CBETA Technical Note MM
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TM 2: Assemble Prototype Girder

Contents

Summary

This Technical Note presents details of the successful achievement of Technical Milestone 2 in the NYSERDA contract with Brookhaven National Laboratory and Cornell University, to design, build and commission the Cornell-BNL Electron Test Accelerator (CBETA). Milestone 2 marks the completion of Task 2, which is defined as:

Task 2: **Assemble Prototype Girder**

Task Goal: Assemble and test the prototype girder using 8 hybrid magnets.

Deliverables:

- An assembled prototype girder to be used in the accelerator circumference made of 8 hybrid magnets blocks embedded into iron poles and back-legs.
- Perform rigorous magnetic, mechanical, alignment and thermal tests on the prototype and document the results of the tests.

The results of the spectrum of tests and measurements that have been performed on the prototype girder and its components are documented below.

1 Introduction

Figure 1 shows the fully assembled girder, including eight magnets surrounding an integrated vacuum beampipe that is resting on a specialized table – a girder. Each magnet consists of a Halbach core surrounded by a relatively weak electromagnet corrector. The magnetic field in the Halbach magnets is driven by a set of many permanent magnet blocks that are assembled in a complete circular arc that surrounds the beampipe. For more details see below, in Section 3.

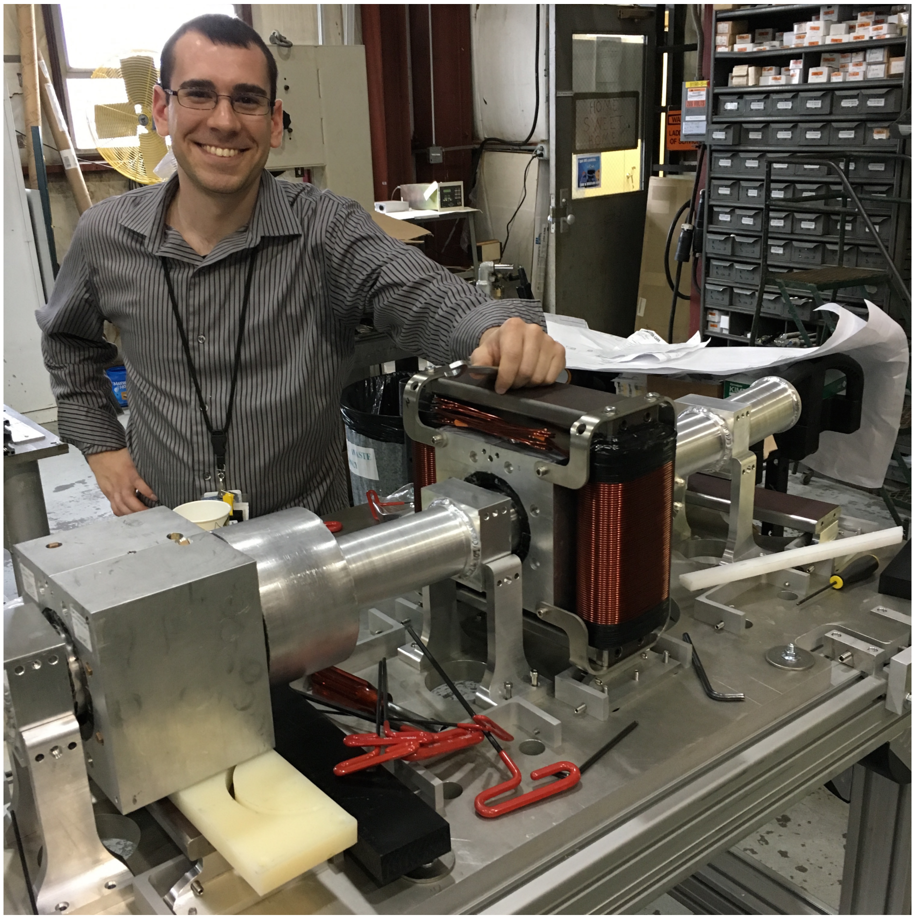

Figure 1: PLACEHOLDER. The prototype girder shown in this figure supports eight Halbach magnets, each surrounded by electromagnetic correctors, constructed around a vacuum beampipe. The fully integrated component is careful aligned on the girder.

The "Task Goal" explicitly states that 8 hybrid magnets would be assembled on the girder. The implicit goal is to include 8 permanent magnets (not electromagnets) in a configuration that provides two Fixed Fileld Alternating Gradient (FFAG) optical cells, following the same layout that will be used in the CBETA return arcs. Two technological choices are available for these magnets: "hybrid" or "Halbach". In January 2017 it was decided to switch from hybrid to Halbach technology. The intent of the Task Goal has been met using Halbach magnets, not hybrid magnets.

