OVERVIEW OF THE FIRST FIVE REFURBISHED CEBAF CRYOMODULES*

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Abstract

The Thomas Jefferson National Accelerator Facility is currently engaged in a cryomodule refurbishment project known as the C50 project. The goal of this project is robust 6 GeV, 5 pass operation of the Continuous Electron Beam Accelerator Facility (CEBAF). The scope of the project includes removing, refurbishing and replacing ten CEBAF cryomodules at a rate of three per year. Refurbishment includes reprocessing of SRF cavities to eliminate field emission and increase the nominal gradient from the original 5 MV/m to 12.5 MV/m. New "dogleg" couplers between the cavity and helium vessel flanges will intercept secondary electrons that produce arcing at the 2 K ceramic window in the fundamental Power Coupler (FPC). Modifications of the external Q (Qext) of the FPC will allow higher gradient operations. Other changes include new ceramic RF windows for the air to vacuum interface of the FPC and improvements to the mechanical tuner. Any damaged or worn components are replaced as well. Currently, six refurbished cryomodules are installed in CEBAF. Five have completed testing and are operational. This paper will summarize the test results and operational experience for the first five cryomodules.

INTRODUCTION

The first of the refurbished cryomodules (C50-01) was installed in the North Linac of CEBAF in January, 2007. The fifth refurbished CEBAF cryomodule (C50-05) was installed in the South Linac of CEBAF in February, 2008. All five of these cryomodules had previously been in service in the accelerator tunnel since 1992. During the refurbishment process, each cryomodule was disassembled and its cavities removed. Improved processing methods were used to eliminate field emission and increase the gradient from the original 5 MV/m to an average of 12.5 MV/m. "Dogleg" waveguides were installed between the cavity and helium vessel flanges to intercept the secondary electrons that produce arcing on the cold ceramic window of the FPC. Improved warm ceramic windows were added as well. 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 these cryomodules are installed, they are subjected to a commissioning process prior to being released for operation in the accelerator. During the commissioning process, each cavity is tested individually to determine the maximum gradient (Emax), and the maximum operating gradient (Emaxop). Measurements of the unloaded Q (Qo) and of field emission are made across the available gradient range. This paper compares the results of commissioning after refurbishment to the results of the original commissioning in 1992. This paper also takes a brief look at the operational history of the refurbished cryomodules.

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GRADIENT IMPROVEMENT

One of the goals of the refurbishment project is to increase the energy gain from 20 MV to a nominal 50 MV. This goal required an increase in the nominal cavity gradient from 5 MV/m to 12.5 MV/m. Improvements in cavity processing are used to increase the quench gradient and eliminate field emission. The dogleg waveguides are designed to eliminate arcing as a limitation on gradient. The improved RF window design reduces FPC operating temperatures and allows higher forward power levels.

Figure 1 shows the distribution of Emax before and after rebuilding. Emax is defined as the highest gradient that can be reached without quenching the cavity or activating one of the machine protection interlocks. These interlocks include arc detectors looking at the waveguide vacuum space, warm window temperature, or beamline and waveguide vacuum set points.

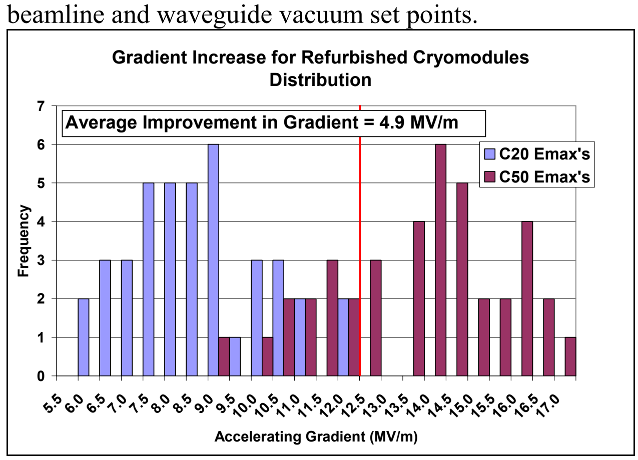

Figure 1: Gradient Improvement

Before reprocessing, these cavities had an average Emax of 8.5 MV/m. The average maximum gradient for the forty cavities has increased to 13.4 MV/m, an increase of 4.9 MV/m or 58%.

