THE JLAB 12 GEV ENERGY UPGRADE OF CEBAF *

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Abstract

CEBAF at Jefferson Lab was a 5-pass, recirculating cw electron linac operating at ~6 GeV and devoted to basic research in nuclear physics. The 12 GeV Upgrade is a major project, sponsored by the DOE Office of Nuclear Physics, that is expanding its research capabilities substantially by doubling the maximum energy and adding major new experimental apparatus. The Upgrade is illustrated in Figure 1 includes: doubling the accelerating voltages of the linacs by adding 10 new high-performance cryomodules; the requisite expansion of the 2K cryogenics plant and rf power systems to support these cryomodules; upgrading the beam transport system from 6 to 12 GeV through extensive re-use and/or modification of existing hardware; and the addition of one recirculation arc, a new experimental area, and the beamline to it; and the construction of major new experimental equipment for the GPD, high-xBjorken, and hybrid meson programs. The accelerator upgrade is essentially complete and the construction of the new experimental apparatus is well underway. This paper provides some details about the accelerator upgrade.

OVERVIEW

Scientific Motivation

In the 20+ years since the original design parameters of CEBAF were defined the understanding of the behavior of strongly interacting matter has evolved significantly, and important new classes of experimental questions have been identified that can be addressed optimally by a CEBAF-type accelerator at higher energy. The original design of the facility, coupled with developments in superconducting RF technology, makes it feasible to triple the initial design value of CEBAF's beam energy to 12 GeV in a cost-effective manner, providing a new research tool capable of addressing the science.

The science motivating the 12 GeV Upgrade includes breakthrough programs that will be launched in four main areas (they are described in detail in [1]):

- Discovering the quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model using precision, parity-violating electron scattering experiments.

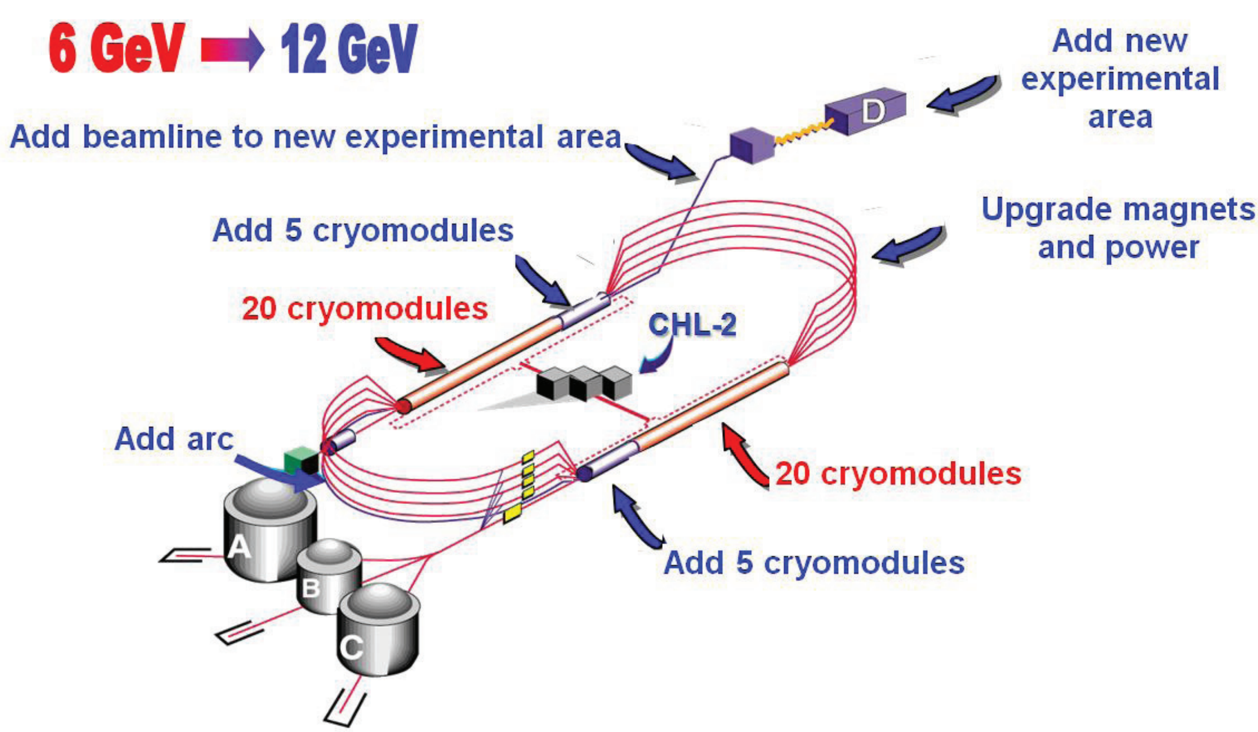

Figure 1: Changes to CEBAF.

