SUMMARY REPORT FOR THE C50 CRYOMODULE PROJECT*

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Abstract

The Thomas Jefferson National Accelerator Facility has recently completed the C50 cryomodule refurbishment project. The goal of this project was to enable robust 6 GeV, 5 pass operation of the Continuous Electron Beam Accelerator Facility (CEBAF). The scope of the project included removal, refurbishment and reinstallation of ten CEBAF cryomodules at a rate of three per year. The refurbishment process included reprocessing of SRF cavities to eliminate field emission and to increase the nominal gradient from the original 5 MV/m to 12.5 MV/m. New dogleg couplers were installed between the cavity and helium vessel flanges to intercept secondary electrons that produce arcing in the fundamental Power Coupler (FPC). Other changes included new ceramic RF windows for the air to vacuum interface of the FPC and improvements to the mechanical tuner. Damaged or worn components were replaced as well. All ten of the refurbished cryomodules are now installed in CEBAF and are currently operational. This paper will summarize the performance of the cryomodules.

INTRODUCTION

The goal of the C50 project was to enable robust 6 GeV, 5 pass operation of the Continuous Electron Beam Accelerator Facility (CEBAF). This was accomplished by removing and rebuilding ten of the worst performing cryomodules from the CEBAF linacs.

The goal of the rebuilding process was to increase the accelerating voltage of each cryomodule to at least 50 MV. The original CEBAF design had called for a 20 MV cryomodule. A 50 MV cryomodule would require that each cavity deliver a usable accelerating gradient of 12.5 MV/m. These cavities were originally designed to achieve 5 MV/m.

During the refurbishment process, each cryomodule was disassembled and its cavities removed and subjected to improved processing techniques. The FPC was redesigned to include a “dogleg” waveguide. The original polyethylene warm RF window was replaced with an improved ceramic model. Improvements were made to the mechanical tuners to reduce backlash. Components that were subject to mechanical wear or radiation damage over the years were replaced as well.

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CAVITY PERFORMANCE

Gradient

To increase the gradients of the C50 cavities, field emission and arc rates needed to be reduced. Field emission is responsible for increased cryogenic heat loads and is the source of electrostatic charging of the cold RF window. This charging is responsible for the periodic arcing behaviour which has been a major limitation on available accelerating gradient. Once field emission turns on for a particular cavity, the frequency of arcing will increase as the gradient increases. Arcing results in RF trips. As a result, gradients are reduced in order to keep RF trip rates manageable. To reduce the arcing behaviour, cavities would be reprocessed and the FPC would be redesigned.

In a cleanroom, cavities were subjected to an acid etch followed by high pressure rinsing with ultra pure water. These processes were designed to eliminate particulate contamination from the surface of the cavities and as a result eliminate field emission.

The dogleg coupler was designed to reduce or eliminate this type of arcing behaviour by eliminating the line of sight from the cavity interior to the cold window. (See Figure 1) Field emitted electrons would not be able to reach the cold window and charging would be reduced or eliminated.

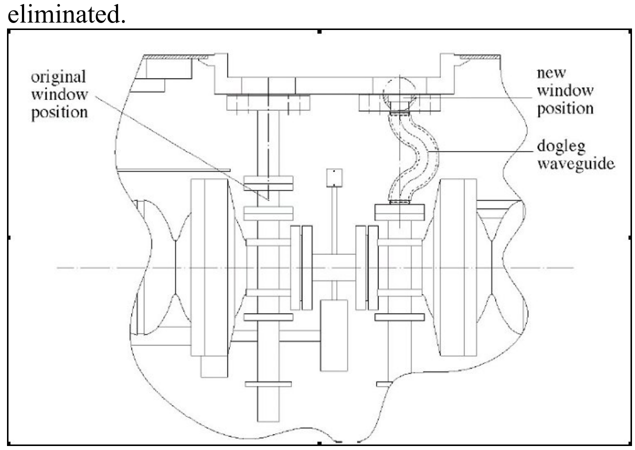

Figure 1: Coupler Modifications

The distribution of maximum accelerating gradients as measured during the original commissioning in 1992-93 is shown in figure 2 and compared with the maximum gradients measured after the rebuilt cryomodules were installed in the linacs. The average maximum gradient increased from 9.1 MV/m for C20 cavities to 14.4 MV/m for the C50 cavities.

