CEBAF ENERGY UPGRADE PROGRAM INCLUDING RE-WORK OF CEBAF CAVITIES*

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Abstract

The Thomas Jefferson National Accelerator Facility, Jefferson Lab, is planning an upgrade of the CEBAF accelerator from a maximum energy of 6 GeV to 12 GeV and from 3 to 4 experimental halls. This paper will discuss the plans for upgrading the energy of the machine which requires improvements of the existing Super Conducting Radio Frequency (SRF) cryomodules and the additions of ten newly designed high performance SRF cryomodules.

12 GEV PROGAM OVERVIEW

Physics Driver

The scientific basis for the energy upgrade of the CEBAF accelerator has been clearly demonstrated identifying four significant areas of research [1]. In recognition of this the CEBAF energy upgrade program has been identified as the highest priority by the U.S. Department of Energy and National Science Foundation Nuclear Science Advisory Committee in its long range plan [2]. Upgrades of the existing experimental halls as well as the addition of a new hall, Hall D, will are included to support these programs.

High Level Accelerator Layout

The CEBAF accelerator [3] will require several significant upgrades to support the 12 GeV program. These include

- additional cryomodules
- expanded Central Helium Liquefier (CHL)
- upgraded transport arcs
- new 10th transport arc
- transport channel to the new Hall D
- Hall D
- Upgrades to the existing 3 experimental Halls

The present high level project planning with current DOE guidance is given in table 1

Table 1: Project Planning

Begin Construction (CD-3)	Fall 2008
Accelerator Down	Spring 2012-Spring 2013
Accelerator Commissioning	Summer 2013
Re-start research program	Fall 2013
Start research at 12 GeV	Summer 2014

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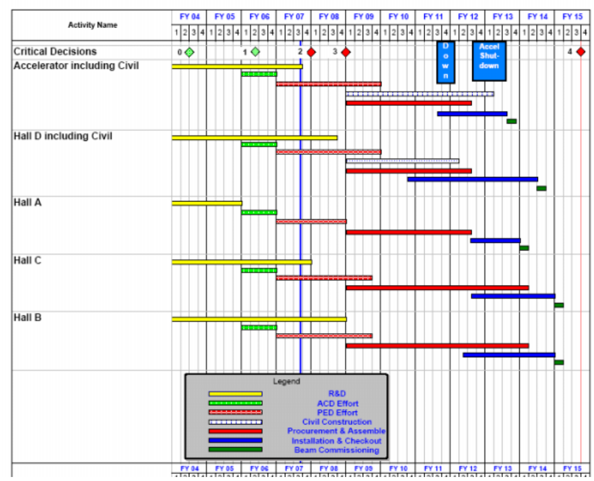
An integrated detailed schedule has been developed for all activities. The high level role up of this schedule is shown in Figure 1.

Figure 1: Project Schedule



High level parameters for the each of the effected systems have been developed. A comparison of these for the 6 GeV and 12 GeV machine are shown in Table 2.

Table 2: CEBAF High Level Parameters

Accelerator	Now	Upgrade
Energy	6 GeV	12 GeV
Voltage per Linac	0.6 GV	1.1 GV
Number of recirculations	5	5 ½
Beam Power (total)	1 MW	1 MW
Beam Current Hall D	-	5 µA
Emittance	1 nm-rad	7 nm-rad
Energy spread	0.01%	0.02 %
Cryoplant @ 2K	4.5 kW	9 kW
Experimental Halls	3	4

Linac Energy Plan

Presently each Linac supplies 0.6 GeV of energy gain resulting in 6 GeV beam energy after 5 passes of two Linacs per pass. The addition of ½ pass adds 1 Linac of energy gain to the total energy resulting in the requirement for 1.1 GeV per Linac to reach 12 GeV. This is a 0.5 GeV increase in Linac energy. In the existing tunnel there is space for 5 additional cryomodules at the end of each Linac so cryomodules providing 0.1 GeV of acceleration reaches the required total of 0.5 GeV per Linac.

The energy gain requirements for the Linacs have been translated into cryomodule level specifications and are shown in table 3. These requirements include a 10% operational contingency factor.