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- Explore the physical origins of quark confinement (GlueX experiment): A potential explanation, supported by lattice QCD calculations, is that quark confinement stems from the formation of a string-like "flux tube" between quarks. This conclusion (and proposed mechanisms of flux tube formation) can be tested by determining the spectrum of the gluonic excitations of mesons (referred to as "hybrid" mesons)

Base Requirements

The exotic meson spectroscopy program needs 9 GeV polarized photons for optimal production of the hybrid mesons and distinguishing them from the other meson excited states. Coherent bremsstrahlung, obtained by passing a high quality, cw beam of 12 GeV electrons through a crystal radiator, is the ideal source of these photons. Similar electron beam energies are nearly ideal for the other research programs outlined above.

CEBAF, which had originally been built to operate at 4 GeV, had been incrementally upgraded to 6GeV. Thus, to reach 12 GeV a net of 6 GV of acceleration had to be added. A new experimental area (for the hybrid meson program) has been added on the opposite end of the accelerator from three existing end stations, so the beam reaching it will transit one linac once more than beams for the existing end stations

12 GeV could have been achieved by increasing the linac capabilities or increasing the number of passes. An analysis determined that it would be more cost effective to increase the linac capabilities than to reconfigure (rebuild) the beam transport system for additional passes. Therefore, the 0.6 GV linacs have been upgraded to 1.1 GV. The hybrid meson studies need < 5 μA; the other programs need much larger beam currents. The original beam power limit of 1 MW has been retained.

The original beam transport system supported 5 pass beam at 6 GeV to the existing end stations. It has been modified to deliver 11 GeV beam to those halls and beam transport must be added to deliver the full 12 GeV beam to the photon radiator target for the new end station, including an additional recirculation arc.

BEAM PHYSICS

Beam Breakup

Beam breakup (BBU) driven by high-order modes (HOM) in the cavities must always be addressed when using srf cavities even if the beam current in the cavities, < 1 mA in this case, is not exceptional on the scale of storage rings. As was done for 4 GeV CEBAF, a BBU analysis was done [2] to set limits on the Q's of the HOM's. An impedance budget of $(R/Q)Qk < 2.4\times10^{10}\ \Omega/m$ for transverse HOM's and $(R/Q)Q < 6.5\times10^{11}$ for longitudinal modes came out of the study. The simulated cavities did not always meet those budgets when evaluated as single cavities because of longitudinal mode asymmetries and the presence of HOM dampers on only one end of the cavity. However, when evaluated as an assembled string, the fundamental power coupler on the adjacent cavity coupled out the asymmetric modes. The cavities on the ends of the cryomodule do not have that benefit so dampers were added in the waveguides for those cavities.

Emittance, Energy Spread, and Halo

Emittance growth from synchrotron radiation of the electrons in dispersive sections of the beam transport was not a limitation to meeting the 1 nm-rad specification for CEBAF at 4 GeV. For the Upgrade, cost containment drove a desire to forego extensive modifications to the existing optics. A so-called "double-bend achromat" lattice was adopted [3] for the higher-energy passes as it reduced the emittance growth relative to the original lattice without requiring reconfiguration of the beamline components. The resulting beam characteristics are summarized in Table 1. These values are consistent with the needs of the proposed research programs. Tracking calculations which included errors (misalignment, mispowering, field nonlinearities, etc) were carried out [4]. With all errors included in the model, the study found that the emittance and energy spread specifications will be met with some margin.

The hybrid meson experiment needs a very low beam halo to prevent unacceptable backgrounds. Particle-tracking calculations with multiple seeds for misalignment, mis-steering, field nonlinearities, and mispowering have shown [5] that the halo requirement for commissioning and early years of operation will be met.

Table 1: Beam Properties at 6 and 12 GeV

	6 GeV	12 GeV
Transverse emittance at Halls A, B, & C	$\varepsilon_x=\varepsilon_y=$ 1 nm-rad	ε_x=7 nm-rad ε_y=1 nm-rad
Transverse emittance at Hall D	NA	ε_x=10 nm-rad ε_y=2 nm-rad
$\delta E/E$ at Halls A, B, & C	0.01%	0.02%

ACCELERATION

SRF

The additional 0.5 GV/linac is achieved by having added five new 100 MV cryomodules to each linac. Each cryomodule has eight 7-cell cavities. While only 17.5 MV/m is required for the cryomodule to reach 100 MV, the goal was set at 19.2 MV/m (on average for the ensemble in a linac) to deal with the likelihood (based on our operations experience with CEBAF) that some cavities might be off-line. The existing linacs could operate at the 5 pass equivalent of 5.6 GeV if none of the margin is needed for off-nominal conditions in the cryomodules.