2 Magnetic testing and performance

The first girder consists of two types of Halbach magnet: a symmetrical quadrupole 'QF' and a lopsided combined quadrupole plus dipole 'BD'. There are four of each type on the girder.

In order to trace potential errors during the assembly of the first girder, the magnets were measured at two stages in production:

- As individual wedge-shaped permanent magnet blocks, each of which has a different size and magnetisation direction.
- As assembled magnets, each containing 32 blocks, which contain a magnetic field that varies across the aperture.

The measurement of individual permanent magnet blocks was done using a Helmholtz coil set-up at Brookhaven National Laboratory (BNL) and for each block gave a 3-dimensional vector showing the direction of magnetisation of the material in that block. This vector also includes information on the magnetisation strength. An example of the data obtained from all 384 permanent magnet blocks ordered is shown in Figure 2.

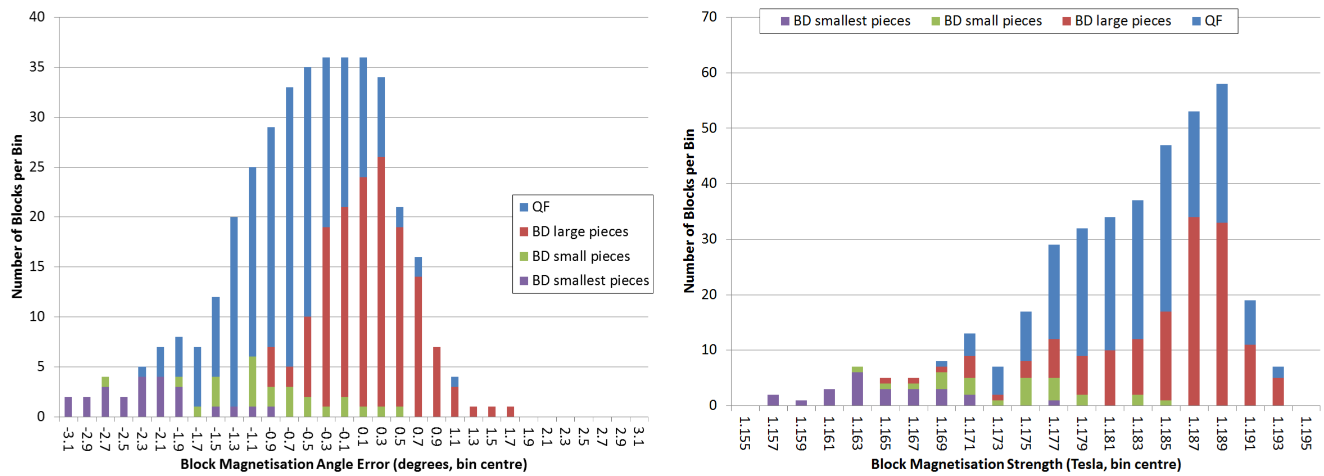

Figure 2: Distribution of block magnetisation measured on a Helmholtz coil at BNL. (left) Magnetisation angle errors relative to specification. (right) Magnetisation strength distribution.

The error of the magnetisation angle of the blocks is particularly important for this magnet design. For the full distribution shown in Figure 2, the RMS (root mean square) angle error is less than one degree, as desired. Two families of very small BD magnets are picked out in this figure, which have larger systematic errors in angle than the rest, but a smaller contribution to the overall magnetic field due to their small size.

The Helmholtz coil also measured the variation in magnetisation strength of the blocks, which is shown on the right of Figure 2. The blocks for the QF magnet had a standard deviation of 0.429% in strength and the larger BD blocks had a standard deviation of 0.466%, both better than the desired 0.6% value. The average value of 1.182 Tesla is within the expected range of 1.17–1.22 Tesla given by the manufacturer. This average strength was used to determine the thicknesses of brass shims inserted around the magnet blocks to finely adjust the strength of the assembled magnet.

The second stage of measurement was done on fully-assembled magnets, using the rotating coil at BNL (Figure 3). The rotating coil goes through the magnet bore and measures the total magnetic field, broken down into a family of components called 'multipoles'.