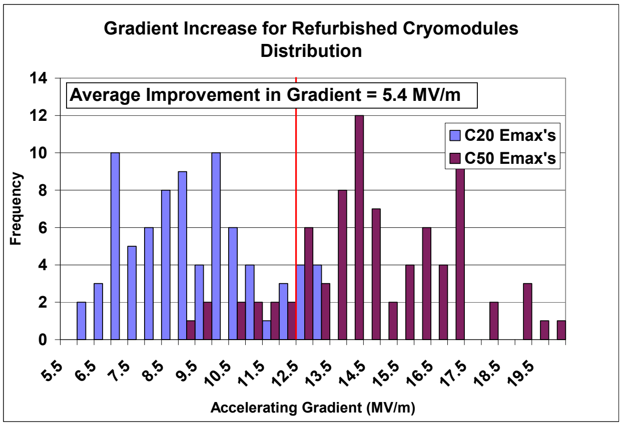

Figure 2: Maximum Gradients

While the increase in Emax is a useful indicator of improved performance, usable gradient is a better indicator. Figure 3 compares the maximum gradients determined during commissioning with the maximum gradients achieved during normal day-to-day operation of the accelerator. Nearly 70% of the reprocessed cavities are operating at or above the 12.5 MV/m specification. Note that while cavity gradients reached as high as 20 MV/m, the current LLRF controls limit usable gradients to 13.5 MV/m. This limit has the effect of reducing the average operating gradient to 12.2 MV/m.

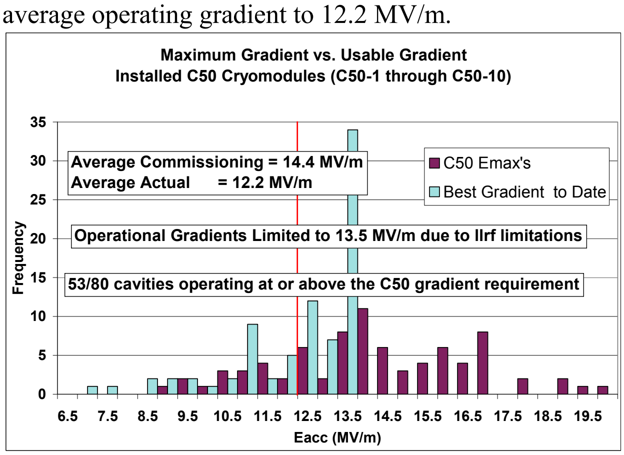

Figure 3: Maximum Gradients vs. Usable Gradients

Field Emission

Reducing field emission in the cavities as a means of increasing the usable gradient was another major goal of the C50 project. Table 1 shows the level of success. More than half of the reprocessed cavities exhibited no field emission.

Table 1: Field Emission Improvements

	C20	C50
Cavities with FE	71	36
Average FE Onset (MV/m)	6.9	11.6

Arcing

Eliminating the charge induced arcing in the FPC was a stated goal of the C50 project. Table 2 shows that the dogleg couplers successfully eliminated arcing as a gradient limit in all but one of the eighty cavities. Furthermore, there has been zero occurrences of periodic arcing for these cavities during accelerator operation

Table 2: Gradient Limits

Gradient Limit	Number of Cavities
Quench	65
Available Power Limit	8
Waveguide Vacuum Fault	3
Reflected Power	2
Warm Window Temp Fault	1
Waveguide Arcs	1

Unloaded Q (Q_O)

Another important measure of cavity performance is the unloaded Q or Q_O. The goal for C50 was a Q_O of 6.8×10^9at 12.5 MV/m. In other words, the cavity would dissipate 12 W into the liquid helium bath at a gradient of 12.5 MV/m. A cryomodule delivering 50 MV would have an RF heat load of approximately 100 W.

