HORIZONTAL SRF CAVITY TESTING AT FERMILAB*

A. Hocker#, E.R. Harms, A. Lunin, A. Sukhanov, FNAL, Batavia, IL 60510, U.S.A.

Abstract

Fermilab makes use of a single-cavity test cryostat to assess the performance of dressed superconducting RF cavities using pulsed high-power RF before they are assembled into a cryomodule. Cavity performance is evaluated in terms of accelerating gradient, unloaded quality factor, and field emission. The functionality of auxiliary components such as tuners and fundamental power couplers is also verified. The latest results from extensive testing of nine-cell 1.3 GHz cavities are presented here, along with a discussion of future extensions of the horizontal test program to include 650 MHz cavities and continuous wave testing.

INTRODUCTION

Fermilab is engaged in a research and development program to construct high gradient accelerator cryomodules based on superconducting radiofrequency (RF) cavity technology for the International Linear Collider (ILC) and Fermilab's Project X. In order to qualify a cavity for assembly into a cryomodule, it is first tested standalone at Fermilab's Horizontal Test Stand (HTS) [1]. At HTS cavities are tested in a configuration similar to operational conditions in a cryomodule; the cavities are welded inside helium vessels and outfitted with high power input couplers, higher-order mode (HOM) couplers, magnetic shielding, and a mechanical tuning system. These dressed cavity packages are then cooled to 2 K in a test cryostat and are operated strongly overcoupled to a klystron-based 300 kW pulsed RF system.

The HTS was first used to test the 3.9 GHz cavities installed in the ACC39 cryomodule now in operation at DESY [2]. This paper presents results from the testing of nine-cell 1.3 GHz TESLA-style cavities at HTS. The two most important cavity performance metrics are the maximum accelerating gradient E_{acc} and the unloaded quality factor Q_0. The ILC requirements for these quantities are $E_{acc} \geq 35$ MV/m and $Q_0 \geq 0.8 \times 10^{10}$. Of additional interest is the amount of X-rays produced due to field emission as this can have an impact on cryomodule operation.

TEST PROCEDURE

The cavity testing steps are quite similar to those described in [2]. Prior to cooling down the cavity the input coupler is conditioned in a standing wave mode by running off-resonance RF pulses at 2 Hz, up to a ≈300 kW pulse with a length of 1.3 ms. After cooling down to 2 K the cavity's blade tuner is employed to tune the cavity resonance to 1.3 GHz and the Q_{ext} of the input coupler is adjusted to 3×10^6 (the position of the input coupler's center conductor is adjustable via an external knob), close to the optimal Q_{ext} value for the ILC. A low power (≈5 kW) RF pulse is used to excite the cavity and the gradient is determined from

$$E_{acc} = 2\sqrt{(R/Q)P_f Q_L}\left(1 - e^{-\frac{\omega t_p}{2Q_L}}\right)/L$$

where L is the active length of the cavity, P_f is the cavity forward power, Q_L is the loaded quality factor (effectively equal to the Q_{ext} of the input coupler), ω is 2π times the cavity frequency, t_p is the pulse length, and R/Q is 1036 Ω for TESLA cavities. As a cross-check, the gradient is also determined from $E_{acc} = \sqrt{(R/Q)P_r Q_{ext}}/L$, where P_r is the power reflected back from the cavity immediately after the RF has been shut off and Q_{ext} refers to the input coupler. These two calculations of the cavity gradient typically agree to within a few percent of each other. The gradient determined at low power is used to evaluate the constant k_t in the relation $E_{acc} = k_t\sqrt{P_t}$, where P_t is the cavity transmitted power. This relation is then used to determine the gradient from the transmitted power for all input powers.

The cavity/coupler system is then conditioned on-resonance at 2 Hz up to a gradient of 25 MV/m and a pulse length of 1.3 ms. When conditioning with pulse lengths longer than 0.5 ms, the cavity is filled at full power for 0.5 ms and then the power is reduced by an approximate factor of four in order to maintain a constant gradient for the remainder of the pulse (the "flat-top" time).