To obtain magnets of sufficiently high quality for use in an accelerator (0.1% error), the raw magnets assembled from blocks were retuned using a family of iron wires, as shown in Figure 4. Magnets were first measured without wires, then the errors seen were used to calculate the lengths of wires to be inserted in slots in a plastic cartridge (the orange object inside the magnet bore in the figure).

An example of the result from this retuning is shown in Figure 5, where the magnet quality has improved by approximately a factor of 20 and the corrected magnet is about a factor of 4 better than the requirement.

Figure 3: John Cintorino operates BNL's rotating coil apparatus for measuring multipoles in one of the girder's QF magnets (bottom center).

Figure 4: Iron wires were placed inside the QF1 magnet bore in order to cancel out field imperfections ("multipoles"). This photos shows them inside the orange 3D printed shim holder.

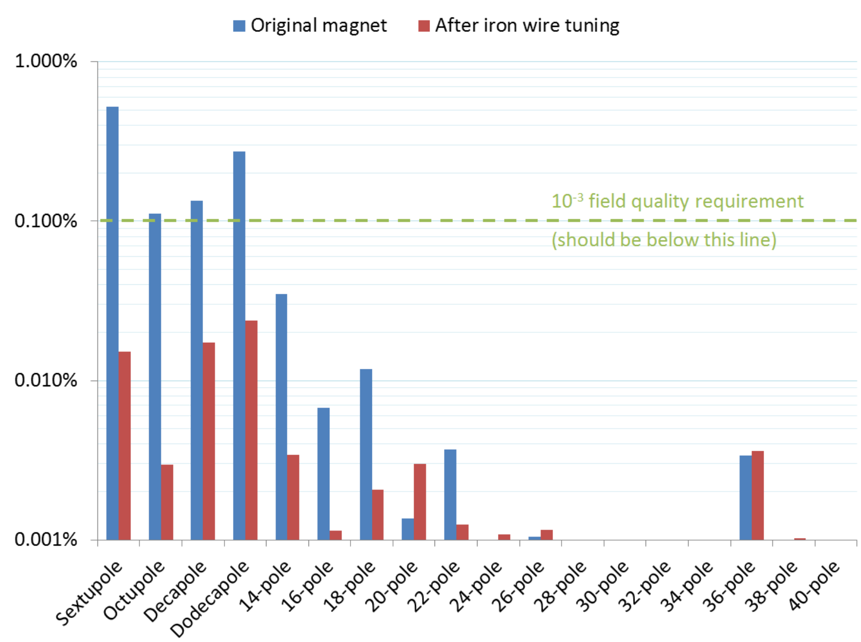

Figure 5: Size of multipole field errors (relative to the main field) in magnet QF1, before and after tuning with iron wires.

3 Mechanical analysis, forces, design and alignment

Halbach proof-of-principle magnets were constructed and tested to verify the ability of these magnet types to meet the CBETA technical and installation requirements as well as the magnetic field quality requirements discussed in the previous section. Another goal of the pre-production was to design and build a double cell assembly (8 magnets, 4 magnets/cell) that would match the requirements for a production cell assembly to be installed in CBETA.

The pre-production assembly incorporated the following features that will be used on the production magnets to meet these goals:

1. For vacuum chamber installation and maintenance, the magnets were built with aluminum outer frames that are split on the vertical plane. The split allows installation of a complete and tested vacuum chamber assembly with beam position monitors installed and tested. The aluminum frames provide higher strength and low deflection when resisting the magnetic forces from the PMM blocks. The frames were also machined with tight tolerances to provide accurate positioning of the blocks.

2. The aluminum frames are cross drilled with water passages for temperature stabilization of the permanent magnet material (PMM) in the magnet. Aluminum also provides excellent thermal conductivity for low temperature variation around the outer circumference of the PMM ring.

3. To deal with the possible variation of the PMM field strength, the magnet assemblies were designed to be built with shims that were used to vary the inner radius of the PMM and therefore the strength of the magnet assembly.

4. These are the first Halbach magnets built for CBETA that use epoxy to hold the PMM blocks in place especially when the magnets are split. Forces on the individual blocks could be up to 150 lbf and the stress on the epoxy as high as 100 psi.

Prior to manufacturing the aluminum frames, they were analyzed with the ANSYS finite element thermal and stress analysis program and their design modified and optimized to reduce stress and deflection. Shown in Figure 6 are analyses performed for deflection and stress distribution. All three magnet frame types were analyzed for stress, deflection, and temperature stability.

