3 THE ACCELERATOR UPGRADE

3.A Overview

To deliver a 12 GeV beam, the CEBAF accelerator must be upgraded from its demonstrated 6 GeV capability. The straightforward plan is to utilize the existing tunnel and not change the basic layout of the accelerator. As such, the Upgrade can be categorized as having two major components: 1) additional acceleration in the linacs; and 2) stronger magnets for the recirculation. In this portion of the White Paper, we begin with an overview of the Upgrade. This is followed by a summary description of the changes to the present accelerator necessary to reach 12 GeV (Section 3.B), and a description of the present status and capabilities of the existing CEBAF accelerator (Section 3.C). Section 3.D presents the details of the Upgrade project. Additional information and details are available in an internal JLab report, *Interim Point Design for the CEBAF 12 GeV Upgrade,* May 25, 1999.

Key points of the CEBAF 12 GeV Upgrade

- The highest-energy beam at 12 GeV needs to be delivered only to the planned new experiment hall, Hall D.
- CW operation must be preserved.
- The maximum circulating linac beam current will be 425 μA (corresponding to an 85 μA delivered beam for five-pass operation).
- The maximum installed refrigeration capacity will be 10 kW at 2 K.
- Technical choices should be made that do not preclude the eventual upgrade of CEBAF to 24 GeV.
- No more than three halls receive beam at any time, and each receives a different energy beam.
- Both cost and impact on accelerator operation must be kept to a minimum.

The key parameters of the upgraded accelerator are presented in Table 6.

Table 6: Selected key parameters of the CEBAF 12 GeV Upgrade

Parameter	Specification
Number of passes for Hall D	5.5 (add a tenth arc)
Max. energy to Hall D	12.1 GeV (for 9 GeV photons)
Number of passes for Halls A,B,C	5
Max. energy to Halls A,B,C	11.0 GeV
Max. energy Gain per pass	2.2 GeV
Range of energy gain per pass	2:1
Duty factor	cw
Max. summed current to Halls A,C* (at full, 5-pass energy)	85 μA
Max. summed current to Halls B,D	5 μA
New cryomodules	10 (5 per linac)
Replacement cryomodules	Up to 6 (3 per linac)
Central Helium Liquifier upgrade	10.1 kW (from present 4.8 kW)

*Max. current is 430 μA (north linac) and 425 μA (south linac) and max. *total* beam power is 1 MW.

3.B Highlights of the Changes to the Accelerator

3.B.1 Acceleration

The extensive series of workshops on the 12 GeV Upgrade organized by the JLab nuclear physics users has determined that 12 GeV is required only for Hall D. This is important because it presents the option of placing that hall at the opposite end of the accelerator from the other halls (see Fig. 57) and achieving the needed 12 GeV beam by accelerating through one more linac than is reachable by the beam going to Halls A, B, or C. The advantage is that the total installed accelerating voltage is thereby reduced by 10% relative to what would have been required otherwise.

Presently each of the two linacs provides ∼550 MV of acceleration per pass. To reach 12 GeV, we will need ∼1090 MV, or roughly double the present performance. Fortunately, there is space in the two linacs for a total of ten additional cryomodules. Adding ten cryomodules that are identical to the originals would only bring us to ∼690 MV/linac. To gain the additional acceleration, we have designed and begun prototyping new cryomodules which will provide at least 68 MV (vs. the 28 MV from the existing cryomodules). Ten of these new cryomodules will be installed and six of the existing cryomodules will be replaced with new ones. The most important feature of the new

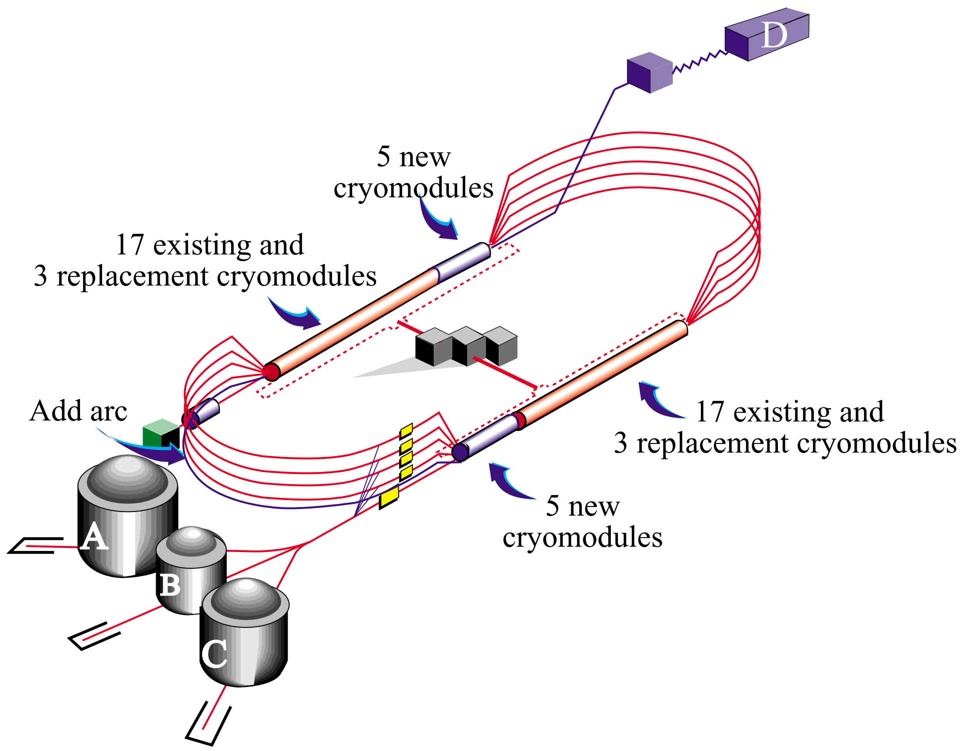

Figure 57: The configuration of the proposed 12 GeV CEBAF upgrade.

cryomodules is a new SRF cavity design. The new cavity has seven cells vs. the five in the present cavity. The cavities will be prepared with improved processes which will result in consistently higher average gradients.

The new cryomodules will increase the static heat load on the cryogenic system. The higher gradients in the cavities in the new cryomodules will increase the dynamic heat load on the system. The result is that the 12 GeV accelerator will require a larger 2 K helium plant than that available for the present accelerator. We plan to increase the 4 K capacity of the helium plant and utilize the already-installed backup 2 K cold box to provide the necessary capacity. The upgraded helium plant will require additional building space, electrical power, and cooling water.

In addition, the behavior of the new cavities will require a change in the rf control. The large Lorentz force at the desired field levels together with a reduced bandwidth to economize power results in a detuning curve that is not single-valued. The present rf control system does not have enough tuning agility to handle this situation. Development has begun of a new rf control module that would not suffer this limitation because it addresses the problem electronically.

3.B.2 Beam Transport

A primary concern of the nuclear physics experimental users is the beam quality. The users have become accustomed to extremely good beam quality. The beam quality will degrade as we push above ∼7 GeV because of synchrotron radiation in the bending dipoles. At 12 GeV the spot size will be five times larger than it is at 4 GeV, and the energy spread will be three times larger than it is at 4 GeV. The User Group Board of Directors has endorsed these beam quality specifications.

The beam transport for the recirculation requires no conceptual change. In essence, the fields in the magnets in the primary bending arcs need to be increased. Although the magnets were not designed for operation at these higher fields, simple work-arounds have been identified for almost all of the magnets.

> Dipoles: The dipoles were designed to exhibit minimal saturation effects at fields appropriate for 6 GeV operation of the 5-pass machine. Pushing these fields to values appropriate for 10.9 GeV operation (the equivalent five-pass energy for a 5.5-pass configuration) would lead to considerable saturation and thus require very large power supplies. However, the present dipoles were designed as C magnets; *i.e.*, they have a return yoke on only one side. Our plans call for turning them into H magnets; *i.e.*,

having return yokes on both sides. This reduces the field levels in the iron to values that are very close to those in the existing C magnets during 6 GeV operation.

Quadrupoles: The prudent engineering margin in the present set of quadrupoles results in their being usable up to ∼7 GeV with no changes. Samples of these quadrupoles have been tested up to 170% of their design current and were found to have acceptable field quality. For the majority of the quadrupoles, changing to higher-current power supplies will suffice to reach 12 GeV.

The most obvious change in the beam transport for the accelerator upgrade to 12 GeV is the addition of the tenth recirculation arc. Clearly this requires the construction of new dipoles and quadrupoles. In particular, stronger dipoles and quadrupoles need to be designed. For both we have taken the basic design used in the original construction and have lengthened it to provide the needed field integral.

Less obvious is the need to modify the spreaders and recombiners. (The beams are collinear in the linacs and must be separated at the ends of the linacs and then put back together before entering the next linac.) The topologies in these portions of the machine are sufficiently congested that adding the requisite iron for higher fields will not be possible. Redesign of these sections has been done. Slight adjustments in several magnets' positions were required; replacement of some magnets with longer magnets was also required. Another change was to accommodate the additional beam that will be present in the spreader at the end of the north linac; *i.e.*, the beam going to Hall D. Magnets had to be added in order to separate this beam from the first five passes and to transport it to Hall D.

It should also be noted that unlike the present configuration, which permits delivery of fifth-pass beam to Halls A, B, and C simultaneously, the new configuration requires Halls A, B, and C to receive different energies. Modifications that would permit same-energy beam to be delivered to multiple halls simultaneously are not within the scope of this project.

Clearly, many new power supplies are needed. These will require additions to the building space, more ac power, and more cooling water. In addition, more cooling water will be required for the magnets themselves. The overall requirements for the Upgrade are summarized in Table 7.

Table 7: Summary of major Upgrade items

Number	Item
10	Additional Upgrade CM & supporting rf
6	Replacement Upgrade CM & rf upgrades
-	Double CHL capacity
-	CHL building addition
-	New arc 10
-	Move injector beam line
17	New S/R dipoles
55	Modified S/R dipoles
-	Box PS upgrade (16 regulators, 25 rectifier modules)
5	Modified arcs (C to H style dipoles)
57	New quadrupoles (two new styles)
85	New 17 A, 55 V trim cards
130	New 60 A shunt modules
2	New extraction Lambertsons
5	New (higher-power) rf separator cavities
3	5 kW rf separator tubes
-	New Hall D transport line
-	North and South Access Building additions

3.C CEBAF Today: A Status Report

The Upgrade builds on the present CEBAF accelerator. This section summarizes the status of the accelerator and our operational experience with it. The present accelerator provides a solid platform for the Upgrade. It has already demonstrated the capability of delivering beam near 6 GeV, a full 50% above design specification. The operation of the five-pass recirculation system and the superconducting linacs is now routine, and the accelerator delivers multiple beams with unprecedented polarization and independently controlled current reliably to the three experimental halls. The support systems operate reliably, and the knowledge gained over the past decade of commissioning and operation has provided important insights into the design of the Upgrade.

