CURRENT STATUS OF PERMANENT MAGNET RADIATION RESILIENCY STUDIES AT CEBAF*

R.M. Bodenstein[†], C. Decker, K.E. Deitrick, B.R. Gamage, J.F. Gubeli, D. Hamlette,
M. Janak, J. Meyers, B. Mosbrucker, E. Nissen, J. Samari, S. Shriner, M. Smith, N. Wilson,
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
S.J. Brooks, Brookhaven National Lab, Upton, NY, USA
S. Boogert, Cockcroft Institute, Daresbury, UK
W. Shields, Royal Holloway University London, Egham, UK
B. Shepherd, STFC, Daresbury, UK
L. Nevay, CERN, Meyrin, Switzerland

Abstract

One possible future for Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) lies in upgrading its maximum nominal energy using Fixed-Field Alternating-gradient (FFA) technology for its recirculating arcs. The current proposal aims to use permanent magnets to supply the fixed fields. One concern among reviewers is the degradation of these permanent magnets during operation due to the radiation environment in which they will be present. This work, funded by a Laboratory Directed R&D grant, aims to measure the magnet degradation in the CEBAF tunnel enclosure, and extrapolate to the energies expected from the upgrade. We present the latest results of this study, as well as plans moving forward.

BACKGROUND

The FFA@CEBAF energy upgrade feasibility study aims to increase the energy of the Continuous Electron Beam Accelerator Facility (CEBAF) from a nominal 12 GeV electron beam to over 20 GeV using fixed field, alternating gradient (FFA) permanent magnet arcs [1]. The permanent magnets proposed for the upgrade have not been tested in an environment similar to that which will be present in the CEBAF machine at over 20 GeV. We have placed samples of several permanent magnet materials in thirty different radiation regions of the operational 12 GeV CEBAF to gather data, which in combination with simulations, external studies, and calculations, will help evaluate the radiation hardness, and thus the lifetime, of the materials to be used for the FFA arcs.

The work being performed in this Laboratory Directed R&D (LDRD) project is the first step toward providing input into the overall design prior to the manufacture and purchase of the FFA magnets for the proposed energy upgrade. While significant work on this topic has been performed elsewhere [2], the results often only cover a very small part of the parameter space required to gain a full understanding of the impact of radiation on permanent magnet materials. Our studies provide vital data and insights into the behavior of various permanent magnet materials in an environment which closely resembles that in which they will operate in the upgraded CEBAF. This work will both help advance the FFA@CEBAF design, and contribute to ongoing worldwide studies of permanent magnet degradation due to radiation exposure.

METHODOLOGY

Hardware and Measurements

After placing the appropriate dosimetry (optichromic rods and optically stimulated luminescence (OSL) area monitors) to map out the expected dose ranges throughout the CEBAF enclosure [3], thirty locations in the complex were identified as having the appropriate range of neutron and gamma radiation for our studies. The requirements were that we must have a range of doses, that the areas were regularly accessible, and that the dosimetry would not always be saturated. In areas of very high doses, they should be in close proximity to radiation monitors which are capable of live readback and archiving data, such as the lab's Neutron Dose Rate Meter with Extended Capabilities (NDX) system [4]. This would allow for dose measurement in the event that our dosimetry is saturated. Prior to beam operation, but with RF turned on, calibration dosimetry was placed alongside the live readback systems so that any differences can be identified and included in the error calculations.

Currently, neodymium iron boron (NdFeB) and samarium cobalt (SmCo) are the main types of permanent magnet materials used in accelerators. Our colleagues at Brookhaven have assumed NdFeB grade N42EH for the prototype magnet design [5]. For comparative studies, N42EH, N52SH, SmCo33H, and SmCo35 have been selected as the focus of our studies. More information on the sample sizes and rationale can be found in last year's proceedings [3].