The project was only partially successful in this regard. After reprocessing, each cavity was tested in a dewar filled with helium cooled to 2 K. The cavities performed extremely well during these tests with measured Q_O's of better than 1×10^{10}. Unfortunately, after installation in cryomodules, all of the cavities exhibited significant Qo degradation. Figure 4 shows a typical example of the change in performance. The unloaded Q was reduced by half after installation in a cryomodule. Note that the performance of the reprocessed cavities was roughly the same as their performance during the original installation in 1993.

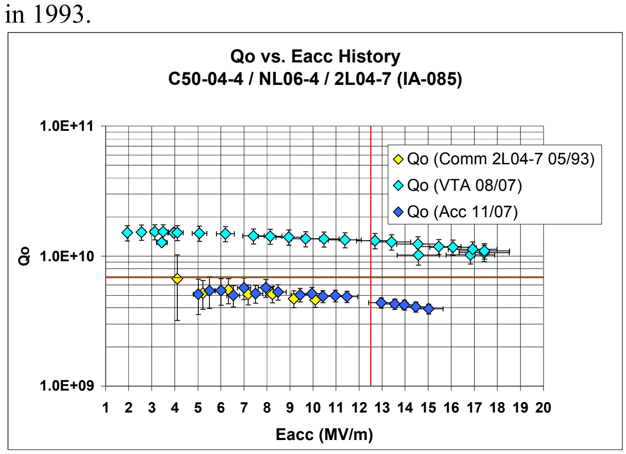

Figure 4: Vertical Test vs. Cryomodule Test

In fact the same level of degradation had been observed during the original production run. At the time, the low Q_O's were attributed to Q-disease.

The C50 cavities were baked at 600°C in a vacuum furnace as part of the reprocessing procedure. The baking step was designed to remove hydrogen dissolved into the bulk niobium. The dissolved hydrogen is responsible for the formation of hydrides on the niobium surfaces at temperatures between 60 K and 150 K. The hydrides have the effect of degrading the cavity Qo. It was thought that the vacuum bake, along with other improved processing techniques, would help to improve the Q_O's of the cavities that were assembled in the cryomodules.

It became clear, after several refurbished cryomodules were tested, that the Q_O degradation was still a problem. Attempts to determine the cause have focused on possible magnetized components or other unrecognized magnetic field sources. During one cryomodule disassembly, a search for magnetized components was conducted with a gaussmeter. This survey determined that components of the mechanical tuner that were in close proximity to the cavity were indeed magnetized. During the reassembly of the cryomodule the magnetized components for four of the eight tuners were wrapped with magnetic shields. While some small improvements was measured, it was clear that tuner components were not the only culprit See Figure 5.

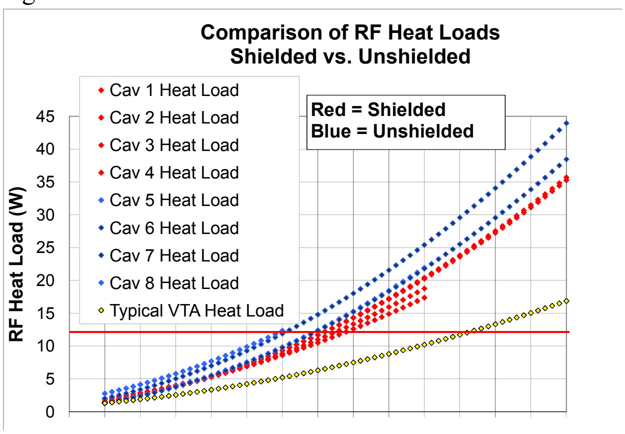

Figure 5: Effects of Magnetic Shielding

The investigation continued as the project proceeded, looking at helium vessels, ion pump magnets and other possible culprits. In the end a solution to the degradation problem has not been found. Figure 6 shows the Qo curves for all of the C50 cavities. None of the C50 cavities met the Q_O goal.

