12 GeV CEBAF INITIAL OPERATIONAL EXPERIENCE AND CHALLENGES*

M. Spata†, Jefferson Lab, Newport News, Virginia 23606, USA

Abstract

The 12 GeV Upgrade for the Continuous Electron Beam Accelerator Facility (CEBAF) achieved CD-4B, or Project Completion, on September 27, 2017. The 13-year $338M project doubled the beam energy of the CEBAF accelerator while also adding a fourth experimental hall. The scope of work for the accelerator complex was completed in 2014. Over the subsequent three years the upgrades for the experimental halls were completed, beamlines and spectrometers commissioned and transitions made to production running for the Nuclear Physics program. This paper will present an overview of the operational experience gained during initial accelerator commissioning through the recent achievements of simultaneous 4-Hall operations at full beam power.

COMMISSIONING EXPERIENCE

The 12 GeV Upgrade for the Continuous Electron Beam Accelerator Facility (CEBAF) was awarded CD-0 status in March of 2004 marking the start of a 13-year project to double the energy of the accelerator facility while upgrading existing halls and adding a fourth experimental hall. A schematic overview indicating the major scope of work for the upgraded facility is shown in Figure 1. Detailed descriptions of the project scope are contained in the references [1, 2].

Major milestones and dates of completion related to the execution of the project and subsequent achievements of reaching four hall operations and full power operations are outlined in Table 1.

Construction for the project officially started in September of 2008 after a 4-1/2 year Project Development Phase to gain approval of the conceptual (CD-1), preliminary (CD-2) and final designs (CD-3).

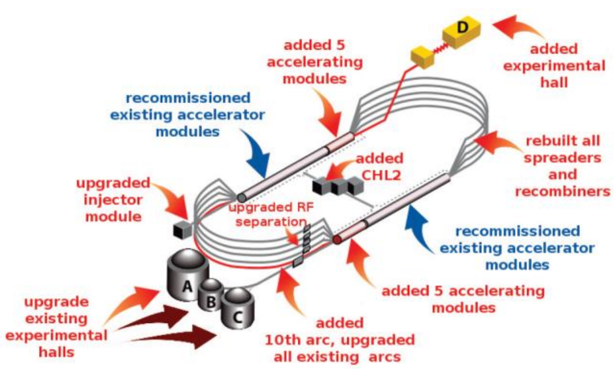

Figure 1: Schematic view of the upgraded CEBAF.

The 6 GeV Nuclear Physics program continued to run in parallel with construction until it was ceremoniously terminated on May 18, 2012 by Lab Director Hugh Montgomery, Associate Director Andrew Hutton, and the Director of Operations Arne Freyberger. Over 175 experiments were conducted and more than 400 doctoral degrees awarded during the combined 4 and 6 GeV eras.

Table 1: Major milestones for the 12 GeV Upgrade

Milestone	**Date**
CD-0 Mission Need	March 2004
CD-1 Alt. Selection and Cost Range	May 2004
CD-2 Approve Performance Baseline	Nov. 2007
CD-3 Start of Construction	Sep. 2008
End of 6 GeV CEBAF Operations	May 2012
Start of 12 GeV Commissioning	Dec. 2013
Accelerator KPP Achieved	May 2014
CD-4A Start of Initial Operations	July 2014
Hall D KPP Achieved	Dec. 2014
Hall B KPP Achieved	Feb. 2017
Hall C KPP Achieved	March 2017
CD-4B Full Ops-Project Complete	Sep. 2017
Four Hall Operations	Jan. 2018
Full Power Operations	April 2018

Fall 2013/Spring 2014 Run

The first two commissioning runs in the fall of 2013 and spring of 2014 were dedicated to achieving the three Key Performance Parameters (KPPs) for the accelerator. A KPP is defined as a key capability that must be met in order for a system to meet its operational goals for the project. The KPPs for the accelerator were to deliver greater than 2 nA at 2.2 GeV in one pass with better than 50% availability over an 8 hour run, greater than 6 GeV beam to Hall A in three passes and 5.5 pass beam to the entrance of Hall D at an energy greater than 10 GeV.

The final KPP for the accelerator complex was achieved on May 5, 2014 clearing the way for the project to be granted CD-4A or Start of Initial Operations in July. This was achieved 5 months ahead of schedule.

