EARLY COMMISSIONING EXPERIENCE AND FUTURE PLANS FOR THE 12 GeV CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY*

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Abstract

Jefferson Lab has recently completed the accelerator portion of the 12 GeV Upgrade for the Continuous Electron Beam Accelerator Facility. All 52 SRF cryomodules have been commissioned and operated with beam. The initial beam transport goals of demonstrating 2.2 GeV per pass, greater than 6 GeV in 3 passes to an existing experimental facility and greater than 10 GeV in 5-1/2 passes have all been accomplished. These results along with future plans to commission the remaining beamlines and to increase the performance of the accelerator to achieve reliable, robust and efficient operations at 12 GeV are presented.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) was initially constructed as a 5-pass 4 GeV CW machine consisting of two 1497 MHz SRF linacs connected by nine 180 degree recirculation arcs (Fig. 1). The accelerator in that configuration had the capability to provide interleaved 499 MHz beams to three experimental halls (A, B, C) with independent control of the beam intensity, energy and polarization. The North (NL) and South (SL) linacs each consisted of 20 SRF cryomodules containing eight 5-cell cavities with an average operating gradient of 5 MV/m to achieve a design energy gain per linac of 400 MeV. These so-called C20 cryomodules provided a nominal 20 MeV/cryomodule energy gain.

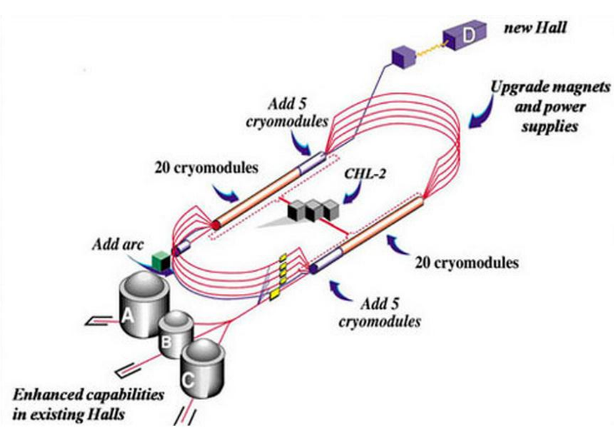

Figure 1: Schematic representation of the CEBAF accelerator showing the original configuration along with the major components of the upgrade.

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The original CEBAF Injector used 2-1/4 cryomodules to provide 45 MeV beam for injection into the NL. The beam was then extracted after one through five transits around the accelerator using transverse deflecting 499 MHz normal conducting RF Separator cavities [1] to selectively and simultaneously direct beams to the three experimental user facilities designated Halls A, B and C.

A cryomodule refurbishment program [2] was started in 2006 and completed in 2009 with the goal of increasing the top energy of the linacs from 400 MeV to 600 MeV. Ten of the 40 original CEBAF cryomodules with the lowest overall energy reach were sequentially removed from the accelerator to be reworked at Jefferson Lab's SRF Institute. The cryomodules were disassembled and the cavities cleaned using advanced processing techniques to eliminate field emission. The original fundamental power couplers and ceramic window designs were also modified to improve performance. The goal was to increase the average operational cavity gradient from the initial 5 MV/m to 12.5 MV/m or 50 MeV/cryomodule energy gain. The so-called C50 program was successful in enabling the facility to routinely operate at 5-pass energies approaching 6 GeV in support of the nuclear physics program.

The CEBAF 12 GeV Upgrade [3,4] is a major project funded by the Department of Energy's Office of Nuclear Physics. The project scope doubles the energy of the CEBAF accelerator by adding 5 high-performance cryomodules and their associated RF power systems in each linac, expanding the capacity of the 2k Central Helium Liquefier (CHL) to manage the additional heat load, upgrading the magnets and power supplies for the existing nine recirculation arcs, adding a 10^{th} recirculation arc and power supply to transport the beam a 6^{th} time in the NL to a new beamline and fourth experimental Hall D. Upgrades to the Extraction System, Beamline Instrumentation, Safety Systems and High Level Applications were also part of the accelerator scope for the 12 GeV Upgrade.

