THE 12 GeV ENERGY UPGRADE AT JEFFERSON LABORATORY

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Abstract

Jefferson Laboratory has undertaken a major upgrade of its flagship facility, the CW re-circulating CEBAF linac, with the goal of doubling the linac energy to 12 GeV. I will discuss here the main scope and timeline of the upgrade and report on recent accomplishments and the present status. I will then discuss in more detail the core of the upgrade, the new additional C100 cryomodules, their production, tests and recent successful performance. I will then conclude by looking at the future plans of Jefferson Laboratory, from the commissioning and operations of the 12 GeV CEBAF to the design of the MEIC electron ion collider.

INDRODUCTION AND OVERVIEW

The CEBAF (Continuous Electron Beam Accelerator Facility) started operations in 1995 as the first CW re-circulating linac and first large accelerator based on superconducting RF technology. Designed for a maximum energy of 6 GeV, CEBAF has operated continuously serving a large nuclear physics community of more than 1400 users for 17 years, its last run at 6 GeV successfully completed in the spring 2012. With 5 recirculation passes and an injector able to tailor different beam characteristics (energy, intensity and polarization) independently for 3 experimental Halls capable to run concurrently, the linac has been a flexible and reliable source that has sustained a rich and successful nuclear physics program.

In the late 1990's the concept for an energy doubling to 12 GeV was defined, and the plan was approved and funded starting in 2004.

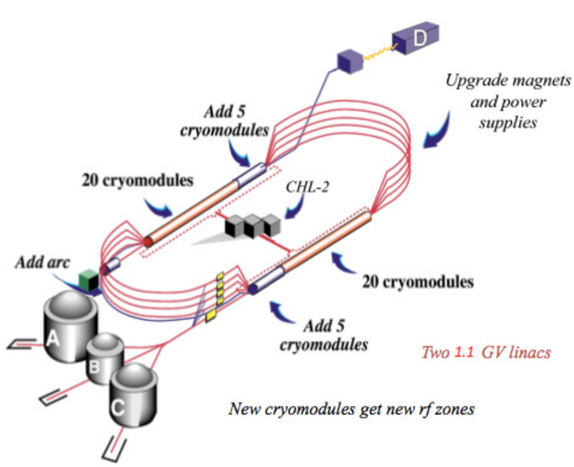

Figure 1: The main components of the CEBAF upgrade to 12 GeV.

The energy doubling is achieved by adding 10 new C100 to the existing 40 CEBAF cryomodules in free space at the end of each linac and by upgrading the magnets in the original 9 arcs to higher fields. The higher cryogenic load necessitates the doubling of the cryogenics capability with the addition of a second cryogenics plant, CHL-2 to the existing CHL-1. In addition, a new arc (Arc 10) provides an additional pass to deliver 12 GeV beam to the new Hall D. Beam for the existing Halls A, B and C is extracted at 11 GeV. The design is for a maximum of 3 Halls operating at the same time. The new Hall D adds the capability of a photon beam dedicated to the new Glue-X experiment. Included in the scope of the upgrade are new experimental detectors for the Halls B and C and infrastructure upgrades for Hall A. The injection line also needs to double the energy to match the linac.

A comparison of the high-level machine parameters between the 6 and 12 GeV CEBAF is given in Table 1.

Table 1: High-level parameters for the 6 and 12 GeV CEBAF.

Parameter	Unit	6 GeV	12 GeV
Max Energy to Halls	GeV	6	12
Passes for Hall ABC/D		5	5/5.5
Max current Hall A,C/B	μA	200 / 5	85/5
Emittance at max E H/V	nm-rad	1 / 1	10 / 2
Energy spread at max E	10^{-5}	2.5	50 at 11 GeV 500 at 12 GeV
Bunch length (rms)	ps	0.2	~1
Polarization	%	80	80

TIMELINE AND STATUS

The 12 GeV Upgrade is being managed as the 12 GeV Project, with project management structure and practices in place. The total Project cost is 310 M$ (excluding the injector upgrade, the path-length adjustors, the 5-pass RF separators and necessary machine maintenance, that are funded and managed off Project) and the Project is at the time of writing 68% complete and 79% obligated. The overall Project timeline is shown in Figure 2.

While procurement and subsystem work as well as civil construction have been in progress since FY04, the bulk of the construction and installation work has been planned during 2 operations shut-downs, the 6 month shutdown, May-November 2011 and the ongoing 16 month long shut-down, May 2012 to September 2013.

