FFA@CEBAF Permanent Magnet Resiliency in Real Radiation Environment

2024 LDRD RENEWAL PROPOSAL (LDRD-2) FOR FY25

RYAN BODENSTEIN, KIRSTEN DEITRICK, EDITH NISSEN, RANDIKA GAMAGE

Outline:

- Overview/Progress of this Project
  - Magnets
  - Measurements
  - Modeling
  - Dosimetry
  - Status & Budget
  - Questions Answered
- The Plan for FY25
  - Changes
  - Quarterly Goals
  - Work Breakdown
  - Budget
- Future Funding
- Concluding Statements

The LDRD is:

- LDRD is studying the degradation of permanent magnet materials in a radiation environment similar to anticipated operational conditions
  - 2 permanent magnet (PM) materials (NdFeB and SmCo)
  - Wide range of radiation doses
  - Appropriate dosimetry to measure doses and types of radiation

- Ryan Bodenstein is PI (35% of time)
- Kirsten Deitrick is Co-I (10% of time)
- Edith Nissen is Co-I (20% of time)
- Randika Gamage is Co-I (30% of time)
- Support from Joe Meyers (Magnet Measurement), David Hamlette (RadCon), and Neil Wilson (Installation), Joe Gubeli (3D Printing)

Directly addresses JLAAC recommendation from March 2023:

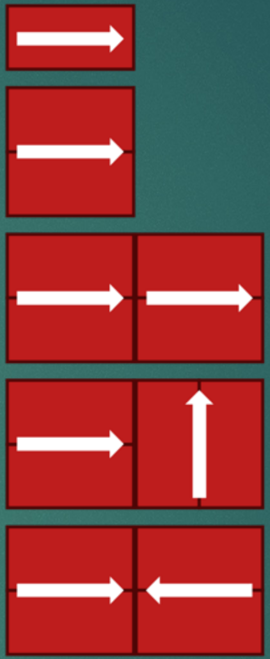
R30 states, "Validate the loss tolerances of the permanent magnet with irradiation experiments."

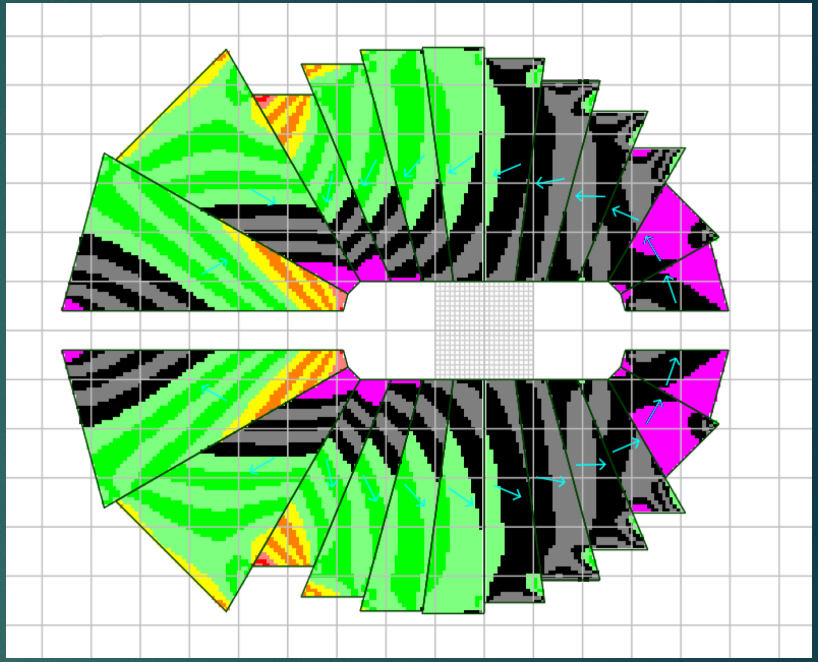
LDRD – The Plan Overview

- The main point of the LDRD is to study the degradation of permanent magnet materials in a radiation environment which resembles their intended operational environment as closely as possible.
  - We will use the data to extrapolate to the energies expected for the FFA@CEBAF energy upgrade.
- Two candidate materials, NdFeB and SmCo, of appropriate grades and treatments, are being studied.
  - NdFeB (N42EH & N52SH) and SmCo (SmCo33H & SmCo35) will be placed in a wide range of radiation environments at the lab (in the tunnel, Halls, etc…).
  - Single samples and reverse-flux assemblies will both be studied.
- Dosimetry will be placed alongside all samples to measure doses and the type of radiation at each location.
- Using a high-precision teslameter and Helmholtz coil on mobile measurement setups, we will measure the samples as often as the CEBAF accelerator schedule allows.
- Using the data gathered from above, as well as detailed simulations of the dosages and external studies, we will extrapolate our data to the relevant energy ranges and model the magnet degradation.

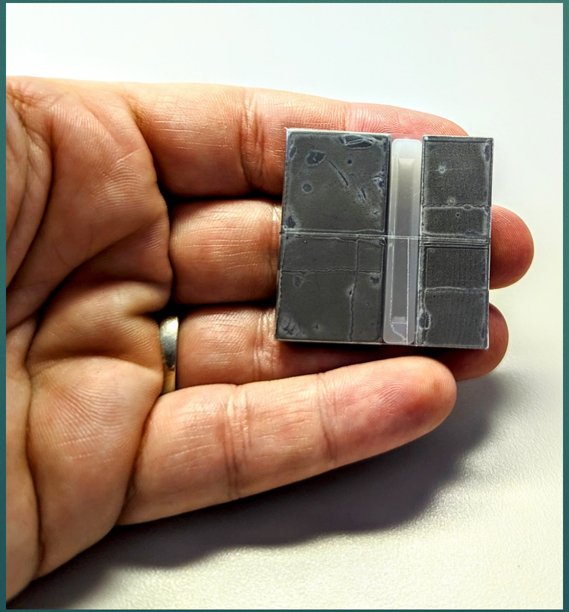
The Magnets

- 2 grades of NdFeB + 2 grades of SmCo
  - Strength, heat resistance, etc…
- 2 sizes:
  - Single samples – 1.5 x 0.75 (m) x 0.25”
  - Pair assembly samples – 1.5 x 0.5 (m) x 0.25”





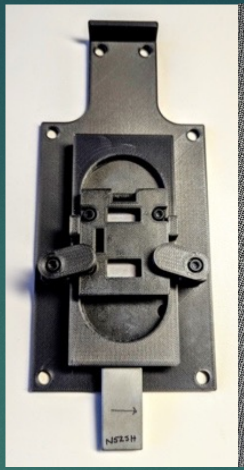
S. J. Brooks, “Permanent Magnets for the CEBAF 24GeV Upgrade”, in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 2792-2795. https://doi.org/10.18429/JACoW-IPAC2022-THPOTK011