The design energy of CEBAF is 4 GeV, based on 20 cryomodules in each of the north and south linacs and $2\frac{1}{4}$ modules in the injector. Because the later modules in the production run significantly exceeded the design specification one of the modules was removed from the south linac to study Upgrade options, leaving only 19 modules in that linac. It was with this complement of cavities that CEBAF reached its design beam specification (4 GeV, 200 μA) in 1997. In subsequent years, the cavity trip rate due to arcing on the rf window (that is believed to be caused by charge build-up from electron emission in the cavity) was reduced by the use of helium processing, and the maximum energy of the accelerator has been steadily increasing. In January 2000, a new cryomodule was installed in the last slot of the south linac, and cryomodules were interchanged between the north and south linacs to equalize the energy gain available from each linac. These improvements significantly reduced the rf trip rate during operation at energies up to 5.6 GeV. A test of 6 GeV operation was performed in August 2000 with cw beam. Further improvements and 6 GeV testing are planned, and we expect to deliver 6 GeV beam for physics in the near-term future. The basic operating characteristics of the CEBAF accelerator are outlined in Table 8.

Maintaining the rf systems in optimum condition has required the development of complex algorithms. These maintain the cavities on resonance, and keep the beam on the crest of the cavity fields. In addition, a sophisticated program optimizes the cavity gradient to minimize the arc trip rate and cryogenic heat load for a required total acceleration energy and beam current. A recent problem is that some cavities are now operating in the regime where the Lorenz detuning exceeds the cavity bandwidth, so that recovering a tripped cavity is time-consuming and must be carried out by hand. Semi-automated routines will be written to improve the recovery time, but new rf modules are needed to operate the new cryomodules. Definition of the system requirements and initial engineering discussions on these new rf control modules have been started.

The magnet and power supply systems, as originally installed, were limited to settings cor-

Table 8: Key parameters of the present CEBAF accelerator

Parameter	Specification
Number of passes for Halls A,B,C	1–5
Max. Energy to Halls A,B,C	≤ 6 GeV
Duty factor	cw
Beam emittance at full energy:	
transverse	3×10^{-7}mm
longitudinal	$\delta p/p \leq 1 \times 10^{-4}$
Max. summed current to Halls A,C*	180 μA
Max. current to Hall B	5 μA
# of cryomodules	$42\frac{1}{4}$
Central Helium Liquifier capacity	4.8 kW (at 2.07 K)

*Max. linac current is 1 mA

responding to slightly above 4 GeV, with the limitation coming from some of the power supplies. These have been upgraded, so the accelerator may now be considered a 6 GeV machine. The stability of the magnet system has undergone several rounds of improvements as the requirements of the users became more demanding. This required the development of off-line analysis tools to find unstable magnets and/or power supplies. Most of the problems were traced to the way the hysteresis loops were handled, and these have now all been changed to a new protocol that provides both short- and long-term stability.

The polarized injector now has two fully operational, horizontally mounted polarized guns. All beam operation, polarized or unpolarized, is now conducted with high-polarization cathodes. When polarized beam is not required, shorter-wavelength lasers are used to take advantage of the higher quantum efficiency at these wavelengths. This has been very successfully demonstrated as of mid-2000, with unpolarized beam up to 130 μA delivered to Hall A while high-polarization beam was delivered to Hall B at 5 nA. The only known problem is that tails on the high-power laser pulses for Halls A and C can produce electrons within the acceptance for Hall B. Typical values for this feedthrough from Hall A to Hall B are about 50 pA. The photocathode lifetime in the new horizontal guns is excellent. The present value is over 10^5 C/cm^2. Though this long lifetime makes absolute statements difficult, our present experience is that the cathode deterioration can be completely removed by a simple heat treatment and reactivation. This cathode recovery can be accomplished during a normal maintenance period, which implies that a single cathode could be used essentially without limit. During the past year, over 280,000 μA-hours were delivered from the polarized guns.

During January 2000, a test run was conducted with a new Ti-sapphire laser, which delivered ∼400 μA of high-polarization beam. The final version of this laser will allow this current to be more than doubled. We installed this laser during the shutdown in August 2000. Once this laser is operational, we will be able to deliver high-polarization beam at full current to one hall. A second laser of this type will be prepared, to allow high-polarization operation to both Halls A and C. Based on the very successful operation of the new guns, and the coming installation of this new laser, we have removed some of the components that allowed beam to be delivered from the thermionic gun. While we could restore these components and operate the thermionic gun again, there is no plan for any further running with unpolarized (or low-polarization) beam.

Over the last three years, most of the operations have been scheduled with polarized beam required in more than one hall. There are only two beam energies (2.115 and 4.230 GeV) at which purely longitudinal spin can be delivered simultaneously to all three halls when the halls have the same energy. There are, however, many combinations of passes and linac energies at which it is possible to deliver beams with perfectly longitudinal polarization to two halls simultaneously, and many combinations at which it is possible to deliver nearly (¿90%) longitudinal polarization to all three halls.

3.D Details of the 12 GeV Upgrade of the CEBAF Accelerator

In this section we address, in turn, the changes necessary to the CEBAF accelerator to upgrade it to the 12 GeV capability required for the physics program. We address, in turn, new accelerating structures, rf power and control, the optics and beam transport, magnet power supplies, instrumentation and control systems, cryogenics, and civil construction. A final section addresses the schedule for the Upgrade.

3.D.1 Accelerating Structures

The Upgrade Cryomodule is clearly the key component of the upgrade of the acceleration system. Its design is also somewhat insensitive to the details of the Upgrade, once the top-level parameters have been defined, and it can be viewed as a building block that can be applied to a large number of Upgrade paths. For these reasons, most of the development efforts in support of the Upgrade are directed toward the development and demonstration of prototype Upgrade cryomodules. Table 9 compares the original CEBAF linac parameters with those of the upgraded linac with the new cryomodules added.

Table 9: CEBAF linac parameters: 4 GeV vs. 12 GeV

Parameter	Linac CMs for 4 GeV (original)	Linac CMs for 12 GeV Retained original	Upgrade
Acceleration	400 MeV	544 MeV	544 MeV
Maximum linac current (at maximum E)	1000 μA	430 μA	430 μA
Linac slot length	9.6 m	9.6 m	9.6 m
CM* slot length	8.25 m	8.25 m	8.71 m
Warm vac. slot length	1.35 m	1.35 m (also 1.12 m)	0.89 m
# CM/linac	20	$\geq$17	$\leq$8
Voltage/CM	20 MV	32 MV	68 MV
E_{acc} average	5 MV/m	8 MV/m	12.2 MV/m
$Q_\circ$ @ E_{acc}	2.4×10^9	5.0×10^9	6.5×10^9
rf windows/cavity	2	Same	1
FPC coupling	$\lambda/2$ stub on stub	Same	$\lambda/4$ stub
Q_{ext} FPC	6.6×10^6	Same	2.2×10^7
HOM coupling	Waveguide	Same	Coaxial
B.L. bellows/CM	5	Same	2
Vac. valves/CM	10	Same	4
Freq. tuner/cavity	Single	Same	Dual (coarse/fine)
Cryounits (CU)/CM	4	Same	1
Cavities/CU	2	Same	8
2 K rf heat load	45 W	72 W	160 W
50 K rf heat load	20 W	40 W	120 W
2 K static heat load	15 W	15 W	25 W
50 K static heat load	140 W	140 W	180 W

*CM = cryomodule

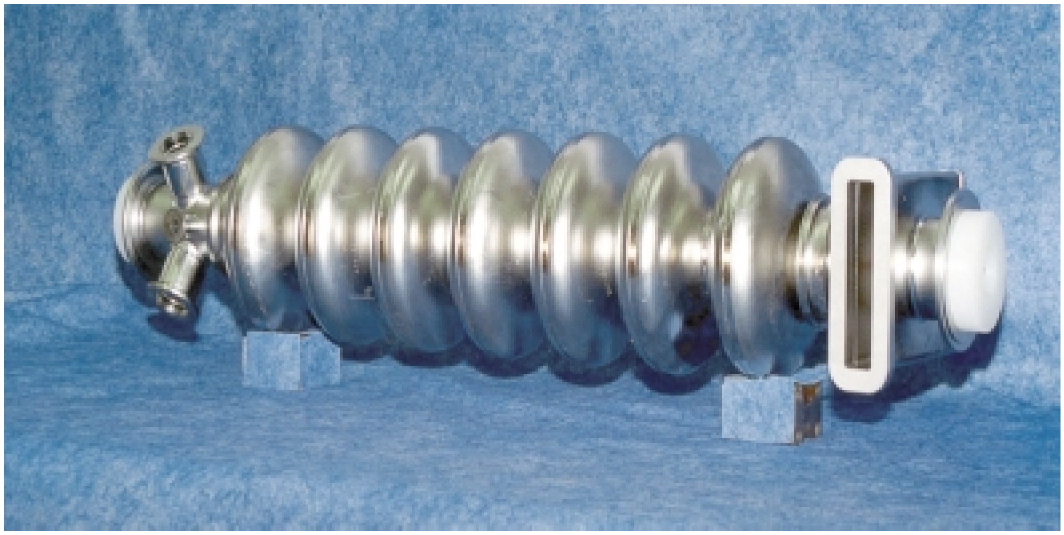

Figure 58: Prototype seven-cell cavity.

Cavities

In order to increase the voltage that is provided by a cryomodule within a given length, one can either increase the gradient at which the cavities are operating, or increase the effective accelerating length, or both. While it may be argued that adding accelerating length is the approach that presents the least technological risk, for cw accelerators such as CEBAF, maximizing the length instead of the gradient has the added advantage of lowering the dynamic load on the refrigeration system.

For this reason, it was decided early that the Upgrade Cryomodule would still include eight cavities, but that these would be seven-cell cavities (70 cm) instead of the present five-cell (50 cm). Meeting the overall system performance goals calls for these cavities to provide a minimum voltage of 8.75 MV with a maximum power dissipation of 17.5 W; *i.e.*, their Q_0 must be at least 6.5×10^9 at 12.5 MV/m. Thus the greatest challenge is not so much in achieving a high gradient but in maintaining a high Q_0 at that high gradient. Given the constraint imposed by the available refrigeration, cw operation at 15 MV/m would be practical only if the Q_0 at that field were at least 10^{10}.

While the CEBAF cavity cell design could be improved, the potential benefits do not seem critically important, and the first seven-cell cavity prototype was built using the existing cell design (see Figs. 58 and 59). The first prototype met the requirement of a Q_0 of 6.5×10^9 at 12.5 MV/m.

