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STATUS OF THE H^- EXTRACTION PROGRAM AT TRIUMF

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ABSTRACT

The principle of utilizing the $\nu_r = 3/2$ resonance for efficient direct extraction of 100 μA of H^- ions at 450 MeV from the TRIUMF cyclotron has been previously demonstrated. The initiation of the KAON Factory Project Definition Study at TRIUMF moves the emphasis of the H^- extraction effort from the design of components compatible with short beam tests to equipment suitable for the final extraction configuration and from beam dynamics studies to engineering studies. To this end a reference exraction design has been chosen and will be described. Designs for the magnetic channels, both air core and iron compensated, ranging in strength from 0.1 T to 0.45 T, are progressing. Engineering constraints complicating the implementation of the reference design will be discussed.

INTRODUCTION

The proposed TRIUMF KAON Factory design[1] requires the direct extraction of 100 μA of H^- from the cyclotron to permit injection by charge exchange into the first of five rings that would increase the energy to 30 GeV. A program to demonstrate the feasibility of H^- extraction was initiated in 1984.[2] Presently the KAON Factory Project Definition Study has made possible a more detailed investigation of both the theoretical and technological aspects of the task.

Extraction employs electrostatic deflectors and magnetic channels in the conventional way. Spill on the septum of the first electrostatic deflector is eliminated by positioning a narrow (1 mm) foil upstream and diverting the stripped proton beam down an existing beamline. The H^- extraction efficiency is enhanced by exploiting the precession of a coherent radial oscillation excited at the $\nu_r = 3/2$ resonance (428 MeV). A local rf electric field[3] oscillating at 11.5 MHz, half the accelerating frequency, will drive the beam off center just as static deflections do at $\nu_r = 1$.

The rf deflector (RFD) which excites the resonance is used regularly for beam tests and remains in the cyclotron permanently. An 85 cm long electrostatic deflector (DCD) has been tested several times *in situ*. A stable operating voltage of 41 kV across the 13 mm radial gap has been achieved for a dc beam of 10 μA. In another test the transmission using a 1 mm protection foil and the DCD septum was 90% for a circulating current equivalent to 66 μA.[4] Presently a new DCD is being constructed with minor modifications for a new series of tests. Most of the recent work has concentrated in three areas; the choice of a reference design to set the component specifications, the design of the magnetic channels, and the engineering associated with realizing the design.

LAYOUT OF COMPONENTS

The first step in the design process is to fix the position of the extraction elements in the cyclotron to determine the design parameters for each component. Several requirements must be considered in choosing an optimal layout. Firstly the protons from the septum protection foil and the H^- ions will be extracted from TRIUMF through an existing extraction port. Secondly, the extraction devices should be placed to minimize modifications to existing hardware. Thirdly, the elements should be positioned and designed to minimize restrictions on the existing physics program during the early commissioning of the KAON Factory. Lastly beam dynamics considerations restrict the positioning of extraction devices.

The DCD must be positioned either immediately downstream from the protection foil or in one of the secondary shadows that recur $N * 2\pi/\nu_r$ downstream. Figure 1 shows the case of a foil at 240° when ν_r is slightly larger than 1.5. The azimuthal length, 2ℓ, of the beam free region is w/x' where w is the foil width and x' is the divergence given by $\gamma A_i/R$ for a matched beam with incoherent amplitude A_i and average radius R. (For a radial emittance of 1πmm-mrad, x' ~0.5 mrad, so 2ℓ ~2 m for w=1mm). The figure shows the shadows gradually filling in as the finite phase band generates an energy difference. This will occur in N turns where N is given by $N \sim 2w/(\Delta\phi^2 * dr/dn)$ where $\Delta\phi$ is the half width of the phase band and dr/dn is the radius gain per turn. (For a 1 mm foil and a conservative phase band of 40° the shadows will disappear after ~3 turns (dr/dn~5mm)). Thus the septum should follow the foil within one or two turns. In addition after several turns more of the circulating beam will be intercepted by the foil due to the large radial off-centering, causing a large

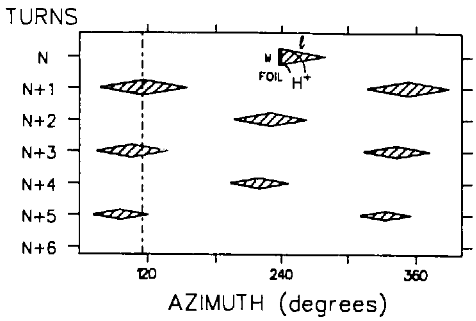

Fig. 1. The secondary shadows produced by a foil @240° are shown schematically for $\nu_r \sim 1.52$. The shadows gradually fill in as the finite phase band generates an energy difference.

reduction in the efficiency. Since the beam is still well inside the isochronous field and $\nu_r \sim 1.5$ the DCD deflected beam will oscillate around the equilibrium orbit reaching maximum separations at $\sim 60° + N * 240°$ downstream from the original deflection. The magnetic channels must be located near one of these maxima.

