Performance of 3.9 GHz SRF Cavities at Fermilab's ILCTA_MDB Horizontal Test Stand

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***Abstract*—Fermilab is building a cryomodule containing four 3.9 GHz superconducting radio frequency (SRF) cavities for the Free electron LASer in Hamburg (FLASH) facility at the Deutsches Elektronen-SYnchrotron (DESY) laboratory. Before assembling the cavities into the cryomodule, each individual cavity is tested at Fermilab's Horizontal Test Stand (HTS). The HTS provides the capability to test fully-dressed SRF cavities at 1.8 K with high-power pulsed RF in order to verify that the cavities achieve performance requirements under these conditions. The performance at the HTS of the 3.9 GHz cavities built for FLASH is presented here.**

***Index Terms*—Superconducting accelerator cavities, testing**

I. Introduction

FERMILAB is constructing a cryomodule containing four superconducting radio frequency (SRF) cavities operating at 3.9 GHz for the Free electron LASer in Hamburg (FLASH) facility at the Deutsches Elektronen-SYnchrotron (DESY) laboratory. This cryomodule was proposed to linearize the energy distribution along a bunch upstream of the bunch compressor. The four 9-cell cavities were designed to operate at 2 K in the TM_{010} π-mode at an accelerating gradient E_{acc} = 14 MV/m and an intrinsic quality factor Q_0 of at least 2.5 x 10^9 [1].

The cavities are first tested "bare" in a vertical test dewar with low-power continuous wave (CW) RF [2]. After verifying their performance in the vertical test, they are welded into a titanium helium vessel and outfitted with an input coupler, blade tuner, and magnetic shielding. These "dressed" cavities are then tested at the Horizontal Test Stand (HTS) located at Fermilab's International Linear Collider Test Area at the Meson Detector Building (ILCTA_MDB).

The ILCTA_MDB HTS [3] is a facility for testing dressed SRF cavities at liquid helium temperatures with pulsed high-power RF, similar to the CHECHIA facility at DESY [4]. A test cryostat with ports for input couplers, instrumentation, and clean ultra-high vacuum pumping lines houses the cavity; an 80 kW 3.9 GHz klystron and high voltage modulator provide the RF. The layout of the facility is shown in Fig. 1.

The first production cavity to be tested at the HTS was 3.9 GHz cavity #5 (C5). In this paper we present the results from C5's horizontal test.

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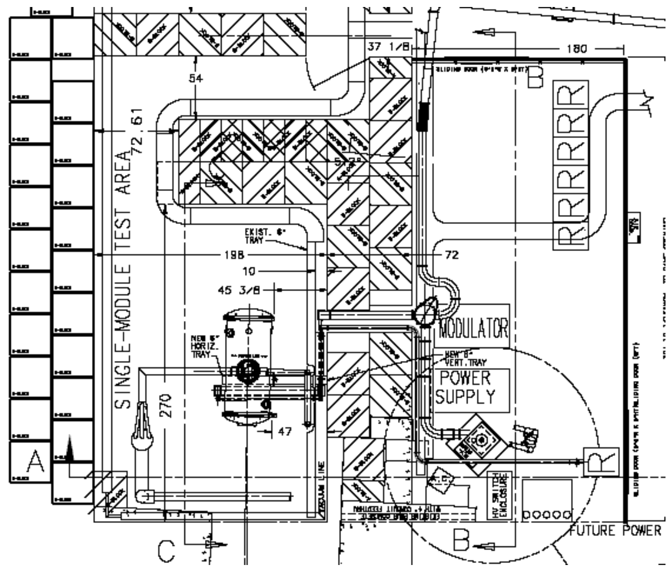

Fig. 1. The ILCTA_MDB Horizontal Test Stand. The shielding cave housing the test cryostat is on the left; the control room and RF system are on the right.

