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RESULTS FROM RF TESTS OF THE FIRST US-BUILT HIGH-GRADIENT SUPERCONDUCTING CRYOMODULE

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Abstract

Fermilab has built a cryomodule comprised of eight 1.3 GHz superconducting RF cavities for use in its Advanced Superconducting Test Accelerator (ASTA) facility. This cryomodule (RFCA002) was intended to achieve the International Linear Collider (ILC) "S1" goal of demonstrating an average accelerating gradient of 31.5 MV/m, and is the first of its kind built in the United States. The module has been cooled down and operated without beam at ASTA in order to assess its performance. The results from these tests are presented here.

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].

Fermilab has built an ILC-type eight-cavity cryomodule (RFCA002) with the goal of achieving this gradient requirement. The eight cavities were tested both bare and dressed in vertical and horizontal test stands at Jefferson Lab and Fermilab and all eight cavities reached gradients from 33-41 MV/m before quenching. Details of the individual cavity tests are summarized in [2].

The assembled RFCA002 cryomodule was installed at Fermilab's Advanced Superconducting Test Accelerator (ASTA) facility [3] which houses the necessary cryogenic and RF infrastructure for high power testing of the CM at 2 K.

TEST PROTOCOL

The CM was tested by connecting each cavity one at a time to the output of a 5 MW klystron. The test procedure followed closely the one developed for the test of a previous ILC-type CM at ASTA [4]. It can be summarized as follows:

- Tune cavity from its cooldown frequency to 1.3 GHz (an increase of approximately 240 kHz)
- Exercise the tunable input coupler through its full range of motion and set to its nominal operating point (the full range corresponds to 1-1.5 decades of Q_L variation, roughly centered around the nominal ILC Q_L of 3.5 x 10^6)
- Preliminary calibrations of cavity signals (forward, reflected, and transmitted powers) using a few kW of forward power
- On-resonance RF conditioning of the cavity/coupler using pulse lengths from 0.02 to 1.3 ms. For the shorter pulses a maximum forward power of 1 MW was used; for the longer pulses (≥ 0.4 ms) the cavity was powered to a maximum gradient of 25 MV/m using a fill time of 0.5 ms
- Final calibrations of cavity signals using ≈100 kW of forward power
- Determination of maximum gradient
- Implementation of adaptive Lorentz force detuning compensation based on fast piezoelectric tuners [5] in order to sustain a constant gradient during the RF pulse
- Measurements of X-rays and dark current as a function of gradient
- Measurements of dynamic heat loads to 2 K as a function of gradient in order to determine the cavity Q_0

The following sections summarize the results from this test program.

GRADIENT PERFORMANCE

The ILC RF pulse parameters shown in Table 1 were used to characterize each cavity. No closed-loop feedback control was used during the testing but Lorentz force detuning compensation was active. An administrative limit of 31.5 MV/m was enforced for these first tests of the RFCA002 cavities. Seven of the eight cavities reached this administrative limit, occasionally requiring a small amount of additional RF processing when increasing the gradient from 25 to 31.5 MV/m. An example of a cavity operating at the 31.5 MV/m limit is shown in Fig. 1.

The only cavity that did not reach 31.5 MV/m was cavity #6 (counting from upstream to downstream), which quenched at a gradient of 30.5 MV/m. As seen in Fig. 2, this cavity also showed the worst performance in vertical testing. The 30.5 MV/m limit was very reproducible; moreover it was completely insensitive to variations of the RF pulse length and repetition rate, eliminating cumulative thermal effects as an explanation. The cavity did exhibit field emission as discussed below.

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Table 1: RFCA002 RF Pulse Parameters

Pulse length	1.565 ms
Fill time	0.596 ms
Flat-top time	0.969 ms
Repetition rate	5 Hz
Q_L	3.5 x 10^6

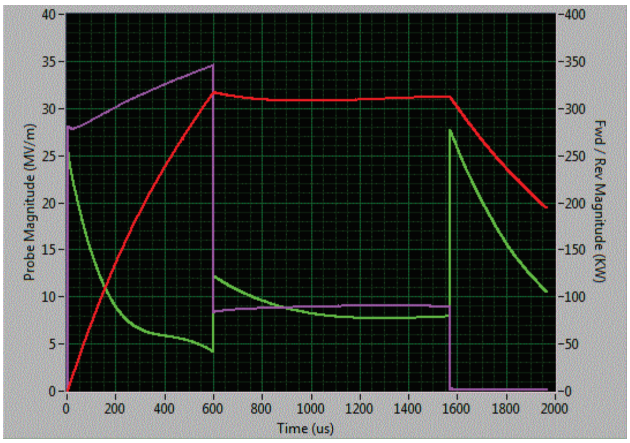

Figure 1: Cavity #8 operating at 31.5 MV/m. The purple trace is forward power, the green trace is reflected power, and the red trace is the accelerating electric field.