The present timeline has machine commissioning at 12 GeV starting in the fall of 2013, beam to Hall A in February 2014, followed by Hall D commissioning in October 2014, and Hall B and C in April 2015. Project completion, assuming the planned funding, is foreseen in June 2015.

The rationale of distributing the installation for the upgrade over 2 separate shutdowns in lieu of one was mainly motivated by two objectives: concluding the 6

GeV physics program in a timely fashion and capitalizing on the opportunity of testing with beam critical components of the upgrade, primarily the refurbished magnets and the new C100 cryo-modules during the final 6 GeV run from November 2011 to May 2012.

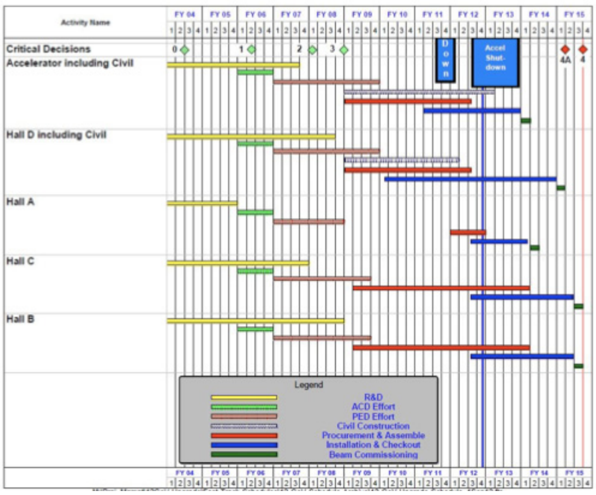

Figure 2: Timeline of the 12 GeV CEBAF Upgrade.

With 12 GeV upgrade activities being planned together with other programs going on concurrently at Jefferson Lab (operations of the JLAB FEL, preparation for CEBAF operations, construction of the TEDF, Technology and Engineering Development Facility, comprising 2 new buildings for a total project cost of 30 M$, a centralized engineering building and a doubling of the present infrastructures for SRF at JLAB, Ref [1]), the shutdowns are being managed by a laboratory-wide coordination structure that uses project management practices and integrated scheduling to minimize interferences of concurrent activities and insure overall proper activity prioritization.

The 6-month shutdown was successfully executed, all the scope of work was completed within the planned resources and budget, and in the area of magnet rework the goals were exceeded with the completion of 8 arcs instead of the baseline plan for 5. Operations started as planned in the middle of November 2011 and the ensuing run saw the completion of the 6 GeV physics program as well as operation of the machine with 2 new C100 cryo-modules. The 16 months long shutdown is in progress now and on schedule as of end of August 2012.

THE C100 CRYOMODULES

The main and more technically challenging components of the 12 GeV upgrade are the 10 new C100 cryomodules, each consisting of 8 seven cell SC cavities. The production and testing of the 80 cavities is completed and as of September 2012, 5 out of 10 cryomodules are in the tunnel and the entire production and installation will be completed by the spring of 2013.

Cavity Preparation and Testing

The 80 seven-cell 1497 MHz SC cavities for the C100s have been supplied by Research Instruments (RI) and, together with 8 pre-production cavities, have been processed, tested and assembled at JLAB. The C100 cavity production and qualification process consists of 19 steps, all documented with Pansophy travellers. [2] The electro-polishing (EP) process in particular was derived from the experience with the EP for the 9-cell JLAB high gradient cavities for the ILC, an excellent example of synergy between different R&D efforts.

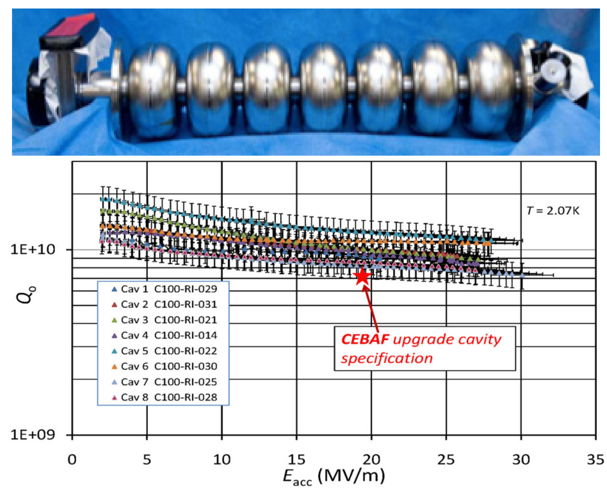

Figure 3: Vertical acceptance test results of the 8 cavities for the C100-3 cryomodule.

