HIGH GRADIENT PERFORMANCE IN FERMILAB ILC CRYOMODULE*

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Abstract

Fermilab has assembled an ILC like cryomodule using U.S. processed high gradient cavities and achieved an average gradient of 31.5 MV/m for the entire cryomodule. Test results and challenges along the way will be discussed.

INTRODUCTION

An intermediate S1 goal of the International Linear Collider is to, "achieve 31.5 MV/m average operational accelerating gradient in a single cryomodule as a proof-of-existence. In case of cavities performing below the average, this could be achieved by tweaking the RF distribution accordingly [1]." With this in mind Fermilab has assembled and brought into operation an ILC-type cryomodule, the 2nd of this type at Fermilab. In Fermilab parlance this device is known as RFCA002 or simply CM-2. CM-2 is composed of eight nine-cell cavities resonating at 1.3 GHz. All eight cavities were fabricated in industry and tested extensively prior to assembly into a single cryomodule. Fabrication and testing results to date have been documented previously [2,3].

CM-2 was first installed in the test cave in March 2012, however leak checking of the 2-phase helium circuit revealed a leak which was in an inaccessible location for further localization, thus necessitating its removal. A faulty bellows was replaced and installation for a second time occurred in April 2013. Warm coupler conditioning was carried out on each cavity individually in parallel with ongoing interconnect and leak checking activities.

INDIVIDUAL CAVITY CHARACTERIZATION

Once the entire cryomodule could be cooled down, a program to individually characterize each cavity was carried out. The suite of tests is typical for testing such cavities at Fermilab and other SRF facilities:

- Tune cavity to resonance
- Map out and set Q_L
- System calibrations, calculate gradient, k
- On-resonance conditioning
- Determine peak performance
- Final (high power) LLRF calibration
- Lorentz Force Detuning Compensation set-up
- Document dark current, x-rays vs. gradient
- Dynamic Heat Load measurements (Q_0).

Typical operating parameters were set to match ILC design ones as much as possible: fill time = 596 microseconds, flattop length = 969 microseconds, Q_{Ext} = 3.5 x 10^7, and pulse repetition = 5 Hz. In this phase the output of the 5MW klystron was directed to one cavity at a time, to a peak of order 1 MW.

The duration of this characterization step was 57 days for the first cavity, but was reduced to as short as six days as experience was gained.

Peak Gradient

An administrative limit of 31.5 MV/m was the maximum allowed peak gradient each cavity was run up to until this first stage of testing as a unit was completed. All cavities but #6 were able to reach this limit. Figure 1 compares the achieved peak gradients for all cavities in bare cavity vertical tests at Jefferson lab, horizontal tests as dressed cavities at Fermilab, and as contained within the cryomodule.

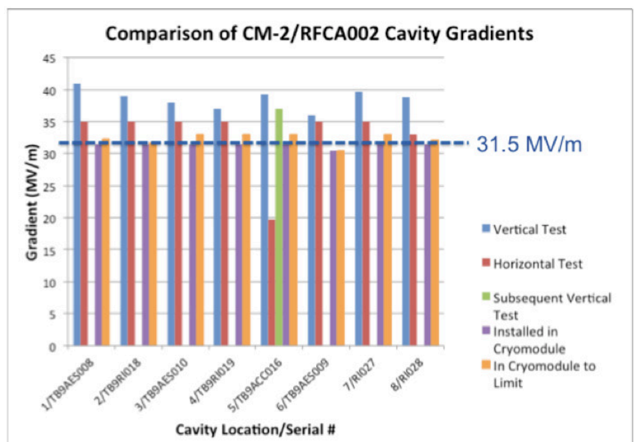

Figure 1: Comparison of CM-2/RFCA002 cavity gradients: vertical test (blue), horizontal (red), in CM-2 (purple) during initial tests, and to absolute gradient in cryomodule (orange). An administrative limit of 31.5 MV/m was set for initial CM-2 testing.