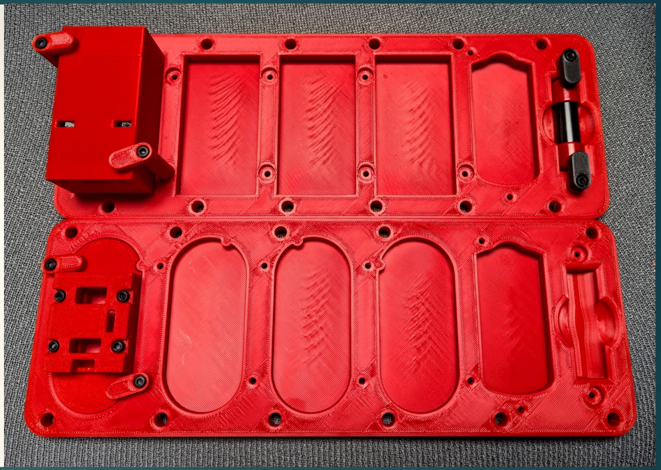


Two samples with spacer. Left is NdFeB single sample, right is SmCo pair assembly sample. Field aligned horizontally in photo. Both are covered in tape for safety.

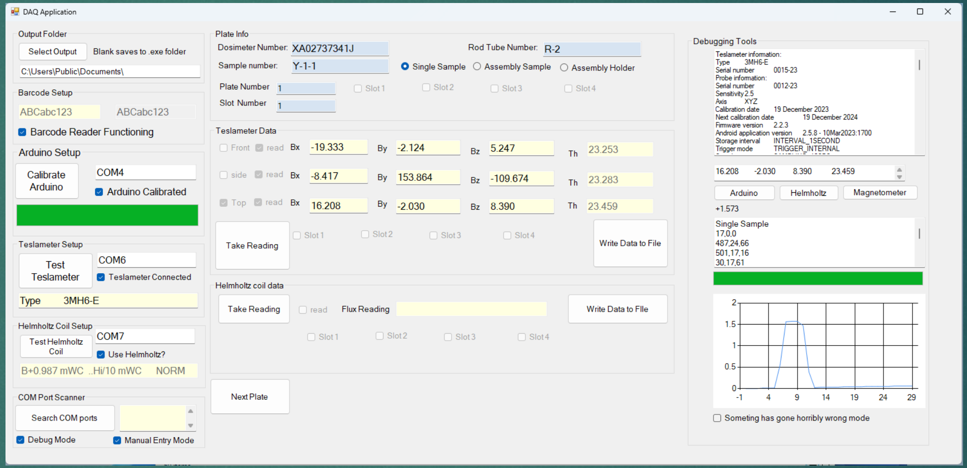
The Measurements

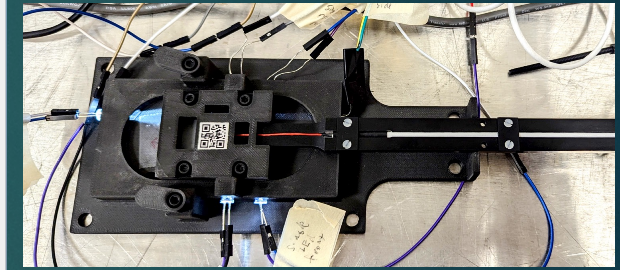
- 3D print mounting systems for the samples, as well as custom DAQ.





- A large range of doses will allow us to better determine the rate at which we can expect demagnetization over time, and at higher energies.