Table 3: Upgrade cryomodule parameters

Voltage	108 MV
Cavity active length	0.7 m
Total active length	5.6 m
Gradient	19.2 MV/m
Qext fundamental pwr coupler (FPC)	$3.2 * 10^7$
FPC power rating, optimized/capable	7.5/12 kW
Higher order mode damping	$Z<6 * 10^8\ \Omega/cm^2$
2 K heat load	≤300 W
50 K heat load	≤300 W
Cryomodule length	~8.5 m

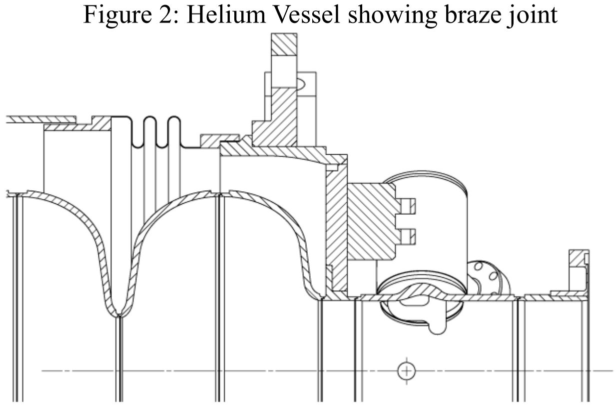
UPGRADE CRYOMODULE

The upgrade cryomodule has benefited from several prototype cryomodules being built and operated in the CEBAF and FEL accelerators. The most recent of these is the Renascence cryomodule reported on in these proceedings [4]. There have been several design modifications to the cryomodule design since the Renascence cryomodule was built which are discussed below.

Cavity

During testing of the final prototype cryomodule, Renascence, limitations where identified in the cavity performances resulting from thermal run away initiated in the HOM loads. After extensive testing and modeling a new design for the cavity assembly end groups was developed and the results are reported on in these proceedings [5]. The assembly maintains an unchanged low loss geometry 7 cell structure. The HOM couplers have been reduced from 4 to 2 and are located away from the FPC.

Figure 2: Helium Vessel showing braze joint



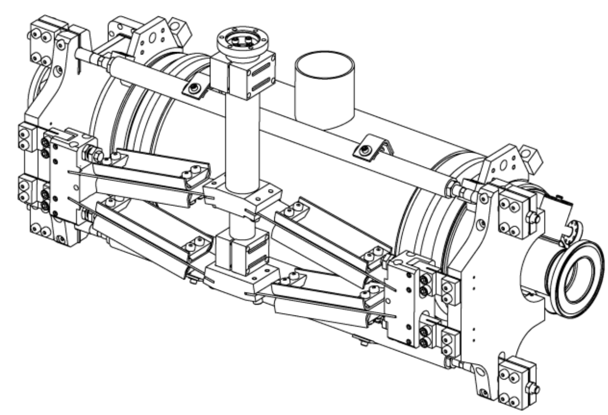
Helium Vessel

Along with the changes in the cavity structure and specifically the relocating of the HOM couplers, space was made available along the beamline just outside the 7 cell structure. This space allows for a niobium to stainless steel transition assembly to be installed. The opportunity to use a stainless steel helium vessel has several advantages including material costs and ease of fabrication. Additional benefits include the elimination of the stainless steel to titanium explosion bonded joints which is both a cost savings and reliability improvement. The added complication of a brazed niobium to stainless joint has been evaluated at Jefferson lab with test pieces and cavity assemblies. These have gone through extensive cold cycle and pressure tests with no failures or problems of any kind [6].

Tuner

The redesigned helium vessel and relocated HOM couplers has allowed the use of our previous tuner [7] found on the first two prototype cryomodules. These tuners are in operations in the CEABF and FEL accelerators and have a proven track record. Important features of these tuners include fine resolution of ≤ 2 Hz from both mechanical and piezo actuators. All actuators are mounted in air and can be changed without warming up the cryomodule, and no friction bearing components are in vacuum. This combination eliminates all significant sources of tuner failures.

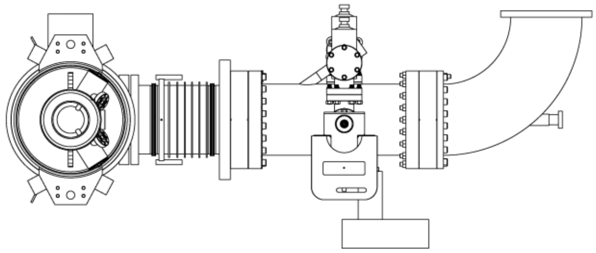
Figure 3: Tuner Mounted on Cavity



Fundamental power coupler

All prototype crymodules have used a single rf window installed during the clean room cavity string assembly. Operational experience with this design has included the failure of windows. The failure mode has been a small punch through of the ceramic resulting in air leaks into the cavity string. These leaks are particular troublesome as you do not see the effects of them until significant amounts of air products have frozen out on the inside of the cavity surfaces. In order to eliminate this failure mode we have returned to the use of redundant rf windows in the FPC similar to the initial CEBAF design. The changes in this design include placing both windows at room temperature eliminating any cryogenic heat load and moving the cavity window well away from the beamline to eliminate charging problems seen in the original CEBAF design.

