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The Design, Fabrication and Testing of an Iron-core Current Compensated Magnetic Channel for Cyclotron Extraction

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Abstract

An iron-core current compensated magnetic channel has been built as part of the TRIUMF 450 MeV H^- extraction feasibility project. The channel would operate in the 0.5 T cyclotron field and was designed using the two-dimensional code POISSON. Recent beam tests with the channel installed in the TRIUMF cyclotron confirmed that the electro-mechanical design is reliable and that the effect on the circulating beam is in agreement with calculation. The design and hardware details will be described and the beam test results reported.

1 INTRODUCTION

The chosen H^- extraction design layout [1] calls for one rf deflector (RFD) to induce precessional extraction [2], two electrostatic deflectors (DCD), five magnetic channels (MC) and a quadrupole channel (QMC). Prototypes of both the RFD and the DCD have been tested several times with beam [3]. Of the five magnetic channels, four are located in the cyclotron and one in the exit port. Two of the cyclotron channels, MC1 and MC2, are of an iron free design [1] with deflecting strengths of 85 mT·m and 130 mT·m respectively. A prototype was tested in 1991 [4]. The other two, MC3 and MC4, have a hollow iron shunt and almost cancel the local magnetic field of 0.56 T, each supplying a deflecting strength of ~0.48 T·m. Dipole coils are wound lengthwise along the iron core to compensate the field perturbation that would be seen by the circulating beam, to further reduce the field inside the channel aperture and to reduce the induction inside the iron. Initial design studies were completed for a channel with an inside aperture of 24 mm × 30 mm [5] but this was later increased to 30 mm × 38 mm [6] and finally to 34 mm × 38 mm in the engineering design [7]. Fabrication of a prototype of MC3 took place in the summer and fall of 1993 and the channel was installed and tested in the fall 1993 shutdown. [8]

2 COMPUTER DESIGN

Tolerances on the field within the channel and on the leakage field set the design goals for the channel and have been defined elsewhere. [1,9] The most restrictive tolerances are on the gradient of the leakage field in the region of the circulating beam and on the field uniformity in the aperture. The circulating beam approaches to within 14 cm of the channel center. Changes to the field gradient alter the value of ν_z and ν_r and drive emittance stretching mechanisms at the $\nu_z = 1/2$ and $\nu_r = 3/2$ resonances. The tolerance was set at $\int dB_z/dr \cdot dl < 5$ mT/m·m. Non-uniformities in the aperture field distort the extracted beam. The internal field integrated along the length must be uniform to within 0.3 mT·m over an aperture of ±1 cm×±1 cm.

The channel was designed using the 2-dimensional code POISSON. Various channel cross-sections were modelled in a uniform background field of 0.56 T until the field perturbations were within the tolerances. The uniformity in the aperture region and the sensitivity to machining errors are improved by avoiding saturation in the iron. In general a larger aperture requires wider side-walls to avoid saturation and more current to compensate the diversion of the extra flux. For example, in going from the small aperture to the larger aperture design the channel wall width was increased from 1 cm to 1.3 cm and the required excitation was increased from 17 kA-turns to 22 kA-turns. The extra current was accommodated by doubling the width of the conductor from 1 cm to 2 cm. The field in the aperture rose from 3 mT to 6 mT.

In the final design the calculated perturbation to the gradient at 14 cm was ~ ±1 mT/m within ±2 cm of the midplane while the aperture field was just within the specified tolerance. The final cross-sectional geometry is shown in Fig. 1. The perturbations in the gradient and the field at 14 cm rise linearly as the compensation current is altered from the optimum value at the rate 3.5 mT/m/% current change and 0.19 mT/% current change respectively. The aperture field grows from 6 mT @ 100% excitation to 137 mT @ 0% excitation. The rate of change is ~0.5 mT/% near the optimum current and almost four times larger as the current approaches zero and the iron nears saturation.

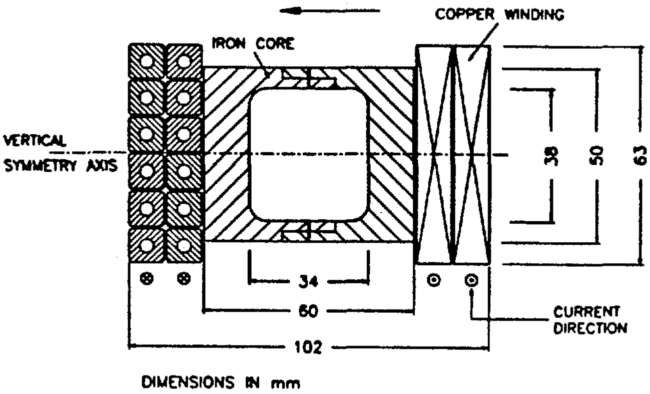

Figure 1: Cross-section of MC3.