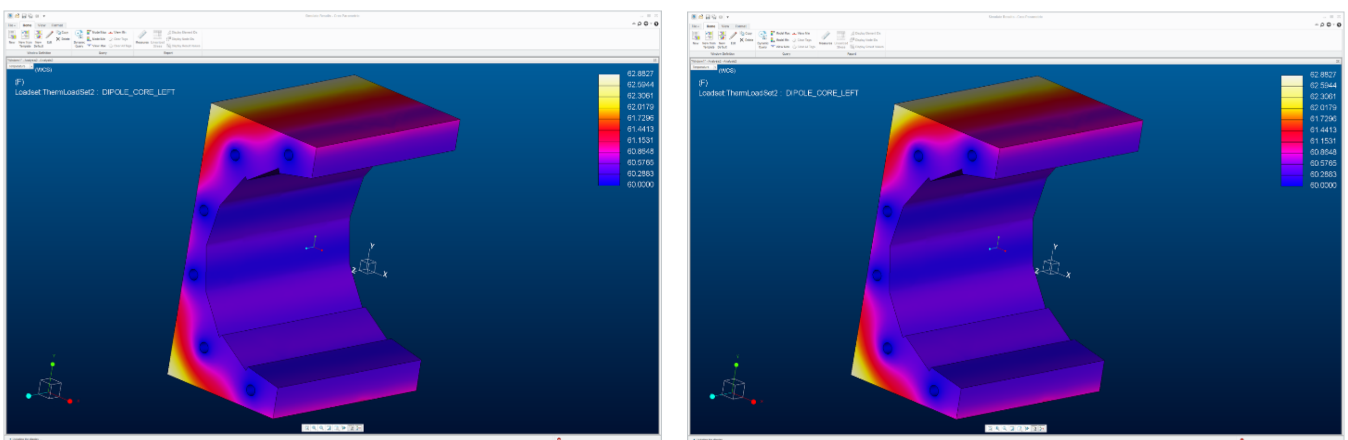

Figure 6: PLACEHOLDER.

Tensile and shear bond strengths for epoxy are typical over 1000 psi. Analysis of the block to block forces of the PMM were completed. These resulted in forces on the aluminum frame and forces on the epoxy tasked with holding the blocks to each other and to the aluminum frame. These were used for the deflection analysis shown above and to verify that the stress on the epoxy was within its design values. Shown in Figure 7 is the analysis for the BD (dipole) Halbach magnets which have the highest force on individual end blocks 343 N (77 lbf) per block. With a block surface area of 2.2 square inches, the tensile stress on the epoxy is less than 100 psi. Properly prepared surfaces and cured epoxy worked well on the pre-production magnets. Adhesion tests will be a requirement for the production magnets.

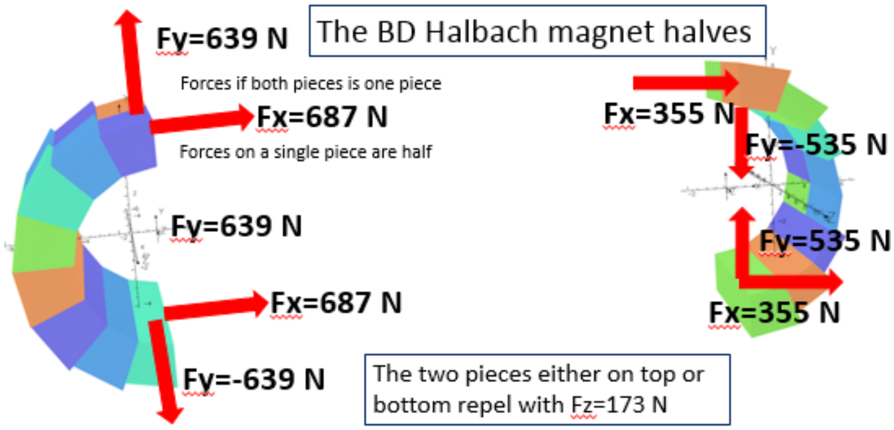

Figure 7: PLACEHOLDER.

The magnet frames were manufactured with alignment dowels which worked repeatedly throughout the measurement process. The measurement results were consistent throughout the measurement and the tuning process. Figure 8 shows the design model for the magnet assembly with assembly brackets and alignment dowls.

