UPGRADING THE CEBAF ACCELERATOR TO 12 GeV*

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Abstract

Jefferson Lab is upgrading its 6 GeV Continuous Electron Beam Accelerator Facility (CEBAF) to 12 GeV. The doubled energy will Greatly extend the research reach of the three existing experimental Halls with upgraded experimental equipment and will make possible a new research program in exotic mesons in a newly constructed fourth hall. The present linacs will have their acceleration roughly doubled through the addition of 10 new cryomodules with performance of ~5 times the original specification for CEBAF. The 2K helium plant will be roughly doubled; new rf systems, including digital controls, will be installed for the new cryomodules. The beam transport system's capability will be doubled by strongly leveraging existing hardware (without incurring significant saturation) but must be enhanced with some replacement magnets, new power supplies, one new recirculation arc, and a beamline to the new Hall. Critical Decision 1 was approved by DOE for this project in February 2006. Technical status for the accelerator systems including R&D will be described as well as the status of the 12 GeV Upgrade Project as a whole.

OVERVIEW

From the outset, the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab has been a world-leading institution in extending the understanding of the quark-structure of matter and non-perturbative QCD. Extending CEBAF's beam energy to 12 GeV will extend those investigations to valence quark behavior, nuclear tomography with generalized parton distributions, and potentially unraveling the mystery of quark confinement through hybrid meson spectroscopy. The proposed overall research program received a strong endorsement by a review committee chartered by the Department of Energy (DOE) in April, 2005 [1].

The most cost effective route to upgrading the accelerator from 6 GeV to 12 GeV is to increase each of the two linacs' voltages from 0.6 MV to 1.1 MV, thereby providing 11 GV of acceleration in 5 passes. Then a tenth recirculation arc is added so that the beam will transit one linac an additional time before being delivered to a new experimental hall which will house the hybrid meson experiment. The three existing halls will be upgraded to receive the maximum 5-pass beam energy of 11 GeV. The layout of the upgrade is given in Figure 1.

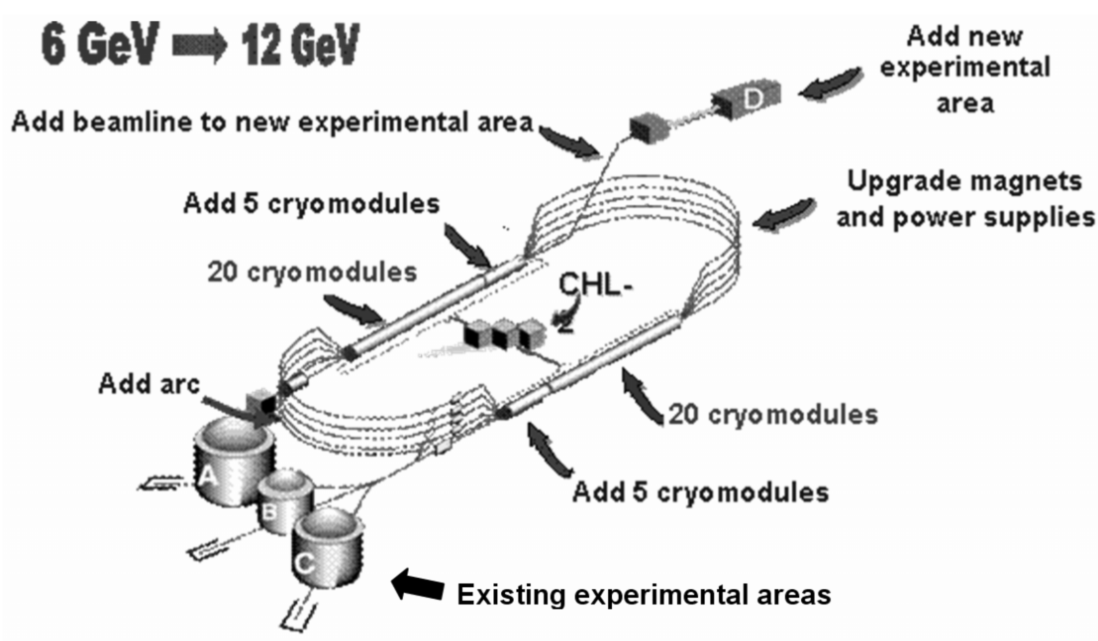

Figure 1: Conceptual illustration of upgrading CEBAF to 12 GeV.