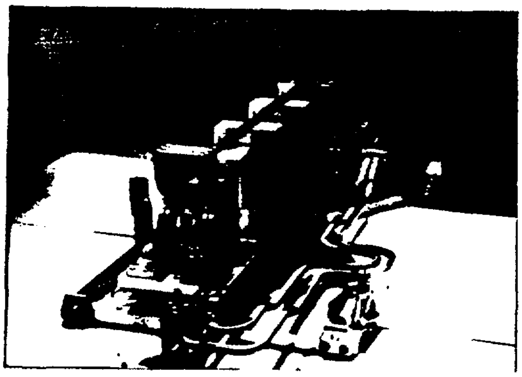

Figure 2: The completed channel prior to installation.

3 ENGINEERING DESIGN AND FABRICATION

The iron channel consists of two 850 mm long pieces of magnet steel hollowed, then mated together and pinned, as shown in Fig.1. The 22 kA-turns are supplied through 12 turns of 10.4 mm × 10.4 mm hollow conductor (hole diameter 5.8 mm) with a current density of 22 A/mm^2 and power dissipation of 28 kW. The six inside and six outside conductors are fabricated into separate coils then joined in series during assembly. For simplicity insulation between the conductors was provided by thin sheets of kapton (0.1 mm) although for the final device it is planned to use plasma sprayed $A\ell_2O_3$ as in the MC1 prototype. Four aluminum clamps distributed along the length hold the conductors in position. The coils are curved away from the median plane at each end then joined across the channel with a straight connecting piece. Any necessary asymmetries in the coil's construction were restricted to the side of the channel furthest from the beam. Fig. 2 shows a photograph of the completed channel prior to installation in the cyclotron.

Current and water are supplied to the channel through a copper coupling block which may be disconnected remotely. To achieve good contact the mating surfaces are polished and the surface to surface contact maintained by a spring loaded bolt. The water connection is sealed with an O-ring. The 5 m span from feed-through to coupling blocks is serviced by parallel inlet and exit copper conductors. The whole water circuit, requires a pressure drop of 20 atm (21 kg/cm^2) to deliver 6.6 ℓ/min flow. The water temperature rises 58°C.

4 BEAM TEST

To simplify the test and the installation, measurements were made only on the beam approaching the channel. This avoided the necessity of installing other extraction components (DCD, MC1), and of supplying motion control for MC3. Drives and motion control had already been tested with MC1 [4]. When powered at the design value of 1800 A (here-after referred to as 100%), effects on the circulating beam were predicted to be immeasurably small, especially considering that the effect of the iron can not be turned off to obtain a null measurement for comparison. The test, then, involved powering the channel at various currents and observing whether the beam was affected in a predictable way based on computer simulation studies.

4.1 Pre-test Simulations

POISSON was used to calculate ΔB_z and $\Delta dB_z/dR$ for various compensation current values. These channel generated perturbation fields were then added to GOBLIN, a single particle orbit code. Separate radial and vertical studies were done. Changes in the radial beam width near the channel and the shift in the precession of RFD induced coherent oscillations, both due to changes in dB_z/dR as well as the shift in beam phase due to the change in B_z were simulated. Changes to the vertical beam envelope and alterations to $\nu_z(R)$, both due to the change in dB_z/dR near the channel, were also studied.

4.2 Experimental Results

A narrow phase width (~5°) beam was selected in the center region to produce a high quality beam for more precise measurements. For all measurements the phase shift generated by ΔB_z at non-optimal channel current settings is compensated by shifting the rf frequency to minimize the overall time-of-flight. The shift in the isochronism to a point 7 cm radially inside the channel center-line is linear with channel excitation and corresponds to $\Delta \sin\phi = 0.013/\%$ of current change.

A probe with five vertically displaced fingers gives information on both the vertical position of the beam centroid and the vertical width as a function of radius. Probe scans were completed for various compensation current settings and the vertical widths from each of these scans are shown in Fig. 3. Superimposed on this plot are the vertical half envelopes from the GOBLIN simulation for a matched set of particles defining an emittance of ϵ_z=1.2 πmm mrad. As the beam nears the chan-

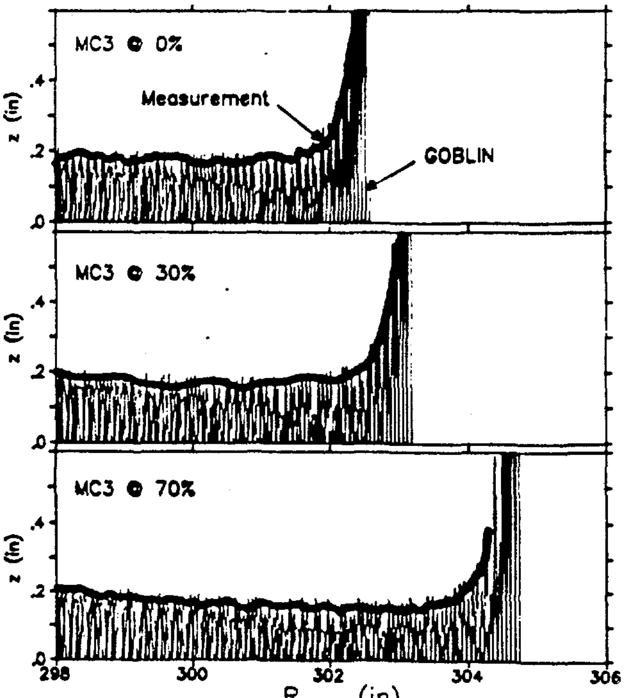

Figure 3: Comparisons of GOBLIN (a single particle orbit code) simulations and experimental results for various compensation current settings. Shown are the vertical half envelopes calculated from 12 particles defining a 1.2πmm-mrad vertical emittance beam and vertical widths measured using a five-finger probe. Radial gradients near the channel cause the rapid increase in vertical width. The center of the channel corresponds to ~307 in.

