INDIVIDUAL RF TEST RESULTS OF THE CAVITIES USED IN THE FIRST US-BUILT ILC-TYPE CRYOMODULE

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Abstract

Eight 1.3 GHz nine-cell SRF cavities have been installed in a cryomodule intended to demonstrate the ILC design goal of 31.5 MV/m. These cavities all underwent two types of individual RF testing: a low-power continuous-wave test of the "bare" cavity and a high-power pulsed test of the "dressed" cavity. Presented here is a discussion of the results from these tests and a comparison of their performance in the two configurations.

INTRODUCTION

The basic accelerating unit for the International Linear Collider (ILC) is a superconducting radiofrequency (SRF) cryomodule (CM) housing eight or nine elliptical nine-cell 1.3 GHz cavities. These cavities are required to operate at an accelerating gradient of 31.5 MV/m with an unloaded quality factor $Q_0 \geq 1 \times 10^{10}$ [1]. To date no cryomodule in which all installed cavities achieved this requirement has been built. One prototype cryomodule for the European X-ray Free Electron Laser contained an octet of cavities with an average gradient of 32.5 MV/m, but due to limitations of the RF distribution can only be operated at 30 MV/m [2].

Fermilab has recently completed the assembly of RFCA002, a cryomodule containing eight cavities manufactured by two different industrial vendors (ACCEL/RI and AES) specifically selected to be likely to achieve the ILC design goal based on their performance in individual RF tests (see Table 1). The cavities were first tested "bare" in a vertical liquid helium dewar using low-power continuous-wave (CW) RF. Cavities which met the ILC vertical test specification ($E_{acc} \geq 35$ MV/m, $Q_0 \geq 0.8 \times 10^{10}$) [1] were then welded into individual helium jackets and outfitted with a high-power input coupler. These "dressed" cavities were then tested in a horizontal test cryostat using high-power pulsed RF.

VERTICAL TESTS

All of the RFCA002 cavities were first processed and vertically tested at Jefferson Lab as part of a high-gradient R&D program for the ILC [3]. Three of these cavities (TB9RI019, TB9ACC016, and TB9RI027) were subsequently vertically tested at Fermilab. All cavities were limited by quenching; the maximum gradients achieved in their final vertical tests are listed in Table 1.

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Table 1: Maximum gradients achieved by RFCA002 cavities (listed by position in CM) in individual RF tests

Cavity	Last Vertical Test	Last Horizontal Test
TB9AES008	41 MV/m	> 35 MV/m
TB9RI018	39 MV/m	> 35 MV/m
TB9AES010	38 MV/m	> 35 MV/m
TB9RI019	38 MV/m	> 35 MV/m
TB9ACC016	37 MV/m	19 MV/m
TB9AES009	36 MV/m	35 MV/m
TB9RI027	40 MV/m	> 35 MV/m
TB9RI028	39 MV/m	33 MV/m

Figure 1a shows the Q_0 vs. E_{acc} behaviour from the last vertical test; all the cavities meet the ILC vertical test specifications and exhibit no high-field *Q*-drop. Figure 1b shows X-ray measurements outside the vertical test dewar as an indication of field emission (FE) from the cavity. Most of the cavities show some FE turning on in the region from 25-30 MV/m; however it does not limit the cavity performance.

HORIZONTAL TESTS

The horizontal test stand (HTS) at Fermilab provides an intermediate test point between the vertical test and the integrated cryomodule test. At this facility an administrative limit of 35 MV/m is placed on the cavities in order to guard against possible high-power failures of the input coupler that could compromise the integrity of the cavity surface (a scenario that did indeed manifest itself; see [4] for details). As seen in Table 1, five of the eight RFCA002 cavities reached this administrative limit. Two others (TB9AES009 and TB9RI028) were limited by a quench at the gradients shown. TB9ACC016 was limited by severe *Q*-drop starting at around 17 MV/m. Glitter-like flakes of copper found on the center conductor of the input coupler upon its removal suggest that a failure of the coupler's copper plating led to contamination of the cavity. A subsequent high-pressure rinse (HPR) of the cavity followed by a vertical test at Fermilab (while still in its helium jacket) resulted in a return to excellent performance as indicated by the results shown in the previous section.