Fall 2014 Run

The main objective of the third run in the fall of 2014 was to deliver greater than 2 nA of beam at greater than 10 GeV to Hall D for detector commissioning and thereby completion of their KPP. Hall A and B were also ready to take beam at this time with the former having been commissioned during the previous run and the latter hosting a

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
† spata@jlab.org

heavy photon search (HPS) experiment that could run independently of the Hall B CLAS12 detector which was still under construction. During the run, the upgraded RF Separation system for passes 1-4 was commissioned to allow simultaneous delivery of CW beams to Halls A, B and D establishing the first multi-hall demonstration of CEBAF in the 12 GeV era. The Hall D KPP was officially demonstrated on November 11, 2014.

Spring 2015 Run

In the spring of 2015, the 249.5 MHz laser [3] and 750 MHz 5th pass RF Separator systems [4], which are necessary for achieving simultaneous four-hall beam delivery, were ready for commissioning. The refinement of beamline tuning procedures and machine vs. model convergence were also a focus for the spring 2015 run. An example result for the horizontal and vertical emittances achieved from beam envelope matching is shown in Figure 2. By this early point in the project, the optics performance for the upgraded facility had already exceeded the out-year specifications defined at the start of the project.

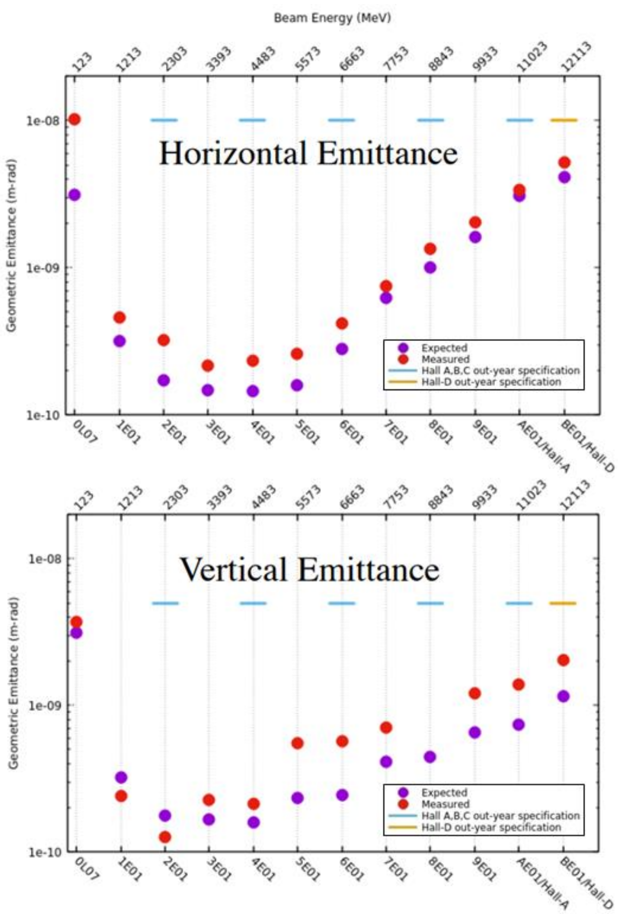

Figure 2: Horizontal and vertical emittances measured at the injector, each arc and at the entrance to Hall D.

The spring 2015 run period also included a 5-week long early physics program for Halls A, B and D. The program was underway and then interrupted by an offsite power outage. The Central Helium Liquefier (CHL) was impacted by the outage resulting in resolvable contamination issues for the North Linac system and a more significant cold compressor failure for the South Linac system. The contamination was cleaned up and both linacs brought to 2k on one CHL to enable a 1 GeV/pass low energy physics program while the failed cold compressor was replaced.

Summer 2015 Helium Processing Campaign

The next commissioning run would be the first attempt to operate the facility at the 12 GeV design energy with high availability. One of the limiting factors to accelerator availability at high energy is fast shutdown (FSD) trips of the RF cavities primarily caused by arc discharges on ceramic windows. The root cause for these trips is field emission from contaminating particles within the SRF cavities [5]. The trip rate can rise sharply with increased gradient as the energy of the field emitted electrons increases. In situ processing of large-scale SRF systems to minimize field emission was pioneered at Jefferson Lab [5]. An extensive campaign of helium processing was conducted in the summer of 2015 [6]. The distribution of the deltas for field emission onset gradients for the 314 cavities processed is shown in Figure 5. The average change was +0.93 MV/m/cavity. It should be noted however that helium processing could result in lower performance due to inadvertent creation of a new field emission site in the cavity. Several events occurred during processing of the new C100 cryomodules in the South Linac that led to a hold on processing these systems. In each case, a cavity quench event caused an increase in field emission resulting in a much lower achievable gradient.