The cavity tests are performed at the Vertical Test Area (VTA), a facility specifically designed for measurement of cavities in super-fluid helium. A typical result of unloaded Q as a function of accelerating gradient for cavities in a C100 string is shown in Figure 3. The cavity specification is 19.2 MV/m average, with 29 W of average heat per cavity. The operational limit at 12 GeV is 25 MV/m, limited by the klystron RF power.

C100 Cryomodules: Design and Production

The design of the C100, started in 2001 and finalized by 2009, is an evolution from the original C20 CEBAF cryomodule and has capitalized on the experience of the C50 program. The goal of the latter was to reduce field emission and raise the gradient from 5.5 MV/m to 12.5 MV/m for 10 of the weakest C20 cryomodules. The latter were disassembled, baked, tuned, surface-processed and reassembled resulting in excellent gradient improvements.

The fact that 10 C100 cryo-module can output the same accelerating voltage of 40 original CEBAF modules is a testimony to the impressive progress in CW SRF in the past 20 years.

To meet the energy upgrade specifications, the C100 need to provide a minimum of 98 MeV but the C100 are designed for 108 MeV output in order to allow for sufficient margin. The production model had the primary components procured from industry and the modules assembled and qualified at JLAB. [3] The cryomodule

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cost is evenly split between procurements and labor, and the most resource-consuming aspects are the assembly and QA processes.

Figure 4: C100 leaving the assembly building.

C100: Tests and Performance

Once assembled, each cryomodule goes through 2 testing cycles, acceptance testing in the Cryomodule Test Facility (CMTF) prior to installation and a final commissioning in the tunnel after installation. [4] During the acceptance procedure, every cavity is tested and tuned to 1497 MHz, HOM are characterized and maximum gradient, field emission and Q_o measured together with microphonics and static heat loads. Commissioning in the tunnel after installation consists of a subset of the acceptance tests.

The measurement of cavity detuning from external vibration sources has been particularly extensive given the potential operational consequences. [5] The peak detuning budget for the C100 cavities is 35 Hz. While within the specifications the initial measurements were higher than predicted, one possible cause being the lack of stiffening rings in the cavity design. The will to retain operational margin for the cavity powering led to a modification of the mechanical tuner system for the successive C100 cryomodules that in turn led to an average reduction in peak detuning of 42%.

In a modification of the original plan, the first 2 production C100 cryomodules were installed in the South Linac during the 6-month shutdown in the Summer 2011. The change in the plan provided a means to validating the main components of the upgrade by testing the modules in the tunnel, performing dedicated studies of HOM modes with beam at the end of the down, and by commissioning and operating the units with beam during the ensuing physics run.

Previous detection of BBU at 40 μA in CEBAF in 2007 with an earlier high gradient prototype motivated the effort to improve the C100 HOM damping and to undertake dedicated studies to measure HOM and compare them with predictions. [6] The predicted BBU threshold for the 12 GeV CEBAF beam is 26 mA, much higher than the nominal 465 μA maximum beam loading. Despite a dedicated beam test at low energy, 282 MeV/linac, and a special optics aimed at lowering the BBU threshold, we were unable to directly observe BBU, which is reassuring. The C100 HOMs were carefully surveyed, in particular the most important TE111, TM110 and TM111 for all cavities in C100-1 and C100-2 by beam transfer function measurements. These measurements and the comparison with prediction allowed us to conclude that BBU is not a likely concern for 12 GeV CEBAF (see Figure 5).

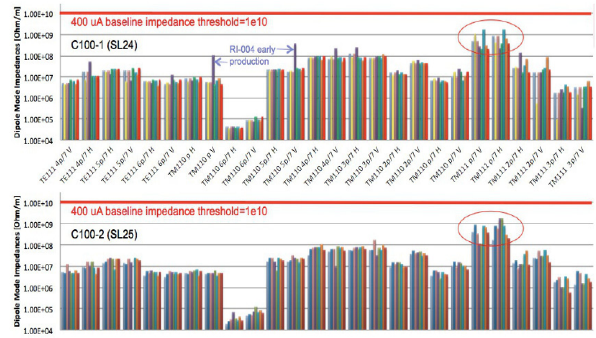

Figure 5: Measured dipole HOM impedances for the first 2 production C100 cryomodules.