CRYOMODULE COMMISSIONING

The ten new C100 cryomodules, as well as the existing C20 and C50 cryomodules, were all commissioned between May 2013 and November 2013. The maximum accelerating voltage, cavity Q_0's and a field emission survey were recorded for each of the cavities in the system. The design specifications [5] for the C100 cryomodules are shown in Table 1. The slot length includes the warm girder assemblies between cryomodules and represents the center-to-center distance between the quadrupole magnets that make up the linac lattice. To meet the 12 GeV energy performance criteria each of the new cryomodules must make 98 MeV. The

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energy specification of 108 MeV provides a performance margin above the requirement. This specification was exceeded for all but one cryomodule. The 2K primary circuit and 50K shield circuit heat load specifications include both the static and dynamic loads on the CHL.

The HOM damping specification [6] is a critical design criterion to meet for recirculating linacs in order to minimize the chance of multi-pass beam break-up or BBU. A beam-based experiment [7] was conducted in November 2011 with the first two C100 cryomodules installed in the machine. The test evaluated the performance of the system and the BBU threshold due to the C100 cavity higher order modes. The test confirmed that the cryomodule design is robust from this perspective.

The average maximum gradient and average Q_0 values at that gradient are shown in Table 2. Using the active cavity length of 0.5 meters for the 5-cell C20 and C50 cavities and 0.7 m for the 7-cell C100 cavities, the expected energy gain for the North (South) linacs is 1335 (1325) MeV respectively. Well above the 1100 MeV/linac requirement for 12 GeV operations.

Table 1: C100 Design Specifications

Parameter	Design Specification	Units
Slot Length	9.8	Meters
Voltage/Cryomodule	108	MeV
2K Heat Load	<300	Watts
50K Heat Load	<300	Watts
HOM Damping (Transverse)	$<2.4\times10^{10}$	Ohms/meter
HOM Damping (Longitudinal)	$<6.5\times10^{11}$	Ohms
Cavity Gradient	19.2	MV/m
Q_0 @ 19.2 MV/m	7.2×10^{9}	N/A

Table 2: Average maximum cavity gradients and average Q_0 at that gradient for each cryomodule type.

Linac	Type	Ncav	<Gmax> (MV/m)	<Q_0@Gmax >
NL	C20	120	8.61	3.91×10^{9}
NL	C50	40	11.72	3.74×10^{9}
NL	C100	40	20.86	8.11×10^{9}
SL	C20	110	9.09	4.33×10^{9}
SL	C50	47	11.55	3.81×10^{9}
SL	C100	40	19.77	7.44×10^{9}

BEAM COMMISSIONING

Organizational Structure

A guiding document called the Accelerator Operations Directives (AOD) establishes standard protocols for operating the CEBAF accelerator and has been in use for nearly 20 years. However it was recognized that commissioning the upgraded accelerator would require a supplemental document that would add commissioning-specific roles, responsibilities and protocols to the existing AOD. The AOD Supplement for 12 GeV Commissioning was developed to capture these concepts and guide us through the commissioning process.

The key elements of the organizational structure established to commission the upgraded facility are the:

- Commissioning Advisory Board – a team of senior upper-level managers that periodically review the commissioning plan and its progress and provide feedback to the Commissioning Planning Team.
- Commissioning Planning Team – responsible for developing, coordinating and ensuring that the commissioning plan is effectively executed.
- Beam Transport Team – a team of Scientists, Engineers and Operations staff responsible for ensuring that the accelerator efficiently and consistently meets the near-term and long-term beam specifications.
- Geographic Integrators – serve as owners of specific geographic regions of the accelerator and experimental halls with the responsibility to ensure that each segment is ready for beam operations.
- Lead Accelerator Scientist on Shift – charged with standing shifts in the control room with the Operations staff to train them and guide them through the commissioning process.

Beam Commissioning Plan

A comprehensive and flexible beam commissioning plan was developed to capture the required steps for restarting CEBAF after the upgrade.

The plan draws on the experience of commissioning the original CEBAF accelerator and the knowledge gained from the many years of successful operations. Careful consideration had been given to carrying forward the diagnostics tools (software and hardware) and procedures developed over the years of increasingly more robust CEBAF operations.

Each document section contains steps to fully commission a specific region of the accelerator. Individual sections are further broken down into the following subsections:

- The process for initially threading beam through the region.
- Steps to commission the beam diagnostics for that region and to perform any beam-based calibrations and measurements in support of commissioning.
- A section for High Level Applications development and the finalization of the beam setup for the region.

