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COMMISSIONING AND OPERATION OF 12GeV CEBAF *

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) located at the Thomas Jefferson National Accelerator Laboratory (JLAB) has been recently upgraded to deliver continuous electron beams to the experimental users at a maximum energy of 12 GeV, three times the original design energy of 4 GeV. This paper will present an overview of the upgrade, referred to as the *12GeV upgrade*, and highlights from recent beam commissioning results.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility, CEBAF, designed for 4 GeV continuous electron beams for nuclear physics, was the first large scale implementation of SRF technology. The CEBAF design included 42 cryomodules with each cryomodule containing 8 SRF cavities to achieve the design energy of 4 GeV. CEBAF reached design energy in 1995. The cryomodules were evenly divided among two linacs, North and South, connected by magnetic spreaders, arcs and recombiner sections. The energy reach of 6 GeV of CEBAF was establish in 2000; CEBAF operated at energies up to 6 GeV until 2012.

The beam parameters for 6 GeV configuration can be found in Table 1. CEBAF supported simultaneous beam delivery to three experimental end-stations; each end-station receiving beams with energy a multiple of the one-pass energy, beam currents from sub 1nA to 190 μA and beam polarization greater than 85%. During 6GeV operations 178 experiments were performed by the experimental users.

THE 12GeV UPGRADE

An experimental case to upgrade CEBAF to 12 GeV was made at the start of the 21st century. *Mission need* was granted in 2004 by the Department of Energy for Jefferson to develop a design for a 12 GeV capable CEBAF. This design was completed and construction started in 2009, construction overlapped with 6 GeV beam operations for work that did not impact CEBAF operations. Construction that did impact CEBAF was interleaved with 6 GeV operations, notably the arc magnet upgrade during the 2011 shutdown. 6 GeV beam operations terminated in 2012, and the accelerator tunnel portion of the upgrade was sufficiently complete by the end of 2013 to start of beam commissioning activities.

The 12GeV upgrade design retained the same footprint as the original 4GeV CEBAF allowing for the new accelerator to use the existing tunnel with the addition of the new extraction line transporting beam to the new end-station, Hall-D. In order to achieve the 12 GeV energy requirement, the design called for:

- A new Arc10 that would enable an additional pass of energy gain in the North linac, 11 linac traverses versus 10 traverses for 6 GeV CEBAF.
- Additional cryomodules in each linac contributing 500MeV of energy gain, increasing the total energy gain to 1100 MeV/linac from 600 MeV/linac.

The beam parameters from for the 12GeV design can be found in Table 1. The main difference with the 6GeV beam parameters, aside from beam energy, is the increase in beam emittance and energy spread due to the copious synchrotron radiation effects in the high energy arcs.

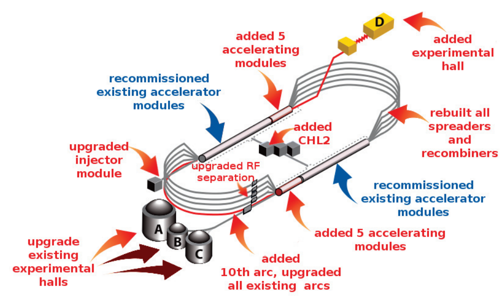

Figure 1: High level overview of the 12GeV upgrade

The scope of the accelerator upgrade is graphically presented in Figure 1.

Injector

The doubling of the CEBAF race-track energy requires that the injector energy be increased in order to maintain the same ratio of injection to one-pass energy. This energy increase was accomplished by replacing an original CEBAF cryomodule, denoted as C20, with a new cryomodule that provides 108 MeV in energy gain, denoted as C100. In addition the laser drive has been modified to allow for subharmonics of 499MHz in order to support the new 5-pass separation system. Details on the injector modifications and results of beam commissioning can be found in [1].