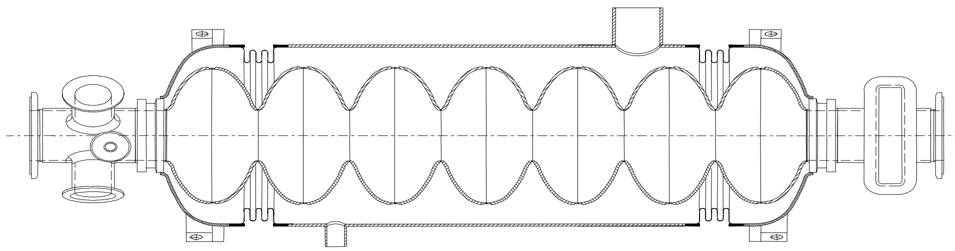

Figure 59: A seven-cell cavity in its helium vessel.

The existing cell shape is characterized by ratios peak fields to accelerating fields, $E_\text{p}/E_\text{acc} = 2.6$ and $H_\text{p}/E_\text{acc} = 47$ Oe/(MV/m). Designs with lower ratios exist; however, as was mentioned before, the greatest challenge is not so much high gradient as low power dissipation. In that respect, the shunt impedance of the existing design compares well with that of others. Another attractive feature of the existing cell design is the relatively high cell-to-cell coupling coefficient (3.3%), which reduces the sensitivity of the field profile to mechanical tolerances and mechanical stability as the number of cells is increased. A redesign of the cells is still an option, although a low-priority one.

Cryomodule design

The existing CEBAF cryomodule is constructed from four cryounits, each containing a sealed cavity pair. These cryounits are then joined with bridging sections. In order to increase the number of cells from five to seven while maintaining the same cryomodule length, this approach had to be abandoned. Several cryostat concepts were explored:

- Cylindrical cryostat with radial penetrations for the power couplers.
- Cylindrical cryostat with axial (through the end plates) penetrations.
- Bathtub-type cryostat where all the internal components are suspended from a top plate.

While all designs had advantages and disadvantages, a cost/benefit analysis did not reveal an obviously preferred option. The radial design was chosen, as it was the one that would require the least amount of development given the on-site experience with the radial design. The Upgrade Cryomodule will include a continuous eight-cavity string assembly without isolation valves between the cavities. The present Upgrade design calls for a 30 cm separation between cavities into which must fit the fundamental power coupler, the higher-mode extraction system, the pick-up probe, connecting flanges, and connections to the helium tank and mechanical tuners. The design does

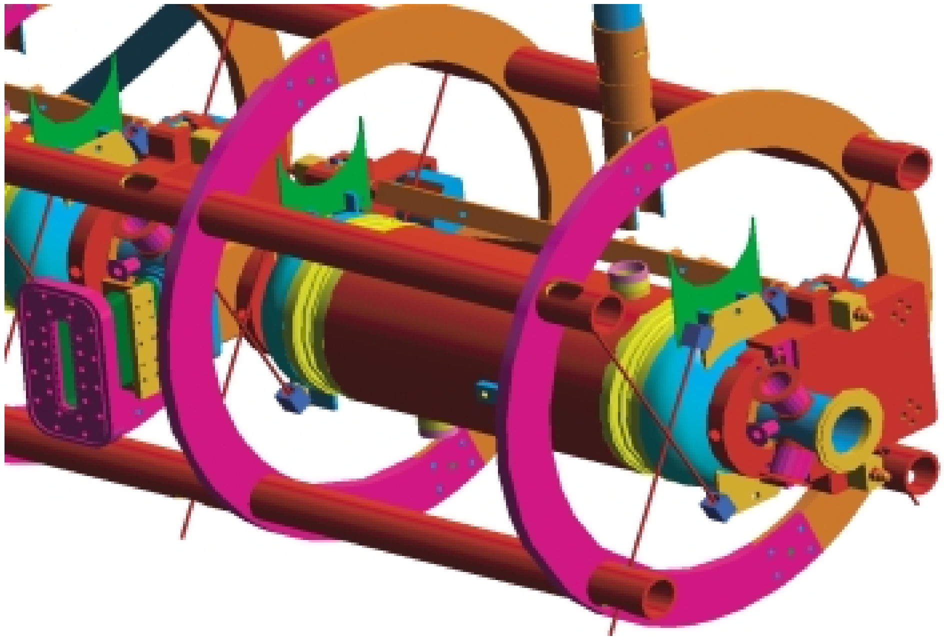

Figure 60: A CAD drawing of the helium vessel in its space-frame.

not include bellows between the cavities. Figure 60 shows the helium vessel in its space-frame. Figure 61 shows a cut-away view of the assembled cryomodule.

Cryomodule components and design choices

Fundamental power coupler Both coaxial and waveguide couplers were explored. The waveguide concept was retained because of its simplicity and flexibility at 1500 MHz. Unlike the present design, though, we have decided to completely separate the functions of fundamental power coupling and higher-mode extraction. This produces a coupler design (Fig. 62) that, unlike the existing CEBAF design, is free of transverse kick imparted to the beam and allows a cryostat design where all the power couplers are on the same side.

Higher-order mode damping The requirements for higher-order mode (HOM) damping for the 12 GeV Upgrade have been substantially relaxed from the original CEBAF design. Not only is the energy increased from 4 to 12 GeV, but the maximum circulating current is being reduced from 1000 to 425 μA. Additionally, the experience acquired during CEBAF operation has led to a

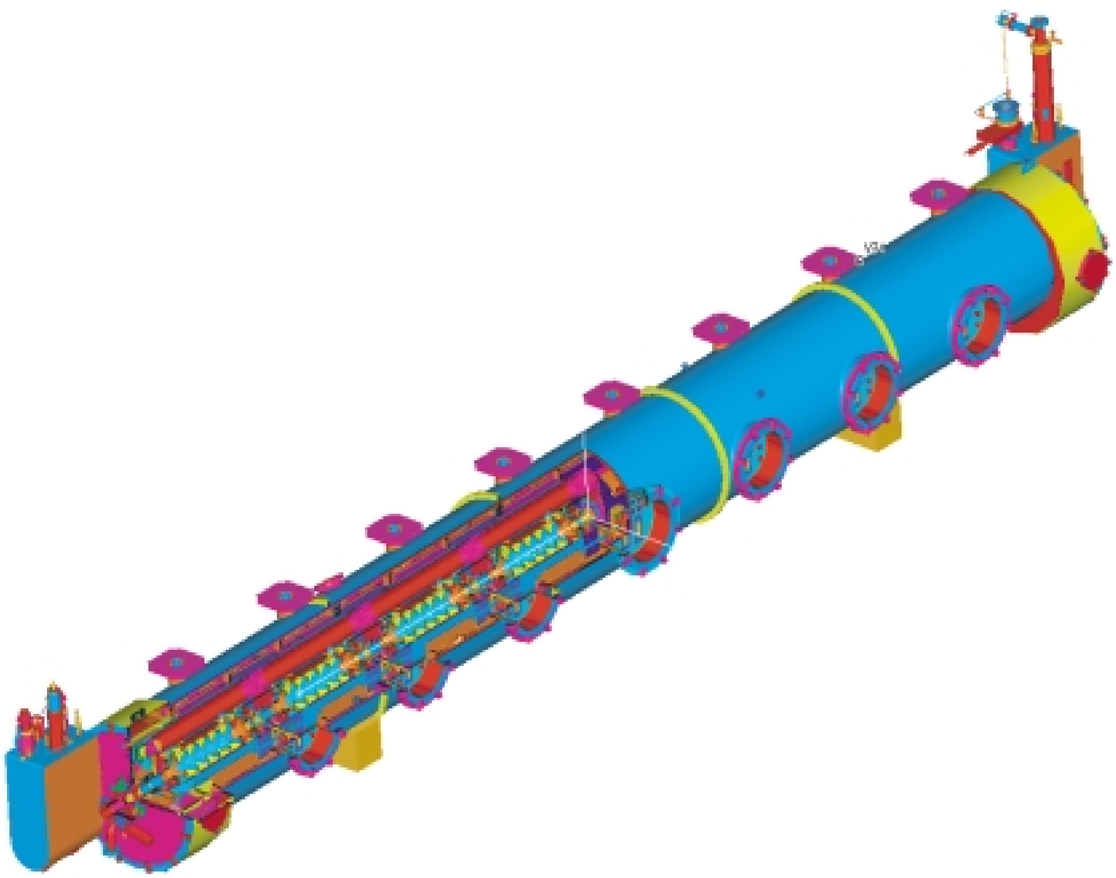

Figure 61: A CAD cut-away drawing of the assembled cryomodule.

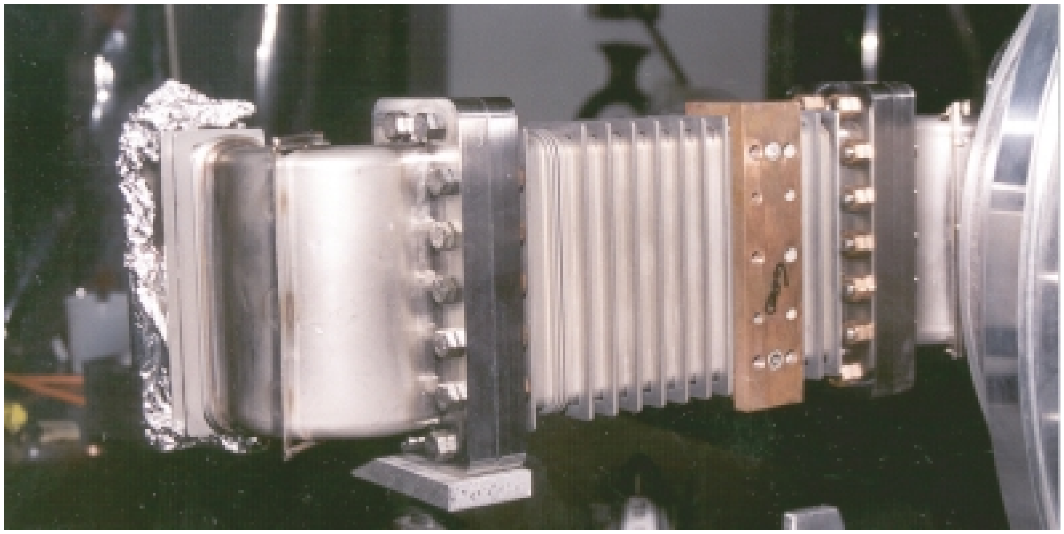

Figure 62: Prototype fundamental power coupler.

reduction of the "safety factor" for the stability threshold current. As a result an upper limit of 10^6 was adopted for the Q_{ext} of the HOMs. The design of the HOM couplers (Fig. 63) is a departure from the existing design in that we do not rely on any HOM extraction with the fundamental power coupler. The new design uses two coaxial-type couplers as opposed to the present waveguide type. These couplers are located outside the helium tank, permitting deposition of the HOM power at a temperature other than 2 K and thereby minimizing the refrigerator load.

Thermal design When 2 K is involved, heat load is always a concern. All supports and penetrations reaching the 2 K volume have been designed to minimize the heat load. The projected static heat load is 25 W per cryomodule.