Q_0

The Q_0 of each cavity was also determined by measuring the dynamic heat load at discrete points just below the peak gradient. Figure 2 summarizes these results. At their peak gradient the Q_0 values ranged from a low of 5.7 x 10^9 on cavity #7 to as high as 1.4 x 10^{10} on cavity #2. There is a large uncertainty on these values owing the nature of the measurement.

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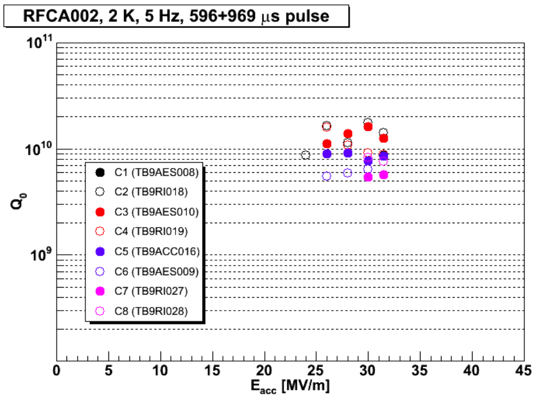

Figure 2: Q0 for CM-2 cavities measured individually in the cryomodule. Some points are invisible due to overlays.

Field Emission/Dark Current

Field Emission was measured using radiation detectors strategically placed in the test cave. The primary devices used were Fermilab-built 'chipmunks' [4] located at each end of the cryomodule on the beam axis as well as one placed immediately below the cavity under test. As a check a 'FOX' detector, another Fermilab built ion chamber especially sensitive to X-rays, was located at the middle of the cryomodule. While there was a wide variation in response, no cavity exhibited any field emission below 19 MV/m as measured on the detector directly below the cavity. Figure 3 shows the response of this detector during single cavity operation.

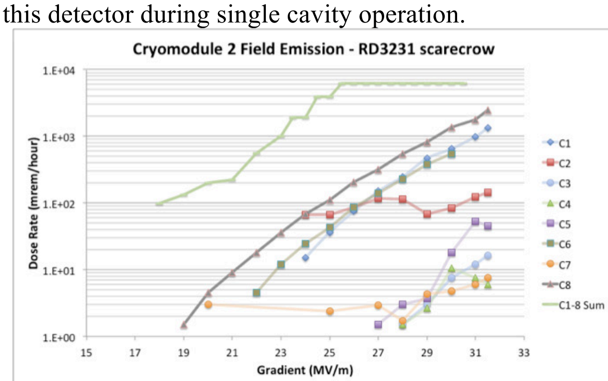

Figure 3: Detected radiation from each cavity when singly powered. The detector was located directly beneath the cavity under test.

Dark current was measured by means of Faraday cups located on the beam center line at each end of the cryomodule. Their outputs were amplified and digitized thus allowing one to see the dark current distribution during the RF pulse, for example as shown in Fig. 4. The magnitude of dark current generated varied from cavity to cavity with only four producing any detectible single during the individual test phase. In all cases, the lower threshold was 22 MV/m as shown in Fig. 5.

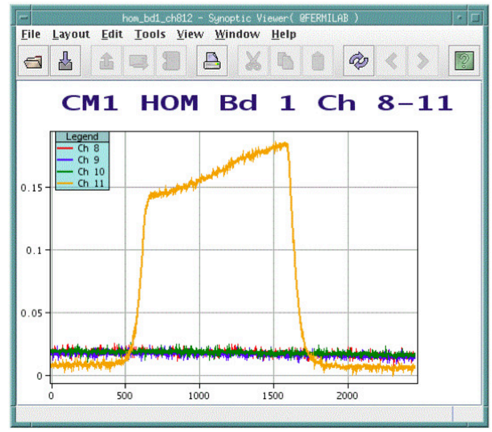

Figure 4: Typical digitized dark current image. Time is in milliseconds (x-axis) and amplitude is Volts (100 nA = 1 V). Gradient for this image was ~26 MV/m.