Given the small amount of degradation expected between measurements, precision equipment and measurement procedures are required. For point measurements on our samples, we are using a precise Teslameter (Senis 3MH6 with a C-type, three component Hall Probe [6]), capable of measuring to 0.005% digital accuracy. For measuring the full sample's

---

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The research described in this work was conducted under the Laboratory Directed Research and Development Program at Thomas Jefferson National Accelerator Facility for the U.S. Department of Energy.

[†] ryanmb@jlab.org

integrated magnetic field, a precision Helmholtz coil (Magnetic Instrumentation Model HCP w/Rotator and Model 2130 Digital Fluxmeter [7]) is being used. Each of these are placed on a separate lab cart so that they can be brought into the accelerator enclosure during scheduled down times, allowing for in-situ, mobile measurements. Since no equipment that is exposed to beam is leaving the tunnel, all possibly activated materials are contained.

To aid in the reproducibility of our measurements, 3D printed mounting systems for both the magnets and the Teslameter probe have been developed. More details on these developments can be found in last year's proceedings [8]. The mounts for the magnets themselves will be used to ensure the samples are held at known positions, and will aid in organization of the data. The mounts for the probe will ensure the placement of the probes at the same magnet measurement points and reduce the occurrence of human error.

Another factor which affects the demagnetization of permanent magnets in Halbach magnet assemblies are how the fields from the magnet wedges interact with each other [5,9]. The sensitivity to demagnetization is related to the reverse H-field's strength, as it runs antiparallel to the magnetization direction.

To investigate this concept, we are mounting several samples together in a manner which will approximate different regions of the Halbach magnets. The concept of these sample assemblies are shown in Figure 1. In this figure, a single magnet sample cross section is shown at the top of the figure, with the direction of magnetization indicated by the white arrow. Moving to the next image down in Figure 1, two samples are placed together with the magnetic fields aligned as indicated, which we refer to as a pair assembly. Another pair assembly is then placed such that the fields are aligned at 0°, 90°, or 180° with respect to the first.

Data is taken during all planned accelerator downtimes, as well as parasitically during some unplanned maintenance stoppages. Given the time and access constraints, this necessitates cycling between sample sites at times, and tracking which sites have had the most recent readings.

Simulations and Calculations

To estimate long-term degradation of permanent magnets in the CEBAF enclosure, we must first understand the radiation doses they will encounter and the relevant operating conditions—such as temperature, beam energy, and secondary particle deposition. This requires simulating the magnets under a range of beam energies, positions, configurations, and assembly types. For this purpose, we use BDSIM (Beam Delivery Simulation) [10], which is built on GEANT4 [11] and enables simulation of both particle transport and interactions with accelerator components. BDSIM is particularly well-suited for this project due to its ability to import full beamline geometries and support complex, custom shapes. Using it, we can identify the permanent magnets most at risk of radiation damage and generate detailed dose maps showing both intensity and spatial distribution. Furthermore, by modeling variations in material, geometry, and assembly, we can correlate simulation results with experimental data and extrapolate degradation trends for individual magnets, assemblies, and the overall FFA@CEBAF system.

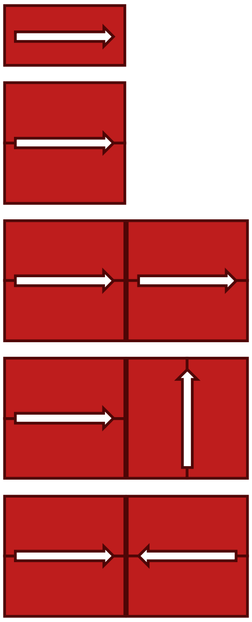

Figure 1: Magnet sample alignments for reverse-flux demagnetization studies. The white arrow indicates the direction of magnetization in the samples.

CURRENT STATUS

Hardware

Sample Installation Despite operational delays at CEBAF, all samples have had their baselines measured, and have been installed at thirty sites in the CEBAF tunnel enclosure. Twenty sites are located in the recirculating arcs in stacks of five (one on each energy pass). Two sites are located in the entrance labyrinths, to act as very low-dose samples. The remaining eight sites are in and around the two LINACs, mainly near the cryomodules.