To assess the cavity's gradient and Q_0 performance, ILC-like RF pulse parameters are adopted. Using a 5 Hz repetition rate, the cavity is filled to a given gradient and then a 1 ms flat-top is maintained. In order to reliably achieve high gradients with the limited klystron power available, a 0.8 ms fill time is used. The forward power to the cavity is slowly increased until either the cavity quenches or 35 MV/m is achieved. Figure 1 shows an example of a cavity operating at this gradient.

Since the input coupler $Q_{ext} \ll Q_0$, the cavity Q_0 can only be determined from the heat dissipated by the cavity walls to the helium bath. In particular,

$$Q_0 = \frac{\langle E_{acc}^2 \rangle L^2}{(R/Q)\langle P_c \rangle}$$

where P_c is the dissipated heat and the brackets denote a time average. The time average of the square of the gradient can be shown to be

*Work supported in part by the U.S. Department of Energy under Contract No. DE-AC02-07CH11359.
#hocker@fnal.gov

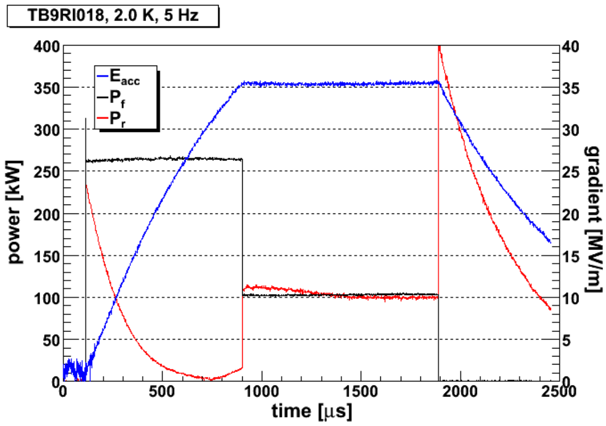

Figure 1: Cavity gradient and forward and reflected power during an RF pulse.

$$\langle E_{acc}^2 \rangle = \frac{E^2}{T}\left\{ \frac{t_f - \frac{\tau_L}{2}\left[4\left(1-e^{-t_f/\tau_L}\right) - \left(1-e^{-2t_f/\tau_L}\right)\right]}{\left(1-e^{-t_f/\tau_L}\right)^2} + \left(t_p - t_f\right) + \frac{\tau_L}{2} \right\}$$

where E is the flat-top gradient, $1/T$ is the repetition rate, t_f is the fill time, and $\tau_L = 2Q_L/\omega$. P_c is measured from the heat load dissipated to the cryo system following the method described in [3].

To map out the Q_0 vs. E_{acc} curve, the total heat load is measured at several different gradients, spending an hour at each point. The first 30 minutes are used to let the cryo system stabilize at the new operating point and an average heat load is determined from the second 30 minutes. In addition a measurement of the static heat load (*i.e.*, RF off) is made at the beginning and end of the set of RF-on measurements. The average of the two static load measurements is subtracted from the total heat load measurements to arrive at the P_c for a given E_{acc}. The difference between the two static load measurements provides an estimate of the uncertainty on P_c. An example Q_0 vs. E_{acc} curve is shown in Figure 2.

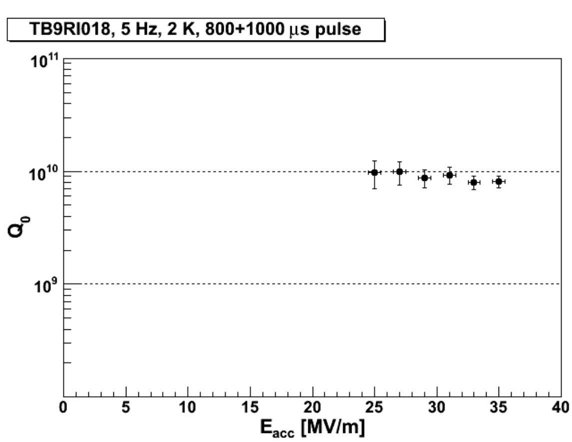

Figure 2: An example Q_0 vs. E_{acc} curve.

