

DEVELOPMENT OF AN UPGRADE OF THE CEBAF ACCELERATION SYSTEM*

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Abstract

Long-term plans for CEBAF at Jefferson Lab call for achieving 12 GeV in the middle of the next decade and 24 GeV after 2010. Such energies can be achieved within the existing footprint by fully populating the accelerator with cryomodules capable of providing 3 to 4 times as much voltage as the design value of the existing ones within the same length. In particular, this requires the development of superconducting cavities capable of operating at gradients above 12 MV/m and Q close to 10^{10} .

1 CEBAF DESIGN AND STATUS

CEBAF was designed and constructed to accelerate an electron beam to 4 GeV by recirculating five times through two 1497 MHz superconducting linacs, each providing 400 MeV per pass at the accelerating gradient of 5 MV/m. The two anti-parallel linacs are connected by 180 degree isochronous, achromatic recirculating arcs. The design maximum current is 200 μ A cw, corresponding to a beam loading current of 1 mA [1].

The superconducting RF (SRF) system consists of 20 cryomodules in each of the two linacs and 2 $\frac{1}{4}$ cryomodules in the injector. Each cryomodule contains 8 accelerating cavities for a total of 338 cavities. The cavities, which are 50 cm long, were designed to operate at a gradient of 5 MV/m, which corresponds to an energy gain of 20 MV for each cryomodule. Each cavity is individually powered by a 5 kW klystron and controlled by a low-level rf control system to stabilize the phase and amplitude of the rf field. Having each cavity individually controlled allows for precise and careful optimization of the system and results in excellent phase and amplitude stability of the accelerating fields in the cavities.

The central helium refrigerator provides 2 K helium to the cavities with availability above 98%. The system, capable of providing 4800 W of refrigeration, presently operates with a constant heat load of 3100 W, of which 1500 W is the actual rf heat load.

From the beginning the performance of the acceleration system exceeded the design goal [2]. Early in 1996 a one-pass energy of 1 GeV was achieved, and in the spring of 1997 a 90 μ A beam was accelerated to 1.16 GeV in a single pass (equivalent to a 5.6 GeV, 18 μ A 5-pass beam). The average accelerating field in the active cavities was

7.8 MV/m, more than 50% above their design field. In the fall of 1997, the full capacity of CEBAF was demonstrated with the delivery of a 4 GeV, 200 μ A beam [3]. Some of the arc dipole power supplies are being upgraded in order to deliver high-energy multipass beams, and physics experiments at 5.6 GeV arc being scheduled for the first half of 1999.

The initial performance of the CEBAF cavities corresponded to a 5-pass energy of about 5 GeV. The performance was predominantly limited by electron field emission that can manifest itself in additional cryogenic losses, x-ray production, and periodic arcs at the cold window which is located close to the beam line [4].

In order to reduce field emission and increase the operational energy of CEBAF, a program to perform *in situ* helium processing of the cavities was initiated in the fall of 1996. To date 224 cavities in 29 of the 40 installed cryomodules have been processed [3]. This has increased the installed voltage by 155 MV, which corresponds to an added energy of 775 MeV for a 5-pass beam. The *in situ* processing program will be completed in February 1999 and it is expected that the additional gain will allow operation close to 6 GeV.

2 UPGRADE OPTIONS FOR THE ACCELERATION SYSTEM

CEBAF's long-term institutional plan calls for an energy upgrade to 12 GeV in the middle of the next decade, and to 24 GeV after 2010. The short-term goal is to have developed, installed in the accelerator, and demonstrated by 2002 prototypes of the key components of such an upgrade.

While the details of the upgrade path are still being developed, a top-level parameter list has been generated which guides the selection between the various options:

- The highest energy beam of 12 GeV needs to be delivered to only one experimental hall.
- CW operation must be preserved.
- The maximum circulating beam current will be 400 μ A (corresponding to an 80 μ A beam for a 5-pass design).
- The maximum installed refrigeration capacity will be 8.5 kW at 2 K.
- Cost and impact on accelerator operation during the upgrade must be kept to a minimum.
- Since the purpose of the 12 GeV electron beam is to generate an 8 GeV photon beam, the requirements on

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the electron beam quality can be relaxed from the existing requirements.

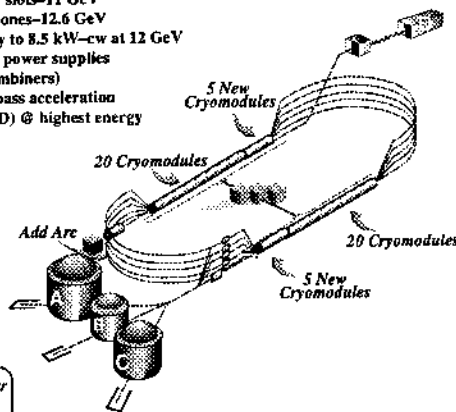
- Since the ultimate goal is an upgrade to 24 GeV, an upgrade path to 12 GeV that could be extended to higher energy would be preferable.

