FERMILAB-FN-1045-AD

Performance Characterization of LCLS-II Superconducting Radiofrequency Cryomodules

RuthAnn Gregory, Michigan State University, East Lansing, MI

ABSTRACT

This paper will describe the LCLS (Linac Coherent Light Source)-II, Fermilab's role in the development of LCLS-II, and my contributions as a Lee Teng intern. LCLS-II is a second generation x-ray free electron laser being constructed at SLAC National Accelerator Laboratory. Fermilab is responsible for the design, construction, and testing of several 1.3 GHz cryomodules to be used in LCLS-II. These cryomodules are currently being tested at Fermilab. Some software was written to analyze the data from the cryomodule tests. This software assesses the performance of the cryomodules by looking at data on the cavity voltage, cavity gradient, dark current, and radiation.

INTRODUCTION

LCLS-II, or Linac Coherent Light Source is a planned upgrade to LCLS, the world's first hard x-ray free electron laser, located at SLAC National Accelerator Laboratory. The main linac of LCLS-II will contain thirty-five 1.3 GHz and two 3.9 GHz superconducting radio frequency (RF) cryomodules. Fermilab is responsible for designing, assembling, and testing seventeen of the 1.3 GHz cryomodules and the two 3.9 GHz cryomodules.[1] These cryomodules will accelerate electrons to 4 GeV in the linac.[2]

Each cryomodule consists of eight nine-cell TESLA-style RF superconducting cavities made from (high purity) niobium and is designed to operate in the continuous wave regime. The cryomodules also contain a set of magnets for beam corrections including a quadrupole and two dipoles.[3] Figure 1 shows a picture of one of these cavities that resonates at 1.3 GHz. These cavities operate at 2 K and are expected to provide an energy gain of 16 MV/m with a Q0 of 2.7×10^{10}.[2]

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

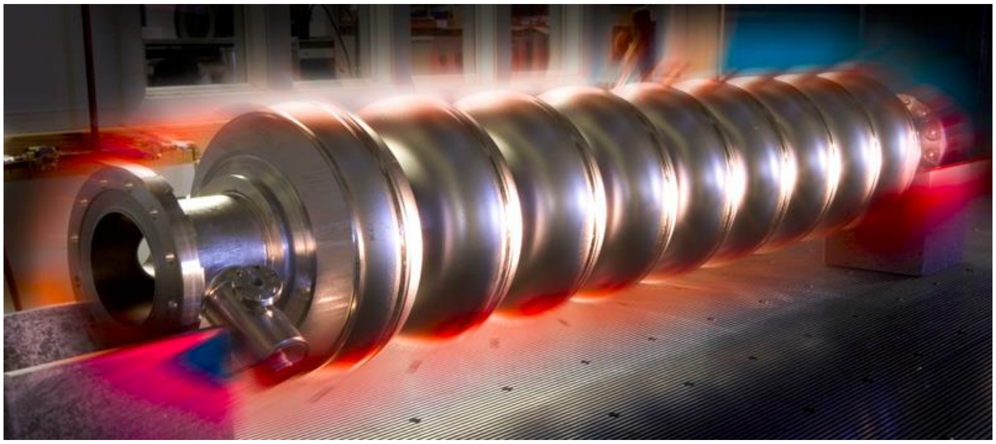


Figure 1: 1.3 GHz Superconducting Radio Frequency (SRF) cavity

These cryomodules will be tested at Fermilab's Cryomodule Test Facility (CMTF) in the Cryomodule Test Stand (CMTS1) cave.[3] Figure 2 shows an SRF cryomodule installed in CMTS1. CMTS1 is a shielded enclosure designed to house the 1.3 GHz cryomodules.[4] The dimensions of CMTS1 are 19.74 m long by 4.57 m wide with a height of 3.2 m. Figure 3 shows a diagram of the CMTS1 radiation detector placement.[4] In this diagram, "chipmunks" and "scarecrows" refer to radiation monitors that are Fermilab-designed ion chambers specifically designed for use in high energy accelerator facilities. References here: http://lss.fnal.gov/archive/2001/pub/Pub-01-337.pdf , https://ad-esh.fnal.gov/ad/adsp/ADSP-10-0101.pdf.