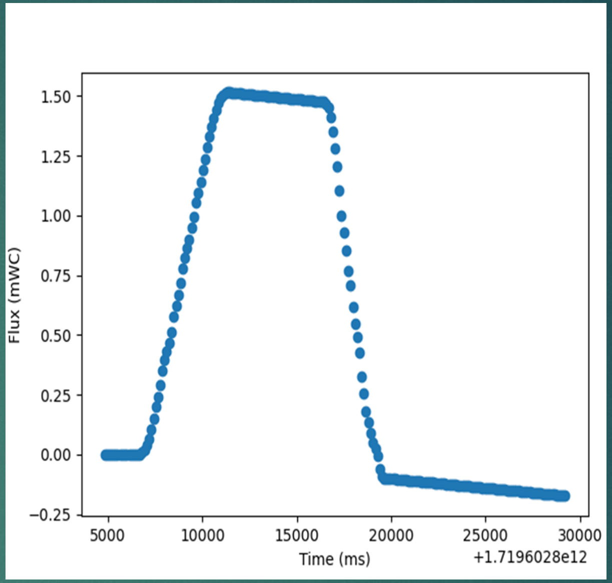


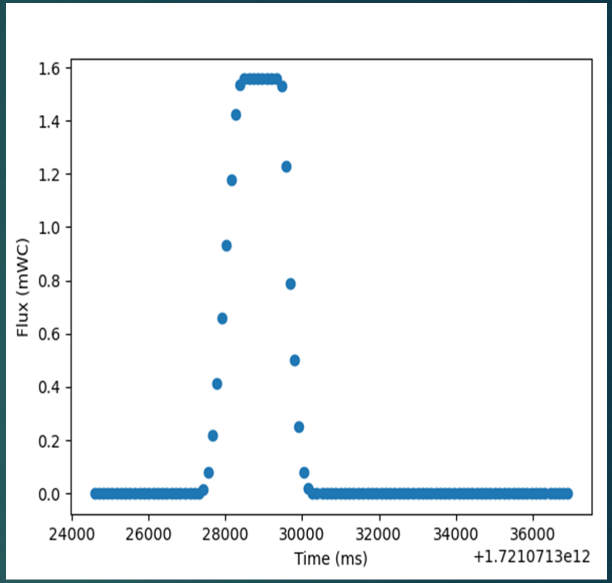


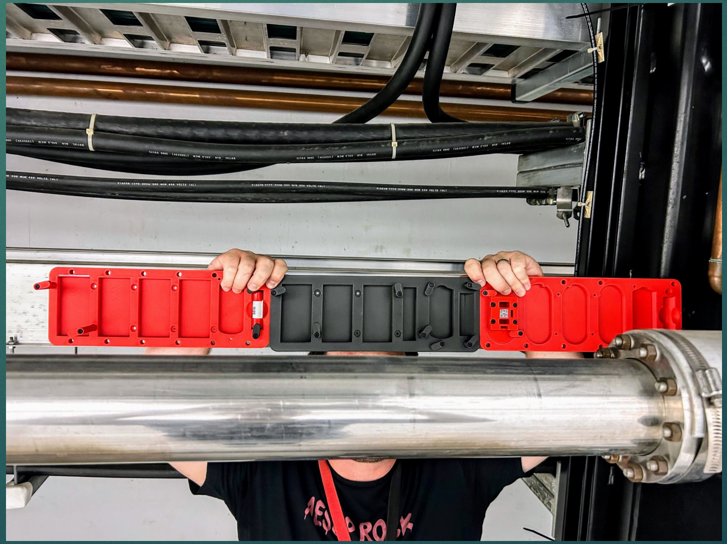
- Using a mobile testing setup with a high-precision teslameter (Senis 3MH6) and a Helmholtz coil (Magnetic Instrumentation Model HCP w/Rotator & Fluxmeter), measure the samples in the tunnel during accelerator down time.

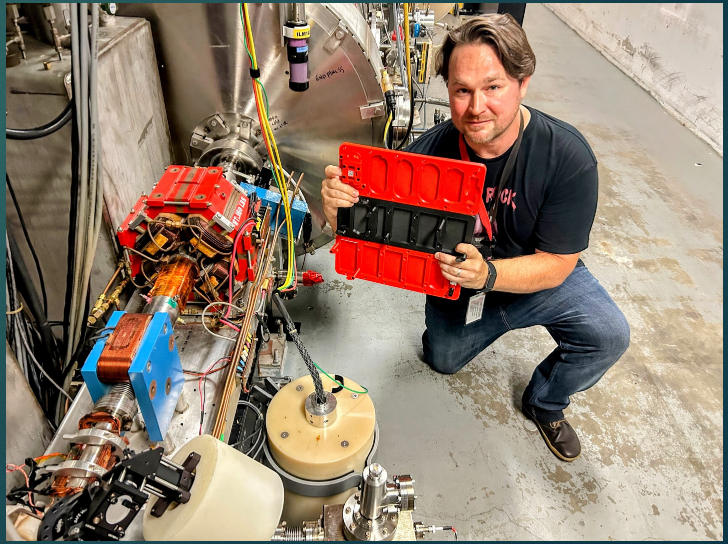
The Measurements

- Summer student (Colin Decker) helped to develop Helmholtz Coil procedures and provided error analysis.
- Installation will occur once all 3D prints arrive and are assembled/measured.
- Measurements will occur during tunnel access – currently planned every two weeks during maintenance.



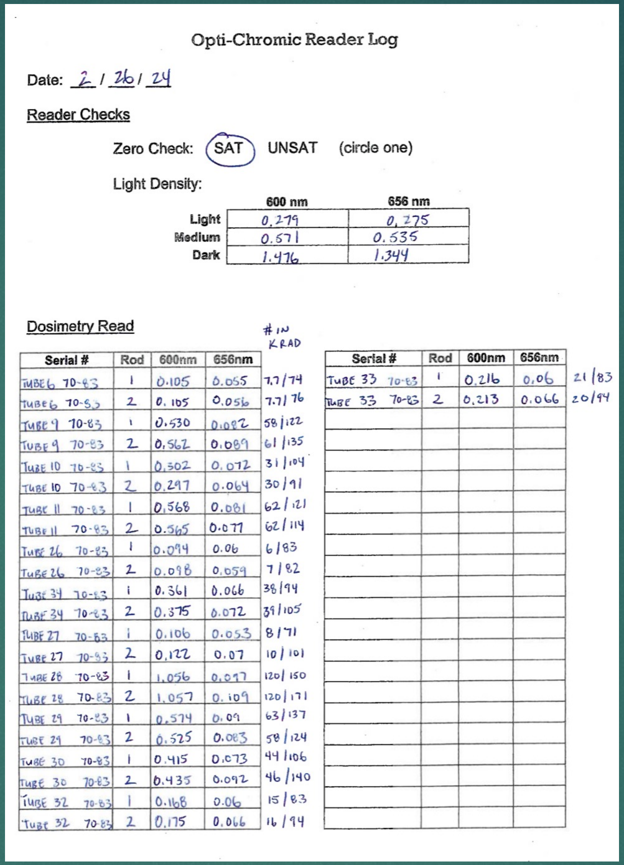






The Dosimetry

- RadCon supplied area dosimeters (neutrons and gamma), as well as low and high-dose optichromic rods will be used to measure radiation dose at samples.
- NDX data will supplement dose reading in locations where present.
- Radiation data is error prone, even with dedicated online radiation monitoring. (More on this later.)



Opti-Chromic Reader Log

Date: 2 / 26 / 24

Reader Checks

Zero Check: (SAT) UNSAT (circle one)

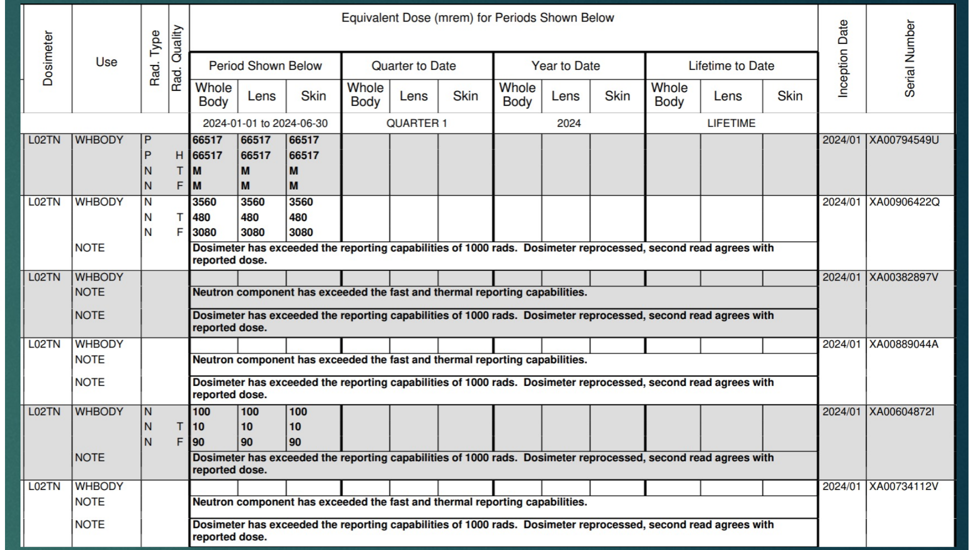
Light Density:

	600 nm	656 nm
Light	0.279	0.275
Medium	0.571	0.535
Dark	1.476	1.344

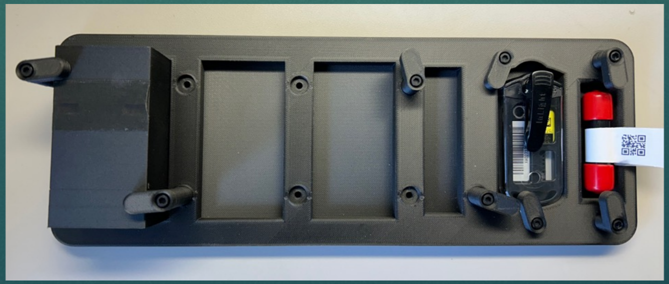
Dosimetry Read

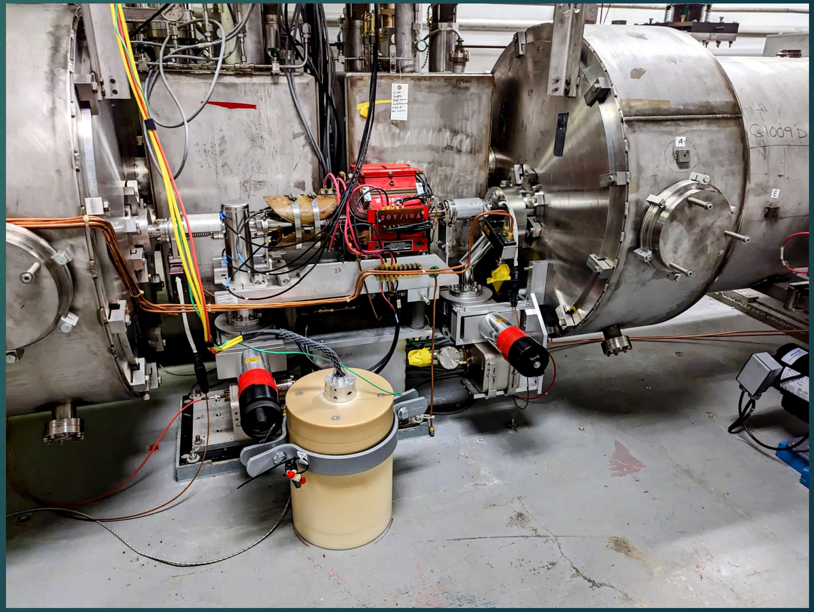
Serial #	Rod	600nm	656nm	# IN KRAD
TUBE 6 70-83	1	0.105	0.055	7.7/74
TUBE 6 70-83	2	0.105	0.056	7.7/76
TUBE 9 70-83	1	0.530	0.082	58/122
TUBE 9 70-83	2	0.562	0.089	61/135
TUBE 10 70-83	1	0.302	0.072	31/104
TUBE 10 70-83	2	0.297	0.064	30/91
TUBE 11 70-83	1	0.568	0.081	62/121
TUBE 11 70-83	2	0.565	0.077	62/114
TUBE 26 70-83	1	0.094	0.06	6/83
TUBE 26 70-83	2	0.098	0.059	7/82
TUBE 34 70-83	1	0.361	0.066	38/94
TUBE 34 70-83	2	0.375	0.072	39/105
TUBE 27 70-83	1	0.106	0.053	8/71
TUBE 27 70-83	2	0.122	0.07	10/101
TUBE 28 70-83	1	1.056	0.097	120/150
TUBE 28 70-83	2	1.057	0.109	120/171
TUBE 29 70-83	1	0.574	0.09	63/137
TUBE 29 70-83	2	0.525	0.083	58/124
TUBE 30 70-83	1	0.415	0.073	44/106
TUBE 30 70-83	2	0.435	0.092	46/140
TUBE 32 70-83	1	0.168	0.06	15/83
TUBE 32 70-83	2	0.175	0.066	16/94

Serial #	Rod	600nm	656nm	
TUBE 33 70-83	1	0.216	0.06	21/83
TUBE 33 70-83	2	0.213	0.066	20/94



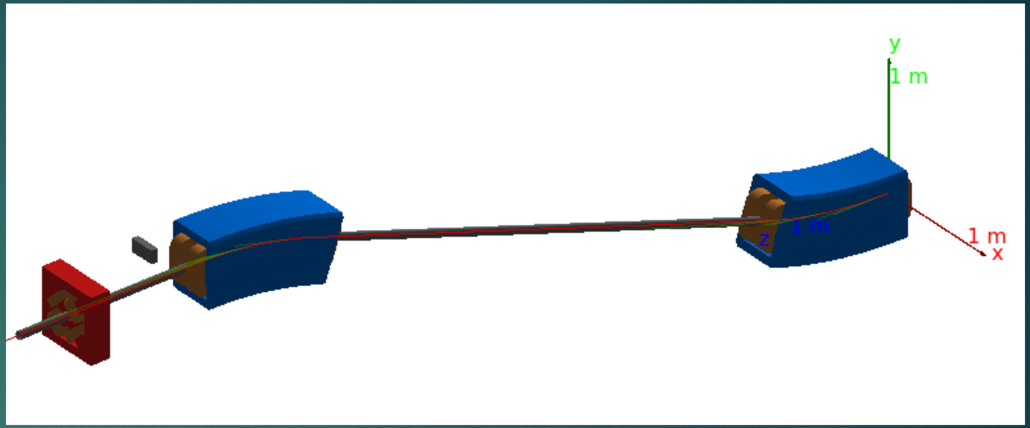
Dosimeter	Use	Rad. Type	Rad. Quality	Equivalent Dose (mrem) for Periods Shown Below												Inception Date	Serial Number
				Period Shown Below			Quarter to Date			Year to Date			Lifetime to Date				
				Whole Body	Lens	Skin	Whole Body	Lens	Skin	Whole Body	Lens	Skin	Whole Body	Lens	Skin		
				2024-01-01 to 2024-06-30			QUARTER 1			2024			LIFETIME				
L02TN	WHBODY	P		66517	66517	66517										2024/01	XA00794549U
		P	H	66517	66517	66517											
		N	T	M	M	M											
		N	F	M	M	M											
L02TN	WHBODY	N		3560	3560	3560										2024/01	XA00906422Q
		N	T	480	480	480											
		N	F	3080	3080	3080											
	NOTE			Dosimeter has exceeded the reporting capabilities of 1000 rads. Dosimeter reprocessed, second read agrees with reported dose.													
L02TN	WHBODY															2024/01	XA00382897V
	NOTE			Neutron component has exceeded the fast and thermal reporting capabilities.													
	NOTE			Dosimeter has exceeded the reporting capabilities of 1000 rads. Dosimeter reprocessed, second read agrees with reported dose.													
L02TN	WHBODY															2024/01	XA00889044A
	NOTE			Neutron component has exceeded the fast and thermal reporting capabilities.													
	NOTE			Dosimeter has exceeded the reporting capabilities of 1000 rads. Dosimeter reprocessed, second read agrees with reported dose.													
L02TN	WHBODY	N		100	100	100										2024/01	XA00604872I
		N	T	10	10	10											
		N	F	90	90	90											
	NOTE			Dosimeter has exceeded the reporting capabilities of 1000 rads. Dosimeter reprocessed, second read agrees with reported dose.													
L02TN	WHBODY															2024/01	XA00734112V
	NOTE			Neutron component has exceeded the fast and thermal reporting capabilities.													
	NOTE			Dosimeter has exceeded the reporting capabilities of 1000 rads. Dosimeter reprocessed, second read agrees with reported dose.													