II. Room Temperature Operation

The first step in the horizontal test sequence is off-resonance conditioning of the input coupler with pulsed high-power RF at 1 Hz repetition rate. The forward power is slowly increased from zero to maximum power (~40 kW) using a pulse length of 20 μs. Maximum power is then maintained for one hour and then the process is repeated for pulse lengths of 50, 100, 200, 400, 800, and 1300 μs. Several input coupler parameters are monitored throughout the sequence: the pressure inside the cavity (a vacuum space shared with the "cold" end of the input coupler) and the pressure inside the "warm" end of the coupler, electron emission measured by two coupler electron pickups, and the temperatures of the two ceramic coupler windows. When these parameters exceed a prescribed limit (2 x 10^{-7} Torr for pressure, 1 mA for emission, and 70° C for temperature), the power is reduced for a short period of time. The conditioning sequence is shown in Fig. 2; some vacuum activity was observed at the highest powers but tended to decrease with conditioning time. The time required for each conditioning step is summarized in Table 1.

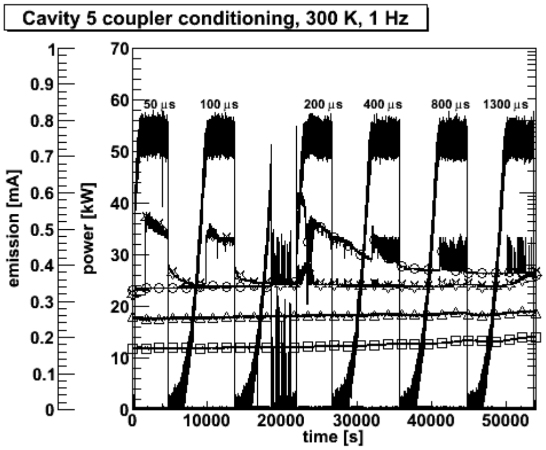

Fig. 2. Off-resonance RF conditioning of the C5 input coupler at room temperature. The solid trace is the forward power, the trace highlighted with squares is the coupler cold window temperature, the trace highlighted with triangles is the coupler warm window temperature, the trace highlighted with circles is the pressure in the cavity/coupler vacuum space, and the trace highlighted with stars is the pressure in the warm coupler vacuum space. The "grass" at the bottom of the plot is the (barely perceptible) emission measured at the coupler electron pickups. The "hole" in the 200 μs step is the result of time spent debugging instrumentation.

TABLE 1 COUPLER CONDITIONING TIMES

Pulse length (μs)	Time required (minutes)
20	165
50	179
100	150
200	160
400	150
800	150
1300	150

III. COLD OPERATION

A. Tuning

After cooling the cavity to 2 K the cavity was tuned to 3.9 GHz by operating its blade tuner's stepping motor while monitoring the π-mode resonance frequency on a network analyzer. The frequency was tuned 1.2 MHz with approximately 700,000 steps from the motor (see Fig. 3).

B. Gradient calibration

The transmitted power signal from the cavity field probe is calibrated against the gradient expected at low power via [5]

$$E_{acc} = 2\sqrt{(R_s / Q_0) Q_L P_f}\left(1 - e^{-\frac{\omega t}{2Q_L}}\right) / L \tag{1}$$

and

$$E_{acc} = k_t \sqrt{P_t} \tag{2}$$

where R_s/Q_0 is the shunt impedance, Q_L is the loaded quality factor, P_f is the forward power, P_t is the transmitted power, ω is 2π times the resonance frequency, L is the active length of the cavity, and t is the time from the start of the RF pulse