Table 1 lists the gradient limits for these cryomodules. The majority of cavities are quench limited. Nine cavities were limited by the warm window temperature. An older style of window had been installed temporarily because of window production delays. These windows were recently replaced with the correct type of ceramic window and the cryomodule (C50-05) is waiting for a retest. It is expected that window-heating will no longer limit gradient in this cryomodule.

Table 1: Gradient Limits

Limit	Number of Instances
Cavity Quench	27
Waveguide Vacuum Fault	2
Warm Window Temp Fault	9
Waveguide Arcs	1
Forward Power Limit	1

While the increase in Emax is a useful indicator of increased performance, Emaxop, is a better measure of the usable gradient. Once Emax has been determined, a stable operating gradient must be determined. In the case of the CEBAF cryomodules, a one-hour run is completed at the highest possible gradient below Emax. This gradient is defined as Emaxop. The average value for Emaxop is 12.5 MV/m, 0.9 MV/m lower than the average for Emax.

Finally, Table 2 shows the predicted energy gain based on the determinations of maximum operating gradient.

Table 2: Energy Gain

Cryomodule	Energy Gain (MV)
C50-01	51.0
C50-02	53.3
C50-03	52.4
C50-04	49.8
C50-05	43.1 (window temp. limited)

FIELD EMISSION

Improved processing techniques, such as high pressure rinsing, are applied to the cavities in the C50 cryomodules to eliminate or reduce field emission and increase operating gradients. Figure 2 is a comparison of the onset gradients for detectable X-rays from field emission before and after refurbishment.

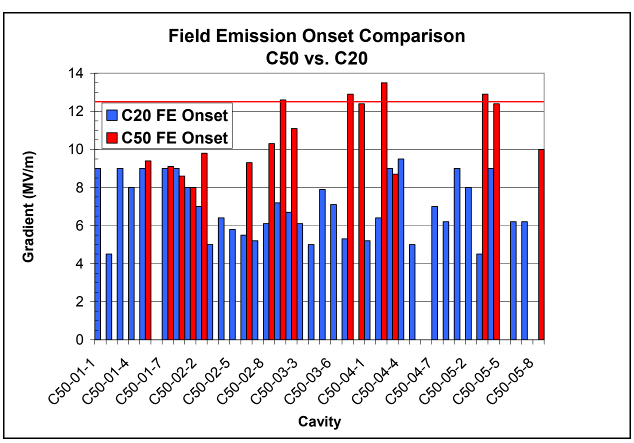

Figure 2: Field Onset Comparison

This graph illustrates several points. First, all but three of the forty cavities originally exhibited field emission. After processing, only sixteen cavities generated any measurable field emission. Second, the average gradient at which field emission turns on, for those cavities that generated field emitted X-rays, has increased from 6.9 MV/m to 10.7 MV/m.

Q_O AND HEAT LOAD

The goal for RF heat dissipated by C50 cryomodules in the 2 K helium circuit is 100 Watts at 50 MV or 12 Watts per cavity at 12.5 MV/m. This implies that Qo for these cavities must be greater than or equal to 6.8×10^9.

For cavities installed in a cryomodule, Qo is measured calorimetrically. The cryomodule is isolated from the cryogenic system and the RF heat load is determined from the rate of rise of the helium bath pressure. The results of these measurements are shown in Figure 3.

