MAGNETIC CHANNEL DESIGN CONCEPTS FOR THE EXTRACTION OF H^- IONS FROM THE TRIUMF CYCLOTRON

J.B. Pearson, E. DeVita, R. Laxdal, R. Lee, G.H. Mackenzie, T.C. Ries, R. Trellé and M. Zach
TRIUMF, Vancouver, B.C., Canada V6T 2A3

Summary

A scheme to extract 450 MeV H^- ions from the TRIUMF cyclotron will require the use of two types of magnetic channel. An electrostatic deflector will produce the initial separation between circulating and extracted beams. This will be followed by a magnetic channel with a radially narrow septum. As the separation increases, more efficient coaxial channels with $\cos\theta$ windings would lead the beam out of the cyclotron. A design is presented for a prototype septum channel, and engineering tests performed on critical subcomponents are described. The radiation-resistant, iron-free channel will have a septum width of 15 mm and generate a peak field reduction of 75 mT, with a mean deflecting power of 60 mT·m. The design, incorporating three independently powered coils, was aided by the use of two and three-dimensional relaxation codes. The coaxial design has a wider effective septum of 55 mm but produces four times the field with proportionally less fringe field. The design concepts of this channel are also presented.

Introduction

At present, the TRIUMF cyclotron accelerates H^- ions to 500 MeV, and extracts up to three cw proton beams simultaneously by stripping. Direct H^- extraction would, however, allow charge exchange injection into a higher-energy accelerator. [1,2] At 450 MeV, the energy most suitable for a post-accelerator, the turns are not separated. The extraction scheme proposed to overcome this problem is described elsewhere. [2,3] In brief, the scheme uses an rf driver cavity to develop a coherent oscillation near the $\nu_r = 3/2$ resonance. Subsequent precession generates a large radius gain per turn, but does not separate the turns. A narrow stripping foil is then used to intercept a small fraction of the beam. The septum of an electrostatic deflector is placed in the shadow of this foil. This is followed by a second electrostatic deflector and a series of magnetic channels. The first of these channels must have a radially narrow septum, since the separation produced by the electrostatic deflectors is ~35 mm. The field produced by this channel should be at least 60 mT·m so that subsequent, stronger channels may have thicker septa. These channels may be of the more efficient coaxial, $\cos\theta$ winding type, [4] which produces a higher bending field with less leakage. Three or four channels would be required to lead the beam out of the cyclotron.

To date, prototypes of the rf driver and the electrostatic deflector have been constructed and tested in the cyclotron, [2,5] in order to test the design and operation of devices suitable for continual operation at high current. This paper describes the design of a prototype magnetic channel with a radially narrow septum, suitable for experiments in the cyclotron. It would produce sufficient separation (9 cm) to test a coaxial channel 60° downstream. A maximum overall length of 1 m is dictated by the location of the channel in the cyclotron and practical considerations for remote handling. Initial testing will be done with only one electrostatic deflector (at ≥ 3 kV/mm·m), which imposes a more stringent upper limit of 18 mm on the width of the septum (for an rf driver strength of 30 V/mm·m, see [3]).

The channel is shown schematically in Fig. 1. It is an iron-free channel consisting of three independently powered coils. The septum coil and the cancellation coil produce most of the desired field, while the trim coils are used to alter the gradient of the field. The ends of the septum coil curve downwards asymmetrically, to allow existing remote handling equipment to be positioned above. This asymmetry produces transverse field components which are discussed in the beam dynamics section. The channel should be radiation resistant, and must accomodate a radial movement of ±50 mm necessary for position adjustment during experiments in the cyclotron.

Field Calculations

A conductor configuration for the magnetic channel was chosen by two-dimensional calculations of the fields produced by infinite rectangular conducting bars in air. Various arrangements of conductors were tried, until a reasonable field profile was obtained, as judged by the beam dynamics criteria discussed below. This configuration was then investigated in detail using both two and three-dimensional field calculation programs. Based on the two-dimensional results, the coil geometry and field pattern shown in Fig. 2 was chosen. The

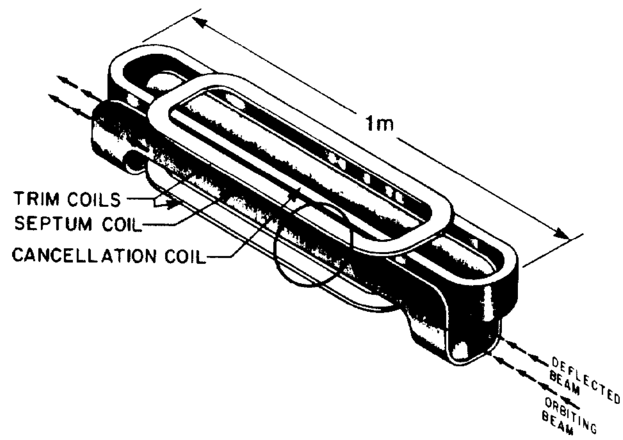

Fig. 1. An isometric view of the prototype magnetic channel. A cross section through the coils (circle) is shown in Fig. 2.