Linac

The ten cryomodules, C100s, that provide in total 1000 MeV per pass of additional energy gain were installed in five empty zones that existed at the end of each linac. The existing 20 cryomodules per linac from 6GeV CEBAF are an integral part of the new 12GeV CEBAF; 1200 MeV of energy is required from these modules to achieve the design energy of 12 GeV. During the upgrade, the linacs were warmed to 300 K to allow for the required cryogenic upgrades. Once the cryomodules were returned to the 2 K operating temperature

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Table 1: Delivered Beam Parameters for 6 GeV CEBAF and Expected Beam Parameters for 12 GeV CEBAF

Parameter	6 GeV	12 GeV
Max. Energy ABC	6 GeV	11 GeV
Max. Energy D	NA	12 GeV
Duty Factor	CW	CW
Max. Beam Power	1 MW	1 MW
Bunch Charge (Min-Max)	0.004 fC – 1.3 pC	0.004 fC – 1.3 pC
Hall Repetition Rate (Min-Max)	31.2 – 499 MHz	31.2 – 499 MHz
Nominal Hall Repetition Rate	499 MHz	249.5/499 MHz
Number of Exp. Halls	3	4
Max. Number of Passes	5	5.5
Emittance (geometric) at full energy	0.1 nm-rad(X)/0.1 nm-rad(Y)	3 nm-rad(X)/1 nm-rad(Y)
Energy Spread at full energy	0.002%	0.018%
Polarization	35%(initial), 85%(final)	>85%

each cavity, old and new, was characterized to provide a comprehensive baseline at the start of the 12GeV CEBAF era. This characterization included determining the cavity maximum operating gradient, cavity quality factor, Q_0, and the on-set of field emission.

The cryomodule average for the maximum cavity gradient and Q_0 are shown in Figures 2 and 3 for the injector, North and South linacs. Cryomodules zones in red denote original CEBAF C20 cryomodules that have been operating for over 20 years. Cryomodules zones in blue, C50s, represent original modules that have been refurbished during the 6GeV era with modern processing technique and internal modifications for reduction in the cavity trip rate. The new C100 modules are displayed in green. The new C100 achieve almost four times the energy gain and a factor two in Q_0 over the original CEBAF C20 cryomodules. More information on SRF performance during the beam commissioning can be found in [2].

Cryogenics

The cryogenic plant capacity had to be increased to accommodate the additional C100 cryomodules. This increase was accomplished by construction of a new helium liquifier, CHL2, with similar capacity as the existing helium liquifier, CHL1. Advances in controls and thermal cycles result in the new CHL2 requiring only 3.8 MW of power for the same liquification capacity as CHL1 (5.5 MW). In order to lower the liquid helium temperature to 2 K, each CHL-linac system includes a series of cold compressors to lower the Helium pressure. The cold compressors are within a vacuum space denoted as the SC1 and SC2 cold-boxes. SC1 is the original CEBAF cold-box which was decommissioned in 2000, rebuilt and placed back in service in 2013. SC2 is the cold-box that was in operation for most of the 6GeV era.

In addition to the new CHL and re-configuring of the cryogenic systems the transfer lines were refurbished and re-configured so that one CHL-SC combination was attached to one linac. This resulted in a halving of the liquid Helium volume while maintaining roughly the same load for each CHL-SC system. This change and the new equipment meant that each system had to be completely commissioned and new pump-down procedures had to be established before beam commissioning activities could start. The cryogenic systems completed their initial commissioning activities and established stable 2 K operations by mid-Dec 2013.

Magnets

Table 2: Tabulation of the Magnet and Power Supply Upgrades

Count	Description
32	New 4 m dipole magnets, Arc-10
256	Large dipole refurbishments (add steel and/or new coil packs)
110	Large (>1 m) dipole magnets removed and measured
130	New quadrupole magnets
120	New corrector magnets
17	New high power supplies (>50 kW)
$O(200)$	< 20 A power supplies for trim and quadrupole magnets

The scope of the magnet upgrade included:

- New dipole and quadrupole magnets for the new tenth arc, Hall-D transport lines and isolated locations were existing magnets could not meet the field specification.
- Refurbishment of existing magnets by adding return steel and/or new coil packs for the increase field needed to support the new energy.
- Existing magnets that were not to be refurbished, were removed from the tunnel for field measurements over the new operating range (50-100% of design energy).
- New power supplies and cable pulls required to support the 12GeV magnet requirements.