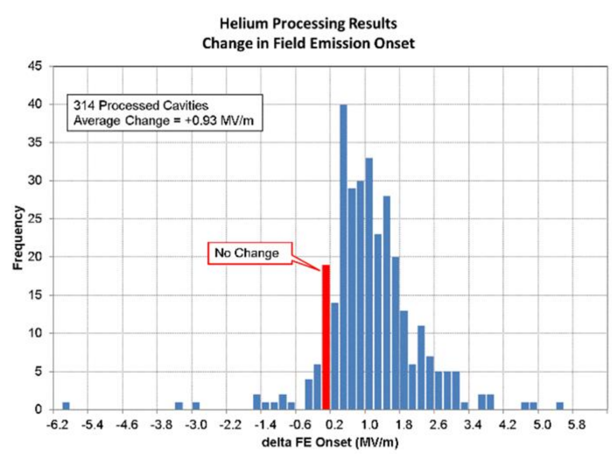

Figure 3: Helium processing results from 2015 campaign.

Fall 2015/Spring 2016 Run

Over the fall 2015 and spring 2016 runs, the accelerator was scheduled for a total of 16 weeks of operation for physics at the design energy. Other highlights from this period were the ongoing commissioning of the 750 MHz RF Separator system and first opportunity to extract beams with it online, completion of the GlueX engineering run in Hall D, additional run time for the HPS experiment in Hall B and significant run time for DVCS/GMp in Hall A.

During the early part of the spring 2016 run, RF performance [7], general system performance and beam tuning convergence proved challenging. Accelerator availability was ~50% for the first five weeks of the run. A technical stop to resolve CHL contamination issues gave us an opportunity to reevaluate the machine tune and work on systems. Upon recovery of the beam on April 7 and through the end of the run on April 25, we achieved the best performance to date with 94% system reliability. This improved performance was largely the result of applying first principles on the machine tune and exercising tighter configuration control on the settings in the system.

The performance of the 750 MHz RF Separator system was very challenging during its inaugural run period. A redesign of the physical cavity layout to maximize the distance to a down-beam septum and an optimization of the High Voltage and RF distribution systems was undertaken in the summer of 2016 to improve the operational overhead. Over that same summer, we also configured the accelerator to run at half energy on one CHL for the PRad experiment in Hall B and a checkout of the Hall C beamline, the last segment of the accelerator to be commissioned with beam.

As we gained run time on the facility, it became more and more evident that the performance of the C100 cryomodules while driven at top energy was not ideal [7]. The cryomodules can be sensitive to helium pressure variations caused by a mismatch between RF resistive heat and electrical heat in combination with the as-built capacity of the return riser to the CHL. The pressure transients induce microphonic vibrations that challenge the RF control system to remain locked. A redesign of the heater configuration to allow for individual control of the eight heaters in each cryomodule had been tested in two zones with good succ0ess. The modification will be installed on the other nine C100 cryomodules in the system. A more limiting issue is the field emission load on the warm girders from C100 operations at design energy. The decision was made to lower the CEBAF energy from 2.2 GeV/pass to 2.1 GeV/pass allowing for a reduced energy gain across C100 cryomodules while having a minimal impact to the ongoing physics program.

During the fall 2016 run, the RF performance was much improved with an acceptable trip rate and a reduction by a factor two on trips from C100 cryomodules. The redesigned 750 MHz Extraction system performed well until a vacuum leak prevented further operation. This run achieved greater than 80% availability for the month of December with a two-hall physics program at 700 kW total beam power. The maximum beam power for CEBAF is 1 MW with an operational limit of 900 kW.