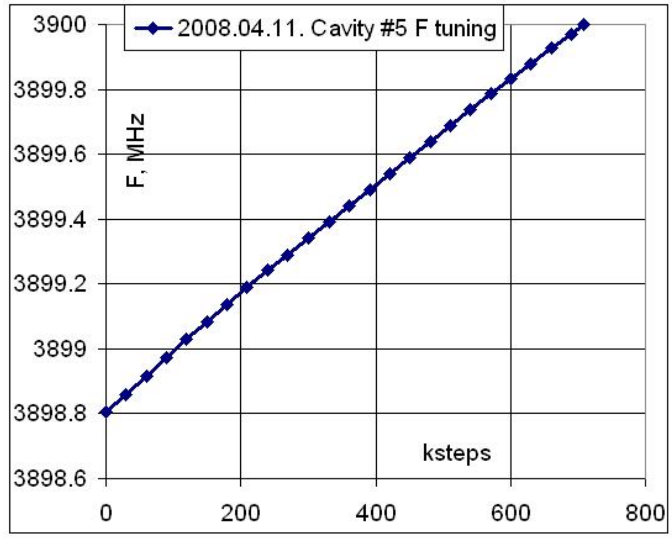

Fig. 3. Use of C5's blade tuner mechanism to bring the cavity to 3.9 GHz.

when the measurement is taken. From these equations the value k_t is determined and applied to measurements of P_t at all powers to determine the gradient.

Q_L was measured from an exponential fit to the decay curve of the transmitted power after the RF was switched off and found to be 9.2 x 10^5. With a forward power of approximately 1 kW, k_t was determined to be 3.3 x 10^6 V / [m·$W^{1/2}$].

C. Maximum gradient

The cavity power (1.3 ms pulse length) was gradually increased until quenching in the cavity was observed at 22.5 MV/m. Examples of the cavity power waveforms just below and at the quench limit are shown in Figures 4 and 5. Running at a 1 Hz or 5 Hz repetition rate had no effect on the quench limit.

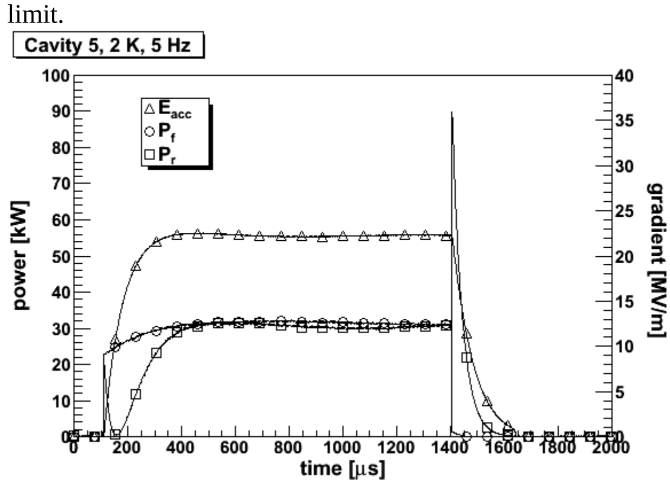

Fig. 4. Example of an RF pulse just below C5's quench limit. The squares show the reflected power, the circles show the forward power, and the triangles show the cavity accelerating gradient.

D. Measurement of Q_0

The Q_{ext} of the input coupler is about 9 x 10^5 and dominates the loaded cavity Q. Therefore the intrinsic quality factor Q_0 must be measured from the power dissipated in the cavity walls, or equivalently, the dynamic heat load to the cryogenic system. A calorimetric method was used to determine the heat load as follows. With the RF off, a heater in the liquid helium

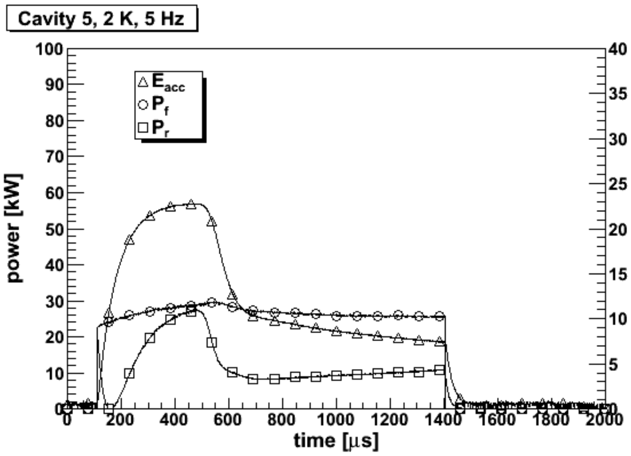

Fig. 5. Example of an RF pulse at quench. The squares show the reflected power, the circles show the forward power, and the triangles show the cavity accelerating gradient.