Table 2 enumerates the magnet upgrade scope. Field quality specifications were developed for each magnet based on

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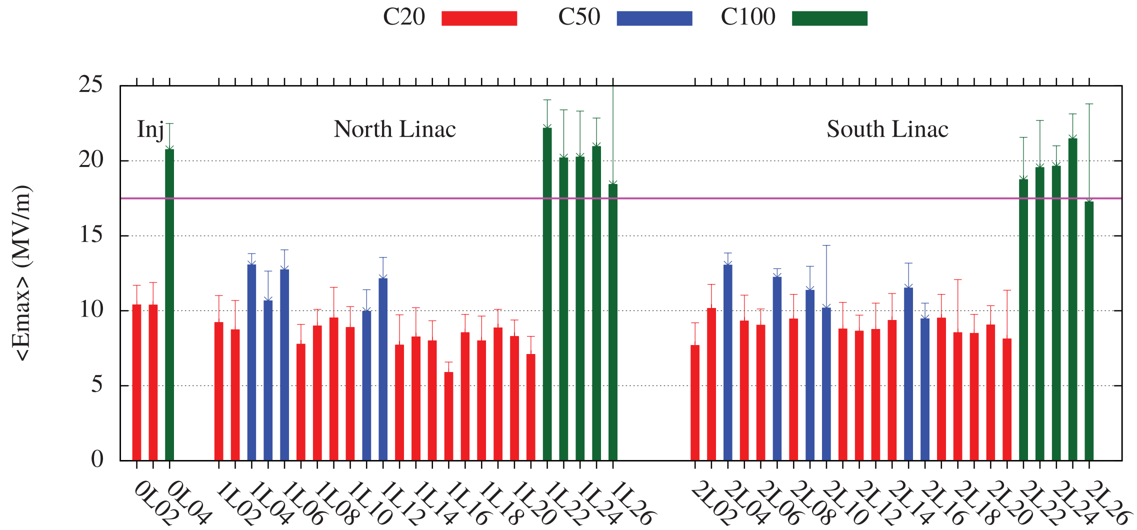

Figure 2: Average maximum cavity gradient per cryomodule as measured prior to the start of 12GeV beam commissioning. The distinction between the C20, C50 and C100 cryomodules is found in the text. The pink line represents the required gradient, 17.5MV/m, needed from the C100 modules.

