

HIGH POWER TESTS OF DRESSED SUPERCONDUCTING 1.3 GHz RF CAVITIES*

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

Abstract

A single-cavity test cryostat is used to conduct pulsed high power RF tests of superconducting 1.3 GHz RF cavities at 2 K. The cavities under test are welded inside individual helium vessels and are outfitted (“dressed”) with a fundamental power coupler, higher-order mode couplers, magnetic shielding, a blade tuner, and piezoelectric tuners. The cavity performance is evaluated in terms of accelerating gradient, unloaded quality factor, and field emission, and the functionality of the auxiliary components is verified. Test results from the first set of dressed cavities are presented here.

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 first set of nine-cell 1.3 GHz TESLA-style cavities tested 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]. Cavities arrive at HTS backfilled with Ar or N₂ gas and are pumped down to the 10⁻⁹ Torr range. 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

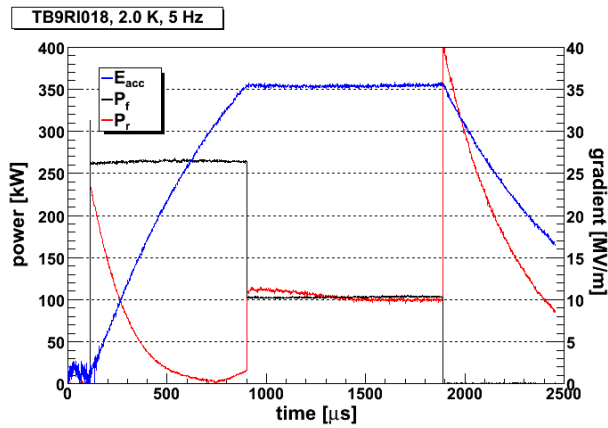


Figure 1: Cavity gradient and forward and reflected power during an RF pulse.

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

where E is the flat-top gradient, $1/T$ is the repetition rate, t_f is the fill time, and $\tau_L = 2Q_0/\omega$. 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.

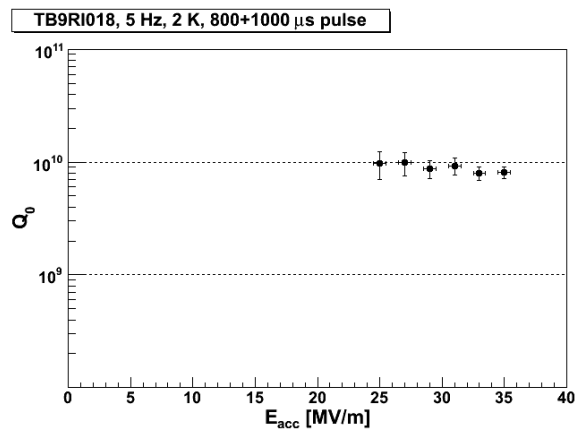


Figure 2: An example Q_0 vs. E_{acc} curve.

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.

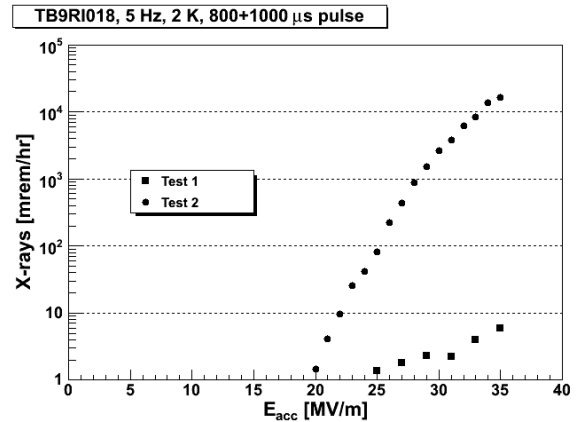


Figure 3: An example of a cavity exhibiting heavy (Test 2) and little (Test 1) field emission. The two tests are described in the discussion of TB9RI018 in the main text.

After the testing is complete, the cavity is detuned to its original cold frequency and warmed up to room temperature. It is then backfilled with N_2 or Ar gas and removed from the test cryostat.

RESULTS AND DISCUSSION

A total of 10 cavities have been cold tested at HTS. A summary of their performance is shown in Table 1. Two cavities, TB9ACC013 and TB9RI018, were tested twice and are discussed in more detail below.

Table 1: Cavity test summary (chronological order)

Cavity	Max E_{acc} (MV/m)	Q_0 at max E_{acc} ($\times 10^{10}$)	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

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.

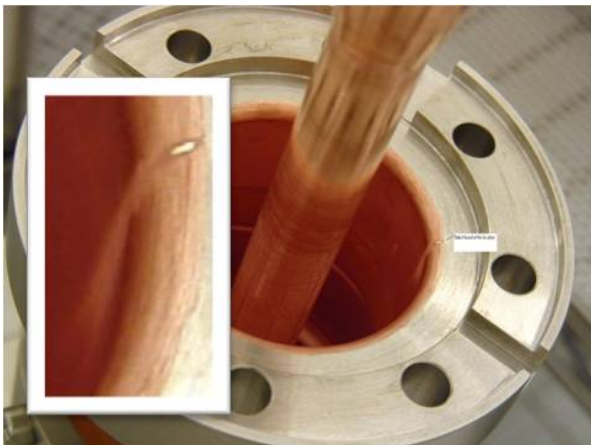


Figure 4: Defect found on TB9ACC013’s input coupler.

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 (ongoing at the time of this conference) into the integrity of the copper plating on the input couplers’ inner surface.

Accelerator Technology

Tech 07: Superconducting RF

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 was very good, with high gradients and little field emission. In order to check that good cavities are not compromised by the post-test backfill and disconnection procedures at HTS, TB9RI018 was immediately re-tested after performing these steps. 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 are being implemented, as well as provisions to obviate the need for such operations at all. It should be noted that the results of the TB9RI018 re-test do call into question the state of the cavities that had previously “passed” the horizontal test. A re-test of one or more of these cavities is planned.

CONCLUSIONS

The first set of high power dressed cavity tests at HTS has proven 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; space constraints prevent a discussion here but a thorough description may be found in [5].

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] Y. Pischalnikov *et al.*, “Test of a Coaxial Blade Tuner at HTS/FNAL,” this conference, TUP082.