ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLO14

FROM START TO FINISH: USING 3D PRINTING TECHNIQUES TO BUILD CBETA*

G.J. Mahler†, S.J. Brooks, S.M. Trabocchi,
Brookhaven National Laboratory, Upton, NY, 11973, USA

Abstract

Accelerator components and ancillary equipment can benefit from 3D printing technologies. Mechanical components that previously had been machined using conventional methods can now be 3D printed. This paper will discuss some of the successes using this technology and specifically will track from initial development of a particular set of Halbach magnets used on the Cornell Brookhaven Experimental Test Accelerator (CBETA) [1] project to the final design.

INTRODUCTION

Many industries are starting to embrace 3D printing technology mainly for economic reasons and this is also true within the accelerator community. One such facility, the Collider Accelerator Department at Brookhaven National Laboratory, is currently using five desktop variety 3D printing units. The unit makes and models are as follows:

- Makerbot Replicator 2X
- Ultimaker 2 Extended (2units)
- Ultimaker 3 Extended
- Ultimaker s5

We have printed parts from two types of plastic: ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid), converging to using PLA plastics exclusively. PLA is a bioplastic, meaning that it is derived from renewable plant products like corn and sugarcane. PLA is biodegradable, has less tendency to warp due to its low melting temperature, develops sharper corners / finer features, and is far less toxic when compared to ABS. One of the distinct advantages of ABS plastic is what can be perceived as overall strength, though it is the ductility of ABS that is responsible for this perception. PLA and ABS possess quite similar mechanical tensile strengths, but the ductility of each is quite different. ABS is more ductile than PLA so it tends to stretch more before breaking, which in turn gives the perception of PLA being a weaker plastic due to its brittle nature.

THE CBETA HALBACH MAGNET

Final CBETA Magnet Assembly

CBETA had a need for Halbach variety quadrupoles of the order in strength, depending on type, of 10 T/m and Halbach variety dipoles up to 0.3T [2]. One type of final Halbach dipole magnet assembly including the windowframe type iron corrector is shown in Fig. 1. Note that this is the final design that was installed in the CBETA lattice, but this paper also discusses the iterations that lead to this design and in specific the integration of 3D printed components.

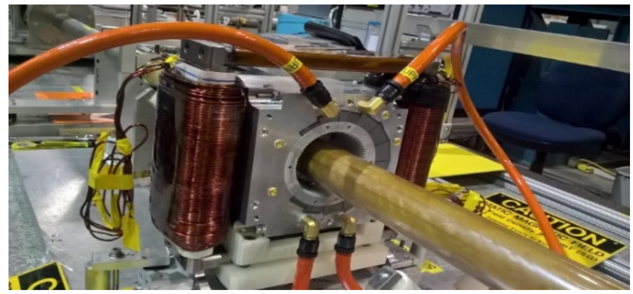

Figure 1: Final design CBETA Halbach magnet with iron core corrector.

Halbach Magnets

The Halbach magnet itself is essentially a series of permanent magnet volumes, each with a specifically defined magnetization direction, arranged in a circular array. A typical Halbach array is depicted in Fig. 2. The array has a spatially rotating pattern of magnetization direction, as shown by the red arrows, which cancels the field on one side but boosts field on the other. The major advantages of Halbach arrays are that they can produce strong magnetic fields on one side while generating very small stray field on the opposite side. In this case, the magnetic field inside the aperture is large and the magnetic field on the outer diameter is extremely small.

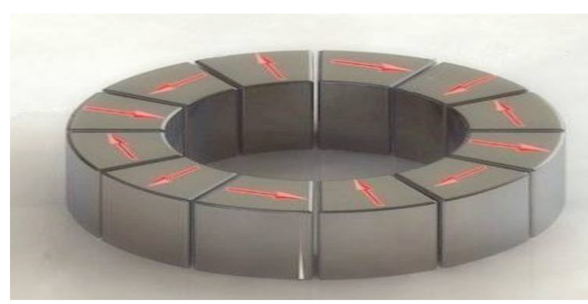

Figure 2: Typical Halbach array.

