JLAB-ACC-99-17

JEFFERSON LAB CEBAF ENERGY UPGRADE PLANS *

C. H. Rode, J. Benesch, Y. Chao, J. R. Delayen, J. Karn, J. Mammosser, W. Oren, J. Preble, W. J. Schneider, R. Wines, M. Wiseman

Thomas Jefferson National Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606-1909 USA

ABSTRACT

This paper presents interim conceptual plans for upgrading the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility to extend Jefferson Lab's world leadership in nuclear physics research. The CEBAF accelerator was designed in the mid-1980s to provide beams of electrons at an energy of 4 GeV (billion electron volts) for use as probes of the atom's nucleus in CEBAF's three experiment halls. As of early 1999, the accelerator exceeds its design energy by routinely operating above 5.5 GeV. When upgraded, it will provide 11 GeV electron beams for studies in existing experimental halls and 12 GeV electrons to generate photon beams for related but qualitatively different nuclear studies in a new Hall D.[1]

PROJECT BACKGROUND AND CONTEXT

Jefferson Lab's CEBAF experimental program fulfills a major, two-decade-old priority of U.S. nuclear science: the construction and scientific use of a 4 GeV, continuous-beam electron accelerator capable of supporting a broad range of innovative research in nuclear physics.

The CEBAF facility is unique. It allows detailed exploration of the energy region where the transition occurs between two basic ways of viewing the nucleus. In the standard picture as seen at lower accelerator energies, the nucleus appears as a group of interacting nucleons—protons and neutrons. At higher energies, the quarks and gluons inside the nucleons must be explicitly included. Applicable at the high-energy end of the transition region between these two views are the essentially exact calculations of a field theory, perturbative quantum chromodynamics (QCD). In the lower-energy non-perturbative region characteristic of normal nuclear matter, an important new "strong QCD" framework is required. Elucidating the nature of this transition is one of the last frontiers in humankind's quest to understand ordinary matter. CEBAF is the key research tool for the task.

Therefore an intense scientific interest exists, not only nationwide but worldwide, for conducting experiments at CEBAF. During the mid-1990s, CEBAF's earliest operations for physics began to generate new contributions to understanding of the nucleus. As of spring 1999, more than 1400 nuclear physicists make up CEBAF's user group, and the

* Supported by U.S. DOE contract DE-AC05-84ER40150

backlog of planned experiments stretches to more than six years. Reference 2 presents a user-focused assessment of the prospects for upgrading CEBAF.

Jefferson Lab's Institutional Plan[3] expresses the vision for extending this success into the future. The lab's top two goals of "enabling and conducting a physics research program of the highest scientific priority at the nuclear/particle physics interface" and "continued world leadership in underlying core competencies" provide the basis for the envisioned upgrade. Increasing the maximum beam energy toward 12 GeV (intermediate-term goal) and the 24 GeV (long-range goal) will extend the scientific reach of the advancing experimental program. Jefferson Lab's main core competency in superconducting radio-frequency (SRF) electron acceleration is the enabling technology at the heart of the upgrade.

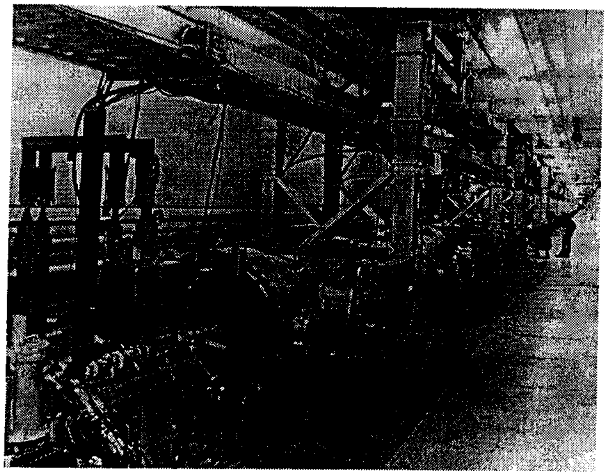
Within the nuclear physics community it is a given that in the long run a strong physics case exists for a CEBAF-like machine operating in the energy range beyond 24 GeV to perhaps 30 GeV. It is Jefferson Lab's intent to continue serving U.S. nuclear science by becoming the obvious cost-effective site for this machine. Two factors make upgrading CEBAF to these higher energies attractive:

- The needed accelerator tunnel already exists at Jefferson Lab. Since the existing racetrack-shaped, 1.3 km CEBAF tunnel was constructed with recirculation arcs of large radius, a 24 GeV machine could operate there without significant synchrotron-radiation-caused degradation of beam quality.
- The necessary expertise and infrastructure will exist at Jefferson Lab. The CEBAF SRF cryomodule development program described here will lead in the next decade to the capability for building the 24 GeV machine.

