MAGNETIC FIELD MAPPING OF THE BEST 70 MeV CYCLOTRON

F.S. Grillet, B.F. Milton, Best Cyclotron Systems, Vancouver, Canada
D.T. Montgomery, Cedarflat Precision, Burnaby, Canada

Abstract

As is well known, the mapping of a cyclotron magnet presents several key challenges including requirements for a high degree of accuracy and difficult space constraints in the region to be measured. Several novel solutions were used to create the mapper for the Best 70 MeV cyclotron, which is based on an earlier version used to map the Best 14 MeV cyclotron. Based on a temperature compensated 3-Axis hall probe that is continuously sampled while the probe travels along a radial arm a high degree of positional accuracy is achieved by simultaneously sampling optical encoders located with the probe. A novel implementation using air bearings and air jets provides axial rotation of the arm with almost no metal parts. The mapper has achieved a full 360 degree map in 1 degree theta steps, and 2.5mm radial steps in 2 hours and 40 minutes, with a relative radial accuracy of ±0.02 mm and angular accuracy of ±0.003 degrees. These tolerances are required due to the steep gradients in field, in the centre region the field varies radially by approximately 150 Gauss/mm. This translated to a 3 Gauss variation per 0.02 mm step, while the measurement accuracy target was ±1 Gauss. This paper will describe how the simultaneous challenges of designing with no metal parts while achieving a high degree of rigidity and precision have been addressed.

INTRODUCTION

Mechanical Requirements

The key challenges of mapping cyclotron magnets comes from the tight space constraints together with the requirement for high accuracy. The area to be measured had a diameter of 2.8 m; the vertical gap in which the mapper sat was 55 mm at the centre and 45 mm at the outer radius. The mapper had to rotate a full 360 degrees (in 1 degree theta steps) and map from the edge of the hill to 150 mm past the centre. Since measurements were taken 'on the fly' there had to be no metal parts moving while measurements were being taken and no magnetic parts whatsoever. The maximum allowable deviation from the median plane was 0.25 mm, absolute radial position accuracy of ±0.5 mm and relative angular accuracy of ±0.003 degrees. The hall probe had to be aligned to the magnetic field to better than 1 degree and the maximum rotation of the probe during a map was 0.25 degrees. As can be seen these are not easily attainable targets, especially when little or no metal parts could be used. As well as meeting the accuracy requirements, the mapper had to be transportable. This resulted in manufacturing the beam in three 1m sections, which also resulted in parts which were more easily manufactured.

Overview of Design

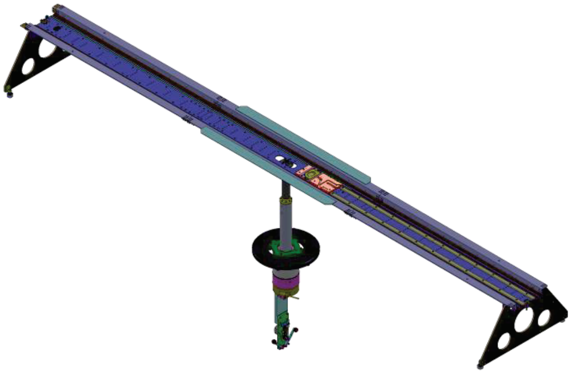

Figure 1: Solid model of the mapper assembly.

The design is based on a rotating shaft to which a carbon fibre beam is connected at its centre, as shown in Fig. 1. At each end of the beam are air bearings which are activated when the mapper rotates, these are mounted on balsa filled carbon fibre legs. Radial motion of the hall probe is achieved by being mounted to a carriage which is driven along the length of the beam by a string and pulley assembly using a stepper motor as drive. A 3-axis probe was used since the 2 "secondary" axes can be used to level the probe in the median plane and verify median plane symmetry.

SYSTEM DESIGN

Carriage Design

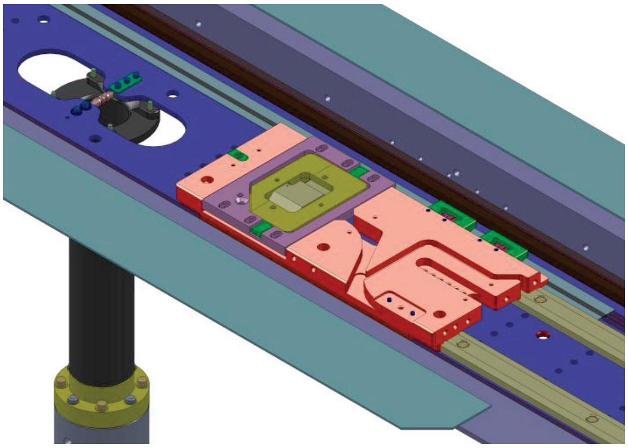

Figure 2: Complex machining is required for carriage and its components.