Figure 2: SRF cryomodule at Fermilab's Cryomodule Test Stand

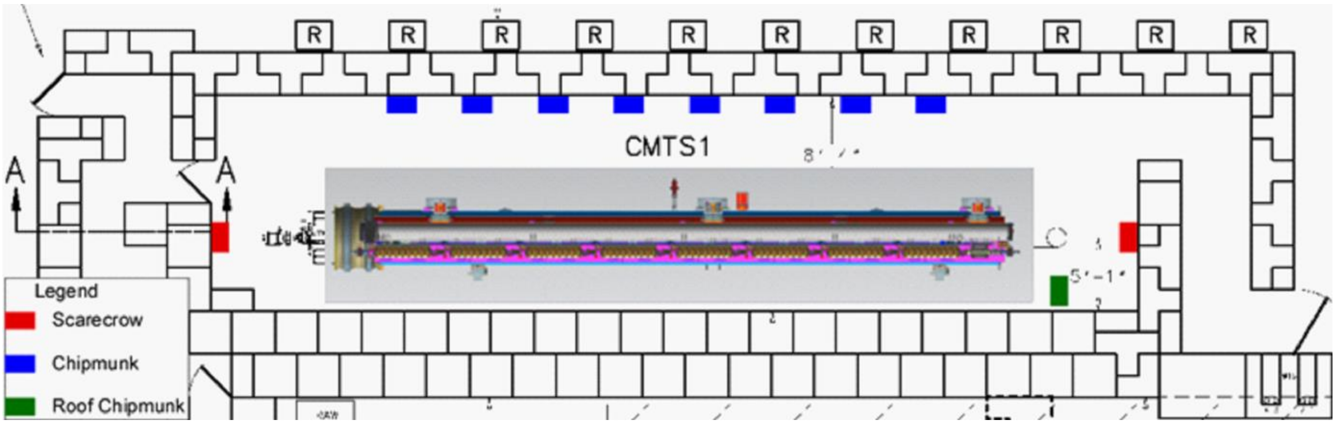
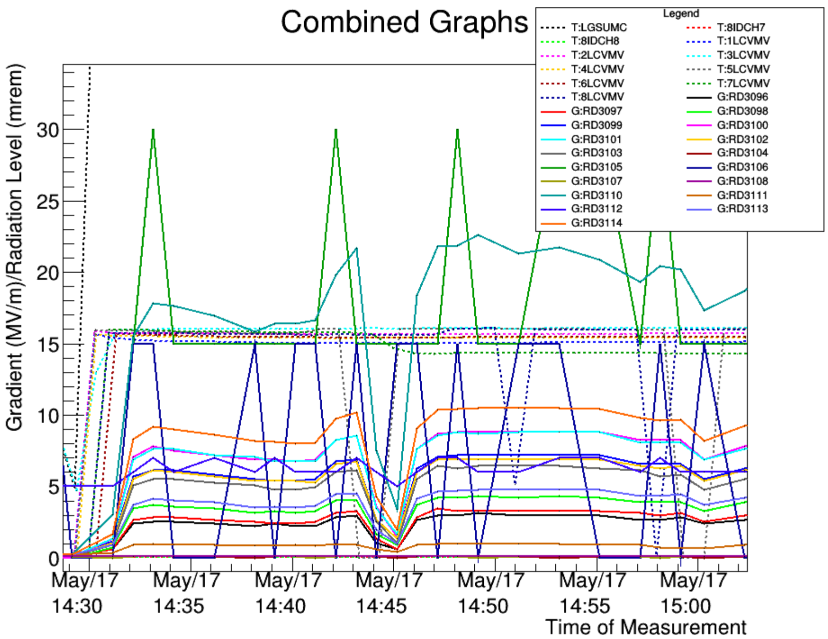


Figure 3: CMTS1 radiation detector placement. Chipmunks CMTS West Wall nos. 1-8 correspond to locations 1,2,3,4,5,6,7,8: G:RD3096, G:RD3097, G:RD3098, G:RD3099, G:RD3100, G:RD3101, G:RD3102, G:RD3103. Drawing adapted from CMTS Preliminary Shielding Assessment v.4 Anthony F Leveling 12/4/2014.

