must be placed on the tails of the channel fringe fields.

Within the aperture of each channel we have aimed to keep the integrated field experienced by any particle in the beam to be within ±0.2 mT·m of the field felt by the central particle, over ±1 cm by ±1 cm, in order to avoid focussing effects that would increase the size of the beam downstream.

Finally, the tolerance imposed on the stability of the channel power supplies is 1×10^{-4}.

Prototype Magnetic Channels

Iron-Free Channels

Channel MC1 is located closest to the circulating beam and must have the thinnest septum (10 mm). It was therefore selected as a prototype for development of the iron-free dipole channels. The initial design was done with the aid of 2D magnetic field computations[2,5], and resulted in a channel which consists of a pair of opposed dipole coils: a thin septum coil (I= 745 A), and a cancellation coil (I= 665 A).

The two dimensional design has been refined using the CANAL_3D program[6] to calculate the field for a fully three dimensional channel, including the end pieces. It was found that the ends have a significant effect on the integrated field along the beam direction ($\int B_z \cdot dl$). Low gradients predicted by 2D calculations at the circulating beam are offset by the contributions from the ends. It was therefore necessary to reposition one pair of septum conductors and to change by ~5% the currents in the septum and cancellation coils. The final design of the channel, including a set of end pieces designed to be as compact and symmetric as possible, is shown in Fig. 2. The field integrated along the beam direction, and its gradient are shown in Fig. 3, and both fall within the beam dynamics tolerances.

The channel is constructed from directly water cooled copper conductors, 5 mm square in the septum, and 10.4 mm square elsewhere. The current density in the conductors is 2.0 kA/cm^2 in the septum and less than 1 kA/cm^2 elsewhere. The total power for both coils is 10 kW. The individual conductors were first insulated with plasma sprayed Al_2O_3 (with 3% TiO_2) to a thickness of 0.1-0.15 mm, and then brazed together into a complete coil. They are clamped in position on seven supporting bulkheads. Because of local imperfections in the insulation we plan to temporarily insulate the bulkheads with a combination of plasma sprayed Al_2O_3, and hard anodizing. Assembly of the prototype channel has been completed, the coils have been powered, and field mapping has begun.

Current and water are supplied to the channel through a coupling block, which may be disconnected remotely so that the channel may be removed from the cyclotron using remote handling equipment. The water connection is sealed by an elastomer "O" ring, while the interface pressure at the current connection is maintained by a stack of Belleville washers. A prototype coupling block has been successfully tested, in vacuum, with up to 3 kA of current

The second magnetic channel (MC2) is similar in design to MC1. In this case the field must be scaled up by 50%, and the currents increased accordingly. Since the separation from the circulating beam is larger, the size of the septum may be doubled, and both the required power and cooling water pressure remain reasonable.

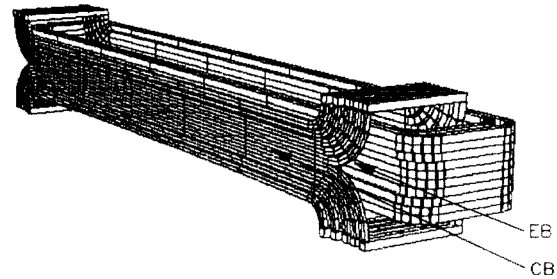

Fig. 2. A perspective view of the prototype MC1 as modelled using CANAL_3D[6], showing the circulating beam (CB) and the extracted beam (EB).

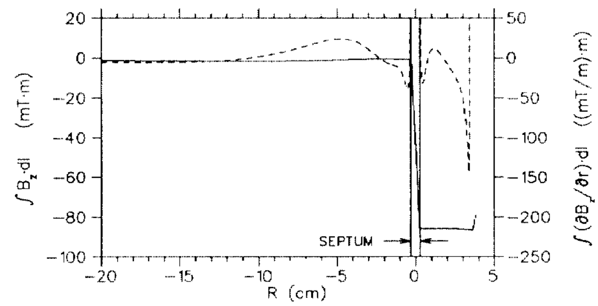

Fig. 3. Results of the CANAL_3D model, in the median plane ($z = 0$). The vertical magnetic field (solid line) and the radial gradient (broken line) are integrated along the beam direction.

Iron-Core, Current-Compensated Channels

The third and fourth dipole channels are iron cored channels which shield the beam from the main cyclotron field. The separation from the circulating beam is ≥ 14 cm, nevertheless current carrying coils are required to adequately compensate the effect of the iron at the circulating beam. The original design[2] was found to be very sensitive to dimensional tolerances of the iron, and the design has been modified to one with non-saturated iron to avoid this effect[7]. To prevent saturation the magnetic induction in the iron was reduced to less than 1.7 T by increasing the thickness of the side walls of the iron channels to 1 cm (see Fig. 4). Dipole coils were wound along the channel walls to generate a compensating field outside the channel and to reduce the induction inside the iron. Results of a POISSON calculation for MC3 are shown in Fig. 5. With this design, tight mechanical construction tolerances are not a requirement. Inside the channel the average field is approximately 3 mT (for a current of 17 kA-turns which is optimal for compensation of the external field of 0.56 T at MC3) uniform to within 0.2 mT over the beam cross section within an aperture of 2 cm by 2 cm. The external field perturbation is 700 μT and −6 mT/m for the gradient at a distance of 14 cm. At 20 cm the perturbation is less than 10 μT and 200 μT/m for the gradient.