Since field measurement was to be done while the carriage was moving through the field there had to be no metallic parts due to the formation of eddy currents. The

ISBN 978-3-95450-128-1

main challenge of the carriage was to find a suitable material to use since it had a complex geometry combined with tight tolerances. It was decided to use ertalyte for the main body of the carriage as the plastic has good dimensional stability after machining. Delrin was also widely used on the carriage; this is a very hard plastic which has good machineability. The carriage held the radial encoders and had 3 contact points to the beam. The section of the carriage holding the hall probe was adjustable in 5 degrees of freedom to allow for complete angular and positional alignment with the median plane.

Beam Design

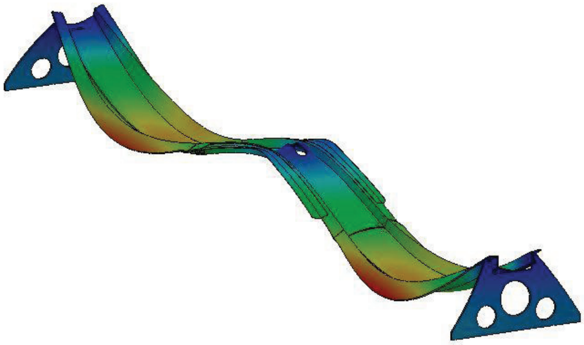

Figure 3: FEA image of the beam.

The beam was required to provide a straight track for the carriage, to locate the linear encoder strip, and to hold an accurate angular orientation with respect to the vertical support shaft, among other functions. The most difficult geometric requirement was to maintain parallelism of 0.2/3000 mm for the beam floor with respect to the cyclotron median plane.

The beam cross section was an upside-down top hat shape which provided high stiffness in bending but relatively low stiffness in torsion along the length of the beam. Although the carriage was not required to travel the full length of the beam from tip to tip, a full length beam was still chosen. This was done for several reasons, the most important of which was so that loading from air jets which rotated the beam created a pure moment about the axis of rotation without causing the vertical support shaft to deflect significantly.

The beam segments were joined together with flexures to create a beam almost 3 m in length supported semi-kinematically in the middle by two half pins seated in a v-groove, and at both ends by vertical plates, themselves each supported by two air bearing pads. The air bearing pads were adjustable in height and pivoted to allow the air bearings free alignment with the cyclotron reference surface on which they rested. Height adjustment was required to set the elevation at the free ends of the beam to be the same as the elevation at the middle, and to minimize any inherent twist in the beam assembly. The joints were located approximately at inflection points of zero beam curvature under self-weight. Therefore the beam bending moment at the location of the flexures was relatively small and they did not play a large role in the overall deflection of the beam. The actual length of each segment was 970 mm allowing them to be machined comfortably on a standard 40 inch travel vertical mill.

The beam itself was constructed of Carbon fibre composite (CFC) for favourable stiffness-to-weight ratio, strength, and availability in various shapes and sizes. Flatness of the CFC sheets was measured to be about 0.1 mm, which did not change significantly following machining. Standard off-the-shelf sections were combined (glued together) to make each open section beam segment. The three beam segments were held together with beryllium copper UNS C17200 flexures bolted to titanium 6Al 4V alloy plates. The titanium plates were bonded to the CFC beam such that the outside surfaces were closely aligned, thus minimizing spring-back from the flexures when the beam sections were joined together.

Beam stiffness was estimated by hand calculations and by finite element analysis of a simplified geometric model. The CFC material stiffness in bending was measured experimentally, and a smaller early mapper of similar construction was measured for deflection under load and compared to analysis. This work improved modelling of the flexure joints and provided confidence that our FEA model of the full sized beam was realistic. Figure 3 shows deflection of the beam for one of several simulations, in this case under an evenly distributed load of 70 N over the beam floor. Maximum deflection was 0.15 mm and all stresses were low.

Since the hall probe passes over the centre and maps an additional 150 mm beyond, it is possible to use this over sampling of the field at the centre to determine errors in the centre of rotation, offset of the probe from the track centreline and verify the radial position along the track. The later item can also be verified at the outer radius since the probe also passed over the radial edge of the hills providing a sharp reference edge in the data. All these we used in the final data analysis to correct for the very small residual mechanical errors in the system.

Shaft Design

The alignment of the shaft was very crucial to the centring accuracy of the mapper. It was decided to place the bearing assembly below the magnet and run a hollow shaft up through the centre. Above the bearings there were 3 sections to the shaft. These were an extension tube, an adaptor and cap. The cap sat at the very top of the shaft and contained the v-groove in which the beam sat. This was screwed into the adapter piece which was in turn bolted to the extension. This assembly provided the ability for concentricity alignment while providing a parallel connection through the assembly to the magnet reference surface. A concentricity of around 0.025 mm was achieved between the shaft cap and bearing assembly. There was no height adjustment of the shaft since the hall probe height adjustment came from the carriage assembly.