C100: Commissioning and Operations

C100-1 and C100-2 were first commissioned and then used in operation with beam continuously from January to May 2012. [7]

The RF system is completely new for these cryomodules: each cavity is powered by one klystron, output power of 12 kW linear and 13 kW saturated, and controlled by the LLRF system. After a test of the RF controls and power systems, the cryomodule is attached to the waveguides, commissioned and handed over to operations.

During operations the cryomodule voltage ranged from 50 to over 100 MV. The fact that the C100 cavities have narrower bandwidth and much higher gradients than the original CEBAF cavities translated into the necessity to progressively learn to operate the C100 efficiently. In particular, turn-on and trip recovery applications proved critical to minimize downtime in operations. A critical aspect was to learn to minimize mechanical coupling between adjacent cavities, of the order of 10% if left uncorrected.

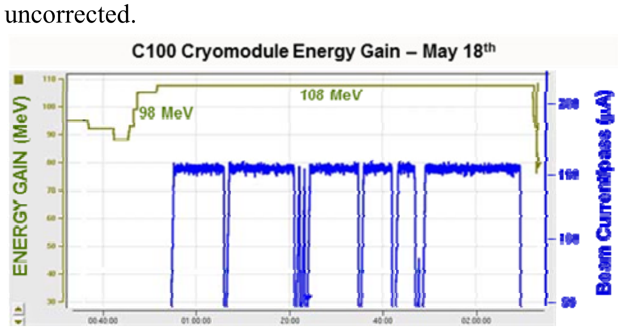

Figure 6: C100 reached the design gradient with the nominal 460 μA of total beam loading.

The goal of demonstrating that the new cryomodules could achieve an energy gain of 108 MeV at the 12 GeV design current of 465 μA for over 1 h of continuous operations was achieved on May 18, 2012 (Figure 6). The operational experience of the first 2 C100 will be invaluable during the machine commissioning in the fall of 2013.

MAGNET UPGRADE

The magnet field needed to be increased to accommodate the higher energy. Adding H-steel to the original C- dipoles in order to reduce saturation solved the problem for most of the arc dipoles in the arc. New magnets were needed for the new Arc 10, the spreaders and recombiners and some transfer lines.

Figure 7: Re-worked and new magnets in the West Arc.

Most of the arc dipoles have been successful re-worked and measured during the 6-month shutdown. All magnets have met their design goals with no post construction modifications needed and performed well in operations. The upgrade of spreaders, recombiners and the remaining beam transport elements is in presently in progress.

CRYOGENICS

The upgrade to 12 GeV for the CEBAF linacs requires the doubling of the JLAB cryogenics capability so a new Central Helium Liquefier (CHL-2) is being added to the existing CHL-1. In addition a new cryo plant for Hall D (HDR – Hall D Refrigerator) is being installed to serve the SC solenoid for the Glue-X experiment. CHL-2 compressors are installed and the lower and upper cold-boxes are being commissioned as well.

As part of the upgrade, the CHL-1 refrigerator has been warmed up in a controlled way together with the linacs for the first time in the CEBAF history. The warm-up started on August 1st 2012 and was successfully completed in less than 2 weeks. An unplanned warm-up in 2005 was caused by Hurricane Isabelle, which resulted in loss of gradient for the CEBAF cryomodules as a consequence of uncontrolled thermo-cycling. Lessons learned from that experience were included in the planning of the controlled warm-up this summer.

Figure 8: CHL-2 compressors are installed and are being commissioned.

The controlled warm-up so far did not appear to present unforeseen challenges, and we are seizing the opportunity for needed cryogenics and cryomodule maintenance activities, including a global realignment of the cryogenics transfer lines and the linac cryomodules. In addition, new cooling towers for CHL-1 are being built that will add reliability and flexibility during the planned cool-down of the linacs in December 2012. The linacs need to be cooled down to commission the remaining C100 cryomodules and to run the JLAB FEL as planned starting in January 2013.