Cavities at HTS are operated strongly overcoupled and therefore Q_0 must be determined from the heat dissipated to the helium bath. The nominally high cavity Q_0 and

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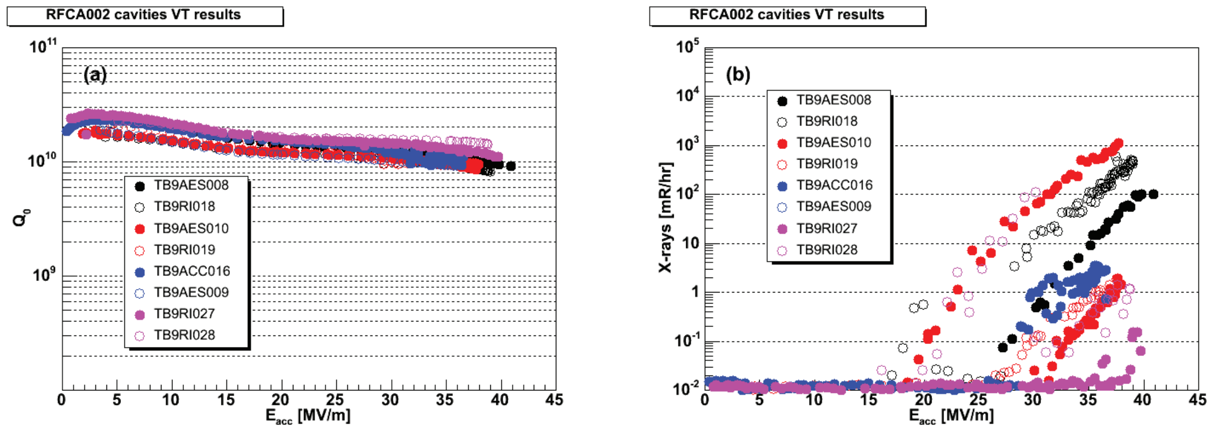

Figure 1: (a) Q_0 vs. E_{acc} from the last vertical test of the RFCA002 cavities. (b) X-rays vs. E_{acc} from the last vertical test of the RFCA002 cavities.

small (< 1%) RF duty factor at HTS result in very small (< 1 W) dynamic heat loads for all but the highest gradients. This combined with poorly understood systematic effects make Q_0 measurements quite difficult. Figure 2a shows Q_0 vs. E_{acc} results from each cavity's last horizontal test; these results will be discussed further in the next section. One can clearly see the aforementioned problem with TB9ACC016, however.

Figure 2b shows the X-rays measured just outside the test cryostat. TB9AES008 is the only cavity with significant field emission; in fact most of the cavities were FE-free after a period of *in situ* RF processing.

COMPARISON OF RESULTS

A comparison of results from the vertical and horizontal tests can help address the question of whether or not vertical test results are predictive of a cavity's performance in a cryomodule, although restricting the discussion to the RFCA002 cavities introduces a selection bias to the analysis since the best HTS performers were chosen for the cryomodule. Nonetheless, it is useful to consider the three main cavity performance metrics: maximum gradient, Q0, and field emission.

Maximum Gradient

The 35 MV/m administrative limit for the horizontal test precludes a direct comparison with the vertical test; however, one can say that a maximum gradient greater than 35 MV/m persisted through the horizontal test for 5/8 of the cavities. For TB9AES009 the different vertical and horizontal quench limits may in fact be consistent with each other given the typical 5-10% uncertainties on RF calibrations. The large discrepancy between horizontal and vertical results for TB9ACC016 is, as mentioned, understood as an input coupler failure. TB9RI028's reduction in gradient from 39 MV/m to 33 MV/m is the only discrepancy without a simple explanation as there are limited quench diagnostics for dressed cavities.