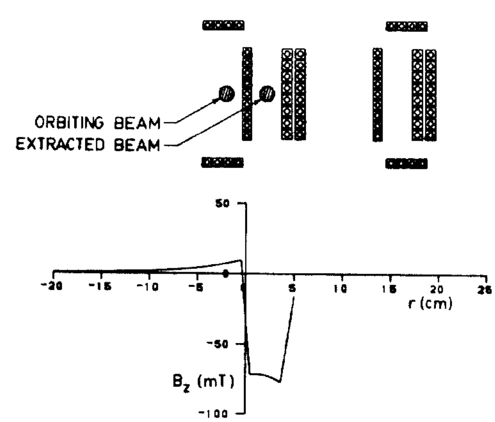

Fig. 2. A cross section through the channel used for the two-dimensional field calculation. The B_z field produced by the channel in the median plane is also shown. Currents in the coils are septum −700 A, cancellation +480 A, trim −120 A.

peak reduction in vertical field (B_z) within the channel is 72 mT and for an effective channel length of 0.9 m, the total deflecting power would be 65 mT·m.

The beam dynamics criteria used for the initial channel design were:

- net phase slip produced by the leakage field $\leq 10°$
- $\frac{\partial B_z}{\partial r} \leq 0.15$ T/m. Orbit-tracking studies showed that this was tolerable for vertical focussing

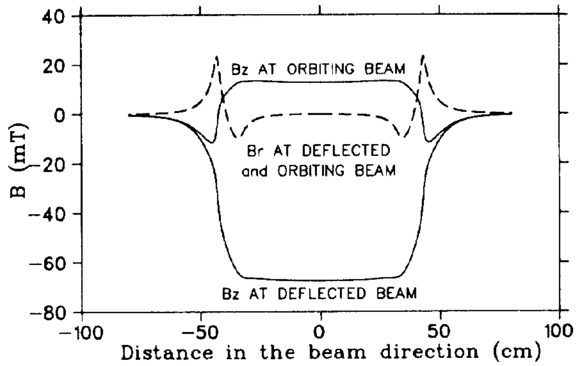

Fig. 3. The B_z and B_r components of the field experienced by the orbiting and extracted beams.

For an effective length of 0.9 m, the phase slip produced by the fringe field is 10°. The gradient of the leakage ($\frac{\partial B_z}{\partial r}$) produced by the channel has a maximum of 0.16 T/m at the septum, but decreases with increasing distance from the septum. Orbit-tracking studies (see next section) were made to accurately assess the consequences of the leakage field.

The water cooling channels in the conductors, and the spaces between the individual conductors in the septum, may affect the beam, since both the orbiting and the extracted beams pass close to the septum. These effects were studied, in two dimensions, by calculating the fields due to the individual conductors in each coil (with realistic spaces between them) and by modelling the water cooling channels as additional conductors carrying a cancellation current in the opposite direction. At the point of closest approach of the beam, the modulation of the field as a function of vertical position is 5%, but falls away very quickly with distance from the septum. Orbit-tracking computations have shown the effect on the beam to be negligible.

A final two-dimensional computation, using POISSON, was done to check the influence of the main magnet steel on the field of the channel. The field of the channel in air was compared with the field of the channel with iron added to simulate the iron of the main magnet. The addition of the iron changes the field in the beam region by less than 0.2 mT. This small perturbation occurs smoothly over 10 to 20 cm, so that the effect of the iron on the channel field may be neglected. The peak field produced in the iron is less than 5 mT. This will not alter the permeability of the steel significantly, and thus the field distribution produced in the cyclotron magnet by its energizing coil will remain unaltered.

GFUN3D [6] was then used to compute the field produced by a practicable three-dimensional design of the channel, including the shape of the windings at each end of the coil. These computations allow the total deflecting impulse produced by the channel to be calculated, and indicate the presence of field perturbations produced by the ends of the coils. Figure 3 shows the B_z and B_r fields experienced by the last turns of the orbiting beam, and the extracted beam. The total deflecting power is 60 mT·m. In the median plane there is a small average radial field (~0.03 mT) which arises because of the asymmetric ends of the septum coil. The effects of this field, and the perturbations at the coil ends were calculated in the beam dynamics studies outlined below.