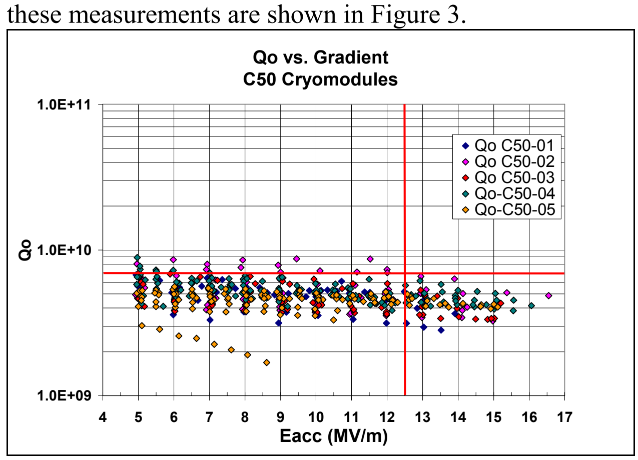

Figure 3: Qo Results

The two red lines on the graph indicate the gradient and Qo requirements. It is obvious from the figure that the cavities are not meeting the goal for Qo and therefore are dissipating more heat than is desired. Figure 4 shows the Qo values for the cavities at their respective Emaxop's.

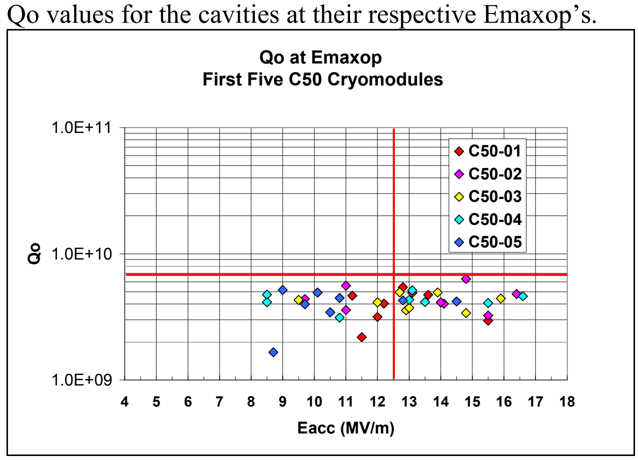

Figure 4: Qo at Emaxop

Table 3 lists the expected 2 K heat load for the cryomodules with all cavities operating at Emaxop. The heat load also includes the average static 2 K heat load of 13.2 Watts.

Improving the unloaded Q of these cavities is one of the biggest challenges facing the C50 project.

Table 3: Overall Heat Load

Cryomodule	Total RF Heat Load (W)
C50-01	198
C50-02	190
C50-03	191
C50-04	198
C50-05	145

After the cavities are reprocessed, they are tested in a dewar in the Vertical Test Area (VTA). This happens before the cavities are installed in a cryomodule. Figure 5 shows the typical disparity between Qo as measured in the VTA and Qo as measured after the cavities are installed in a cryomodule. Generally, Qo's of 1×10^{10} or better are measured in the VTA, followed by a reduction of as much as 50% after the cavities are installed in a cryomodule.

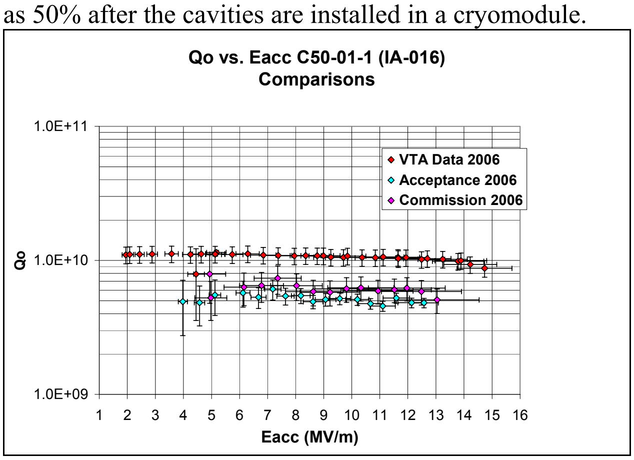

Figure 5: Qo Discrepancy

Several possible reasons for this reduction have been or are being investigated. The presence of unaccounted for magnetic components near the cavities is viewed as a likely reason for the reduction in Qo performance. One magnetized component in the tuner assembly has so far been identified. During the reconstruction of the sixth C50 cryomodule, magnetic shielding was wrapped around the magnetized components associated with four of the cavities. This cryomodule is still under test and so is not covered in any detail in this paper. However, Figure 6 shows the initial results of the attempted mitigation.