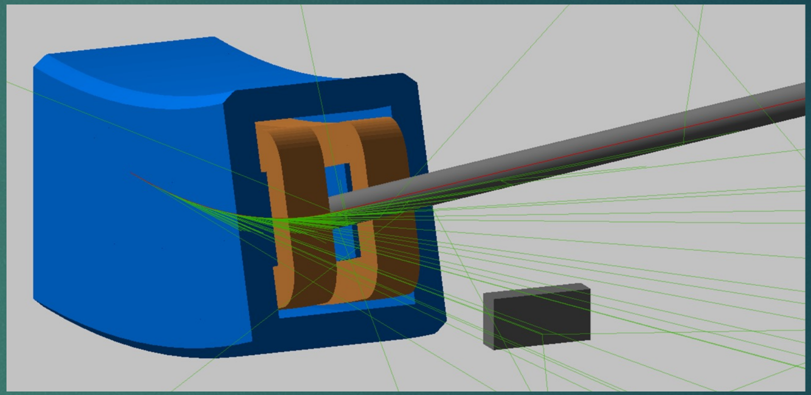


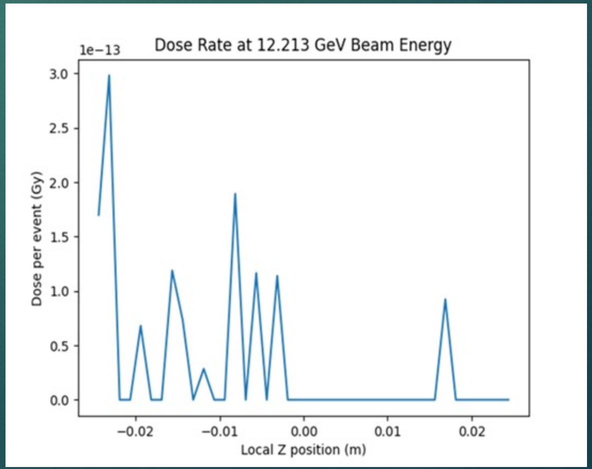


The Simulations

- BDSIM simulations will be used to better understand the doses that occur at the FFA@CEBAF energies.
- Our starting models will be based upon the simulated doses and previous external studies which most closely resemble our operating environment.
- As we gather data, we will refine the models to best explain the observed behaviors.
  - This will be used to extrapolate for the higher energies that we cannot yet reach.







The Status

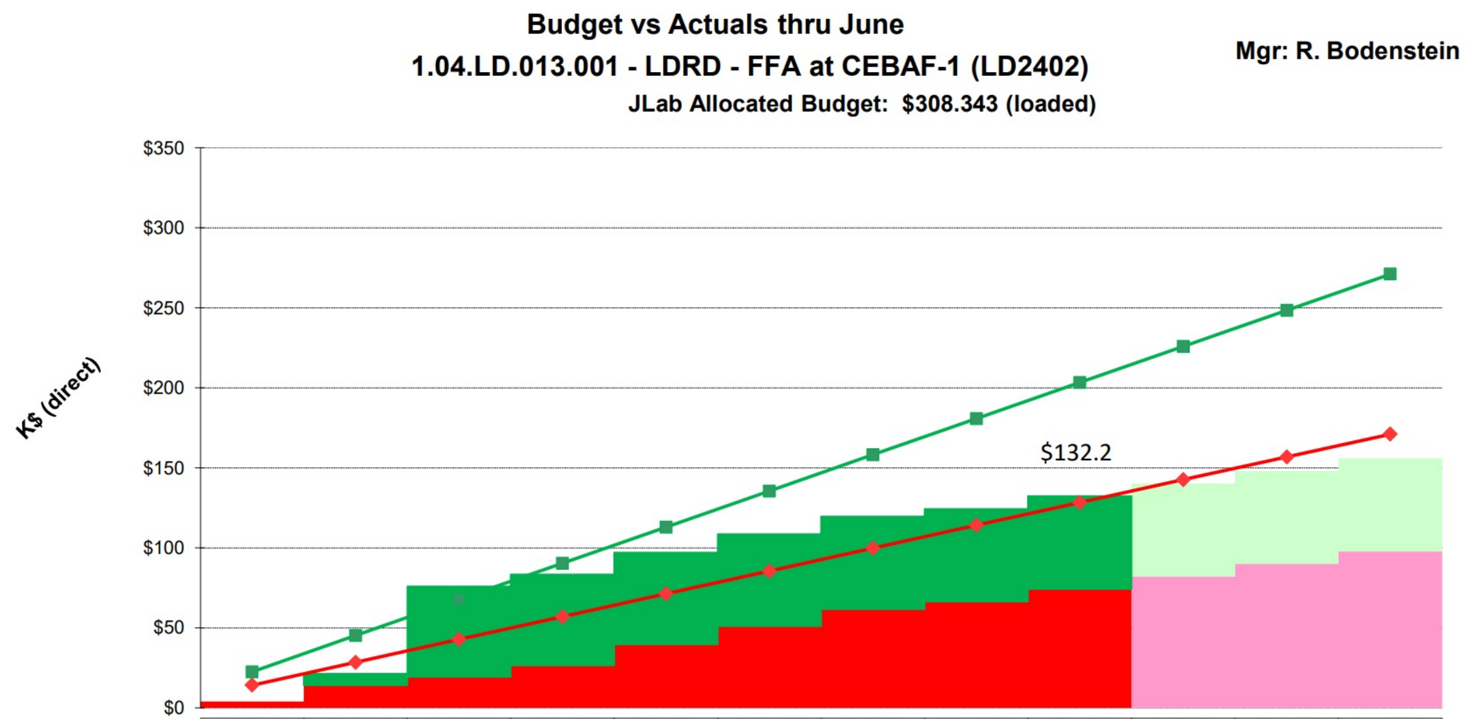
- All Q1 and Q2 milestones met, except "bonus" studies.
- Shipping delays, broken components, and work pauses (and associated fallout/re-prioritizations) have impacted our timeline.
  - Extended SAD is a mixed blessing: it gives us time to install during the SAD, but delays data taking until after January 2025.
- **Presented at IPAC24 (3 proceedings), invited talk at ERL 2024 in September (1 proceedings).**
- **Interest in collaboration with Cockcroft Institute, RHUL, BNL, and possibly CERN.**

Progress tracker li...