Beam Dynamics

The effect of the channel on the beam, was studied using a modified version of our orbit-tracking code GOBLIN. The separation produced between the extracted beam and the orbiting beam downstream of the channel was calculated, and the proper curvature and location for the channel in the cyclotron was determined. The GOBLIN studies also permit a check for any distortion of the beam emittance produced by the field of the channel.

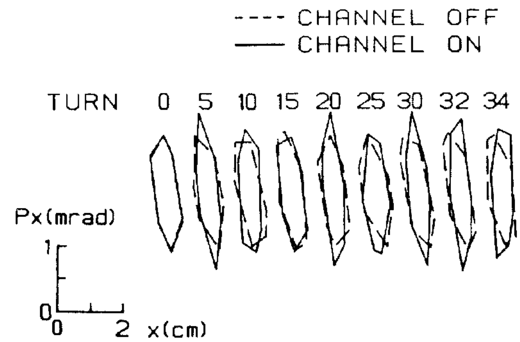

Fig. 4. Ellipses in radial phase space plotted every 5 turns (at the azimuth of the channel) as the beam passes through the leakage field. Turn 32 is the closest orbiting beam to the septum, and turn 34 is the extracted beam. Ellipses from calculations made without the channel field have been superimposed for comparison.

In order to include the effect of the channel in GOBLIN the channel field was added to the magnetic field used for particle tracking in GOBLIN. The distance to the centre of the channel (along the beam orbit) and the perpendicular distance to the curved septum in GOBLIN were used as rectangular coordinates to calculate the channel field based on the GFUN3D results. This approximation is permissible because of the large radius of curvature of the septum (14 m) compared to the limited radial extent of the leakage field (10-20 cm). The channel field used by GOBLIN was the GFUN3D field calculated in the median plane of the channel. A Taylor series, carried to second order in z, was used to calculate the off-median plane fields due to the channel. The validity of this expansion was checked against GFUN3D calculations of the fields at ±5 mm off the median plane.

The trajectory of a central ray was calculated over the last 34 turns (~5 cm) leading up to the channel (to examine the effects of the leakage field), through the channel itself, and 60° downstream to a location where the beam could be observed on a probe. The starting conditions for the run were established from previous calculations done without the magnetic channel. After 32 turns, the beam receives a kick from the electrostatic deflector, and one and one-half turns later it enters the magnetic channel. Since the leakage field from the channel affects the centring of the beam an iterative procedure was required to locate the magnetic channel so that the septum fits between the orbiting and extracted beams. After positioning the channel, the effect on the beam quality was studied by tracking ellipses in both $x - p_x$ space and $z - p_z$ space. For each ellipse, a central ray and six particles on the ellipse were tracked through the field. The electrostatic deflector strength used was 3 kV/mm·m and the rf driver strength was 30 V/mm·m (see [3]).

Figures 4 and 5 show the effect of the leakage field on the beam in radial phase space. The results show that there is very little distortion of the radial emittance (see Fig. 4). The clearance between the septum and the orbiting and extracted beams can be seen in Fig. 5. The separation produced reaches a maximum of 9 cm (60° downstream), and at the location of the probe used for experimental measurements (40° downstream) the separation is 7.5 cm. In this region the beam is slightly mismatched to the cyclotron acceptance. Twenty degrees downstream, at the point where a second channel in a final extraction scheme might be located, the radial beam width is increased ~20%. The present orbit-tracking studies do not include the effect of the gradient of the 3rd harmonic $\frac{\partial B_{z3}}{\partial r}$ at the $\nu_r = 3/2$ resonance (12.5 cm inside the septum), which may produce some stretching of the radial emittance, and growth of the effective emittance after precession. This gradient can be corrected to some degree with existing trim coils, and the details are being investigated. At the radius of the $\nu_r - 2\nu_z = 1$ resonance (18 cm inside the septum) the gradient of 1st harmonic, ($\frac{\partial B_{z1}}{\partial r}$) is 0.6 mT/m, well below the

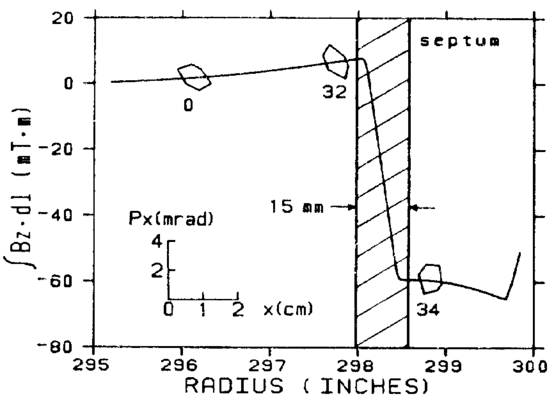

Fig. 5. Position of the septum with respect to the orbiting and extracted beams. The azimuthally integrated B_z field of the channel is superimposed.