Frequency tuning The frequency tuners perform several functions: bringing the cavities on resonance after installation, detuning the cavities that are not operating, and tracking the changes in frequency due to Lorentz detuning pressure and temperature fluctuations. For the Upgrade Cryomodule, the bandwidth will be small (∼75 Hz), the Lorentz detuning large (∼500 Hz), and we want to track the frequency accurately (∼2 Hz) in order to minimize the rf power requirements. For this reason the baseline design incorporates two different tuning schemes: a coarse mechanical tuner with 400 kHz range and 100 Hz resolution that will be used infrequently, and a fine piezoelectric tuner with 1 kHz range and 1 Hz resolution that will provide the fine, frequent tracking. Figure 64

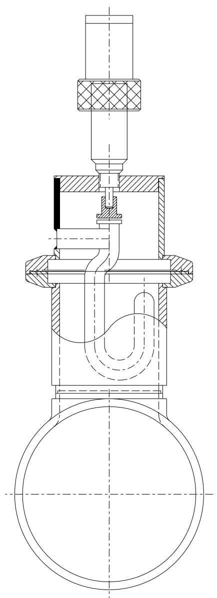

Figure 63: A drawing of the new HOM coupler design.

shows a prototype of the cavity tuning mechanism containing hardware for both schemes.

Processes and procedures While the gradients required are modest compared to those for proposed linear colliders, a high Q_0 is of primary importance. Furthermore, since rf power will be a hard constraint, "outstanding" cavities cannot operate at higher gradient in order to compensate for "weaker" ones. For these reasons our main goal is to achieve consistent performance. We are engaged in a complete review of all the processes and procedures involved in the fabrication and assembly of cavities and cryomodules. Modifications to the processing and assembly facilities, such as implementation of final chemistry and rinsing in the clean room, are under way.

Microphonics, rf control, and rf power Cost containment was a major goal in the overall system design. In order to contain the cost of the Upgrade we have adopted as a goal only a modest increase of the rf power per cavity from 5.0 to 8 kW for the Upgrade cryomodules. This has two effects:

- Total required rf power is a major driver in the cost of the new rf systems and in operational cost. In order to minimize the required rf power at the design gradient and circulating current, a cavity-coupling factor was chosen: 2.2×10^7. A $\lambda/4$ stub waveguide coupler intersecting

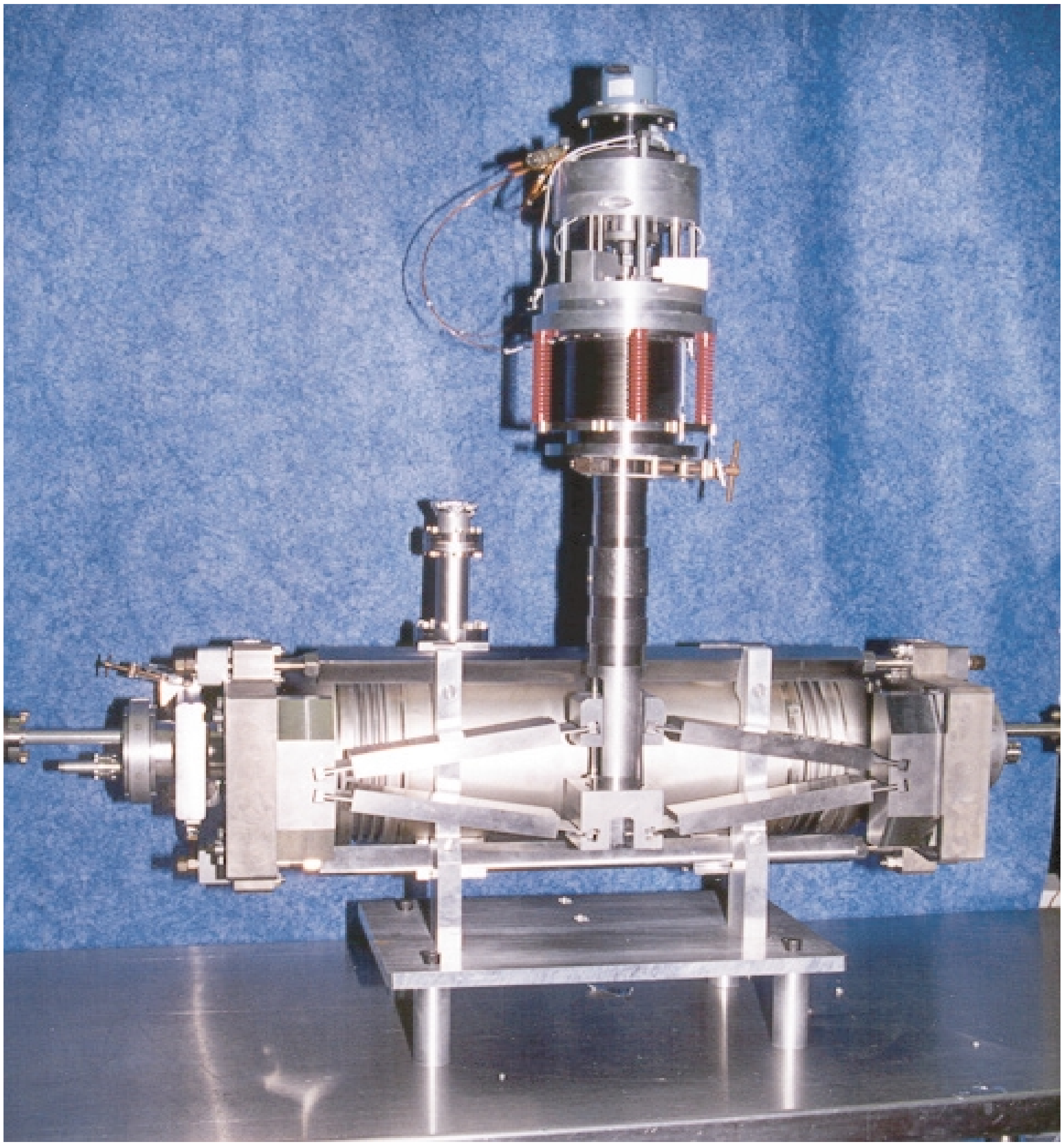

Figure 64: Prototype cavity tuning mechanism.

the beam pipe couples the TE_{01} waveguide mode to the evanescent TM_{01} cavity mode. The waveguide-coupler-to-cavity separation was selected to achieve the desired coupling.

- This puts stringent requirements on microphonics and the control system. At an accelerating gradient of 12.5 MV/m and 400 μA circulating current, the maximum allowable amount of detuning (including static and microphonics) is 25 Hz. The optimum Q_{ext} is 2×10^7, and the Lorentz detuning is much larger than the loaded bandwidth; for this reason a new low-level rf control system will be required. The baseline concept is an agile digital system capable of implementing a self-excited loop on I/Q feedback.

3.D.2 RF Power and Control

To meet the beam energy requirement for the Upgrade, the linacs must be expanded and additional rf systems procured. Presently the CEBAF rf system consists of an injector (warm-temperature chopper, buncher, and capture sections followed by a superconducting quarter-cryomodule and two full cryomodules) plus two linacs of 20 superconducting cryomodules each. A total of 42 eight-cavity cryomodules are powered by 42 identical rf systems. Each zone comprises both low- and high-level rf equipment located in the service buildings above the tunnel. Each cavity has its own klystron and low-level controls.

The energy upgrade will require new rf systems for the additional ten new cryomodules and six upgraded rf systems for replacement cryomodules. The new rf systems will require 8 kW klystrons (vs. the original 5 kW). To control the new higher-gradient cavities the rf phase and amplitude controls will be redesigned to handle the higher loaded Q and hence increased fluctuations from microphonics.

Control

The most significant change in the rf system is the new control module. The need for a major change is due to the dramatically different resonance curve for the new cryomodule vs. the existing ones. The curve for the new cryomodule is shown Fig. 65. As can be seen readily, the curve is not single-valued, whereas it was single-valued for the existing cryomodule. The change is due to the large Lorentz detuning of the cavities at the anticipated higher gradients. An effect of this detuning curve is that should a cavity trip off, the cavity is at the wrong frequency. With the present cavity control, the mechanical tuner would have to be used to bring the cavity back onto resonance; this is a slow process (minutes) and would seriously degrade the overall beam availability. The new

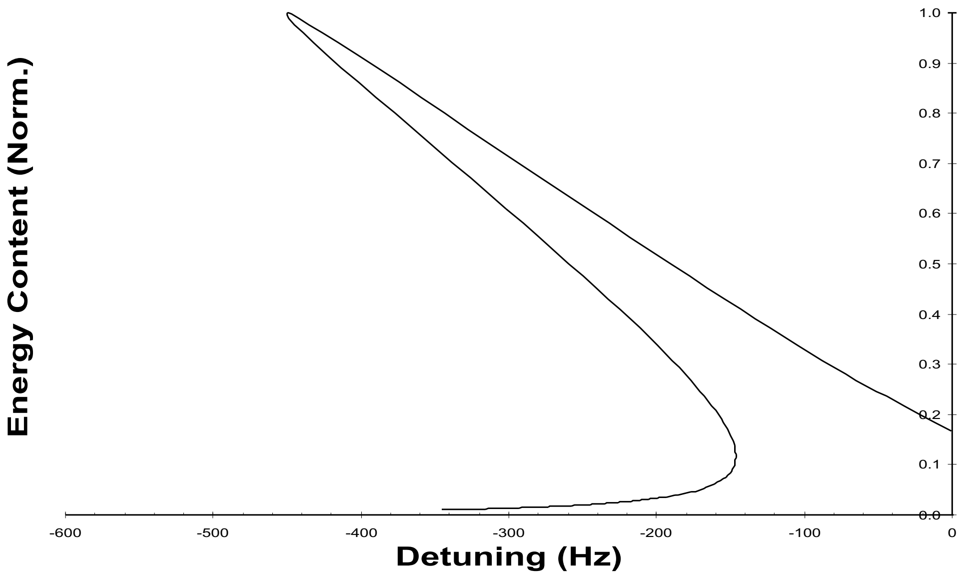

Figure 65: The detuning curve for the seven-cell cavities.

control module will handle this without use of the mechanical tuner.

The existing rf controls and interfaces include a separate rf control module plus CAMAC crate and modules: CAMAC-to-CM interface, CAMAC I/O for other analog and digital functions (status, interlocks, controls, tuning), and CAMAC-to-IOC interface for connection to the EPICS control system. The rf control design is over 10 years old, with CAMAC substantially older still. The years are beginning to show, and some replacement parts have become extremely limited or completely obsolete and unavailable. Additionally, critical eurocard connectors are about to exceed their rated lifetime insertions. Induced power-line noise makes numerous modules unable to meet full specifications. Duplicating the present design for new zones with higher-performance SRF cavities is not appropriate because the higher gradient of the new seven-cell SRF cavities will likely be uncontrollable using the present rf module design.

