UPGRADE OF THE CEBAF ACCELERATION SYSTEM*

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Abstract

Long-term plans for CEBAF at Jefferson Lab call for providing 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 tunnel with cryomodules capable of twice the operating voltage 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~10^{10}. An R&D program for the development of the cryomodules is under way and will be presented, as well as various options for the upgrade path.

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. 180-degree isochronous, achromatic recirculating arcs connect the two anti-parallel linacs. The design maximum current is 200 μA cw, corresponding to a beam loading current of 1 mA [1].

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 μA beam was accelerated to 1.16 GeV in a single pass (equivalent to a 5.6 GeV, 18 μA 5-pass beam), albeit with stability less than suitable for regular operation.

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 μA beam [3]. The initial performance of the CEBAF cavities corresponded to a reliable 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 ceramic 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 and took place during the scheduled machine shutdown periods in 1997, 1998, and 1999 [3]. The *in situ* processing program was nearly completed in February 1999 and has increased the installed voltage by about 200 MV, which corresponds to an added voltage of 1 GeV for a 5-pass beam, and it is expected that the additional gain will allow operation just above 6 GeV.

Some of the arc dipole power supplies have been upgraded in order to deliver high-energy multipass beams, and physics experiments at 5.5 GeV are scheduled to start in April 1999. In order to support high-energy, high-current operation new optimization algorithms and tools have been developed [5].

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 μA (corresponding to an 80 μA 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 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 first 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

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seemed attractive toward obtaining 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: (see Figure 1)

- 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 and construction of high-voltage, high-Q cryomodules to be installed in the 5 empty slots in each of the linacs,
- replacement of a limited number of existing cryomodules by 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.

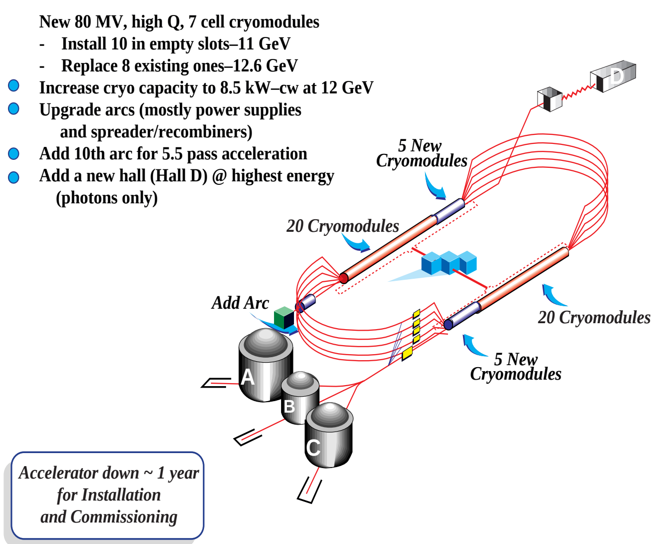

Figure 1: Upgrade path to 12 GeV CEBAF.

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 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.

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 lowering the 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 be improved, the potential benefits do not seem critically important, and the first 7-cell cavity prototype has been 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 [6]. 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.

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.

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 connections to the helium tank and mechanical tuners [7]. The design does not include bellows between the cavities.

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 [8,9].

3.4 Higher Order Modes 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 400 μA. 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 piezoelectric tuner with 1 kHz range and 1 Hz resolution that will provide the fine, frequent tracking [10].

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, "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 as opposed to the less frequent exceptional one. 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 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 μA circulating current, the maximum allowable amount of detuning (including static and microphonics) is 25 Hz. The optimum Q_{ext} is $2x10^7$, 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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REFERENCES

[1] H. Grunder, “CEBAF Commissioning and Future Plans,” Proceedings of PAC95, p.1-3.

[2] C. Reece *et al.*, “Performance Experience with the CEBAF SRF Cavities,” Proceedings of PAC95, p.1512.

[3] C. Reece, “Achieving 800 kW CW Beam Power and Continuing Energy Improvements at CEBAF,” Proceedings of LINAC98.

[4] J. R. Delayen, L. R. Doolittle and C. E. Reece, “Analysis of Performance Limitations for Superconducting Cavities,” Proceedings of LINAC98.

[5] J. R. Delayen, L. R. Doolittle, C. E. Reece, “Operational Optimization of Large-Scale SRF Accelerators, these Proceedings

[6] I. E. Campisi *et al.*, “Superconducting Cavity Development for the CEBAF Upgrade”, these Proceedings.

[7] J. R. Delayen *et al.*, “Cryomodule Development for the CEBAF Upgrade”, these Proceedings.

[8] L. R. Doolittle, “Strategies for Waveguide Coupling for SRF Cavities,” Proceedings of LINAC98.

[9] J. R. Delayen *et al.*, “An RF Input Coupler System for the CEBAF Upgrade Cryomodule”, these Proceedings.

[10] J. R. Delayen *et al.*, “Frequency Tuning of the CEBAF Upgrade Cavity”, these Proceedings.