Typically, the performance specification for cavities is stated as a Q0 at a particular gradient. We chose to keep with the parameters determined by the overall system. For 12 GeV we used a dynamic heat requirement rather

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than a Q0. After taking into account the load from the waveguides, the heat budget for dynamic load of each cavity was 29 W.

The cavity and cryomodule designs have undergone some evolution since the start of the design process. There had been a number of challenges that needed to be addressed during that evolution:

- RF windows: One of the developmental cryomodules used a single RF window on each cavity. It had some unexplained window failures. Those failures led to contamination of the cryomodule and seriously reduced performance. The incremental cost savings of using a single window did not offset the long term risk, so we returned to using both primary and secondary rf windows between the cavity and the external waveguide. All ten of the new cryomodules use the double-window configuration.
- Tuner: A new, less-expensive "rock crusher" tuner concept was developed for another of the developmental cryomodules. During testing some problems were experienced with the mechanical robustness of the tuner. Subsequent to that, SNS had some problems with their cryogenic motors. The original scissor-jack design was reworked for cost reduction. That design improved reliability with little cost impact, so it was used for all of the new cryomodules. It has the additional advantage that the motor and piezo-electric element are at room temperature, thus simplifying any required maintenance.
- Microphonics: During testing of the initial new cryomodules it was found that the cavity-tuner assembly was less stiff than those in previous JLab cryomodules with the result that their sensitivity to mechanical vibrations was much higher than had been seen in any of JLab's previous designs. It was determined that a number of factors (cell shape, lack of inter-cell stiffening rings, lack of bellows between the cavities, and a tuner-to-cavity interface that wasn't very stiff) were contributing factors. Finite element analysis indicated that a significant improvement in the overall stiffness could be achieved by a redesign of some of the tuner cavity interface components. That new design was implemented on the fourth cryomodule to be completed. The seven cryomodules with that change have ~2x lower microphonics than the three that were completed prior to the change.

All ten new cryomodules have been fabricated, tested, and installed. Nine have re-tested after installation. The performance goals have been met. The tenth cryomodule will be tested in October. A summary of the achieved voltages is given in Table 2.. Additional information can be found in the paper by John Hogan at this conference [6]

Table 2: Cryomodule Performance

Cryomodule	In-tunnel performance
#1	104 MV
#2	110 MV
#3	118 MV
#4	105 MV
#5	109 MV
#6	108 MV
#7	108 MV
#8	Testing in progress
#9	108 MV
#10	109 MV

RF

Each cavity is energized by its own klystron. In a 2001 overall system design initiative, the required saturated output power for the klystrons was based on the following criteria: 1) ≤450 μA of beam transiting the cavity (limited by 1 MW total beam power limit), 2) Qext is off-optimum by ≤30%, 3) maximum detuning ≤25 Hz of (4 Hz is 2x the tuner resolution and 21 Hz was 6σ of the measured microphonics spectrum on the original cavities), 4) some cavities would be able to operate at 21 MV/m (10% above the mean of the population but within the range that had been seen in early testing of prototype cavities) and stay within the cryogenic budget, 5) losses in the waveguides, and 6) add 10% so that the klystron would still have gain. The result of the calculation was 12.8 kW per cavity. In 2006 a study was performed to determine the cost-effectiveness of powering mutiple cavities with a single klystron. It was found that cost reduction was possible but only at the expense of failing to meet the phase and amplitude control goals. This option was not adopted and 12 GeV Upgrade uses one klystron per cavity. [7] Eighty 13 kW klystrons have been installed (one per cavity). Since the original klystron performance was established, cavity characteristics and waveguide losses have changed. The current de-tuning budget (static plus microphonics) with the 13kW klystrons is now 35Hz.

A new rf control module was developed using digital technology. Important control issues that were addressed were:

- Phase and amplitude control must meet the following specifications: 1) Amplitude noise <0.01% and 2) Phase noise < 0.2°
- The system has multi-valued resonance detuning curves resulting from the cavities' high fields and the accompanying high external Q (>2x107 for 12 GeV), as illustrated in Figure 2.