Early CBETA Halbach Magnet Designs

The permanent magnet material in the CBETA magnet array was specified to be Neodymium/Iron/Boron, which is one of the strongest rare earth magnet materials. The forces between two adjacent magnets in the array are large enough to require a supporting structure to both retain and position all magnets within the array. In early iterations of these Halbach magnet assemblies we used 3D plotted ABS frames as shown in Fig. 3. This allowed us to economically change both configuration and dimensional specifications due to tolerances associated with assembly, as the cost this

* Work supported by NYSERDA contract with BNL
† Mahler@bnl.gov

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLO14

ABS frame is a few dollars and roughly 10 hours of machine plotting time.

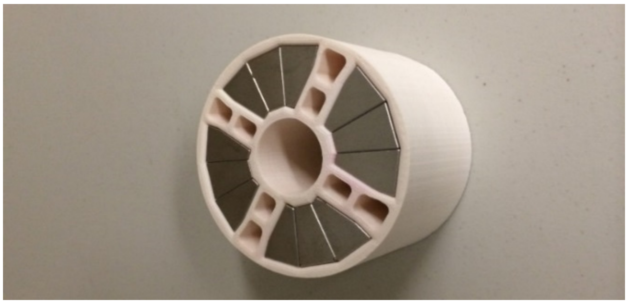

Figure 3: Early Halbach array.

Magnet Measurement Fixturing

It should also be noted that each individual magnetic volume was measured using a Helmholtz Coil to determine both magnetic strength and direction. In order to complete this measurement, the magnetic volume must be correctly oriented within the Helmholtz Coil. Initital tests were also conducted using a Hall Probe. We again used the 3D plotter to develop fixtures, as shown in Fig. 4 and Fig. 5. These fixtures were quickly developed for a variety of different sizes and shapes of individual magnetic volumes.

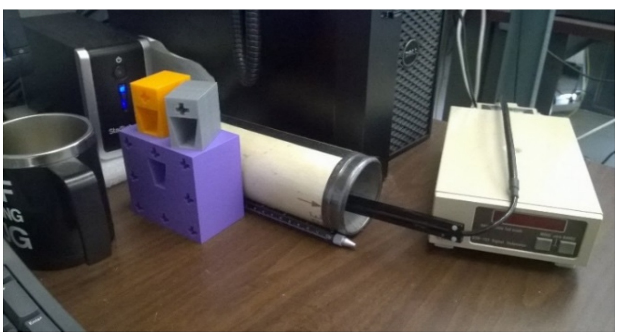

Figure 4: Block measurement fixtures / used with Hall Probe.

Figure 5: Block measurement fixtures / used with Helmholtz Coil.

Each Halbach assembly, 216 in total, required magnetic field measurement using a rotating coil system and subsequent development of tuning assemblies. These measurements were all done with a dummy iron core corrector, thereby requiring a series of Halbach magnet assembly locating fixtures. These locating fixtures allowed for easy removal and replacement of seven varities of Halbach assemblies. Figures 6, 7 and 8 depict the various types of fixturing required for magnet measurement. 3D printing of these fixtures allowed for fast and inexpensive turnaround which enabled the desired design iterations. Using conventional machining methods would have resulted in a prolonged schedule as well as being cost prohibitive.

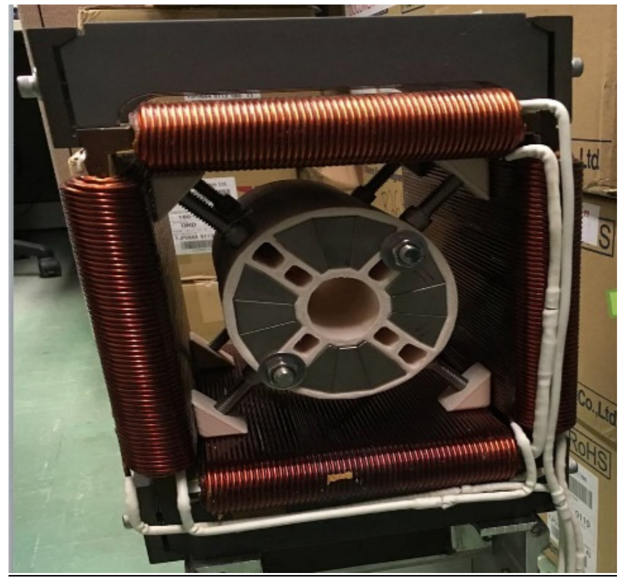

Figure 6: Halbach magnet fixturing.