Work item	Descripti...	Category	Progress
Due date: 04/01/2024 (10)			
Due date: 07/01/2024 (3)			
SAD Installation	All samples, available assemblies, and available spares will be installed during the SAD, along with appropriate dosimetry. - If all are not installed, prioritized locations must be installed.	Engineering, Research	Behind
Test In-Situ Magnet Test Setup and Procedures	Test the portable in-situ magnet test setup and procedures. - If equipment delayed, use temporary measures. - Refine test setup and procedures as needed.	Research	Behind
Simulations - Underway	Simulations should be underway, with some initial trials completed.	Research	In progress
Due date: 10/01/2024 (4)			
Priority Simulations Complete	Highest-priority simulations should be complete.	Research	In progress
Model Development Underway	Initial data will be used to start model development and calculations.	Research	In progress
Test refinement	Identify any problematic areas and move and/or install samples to accommodate.	Planning	In progress
1st Year Writeup	Write up the progress from the first year, including conference proceedings, tech notes, and publications.	Planning	In progress

The Budget

- Will bulk order 3D prints upon review of test prints (2nd round)
  - ~$7K (estimate, TBD)
- 2 X Lab Carts
  - $1-1.5K
- Installation may not happen until FY25 (extended SAD)
- Teslameter calibration due December



	Oct-23	Nov-23	Dec-23	Jan-24	Feb-24	Mar-24	Apr-24	May-24	Jun-24	Jul-24	Aug-24	Sep-24
Spent - Proc	$0.0	$7.1	$56.5	$56.9	$57.5	$57.6	$57.8	$57.8	$57.9			
Spent - Labor	$4.0	$14.2	$19.3	$26.5	$39.6	$51.0	$61.7	$66.4	$74.3			
Proj - Proc									$0.0	$58.0	$58.1	$58.2
Proj - Labor									$0.0	$82.1	$89.9	$97.7
Spent/Proj - Total	$4.0	$21.3	$75.9	$83.4	$97.0	$108.5	$119.5	$124.3	$132.2	$140.1	$148.0	$155.9
Budget - Total	$22.6	$45.2	$67.8	$90.4	$112.9	$135.5	$158.1	$180.7	$203.3	$225.9	$248.5	$271.1
Budget - Proc	$8.3	$16.7	$25.0	$33.3	$41.7	$50.0	$58.3	$66.7	$75.0	$83.3	$91.7	$100.0
Budget - Labor	$14.3	$28.5	$42.8	$57.0	$71.3	$85.5	$99.8	$114.0	$128.3	$142.6	$156.8	$171.1

FY24

Spent Includes

Open Commits: $0.0

Pending: $0.0

Questions Answered - 1

- **Q: There were apparently many issues with understanding the collected radiation dose data in FY24. It is not clear if these issues were fully resolved with the plans for FY25. What impact does the problematic FY24 data have on the LDRD outcome?**
- Problem 1: Saturation – We found a gap in coverage, and are filling that gap with additional low-dose optichromic rods.
- Problem 2: NDX produces odd, large negative values at times – An operator has shown us how to pull raw data in a new way so that we can cut and integrate ourselves.
- Note: Few studies measure actual dose – most calculate. Those that measure also have very large error bars.

F. Wolff-Fabris, et al., "Status of the Radiation Damage on the European XFEL Undulator Systems", doi:10.18429/JACoW-IPAC2018-WEYGBD2

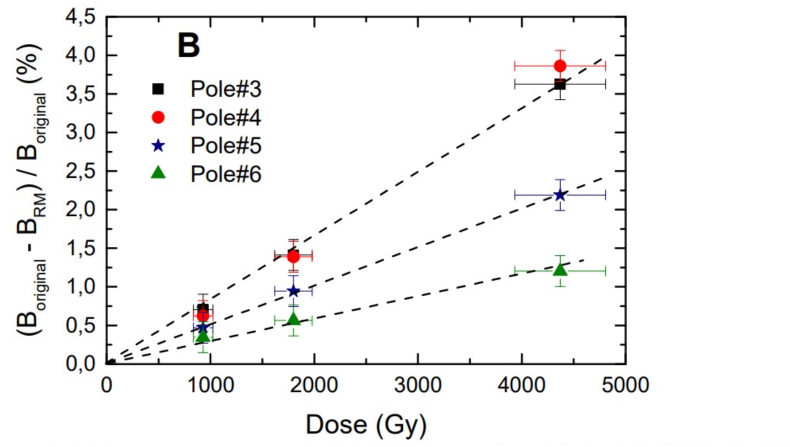
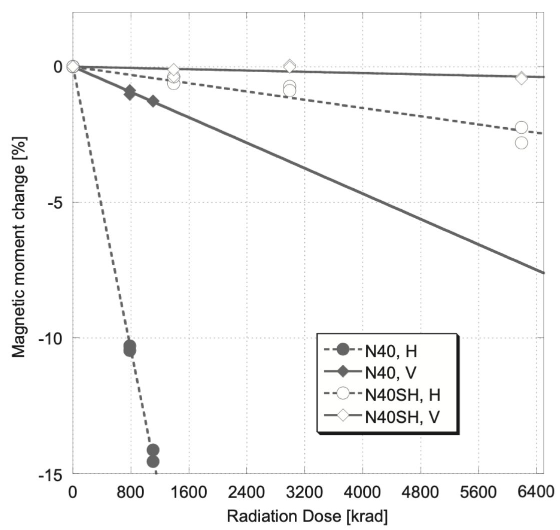


Figure 3: Magnetic degradation on the (A) SASE3 DU and (B) for poles #3 to #6 as function of absorbed doses.