While the plan presented here does not directly address the 24 GeV upgrade, the future project does constitute an important part of the context, rationale, and planning for 12 GeV. Also, a clear consensus already exists amongst CEBAF's users in support of the currently envisioned 12 GeV upgrade. Thus, the next logical step toward 24 GeV is fully consistent with the nearer-term needs of nuclear physics researchers.

Though integrated with the longer-term vision, the 12 GeV upgrade also stands alone as a project that is both physics-driven and achievable with modest modifications and additions to the existing machine. Figures 1 through 3 represent what is to be upgraded. Figure 1 is the entire CEBAF accelerator complex as seen from the air; one of the twin linear accelerators (linacs) made up of 20 cryomodules consisting of four pairs of superconducting cavities each is shown in Figure 2. Figure 3 is a photograph of key components within the Central Helium Liquifier (CHL), which supplies liquid helium at 2 K for the superconducting operation of the accelerator.

Figure 1. Aerial view of the CEBAF accelerator complex. CEBAF's nuclear physics users conduct their experiments in the earthen-topped, domed, semi-underground structures in the foreground—from left to right, Experimental Halls A, B, and C. The underground accelerator's racetrack shape can be traced by the service buildings and road above ground. RF power reaches the accelerating components of each linac from within the long service buildings above the "straightaways." Service buildings above the recirculation arcs that interconnect the two linacs house DC power supplies for the recirculation-arc beam-transport magnets.



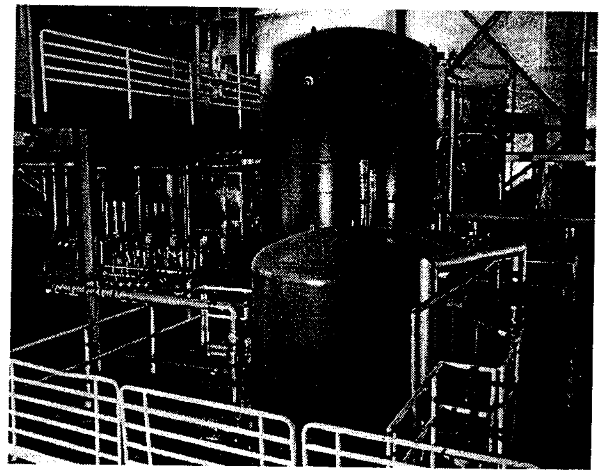


Figure 2. (on the left) Cryomodules in CEBAF's South Linac, with RF power waveguides descending from service buildings

Figure 3. (on the right) The 2 K and 4 K cold boxes in CEBAF's 4.8 kW Central Helium Liquifier (CHL), which represents the world's largest 2 K cryogenics capacity.

The following requirements were established to support the envisioned physics program and keep modifications and additions to the present machine modest:

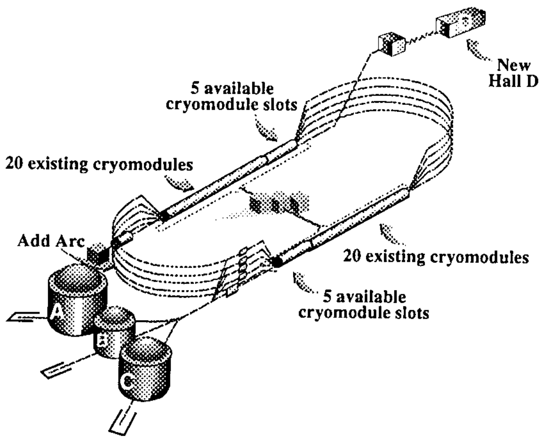
- The highest-energy beam at 12 GeV must only be delivered for 8 GeV photon beam production to the new experimental hall, Hall D. Electron beam quality requirements are somewhat relaxed from original machine specifications.
- CW operation must be preserved.
- The maximum circulating beam current will be 430 μA (corresponding to an 85 μA beam for a five-pass design).
- The maximum installed refrigeration capacity will be 10.1 kW at 2 K.
- Technical choices should be made with the ultimate goal of 24 GeV in mind.
- Cost and impact on accelerator operation must be kept to a minimum.