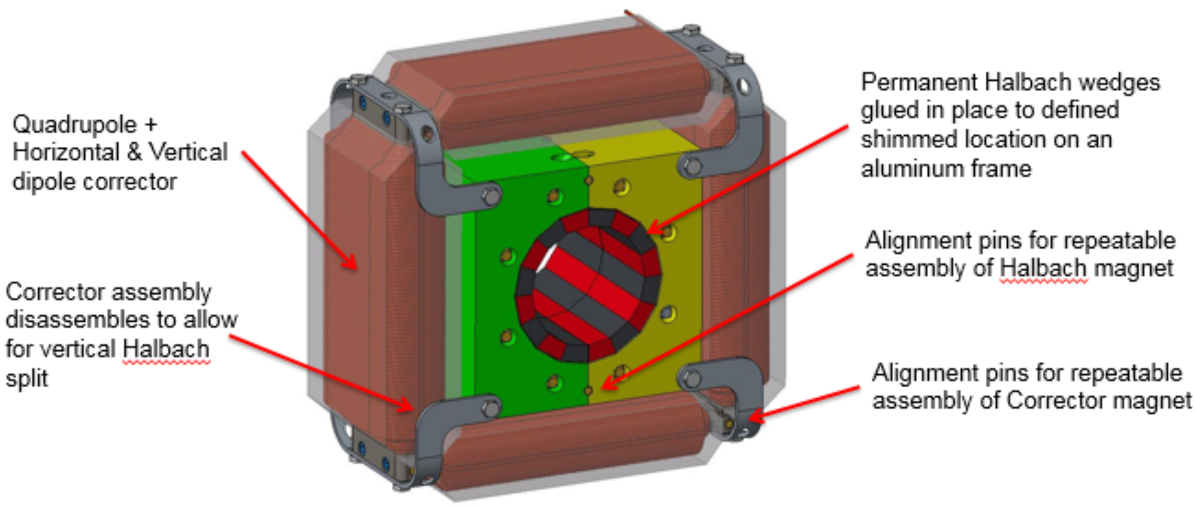

Figure 8: PLACEHOLDER.

The girder for supporting the 8 FFAG magnets in a double cell assembly has been significantly simplified because the Halbach magnets are 1/10 the weight of the originally planned Hybrid (Steel/PMM) magnets. The magnets for the preproduction magnet assembly have been mounted on an accurately machined aluminum plate. The aluminum plate was accurate machined using a CNC water jet cutter which included access holes below for the water lines and to aid in the passive cooling of the correctors. Taped holes and smaller mounting holes can be located with a single CNC operation for the magnet mounting points.

The Halbach magnet frames were accurately machined to provide accurate positioning of the PMM blocks and accurate alignment of the magnet halves. Accurate positioning of the magnet assemblies is achieved with multi-position jacking and alignment screws that can be locked into place after survey. The model and photo shown in Figure 9 illustrate the kinematic mount for the magnets. A lesson learned during construction was to modify the bracket to provide more space for the vertical corrector coil.

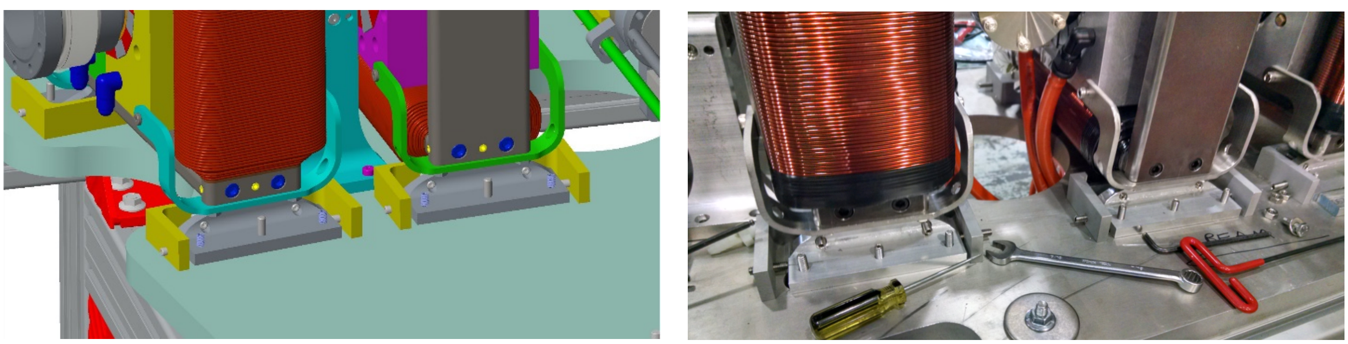

Figure 9: PLACEHOLDER.