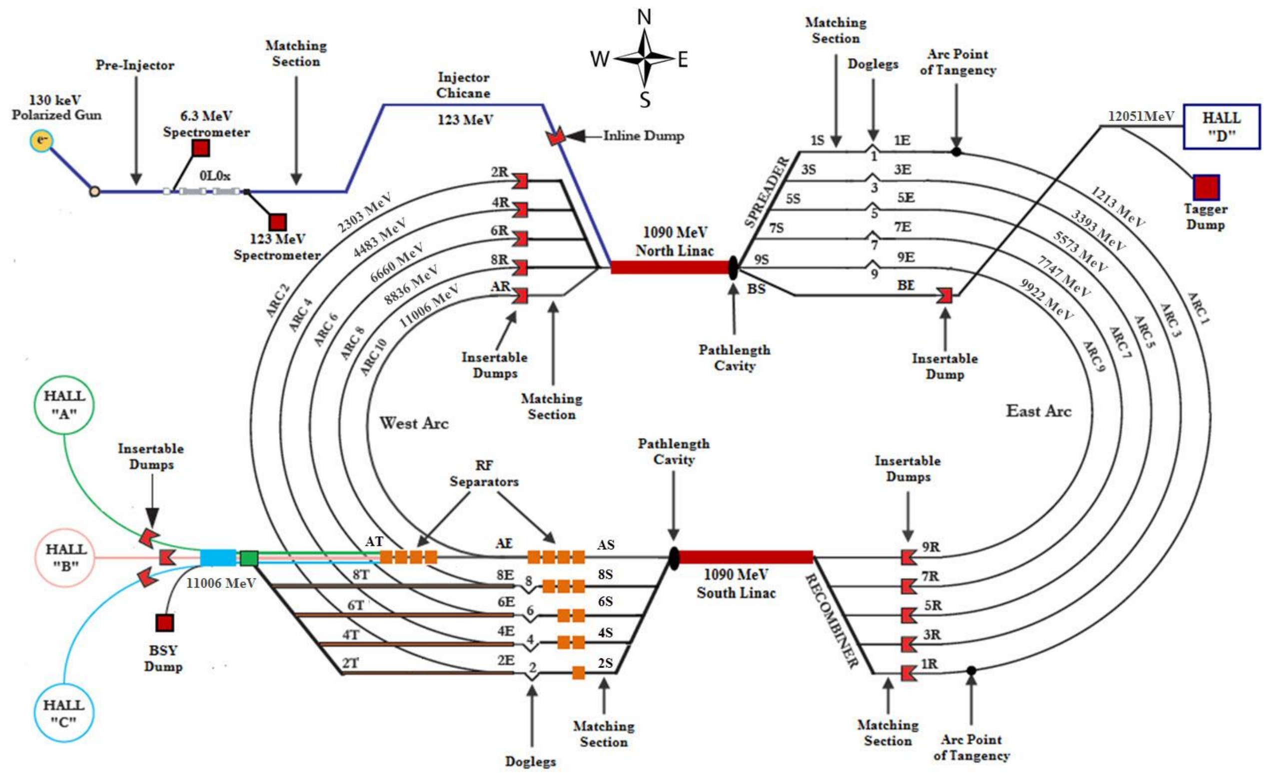

Figure 2: Schematic representation of the CEBAF accelerator with nominal energies shown for a 12 GeV configuration.

Beam Commissioning

Beam commissioning for this initial run period started in December 2013 and continued into May 2014. A timeline of significant events is shown in Table 3.

The first beam delivery goal was to demonstrate full energy capability of the two linacs by sending 2.2 GeV beam to the 2R insertable dump (See Fig. 2). The Injector, NL and SL energies for this run are shown in Table 4. The second Injector cryomodule (R100) was not yet ready for commissioning which temporarily limited the peak energy of the Injector below the nominal 123 MeV.

Table 3: A timeline of significant achievements for the run period between November 2013 and May 2014.

Date	Achievement
12/9/13	North and South Linac 2K operations established for the first time with 2 CHL plants connected to CEBAF.
12/13/13	Start of 12 GeV CEBAF commissioning.
2/5/14	Beam transported to the 2R beam dump at 2.2 GeV with greater than 50% availability.
3/10/14	Injector achieves 12 GeV design energy goal of 123 MeV.
3/20/14	3-pass beam transported to Hall A.
4/1/14	3-pass CW beam to Hall A and first interactions with a target are recorded.
5/7/14	Transported 10.5 GeV 5.5 pass beam to Hall D Tagger dump.