*Work supported by US Dept. of Energy under contract DE-AC05-6OR23177.

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ACCELERATION

Note: The details of the acceleration systems (cryomodules, rf, and cryogenics) are described in detail in ref. [2]. The following is a summary of that information. It should be remembered that the existing acceleration systems will be used without modification.

Cryomodules

The additional 0.5 GV/linac increase will be achieved by adding 5 new cryomodules (total of 10 needed for both linacs) each providing 100 MV. Each cryomodule will have eight 7-cell cavities. While only 17.5 MV/m is required for the cryomodule to reach 100 MV, the specification was set at 19.2 MV/m to overcome the potential that some cavities might be off-line. A limit of 29 W of 2K dynamic heat load (Q0 =8x109) was set by the requirement to fit within the projected cryogenics plant's capacity (see below). Prototype cavities have performed within the 29 W limit at 21 MV/m.

A developmental cryomodule (designated "Renascence") was constructed based on the design then planned for the 12 GeV Upgrade. That design was considerably different from the one used for the original CEBAF cryomodules but was an evolution of previous developmental units for use in CEBAF and the JLab FEL as well being conceptually similar to the cryomodules built by JLab for the Spallation Neutron Source (SNS) project. Testing of Renascence during 2005 found serious limitations in its performance. Additional testing with enhanced thermal monitoring was then done. Subsequent evaluation of the data and extensively expanded and improved thermal modeling of the components showed that some features of the cavity design needed improvement, i.e. in the endgroups. The problems stemmed largely from: 1) an error in the assumed thermal impedance of a weld in the high-order mode (HOM) coupler and 2) component placement requirements introduced to meet HOM damping requirements beyond the needs of the 12 GeV Upgrade, i.e. for potential use in the JLab FEL. Further work has led to a design that is specifically tailored to the needs of the 12 GeV Upgrade and which is predicted to meet those performance levels. The final design will be tested on two cavities in a "¼ cryomodule" test planned FY07.

Cryogenics

The present 2K helium plant is now operating at its full capacity. The helium plant can be viewed as having two major components; the first generates a 4K liquid and the second turns the liquid into superfluid at 2K. A new 4K plant will be constructed; this is anticipated to be done by a commercial firm after competitive bidding. JLab has a redundant ("hot spare") 2K coldbox which will be combined with the new 4K plant and an 80K exchanger to construct a 2K plant with maximum capacity of ~5 kW at 2K.

After allowance for system control headroom, there would be ~300W available for each of the new cryomodules, 250W of which would be available for dynamic load. The plan is to use the present plant to supply one linac and the new one to supply the other. No changes in the cryogenic transfer lines are required.

Recent conceptual design work has identified a new process cycle that would decrease the power requirements by 1/3. This cycle utilizes a JLab development.(see ref. [3])

Radio-frequency Power and Control

The 12 GeV Upgrade will use the same power/control topology as was used for the original construction of CEBAF wherein each cavity is energized by its own dedicated power source which has its own individual low-level controls. It was most recently again used for SNS. Other topologies which power multiple cavities with a single source have been explored and found to be more costly if they include components required to meet the amplitude and field control requirements, i.e. 0.01% and 0.2°, respectively.

Up to 450 µA of beam could be transiting a cavity and sufficient power must be provided to operate exceptionally good cavities at up to 21.2 MV/m. A margin must be allocated for the cavities being off-resonance; for this margin we presently assume 25 Hz. This value comes from: 1) 4 Hz allowance for tuner accuracy and 21 Hz (6x the historical 3.5 Hz standard deviation seen at CEBAF) allowance for uncompensated frequency shifts, also known as "microphonics". Folding into the calculation these factors plus reasonable engineering margins for loss in the waveguide, staying far enough below saturation that there is gain, and the potential for mistuning the cavities' optimum Q_{loaded}, it has been determined that 13 kW power sources are needed. As of the date of this writing, a commercial firm has demonstrated ~14 kW output from a klystron at CEBAF frequency; further development is needed however before it will meet all the specifications. Both IOT's and klystrons are presently under consideration, each having its own pro's and cons. A final choice for the amplifier technology has not been made.