INJECTOR

The CEBAF elements responsible for the generation of polarized electrons, spin manipulation, acceleration up to the injection energy and merging into the North Linac is called the CEBAF Injector. For 12 GeV CEBAF operations the Injector will be upgraded in several phases to achieve an increase in the final injection energy and improvements geared toward improving the helicity correlated beam parameters. The increase in the final injector energy from 67 MeV to 123MeV is accomplished by replacing an original CEBAF cryomodule in the final acceleration portion of the injector with a new 100MeV C100 cryomodule. This upgrade is required to maintain the same injection to first pass energy ratio as in the original 4GeV CEBAF design.

Parity violated experiments have been one of the highlights of the 6 GeV CEBAF program and several parity violated experiments have been approved for the 12GeV physics program. In order to improve beam helicity correlated beam parameters required for these demanding experiments and reduce the amount of beam tuning to maintain the required beam quality the front-end of the Injector will be upgraded during the initial years of 12GeV operation. This upgrade includes raising the DC gun from 130keV to 200keV to reduce space charge effects and a new ¼-cryomodule. The ¼- cryomodule will eliminate the X-Y coupling of the old asymmetric module.

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JEFFERSON LAB OUTLOOK

I will conclude by giving an overview of JLAB future plans in the 12 GeV era and beyond.

12 GeV Commissioning and Operations

Commissioning of the 12 GeV CEBAF will start in the fall of 2013. A draft-commissioning plan exists already and it will get finalized during the long shutdown. The most relevant difference from operations at 6 GeV is synchrotron radiation at 12 GeV. Hall commissioning will start with A, followed by D, C and B respectively. The projections for the out-years are for 30-34 weeks of machine operations per year. The Physics Advisory Committee has already approved more than 50 experiments for the 12 GeV era and we project at least 15 years of productive physics running.

The Electron-Ion Collider

The nuclear physics community is developing a strong physics case for an electron-ion collider as the next needed step in the development of the field. Jefferson Laboratory has just completed the conceptual design for a Medium Energy Ion Collider [8] that would fit strategically in the laboratory future plans as well as physically in within the laboratory footprints.

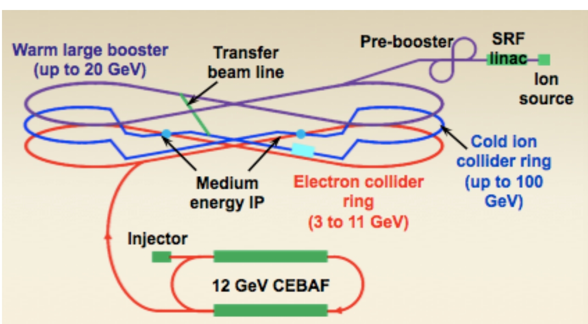

Figure 9: The MEIC collider complex at JLAB.

The design is for a ring-ring collider, with an energy range of 3-11 GeV for the electrons and 20-100 GeV for protons and ions, a luminosity of a few 10^{34} e-nucleons cm^{-2} s^{-1} and longitudinal and transverse polarization. CEBAF is the e- injector while the ion complex is new. Unique characteristics of this design are the figure-8 rings to insure preservation of polarization. Figure 10 outlines a possible timeline for the project that is compatible with 12 GeV CEBAF running and the long-term plans for DoE Office of Nuclear Physics.

CONCLUSIONS

The 12 GeV Upgrade for CEBAF at JLAB is progressing well and the start of commissioning is planned for the fall of 2013. A robust program of nuclear physics will follow. JLAB will complete a doubling of its SRF infrastructure in summer 2013 greatly enhancing its SRF R&D and production capabilities. An electron-ion collider is the long-term strategic goal of the laboratory.

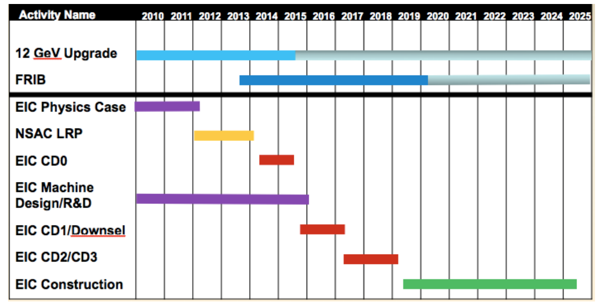

Figure 10: A possible timeline for the EIC realization consistent with DoE Nuclear Physics and JLAB plans.

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