Before the cryomodules are shipped to SLAC they are thoroughly tested to ensure that they meet their performance criteria. While the cryomodules are being tested data is collected including the cavity voltages for each cavity, the radiation levels or field emission for each radiation detector, and dark current. The data from these cryomodule tests will be compiled and put in a data traveler that will be sent to SLAC along with the cryomodules.

Some of the goals of analyzing the cryomodule data include (for each cryomodule), assessing which of the eight cavities produce the most (if any) dark current, mapping out the field emission (X-ray radiation) and dark current as a function of accelerating voltage, finding the peak radiation for each cavity, and finding the onset of field emission for each cavity. The data for the travelers needs to be collected and analyzed efficiently, and displayed in a way that is meaningful and understandable. This is done using an ACL[5] script and a ROOT/C++[6] program.

The first step in the cryomodule field emission and dark current assessment is to collect the raw data using an ACL script that runs on Fermilab's Accelerator Control System (ACNET). The script takes a list of cryomodule devices (voltage cavities, radiation detectors, etc.) and a time range, and outputs the data taken for each device within the given time range. This raw data is then used as the input for the ROOT/C++ program. This program generates a root file containing, among other things, a plot of all the cryomodule device data plotted over time. Plot 1 is an example of this kind of plot.

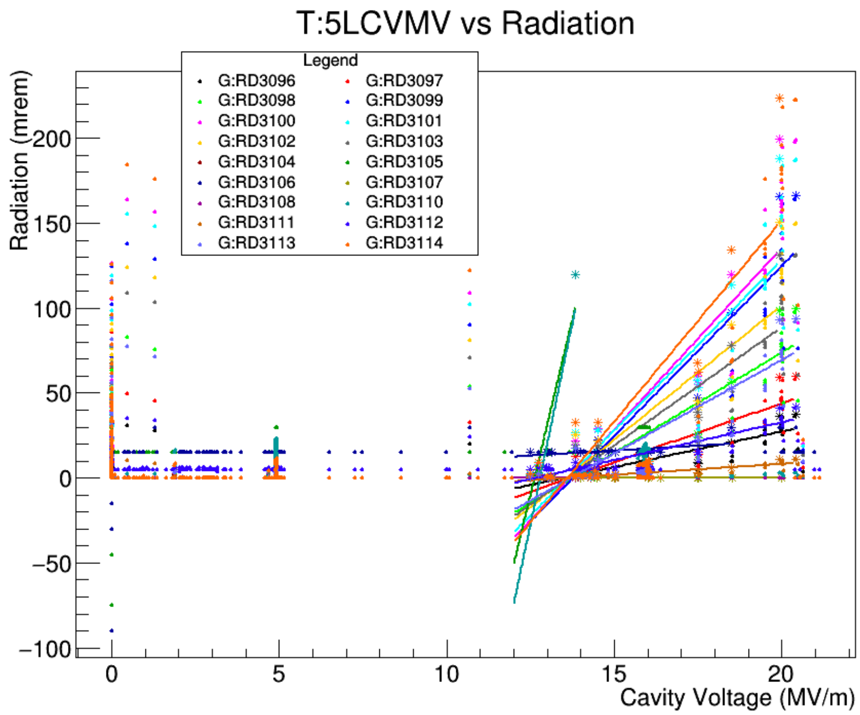


Plot 1: Data from various cryomodule devices plotted over time. The data from the voltage cavities has y-axis units of MV/m (except for the sum voltage, called T:LGSUMC in the legend, which has y-axis units of volts), and is plotted with dotted lines. The data from the radiation detectors has y-axis units of mrem, and is plotted with solid lines.

Plot 1 shows a drop in radiation levels around the timestamp of May 17, 14:45. This corresponds to a drop in cavity voltage for cavity 5 (formally named T:5LCVMV), represented by the dotted gray line. This indicates that a drop in voltage from even a single SRF cavity can cause a large change in radiation levels for many radiation detectors. This is why it is important that all the SRF cavities are working properly.