Table 1 and Figure 4 summarize key elements of a 12 GeV upgrade plan that meets the above requirements.

Table 1. Selected key parameters of the CEBAF 12 GeV Upgrade

Parameter	Specification
Number of passes for Hall D	5.5 (add a tenth arc)
Energy to Hall D	12.113 GeV (for 8 GeV photons)
Number of passes for Halls A,B,C	5
Energy to Halls A,B,C	11.023 GeV
Duty factor	CW
Max. current to Halls A,C*	85 μA
Max current to Halls B,D	5 μA
New cryomodules	10 (5 per linac)
Replacement cryomodules	8 (3 per linac, 2 in injector)
Central Helium Liquifier upgrade	10.1 kW (from present 4.8 kW)

*Max. North Linac current is 430 μA; max. South Linac current is 425 μA.



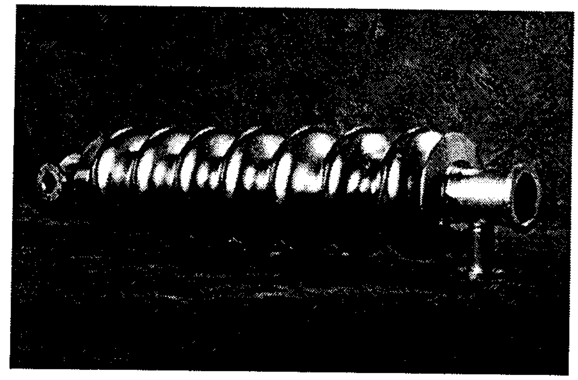


Figure 4. (on the left) Cryomodule slots available for upgrading existing CEBAF accelerator to a 12 GeV machine.

Figure 5. (on the right) Prototype seven-cell, 1497 MHz CEBAF SRF accelerating cavity.

SRF CRYOMODULES

The higher energy will be obtained by adding new, higher voltage cryomodules (five per linac) and replacing old units with new ones. The new cryomodules are being developed based on SRF technology improvements achieved at Jefferson Lab and elsewhere in the last decade. To increase the voltage provided by a cryomodule of given slot length requires increasing the cavity accelerating gradient, or increasing the effective accelerating length within the cryomodule, or both. However, maximizing the accelerating length involves less technical risk and, for CW operation, has the added advantage of lowering the dynamic refrigeration load. So the upgrade cryomodule will contain eight seven-cell cavities (Figure 5), as opposed to the four distinct pairs of five-cell cavities in the existing configuration. Since the cell design itself has not been changed for the upgrade, this means 8 × 70 cm of active length per cryomodule, rather than the previous 8 × 50 cm. To accommodate the increased cavity length within an unchanged cryomodule slot length, the upgrade has been redesigned to exclude the original pair-to-pair bridging sections. With gradients exceeding 12 MV/m routinely available from CEBAF SRF cavity technology in the late 1990s, 68 MV can be conservatively specified for the upgrade cryomodule. A Q of 6.5×10^9 at 12.5 MV/m has been specified for the seven-cell cavities, and has been met in tests of a seven-cell prototype.[4]

The key to the upgrade—and the majority of the project cost—lies in doubling the accelerating voltage of each superconducting radio-frequency (SRF) linac. Doubling the energy means:

- adding in available slots five new, improved-performance cryomodules to each linac,
- replacing three more in each linac, and
- as an option, replacing two more in the injector.

Table 2 details the 25 cryomodules per upgraded linac according to accelerating gradient, cryomodule energy, and total linac energy.