The insulation and construction of these channels is similar to that of MC1. The final prototype of MC3 has been assembled, and is being field mapped in a laboratory magnet.

Recent Beam Tests

During the spring 1990 shutdown the DCD was installed in the cyclotron with the goal of testing it with beam currents higher than previously achieved. To utilize a beam line capable of handling high currents, the DCD was installed on the opposite side of the machine from the previous tests. The protons from the protection foil were diverted down beam line 4A, which can handle up to 10 μA of

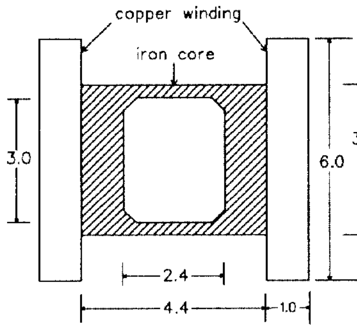

Fig. 4. A cross section through the prototype MC3. All dimensions in cm.

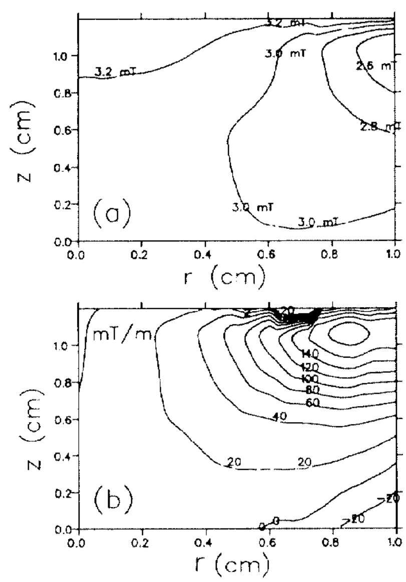

Fig. 5. Contour plot of the magnetic field (a) and the gradient (b) for one quadrant inside MC3.

beam. The beam which passes through the DCD was deflected outwards onto a wide stripping foil $1\frac{1}{2}$ turns downstream, and extracted as protons down beam line 1A, which is capable of handling up to 200 μA. For high current running, additional beam spill sensors and hardware protection were installed and tested. This is particularly important for an H^- beam since uncontrolled stripping on the extraction elements during unstable conditions would damage the vacuum tank wall.

With the DCD operating at a positive voltage of 55 kV (42 kV/cm) a current equivalent to 100 μA dc (at up to 5% duty factor) was extracted with 86% efficiency (see Fig. 6). The current was then increased to 10 μA (at 60 μA equivalent), where the system ran very stably for 20 minutes. Later 20 μA was run for several minutes. Although the extracted beam current was somewhat unstable under these conditions, the DCD voltage itself was very stable. One of the factors contributing to the instability was the large radial width of the extracted beamlet, which made it difficult to fit on the stripping foil. Beam dynamics studies have since shown that this can be induced by a deviation from isochronism or a phase drift in the radial region between the RFD and the DCD. This emphasizes the need to improve the beam phase stability at extraction.

After the completion of the beam tests, the DCD voltage was raised (without beam) to determine the ultimate voltage holding limit. These tests demonstrated that the unit was capable of holding up to 75 kV, well in excess of the 50 kV required.

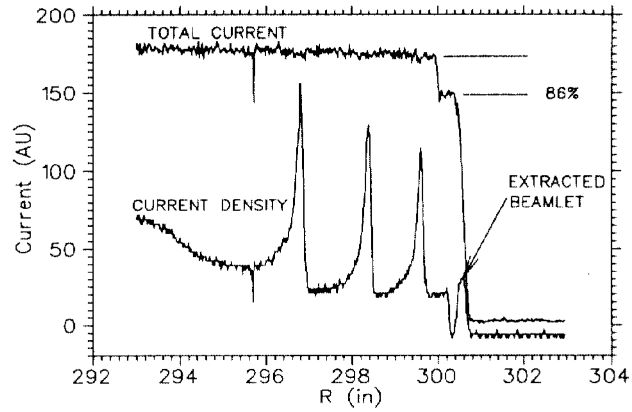

Fig. 6. Experimental results from April, 1990 for a circulating current equivalent to 100 μA dc (at up to 5% D.F.). The beam density, as measured by a 1.25 mm differential probe finger, shows the modulations produced by the RFD (83 V/mm·m), and the separated beamlet, deflected by the DCD (42 kV/cm). The extraction efficiency, as indicated by a total beam probe is 86%.

Future Beam Tests

In order to achieve the goal of extracting an H^- beam within two years of the funding of the TRIUMF KAON Factory, we will continue tests of the extraction system. We plan to re-install the DCD in the cyclotron in the fall 1990 shutdown, with an improved beam dump to intercept the high current beam during a DCD spark, and run up to 100 μA through the deflector. Tests of the prototype MC1 in the cyclotron will also be carried out.

Acknowledgements

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