An improved low-level rf control module is required. The existing design is 1990-vintage and is fully analog; repair parts are becoming rather difficult to find. Furthermore, the high optimum Q_{loaded} and sizeable Lorentz-force induced detuning results in significant new control challenges. Development work on a new digital system is presently underway in collaboration with Cornell, and DESY. A prototype system has been tested [4] and met the performance requirements on amplitude and phase control at gradients as high as 17 MV/m and with Q_{loaded} of $2x10^7$. Under those conditions, the detuning curve is double-valued; the prototype system was able to ramp to 13 MV/m in less than 1 sec using a piezo-electric component of the tuner. Further algorithm refinements are underway, including exploration of a selfexcited loop (SEL). Use of an SEL has several benefits, including rapid recovery of cavities that have tripped off and simplified resonance "identification" should a cavity be very off-resonance.

Some of the cryomodule testing has indicated that the cavities' resonant-frequency noise spectrum is not characterized by "white noise". Feed-forward could potentially damp a few of the major terms in the microphonics spectrum and thus reduce the mean detuning of the cavities. This would lead to a reduction in the required amplifier power.

Further testing will include a "vertical slice" test which will incorporate: 1) a high-gradient cavity, 2) a high-power klystron (such as the 13 kW unit under development by a commercial firm using SBIR funding), and 3) the improved version of the digital low-level controls. This testing is anticipated for Spring, 2007. These tests will provide overall system performance data as well as further information on the microphonics spectrum and thus the real power requirements.

BEAM TRANSPORT

The existing beam transport system consists of ~400 dipoles (B*L≥0.2T-m) and ~700 quads. Calculations of the emittance growth from synchrotron radiation of the electrons in dispersive sections of the beam transport found that the present 1 nm-rad emittance at 6 GeV will increase to ~5 nm-rad at 12 GeV with a "perfect" beam transport system using the present beam-optics lattice. The planned research program needs ≤ 10 nm-rad. Thus there is a margin of 2x to accommodate the reality of an "imperfect" transport system. The plan is therefore to retain the existing optics and associated magnet configuration with only minor changes in the optics to re-optimize the beta functions in the linacs to minimize the beam sizes there. The new tenth arc will be an optical clone of the lower arcs.

Most importantly, the fields in the existing beam transport system must be roughly doubled in order to deliver 12 GeV beams. Strategies have been developed which meet that goal but do not require replacing many magnets. To forestall saturation in the 250 (of 340 total) major dipoles located in the recirculation arcs, we will add iron which will change them from "C" designs to "H" designs. The remaining 90 dipoles will be replaced. Only 10% of the ~700 quadrupoles must be replaced with new magnets; another 10% will get stronger power supplies (testing has shown that they can be driven to 130% of design field without significant change in field quality). Fifteen of the 36 large (<750kW) dipole power supplies will be replaced.

A new recirculation arc will be added to bring the 5-pass beam back to the North Linac for continued acceleration. A beamline from the end of the North Linac to Hall D will be added. The optics and magnet designs for each will be slight variations on existing designs.

Specifications for the magnets have been developed using analytic methods. (see ref. [5]) These specifications have been checked with particle tracking. The tracking studies have included the impact of misalignment, mispowering, and limitations in steering algorithms, in addition to the magnet field quality. Prototype dipoles and quads have met the specifications.

PROJECT STATUS

DOE approved Critical Decision 1 (Approve Alternative Selection and Cost Range) in February, 2006 with a cost range of $225M-300M. Critical Decision 2 (Approve Project Baseline) is anticipated for September, 2007.

With the current funding profile, construction is scheduled to begin late in 2008. The 6 GeV accelerator will continue to deliver beam for the users until early 2012 when it will be shut down for 9-12 months for the major re-configuration and installation work in the accelerator tunnel. Accelerator commissioning will start in early 2013, followed by the start of Hall commissioning.

ACKNOWLEDGEMENTS

This manuscript has been authored by Jefferson Science Associates, LLC under Contract No. DE-AC05-06OR23177 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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