A proposed new control module retains the concept of the "individual microprocessor per klystron rf source", but replaces the other hardware with an FPGA- and DSP-based design, and eliminates CAMAC entirely. Much of the present analog function will be created using stable digital circuitry. This allows greater flexibility in refining rf control algorithms, plus opens the capability of running true pulse-mode operation in addition to cw.

Moving the functionality of the multiple CAMAC modules into the rf control block more tightly

Table 10: Components for an 8 kW rf power zone

Item	#/Zone	Description
(High-power amplifier)	1	HPA w/ auxiliary power supplies (heater, mod anode, etc.), LCW manifold, WG pressurization manifold and interlock
Klystron	8	Rated 8 kW cw @ 1497 MHz
Waveguide components		Includes 8 each, circulators, couplers, transitions, HOM, sweeps, flexes, and straight waveguide
(Cathode power supply)	1	14 kV @ 14.5 A power supply, variable output w/crowbar
Control module	8	New design modules (replaces CAMAC as well)
Power supplies	1	dc power for control modules and interfaces
MOPS	1	(Multi-output power supply) for controls and interlocks
Rack cooling	1	Filtered, forced air cooling for low-level racks
Racks	3	Low-level rack assembly

integrates all of the rf controls, makes all rf signals immediately available to the control module, and reduces the number of interconnects by reducing the number of separate chassis and associated cabling. The effects of improved reliability and maintainability are also enhanced through better built-in, on-board diagnostics. The new digital design reduces the analog component count greatly, thereby reducing the time required for calibration to achieve, and maintain, design goals.

Power

8 kW rf systems To support the higher-gradient cavities, 8 kW of rf power is needed. This will include a modified klystron tube (modified gun and collector) beyond our present 5 kW tubes. In addition the dc power supply will be larger to support the additional power requirements. The new rf phase and amplitude controls will be based on modern digital receiver technology to take advantage of commercial, industrial, and military improvements. Sixteen 8 kW systems are needed for the energy upgrade. Table 10 summarizes the components of an "8 kW" rf power zone.

Master reference oscillator and drive line The base frequency of the master oscillator (MO) is 499 MHz. This frequency and 70 MHz are distributed around the complex. At each service building, the 499 MHz is tripled to 1497 MHz and then mixed with the 70 MHz to get a 1427 MHz signal. The 1427 MHz and 70 MHz are distributed throughout each service building with a thermally stabilized drive line. Directional couplers deliver the signals to each zone where it is further split for each cavity's control module.

The new controls will use the same frequencies as presently used: 10 MHz, 70 MHz, and 1427 MHz. The drive line in one linac will need to be extended and couplers added. As described in the section on beam transport, the new MO system (being tested as of fall 2000) will have a large (0.001%) base frequency adjustment capability.

3.D.3 Optics and Beam Transport

Beam transport for the 12 GeV Upgrade project is straightforward. The basic layout and optics need not be changed. As such the changes amount to ensuring that all deflecting/focusing elements can reach the higher fields that are required, adding arc 10, adding the Hall D beam line, and adjusting the fifth-pass extraction. One additional feature of the Upgrade is to recirculate the beam in the injector before injection into the main accelerator. All magnets are "resistive" – *i.e.*, not superconducting.

Layout and optics

Beam quality The existing CEBAF accelerator has delivered outstanding beam quality. The unnormalized rms (4σ) emittances for the full-energy five-pass beam are 2.9×10^{-7} mm in both the horizontal and vertical planes. The energy spread is ~0.01%. With the upgraded accelerator, these values will be larger due to the greatly increased synchrotron radiation emitted in the bends. The 12 GeV emittances are projected to be $\epsilon_x = 9\times10^{-6}$ mm and $\epsilon_y = 1.9\times10^{-6}$ mm; the energy spread is projected to be 0.02%. (See Table 11.)

Spot sizes would nominally scale with the square roots of the emittances; there is flexibility in the final optics before the targets, so it is possible to overcome some of the problems that are strictly spot-size-related. These values have been reviewed by the User Group Board of Directors (UGBOD) and approved as being consistent with the needs of the physics program. Some changes in local optics/central orbits may be required to ensure there is no beam scraping with the enlarged beams.

Table 11: Unnormalized rms transverse emittances and momentum spreads for a $5\frac{1}{2}$-pass, 12 GeV CEBAF.

Area	δp/p $\times 10^{-3}$	ϵ_x (mm)	ϵ_y (mm)
Chicane	0.200	4.17×10^{-06}	4.17×10^{-06}
Arc 1	0.200	4.34×10^{-07}	4.34×10^{-07}
Arc 2	0.106	3.13×10^{-07}	2.63×10^{-07}
Arc 3	0.078	2.89×10^{-07}	2.83×10^{-07}
Arc 4	0.069	3.15×10^{-07}	4.15×10^{-07}
Arc 5	0.074	5.81×10^{-07}	4.81×10^{-07}
Arc 6	0.097	1.41×10^{-06}	6.44×10^{-07}
Arc 7	0.110	2.21×10^{-06}	7.03×10^{-07}
Arc 8	0.140	3.58×10^{-06}	1.03×10^{-06}
Arc 9	0.178	6.67×10^{-06}	1.12×10^{-06}
Arc 10	0.213	9.43×10^{-06}	1.91×10^{-06}

It should be noted that a study determined that it is indeed possible to decrease the emittances. In order to achieve the improvement, the last two or three arcs would have to be completely replaced. The UGBOD did not view the improvements worth the projected several-million-dollar cost or worth the loss of beam time associated with the required additional facility down time. This option could be considered for a future project.

Injector One inconvenient feature of a several-pass recirculating linac is the fact that the highest-pass beam experiences the same focusing magnets as does the first-pass beam as they transit the linacs. In our 4 GeV baseline, the ratio of injected beam energy to final-pass beam energy is 3200 MeV/45 MeV $\simeq$ 71. As a result, the higher-pass beams experience essentially no focusing while transiting the north linac. To deal with this it is necessary to set up large beta functions in the final recombiner, with the resulting sensitivity to magnet settings.

The problem is exacerbated if the linac energy is increased but the injector energy is not. The present injector cryomodules cannot reach the total energy gain needed to maintain the present injector-linac energy ratio. Several options have been examined to deal with this problem. Although the studies are not complete, the likely solution will be to retain the present cryomodules and recirculate the beam; this option is much cheaper than replacing the cryomodules and rf systems, for example.

Linacs The optics in the linacs consists of a single quadrupole dividing each pair of cryomodules. The quadrupoles are set for a FODO with 120°/cell phase advance for the first-pass beam. The exact settings of the quads are adjusted to incorporate the focusing from the SRF cavities. An additional focusing effect of the cavities' fields is a skew quadrupole component; this component is compensated by small, air-core skew magnets located between the cryomodules.

As a consequence of multipass recirculation, beams with quite different energies "see" the same magnets (*e.g.*, $E_{\mathrm{pass6}}/E_{\mathrm{pass1}} \cong 90$ at the entrance to the north linac). Since focal lengths scale proportionally with the beam energy, the focusing on the higher passes is quite different from what the first-pass beam experiences. The problem is particularly acute in the north linac, which has both the lowest-energy beam – *i.e.*, that from the injector – and the highest, *i.e.*, the sixth-pass beam. The linacs are essentially optical drifts for the higher-pass beams. Thus, the beta functions need to be set up specifically for each pass through a linac; this is done in the recombiners.

Spreaders/recombiners At the exit of each linac, the collinear beams (one for each pass) are spread apart vertically for transport through the recirculation arcs. These beam lines carry the beams through 180°, after which they are recombined into collinear beams before entering the subsequent linac. Both the spreaders and recombiners on a given "end" of the machine have dispersion suppression. The spreaders and recombiners are essentially mirror images of each other. Matching into the 180° arcs is functionally included in the spreaders; likewise matching into the linacs is included in the recombiners. There is one recombiner in the beam switchyard that can put beam from any pass onto the correct trajectory to reach any of the original three experimental halls.

The spreaders and recombiners are very congested physically. The magnets are not small, and the space is limited, so a lot of effort was expended getting everything to fit. Unfortunately, even larger magnets are needed for the Upgrade. The limited space precludes simply going to higher fields, as this would require more return yoke. A longer-magnet alternative was chosen. This results in small changes in the central beam path that must be accommodated with slight shifts in about 50% of the magnet positions. The northeast spreader (which includes the sixth-pass beam) is shown in Fig. 66.

Recirculation The nine original CEBAF recirculation arcs perform the function of achromatic, linearly isochronous[5] transport of beam for re-injection into the linacs. An effort was made

[5] In practice the optics within the arc is tuned such that the overall momentum compaction including spreader, arc, and recombiner is zero.

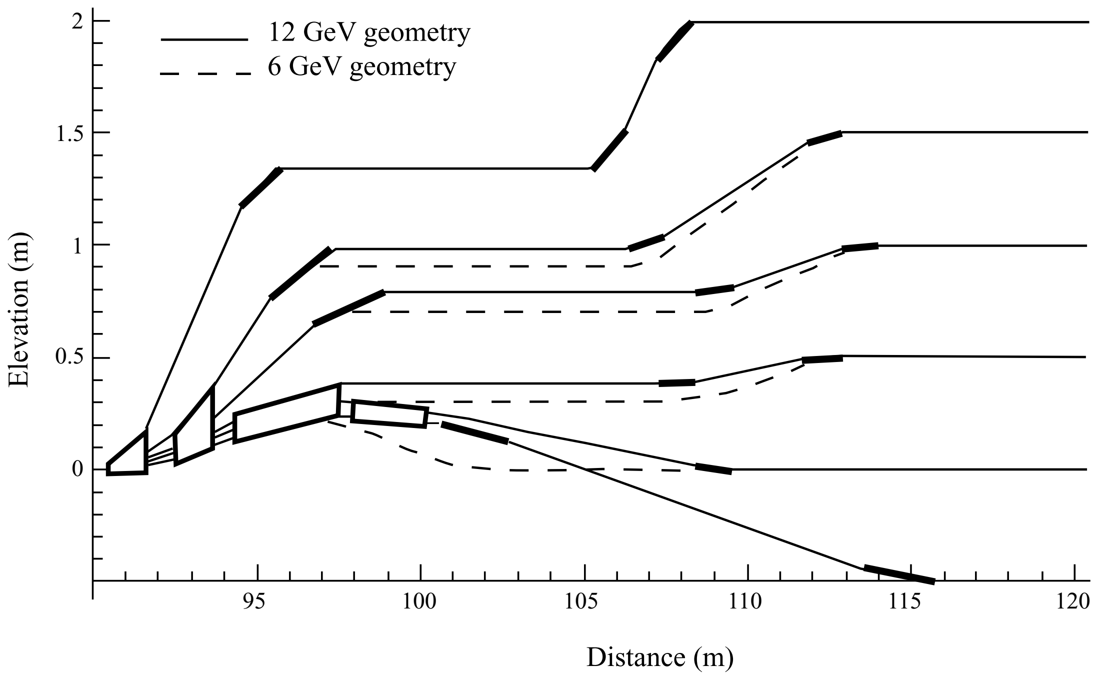

Figure 66: The original and upgraded versions of the northeast spreader.

in the original design to minimize quantum excitation and error sensitivity. Each arc consists of four super-periods, each with four FODO cells. The design of each super-period is based on a pair of back-to-back 90° dispersion suppressors which were re-tuned for overall isochronicity (including compensating for the effects of the spreaders and recombiners), providing minimal betatron function mismatch, and giving phase advance appropriate[6] to generate a second-order achromat. The lattice allows independent tuning of horizontal dispersion and momentum compaction. The first two arcs have been tuned to moderate (6 m) dispersion modes in recent running to provide high-resolution signals for energy monitoring and stabilization. The optics in the original nine arcs will be unchanged by the Upgrade. Magnetic fields are required which exceed the capability of the presently installed magnets. The plans for accommodating this will be addressed below.