Drive System

The drive system of the mapper can be broken down into 2 subsystems; these include rotational drive and radial drive. For radial motion the carriage is driven by a string connected to a stepper motor mounted at the bottom of the shaft. The string runs from the carriage through a Teflon tube in the centre of the shaft, around a tensioning system and the stepper motor then up through another Teflon tube back to the carriage. This is illustrated in Fig. 4 below. The need for precision in the radial positioning is removed by using linear encoders.

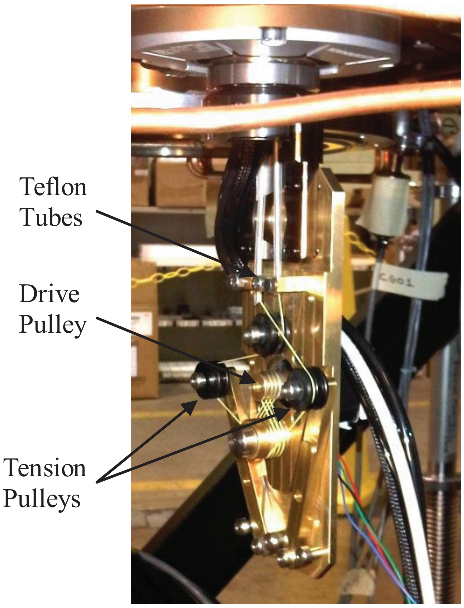

Figure 4: Drive system connected to the bottom of the shaft.

Beam rotation is achieved by floating the ends of the beam on air bearings and using air jets to provide drive. Three solenoid valves located below the magnet were used to control air flow through the jets and bearings. Since it was decided to use the vacuum wall surface as the bearing surface custom Ertalyte bearings had to be made so as not to damage the surface. Air bearings were the obvious choice since they could be fully non-magnetic, could be remotely actuated; they offer near zero friction and require no lubrication.

INITIAL TESTING

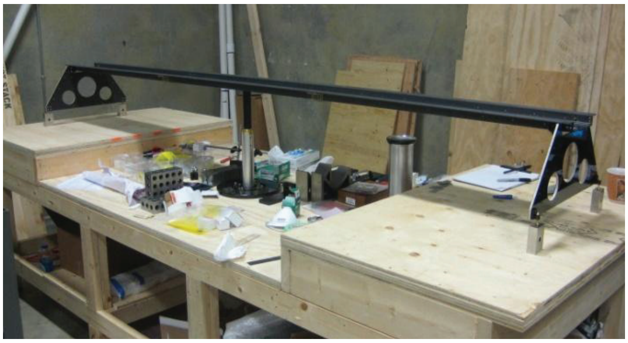

Figure 5: Mapper set up on test bench.

For preliminary testing a custom test bench was built to simulate the cyclotron geometry. On this the critical dimensions and tolerances were measured. It was found that the flatness of the beam was 0.2 mm over the section of the beam on which the carriage travels (approx. 1.6 m); the flatness of travel of the carriage was 0.13 mm. It was found that the rotation of the carriage in any direction was less than 0.25 degrees. The height at the beam ends was adjusted to be 0.025 mm from the height at the centre. The bench also provided the ability to run predictions on a full map time, which was initially predicted at 2 h 25 min.

ISSUES

From the initial tests it was found that mechanically there were very few problems with the mapper. The majority of problems came from the control system, which had originally been written for a similar mapper designed for the Best 14 MeV cyclotron. One of the major hurdles arose from having the beam in sections, since there was a gap in the encoder strip (which is permanently attached to the beam). This required the use of 2 optical encoders, one of which was the primary which is used the majority of the time, the other of which is a secondary encoder which gets used to calculate the gap crossing. Other issues came from using air jets and bearings for angular drive. This meant that there was an uncertainty in how much the beam would rotate for a give jet run time. The program was designed to "learn" the amount of jet time require for a given angular move. This had to be done in sections due to the cables winding up underneath the magnet and producing more or less rotational resistance. String wear is an ongoing problem with the mapper, initially a kelvar string was used as the material is very stiff and provides little stretching though the life of the string was short. Polyester string with an anodized aluminium drive pulley is currently being used. This combination provides a good string lifespan although debris from the string accumulates in the pulley grooves and can cause slipping.

CONCLUSION

Once the major software issues had been ironed out, the final mapping time was 2 h 40 m for a 360 degree map in 1 degree theta steps. The repeatability of mapping was in the order of ±2 gauss (including magnet drift). The deviation of the hall probe from the median plane was less than 0.13 mm. Relative angular position is known to within 0.001 degrees and absolute is known to 0.003 degrees as well as relative radial position to within ±0.02 mm. The ability to scan in both directions cut the mapping time in half (from single direction scanning); the other major time saving came from being able to get to the required angle in one move without the need for iterative steps.

ACKNOWLEDGMENTS

The authors would like to thank Andrew Cavers, Bill Lovatt, Steven Singbeil, Lester Lao and Graham Cross for their efforts and contributions towards the magnet mapper project.

ISBN 978-3-95450-128-1