In addition to measuring the heat load, at each gradient point the X-ray flux is measured as an indicator of field emission. The detector is located just outside the cryostat on the input coupler end of the cavity and centered on the beamline. Examples of heavy and little field emission are shown in Figure 3.

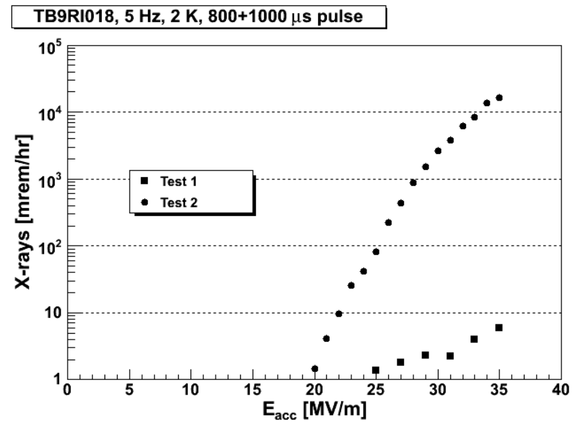

Figure 3: An example of a cavity exhibiting heavy (Test 2) and little (Test 1) field emission. The two tests are described in the discussion of TB9RI018 in the main text.

After the testing is complete, the cavity is detuned to its original cold frequency, warmed up to room temperature, and removed from the test cryostat.

RESULTS AND DISCUSSION

A total of thirteen 1.3 GHz cavities have been cold tested at HTS. A summary of their performance is shown in Table 1. Two cavities, TB9ACC013 and TB9RI018, were tested more than once and are discussed in more detail below.

It is important to note that prior to testing at HTS, all cavities are tested "bare" with low power continuous wave RF in a vertical test dewar. The cavities selected for dressing and HTS testing are generally the ones that achieve gradients ≥ 35 MV/m with good Q_0 and acceptable field emission in the vertical test. The two exceptions to this in Table 1 are TB9AES004 and ACCEL8, which only reached 31 MV/m in their respective vertical tests. Bearing this in mind, and temporarily disregarding cavity TB9ACC013 (to be discussed shortly), Table 1 shows no significant performance degradation between the vertical and horizontal tests prior to cavity TB9ACC016. We now turn to a discussion of cavities that did not fare as well.

TB9ACC013

This cavity originally performed quite well, achieving 35 MV/m with almost no field emission. However, when pushed to 37 MV/m, an arc/breakdown event in the input coupler occurred. After this event the cavity exhibited heavy field emission. This event spurred the precautionary decision to not test subsequent cavities beyond 35 MV/m. When the input coupler was removed from the cavity, a small void in the copper plating on the coupler's outer conductor was discovered, along with a white-colored "vapor trail" emanating from the void (see

Figure 4). This void was not present prior to the horizontal test. The cavity was high-pressure rinsed and re-tested with a different input coupler, but the heavy field emission persisted and the test was aborted.

Table 1: Cavity test summary (chronological order)

Cavity	Max E_{acc} (MV/m)	Q_o at max E_{acc} (x 10^{10})	Field emission
TB9AES004	31	1.1 [4]	Little
TB9ACC013 (1)	>35	1.2	Heavy
TB9AES009	35	0.7	None
ACCEL8	31	1.1	None
TB9ACC013 (2)	20	N/A	Heavy
TB9AES010	>35	1.4	Little
TB9AES008	>35	0.9	Moderate
TB9ACC016	19	0.0055	Moderate
TB9RI029	29	0.7	Little
TB9AES007	33	0.8	Moderate
TB9RI018 (1)	>35	0.8	Little
TB9RI018 (2)	>35	N/A	Heavy
TB9RI019	>35	0.7	Little
TB9RI018 (3)	>35	0.4	Little
TB9RI024	34.5	0.5	Heavy
TB9RI027	>35	0.4	Little