Table 4: Sum of the energy gain in each linac and the Arc momentum during the February 2014 2.2 GeV/pass run.

Linac	Egain (MeV)	$\sum$ E (MeV)	Arc Momentum (MeV/c)
Inj	33.58	33.58	33.41
NL	1116.15	1149.73	1124.03
SL	1083.44	2233.17	2214.51

The beam was initially setup to the Inline Dump at the end of the Injector chicane and then threaded through the NL into the East Spreader. A viewer in the dispersive 1S Spreader beamline was used to phase the NL SRF cavities relative to the beam. The beam was then transported around Arc 1 and down the East Recombiner for transport across the SL and up the West Spreader to the 2S section.

Cavity phases relative to the beam for the South Linac were set using a beam viewer at the top of the ramp. The beam was then finally threaded around Arc 2 to the 2R Insertable Dump to achieve the 2.2 GeV goal. The average cavity gradient and energy distribution across C20, C50 and C100 cryomodules for the Injector, NL and SL is shown in Table 5.

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Table 5: The RF gradient and energy distribution during the 2.2 GeV/pass run in February 2012.

Linac	Cavity Type	Ncav	<GMES> (MV/m)	Egain (MeV)
Inj	C20	10	6.72	33.6
NL	C20	119	7.19	427.6
NL	C50	40	11.03	220.7
NL	C100	38	17.59	467.9
SL	C20	108	7.05	380.7
SL	C50	47	10.06	236.4
SL	C100	40	16.66	466.4

The next commissioning milestone was to deliver 3-pass beam to experimental Hall A. For this run the Injector was set to 115 MeV and the two linacs at 1000 MeV each providing a total energy gain of greater than 6 GeV in three passes which set a new energy record for CEBAF beam delivery.

The tuning procedure up to the 2R Insertable Dump at the end of Arc 2 is essentially the same as for the 2.2 GeV run.

To control the arrival time of the beam upon reinjection into the linacs for subsequent passes the Dogleg chicanes at the entrance of each Arc (see Fig. 2) were historically used to increase or decrease the distance the beam travels thereby affecting the arrival time and phase relative to the beam in the next linac. The Dogleg chicanes were not part of the 12 GeV Upgrade; this limits their capacity to change the pathlength in the 12 GeV era. We planned to use frequency shifts of the Master Oscillator (MO) that feeds the SRF linacs as the primary means of uniformly controlling the pathlength across all passes. The Dogleg magnets would then be used for fine control pass-to-pass. The first multi-pass beam was seen on March 15. The accelerator was found to be short by ~ 2 cm as measured by the pathlength cavity at the end of the NL. This is equivalent to a 40° phase error at the 1497 MHz linac frequency. A 7.39 kHz adjustment of the 499 MHz MO was required to account for the pathlength error.

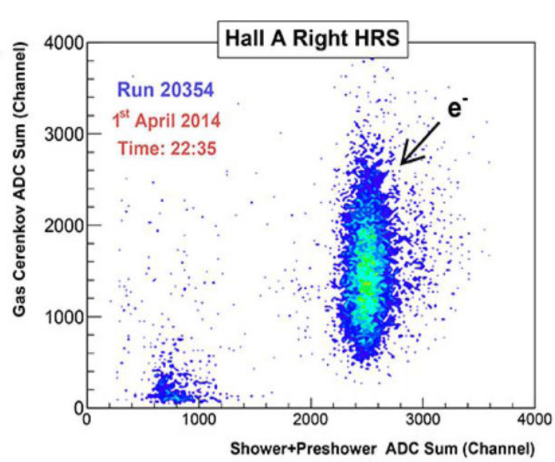

Figure 3: First CW electrons detected in the Hall A High Resolution Spectrometer.

The beam was then systematically threaded around the accelerator three times to the 6R Insertable Dump followed by magnetic extraction into the 6T beamline and ultimately to Hall A to achieve the 3-pass milestone on March 20. The goal for first CW beam to an experimental hall in the 12 GeV era was reached on April 1. Data from the scattered electrons that were detected in the Hall A High Resolution Spectrometer is shown in Figure 3.