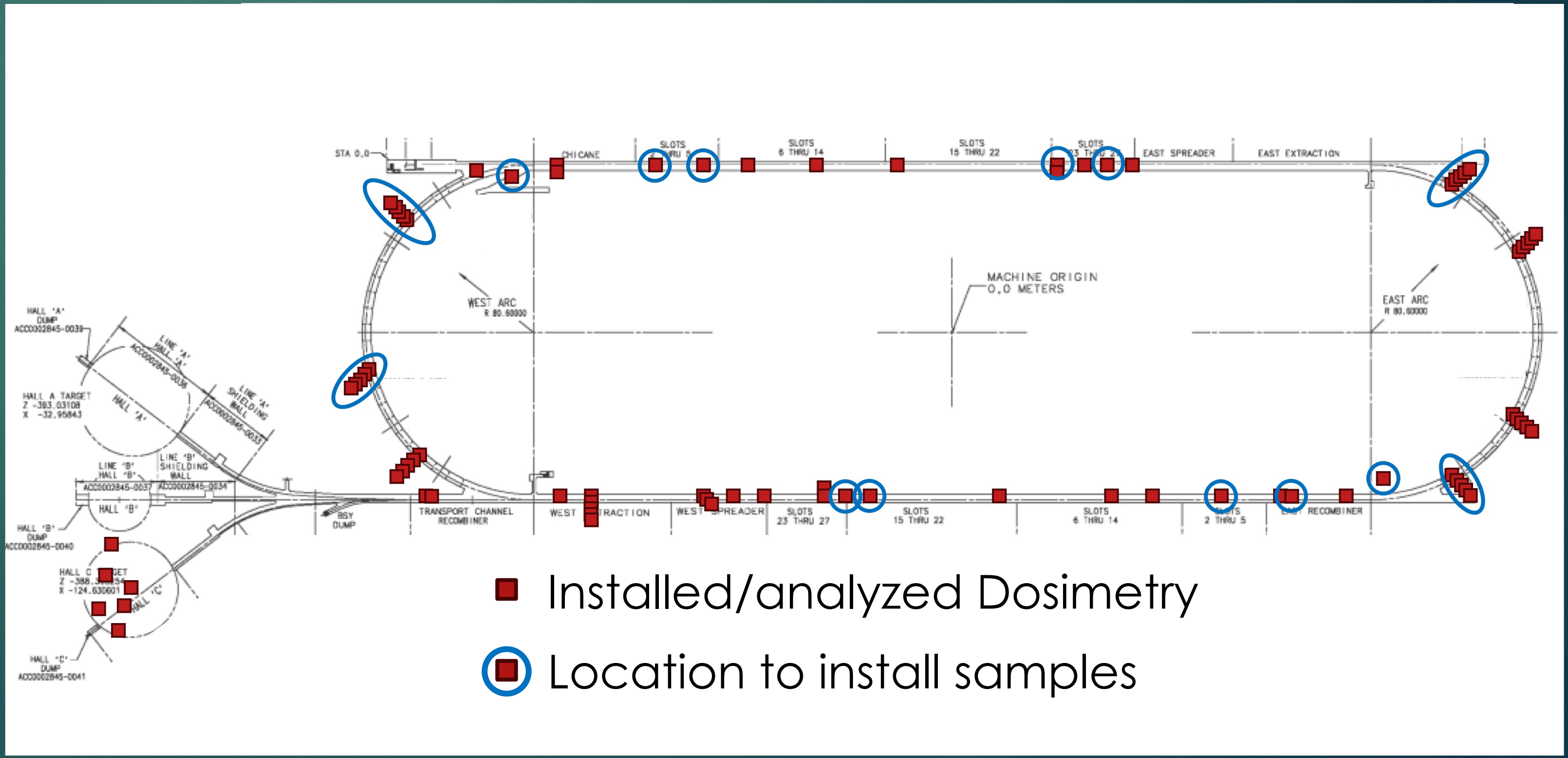


A.B. Temnykh, "Measurement of NdFeB permanent magnets demagnetization induced by high energy electron radiation", https://doi.org/10.1016/j.nima.2008.01.002.

Questions Answered - 2

- **Q: No results were shown in the proposal for data collection results from the FY24 monitoring. It would be appropriate to see a map of the accelerator showing where the monitoring is being conducted and some overview of the results.**

- Doses ranged:
  - 0 - 120 krad for photons,
  - 0 – Saturated for neutrons.
- Low dose rods will help.



Questions Answered - 3

- **Q: What is your method for relating radiation hardness based on short-term dose accumulation numbers to those relevant for long-term exposure of the magnets?**

- Studies show that the demagnetization is due to total integrated dose, with the exception of beam-strike events.
  - Some parts of the mechanism is due to thermal changes, but these are also related to integrated dose.
  - Our study will be using a wide range of doses, and reading the magnet data many times, giving demagnetization data along with integrated doses.
    - We will then use our range of integrated doses and demagnetization data to extrapolate for higher integrated doses.
  - Beam strike events *can* show some level of ”recovery” after the event – this would be investigated if our “bonus” study for FY25 is approved by JLab and CERN.

Questions Answered - 4

- **Q: Your metrics for studying radiation hardware are limited only to measurements of the magnetic field of the samples. Do you plan any testing of the samples after long radiation exposure to measure their mechanical properties?**

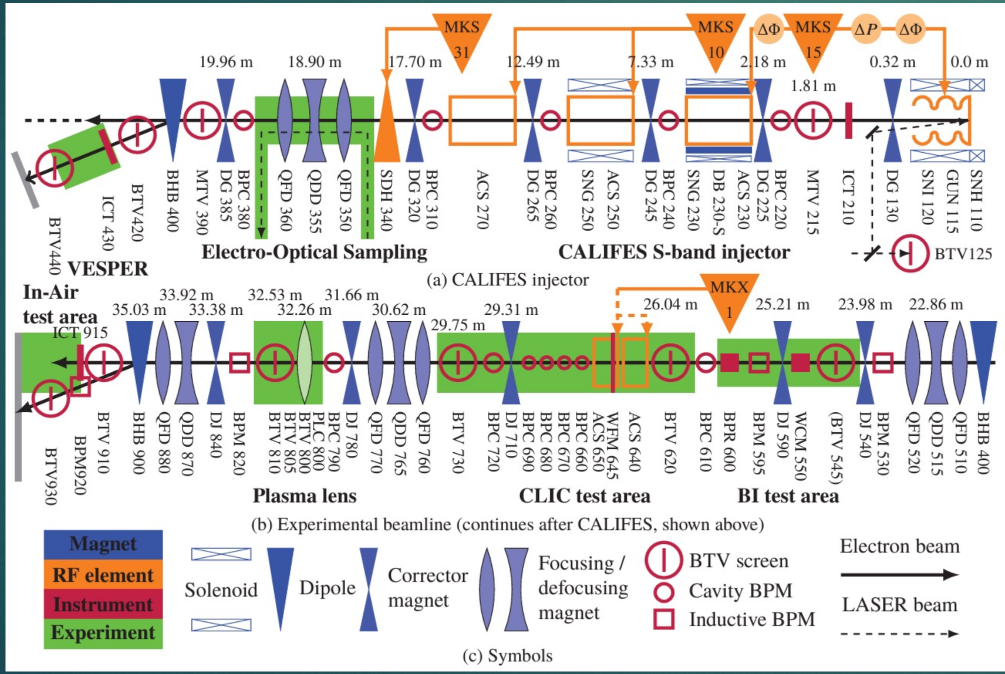
- This is outside of the scope of our study, as well as our expertise. However, such a study could be possible. If interested parties would like, and the magnets are later removed from the tunnel and cleared by RadCon, they could be compared to non-irradiated samples to study the differences.
  - We are avoiding removing the magnets from the tunnel due to concerns of activation.
  - SmCo does contain cobalt, which can be activated. This would need to be considered for any such study.