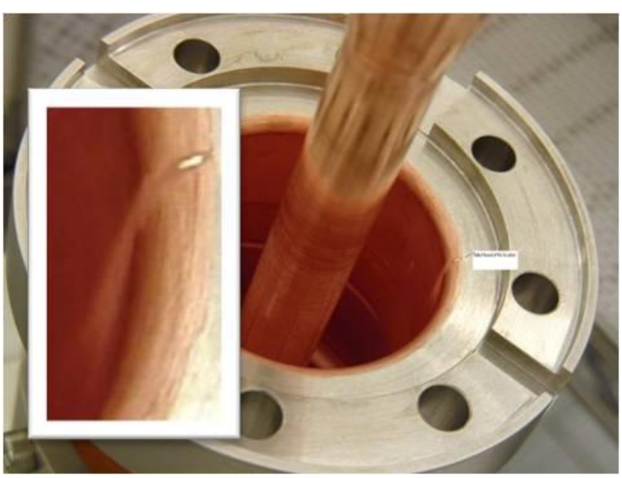

Figure 4: Defect found on TB9ACC013's input coupler.

TB9ACC016

This cavity began exhibiting field emission at ≈17 MV/m and the Q_0 dropped dramatically. Upon removal of the input coupler, glitter-like copper particles were observed falling from the coupler and more were found stuck to the tip of the center conductor. Microscopy of these particles revealed them to be ≈100 µm in size and irregularly shaped. Along with TB9ACC013, this failure has prompted an investigation into the integrity of the copper plating on the input couplers' inner surface [5]. TB9ACC016 was high-pressure rinsed and re-tested in a vertical test dewar; a full recovery of the cavity's performance was observed.

TB9RI029 and TB9AES007

TB9RI029 quenched at 29 MV/m; as there was little to no field emission accompanying the quench it is difficult to explain why. Traditional quench location techniques such as temperature mapping and second sound are not possible at HTS due to the cavity's enclosure in a tight-fitting helium vessel. TB9AES007's premature quench at 33 MV/m could be explained by surface heating due to field emission; higher gradients were reached when the flat-top time was shortened.

TB9RI018

Due to the above sequential cavity failures, prior to testing TB9RI018 the HTS cavity pumping line was cleaned and baked out. The subsequent test of TB9RI018 (test 1 in Table 1) was very good, with high gradients and little field emission. However, an enlightening experiment was then performed that requires some background explanation. Up until this point, cavities were delivered to HTS backfilled with N_2 or Ar gas and evacuated *in situ* after connecting them to the HTS cavity pumping line. Upon completion of the test, cavities were backfilled again before being removed from the cryostat. In order to check that good cavities are not compromised by the post-test backfill and disconnection procedures, TB9RI018 was immediately re-tested after performing these steps (test 2 in Table 1). The cavity exhibited heavy field emission in this second test as shown in Figure 3. As a result, improvements to the cavity pump-down and backfill procedures and hardware were implemented. More importantly, a new paradigm was adopted wherein cavities were evacuated in a class 10 clean room prior to their arrival at HTS and left under vacuum when departing HTS, thus eliminating some potential contamination points. TB9RI018 was high-pressure rinsed and re-tested at HTS using this new procedure (test 3 in Table 1) and high gradients with little field emission were achieved. Encouraged by this result, all the cavities that had previously "passed" the horizontal test, but which were suspect in light of the results of the second TB9RI018 test, were subsequently re-rinsed.

TB9RI024

This cavity exhibited heavy field emission and the resultant surface heating caused the cavity to quench just below 35 MV/m; when running at a lower repetition rate 35 MV/m could be achieved. One hypothesis for the high field emission is that the bellows sections in the HTS cavity pumping line had to be heavily flexed (which can create particulate contamination) to accommodate a misalignment of the cavity's vacuum valve. However, this valve had not yet been opened when these manipulations were done, and it seems unlikely that any particulate would have migrated from the pumping line to the cavity (against the direction of flow) when the valve was opened. TB9RI024 was high-pressure rinsed and, at conference time, was being prepared for a re-test at HTS.