Spring 2017 Run

The main objective of the spring 2017 run was to demonstrate the KPPs for Hall B and C with the verification of their detector performance. Hall B was completed on February 7 and Hall C on March 9. Running to Hall D for the GlueX, experiment was also part of the ~8 week run. The run was cut short by two weeks due to a broken electrical connection on a vacuum feedthrough in our original CHL system.

The 12 GeV upgrade achieved CD-4B or Project Complete on September 27, 2017 after the demonstration of the performance of the Hall B solenoid, the final component for the project.

Fall 2017 Run

The fall 2017 run was intended to be the first attempt at simultaneous four-hall beam delivery. Production running in Hall A, a CLAS12 engineering run in Hall B, detector commissioning and production running in Hall C and the ongoing GlueX program for Hall D were all part of the program. Excessive beam tuning to mitigate the effect of x-y coupling errors and manage loss issues as well as difficulty recommissioning the 750 MHz RF Separator system reduced the available beam time for physics during this run. The program reverted to three-hall operations after efficient four-hall performance could not be demonstrated.

Spring 2018 Run

The spring 2018 run was scheduled for 12 weeks of operations with production running in Hall A, an engineering run and first production running with the fully competed CLAS12 detector in Hall B, final commissioning runs and production physics runs for Hall C and the continuation of the GlueX experimental program in Hall D. The run was shaping up to be a very good opportunity to achieve simultaneous 4-hall operations with the added goal of reaching full power in the 12 GeV era. Most of the hardware difficulties with the 750 MHz RF Separator system were resolved over the winter break leading into this run. The system performed well with high availability for the spring 2018 run.

The milestone of simultaneous 4-hall operation for the upgraded facility was officially met on January 12, 2018. Plots of the beam current leaving the injector and entering each of the target systems in the four experimental halls is shown in Figure 4.

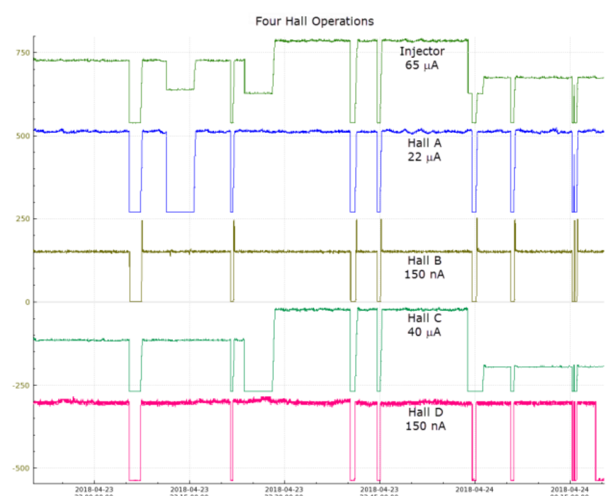

Figure 4: Beam current traces for Injector and four halls.

The energy and current requirements of the overall physics program for this run called for sustained operations of the accelerator at or near the maximum beam power of 900 kW. Full power beam delivery was first demonstrated on February 6, 2018. Initially the accelerator could only support brief bursts of high power beam before tripping on an RF or loss monitor fault. Over the course of the run, the RF systems were optimized under load to minimize or eliminate trips at high power. Perhaps more importantly the injector bunching system was optimized to suppress low intensity tails that were contributing to the beam loss monitor trips in the main accelerator. On April 23, 2018 the CEBAF accelerator achieved the milestone of providing stable 900 kW CW beam on target. Figure 5 shows the results with an 85 μA 5-pass beam to Hall C and then a combined run with 75 μA 5-pass to Hall C with 22 μA 2-pass to Hall A. This test demonstrated 900 kW beam delivery in single hall and then multi-hall mode.

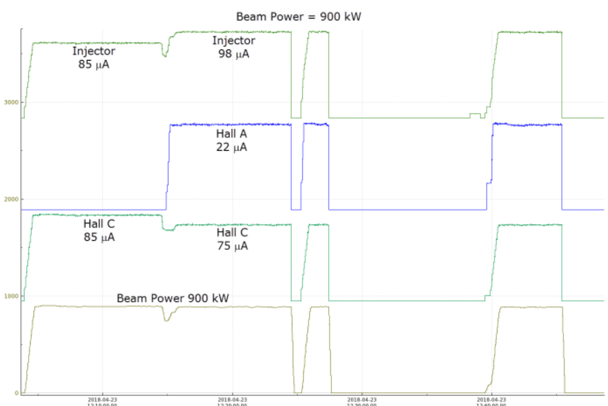

Figure 5: Beam Current for Injector, Hall A, Hall C and beam power signal from Beam Envelope Limit System.