The new system has been completely installed and used to operate all of the installed new cryomodules including delivering beam at full system performance goals. [8]

Integrated RF-cryomodule Performance

Two of the new cryomodules were operating in the south linac during the 2011-2012 final nuclear physics run prior to shutting down to do the bulk of the upgrades. As the focus of that run was acquiring data for the nuclear physics experiments, the digital control algorithms could be optimized in only one of the two cryomodules. That one was able to deliver the targeted 108 MV with the full beam loading planned for the 12 GeV era. The nuclear physics experiment was a particularly precise measurement that required high quality beam. The users reported no change in beam quality.

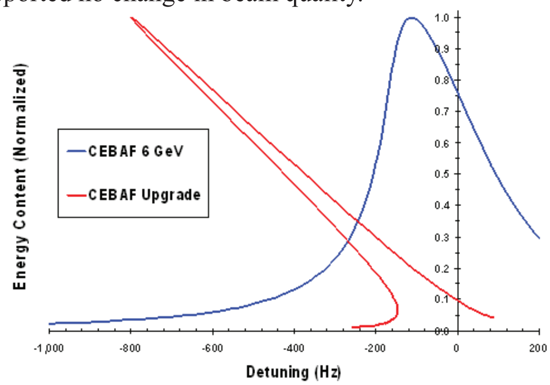

Figure 2: Detuning curves for 6 and 12 GeV.

As mentioned earlier, the cavities in the string were more mechanically coupled and "softer" than previous versions. As a result, if one cavity tripped off, then the others on that end of the cryomodule tripped as the field in the first one collapsed, thereby eliminating the Lorentz forces on that cavity which, in turn, pushed on the other cavities and took their resonant frequency outside the control band and they tripped also. Automated recovery of tripped cavities is still under development. For the 2012 run, a workaround was developed in which the cavities that don't trip are shifted to SEL mode and thus can stay energized; recovery is then simply turning on the resonance control then shifting back to phase and amplitude control once the cavity that tripped has been brought back up to full field.

Cryogenics

The original 2K helium plant was operating at its full capacity; any additional load, such as the new cryomodules, required an expansion. JLab had an unused 2K coldbox identical to the primary 2K coldbox. A plan was established to combine that 2K coldbox with a new 4.5K coldbox plus requisite new warm compressors to get a plant with maximum capacity of ~5kW at 2K. That new hardware has been fabricated, installed and successfully tested. [9] As the new 4.5K coldbox uses the JLab-patented "Ganni cycle", the power consumption of the new 4.5K plant is 30% less than that of the similarly sized original plant. Connections between the 4.5K and 2K systems have been completed. Commissioning of the integrated new plant is about to start.

BEAMLINES

Upgrading Existing Beamlines

The existing beam transport system consists of ~400 dipoles (BxL $\geq$ 0.2T-m) and ~700 quads. Simply replacing their power supplies was not viable because, at the approximately doubled fields, saturation in the return iron would require excessively large power supplies and installation of a large refrigerated cooling-water system. Replacing the magnets is also cost prohibitive. Happily, another alternative was identified.

For the majority of the dipoles, i.e. those in the nine 180° arcs and in the beamlines to the existing end stations, the present "C" shape was changed to "H" profiles by adding bolted on iron plates. The magnets will be operated at ~2x the original currents. The saturation would have exceeded 50% without that change. With the change the maximum is 1%. However, the roughly doubled currents result in much hotter magnets. The temperature rise (above the cooling water supply temperature) is now as much as 38C.

The dipoles in the spreaders and recombiners (S/R), i.e. the sections of the beam transport system which separate the co-linear beams after they exit the linacs or combine them before re-injection into the linacs, are so closely spaced that the bolt-on iron option is often not viable. A combination of three approaches was used: 1) reshape the poles to reduce the flux, and thus the saturation, 2) add coil packs and accept some saturation, and 3) add iron, but in lesser amounts than in the 180° arcs.

All the reused magnets were refurbished to extend their lives. The refurbishment included: replacing all the elastomers with material suited to the new operating temperatures, installing new coil constraints, re-silvering the contacts for the buss cables, and installing Belleville washers to insure that the bolts stay tight.

A small number of new magnets were for the spreaders and recombiners. They were procured with a build-to-print contract. Principal among the new magnets were seven 3m-long septa, which are critical for separating the beams in the higher passes. Six new curved dipoles were also bought. All of the magnets have been fabricated, received, inspected, field mapped, and installed.

The quadrupole fields required for the Upgrade exceeded the original design specifications of the original magnets for ~20% of the population. Testing found satisfactory field quality if the units were pushed to the required field levels, even though there was saturation. That ~20% of the quadrupoles are receiving new power supplies (20A vs the original 10A). The remainder were left as is. In some locations increasing the power supplies did not bring the quad to the required field. New magnets were bought for those locations; all of the new quads get the 20A supplies. Most of the 240 new 20A supplies have been received and installed.