4 Thermal variation and stability

The CBETA magnets will be operated at a controlled temperature because the neodymium-iron-boron (NdFeB) permanent magnet material has a magnetisation strength that varies with temperature. The thermal coefficient of this material is -0.11% per degree Kelvin temperature rise. To account for this, the temperature of the magnet was recorded each time the rotating coil field measurement was performed. The results are shown in Figure 10, which plots magnet strength against temperature.

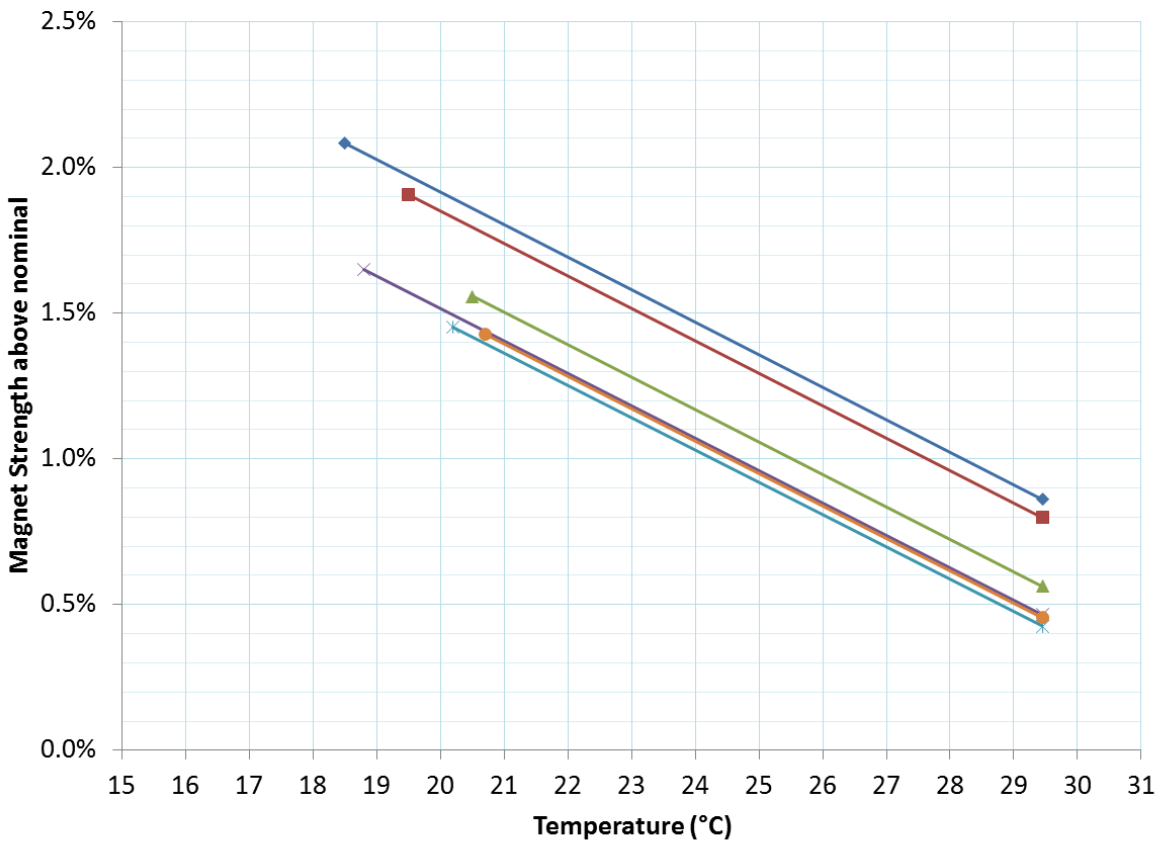

Figure 10: Thermal behaviour of magnet strengths, with lines from the measurement temperature to the operating temperature of 85°F (29.4°C).

The field strengths of the magnets at the measurement temperature are extrapolated to the running temperature for CBETA, which is the 85°F temperature of the Cornell University water circuit. The field strengths become much closer to the target strength once this correction is performed, with strength differences of less than 1% correctable by other means, either using the wire tuning method in Section 2 or by installing quadrupole correctors.

5 Acknowledgments

The authors of this note are just the individuals who participated directly in writing and editing. We are glad to acknowledge the hard work and support of many other people who contributed to the successful assembly of the prototype girder, including Henry Ashby, Steven Bellavia, Scott Berg, Cyrus Biscardi, John Cintorino, Michael Hartsough, Robert Karl, Robert Lehn, George Mahler, Gary McIntyre, Rob Michnoff, Humberto Palacios, Thomas Roser, John Siano, Charkes Trabocchi, Steven Trabocchi, and Nick Tsoupas.