(LHe) circuit was used to provide an artificial heat load of several watts, leading to boil-off and hence a decrease of the liquid level in the cavity's helium vessel. The helium supply was then adjusted to compensate for this boil-off such that a steady liquid level was maintained. When the RF was switched on, the heater power was then reduced until the liquid level steady state was recovered. The reduction in heater power is then used as an estimate of the dynamic heat load P_c. Q_0 is then calculated as [5]

$$Q_0 = \frac{E_{acc}^2 L^2}{(R_s / Q_0) P_c} \times DF \tag{3}$$

where *DF* is the RF duty factor. It was observed that no effect on the liquid level could be observed for heater changes < 0.1 W. Thus at each gradient there is an upper limit on the Q_0 that can be measured. This can be seen in the summary Q_0 vs. E_{acc} measurements shown in Fig. 6. At 14.5 MV/m a dynamic heat load ≥ 0.1 W was not observed and therefore the Q_0 corresponding to 0.1 W at this gradient is quoted as a lower limit. At higher gradients (18 and 22 MV/m) a drop in Q_0 was observed along with X-ray production from the cavity, and the corresponding increased dynamic heat load (0.1 and 0.8 W, respectively) was observable. From Fig. 6 it can be seen that C5's Q_0 vs. E_{acc} data lie well above the designed operating point and therefore C5 "passes" the horizontal test.

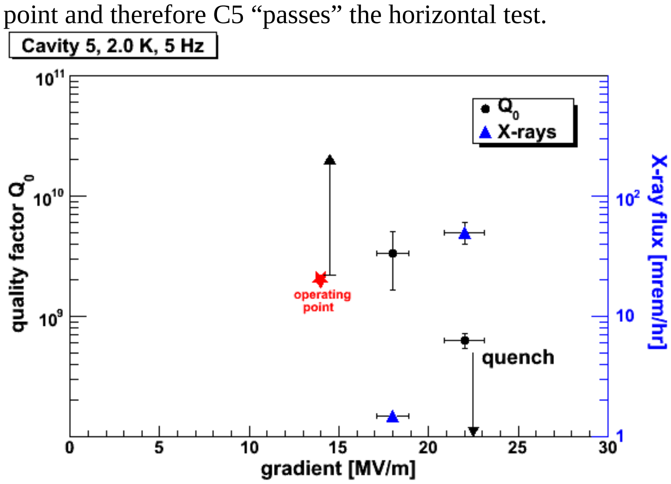

Fig. 6. Q_0 vs. E_{acc} and X-rays vs. E_{acc} measurements for C5.

IV. Additional Observations

On the initial cooldown and RF test of C5, we were unable to reach full quenching gradient at 5 Hz due to runaway heating of the higher-order mode (HOM) coupler antenna. Both of C5's HOM couplers were instrumented with a temperature sensor on the HOM body and a temperature sensor on the HOM antenna flange. Fig. 7 shows the behavior of the HOM #1 (closest to input coupler) antenna temperature. It increases with gradient but tends to plateau for gradients below ~20 MV/m. At higher gradients the temperature increases with no sign of reaching a plateau. As there are no interlocks on the HOM temperatures the RF was quickly shut off manually when this behavior was observed in order to avoid damaging the HOMs. It should also be noted that even with the RF off, the temperature is almost 20 K. This casts suspicion upon the absolute scale of the temperature measurement since at this temperature the HOM antenna would be normal-conducting and hence an enormous heat source.