FUTURE FACILITIES

A new facility called HTS2, to be located in the Meson Detector Building (MDB) along with the current HTS, is being planned to extend Fermilab's horizontal testing program. This test stand will be based on a cryostat designed to house two cavities (see Figure 5) in order to increase horizontal testing throughput. The longer cryostat also offers the possibility of testing a cavity in close proximity to a magnet, a configuration found in many accelerator cryomodule designs. The cryostat will be capable of testing either nine-cell 1.3 GHz cavities or the five-cell 650 MHz cavities envisioned for the 3 GeV Project X continuous wave linac. HTS2 must therefore accommodate the higher cryogenic heat loads associated with 650 MHz CW testing. The HTS2 cryostat is currently under design at RRCAT in India [6], and Fermilab is specifying and procuring the necessary upgrades to the cryogenic distribution and RF infrastructure at MDB. HTS2 is scheduled to begin operations in 2013.

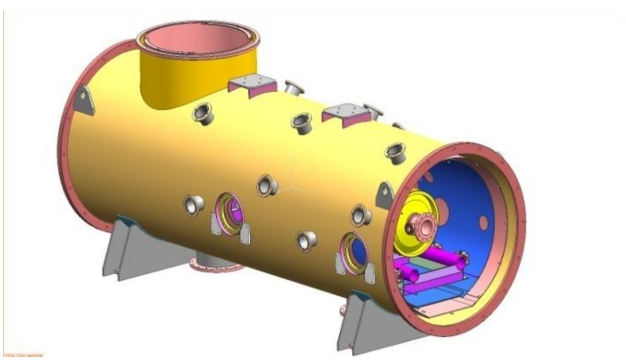

Figure 5: 3D model of HTS2 cryostat.

CONCLUSIONS

Horizontal cavity testing at Fermilab has proven to be extremely useful. Most of the failures have identified points in the complex cryomodule production chain that can be improved, while the successes demonstrate that high gradient performance can be preserved through the cavity dressing process. The HTS has also provided a useful test bed for studies of the cavity tuning system and Lorentz force detuning [7, 8]. The experience gained at HTS has been invaluable for the recent successful tests of a full cryomodule at Fermilab [9], and is guiding the development of future facilities to support the lab's expanding superconducting RF research and development program.

REFERENCES

[1] R. Carcagno *et al.*, "Commissioning and Early Operating Experience with the Fermilab Horizontal Test Facility," SRF'07, Beijing, October 2007, WEP14, p. 469 (2007).

[2] Elvin Harms and Andy Hocker, IEEE Trans. Appl. Supercond., volume 19, issue 3 (2009) 1412.

[3] B.D. DeGraff, R.J. Bossert, L. Pei, and W.M. Soyars, "Measurement of SCRF Cavity Dynamic Heat Load in Horizontal Test System," Adv. Cryog. Eng. 55A (2009) 609.

[4] This value was measured at 24 MV/m, not 31 MV/m as the table would indicate.

[5] Chris Adolphsen *et al.*, "SLAC/FNAL TTF3 Coupler Assembly and Processing Experience," this conference, TUPO042.

[6] P.K. Kush *et al.*, "Design of Horizontal Test Stand (HTS-2) for SCRF Cavities at RRCAT," InPAC2011, New Delhi, February 2011.

[7] Y. Pischalnikov *et al.*, "Test of a Coaxial Blade Tuner at HTS/FNAL," PAC '11, New York, March 2011, TUP082.

[8] Y. Pischalnikov and W. Schappert, "Adaptive Compensation for Lorentz Force Detuning in Superconducting RF Cavities," this conference, FRIOA01.

[9] E.R. Harms *et al.*, "RF Test Results from Cryomodule 1 at the Fermilab SRF Beam Test Facility," this conference, MOPO013.