Table 2. Cryomodule (CM) and Linac Voltage (per Linac)in the 12 GeV Upgrade

Number of CMs	CM Length (meters)	CM gradient (MV/m)	CM energy (MV)	Linac energy (MV)
(upgrade) 8	5.6	12.19	68.25	546.0
(existing) 17	4.0	8.00	32.00	544.0
Total: 25	112.8			1090.0

CHL UPGRADE

Overview

Besides the SRF effort summarized above, the upgrade project involves a number of much smaller but still significant tasks. The most costly of these is doubling the capacity of the Central Helium Liquifier (CHL), to support the increased SRF loads. For 6 GeV one refrigerator (CHL #1) cools both linacs, while for the upgrade each linac will have its own refrigerator.

The current setup has the existing CHL#1 feeding two linacs with the injector as an extension of the North Linac and Jefferson Lab's FEL plugged into a tee on the South Linac U-tube.[5] The 12 GeV upgrade has CHL#1 feeding only the North Linac, while the new CHL#2 is feeding the South Linac and the FEL.

CHL#2 consists of a compressor system very similar to CHL#1, a 300 to 80 K cold box, an 80 to 4.5 K cold box (the existing cold box from MFTF-B), and the new "redundant 2 K cold box". CHL#2 is being designed to have 10% larger capacity than CHL#1 in order to handle a FEL upgrade.

Cycle Design

The fifth-stage cold compressor (CC) was installed in the "redundant 2 K cold box" in FY98-99 and will be installed in the original 2 K cold box next year. This permits much greater flexibility of operation. It also will permit operation at capacities of 70 to 120% and 140 to 220% of the original 4800 W. As the Q of the cavities improves, the BCS heat load fraction increases, which in turn changes the temperature optimization. For the 12 GeV upgrade we plan to operate at 1.95 K vs. the current 2.08 K.

Hardware

The new fifth-stage CC increases the total potential compression ratio by a factor of two, tremendously increasing the flexibility of the system. It provides:

- Higher discharge pressure: the system is easier to start and less sensitive to warm compressor upsets.
- Higher maximum capacity: the fifth stage can be used to reduce the load on the third and fourth stage.
- Lower minimum capacity: one can use the smaller stages 2 to 5 vs. 1 to 4.
- Lower operating temperature: one can reduce the operating pressure and return at the 35 K tap.

Distribution System

With the exception of eight bayonet valves (zones 22 through 25) and the related controls, the distribution system is ready to accept the ten new cryomodules. The zone 26 "dummy cryomodules" required to keep the ends of the transfer lines cold will be removed.

Doubling the refrigeration capacity has two impacts. First due to higher flow rates, the return pressure drops will approximately double. Second with the ratio of dynamic vs. static heat loads increasing, the return temperature will decrease. This will permit the CCs to operate closer to their design point.

SUBSYSTEM UPGRADES

Relatively minor changes must also be made to other accelerator subsystems to accommodate the higher energy. A tenth arc beamline will be added so that the Hall D beam can be accelerated in a sixth pass through the north linac to Hall D, for a total of 5.5 passes through the entire machine. This yields a 12 GeV beam for 8 GeV photon production in Hall D utilizing hardware and processes addressed in Reference 1. Changes in DC power supplies and spreader/recombiner magnets represent the upgrade's other main impacts on the recirculation arcs. The project also necessitates ten new RF stations, plus minor modifications to other RF systems. Table 3 is an itemized list of major upgrade items.

Table 3. Major Upgrade Items

Number	Item
10	Additional upgrade CM & supporting RF
8	Replacement upgrade CM & RF upgrades
-	Double CHL capacity
-	CHL building addition
-	New Arc 10
-	Move injector beamline
17	New spreader/recombiner dipoles
55	Modified spreader/recombiner dipoles
-	Box PS upgrade (16 regulators, 25 rectifier modules)
5	Modified arcs (C to H style dipoles)
57	New quads (two new styles)
85	New 17 A, 55 V trim cards
130	New 60 A shunt modules
2	New extraction Lambertson magnets
5	New (higher-power) RF separator cavities
3	5 kW RF separator tubes
-	New Hall D transport line
2	Service building additions

Increased Bending and Focusing Strengths of Beam Transport Magnets

The increase in design energy from 6 GeV to 12 GeV demands stronger bending and focusing power from the magnets. In the recirculation arcs this can be achieved with modifications to the dipoles to reduce saturation. In five of the nine existing arcs the "C" dipoles with the highest fields saturate the backleg iron. We will replace the aluminum coil supports on the open face of the existing dipoles with a steel U-channels (Figure 6). This simple but time-consuming (160 dipoles) upgrade will be accomplished during bi-weekly maintenance shifts and dramatically improves the magnets saturation at higher currents (Figure 7).