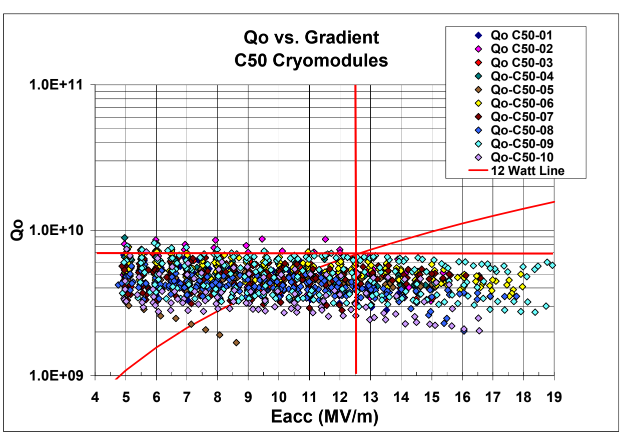

Figure 6: Qo vs. Eacc, C50 Cavities

OUTCOME OF THE C50 PROJECT

The ultimate goal of the C50 project was to enable robust 6 GeV operation of the CEBAF accelerator. This was to be accomplished by rebuilding ten cryomodules and increasing their accelerating voltage to 50 MV.

Figure 7 illustrates the capability of the ten cryomodules with respect to energy gain.

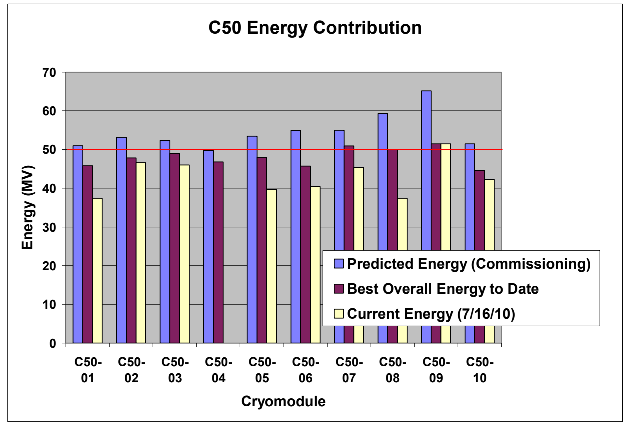

Figure 7: Cryomodule Energy Gain

All ten of the cryomodules have delivered from 45 to 50 MV during normal operations. Three of the cryomodules are providing 50 MV or better on a daily basis. The outcome for the accelerator is shown in Figure 8.

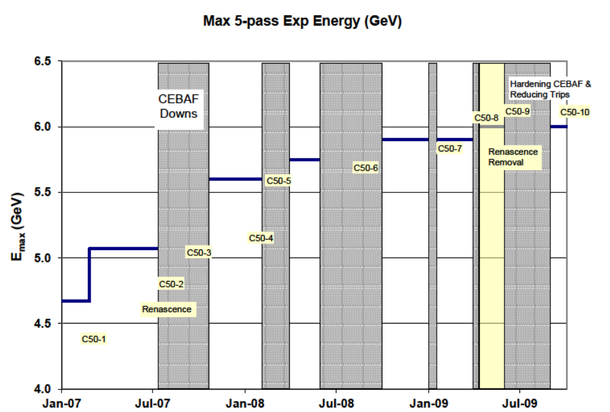

Figure 8: Performance Increase during C50 Installations

This figure shows the rise in the Maximum available energy during 5-pass operation of the machine during the span of the C50 project. The maximum energy had risen from 4.5 GeV to 6 GeV when the eighth cryomodule was installed. Further cryomodule installations served to increase reliability and reduce RF trip rates.

CONCLUSION

The C50 cryomodule refurbishment project has enabled CEBAF to deliver robust 6 GeV, 5-pass beam. The charge induced arcing problem has been eliminated. Further investigation is required to understand the mechanism behind Qo degradation in this cryomodule design.