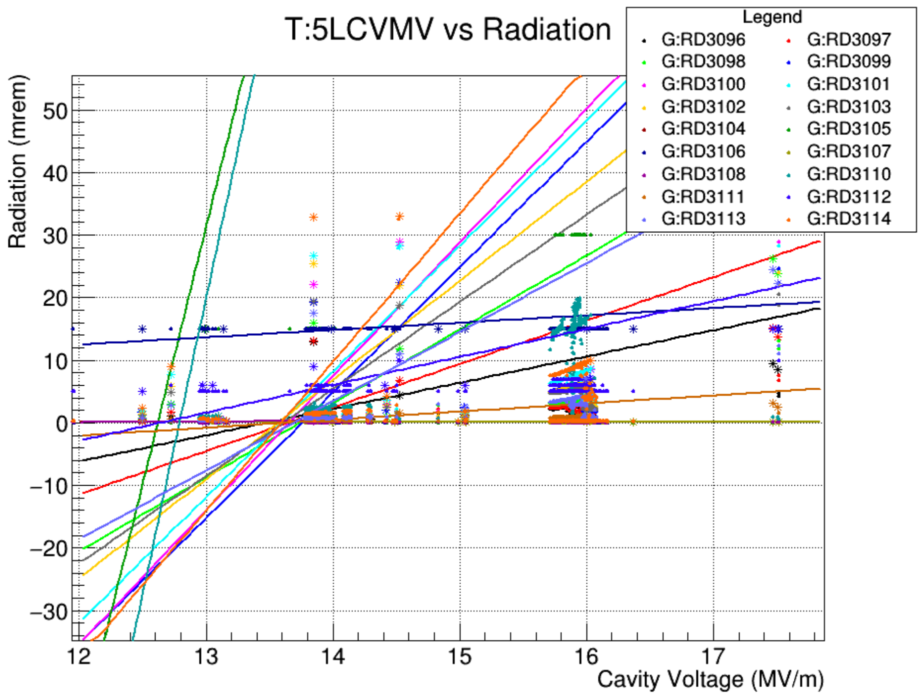
One of the challenges of making this kind of plot was making the time axis for all the data sets line up properly. A given data set could contain data from cryomodule devices that were sampled at different rates, such as 1 Hz or 1 minute. The starting times for each device also varied. To accommodate this, the cryomodule device with the latest starting time was identified, and any data from any other device that had an earlier timestamp than this latest starting time was ignored. The timestamps from each device were taken and converted to a number of seconds since the latest starting time. ROOT was able to take this information and automatically convert it to a time display on the x-axis.

The ROOT/C++ program also generates plots of field emission vs cavity voltage for each cavity. These plots allow us to estimate the cavity voltage at which detectable radiation starts to appear. An example is shown below in Plot 2. Plot 2 shows the radiation levels recorded by each radiation detector in the data set plotted over the cavity voltage for cavity 5 (T:5LCVMV). The lines in Plot 2 are linear fits taken from a subset of the data points. Each radiation detector data set is fitted independently. The range of the fit function starts at 12 MV/m for each detector. The end of the fit function range is at the location of the data point corresponding to the maximum radiation level that was recorded at a gradient of 12 MV/m or higher. In the plot the data points that are included in the fit are star-shaped.