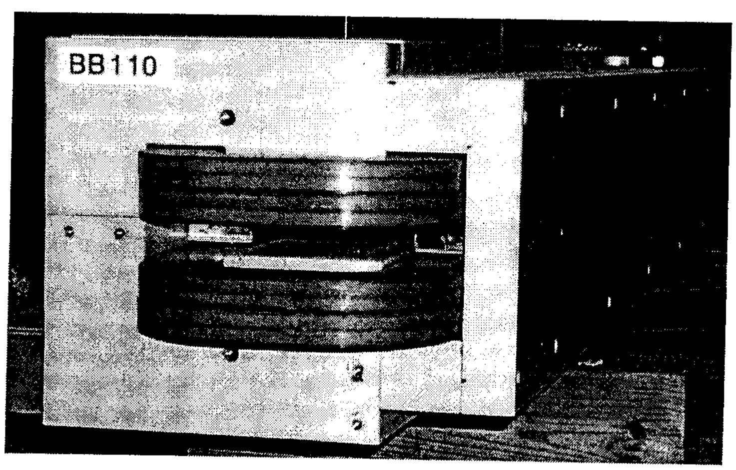


Figure 6. Prototype BB with added H-Steel.

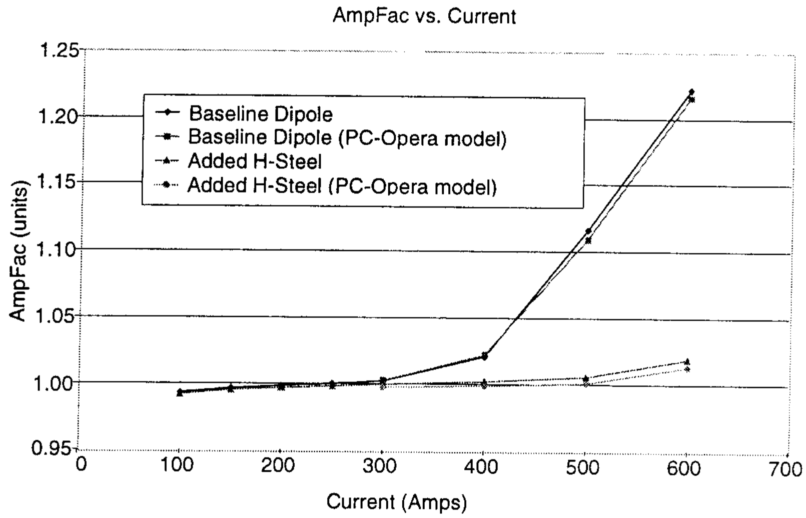


Figure 7. Saturation versus current for prototype BB dipole.

The most difficult of the non-SRF tasks will be the modification of the spreader/recombiner magnets, which will represent the largest contribution to upgrade driven accelerator down time. This is a very densely packed area with five or six vertically separated beams. Due to this limitation, the dipoles have a cross section aspect ratio reversed from normal dipoles, which leads to a severe saturation of the pole tips. In order to fix this and maintain good field quality, we are adding U-channel steel and four or six turns to the pole tip gap (see Figure 8). These coils will be in series with the main coils.

Quadrupole upgrades are scattered throughout the machine. The majority of these focusing issues are resolved by rearranging existing magnets and manufacturing two new styles which accommodate the more energetic beam.