Care was taken to ensure the proximity of the samples to the beamlines will not impact beam operations. Field map measurements and simulations have demonstrated that any impact on beam operations is negligible. Furthermore, all samples were installed prior to beam restoration from a long maintenance period, allowing correction of any small fields during spin-up.

Mobile Measurement Rigs The mobile measurement rigs have been completed, including the 3D printed holders and measurement system, QR-code data gathering setup, custom DAQ, and measurement protocols.

The Teslameter and Helmholtz coil sit on separate lab carts. Each plate of samples is removed from the mount, and measurements are performed before replacing the plate to its assigned mount. The DAQ is flexible, allowing full measurements with all devices, partial measurements, or only the swapping of dosimetry (which occurs at every access). Each plate has its own associated dosimetry.

Measurements

Dosimetry Dose information has been collected every two weeks since January 2025. There have been some delays in receiving some of this data from the area dosimeters, but what data has been delivered appears to be reasonable. The data from the optichromic rods has been collected and read, and is currently being processed and analyzed so that the appropriate errors are taken into account, along with comparisons to the live-readback dosimetry in the accelerator tunnel.

Helmholtz Coil After a late beam restoration from the extended Scheduled Accelerator Maintenance (SAM) period, Helmholtz coil measurements have started. Every sample has been measured multiple times. When feasible, disassembly of the pair assemblies also occurs, so each pair in the assembly can also be measured. At times, this is infeasible, and the assembly itself is measured. All single samples are measured in full. There are not yet enough measurements to draw any conclusions, as error analysis is ongoing. Figure 2 shows the Helmholtz Coil and Fluxmeter mobile measurement setup, alongside a set of samples mounted on a tripod near the LINAC cryomodules. Note the nearby white cylinder, which is an NDX detector.

Figure 2: Helmholtz coil and fluxmeter measurement rig in the tunnel next to a set of samples on a tripod. Note the adjacent NDX detector.

Teslameter All of the installed samples were measured with the Teslameter for baseline measurements. However, after these measurements, the Hall Probe's ceramic head broke, as did the replacement. More replacements are en route, and a new protective holder is being designed and fabricated to reduce this risk moving forward. The small differences that we expect from the new setup will need to be carefully taken into account during the error propagation analysis.

Simulations and Calculations

The BDSIM simulations are currently progressing [12], with a focus on translating our current CEBAF beamlines from elegant [13] to BDSIM. Efforts are ongoing to include the appropriate apertures and element geometries. Most of the machine is straightforward to simulate, however the cryomodules, and specifically the non-beam-induced field emission experienced by some of our cavities has been a struggle to implement. There are also some difficulties with importing complicated CAD drawings, mainly due to overlaps in the designs. These are secondary concerns, however, as the majority of the priority simulations must occur in the recirculating arcs where the primary source of radiation is through synchrotron radiation loss (Figure 3).

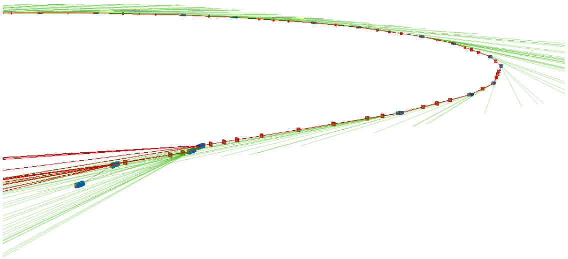

Figure 3: An example of CEBAF's lowest-energy arc in BDSIM. Here, a large vertical steering error was included, as well as synchrotron radiation.

Once the simulation setup is adequately complete, comparisons of the measured doses to those found via simulation will take place. The simulations will be adjusted until they agree with the measurements. The degree of necessary agreement is still to be determined, as the errors on radiation measurements tends to be large.