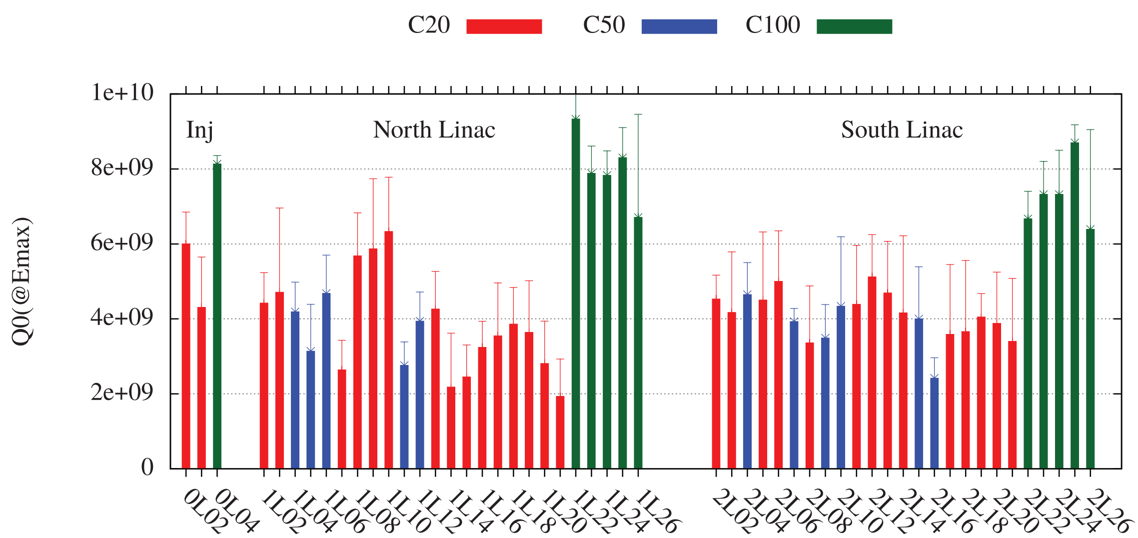

Figure 3: Average cavity Q_0 per cryomodule as measured prior to the start of 12GeV beam commissioning. The distinction between the C20, C50 and C100 cryomodules is found in the text.

maintaining the emittance growth at less than 10% per arc due to non-linear fields. Every magnet type, old, new or refurbished, was measured and verified to meet the specification before installation. The 12GeV power needs of the magnet system increased from the 6 GeV value of 4 MW to 12 MW.

System Checkout

The 12GeV CEBAF configuration is captured in a single relational database, CEBAF Element Database (CED) [3]. This database captures magnets, SRF cavities, diagnostics, vacuum system, safety system and machine model information. One for the first uses of CED was to develop a new system checkout tool for the new 12 GeV CEBAF system checkout process, referred to as *hot check out or HCO*. The new HCO process was developed to improve upon the 6 GeV process and also to reflect that the unique nature of the first instance of HCO on 12 GeV CEBAF. The system checkout was improved to track each individual component status and required two levels of sign offs corresponding to a *checked* and *ready* state for each element which the software would roll-up to display over-all system status. The database enabled a configurable interface that allowed for different views and reports on the CEBAF hardware. The most important aspect is that the operations crew chief had a simple view of each element's status between the electron source and the proposed termination point. If any element was not in the ready state, beam operations did not proceed until the

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Table 3: The Averaged Measured RF Gradient (GMES) per Cavity Type During the 2014-02-05 Successful 2.2 GeV/pass Operations. The RF Gradient Distribution Was Held Constant During the 8h Period.

Linac	Type	Ncav	<GMES> (MV/m)	$GMES_{RMS}$ (MV/m)	Egain (MeV)
Inj	C20	10	6.72	0.81	33.6
NL	C20	119	7.19	1.64	427.6
NL	C50	40	11.03	1.49	220.7
NL	C100	38	17.59	2.40	467.9
SL	C20	108	7.05	1.40	380.7
SL	C50	47	10.06	1.90	236.4
SL	C100	40	16.66	2.75	466.4

not ready element was corrected. This ensured that beam operations did not start until the required hardware elements were checked out and ready to support beam operations.

BEAM COMMISSIONING

Beam commissioning activities started once the linacs were at 2 K operating temperature and HCO had been completed to the first beam termination point, the end of the injector. Several pauses in the beam commissioning plan were planned to accommodate the completion of CEBAF hardware or the end-station installation. The next sections capture some of the highlights of the beam commissioning effort to date.

Run I: 2013-Dec-13 to 2014-Feb-06

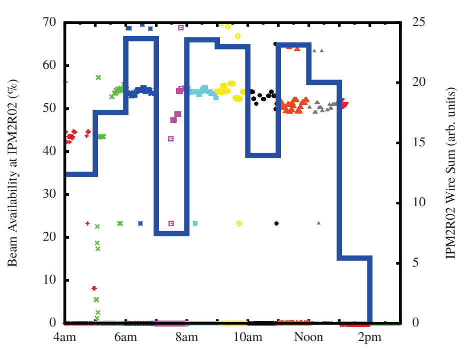

Figure 4: Beam presence in Arc2 as measured by signal on a BPM for eight hours on 2014-02-05. The linacs were set to deliver 1100 MeV/linac, the design energy, during this period.