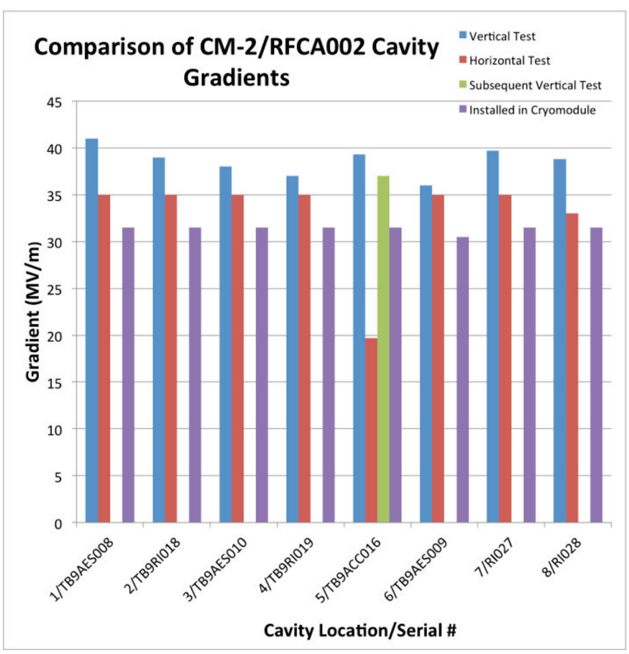

Figure 2: Comparison of gradient performances in vertical, horizontal, and CM tests.

FIELD EMISSION AND DARK CURRENT

Field emission from the cavities was monitored using an X-ray detector placed underneath the cryomodule near the input coupler for the cavity under test. The X-ray rate for each cavity is shown in Fig. 3. Three of the cavities exhibited significant field emission: the two cavities at either end of the cryomodule and the quench-limited cavity #6. The field emission onset ranged from 20 to 29 MV/m.

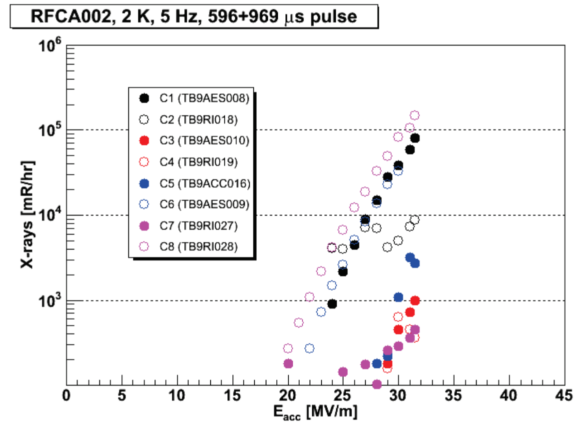

Figure 3: RFCA002 X-rays vs. E_{acc}.

Dark current was monitored using Faraday cups mounted on both ends of the cryomodule. Only two cavities showed significant dark current, again the cavities at either end of the cryomodule. The onset of dark current for cavity #1 (#8) was 22 MV/m (25 MV/m) and reached ≈200 nA (≈20 nA) at maximum gradient.

UNLOADED QUALITY FACTOR

Because the RFCA002 cavities are operated strongly overcoupled, a cavity's unloaded quality factor Q_0 must be determined from the dynamic heat load to 2 K. This heat load was measured using a helium mass flow meter located at the discharge of the helium vacuum pump. The steady-state mass flow was multiplied by the enthalpy change from inlet to outlet (calculated from the helium supply and return temperatures and pressures) in order to determine the dissipated heat. This measurement takes several hours to perform; measurements of the static load before and after the cavity-on measurements were done in order to account for possible drifts in the cryogenic system. Therefore only the upper end of the Q vs. E curve was explored, as shown in Fig. 4.

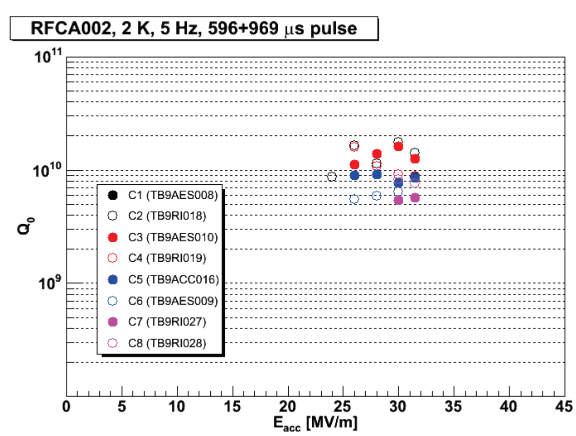

Figure 4: RFCA002 Q_0 vs. E_{acc}.

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The low duty factor (< 1%) of the RF results in dynamic heat loads of about 1 W or less, which are difficult to measure on a static background of around 20 W (the static load includes the cryomodule and its associated cryogenic feed boxes). This is a partial explanation for the scatter seen in Fig. 4. An average cryomodule Q_0 determined from the heat load of all eight cavities powered simultaneously should be much easier to measure.

DISCUSSION AND FUTURE PLANS

In order to truly demonstrate the ILC goal of a 31.5 MV/m cryomodule, some cavities will have to be run at a slightly higher gradient in order to compensate for the reduced performance of cavity #6. Because RF is distributed to the cavities in a pairwise manner, cavity #5 will have to be run at a reduced gradient as well. Assuming an operating gradient of 30 MV/m for the 5/6 pair, an additional 3 MV/m will need to be distributed in some manner over the remaining three pairs. Given the results of the horizontal tests shown in Fig. 2, there appears to be a comfortable margin with which to achieve this.

In the near future cavity #6 will be revisited for more studies of the quench behavior, and a re-conditioning of cavity #1 will be tried in order to address some vacuum spikes observed on the warm side of the input coupler. The full cryomodule RF distribution system will then be installed and the CM will be powered as a unit, which opens up a new regime of RF control to study. Beam to the cryomodule is expected in 2015.

CONCLUSION

The first ILC-type cryomodule built by Fermilab has been successfully installed and tested at ASTA. Seven of the eight cavities achieve a gradient of 31.5 MV/m for an average of 31.375 MV/m, just short of the ILC goal. Prospects for operating some cavities at a higher gradient to meet or exceed the ILC specifications are good and will be realized in the near future.

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