The original dipole strings were energized by 32 power supplies varying in size from 35kW up to 260 kW. Half have been reused for the Upgrade. The rest are being replaced by larger units with output power ratings ranging up to 1.1MW. The new supplies are being fabricated by a commercial firm. The first three units have been received and onsite testing is underway.

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New Beamlines

A new recirculation arc was needed to return the beam to the north linac for its final acceleration before going to the new Hall D. Arc 10 uses the double-bend achromat mentioned above. Thirty six new 4m-long dipoles and forty five new quadrupoles were purchased for Arc 10 and the Hall D beamline. New units of existing diagnostics designs had been planned for Arc 10 and for the beamline to Hall D. However, it became impossible to find components for the beam position monitor electronics needed for the beamline to Hall D due to parts obsolescence, so a new system using stripline bpm's was designed and has been installed on the new beamlines. The other diagnostics used the original designs.

Extraction

A key to the effectiveness of CEBAF's research program has been the ability to deliver beam to multiple halls simultaneously. This feature has been retained in the Upgrade. One or two of the three interleaved but independent 499 MHz bunch streams can be extracted at any of the five passes. Extraction is done through the use of properly phased 499 MHz horizontally deflecting copper cavities; the horizontal split is amplified by the downstream lattice and a septum. A second, stronger septum completes the separation into two separate beamlines, one going to the beam switchyard and the other entering the recirculation arcs. This is done on all five passes.

The field integrals of the magnets and rf kickers was doubled for the Upgrade. The rf kick was increased by a combination of running some cavities at higher fields and increasing the number of cavities. The magnet integrals were increased by reuse of longer magnets from other locations. The optics for all five passes are identical.

CONTROL AND SAFETY SYSTEMS

The control network has been extended to cover the beamline to Hall D and Hall D itself. No new technology was required.

All of the safety systems have been expanded to incorporate Hall D and the beamline to the associated tagger dump. Specifically we upgraded the Personnel Safety System (PSS), the Beam Envelop Limit System (BELS), and Machine Protection System (MPS). The MPS and BELS modifications were simple extensions of the present systems. A new engineering approach was developed for the PSS in order to be in compliance with present regulations.

CHALLENGES ALONG THE WAY

Aside from the usual changes in funding profile, the 12 GeV Upgrade accelerator systems encountered some procurement challenges because of market conditions.

When contracting for the components of the new 4.5K coldbox we were in competition with major natural gas and oil companies. Those firms use similar equipment as some we needed and thus use the same vendors as we needed for those components. In addition, the price for the carbon steel was elevated due to international market conditions. As a result, the 4.5K coldbox was rather more expensive than had been anticipated and was delivered later than anticipated. Similarly, the srf cavities cost more than expected because of the market price for high RRR niobium.

A rather different problem occurred with the contract for the large magnet supplies. The original vendor had a large US manufacturing arm and a smaller offshore design arm. Well into the contract, the design arm went bankrupt and the manufacturing arm was unable to fulfill the contract. A new higher-priced contract was placed with a new vendor. Considerable schedule delay was incurred in the process, too.

STATUS

The upgrade of the accelerator is essentially complete. The beamlines to the end stations are still to be completed. Commissioning of the accelerator is scheduled to begin in Novermber of this year.

SUMMARY

An exciting new range of scientific inquiry into the quark nature of nuclear matter will soon be opened by the availability of a 12 GeV cw electron beam at JLab. The needed upgrade of the CEBAF accelerator is nearly complete and commissioning is about to begin. The new research program could begin as early as 2014.

REFERENCES

[1] http://www.jlab.org/12GeV/
[2] Ilkyoung Shin, Thesis, University of Connecticut, (2013).
[3] S. Bogacz, JLab internal report TN-07-010.
[4] Y.Roblin, JLab internal report TN-08-042.
[5] A. Freyberger and Y. Roblin, JLab internal report TN-06-048.
[6] John Hogan,"Overview and Lessons Learned of the Jefferson Lab Cryomodule Production for the CEBAF 12GeV Upgrade", WEZAA2, NA-PAC'13.
[7] R. Nelson and A Kimber, CWRF-2012, "RF Power Upgrade at Jefferson Lab".
[8] Hovater et al., IPAC12, "Commissioning and Operation of the CEBAF 100MV Cryomodules", WEPPC.
[9] CEC/ICMC-2012 V, Ganni, et al., "Commissioning Status of Helium Refrigeration System at JLab for the 12 GeV Upgrade, V. Ganni, et al", 2EOrC4-01.