A detailed analysis of the problem produced six basic schemes for extraction utilizing three different beamlines for proton extraction.[5] The optimal scheme is shown schematically in Fig. 2. The protection foil is positioned to extract protons down beamline 1 (BL1) which is capable of accepting 200 μA. During KAON Factory commissioning a wide foil can be used to extract 100 μA or more of protons into BL1 leaving a trickle of current extracted as H^-. Two DCD's are positioned to deflect the beam at the position of the first secondary shadow. 1 1/2 turns later, four channels will steer the deflected beam out of the cyclotron. The specifications for each device for this layout are given in Table 1 including the separation (ΔR) of the deflected beam from the circulating beam at each

Table 1. Design Specifications for Extraction Devices

Device	θ^0_{deegap}	Strength	ΔR(mm)	L(m)
Foil	233.6	-	-	-
RFD	133.1	0.2 MV/m	-	0.5
DCD1	108.6	3.9 MV/m	-	1.0
DCD2	118.1	3.9 MV/m	-	1.0
MC1	255.0	0.1 T	30	1.0
MC2	265.5	0.175 T	60	1.0
MC3	275.5	0.225 T	150	1.0
MC4	286.5	0.425	370	1.0

channel. Studies are still underway to determine the channel gradients necessary to optimize the extraction optics. Room has also been left to install an auxilliary accelerating cavity[3] (RFB) to double the energy gain per turn at extraction to further dilute the beam density. However, the corresponding doubling of the energy spread and slight increase in the radial emittance in the extracted beam makes injection into the accumulator of the KAON Factory less efficient.[6]

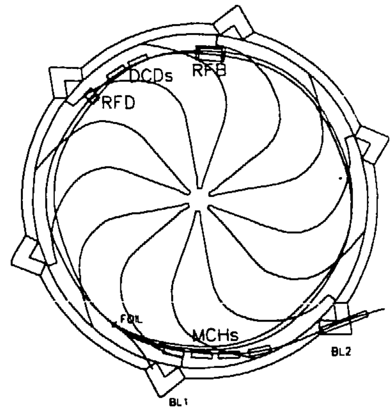

Fig. 2. Reference position of extraction elements in the cyclotron.

The positioning of the first DCD in the secondary shadow of the septum protection foil has two advantages. Firstly, the azimuthal position can be chosen to coincide with the maximum width of the shadow whereas in the primary shadow some azimuthal separation is needed to allow the protons to clear the DCD (see Fig. 1). Secondly, it avoids locating the DCD in an extraction path used in normal TRIUMF operation. The stability and width of the secondary shadow has been confirmed by a recent experiment. A 3 mm foil was positioned in a beam density minimum produced by the RFD. A 1.5 mm radial differential probe positioned 240° downstream was scanned to observe the foil shadows. The stability and width of the primary shadow matched that predicted by computer simulation and remained fixed for an eight-fold increase in the radial emittance and a phase excursion of ±10°. (Fig. 3)

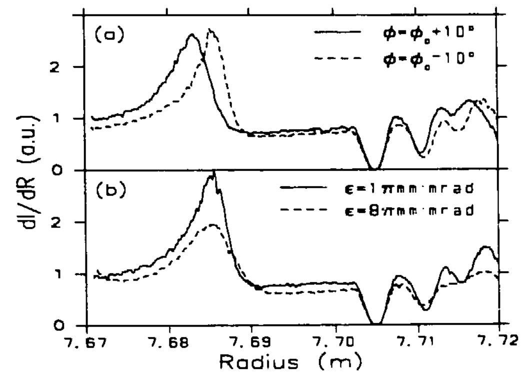

Fig. 3. Experimental result showing the stability of the first secondary shadow. A 1.5 mm differential probe, 240° downstream from a 3 mm foil (see dotted line in Fig. 1) records beam density for (a) a ±10° swing in the 20° phase band and (b) an eight-fold increase in the radial emittance.