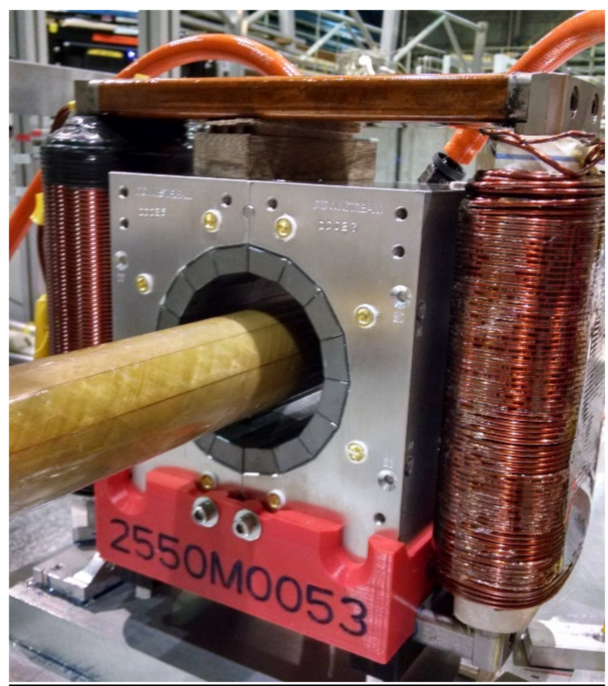

Figure 7: Halbach magnet fixturing.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLO14

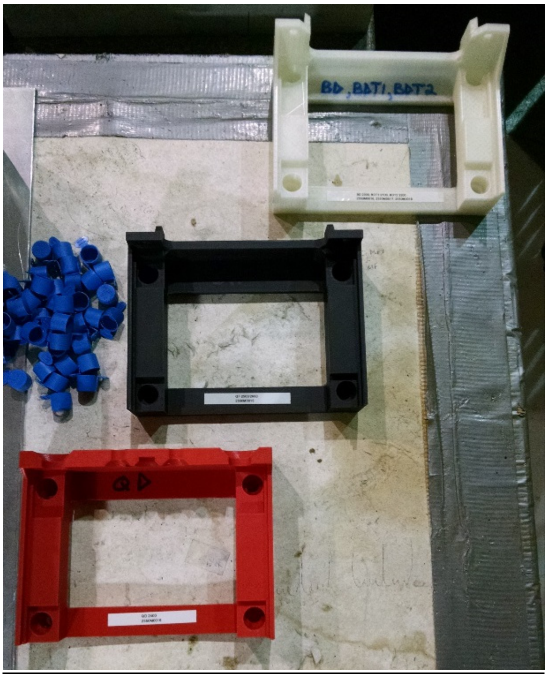

Figure 8: Halbach magnet fixturing.

Assembly of the Final CBETA Magnets

Assembling the final CBETA magnets proved to be quite challenging, but we eventually converged on a "block replacement technique". Figure 9 shows 3D printed individual magnet volumes and a center assembly mandrel that was used during the assembly process.