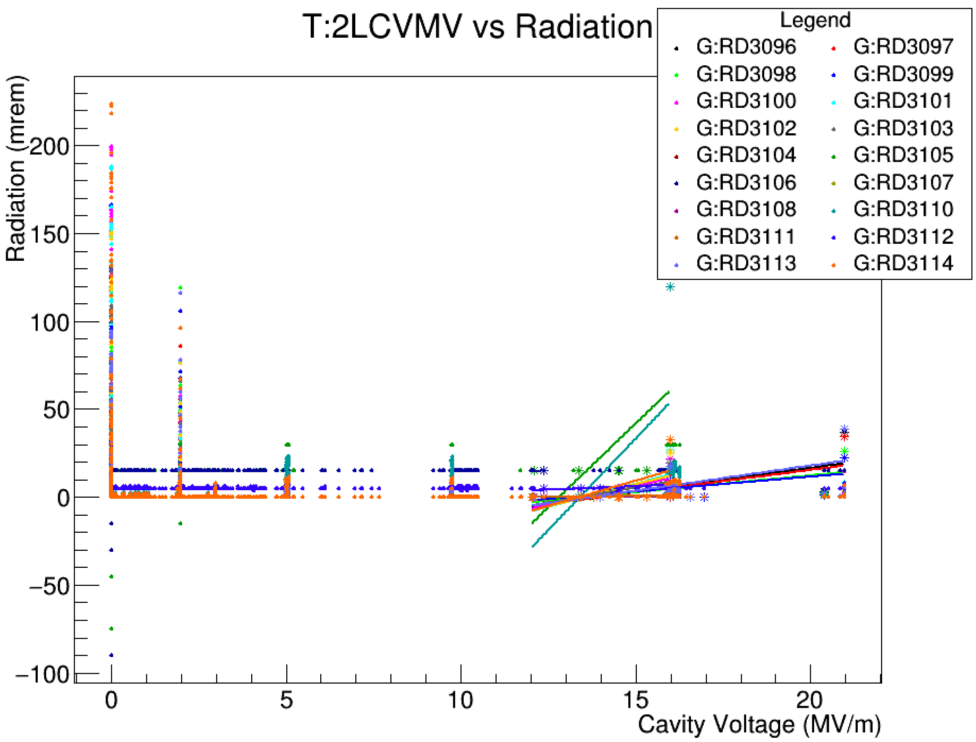
Plot 2: Field emission vs cavity voltage for cavity 5. Legend entry corresponds to a different radiation detector. The lines are linear fits of each radiation detector data set, which range from 12 MV/m to the cavity voltage corresponding to the maximum radiation level recorded at a gradient of 12 MV/m or higher.

Plot 3 is a zoomed in view of Plot 2. Plot 3 shows the range in which most of the fit lines intersect. This point of intersection is taken to be the onset of field emission. From looking at Plot 3 one can conclude that this onset occurs just before 14 MV/m for cavity 5.

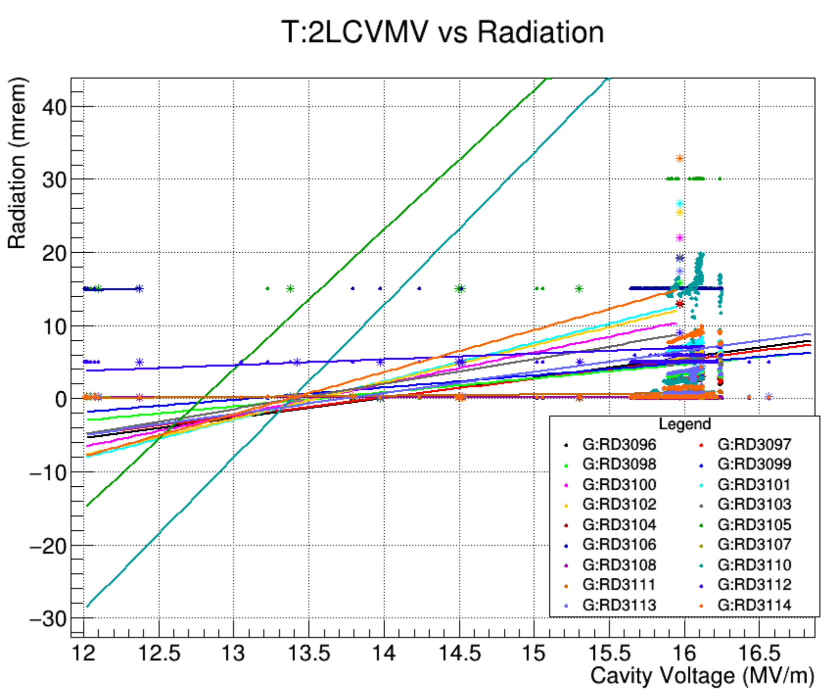


Plot 3: Field emission vs cavity voltage for cavity 5, zoomed in on the intersection points of the fit lines.