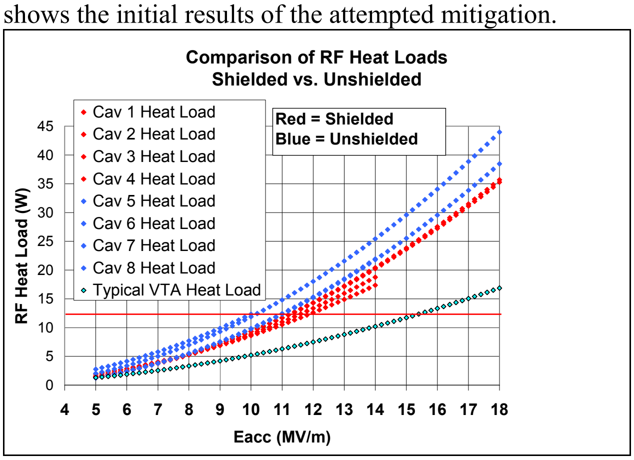

Figure 6: Effects of Magnetic Shielding

Figure 6 shows that the shielded cavities have a reduced RF heat load (increased Qo). However, the reduction was not enough to account for all of the discrepancy between the VTA measurements and the cryomodule measurements. The investigation will continue.

OPERATIONAL EXPERIENCE

The first of the refurbished cryomodules has been in operation in the accelerator, except for maintenance periods, since May 2007. The last two of this group have been in operation since March 2008. Table 4 compares the predicted energy gain with the best energy gain achieved during beam operations since installation.

Table 4: Energy Gain Comparison

Cryomodule	Predicted Energy (MV)	Best Actual (MV)
C50-01	51.0	45.8
C50-02	53.2	45.5
C50-03	52.3	49.6
C50-04	49.8	46.8
C50-05	43.1	39.6

Among the reasons for the lower actual energy gains are issues that occur with run times longer than an hour, such as waveguide vacuums that degrade over longer time periods.

Figure 7 shows RF trip totals for the five cryomodules over time. The graph shows a decrease in total trips for the first of the cryomodules. The slow cleanup of the waveguide vacuum spaces is responsible for most of that reduction. The graph also shows a big increase in faults for C50-03 during the latest run. The cavities in this cryomodule had not been pushed to their gradient limits until the most recent run. When they were finally pushed to their limits, an increase in vacuum trips would be expected.

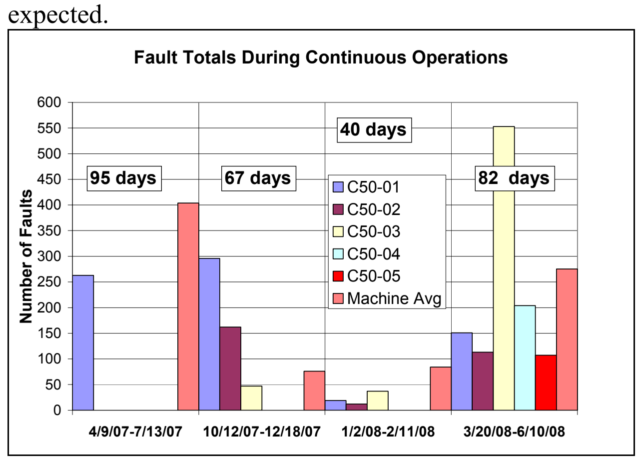

Figure 7: RF Fault Totals

CONCLUSION

The C50 project, so far, has met the goals for increased gradient and reduced field emission. The project has not met the goal set for Qo. We are investigating how to meet that specification in future C50 cryomodules.