Throughout the 5-year period of bringing the upgraded facility online, an integrated program of accelerator commissioning, experimental hall commissioning and sequential transitions to physics running has been the theme. Figure 6 gives a status of the CEBAF science program indicating that 12 GeV Physics is underway.

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	3	1	3	0	**7**
Transverse structure of the hadrons	5	4	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	6	0	0	**11**
3D structure of the hadrons	5	9	7	0	0	**21**
Hadrons and cold nuclear matter	7	3	7	0	1	**18**
Low-energy tests of the Standard Model	3	1	0	1	1	**6**
Total	**22**	**23**	**24**	**5**	**2**	**76**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**19.5**	**21.9**	**24**	**4.6**	**2**	**72.0**

Figure 6: Overview of CEBAF science program showing approved and completed experiments as of March 2018.

CHALLENGES

Despite the many successes of the 12 GeV commissioning program, hardware challenges have occurred over each run period with measureable impact to the physics program. A number of the failures can be attributed to infant mortality while others are clearly due to aging hardware. In addition to discrete system failures, there are also the following ongoing challenges:

- Establishing an energy reach of 12 GeV with sufficient overhead to absorb short-term loss of RF cavities taken offline for maintenance.
- Confronting obsolescence issues for the older systems in CEBAF that have been online for nearly 30 years.
- Minimizing downtime due to a lack of critical system spares.
- Transitioning into a program of sustained four hall operations for over 30 weeks/year.

CEBAF PERFORMANCE PLAN

The challenging performance of the CEBAF accelerator over the initial years of the 12 GeV era prompted the Director of Operations to convene a Reliability Team. The team's objective was to perform a gap analysis of each accelerator system from the perspective of evaluated historical performance relative to a set of reliability metrics for the facility. Table 2 captures the metrics, which define standard operations for the CEBAF accelerator.

Table 2: Reliability Metrics

Category	Goal	Unit/Metric
Reliability	> 80	%
Optimal Running Weeks	> 32	weeks/year
Beam Tuning Hours	< 8	hours/week
Beam Studies Hours	8	hours/week
Peak Hall Multiplicity	4	number of halls
Linac Design Energy	1090	MeV
Linac Energy Margin	> 100	MeV
Overall FSD Trip Rate	< 15	trips/hour
Overall FSD Down Time	< 5	minutes/hour
RF Trip Rate	< 10	trips/hour
Beam Loss Trip Rate	< 5	trips/hour

This study to evaluate CEBAF performance issues resulted in the development of a comprehensive 10-year plan to recover the 4% gap in design energy and to improve reliability. The CEBAF Performance Plan (CPP) is the roadmap to achieve these goals [8]. Figure 7 outlines the timeline for closing the gap. The plan is for the accelerator to remain at 1050 MeV/linac until 2021 and then to ramp to design energy by 2023. The plan calls for 80% reliability by 2021 and then a steady climb in the out-years towards ever-increasing accelerator performance.

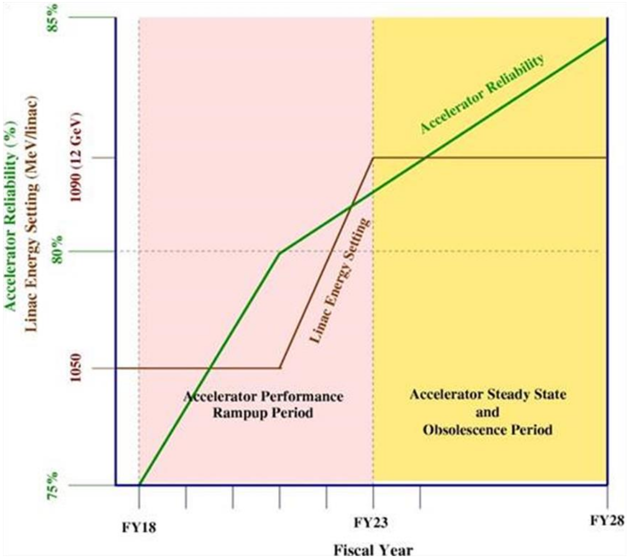

Figure 7: Timeline for ramping up CEBAF availability to 80% by 2021 and design energy by 2023.