The primary goal of the first commissioning run was to establish beam to the end of Arc2 with an energy gain of 1100 MeV/linac. This was accomplished on 2014-02-05 and sustained for over eight hours with an average availability greater than 50%. The availability was measured by counting seconds with beam signal at the last Arc2 beam position monitor (BPM). The gradients used to established the energy gain are in Table 3.

Run II: 2014-Mar-07 to 2014-May-11

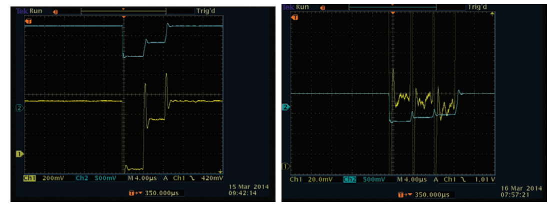

Figure 5: The yellow scope traces represent the relative phase of the different passes in the North linac. The left scope image displays a large difference in phase of about 40° between 1^{st} and 2^{nd} pass. This was corrected in the right figure (note the different scales, 200 mV/div left, 20 mV/div right) which is shows the relative time of arrival of 3-pass beam after a 22 kHz adjustment of the MO frequency.

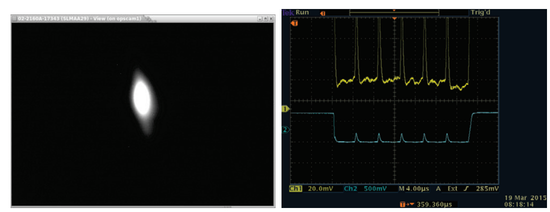

Figure 6: The Arc10 SLM image (left) and the North linac pathlength scope image (right) showing the presence of six beams in the North linac.

Beam operations resumed after a brief stop in beam commissioning to install and complete HCO on the elements needed for multipass operations. Figure 5 displays the initial pathlength measurement for multipass beams. The large reduction of about 2cm, or 40° of 1497MHz, in the machine circumference was observed and needed to be corrected. The nominal pathlength knobs, arc orbit offsets and pathlength chicane, were not capable of correcting such a large change in circumference. A third, new knob, was used to make this correction; the master oscillator (MO) frequency was changed by 22kHz. By 2014-04-01, 3-pass CW beam at 6.1 GeV had establish to Hall-A for detector commissioning.

The later half of this run was to complete the initial commissioning of CEBAF including the new Arc10 and Hall-D transport lines, and in the process send six recirculated beams through the North linac for the first time. Figure 6 shows the synchrotron light monitor (SLM) image in Arc10 and the North linac pathlength monitor showing the six beam pulses corresponding to the six recirculated beams in the North linac for the first time. At the end of this run, beam had traversed all the arcs and had been transported to the Hall-A and D dumps.

Run III: 2014-Oct-08 to 2014-Dec-21

The Hall-D detector was ready for beam commissioning by Fall 2014. High quality CW beam was established to the Hall-D dump, the radiator inserted, photons produced and sent into the new Hall-D for the first time. The detector

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commissioning proceeded and the detector program goals were deemed complete by mid Dec. 2014 [4]. In addition to supporting CW beams to Hall-D during this period the 499MHz RF seperators were commissioning and multi-user capability was establish for the first time in the 12GeV era. Halls A (4-pass), B (1-pass) and D (5.5-pass) received beam simultaneously during this run period.

Run IV: 2014-Feb-13 to 2014-May-18

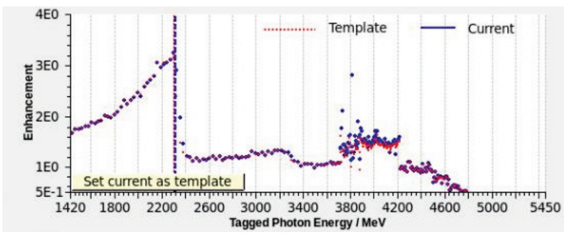

Figure 7: Coherent bremsstrahlung spectrum produced by a 6.6 GeV e^{-} beam incident on a diamond radiator.

