MECHANICAL DESIGN AND MANUFACTURING OF A TWO METER PRECISION NON-LINEAR MAGNET SYSTEM*

J. D. McNevin, R. B. Agustsson, F. H. O'Shea
RadiaBeam Technologies, Santa Monica, United States

Abstract

RadiaBeam Technologies is currently developing a non-linear magnet insert for Fermilab's Integrable Optics Test Accelerator (IOTA), a 150 MeV circulating electron beam storage ring designed for investigating advanced beam physics concepts. The physics requirements of the insert demand a high level of precision in magnet geometry, magnet axis alignment, and corresponding alignment of the vacuum chamber geometry within the magnet modules to maximize chamber aperture size. Here we report on the design and manufacturing of the vacuum chamber, magnet manufacturing, and kinematic systems.

OPERATIONAL INTRODUCTION

The DOE High Energy Physics research aims to experiment with extreme high-intensity proton accelerators to observe rare processes and small deviations from the standard model, including neutrino and charged lepton oscillations [1]. RadiaBeam Technologies is developing the Integrable Optics Test Accelerator (IOTA) insert in order to produce an adequate beam for these experiments at the Advance Superconducting Test Accelerotor facility at Fermi National Lab [2]. This insert employs a non-linear integrable lattice that is intended to greatly increase the stable phase space area in circular high intensity accelerators by using specifically tailored non-linear inserts of the magneto static optics with the benefit of expanding the dynamic aperture of circular machines [2].

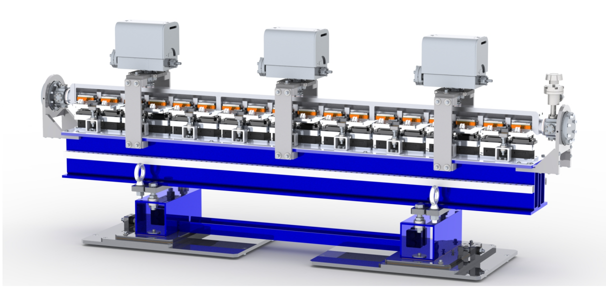

Figure 1: IOTA Insert.

RadiaBeam Technologies is currently near the completion of a full scale prototype non-linear insert, see Fig. 1. Production of the insert has brought forth numerous notable challenges all derived from the extremely governing tolerances dictated by physics requirements. The magnets were each optimized to comply best with ideal physics. Manufacture of the magnets in turn had to closely adhere to the optimized model so as to ensure adequate performance as well as to avoid interference with the vacuum chamber that sits inside the array of magnets. Numerous strategies were employed in the design and manufacture of the vacuum chamber to in reciprocation prevent interference with the magnet faces while simultaneously allowing for the largest internal aperture possible.

* Work supported by DOE under contract DE-SC0009531

DESIGN AND MANUFACTURE OF THE MAGNET MODULES

The magnetic field strength and physical apertures size of the non-linear insert are directly related to the longitudinal distance from the center of the insert [1–3]. We have taken the approach of sectioning the insert in a manor that the physical aperture size and magnetic field properties of the magnets are constant along short partitions of the insert however very between adjacent sections along the length of the insert. This magnet section to section varience is frequent and great enough to allow the insert to comply with the physics compulsions of the integrable optics theory. The IOTA insert contains two each of nine different magnet configurations. We have assigned each configuration a name module one through module nine in order of ascending aperture size, see Fig. 2. The magnets modules are located in ascending order from the center of the insert outwards. This generates a stepwise magnetic aperture size that decreases as the beam approaches the center of the insert then increases as it exits.

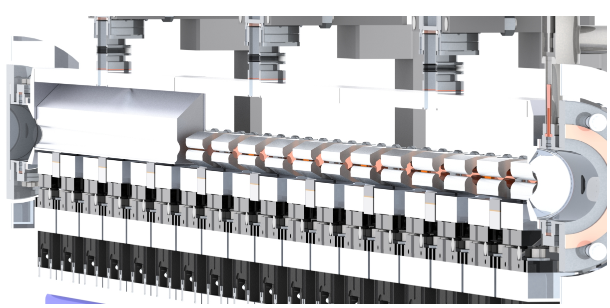

Figure 2: Array of magnets from the a bifurcated view of the insert. Portions of the vacuum chamber are hidden.

Magnet Module Physical Requirements

The design of the magnet magnets is based off of previous prototypes developed in phase one of this project wherein the level of required compliance of real geometry to idealized models was realized. The physical requirements of the magnets were evaluated by use of 2D and 3D simulations for magnetic circuit design and pole shaping [4]. This analysis included study on the fabrication and assembly tolerances as well as magnetic “cross talk” between adjacent magnets. Pulse wire measurements were conducted on prototypes to establish alignment between adjacent magnets. A hall probe provided measurement data to back up field map simulations. Results from magnet analysis demonstrated the following:

1. Magnetic axes of all eighteen magnets must be within 50 μm of each other,
2. The magnetic field must be within one percent of the theoretical idealized field,
3. The good field region should aim to cover as much of the aperture as possible,
4. Geometric confinement of certain magnet faces is more critical than others.