A significant change in the recirculation is the addition of arc 10, which brings the beam to the north linac for its sixth pass through. The optics for this arc is the same as for the original nine arcs.

[6]This results in 5/4 of the horizontal and 3/4 of the vertical betatron wavelength per super-period.

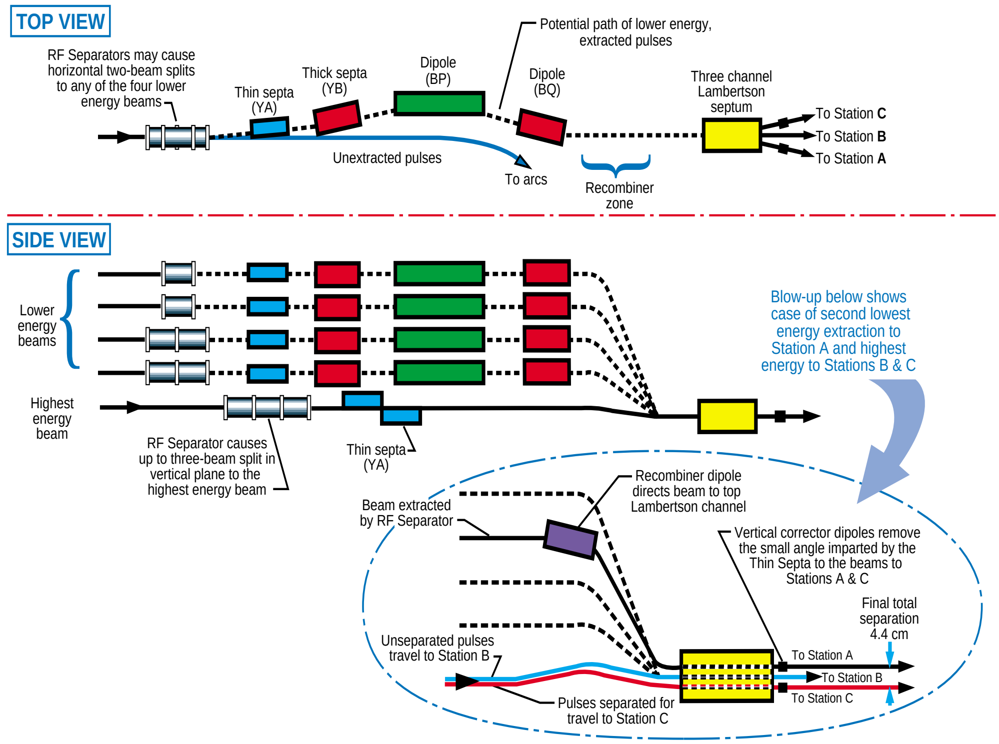

Figure 67: The extraction scheme for the present CEBAF accelerator.

Extraction The extraction region consists of a pair of 33.1-m-long FODO cells tuned to one quarter-wavelength phase advance. Thus the entire unit comprises a $(-I)$ transform in both planes. The large horizontal beta function is exploited for beam extraction using rf separator kicks in all the west-end extraction regions. Pass-by-pass path-length control is also realized within the extraction region with three-magnet chicanes (doglegs) located in the second half-cell. The layout is illustrated in Fig. 67.

For the Upgrade, the extraction scheme will be unchanged for passes 1–3. Additional field will be needed for the rf separators and magnets. The separator performance will be upgraded by adding cavities to passes 2 and 3 and by increasing the rf power for each cavity.

Passes 4 and 5 will have their present configurations changed noticeably. There will be four separator cavities in each line. They will be followed by horizontal-kick Lambertson magnets. Pass 5 will have an extraction chicane added that parallels the ones used in passes 1–4. The change in pass 5 eliminates the present capability of delivering the same energy to all three experimental halls simultaneously. Adding a three- or four-way split is not within the scope of the Upgrade.

However, it could potentially be done in the out-years.

Hall D beam line The beam trains (there are three, each at 499 MHz) that are not extracted by the two-way rf separators in passes 1 to 5 will enter arc 10. The northwest recombiner re-injects them into the north linac for their final gain of 1.09 GeV. The northeast spreader does a six-way momentum separation with Hall D beam being 0.5 m below the fifth-pass beam (arc 9). It then goes straight to the northeast stub, passing under the doglegs for arcs 1, 3, 5, 7, and 9 and the arcs themselves. The beam line to the Hall D radiator is dispersion-suppressed and has a matching section so that beta functions can be adjusted to meet the needs of experimenters.

Magnet and power supply changes

Overview The CEBAF accelerator contains over 2200 magnets, including approximately 415 bending dipoles, 650 quadrupoles, 96 sextupoles, and 1050 corrector dipoles. These magnets were designed and magnetically mapped to support 6 GeV. The total number of families of magnets was kept to a minimum to reduce construction costs. This resulted in the magnets of a given family operating over a wide dynamic range and in various regions of the accelerator. Thus, when planning an upgrade to higher energies, only those magnets operating at the upper end of their original design range need consideration. The sections below detail the magnet changes required to support the 11 GeV Upgrade of the existing five-pass machine and the additional magnets required for transporting the sixth-pass, 12 GeV beam to Hall D.

Field quality requirements Unlike during the original design of CEBAF, we now benefit from several years of operating experience and have well-established procedures for machine setup and monitoring. The field quality specifications for the Upgrade are based on this experience and are aimed at accommodating the present procedures. The new procedures focus on uniformity of any focusing component in a magnet when experience-based estimates of beam motion are included.

Arc dipoles As mentioned previously, many of the present magnets do not provide sufficient fields without becoming extremely saturated. This is particularly true for the arc dipoles. They were designed for efficient performance up to ∼300 A; 550 A would be required for 12 GeV operation. However, there is a fairly easy and inexpensive remedy for this. Figure 68 shows a cross section of an arc dipole. The basic design is that of a C. This means that all the flux must route through

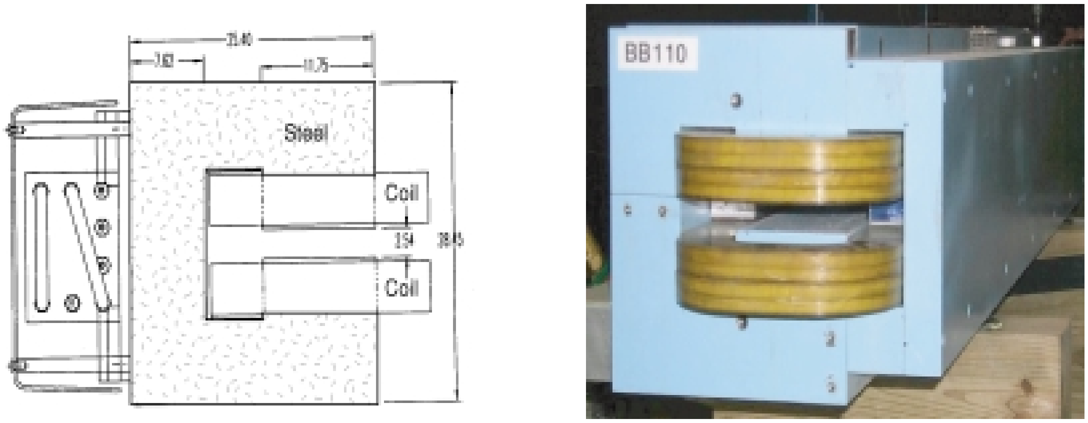

Figure 68: The cross section of a typical arc dipole (left); and a photo of the dipole modified from the C to H configuration by the addition of three iron plates (right).

one side of the magnet. It is the backleg of the return iron that saturates. We can add a C on the open side (right side in this figure) which turns them into H style dipoles, thereby increase the area for flux return, and essentially eliminate the saturation. Computer modeling has been done and verified by a prototype. The modification is sufficiently simple that the magnets can be modified in situ. The modification will be made to the dipoles in arcs 3, 5, 6, 8, and 9 and the dipoles in the beam line leading to Hall B. Arc 10 will have brand new dipoles that will be manufactured as H magnets; in addition, they will be 4 m long, whereas the longest magnet in the existing machine is 3 m.

Spreader/recombiner dipoles Most of the S/R dipoles are built using a C-shaped steel core. Several of these cores are limited by return legs and can be improved with the H-steel modification, as described earlier. All cores are limited by saturation in the pole. Several of the families of the pole-limited dipoles use a common core cross section and vary the number and turn-counts of coils. This produces an air pocket in the coil gap for families with fewer coils. Filling these gaps with steel, such that the coils are flush with the pole, reduces the saturation in the poles. Further, the coil stacking order of some families can be inverted to place the higher-turns coils closer to the gap. In some cases, it will be necessary to completely replace S/R dipoles. Typically, the required change is to lengthen the magnet. In some cases it is also necessary to modify the coil package and/or pole shape to achieve acceptable field quality over the full operating range.

The northeast spreader – *i.e.*, the one at the end of the north linac – will have magnets added to accommodate the separation and transport of the sixth-pass beam to Hall D.

Table 12: Summary of magnet changes needed to upgrade existing beam lines.

Action	Using existing designs	Using new designs
Procure and install	16 (including 3 spares)	60 (including 10 spares)
Relocate	81	
Remove/salvage	28	
Re-cable	60	
New power supplies	25	60

Quadrupoles Of the ~650 quadrupoles in the existing beam lines – *i.e.*, injector, recirculation through five passes and delivery to Halls A, B, and C – relatively few need to be modified for the Upgrade. In most cases nothing needs to be done. Eighty-five need larger power supplies. We need to procure 76 new magnets (including 13 spares), 60 of which will be built using one of two new designs which provide more field than existing designs. In addition, 60 of the quads need to be re-cabled with larger cables so that total load impedance is matched to the power supply I/V. Some of the magnets will be moved to match operating ranges with needs. The Hall D beam line will receive new quadrupoles using one of the new designs.