The CPP focusses on three major topical areas:

1. Critical Spares
2. Energy reach
3. Obsolescence

Critical Spares

An evaluation of the potential for single point failures resulted in the development of a list of critical spares for systems. The list was ranked based on the likelihood of occurrence, expected downtime that would be incurred and overall cost/benefit. The highest priority items include ARC magnet power supplies, magnet coils, CHL compressor motors/bodies and klystrons. A multi-year spend plan is underway with a significant investment already made in FY18.

Energy Reach

A cryomodule refurbishment program to remove the lowest performing systems, reprocess cavities with improved procedures, replace consumables and reinstall was the approach used to increase CEBAF from 4 GeV to 6 GeV. The so-called C50 program [9] has upgraded 13 original C20 CEBAF cryomodules to date. A similar program has been adopted for the energy reach program, which will upgrade cryomodules to 75 MeV. The first cryomodule is under refurbishment and planned for installation in 2019. The program will continue over the subsequent years at a pace of one or two per year depending on funding and incremental gains on linac performance.

One of the C100 cryomodules will be removed this summer as a first candidate for refurbishment. The approach is to analyze the system from the perspective of mitigating field emission through applying advanced procedures developed as part of the LCLS-II project.

Finally, five cryomodules will be helium processed over the FY19 summer down period to gain energy margin in the system. Based on historical results this is expected to recover 10-15 MeV/pass.

Obsolescence

The 12 GeV upgrade was built on the foundation of the 4 GeV and 6 GeV CEBAF. A long-standing program of replacing or upgrading systems that have obsolete components has been in place for many years. The CPP takes a hard look at the remaining older systems and provides a prioritized plan of continued improvement.

CONCLUSIONS

The 12 GeV Upgrade project for the CEBAF accelerator has fully executed all scope of work and the facility has made the transition to 4-Hall operation at full power. The 12 GeV Nuclear Physics program is well underway. Over the course of commissioning, many challenges were encountered and successfully mitigated with the ultimate result of high availability. In order to maintain this level of performance a comprehensive plan has been developed to manage energy reach, provide critical system spares and to stay ahead of obsolescence issues to ensure high reliability and prepare the facility for the 12 GeV science program.

ACKNOWLEDGMENTS

I would like to thank Arne Freyberger, Matt Bickley, Randy Michaud, Steve Suhring, Ken Baggett and the Accelerator System Owners for their analysis of CEBAF performance and development of the CBEAF Performance Plan. I also would like to thank Tony Reilly, Charlie Reece, Bob Legg and Mike Drury for providing information related to SRF cryomodule performance and the plans going forward to improve the performance.

REFERENCES

[1] L. Harwood, “The JLAB 12 GeV Energy Upgrade of CEBAF”, Proceedings of NAPAC’13, Pasadena, CA.

[2] Arne Freyberger, “Commissioning and Operation of 12 GeV CEBAF”, Proceedings of IPAC’15, Richmond VA.

[3] R. Kazimi et al., “Four Beam Generation for Simultaneous Four-Hall Operation at CEBAF’, Proceedings of IPAC’16, Busan, Korea.

[4] R. Kazimi, “Simultaneous Four-Hall Operation for 12 GeV CEBAF”, Proceedings of IPAC’13, Shanghai, China.

[5] C. Reece et al., “Improvement of the Operational Performance of SRF Cavities via *In Situ* Helium Processing and Waveguide Vacuum Processing”, Proceedings of PAC’97, Vancouver, B.C., Canada.

[6] M. Drury et al., “Results of the 2015 Helium Processing of CEBAF Cryomodules”, Proceedings of NAPAC’16, Pasadena, CA.

[7] C. Hovater et al., “Operation of the CEBAF 100 MV Cryomodules”, Proceedings of LINAC16, East Lansing MI.

[8] Arne Freyberger et al., “CEBAF Performance Plan”, JLAB Internal Tech Note, JLAB-TN-17-022.

[9] M. Drury et al., “Summary Report for the C50 Cryomodule Project”, Proc. of PAC2011.