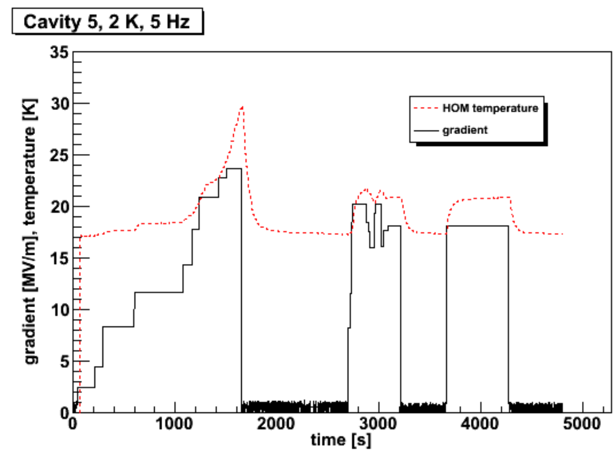

Fig. 7. Behavior of HOM antenna flange temperature (dashed trace) with respect to cavity gradient (solid trace). Note the sharp increase in temperature for gradients > 20 MV/m compared to the plateaus observed at lower gradients.

Debugging this problem was not simple as every change to the system cost about a week (warming up the cavity, opening the cryostat, effecting the change, closing up, and cooling back down). Therefore a systematic piecemeal investigation was eschewed in favor of fixing every possible culprit at once. A few of the remedies employed were installing radiation baffles over instrumentation ports in the cryostat thermal shields, improving the heat-sinking of instrumentation wires, and improving the thermal connection of the HOMs to the cryogenic system (each HOM has a braided copper thermal strap attached to its body and its antenna flange). This latter improvement seemed to be the most effective, and afterwards the cavity could reach full gradient at 5 Hz with stable HOM temperatures as seen in Fig. 8. However, note that the "baseline" (RF off) HOM antenna temperature, although reduced, is still surprisingly large. This problem is still not understood.

One factor contributing to the heating of the HOM antennas is the amount of fundamental power that the HOMs couple to. Comparing the HOM notch frequencies measured at both room temperature and 2 K, it was noted that the thermally-

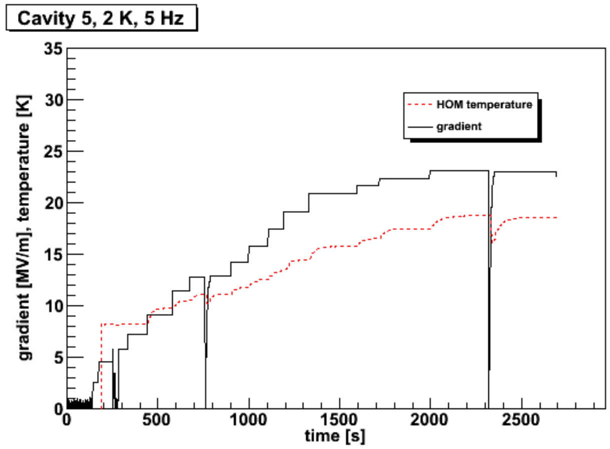

Fig. 8. Behavior of HOM antenna flange temperature (dashed trace) with respect to cavity gradient (solid trace) after improving the thermal connection to the cryogenic system (among other improvements).

induced shift in notch frequency observed (~20 MHz) was much larger than what was expected (~7 MHz). It was suspected that the differential thermal contraction of the copper clamps holding the thermal strap to the HOM body was deforming the HOM. Noting that the HOM bodies did not have nearly the problems with heating that the antennas did, we suspected that the thermal straps on the HOM bodies could be removed. This proved to be the case; the HOMs' thermal behavior was insensitive to the presence of the HOM body thermal straps, and the notch frequency shift was reduced by the expected amount. We emphasize that the HOM antenna thermal straps were left intact; as mentioned above, they are quite important.

V. Conclusion

The 3.9 GHz 9-cell SRF cavity C5 (the first of its kind) has been successfully tested with high power at the ILCTA_MDB Horizontal Test Stand. Three more of these cavities will be required to complete the Fermilab-built cryomodule for FLASH. C5 establishes proof-of-principle for the successful construction of dressed third-harmonic cavities for SRF accelerators.

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