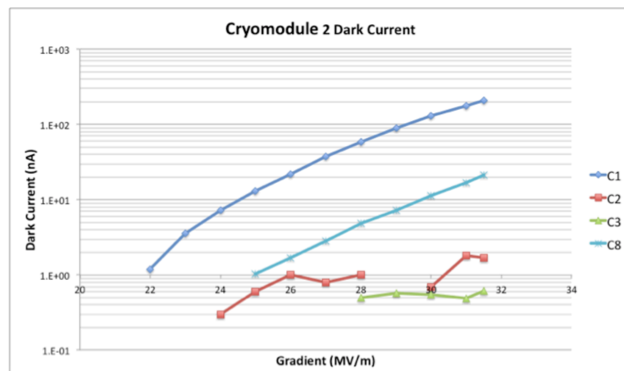

Figure 5: Dark current generated by cavity during individual characterization. Only four of the eight cavities generated any detectable dark current.

UNIT TESTS

Once all eight cavities were individually characterized, powering of the cryomodule as a unit was initiated. This required installing a waveguide distribution system to feed all eight cavities from the single klystron power source. This system was provided by SLAC and was the same as used for CM-1 operation which has been described previously [5]. In Fig. 10 the 'complete' cryomodule operated as a unit is pictured.

Gradient

As seen in Fig. 6 a total voltage of slightly more than 252 MV was achieved, thus an average cavity gradient of 31.5 MV/m was realized. The operating parameters were identical to those of the previous phase of testing including a pulse repetition rate of 5 Hz. Adaptive Lorentz Force Detuning Compensation was also active and the Low Level RF was operated in open loop. Dynamic Heat Load/Q_0 measurements were carried out on the cryomodule in two conditions – one with cavities #1 through #7 only while #8 had coupler vacuum issues described below and eventually with all eight cavities

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powered simultaneously (once the vacuum issue was temporarily resolved).

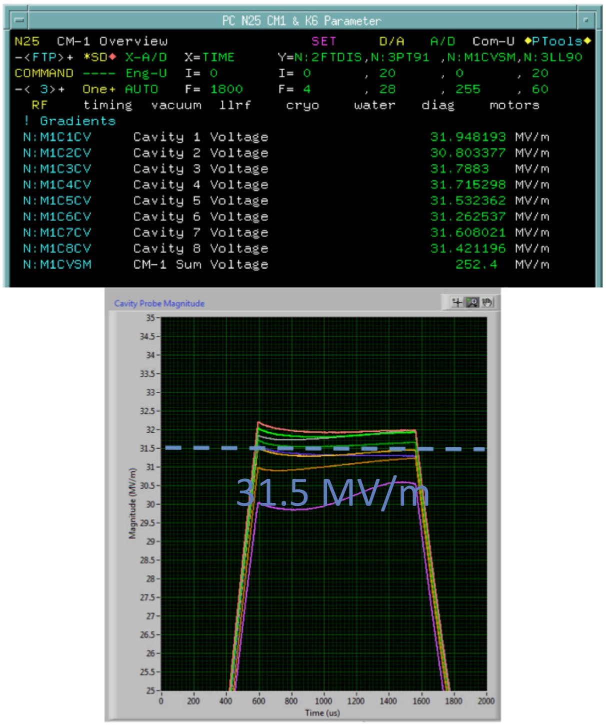


Figure 6: Comparison of CM-2/RFCA002 cavity gradients: vertical test (blue), horizontal (red), and in CM-2 (purple). An administrative limit of 31.5 MV/m was set for the initial phase of CM-2 testing.

Dynamic Heat Load/Q0

Figure 7 compares Q_0 vs. gradient for both seven and eight cavity operation. There is of order 20% difference between the results. Operation during these tests were again with the operating parameters noted above.