The scale of the total job associated with upgrading the existing beam lines is summarized in Table 12.

Path-length adjustment For optical energy spread and stability, the beam should run on the crest of the rf wave. The machine layout includes nine locations where the path length can be adjusted so that the beam will meet this criterion as it transits each linac on each pass. The adjustment is done with a three-magnet chicane, referred to as "doglegs".

It has been our experience that the path length is stable over the short term (days). Slight adjustments are needed to correct for changes in the beam's central orbit from one setup to the next. We have also observed an overall "breathing" to the path lengths. This "breathing" is seen in all passes of the recirculation; it closely follows a sine curve with a one-year period and a peak-peak amplitude of 5.5 mm (equivalent to 10° of 1497 MHz) for each pass. The source has not been identified.

We have determined that new dogleg magnets and power supplies will not be needed if the "breathing" can be handled separately. The plan for dealing with it is to slightly adjust the master oscillator frequency and thereby cause the path length to become an integer number of rf wavelengths. A new master oscillator has been installed with this feature, and frequency adjustment tests started in October 2000.

3.D.4 Magnet Power Supplies

Overview

The ∼2200 magnets in the CEBAF accelerator are powered by ∼1800 separate power supplies. The vast majority are 10A/30V "trim" supplies which power individual quadrupoles, sextupoles, and steering dipoles ("correctors"). The primary bending dipoles are powered in strings, with one large power supply ("box"supply) for each string. Some of the dipoles need individual adjustment capability; these receive an electronic shunt controller ("shunt regulator"). The 12 GeV Upgrade will require replacement of a number of the supplies, particularly the box supplies. The required changes are outlined below.

Box power supplies

There presently are 35 box supplies in the CEBAF beam transport system, ranging from 13.5 kW to 266 kW output power. All are of the SCR pre-regulator with transistor post-regulator configuration. Regulation is 0.001%. All supplies are from one vendor and use many interchangeable parts to minimize spares count and ease maintenance.

The energy upgrade will require replacing all eleven of the box supplies for the arc dipole strings and adding a supply for arc 10, as summarized in Table 13. To economically meet this wide range of voltages and currents, a planned modular system of power supply "building blocks" will use a common design of rectifier modules and transistor post-regulator modules which can be "stacked" into either series or parallel configurations to meet the required output. A block diagram is shown in Fig. 69.

Each rectifier module will utilize a 12-phase thyristor bridge with L-C filtering and have 0–800 VDC @ 600 A maximum output. The passbank module will have ∼400 power transistors configured to handle the maximum 1200 A. A current transductor, strappable 600/1200 A, will provide a feedback signal from the output. Regulation will be 0.001%. Interface to the PSS, magnet thermal interlocks, and shunts will remain unchanged.

All arc magnet strings will be grounded at their midpoint, via a ground fault detector circuit.

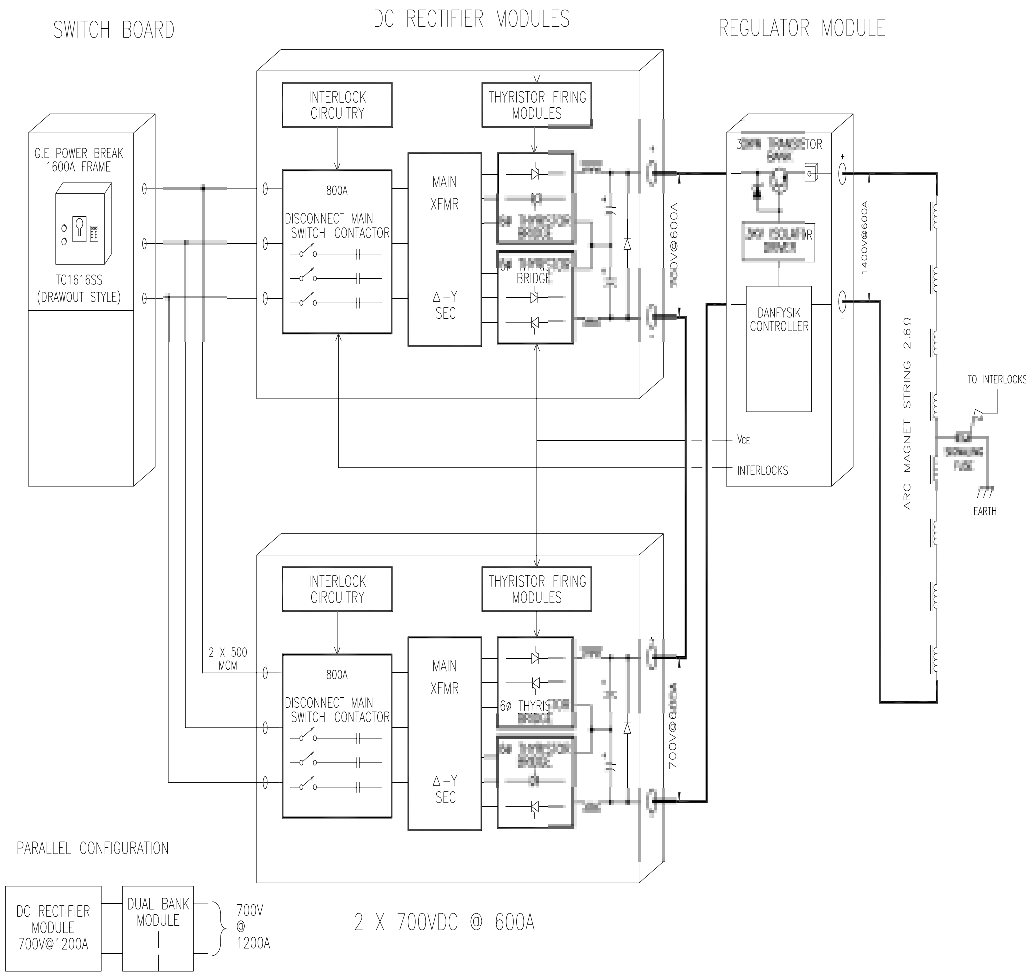

Figure 69: Block diagram of modular power supply.

Table 13: Major box supplies required for 12 GeV

Location	Present $E_{\max}$ (GeV)	Supply Requirements for 12 GeV Current (A)	Voltage (V)	Power (kW)
EAST ARC				
Arc 1	7.1	390	415	162
Arc 3	7.1	549	781	428
Arc 5	7.8	456	955	435
Arc 7	8.1	423	1132	478
Arc 9	6.5	546	1471	803
Recirculation septa	6.5	1081	401	433
WEST ARC				
Arc 2	7.1	386	612	235
Arc 4	7.3	365	941	343
Arc 6	7.1	543	1167	634
Arc 8	7.0	483	1384	668
Arc10	-	575	1495	860
Recirculation septa	6.5	1188	567	674

This will lower the conductor-to-ground potentials throughout the string, placing less stress on magnet and cable insulation and lowering the safety hazard associated with the required voltages. It will be necessary to double up on the 500 MCM cables serving arcs 3, 5, 6, and 9.

Additional electrical power

The maximum ac power requirements for the arc box supplies will increase from 2.28 MVA to an estimated 9.92 MVA. Two additional 5 MVA unit substations will be required, one near the North Access Building, one near the South Access Building. Each of these locations will require two new 2,000 A switchboards. The existing 12.47 kV feeder loops serving these new substations have sufficient capacity. New concrete pads and duct banks will be required for the new substations.

LCW cooling requirements for magnets and power supplies

Low-conductivity water (LCW) cools the magnets and power supplies. The heat load will increase as identified in Table 14.

Table 14: Increased LCW cooling requirements for magnets and power supplies

	South Access Bldg. South Linac Cooling Loop	South Access Bldg. East Arc Cooling Loop	North Access Bldg. North Linac Cooling Loop	North Access Bldg. West Arc Cooling Loop
6.0 GeV Heat Load	147 kW	774 kW	182 kW	959 kW
12.0 GeV Heat Load	588 kW	3095 kW	729 kW	3873 kW

Required civil construction

The footprint of the new arc box supplies will be approximately three times that of the present units. Adding a 20 ft extension on the 60 ft width of the existing North and South Access Buildings will provide sufficient floor space both for the new box supplies and for the required additions to the LCW system, which presently share common space. These building additions have been designed and were bid in early fall 2000.

Other box supplies

The remaining 24 box supplies are distributed around the accelerator, the extraction region, and beam switchyard. With a single exception, they have less than 66 kW outputs. Where present supplies would be inadequate for the new energies, they will be replaced with units surplused from the arcs. In some cases, surplus supplies may be rebuilt to provide different voltage/current output capability while staying within the basic power rating of the unit. Such rebuilding has already been proven successful for supplies for the Hall A, B, and C transport lines.

Trim power supplies

There are approximately 1800 bipolar trim power supplies serving the quadrupoles, solenoids, and small corrector dipoles. Each supply output is realized as a single, plug-in printed circuit board. The nominal output from each channel is presently ±30 V at 10 A.

For the energy upgrade, approximately 75 channels will have to be upgraded to ±65 V at 17 A output capability. The new supply is envisioned as a separate chassis, utilizing hybrid switching technology and post-transistor regulation to achieve the required 0.01% regulation. The chassis would be powered directly from the ac line, rather than from common bulk supplies.

Shunt regulators

In the large dipole magnet strings, individual control over certain magnets is achieved by shunt regulators, which can divert up to 5% (20 A) of the current around a given magnet. Presently, each of the 84 shunt regulators is realized as a plug-in module. The energy upgrade will double the current in these magnet strings, requiring increased power dissipation in the shunts to achieve the same percentage of control. A new regulator module, to be realized as a single chassis per channel, will have a current-shunting capacity of 60 A and a power dissipation of 1.2 kW. The design will closely approximate the existing circuitry; however, the power-dissipation transistors will be water-cooled to increase their dissipation capability.

Control interface and software

The present box supplies and trim racks interface to the EPICS control system via an RS-232 link to CAMAC or VME serial ports. In general, the data communications interface for all power supplies and shunts will be upgraded to purchased VME hardware. Software changes will be minimal, with a few new driver routines being required for the 480 kW box supplies, 17 A trim supplies, and 60 A shunts. The EPICS operator screens should remain unchanged.

3.D.5 Instrumentation and Control

I&C for the Upgrade will require the fewest changes of all the systems from the present configuration. The beam diagnostics, machine protection system, and personnel protection systems associated with delivery of five-pass beam to Halls A, B, and C will require no changes.

Beam delivery to Hall D will require an expansion of all the I&C systems. In all cases copies of the existing system can be used. For example, additional beam position monitors will need to be installed for arc 10, but their signals can be simply added to the existing multiplexers.

The control network will have to be extended to Hall D. The associated electronics and racks will share space in a new surface service building with the magnet power supplies for the Hall D beam line.