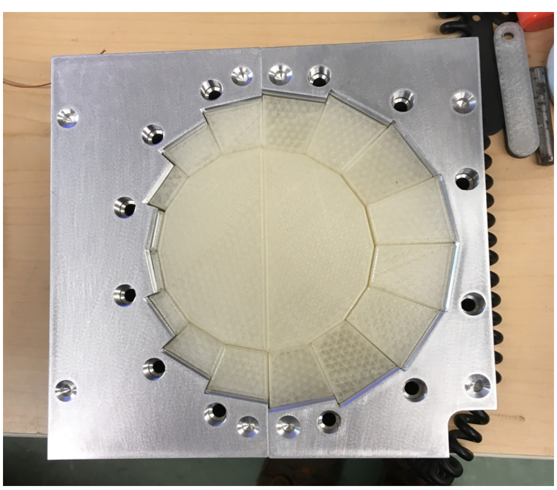

Figure 9: Block replacement.

Positionally and rotationally retaining all blocks during assembly of the Halbach array proved to be critical. The 3D printed dummy blocks allowed for individual replacement with the desired magnet blocks while restraining all previously placed magnet blocks. It should also be noted that the center assembly mandrel was left in place during the epoxy impregnation of the magnet assembly. An added complication to these Halbach array assemblies was the requirement to split the assemblies, allowing for installation on the vacuum pipe. Figure 10 shows an epoxy impregnated and split assembly of the final CBETA Halbach magnet array.

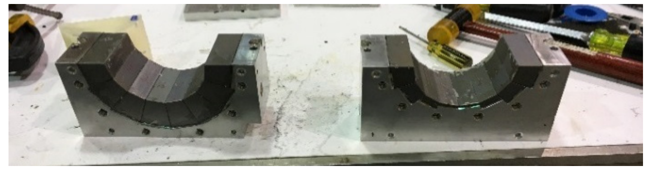

Figure 10: Final CBETA magnet assembly.

Tuning of the Final CBETA Magnets

Upon completion of the first round of magnetic measurement of the assemblies a tuning pack [3] was developed. The tuning scheme [4] was to strategically place a series of iron wires on the internal bore of the magnet assemblies. These wires, of varied lengths and position, would effectively cancel the originally measured multipole errors. We 3D printed a tuning wire carrier to place and constrain the tuning wire array. Figures 11 and 12 show the tuning packs and the tuning pack installation.

Figure 11: Tuning packs.

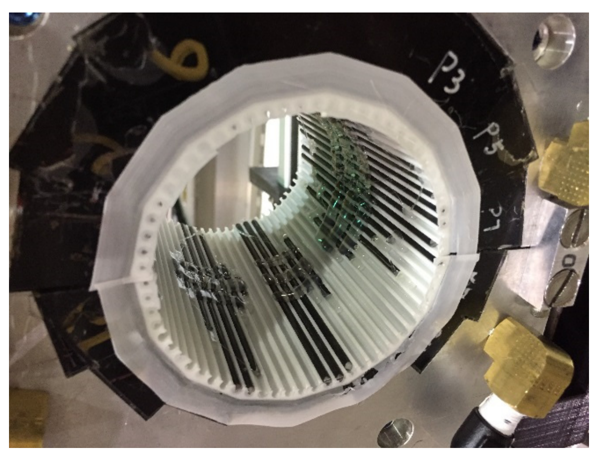

Figure 12: Tuning pack installation.

CONCLUSION

The use of 3D printed parts allowed us to accelerate our assembly schedule in prototyping, final assembly, and magnet measurement phases. The 3D printed components had been developed economically and rapidly.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLO14

REFERENCES

[1] G.H. Hoffstaetter *et al.*, "CBETA Design Report, Cornell-BNL ERL Test Accelerator", arXiv:1706.04245, 2017.

[2] S. J. Brooks, G. J. Mahler, R. J. Michnoff, and J. E. Tuozzolo, "CBETA Permanent Magnet Production Run", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 4318-4321. doi:10.18429/JACoW-IPAC2019-THPTS088

[3] S.J. Brooks, CBETA note 018 "Description of CBETA Magnet Tuning Wire Holders", 2017, available from https://www.classe.cornell.edu/CBETA_PM/index_notes.html

[4] S. J. Brooks, J. Cintorino, A. K. Jain, and G. J. Mahler, "Production of Low Cost, High Field Quality Halbach Magnets", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 4118-4120. doi:10.18429/JACoW-IPAC2017-THPIK007