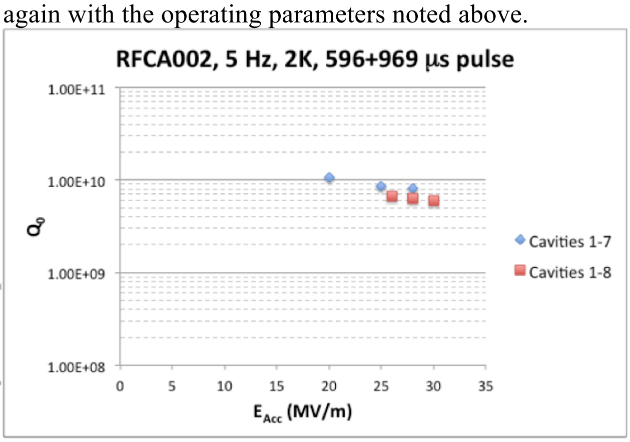


Figure 7: Q_0 versus gradient for CM-2. Blue points are with cavities 1-7 only powered, red are with all 8 cavities operating simultaneously.

Recent Results

With the basic goals of CM-2 achieved, attention has recently turned to pushing each cavity's gradient to the limit. Table 1 summarizes the gradient limit of each cavity to date as do the orange bars of Fig. 1. Upper limits on four of the cavities have been determined with the remaining cavities able to achieve at least 33 MV/m. Limits will continue to be explored and it is expected that the VTO's of the waveguide distribution system will have to be adjusted to allow the highest possible voltage from each cavity and thus the cryomodule.

Consistent with individual cavity tests, investigation of dark current and field emission at high gradient indicates that the primary contributors are cavities 1, 2 and 8.

Table 1: Peak CM-2 Cavity Gradients with all 8 Powered at once. Sum = 258.1 MV, Average = 32.2 MV/m

Cavity	Peak Gradient (MV/m)	Limitation
1/TB9AES008	32.3	Quench
2/TB9RI018	31.8	Quench
3/TB9AES010	≥ 33	tbd
4/TB9RI019	≥ 33	tbd
5/TB9ACC016	≥ 33	tbd
6/TB9AES009	29.8	Quench
7/RI027	≥ 33	tbd
8/RI028	32.2	Quench

ANCILLARY SYSTEMS & RELIABILITY

In the course of CM-2 operation the supporting systems have had to perform to a high level and their characteristics explored. Equally important as high gradient achievement is high reliability which is necessary for operation in a particle accelerator. The numerous subsystems – RF, cryogenics, vacuum, interlocks, controls, etc. - all must and have functioned well. Occasional overnight runs of CM-2 have resulted in continuous operation for up to 3+ days at moderate gradients. The limiting factor of running at high gradients for more than a few hours is the warm coupler window temperature for cavity #7. Even with power off to the cryomodule this sensor runs several degrees warmer than the others indicative of a possible thermal short.

Cavity #8 Warm Coupler Vacuum

The most significant impediment to operation was a vacuum leak on the common vacuum circuit for the warm side of the fundamental (input) power couplers. It developed spontaneously during cavity #7 characterization with vacuum degrading from a nominal value of 5×10^{-9} to 1.4×10^{-6} Torr in a matter of minutes as documented in Fig. 8. This event occurred during off-hours when no power was being delivered to the cryomodule; the magnitude exceeded the limit allowed for high power operation. Investigation isolated the source to the coupler of cavity #8 as shown in Fig. 9a. The vacuum section was able to be isolated and pumped on independently from the remainder of the coupler line. In this situation it was possible to complete all cavity characterizations and operate all eight cavities at once.

Repairs were made in situ, but did require warm-up of the cryomodule to room temperature and venting of the beam tube vacuum to assure no pressure differential was acting on the bellows within the coupler. Repair consisted of replacing the warm end coupler assembly. Subsequent leak check of the removed piece revealed a very localized leak on a bellows convolution as shown in Fig. 9b.