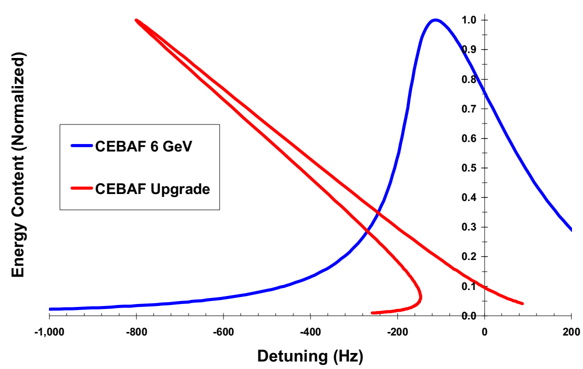
Figure 4: FPC with a double rf window



Low Level RF Control

The combination of high gradient operation and high FPC Qext of the upgrade cavities creates new rf control issues for CEBAF operations. Even though CEBAF is operated in continuous wave eliminating the problems of a pulsed machine there are still turn on transients that need to be dealt with. The Lorentz detuning curve for the cavity becomes a multi valued function making the existing CEBAF Low Level RF (LLRF) control a non-option. A new control system has been developed [8] at CEBAF using digital technology and a Self Excited Loop. The prototype system has been tested and the system should prove to be useful over a broad range of applications.

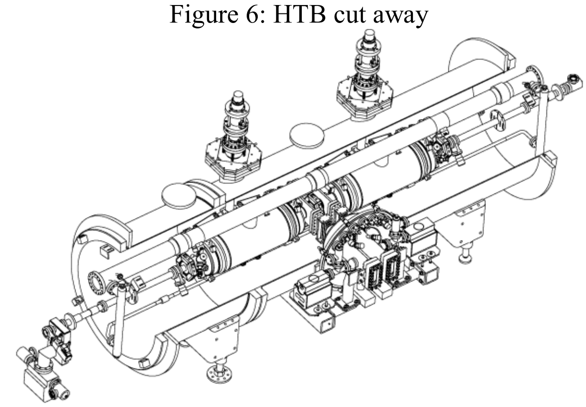
Figure 5: Cavity Lorentz Detuning



Integrated Testing

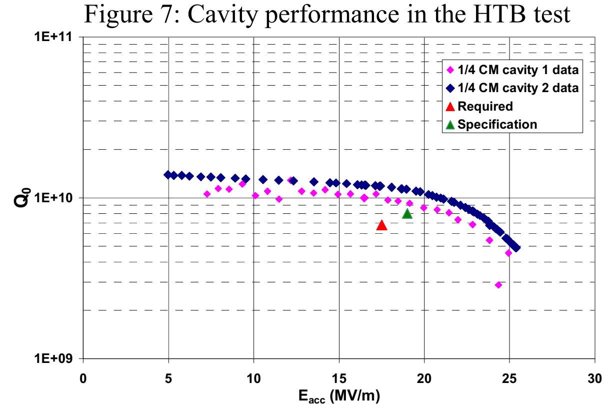
All redesigned components were prototyped and tested as sub-assemblies. This included Vertical Test Area (VTA) testing for the cavities, cold cycle and pressure test for the helium vessels, and rf and vacuum qualification for the FPC components. In addition to these an integrated test of all components was performed using our Horizontal Test Bed (HTB). The HTB is a test cryostat that can be configured for testing a diverse set of cavities and components from 2 K to room temperature. The test in the cryostat configuration with all systems in place is important as it is the first time sub-systems are tested along with the effects of being integrated into the larger system. In this instance we tested the cavities, couplers, and tuner at 2 K throughout their specified performance ranges. In all cases specification were met or exceeded.

Figure 6: HTB cut away



At this time we have qualified all the designs for the Upgrade Cryomodule. The requirements for the cryomodule have been developed from the 12 GeV upgrade integrated project plan. The Linac energy plan assumes the existing CEBAF Linacs are performing at 6 GeV as they have in the past.

Figure 7: Cavity performance in the HTB test



Rework

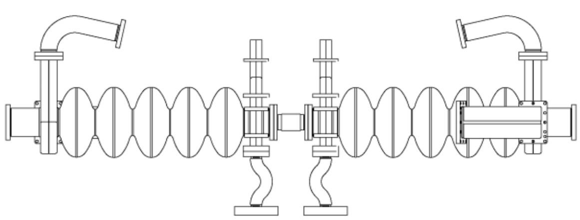
The existing CEBAF Linacs have operated at 0.6 GV per Linac and have aged well. There is however a degradation in voltage over time. Much of this resulted from the effects of an unplanned and uncontrolled warm-up of the Linacs when the accelerator site lost electrical power for several days after a hurricane. This included the loss of one entire cryomodule and ½ of another to helium leaks into the beamline and power coupler vacuum spaces respectively. In addition to this we lost one cryomodule to a beamline helium leak after a planned thermal cycle for maintenance activities and have an additional reduction in voltage of ~65 MeV/yr [9] resulting from required lowering of individual cavity gradient operating levels.