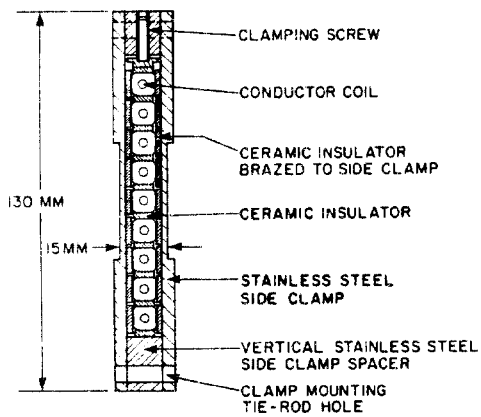

Fig. 6. A cross section through one of the radiation-resistant clamps which hold the septum conductors in place.

tolerable gradient of 4 mT/m.

In vertical phase space the net B_r caused by the coil ends produces a 1.5 cm shift in the vertical position of the beam. Some of this may be compensated by the existing trim coils, but since the effective vertical aperture of the cyclotron is ± 2.5 cm, ways of reducing the shift are being studied (e.g. asymmetric powering of the channel trim coil).

Electrical and Mechanical Design

The septum coil consists of 9 turns, each carrying 700 A, while the cancellation coil consists of 16 turns, each carrying 480 A. The trim coil consists of four turns, each carrying 120 A. A total power of 5.5 kW is required, and all coils are directly water-cooled, using hollow copper conductors.

A magnetic channel operating in the TRIUMF cyclotron will be exposed to a high flux of stripped H^- particles (2×10^{10} s^{-1} cm^{-2} at 100 μA extracted), and also must withstand some accidental direct beam spill from the orbiting or extracted beams. The prototype magnetic channel was therefore designed to be radiation resistant. The coils are wound from bare copper and held in postition by insulated stainless steel clamps. The clamps are designed to withstand a total side force on the septum of 3 kN, most of which arises from the interaction between the current in the coils and the 0.5 T ambient field in the cyclotron magnet. Alumina ceramic plates provide insulation between neighbouring conductors, and between the clamps and the conductors (see Fig. 6). The total width of the septum, including the clamps, is 15 mm. The ceramics on either side of the conductors are metalized on one side, and brazed to the side plates of the clamp to hold them in place. Initial tests of this process in an induction furnace have been successfully completed. The insulated clamp is expected to withstand a direct beam spill of 100 nA from thermal considerations.

The desired range of radial movement in the channel position is provided by a pair of worm drives, one at each end of the channel. A feedthrough to a motor drive outside the vacuum chamber allows the position of the channel to be adjusted under vacuum, with the cyclotron running. In order to accomodate this motion, the current leads to the channel must be flexible. A water-cooled, radiation-resistant, vacuum-compatible, flexible high-current lead has therefore been developed. It consists of a 25 mm diameter stainless steel bellows, approximately 1 m long. The bellows, stabilized by an outer sheath of stainless steel mesh, contains a flexible copper welding cable to carry the current. Water flows inside the bellows to cool both the bellows and the welding cable. A prototype of such a unit has been successfully tested in a thermally insulating jacket (to simulate a vacuum environment) with a current of 750 A.

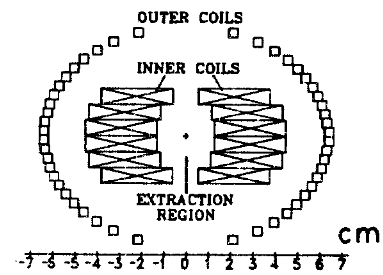

Fig. 7. A cross section through the coaxial channel, 1.3 and 0.6 kA, in the inner and outer coils respectively produces B_z of 0.3 T.

Coaxial Channels

Conceptual designs for subsequent channels, such as the coaxial channel, have been studied. This channel consists of two concentric current-carrying coils, with a winding density that varies in a $\cos\theta$ distribution (see Fig. 7). Currents of 1.3 kA and 0.6 kA flow in the inner and outer coils, respectively, to produce a field reduction of 0.3 T on the axis of the channel. The leakage field in the region of the orbiting beam is almost uniform at 1.2 mT, which is easily compensated by low-power trim coils. The total power is ~12 kW, and cooling is provided by using water-cooled conductors. To allow passage of the beam, the coil ends are taken vertically above and below the median plane in a saddle shape. The overall septum thickness for this channel is ~50 mm.

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