3.D.6 Cryogenics

Overview

The cryogenic requirements for the 12 GeV Upgrade are: 7155 W at 2 K and 16,270 W at 50 K. The existing JLab cryogenic system is capable of 4600 W at 2 K and 12,000 W at 50 K for both the north and south linacs. The 12 GeV-capable cryogenics complex will distribute liquid helium as shown in Fig. 70 using two parallel systems:

> One system will utilize the existing JLab cryogenic system, which presently serves both the north and south linacs and the FEL, to provide cryogens to the north linac only. JLab's primary 2 K cold compressors will be modified from four-stage to five-stage compression to provide the reduced-flow turndown capability required for the north linac loads.

> A second cryogenic system will be installed which will provide cryogens for the south linac and the FEL. The new south linac/FEL cryogenic system will consist of subsystem components of the former MFTF-B test facility at Lawrence Livermore National Laboratory. These subsystems include warm helium gas compressors and a 4 K refrigerator. They will be coupled to an existing JLab spare five-stage, 2 K cold compressor, and an expanded control system to provide a complete operating cryogenic plant. A warm helium compressor building and utilities will be provided for the compressors of the former MFTF-B system.

A small satellite 4 K refrigerator will installed at the Hall D location for the hall cryogen load requirements. A summary of the cryogenic plant upgrades is presented in Table 15. A summary of linac heat loads for the Upgrade is presented in Table 16.

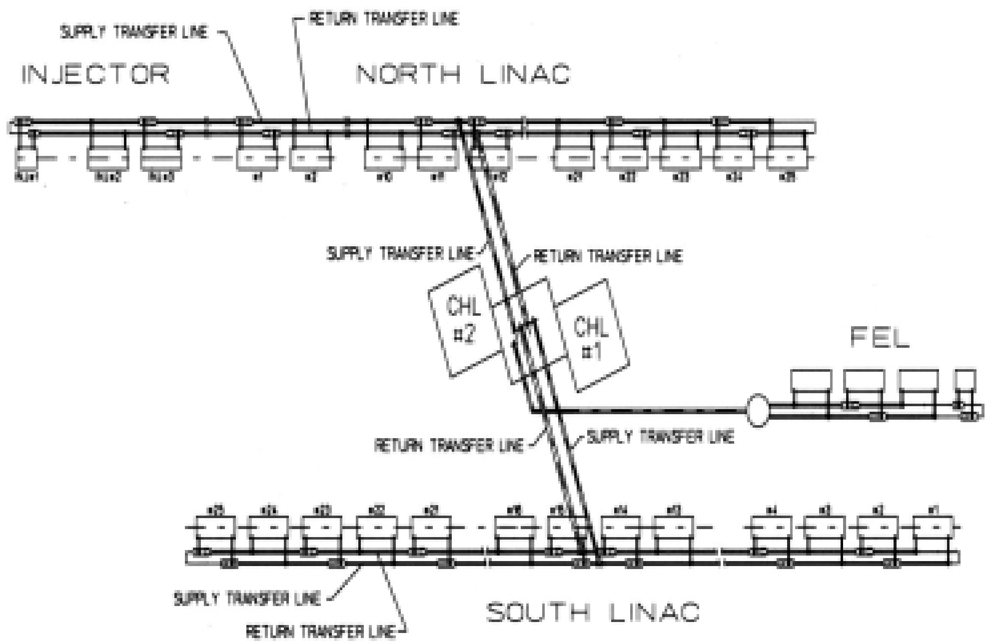

Figure 70: The layout of the 12 GeV cryogenics distribution system.

Table 15: Upgraded CHL refrigeration capacities

	He Temp. (K)	Capacity	Pressure (atm)	Flow (g/s)
CHL #1				
Linac shields	35–52	12,000 W	4.0	136
Linac cavities	2.0	4800 W	0.031	240
Liquefaction	4.5	288 l/hr	2.8	10
SBR				
Linac shield	35–52	12,000 W	4.0	136
Linac cavities	4.5	1900 W	1.3	150
CHL #2				
Linac shields	35–52	12,000 W	4.0	136
Linac cavities	2.0	5280 W	0.031	264
Liquefaction	4.5	280 l/hr	2.8	10
Hall D*				
Magnet shields	85	LN2	3.0	NA
Target	20	10 W	?	?
Magnet	4.5	160 W (@ 2 g/s)	2.8	10
Magnet power leads	4.5	84 l/hr	2.8	3

*Capacity in satellite mode with liquid from CHL

Table 16: Linac heat loads (W)

	Unit Loads		6 GeV Loads			12 GeV NL Loads			12 GeV SL Loads		
	2 K	50 K	#	2 K	50 K	#	2 K	50 K	#	2 K	50 K
Static											
Transfer line	250	2950	2	500	5900	1	250	2950	1	250	2950
CEBAF CM	16	110	42.5	680	4675	27.5	440	3025	25	400	2750
FEL CM	16	110	1.5	24	165	0		0	3.5	56	385
Dynamic rf load											
@ 30 MV	72	49	42.25	3042	2070	0.25	18	12	0	0	
@ 32 MV	72	49	1.25	90	61	17	1224	833	17.25	1242	845
@ 68 MV	175	120				8	1750	1200	8	1925	1320
Total required			43.5	4336	12872	27.25	3682	8020	28.25	3873	8250
Capacity											
CHL#1				4800	12000		4800	12000			
% of required				111%	93%		130%	150%			
CHL#2										5280	12000
% of required										136%	145%

12 GeV cryogenic upgrade summary

A) North linac refrigeration loads

a) 3282 W at 2 K, 8020 W at 50 K

b) Use existing CHL compressors, 4 K cold box, and modified original 2 K cold box (five stage)

B) South linac refrigeration loads

a) 3873 W at 2 K, 8250 W at 50 K

b) Use modified MFTF-B compressors, modified MFTF-B 4 K cold box, new 80 K cold box, and the newly commissioned 2 K cold box, and new oil removal system

c) Requires additional CHL compressor building, 4160 V electrical and cooling water utility, 4 K cold box pit construction, and expanded control system

C) Hall D satellite refrigerator

a) New satellite 4 K refrigerator, transfer and gas lines from CHL, expanded controls

3.D.7 Civil Construction

Additional beam energy requires additional cooling capacity electrical capacity and building space to house and maintain the extra equipment. The following items are required:

Electrical

For the North and South Access Buildings, two new 5 MVA substation will be required including bus duct and bus work. The CHL will require a 12 MVA substation with primary duct bank, plus a 1.5 MVA substation, associated duct banks, switch boards, and motor control centers.

Mechanical

Mechanical systems capacity increases will be required to extract unwanted heat from the arc magnets. This includes low-conductivity water (LCW) upgrades (Table 17) and arc environmental control. The LCW will be improved by increasing the motor size in both the arc magnet circuits and

Table 17: LCW system parameters

Requirement	North Access		South Access	
	Magnets (W. arc & BSY)	Magnet Power Supplies(W. arc, N. linac rf)	Magnets (E. arc & Hall D)	Magnet Power Supplies (E. arc & BSY, S. linac rf)
Existing flows @ 6.0 GeV	510 gpm	1300 gpm	410 gpm	1650 gpm
Needed flow @ 12.0 GeV	610 gpm	1750 gpm	510 gpm	2375 gpm

the service building circuits. An additional heat exchanger will be required for the arc magnets as well as piping and valve reconfiguration of the existing heat exchangers to accommodate the service building loads. An extra cooling tower is required at each location. Existing service building air conditioning is sufficient.

To avoid a major revamping of existing magnet cooling circuits, it has been deemed advisable to allow the LCW water differential temperature to rise to accommodate the extra heating. Pipe insulation and mechanical cooling must be used to counteract the tunnel air temperature rise. This will allow maintenance personnel access to the tunnel without a protracted cooldown period. Since space is at a premium, a direct expansion unit is planned. With careful positioning of the evaporator, buoyantly driven flow would eliminate the need for fans and fan-induced noise.

Building space

Additions to the North and South Access Buildings are required to accommodate the larger magnet power supplies and larger LCW systems; each addition will be 20'$\times$ 60'. An addition to the existing CHL will be required to house compressors for "CHL #2". A pit will also be needed in the northeast corner of the existing cold-box room to house the 80 to 4.5 K "CHL #2" cold box (MFTF refrigerator).

3.D.8 Schedule

While the final schedule for the Upgrade is contingent on special funding from DOE, it is possible to present information about early work aimed at the final goal. Also we can address how to accomplish the Upgrade with minimal impact on the ongoing research program. The 12 GeV Upgrade is part of DOE's 20 Year Plan, and is also central to Jefferson Lab's Institutional Plan. Nevertheless, as a practical matter in the present funding climate, a fully operational prototype of the primary high-tech component is required in order to submit a proposal to DOE. In our case this means the Upgrade Cryomodule. Much of the technology that must be validated will come naturally from the JLab involvement in the SNS project. However, development of a 1497 MHz cryomodule that delivers 68 MV is critical to the credibility of the Upgrade project. We are presently working toward the following schedule:

Cavity string complete:	10/00
CM assembled:	4/02
CM testing complete:	8/02
CM installed SL21:	9/02

Critical path issues

The critical path for the Upgrade starts with the civil engineering building design. A two-year timeline for the two access building additions, including PS installation, is needed in the energy region below 7.5 GeV–an intermediate energy stage in the operational progression of CEBAF from its originally specified 4 GeV towards 12 GeV. CHL#2 is the most time-sensitive, as we estimate that it will require a minimum of four years' lead time. This includes building design, building construction, CHL#2 assembly and installation, commissioning, and burn-in. This work has not been started. We currently have much of the CHL#2 hardware from the SSC and MFTF-B. It could be started early as an AIP project, as the early availability of CHL#2 will support higher end station target loads for our ongoing (4 to 6 GeV) research program, and also support high CHL#1 availability as we push the limits of the present installation (5.5 to 6 GeV operation).

Installation and major shutdown scheduling

The installation of the new cryomodules in the linacs can be accomplished easily during routine maintenance shutdowns, and the commissioning of their rf power and control systems can be accomplished with no impact on beam delivery. Indeed, early installation of a few new cryomodules would improve accelerator performance at the present limit of 6 GeV. Completion of the Upgrade project will require one major shutdown. The shutdown has four main goals:

1. Install the 12 GeV magnet modifications in the five spreader/recombiner regions (including moving the injection beam line and start of the chicane).

2. Install the 11 GeV Hall A, B, and C extraction magnets.
3. Install the tenth arc.
4. Install the new Hall D beamline.

It probably will be possible to complete at least portions of some of these tasks during maintenance periods and during the semi-annual shutdowns associated with routine accelerator operations, with no effect on beam availability; this would relieve the duration of the major shutdown which would otherwise require about six months for hardware installation and six months for recommissioning the accelerator.