Mechanical limitations of the system and assembly inflicted the following requirements:

1. Magnet faces must fit around the vacuum chamber without interference,
2. Magnets must be separable to permit removal of the vacuum chamber and coils,
3. Magnets must come back together in a highly repeatable manor to preserve magnet quality and axis location.

Magnet Module Design

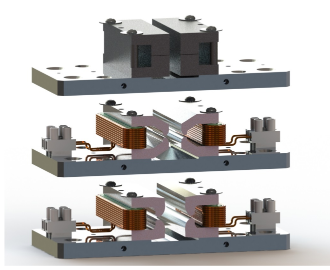

Figure 3: Top: Blank Magnet Module prior to EDM; Middle: Magnet Module 1 post EDM, plating, and assembly; Bottom: Magnet Module 9 post EDM, plating, and assembly.

2D and 3d simulation proved that using eighteen continuous aperture magnets over the length of the insert would comply with the physics requirements of the integrable optics theory [4]. Radial geometry of each magnet configuration was optimized for its position along the roughly two meter long insert. Each magnet was maximized in axial length to ensure that the good field region of every magnet would cover the greatest possible amount of aperture. The magnets are laterally symmetrical and split in to four pure iron components, or poles, see Fig. 3. On each side the top pole fastens to the bottom pole which in turn is secured to the mounting plate. Dowel pins are used to position each component in place and ensure repeatability of each component’s location after taking the magnet apart. In total, each magnet configuration contains two of each a top iron pole and a bottom pole, generating eighteen total pole configurations.

Magnet Module Manufacture

Precision ground blocks were cut and ground out of pure iron sheet. These blocks were then CNC mill cut to the rough outer dimensions of the eighteen iron pole configurations and verified for compliance with critical dimensions. These roughed poles were then assembled in to magnet assemblies. The magnet assemblies then moved back to the CNC mill where critical faces were machined in to the assembly and each top pole was match drilled in to the bottom pole to allow for a taper pin to hold them in to place. Magnets were subsequently dissembled, cleaned, reassembled, and inspected for pole position repeatability. After this verification, magnet assemblies had critical pole geometry electrical discharge machined (EDM). The EDM cutting of critical pole features on each magnet assembly individually generated highly precise critical pole geometry with a very precise relative position, see Fig. 3. Magnet geometry was verified using a coordinate measuring machine (CMM) before and after disassembly and reassembly. Iron components were then nickel plated on non mating or locating surfaces to prevent corrosion. CMM measurements proved the critical magnet surfaces to be within 25 μm of their nominal position relative to eachother.

DESIGN AND MANUFACTURE OF THE VACUUM CHAMBER

The vacuum chamber is roughly rectangular with outer dimensions of 70mmx50mmx2m, see Fig. 4. It is designed to fit within the mechanical aperture of the assembled magnet array. Due to the fact that there are two each of nine different magnet configurations all with different apertures sizes the chamber had to be customized to fit within each specific magnet. In order to accommodate the largest possible chamber aperture the wall thickness was minimized between the inside of the chamber and the adjacent magnet faces which creates a tapered chamber aperture to match that of the magnet array, see Fig. 4. Accommodations for beam position monitors (BPMs) were modified from components provided by Fermilab and installed on the ends of the chamber to allow for feedback on relative position of the beam as it passes through the chamber. A custom transition connects the BPMs to the chamber.

Vacuum Chamber Requirements

The vacuum chamber had to fit between the aperture of every magnet while allowing for some room for magnets to be positioned and adjusted. In order to accomplish this we required the following of the vacuum chamber:

1. A maximum wall thickness adjacent to the magnet of about 250 μm (allows for largest local aperture),

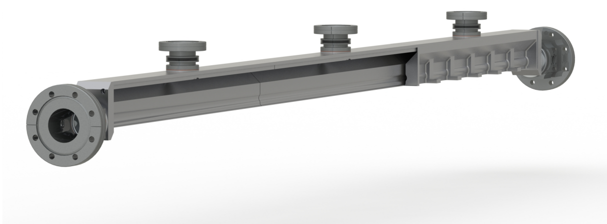

Figure 4: View of the vacuum chamber with two hidden walls.

2. Geometric compliance of each magnet pocket within 50 µm of nominal along entire length of the chamber,
3. Static, thermal, and harmonic stability,
4. Ultimate pressure of at most 1 x 10E-9 Torr.