LDRD – The Plan – Goals for FY25

- **FY25 Quarter 1:**
  - Finish simulation layouts (geometric layout, GEANT4 physics lists, etc…) and placements for sample sites around CEBAF
    - If delayed, focus on highest-priority sites
  - Finish installation of components during extended SAD
    - If further delays, install priority locations first
  - Test and refine in-situ measurement protocols in the tunnel before CEBAF beam returns to users
    - If unable, have plan to test during maintenance and other beam downtimes
- **FY25 Quarter 2:**
  - Gather data as regularly as feasible, given safety and access restrictions
    - Currently plan every maintenance day (every two weeks) and parasitically as available
  - Using partial data, external results, and partial simulation results gathered thus far, refine the extrapolation model(s) to reflect the most up-to-date expectations for magnet degradation at higher beam energies
  - Prepare to present the status at IPAC and/or other conferences
- **FY25 Quarter 3:**
  - All priority simulations should be complete
    - If not all, the highest priority simulations, which contribute most to the extrapolation models, must be complete
  - Present results at IPAC and/or other conferences
  - Start writing journal paper(s)
- **FY25 Quarter 4:**
  - Wrap up all data taking for project
    - If allowed, samples can remain in place for future study
      - Request dosimetry funding for continued study
  - Finalize models and extrapolations, including errors and uncertainties
  - Write up project (tech notes, proceedings, etc…) and submit to at least one journal

The Bonus Beam Strike Study

- In discussions with CERN to write a proposal for beam strike study at CLEAR facility.
- If approved, the beam time would be free. The only costs would be shipping samples and/or travel.



K. Sjobak et al, "Status of the CLEAR Electron Beam User Facility at CERN", in proceedings of IPAC2019 (Melbourne), May 2019, MOPTS054, doi:10.18429/JACoW-IPAC2019-MOPTS054, https://cds.cern.ch/record/2695092.

Beam Parameters

The beam parameters at the end of the linac are summarised in the following table:

Beam parameter (end of linac)	Value range
Energy	60 - 220 MeV
Bunch charge	0.01 - 1.5 nC
Normalized emittances	3 um for 0.05 nC per bunch 20 um for 0.4 nC per bunch (in both planes)
Bunch length	~100 um - 1.2 mm
Relative energy spread	< 0.2 % rms (< 1 MeV FWHM)
Repetition rate	0.8 - 10 Hz
Number of micro-bunches in train	1 - 150
Micro-bunch spacing	1.5 or 3.0 GHz

https://clear.cern/content/beam-line-description

Work Breakdown

Budget ($K)	Total	FY25
	$292.4	$292.4

Requested Budget for Effort by Investigator

Name of Investigator	Role (PI, Co-I, etc.)	FY25 Budget ($K)	FY25 Effort (% FTE)	Total Effort (%FTE)
Ryan Bodenstein	PI	77.9	0.35	0.35
Kirsten Deitrick	Co-I	20.4	0.10	0.10
Edith Nissen	Co-I	45.9	0.20	0.20
Bamunuvita Gamage	Co-I	58.7	0.30	0.30
Joseph Meyers	Support	9.3	0.05	0.05
David Hamlette	Support	10.9	0.05	0.05
Neil Wilson	Support	9.4	0.05	0.05
Subtotal for effort		232.5	1.1	1.1
Equipment	Non-capital	10.6		
	Capital			
Subcontracts	Person/ organization			
Materials/ Supplies		39		
Travel		10		

Equipment	Justification	Projected Cost ($K in FY25)
Spare Teslameter Probe	Funds to replace and calibrate fragile Teslameter probe if it fails/breaks.	10.6

Name of Material	Description	Cost per FY ($K)	Total Cost ($K)
Dosimetry	Area dosimeters, low & high-dose optichromic rods (through RadCon)	28.7	28.7
3D Printing	Funds for printing or replacing mounts, etc…	5.3	5.3
Misc. Supplies	Cables, connectors, safety equipment, power supplies, and other supporting items.	5.4	5.4

Activity	Destination	Name of travelers	Estimated Cost ($K)
"Bonus" beam-strike studies at CLEAR/CERN (Days TBD, 1-2 weeks likely)	Meyrin, Switzerland (CERN)	TBD – up to two of the Co-Investigators	10

Future Funding

- As the FFA@CEBAF energy upgrade study continues, further hardware tests will likely follow.

- FFA@CEBAF collaboration plans to apply for future FOA's to further larger hardware tests.

- If the FFA@CEBAF proposal is selected as the path forward for Jefferson Lab, the larger collaboration will likely move onto specifically allocated funds.

- External parties (Cockcroft Institute, RHUL, BNL, etc…) have shown interest in future collaboration on this work, which may result in funding.

Concluding Statements

- This LDRD directly addresses a JLAAC recommendation for the development of the FFA@CEBAF project.
- By the end of this project, we expect to have a data-driven model capable of assessing the degradation various materials/grades/assemblies will experience during FFA@CEBAF operation.
- In addition to furthering general knowledge of permanent magnet material behavior in multi-GeV environments, it develops measurement methods and techniques new to the lab.
- The results of this project will further support the FFA@CEBAF concept and provide insight into Halbach permanent magnets for the wider community.
- This work has already garnered broad attention and interest in the accelerator community.