Q_0

As mentioned in the previous section, the measurement of Q_0 from the dynamic heat load is difficult and currently not well understood at HTS. Uncertainties on Q_0 deriving from uncertainties on the static heat load have been assessed and vary from 10-50% (the lowest-gradient points measured for TB9ACC016, where the dynamic

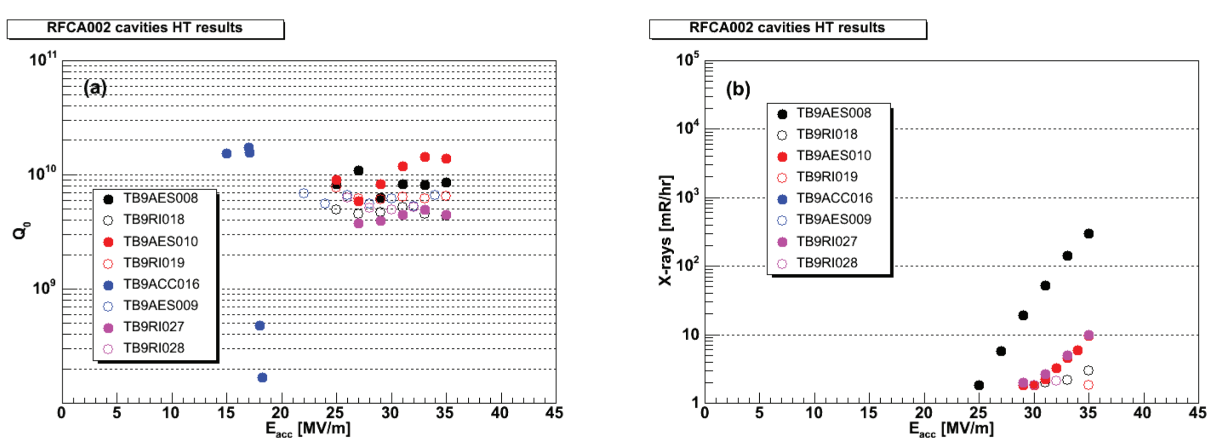

Figure 2: (a) Q_0 vs. E_{acc} from the last horizontal test of the RFCA002 cavities. (b) X-rays vs. E_{acc} from the last horizontal test of the RFCA002 cavities. Note the *y*-axis range differs from Figure 1b.

heat load is similar to the uncertainty on the static load, have associated uncertainties of nearly 100%). Other systematic effects have yet to be quantified. For these reasons it is difficult to draw strong conclusions from a comparison of vertical and horizontal Q_0 results. One can note that the horizontal results seem systematically lower than the vertical results, by a factor of up to 0.5. The HTS measurement methodology is being revisited so that future Q_0 discrepancies can be attributed to real drops in performance rather than measurement artifacts.

Field Emission

A comparison of absolute X-ray fluxes in the two test configurations is certainly not meaningful due to the differing shielding geometries and RF duty factors. What the data do show is that a cavity that exhibits FE in the vertical test will not necessarily do the same in the horizontal test, presumably due to the HPR cycle the cavity undergoes in the interim and/or the higher peak power available for RF processing at HTS. It should also be noted that the cavities that do still show some FE during the horizontal test share the same 25-30 MV/m onset range observed in the vertical test.

DISCUSSION AND CONCLUSIONS

The fact that the cavities comprising RFCA002 showed excellent performance in both the vertical and horizontal tests provides some confidence that they will perform similarly in a cryomodule but is by no means a guarantee. For example, although TB9ACC016's good performance was restored following a high-pressure rinse and a vertical re-test, no horizontal re-test was done prior to its assembly into the cryomodule. Additionally, 4 cavities (TB9AES008-010 and TB9RI018) underwent an additional HPR after the horizontal test (for reasons described in [4]) and only TB9RI018 was horizontally re-tested. Should performance reduction be observed in RFCA002, however, the extensive vertical and horizontal testing performed on the cavities will greatly restrict the space of possible sources of degradation in the cryomodule production chain.

At the time of this conference RFCA002 is being installed at Fermilab's Advanced Superconducting Test Accelerator facility. A full test of the cryomodule similar to that described in [5] is planned. The results from this test will offer a third comparison point for the data presented here and will be an important technical milestone for the ILC.

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