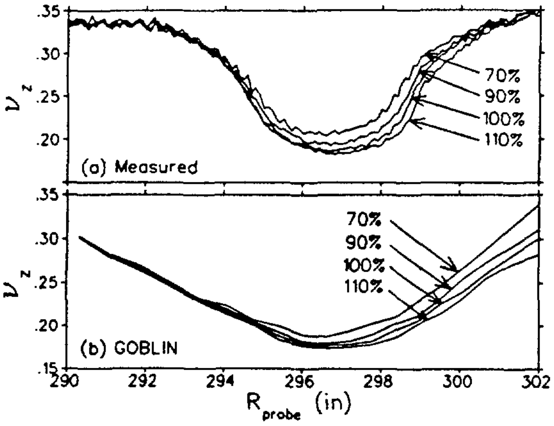

Figure 4: Comparison of measured and calculated (GOBLIN) values of ν_z for various MC3 current settings. The center of MC3 corresponds to ~307 in.

nel the added radial gradients increase the vertical focussing and push the vertical tune to the ν_z=0.5 resonance. The beam width expands rapidly driven by the strong gradient in the first harmonic of B_z. There is good agreement between simulation and experiment.

Near the channel the vertical tune, ν_z, was also measured by introducing a radially broad $\overline{\Delta B_r}$ bump using 10 trim coils and measuring the vertical shift, $\overline{\Delta z}$, in the beam. The relationship

$$\nu_z^2 \simeq \frac{\overline{R}}{\overline{B_z}}\frac{\overline{\Delta B_r}}{\overline{\Delta z}}$$

is used to produce the results shown in Fig. 4(a). Calculated results from GOBLIN are shown in Fig. 4(b). The agreement is good where low ν_z values give large vertical shifts and overcome the poor resolution of the probe fingers (6.4 mm).

Compensating currents less than the optimum lower the radial tune, ν_r, near the channel. A sensitive measure of ν_r in the channel region is the rate of precession of the coherent radial oscillation produced by the RFD at ν_r=3/2. As the defocussing radial gradient increases and the tune is reduced, the number of turns in each precession cycle grows, causing the separation between beam density peaks to increase. A number of differential probe scans were taken to record the beam density modulation pattern for several different compensation current strengths. Fig. 5 shows scans for currents of 100% and 70%. The results agree closely with simulations.

Radial beam widths near the channel were measured with a shadowing technique. These confirmed that for some compensation current settings the radial focussing is reduced and the radial envelope stretched. The increased gradient in the third harmonic of B_z drives the ν_r=3/2 resonance. The experimental results agree well with the predictions of the GOBLIN studies.

5 CONCLUSION

The beam tests prove that the engineering design is reliable and confirm that the 2-D computer model gives an accurate representation of the perturbation to the magnetic field in the radial region approaching the channel. The MC3 test completes the successful prototyping of the major H$^-$ extraction devices.

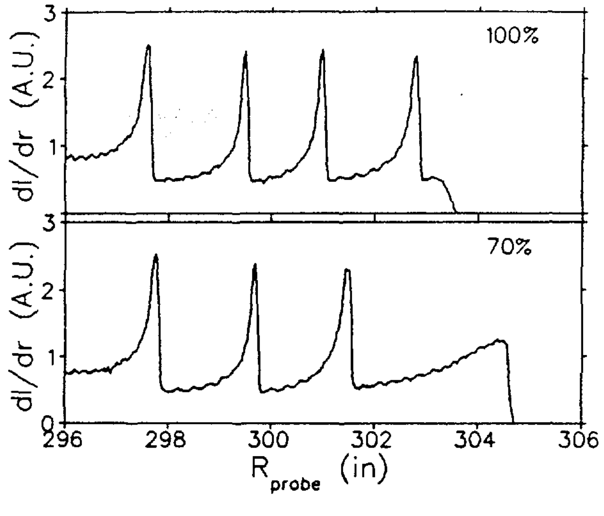

Figure 5: Shown are measured radial beam densities from a differential probe for compensation current settings of 100% and 70% of the nominal. The modulation in beam density is caused by precession of a large coherent radial oscillation generated by the RFD at ν_r=3/2. As the defocussing radial gradient from MC3 increases and ν_r is reduced, the number of turns in each precession cycle grows, causing the separation between density peaks to increase. The center of MC3 corresponds to ~307 in.

6 ACKNOWLEDGEMENTS

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