Vacuum Chamber Design

With the goal of maximizing aperture size, we minimized the nominal normal distance between the outer chamber wall and each magnet to 250 µm, this gives 500 µm from each pole face to the inner aperture of the vacuum chamber, see Fig. 5. Each magnet cutout was designed specific to the magnet that it sits within. The inner aperture is tapered to allow for vacuum conductance and beam emittance considerations. The inner hourglass shape above the beam aperture was designed to allow for high vacuum conductance, see Fig. 4. For ease of manufacture, the length of the chamber was divided in to three subsections, each comprised of two side walls and one top cover. Mating joints between section walls were tailored to be electron beam welded (EBW) and design to prevent weld spatter on the inside of the chamber, minimize deformation, and eliminate virtual leaks. Weldable aluminum was chosen as the material in order to limit weight, ease machining, and allow for the chamber to be manipulated and tweaked in to position using kinematics. Simulations were run on the chamber to ensure that deformation under gravity and pressure conditions was within an acceptable level.

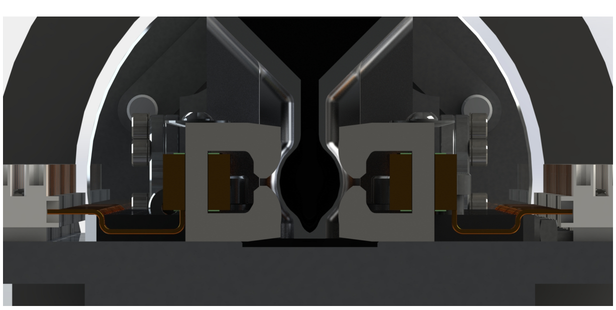

Figure 5: View of the vacuum chamber inside of a magnet module.

A prototype approximately a quarter of the length and consisting of only two chamber sections was designed and manufactured as a proof of principal. This prototype allowed for demonstration of machining practices, weld practices, and for estimation of final chamber ultimate pressure (estimated to be around 6E-11 Torr).

Vacum Chamber Manufacture

Each chamber wall and cover was carefully constructed from aluminum sheet stock to very tight tolerances using a CNC mill. Custom bellows were EBW joined to all three chamber section covers using custom fixturing to ensure adequate alignment. After welding, joint geometry for mating the side walls to the top cover was cut in to each cover. Fixturing was developed to align the two side walls to the cover assembly for welding. Weld perameters and methods were honed in using sample welds on sample joints. Concurrently custom explosion bonded bimetallic stainless steel to aluminum coupler were made to mate the stainless steel BPM housing to the transition that joins it to the chamber. Tunable fixturing was manufactured to EBW the BPM housing to the bimetallic coupler and a 4-1/2" conflat flange on the opposite side. The bimetallic coupler was then EBW to the chamber transition. After two BPM assemblies and three chamber sections were welded, each assembly had weld joints CNC milled in to their joining ends. This allowed for the greatest amount of position control if any deformation from welding and error in machining occurred. RadiaBeam is currently in the process of finalizing weld fixturing for the final electron beam welds which will join the BPM assemblies to the two outer chamber sections, then those outer sections to the center section.

ALIGNMENT AND KINEMATICS

CMM measurements will collect position data of fiducials located on each magnet mount plate. This data is then used in conjunction with a vibrating wire assembly to collect data on each magnets magnetic center relative the the fiducials. All magnets are then installed on the strongback atop precision tip-tilt and goniometer alignment stages which are used to manipulate the position of each magnet's magnetic center relative to a best fit of all magnetic centers and nominal beam line. The chamber is also mounted to kinematics that allow it to be positioned and manipulated around within the magnets. Global positioning kinematics are used to position the entire IOTA insert relative the the beamline, see Fig. 1.

ACKNOWLEDGEMENTS

RadiaBeam wishes to acknowledge the important work for this project by D. Martin and the entire Fermilab team with thanks to R. Andrews, M. Mcgee, L. Nobrega, and A. Valishev for all of their diligent efforts and involvement in this project. This work is supported by US DOE Grant No. DE-SC0009531.

REFERENCES

[1] V. Danilov and S. Nagaitsev, *Phys. Rev. ST Accel. Beams* vol. 13, p. 084002, 2010.

[2] F. H. O'Shea, *et al*., in *Proc. NA-PAC'13*, Pasadena, USA, September 2013, p. 922, paper WEPBA17.

[3] A. Valishev, S. Nagaitsev, V. V. Danilov, and D. N. Shatilov, in *Proc. of IPAC 2012*, p. 1371, 2012.

[4] F. H. O'Shea, *et al.*, "Non-Linear Magnetic Inserts for the Integrable Optics Test Accelerator," in *Proc. IPAC2015*, 2015, paper MOPMN010.