Since the repair was made CM-2 has been cooled back down to 2 Kelvin and has operated more or less as it did prior to being thermally cycled.

FUTURE PLANS

As conditions permit, further studies will be carried out to determine all cavity peak gradients and continue to study LLRF and LFDC performance. A pair of radiation detectors – a diamond detector and helium-filled ion chamber designed to operate in cryogenic conditions were installed within CM-2 and are only in the very early stages of evaluation. Similarly, the magnet package installed in the cryomodule has yet to be powered and evaluated.

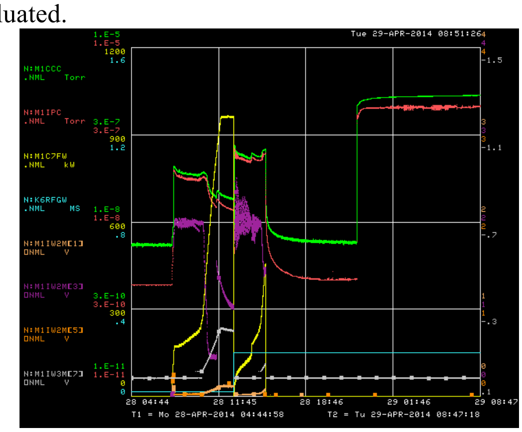
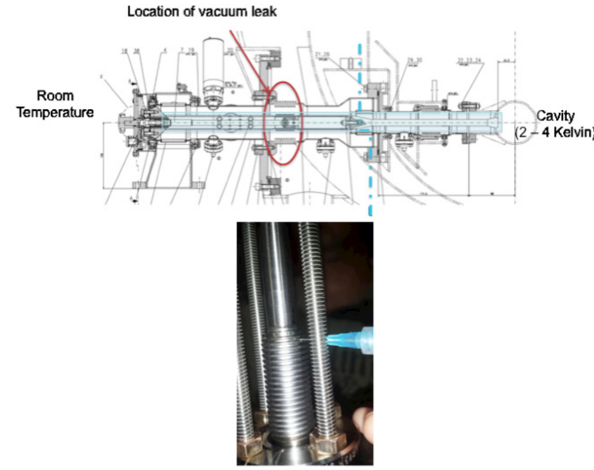


Figure 8: Vacuum excursion on coupler line eventually traced to Cavity #8 coupler warm bellows. The x-axis is time and spans 4 hours. The y-axis is vacuum pressure with range from 1 x 10^{-11} to 1 x 10^{-5} Torr.

CM-2 is installed within an accelerator enclosure containing a test electron accelerator, the Fermilab Accelerator Science & Technology (FAST) facility which recently accelerated its first 20 MeV photoelectrons [6].

In the coming months it is planned to connect the FAST injector to CM-2 to create a facility that can provide up to 300 MeV electrons for accelerator R&D.



Figures 9a, b: Cavity #8 coupler vacuum leak. (a) points to the area identified during in-situ check and (b) shows the actual location determined by post-mortem.

SUMMARY

The primary goal of demonstrating that an ILC-type cryomodule of eight cavities can be operated at an average gradient of 31.5 MV/m with all cavities powered simultaneously has been achieved with CM-2, thus meeting the ILC S1 goal. This was accomplished with cavities processed in the U.S. and demonstrates that Fermilab has developed the infrastructure and expertise to produce high gradient cryomodules. Repair of the warm coupler vacuum has demonstrated that the technical staff is able to address and successfully make in-situ repairs. CM-2 appears to be operationally ready to provide an accelerating voltage of up to 250 MeV.

Figure 10: CM-2 installed in the FAST cave at Fermilab. In the foreground is the waveguide distribution system which delivers RF output from a single 5 MW klystron to the coupler of each cavity.

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Successful operation of CM-2, particularly achieving high gradient, was truly a team effort involving not only the technical staff of the Fermilab Technical and Accelerator Divisions but also colleagues from many institutions around the world. This is truly an international endeavour.

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