The original upgrade plan for CEBAF called for a maximum energy of about 9 GeV. The most attractive option to achieve this goal called for a systematic “reworking” of the cryomodules. This consisted of removing the cryomodules from the accelerator one at a time, reprocessing the superconducting cavities, and replacing or modifying some of the limiting components (for example relocating the cold windows and shielding them from field-emitted electrons). While this option seemed attractive to 9 GeV, it could not be easily extended beyond, either because it could not provide enough energy or because the cryogenic consumption would be excessive.

The most attractive option that has emerged from the studies that have been conducted during the last year consists of:

- addition of a fourth experimental Hall D at the end of the North Linac (turning CEBAF into a 5-pass machine for Halls A, B, and C, and a 5 1/2-pass machine for Hall D),
- development of high-voltage, high-Q cryomodules that would be installed in the 5 empty slots in each of the linacs,
- replacement of a limited number of existing cryomodules by the new ones (typically 3 in each of the linacs and 2 in the injector),
- upgrade of the refrigeration capability to 8.5 kW,
- addition of a 10th arc and upgrade of the existing ones.

- New 80 MV, high Q, 7 cell cryomodules
- Install 10 in empty slots—11 GeV
- Replace 8 existing ones—12.6 GeV
- Increase cryo capacity to 8.5 kW—cw at 12 GeV
- Upgrade arcs (mostly power supplies and spreader/recombiners)
- Add 10th arc for 5.5 pass acceleration
- Add a new hall (Hall D) @ highest energy (photons only)



3 DESIGN OF THE UPGRADE CRYOMODULE

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 option that is ultimately chosen, 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 options. For these reasons, most of the development efforts in support of the upgrade are directed toward the development and demonstration of prototype Upgrade Cryomodules.

3.1 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 maximizing the 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 lower dynamic load on the refrigeration system.

For this reason, it was decided early that the Upgrade Cryomodule would still include 8 cavities, but that these would be 7-cell cavities (70 cm) instead of the present 5-cell (50 cm). The option described in Section 2 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 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 at high gradient. Given the constraint imposed by the available refrigeration, cw operation at 15 MV/m would be practical only if the Q at that field were at least 10^{10} .

While the CEBAF cavity cell design could have been improved, the potential benefits did not seem important enough at that time, and the first 7-cell cavity prototype was built using the existing cell design. The first prototype met the requirement of a Q of 6.5×10^9 at 12.5 MV/m. A redesign of the cells is still an option, although a low priority one.

3.2 Cryostat Concept and Cavity String Assembly

The existing CEBAF cryomodule is constructed from 4 cryounits, each containing a sealed cavity pair. These cryounits are then joined with bridging sections. In order to increase the number of cells from 5 to 7 while maintaining the same cryomodule length, this approach had to be abandoned. The Upgrade Cryomodule will include a continuous 8-cavity string assembly without isolation valves between the cavities. The present 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 bellows, and connections to the helium tank and mechanical tuners.

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 innards 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 overriding consideration was the limited amount of time and resources expected to be available, and the radial design was chosen as it was deemed the one that would require the least amount of development given the on-site experience with the radial design.

3.3 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 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 [5].

3.4 Higher Order Modes Damping

The requirements for high order modes (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 400 μ A. Additionally, the experience acquired during CEBAF operation has led to a 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 is a departure from the existing design: we do not rely on any HOM being extracted from the fundamental power coupler, the 2 HOM couplers will be of a coaxial type as opposed to a waveguide type, the HOM couplers will be located outside the helium tank and the HOM power can be deposited at a temperature other than 2 K.

3.5 Frequency Tuning

The frequency tuners perform several functions: bring the cavities on resonance after installation, detune the cavities that are not operating, and track 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 tuner,

probably piezoelectric, with 1 kHz range and 1 Hz resolution that will provide the fine, frequent tracking.

3.6 Processes and Procedures

While the gradients required are modest compared to those for proposed linear colliders, a high Q is of primary importance. Furthermore, since rf power will be a hard constraint, "good" cavities cannot operate at higher gradient in order to compensate for "weaker" ones. For these reasons our main goal is to achieve consistent performance as opposed to the less frequent exceptional one. We have 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 cleanroom, are under way.

3.7 Microphonics, RF Control, and RF Power

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 5.5 to 6 kW. This puts stringent requirements on microphonics and the control system. At 12.5 MV/m and 400 μ A 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.

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