MAGNETIC CHANNEL FIELD DESIGN

The initial design of the magnetic channels has been carried out using guidelines for field tolerances derived from previous beam dynamic studies of the H^- extraction system.[7] Practical considerations of remote handling dictate a maximum length of one meter for each channel. We begin with the total allowable tolerance for all the channels and divide it amongst them. MC1 is closest to the circulating beam and we apportion it half of the total allowable perturbation of the circulating beam.

TRIUMF is relatively weakly focussing compared to many other cyclotrons. This demands a low radial gradient of the leakage field in the region of the circulating beam. A total tolerance of $\partial B_z/\partial r \leq 80$ mTm^{-1} ·m is required to keep the change in ν_z to less than ± 0.04. In addition the $\nu_r = 3/2$ resonance (12.5 cm inside the septum), places a further restriction on the gradient of the 3[rd] harmonic ($\frac{\partial B_{z3}}{\partial r}$) which places a tolerance of $\partial B_z/\partial r \leq$ 10 mTm^{-1} ·m at this radius. Finally, we require that the total net phase slip produced by the leakage field be less than 10°. Within the channel itself, we have aimed to keep the radial gradient below 150 mTm^{-1} in order to avoid focussing effects that would increase the size of the beam downstream.

The perturbation to the circulating beam by MC1 is minimized by using an iron-free design. Figure 4 shows a cross section of the channel, which comprises two curved interlocking coils, a septum coil and a cancellation coil, with currents of 810 A and 850 A respectively. The septum is 5 mm thick, with a current density of 2.2 kA/cm^2 (assuming 75% of the conductor cross section for cooling). The maximum current density elsewhere is 1.2 kA/cm^2.

Fields were calculated using a Biot-Savart integration code. The peak field produced by the channel is just over 0.1 T (see Fig. 4), and the gradient outside reaches a peak of 40 mTm^{-1}, and falls to ~ 7.5 mTm^{-1} at 12.5 cm. A strong cancellation coil and displaced top and bottom conductors of the septum are utilized to reach these very small gradients. Within the channel, the gradient is $< \pm 150$ mTm^{-1}. The cancellation coil conductors were displaced radially to reach this gradient. The field is acceptable at $z = \pm 1$ cm from the median plane.

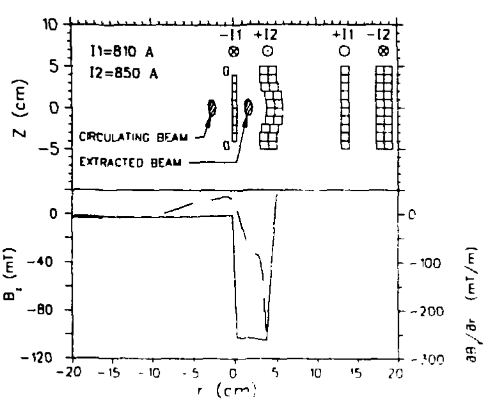

Fig. 4. Proposed design of MC1. The upper plot shows the conductor configuration and currents, while the lower plot shows the axial field (solid line), and the field gradient (dotted line).

MC3 and MC4 require higher field reduction (Table 1) but the larger beam separation permits the use of iron channels, with coils to compensate for the perturbation to the cyclotron field which extends 30 cm inside the channel. Channel 3 is located in a region where the background field varies from 0.39 T to 0.54 T (see Fig. 2). This has very litte effect on the field outside of the channel, but the inside field is strongly affected. POISSON has been used to study the effect on the internal field due to different geometries of iron and coils. At a particular background field a small radial gradient can be achieved by using a simple rectangular cross section. However, the field gradient is very sensitive to variations in the thickness of the side wall of the channel, and the under/over-compensation due to the non-uniform background field can be minimized by a thickness variation along the channel side-wall. Figure 5 shows the calculated field and field gradient both outside and inside of the channel for two background fields.

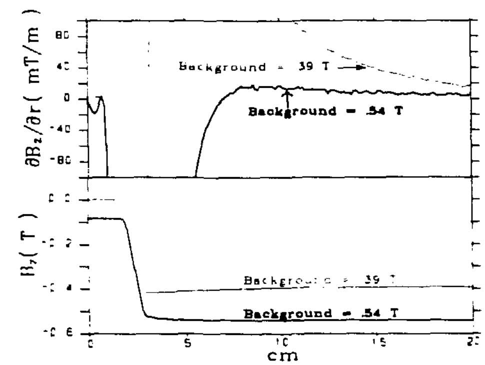

Fig. 5. POISSON results showing radial gradients both outside and inside the coil compensated iron-channel of rectangular cross section (1.2 cm half aperture) for two background fields. The thickness of the channel wall was varied in each case to reduce the gradients inside the channel for constant coil current.