Once the simulations reach the agreement threshold, the simulations will be expanded to the higher energies expected in the upgraded CEBAF facility. This, combined with our measurement-based models will be used to extrapolate what doses are expected in the new machine, and predict the rate of degradation in the permanent magnets.

CONCLUSION

At the time of this writing, this project is well underway in the collection of data. Despite delays due to operational and equipment problems, measurements are ongoing. A recent review at lab also explicitly stated that it ”congratulates the magnet team on the well thought out and implemented magnet irradiation measurement program” during it's summary [14].

Data collection will continue alongside data and error analysis and simulations. As this study evolves, a model will be developed and modified, as well as compared to similar studies.

ACKNOWLEDGEMENTS

In addition to those listed as co-authors, we would like to thank the support of the CEBAF Operations and Operability groups, the Radiation Control Group, and the Installation Group.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPB093

REFERENCES

[1] D. Khan *et al.*, "Current status of the FFA@CEBAF energy upgrade", in *Proc. IPAC'24*, Nashville, TN, May 2024, pp. 474-477. `doi:10.18429/JACoW-IPAC2024-MOPR08`

[2] B. Shepherd, "Radiation damage to permanent magnet materials: A survey of experimental results", CERN, Meyrin, Switzerland, CERN-ACC-2018-0029, CLIC-Note-1079, 2018. `https://cds.cern.ch/record/2642418`

[3] R.M. Bodenstein *et al.*, "Permanent magnet resiliency in CEBAF's radiation environment: LDRD grant status and plans", in *Proc. IPAC'24*, Nashville, TN, May 2024, pp. 3875–3878. `doi:10.18429/JACoW-IPAC2024-THPS58`

[4] P.V. Degtiarenko, "Neutron detector and dose rate meter using beryllium-loaded materials", in *US Patent Number 10281600B2*, 2019. `https://www.osti.gov/servlets/purl/1568305`

[5] S. J. Brooks and S. A. Bogacz, "Permanent Magnets for the CEBAF 24GeV Upgrade", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2792–2795. `doi:10.18429/JACoW-IPAC2022-THPOTK011`

[6] "3MH6 High-Precision, Low-Noise Teslameter", `https://www.senis.swiss/magnetometers/teslameter-digital/3mh6-high-precision-low-noise-teslameter`

[7] "Model HCP Precision Helmholtz Coil Series With Rotator", `https://maginst.com/products/measurement-and-testing/precision-helmholtz-coils`

[8] E. Nissen *et al.*, "Design and instrumentation for permanent magnet samples exposed to a radiation environment", in *Proc. IPAC'24*, Nashville, TN, May 2024, pp. 3879-3881. `doi:10.18429/JACoW-IPAC2024-THPS59`

[9] S. Brooks, "Open-midplane gradient permanent magnet with 1.53 T peak field", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3870–3873. `doi:10.18429/JACoW-IPAC2023-WEPM128`

[10] L.J. Nevay *et al.*, "BDSIM: An accelerator tracking code with particle–matter interactions", *Computer Physics Communications*, vol. 252, p. 107200, 2020. `doi:10.1016/j.cpc.2020.107200`

[11] S. Agostinelli *et al.*, "Geant4—a simulation toolkit", *Nucl. Instrum. Methods Phys. Res. A*, vol. 506, no. 3, pp. 250–303, 2003. `doi:10.1016/S0168-9002(03)01368-8`

[12] B. Gamage *et al.*, "Radiation dose simulations for Jefferson Lab's permanent magnet resiliency LDRD study", in *Proc. IPAC'24*, Nashville, TN, May 2024, pp. 3872-3874. `doi:10.18429/JACoW-IPAC2024-THPS57`

[13] M. Borland, "ELEGANT: A flexible SDDS-compliant code for accelerator simulation", `doi:10.2172/761286`

[14] Jefferson Lab Accelerator Advisory Committee (JLAAC) Summary Discussion, May 2025, unpublished.