The original operations plans for the CEBAF accelerator included the rework of as many as 4 cryomodules per year to maintain Linac performance. Until recently we have not put that plan into effect. Now, after over 10 years of operations, we have initiated a rework program for 3 cryomodules per year. The present plan includes the rework of a total of 10 cryomodules.

This will result in robust Linac operation with voltages of 0.6 GV with available operational overhead.

At this time we have completed the first three cryomodules and they have been returned to operations this fall. An additional 4 cryomodules have been removed from the machine and are in various stages of rework. The 4th and 5th cryomodules are schedules for installation into the accelerator during the next maintenance period which is presently schedule for March of 2008.

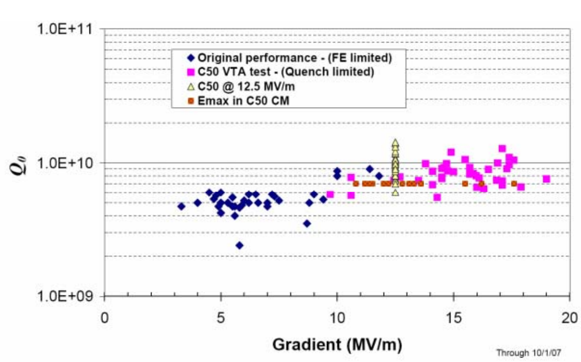
Figure 8: Cavity Pair with Dogleg Coupler



The rework program includes limited changes to the original design. These changes are listed below.

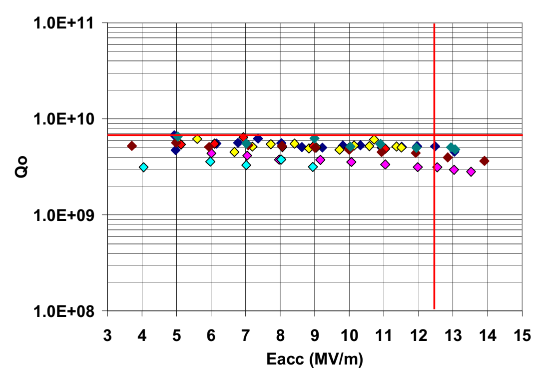
1. Moving the cold RF ceramic window in the power coupler away from the cavity beamline to eliminate charging and flash over. This is the main source of operational trips in the Linacs [10].
2. Add a dogleg section of waveguide to remove a direct line of sight from the beamline to the cold ceramic RF window. This also reduces charging of the window, figure 8.
3. Stiffening the cavity tuner mechanical linkage reducing backlash in the tuner operations.
4. Replaced the polyethylene warm RF window with a ceramic window.
5. Applied "best practices" to the processing and assembly of the cavity pairs. The planned performance of the cavities is increased from the original 5 MV/m to 12.5 MV/m. Best practices include,
    a. Closed chemistry BCP
    b. High Pressure rinsing
    c. 600° C hydrogen degassing
    d. Controlled clean room procedures.

Figure 9: Comparison of cavity performance



The startup of the cavity reprocessing program was a painful one. We had "lost" our ability to rework cavity pairs and had an excessive amount of rework required due to field emission and helium leaks during VTA testing. A dedicated program to re-learn the production process was initiated. The focus was the development of detailed and controlled procedures that resulted in field emission free cavity performance in VTA testing. In order to properly implement these procedures a training and qualification program was put into place. The result of these actions has been the elimination of field emission and cavity performance routinely going out to hard quench field levels. At this time the average cavity performance exceeds our planned 12.5 MV/m. A comparison of individual cavity performance for the original CEBAF construction and the reprocessed performance is shown in figure 9. Cavity performance measured in the accelerator during cryomodule commissioning is shown in figure 10. It is notable that the Q_0 is reduced in the cryomodule with no field emission. Investigations are underway to understand the cause of this.

Figure 10: Cavity performance during commissioning



Summary

Jefferson Lab is well on its way to implementing a 12 GeV upgrade of the CEBAF accelerator. This project includes the addition of a new experimental hall as well as the upgrade of the existing halls. Construction start is planned for the fall of 2008 with no interruption to the physics program until 20012. The re-start of the research program is scheduled for the fall of 2013. The energy plan for the machine is based on an additional 10 new cryomodules operating at 100 MV and robust operation of the existing machine at 6 GeV. Although demonstrated in the past, the present energy reach of the CEBAF machine is less than 6 GeV and a rework program of the existing cryomodules has been undertaken. The program, roughly half completed, includes reworking 10 of the 42 original CEBAF cryomodules. The performance specification of these reworked cryomodules is increased from the original 20 MV to 50 MV. This increase is made possible by improvements in cavity processing and assembly techniques.

Acknowledgements

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