The latest run is still on going, to date achievements include commissioning the new 5-pass separation system [5,6], and the production of linearly polarized photons in Hall-D, see Figure 7. The low energy for Hall-D result is due to the fact that CEBAF needed to be reconfigured to operate on one CHL due to a power outage on 2015-03-25 that resulted in a damaged cold compressor in SC1.

FUTURE PLANS

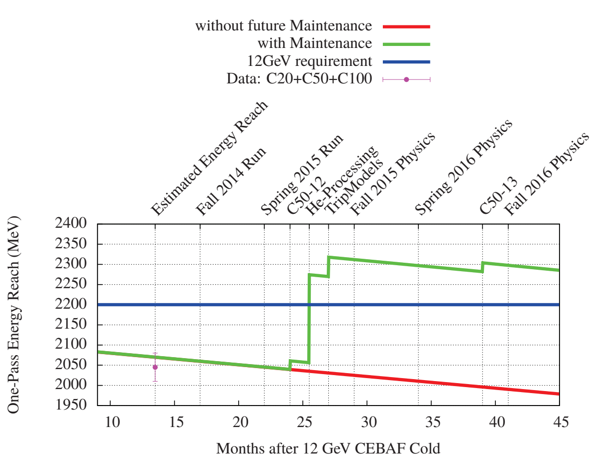

Figure 8: The CEBAF energy reach with and without gradient maintenance. The original CEBAF cryomodule have a measured degradation of about 34 MeV/year.

In order to establish a robust SRF energy gain to support high availability 12 GeV operations every SRF cavity in CEBAF will be Helium processed, see Figure 8 during Summer2015. In addition, the seized cold-compressor in SC1 will be repaired. Additional activities in support of robust 12 GeV operation include completing tunnel air-conditioning and pathlength chicane upgrade.

Beam operations in Fall2015 will be at the design energy, 12 GeV. Accelerator activities include measuring the beam emittance and energy spread evolution [7] and machine model improvement [8]. The program will transition into an early physics program at 12 GeV in Hall-D and at 11 GeV beam in Hall-A.

CONCLUSION

The program goals for the accelerator portion of the 12GeV upgrade have been achieved five months ahead of schedule. Beam quality has been sufficient for the detector commissioning in Halls A & D to achieve their program goals ahead of schedule as well.

In order to support high availability 12 GeV operations, Helium processing is planned for the Summer 2015 as well as other improvements. The program for Fall 2015 and beyond is to operate CEBAF at the design energy of 12 GeV.

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REFERENCES

[1] Yan Wang, Reza Kazimi, Alicia Hofler, “Commissioning of the 123 MeV Injector 12GeV CEBAF”, TUPMA037, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[2] Rama Bachimanchi, “CEBAF SRF Performance during the initial 12GeV Commissioning”, THXB1, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[3] Theo Larrieu et al., “The CEBAF Element Database and Related Operational Software”, MOPWI045, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[4] Mike McCaughan, “First e^{-}/Photon Commissioning Results for the GlueX Experiment/Hall-D at CEBAF”, TUPMA036, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[5] Shukui Zhang and John Hansknecht, “Gain-switched Photocathode Drive Lasers with Variable Repetition Rates for High Current Accelerators”, WEPWI031, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[6] Haipeng Wang, et. al., “Cavity Design Fabrication and Test Performance of 750MHz, 4-Rod Separators for 4-Hall Beam Delivery System”, WEPWI029, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[7] Todd Satogata, “12GeV CEBAF Transverse Emittance Evolution”, WEBD1, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).

[8] Dennis Turner, “eDT and Model-based Configuration of 12 GeV CEBAF”, MOPWI045, *These Proceedings*, IPAC'15, Richmond, VA USA (2015).