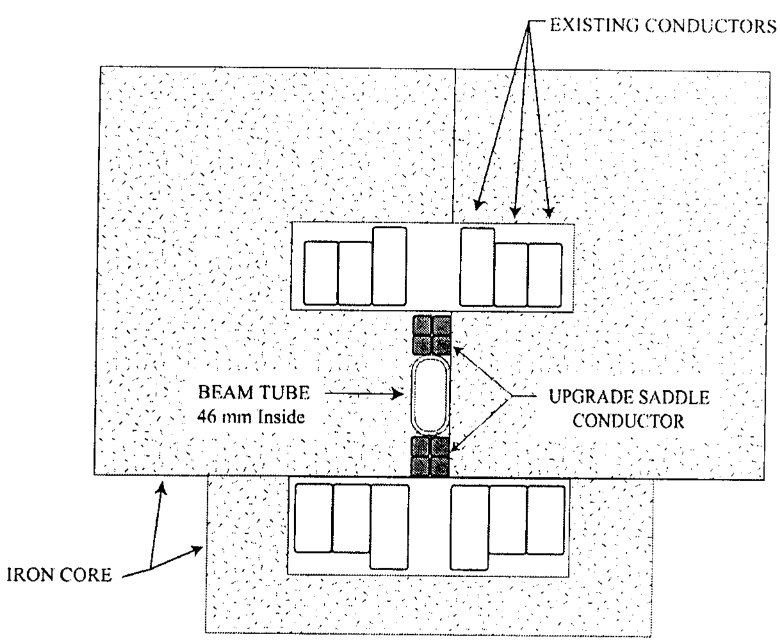


Figure 8. Upgrade 1 m spreader/recombiner dipole (at center).

Delivery of 5.5-Pass Beam to Experiment

Transporting the beam back to a sixth North Linac acceleration pass en route to Hall D, will require installation of a fifth arc at the west end of the accelerator (Arc 10). This will use longer 4 m "H" dipoles installed under the existing 3 m dipoles of Arc 8.

A new beam separation scheme allowing a six-way separation out of the North Linac is a major feature of the 12 GeV upgrade. This is motivated by an additional line transporting the highest-energy (12.113 GeV) beam to Hall D. The sixth-pass beamline will branch out of the northeast spreader at an elevation 0.5 m below the linac axis. This implies staged separation of the last three passes (versus the current two) using septum magnets while attending to tolerances on trajectory clearance inside septa and dispersion suppression within the existing longitudinal space.

FUTURE PLANS

Next Steps for FY 1999

- Continue upgrade CM design
- Test RF 6.5 kW upgrade
- Continue on 3D field quality calculations

Steps Planned for FY 2000

- Finalize CM design and fabricate cavities for 1/2 CM test
- Test 1 m Spreader/Recombiner dipole with six-turn gap coil
- Detailed cryo design and cost estimate
- Finalize Hall A, B, C extraction design and cost estimate
- High power test of spare RF separator cavity

Steps Planned for FY 2001

- Assemble and test 1/2 CM
- RF control module upgrade design and prototype

MAJOR OPEN ISSUES

1. RF control for the New Cryomodules. At 68 MV/CM (as opposed to the present nominal 30 MV/CM), there is a need to increase external Q leading to a bandwidth that is a factor of 4 or 5 narrower than at present. At 12.5 MV/m and 400 μA circulating current the maximum allowable amount of detuning (including static and microphonics) is 25 Hz. With the Lorentz detuning being much larger than the loaded bandwidth and the completely new tuning system hardware, a new more agile RF control interface will be required.

2. Injector recirculation. If the 12 GeV upgrade incorporated the added complexity of recirculation in the injector to increase injection energy, the two replacement cryomodules slated for this area could be dispensed with. For 24 GeV, injector recirculation is the baseline concept.

ACKNOWLEDGMENTS

This paper represents the efforts of the Jefferson Lab Accelerator Division.

REFERENCES

1. Jefferson Lab, *Photoproduction of Unusual Mesons and Gluonic Excitations: Hall D Preliminary Design Report*, January 1999.
2. L. S. Cardman, "Jefferson Lab at Higher Energies: Options and Opportunities," Jefferson Lab internal document, 15 June 1998.
3. The present report reflects the 2000-2004 update of Jefferson Lab's Institutional Plan; to be released in the fall of 1999.
4. I. E. Campisi et al., "Superconducting cavity development for the CEBAF upgrade," Proceedings of the 1999 Particle Accelerator Conference (in press).
5. C. H. Rode, "CEBAF Cryogenic System," Proceedings of the 1995 Particle Accelerator Conference.