In MC4, the background field varies less than 0.02 T along its length, but it may require an internal field gradient to pre-compensate the strong radial defocussing forces from the cyclotron fringe field.[4] The possibility of achieving this by shaping the inside profile of the iron channel is being investigated. An iron-free design for MC2 is progressing.

ENGINEERING CONSTRAINTS

The parameters of the extraction elements are relatively modest, and units of similar strengths are in use at many accelerators. What makes the engineering difficult is the sum of constraints facing the designer.

All elements introduced to the vacuum chamber must be radiation resistent and must be compatible with the vacuum of $\sim 3 \times 10^8$ Torr.

The tight tolerances on the TRIUMF magnetic field practically prohibit the use of any ferromagnetic material within at least 1 m from the median plane, while the large gap gives rise to leakage fields of several tens of mT in the immediate vicinity of the cyclotron tank where auxilliary equipment (electric motors, mechanical drives, control elements etc.) is either forbidden or must be well shielded.

It is not possible to mount any additional equipment on the vertical side wall of the cyclotron vessel. There is no access through the six magnet yokes which occupy most of the perimeter, and, due to material activation in the beam plane, any new penetrations are virtually impossible. The leads and services for all new components must therefore come through the floor or lid of the vacuum tank. All available ports are presently utilized to capacity, and new holes have to be cut and flanges welded. There are several limitations to this process. The force of atmospheric pressure on the vessel is counteracted by over 300 pairs of tie-rods spaced 0.8 m apart. The 55 pairs of trim coils, 13 sets of harmonic coils and numerous cooling lines also severly restrict the space.

With temporary Pb shielding in place the residual radiation fields in the 16 m cyclotron tank are approximately 8 mSv at the centre, reaching 100 - 300 mSv at the periphery, compared to the dose limit to personnel of 5 mSv per day. This necessitates remote installation and removal of all equipment.

TRIUMF is a facility with an ongoing experimental program using protons in energy ranges 68 - 520 MeV, and it is planned to continue this for most of the Kaon Factory construction phase. Placement of the extraction elements for the H^- beam @ 450 MeV precludes proton extraction above that energy unless the septa and channels are removed from the beam path. Any beam related experiments can only be performed during facility shutdowns, limiting the available time to two short periods in a year.

EXTRACTION HARDWARE

A new version of the DCD with longer high voltage insulators, built-in bleed-resistors, and with re-routed leads to the antiseptum will soon be tested. Of the four magnetic channels MC1 and MC3 are the difficult ones to be built. The design of the septum is strongly affected by the choice of the copper coil insulation. Presently three materials are being considered: sprayed-on alumina, vitreous enamel, and hard anodized aluminum sheath.[8] Studies are under way, and a 10 kA, 15 V dc power supply is on order for tests. Unsaturated iron is used in MC3 in the inhomogenious field of the hill - valley boundary. In order to test the validity of the computer modelling a simple test channel is being built for measurements in air. A cross-section through the channel is shown in Fig. 6. The position of all extraction elements will be adjustable under operating conditions. For that purpose a generic drive system has been designed and successfully tested on the DCD. The other systems will differ only in the magnitude of forces acting upon each respective device. The dual function feedthroughs (current and cooling water) for magnetic channels will connect inside the cyclotron to flexible leads consisting of a soft welding cable surrounded by a stainless steel bellows. Several units are presently being tested for corrosion resistance.

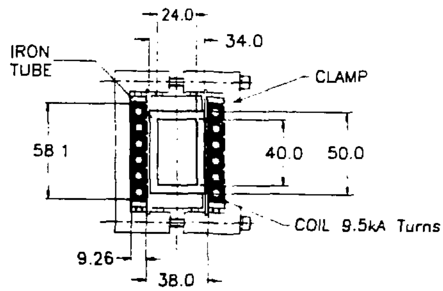

Fig. 6. Design of test channel with iron core and compensating coils to test computer modelling of MC3. Dimensions are in millimeters.

Three new ports 18 cm in diameter have been added to the cyclotron floor and lid by remotely cutting holes in the 22 mm and 45 mm thick stainless steel plates by spark erosion. The technology, using a modified commercial unit has been developed at TRIUMF. New extensions and flanges were then remotely welded and leaktested.

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