In the case of cavity 5, there was a large amount of field emission. However, some voltage cavities show little to no field emission. An example of one such cavity is cavity 2 (T:2LCVMV). Plots 4 and 5 are of the same format as plots 2 and 3, but show data for cavity 2 instead of cavity 5.



Plot 4: Field emission vs cavity voltage for cavity 2. Legend entry corresponds to a different radiation detector. The lines are linear fits of each radiation detector data set, which range from 12 MV/m to the cavity voltage corresponding to the maximum radiation level recorded at a gradient of 12 MV/m or higher.

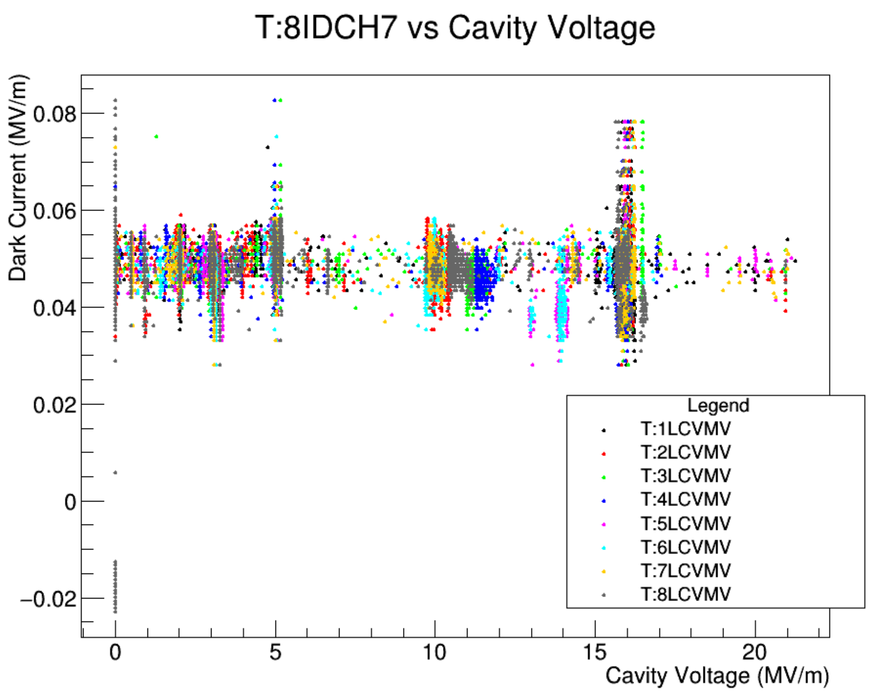


Plot 5: Field emission vs cavity voltage for cavity 2, zoomed in on the intersection points of the fit lines.

For cavity 2 there are no significant spikes in radiation levels aside from a few outliers. This is the preferred behavior for voltage cavities.

One of the challenges of making these fits was that the data points were not evenly distributed. Certain cavity voltages would have higher concentrations of data points, which would affect the fit function. To accommodate this, the data for the cavity voltage and radiation was sampled. Within each interval of 0.5 MV/m, the largest radiation value for each radiation detector was found, and plotted with a star-shaped data point. These data points were then used as the input for the fit function.

The ROOT/C++ program also produces plots of dark current vs cavity voltage. One such plot is shown below.



Plot 6: Dark current (T:8IDCH7) plotted as a function of cavity voltage for each cavity.

The ROOT/C++ file also generates data tables containing the maximum recorded values for each cryomodule device. This program can generate data tables containing the maximum radiation values for a list of voltage cavities and radiation detectors within a given cavity gradient range. Table 1 is an example of this kind of table for the gradient range of 15.5 to 16.5 MV/m.