The final commissioning milestone was reached on May 7 after the beam was successfully transported 5.5 passes to the Hall D Tagger dump at 10.5 GeV. This significant achievement brought beam for the first time into the new ARC 10, into the NL for a 6th pass and through the new beamline to Hall D. For this run the Injector was set to 107 MeV and the two linacs at 950.4 MeV each. Figures 4 shows the response from a 499 MHz cavity designed to detect a 4 µs macropulse as it traverses the linac. The transit time around the ring is 4.2 µs resulting in the six distinct yellow traces. Figure 5 shows beam on a viewer at the entrance to Hall D.

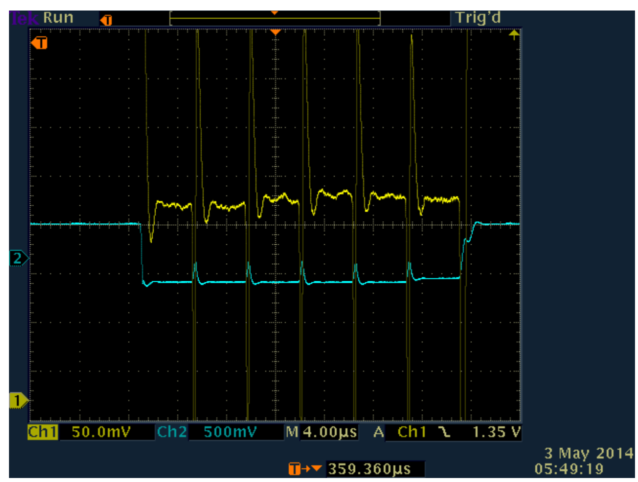

Figure 4: Oscilloscope trace showing 6 beams for the first time in the NL as measured by a linac M_{56} cavity.

Figure 5: First 5.5 pass beam at start of Hall D Beamline.

FUTURE PLANS

Fall 2014 Run

A 13 week run is planned for this fall. The top energy will be limited to 11 GeV to Hall D. The major goals for the run are:

- Beam restoration to the Hall D Tagger vault.
- CW beam to Hall D Tagger for detector checkout and first photons to the Hall D detector.
- Commission the 499 MHz RF Separators and extraction beamlines for 2T, 4T, 6T, 8T and AT beamlines.
- Characterize upper pass magnetic elements to establish efficient out-year operations.
- Study synchrotron radiation induced emittance growth in the upper passes.
- Parasitic support of an early Physics run in Hall A and beamline commissioning in Hall B.

Winter 2015 Shutdown

- An upgrade to the Dogleg system will be completed to provide additional capacity to adjust the machine pathlength.
- Install the 5th pass 750 MHz RF Separator system.
- Install the 250 MHz drive lasers for the polarized source.

These last two bullets will allow for simultaneous operation of Hall A and Hall D at the highest pass and for simultaneous 4-Hall operations [8] in the future.

Spring 2015 Run

A 7 week run is planned with the goals to:

- Commission the 750 MHz RF Separators
- Commission the 250 MHz Drive Laser system.
- Deliver beam for Physics contingent on funding.

Summer 2015 Shutdown

Major installation work is planned for this shutdown that will enable us to make the push to 12 GeV for the first time. The highlights for the shutdown are:

- Installation of a C50 cryomodule.
- Installation of the tunnel air conditioning.
- Completion of a lab wide upgrade of the power distribution, cooling towers and network.
- Helium processing of SRF cryomodules to reduce field emission and increase the energy reach of the linacs.

Fall 2015 Run

A 7 week run is planned with the goals to:

- Demonstrate 12 GeV capability for the first time.
- Finalize optics setup, energy scaling and procedures.

Spring 2016 Run

A 13 week run is planned with the goals to:

- Establish beam to Halls B and C in preparation for detector checkout.
- Deliver beam in support of Hall B and C detector checkout.
- Support Engineering run in Hall D and Physics in Hall A.
- Deliver beam for Physics contingent on funding.

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CONCLUSION

Significant progress has been made during this initial commissioning run for the 12 GeV CEBAF. The majority of the accelerator facility has been commissioned with beam. Plans are in place to commission the remaining beamlines, to systematically increase our understanding of the beam physics and improve our efficiency in setting up the machine, to reduce the trip rate of the SRF cavities for increased availability and to effectively transition to reliable and efficient beam operations for the 12 GeV Physics community.

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