Maximum Radiation values between 15.500000 and 16.500000 MV/m for each cavity

	T_1LCVMV	T_2LCVMV	T_3LCVMV	T_4LCVMV	T_5LCVMV	T_6LCVMV	T_7LCVMV	T_8LCVMV
G_RD3096	12.9	12.9	12.9	23.4	3.3	2.85	3	3
G_RD3097	13.05	13.05	13.05	33.75	5.25	3	3.15	3.15
G_RD3098	15.9	15.9	15.9	49.8	6.75	4.05	4.2	4.2
G_RD3099	19.2	19.2	19.2	51.3	7.95	6.75	6.9	6.9
G_RD3100	22.05	22.05	22.05	35.7	8.55	8.4	8.55	8.55
G_RD3101	26.7	26.7	26.7	26.7	8.7	8.4	8.7	8.7
G_RD3102	25.5	25.5	25.5	25.5	6.45	6.45	6.45	6.45
G_RD3103	19.35	19.35	19.35	19.35	5.85	5.85	5.85	5.85
G_RD3104	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
G_RD3105	120	120	120	120	30	30	30	30
G_RD3106	15	15	15	15	15	15	15	15
G_RD3107	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
G_RD3108	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
G_RD3110	119.58	119.58	119.58	119.58	19.86	19.86	19.86	19.86
G_RD3111	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
G_RD3112	9	9	9	11	7	7	7	7
G_RD3113	17.46	17.46	17.46	46.92	7.08	4.32	4.44	4.44
G_RD3114	32.88	32.88	32.88	32.88	9.96	9.72	9.96	9.96

Table 1: Along the top of the table is a list of SRF cavities. Along the side of the table is a list of radiation detectors. The numbers in the table are radiation levels in mrem. These are the highest recorded radiation levels for the corresponding voltage cavities and radiation detectors within the gradient range of 15.5 to 16.5 MV/m.

CONCLUSION

LCLS-II, an x-ray free electron laser, is under construction at SLAC. Fermilab is currently in the process of testing 1.3 GHz SRF cryomodules that will be used in LCLS-II. Some of the data from these cryomodules can now be analyzed mostly automatically using a ROOT/C++ program. This program generates plots of cryomodule-device data over time, radiation vs cavity voltage, and dark current. Data tables containing the maximum values for selected cryomodule devices can also be generated. This data will be used in the data travelers that will be sent to SLAC along with the cryomodules. A tutorial on how to use the ACL script and ROOT/C++ program is being provided to allow future analysis on the cryomodules.

ACKNOWLEDGEMENTS

This internship would not have been possible without funding from Lee Teng Undergraduate Fellowship in Accelerator Science and Technology and the Illinois Accelerator Institute. I would like to give a special thanks to my mentor Elvin Harms for his guidance and for answering my questions. I would also like to thank Brian Hendricks for helping me learn how to write and use ACL scripts, as well as Eric Prebys and Rosa Foote for organizing this internship.

REFERENCES

1) T. Arkan et al., “LCLS-II 1.3 GHz Design Integration for Assembly and Cryomodule Assembly Facility Readiness at Fermilab,” in Proc. 17th Int. Conf. on RF Superconductivity (SRF2015), Whistler, BC, Canada, Sep. 2015, paper TUPB110

2) T. Peterson et al., “LCLS-II 1.3 GHz Cryomodule Design – Modified TESLA-Style Cryomodule for CW Operation,” in Proc. 17th Int. Conf. on RF Superconductivity (SRF2015), Whistler, BC, Canada, Sep. 2015, paper THPB119
3) McGee, Mike, Saravan Kumar Chandrasekaran, Anthony Crawford, Elvin Harms, Jerry Leibfritz, and Genfa Wu. ‘Cryomodule Test Stand Reduce-Magnetic Support Design at Fermilab’. Edited by Christine Petit-Jean-Genaz, Dong Eon Kim, Kyung Sook Kim, In Soo Ko, and Volker RW Schaa. Proc. 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper WEPMR004, pp. 2262-2264. JACoW, Geneva, Switzerland, 2016.
4) E. Harms et al., “Fermilab Cryomodule Test Stand Design and Plans,” in Proc. 17th Int. Conf. on RF Superconductivity (SRF2015), Whistler, BC, Canada, Sep. 2015, paper TUPB013
5) Fermi Research Alliance, LLC. (1998-2017). ACNET.
6) Rene Brun and Fons Rademakers, ROOT - An Object Oriented Data Analysis Framework, Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, Nucl. Inst. & Meth. In Phys. Res. A 389 (1997) 81-86. See also root.cern.ch/.