VERTICAL AND HORIZONTAL TEST RESULTS OF 3.9 GHZ ACCELERATING CAVITIES AT FNAL*

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Abstract

The 3rd harmonic 3.9GHz accelerating cavity was proposed to improve the beam performance of the VUV FEL, FLASH. In the frame of a collaborative agreement, Fermilab will provide DESY with a cryomodule containing a string of four cavities. Seven 9-cell Nb cavities were tested and six of them did reach accelerating gradient up to 24 MV/m almost twice more than design value of 14 MV/m. Two of these cavities are with new HOM couplers with improved design. In this paper we present all results of the vertical and horizontal tests.

INTRODUCTION

Four 3rd harmonic nine-cell 3.9 GHz superconducting cavities will operate at gradient 14 MV/m in the TM010 mode and will be placed in TTF/FLASH. These cavities are designed to linearize the accelerating gradient of the accelerator, providing improved longitudinal emittance for bunch compression. Table 1 contains a list of cryomodule parameters.

Table 1: Cryomodule parameters

Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179°
R/Q [$=U^2/(\omega W)$]	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	1.3×10^6
BBU Limit for HOM, Q	$<1 \times 10^5$
Total Energy	20 MeV
Beam Current	9 mA
Forward Power, per cavity	9 kW
Coupler Power, per coupler	45 kW

Vertical cold tests of the six full size 9-cell cavities demonstrated accelerating gradient of ~23-24 MV/m, limited by thermal breakdown quench in the cavity. Four of these cavities are built with trimmed tip of the HOM coupler. Two cavities, #7 and #8, with completely new HOM coupler with one leg formteil design.

One cavity was successfully tested in Horizontal Test Station (HTS) and is ready for an installation in a cryomodule. It is intended that additional three dressed cavities will be tested soon. Cryomodule assembly work will be completed during summer of this year and the cryomodule delivered to DESY in the end of 2008.

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PRODUCTION STATUS

Eight 3.9 GHz cavities have been now fabricated. A summary of the test results can be found in Table 2. The first two are prototypes and are not succeeding to be operational [1]. Cavity #1 is used as a prototype for helium vessel welding. In the cavity #2 failed HOM couplers were removed, those will be replaced by new ones. All cavities from #3 to #8 have undergone extensive vertical testing and successfully achieved gradients in excess of 22 MV/m. Cavities #3, #5 and #7 were already welded into helium vessels.

Table 2: Cavity Fabrication & Testing Status

Cavity	Assembled by	Completion date	Test results
#1: 2-leg HOM	Fermilab	January 2006	Never tested – HOM membrane break during cleaning
#2: 2-leg HOM	Fermilab	February 2006	12 MV/m limited by HOM heating - fractured Formteils
#3: 2-leg trimmed HOM	Fermilab JLab	August 2006	24.5 MV/m, achieved after HOM trimming
#4: 2-leg trimmed HOM	Fermilab JLab	March 2007	23 MV/m, 2008.04.26
#5: 2-leg trimmed HOM	Fermilab JLab	May 2007	24 MV/m, 2007.08.22
#6: 2-leg trimmed HOM	Fermilab JLab	May 2007	22 MV/m, 2007.07.24
#7 single-post HOM	Fermilab JLab DESY	November 2007	24.5 MV/m, 2008.02.07
#8 single-post HOM	Fermilab DESY	October 2007	24 MV/m 2007.11.08

Fabrication

All component parts and end tube sub-assemblies were fabricated under the direction of Fermilab personnel. Cavities #3 through #6 had final welding and assembly done at Jefferson Lab. The first six cavities contain a 2-leg Formteil design. Cavity #7 was assembled partly at Fermilab and partly at JLab. Cavity #8 was assembled at Fermilab. Both used a revised single post Formteil design. The single post Formteils were welded into the HOM housing at DESY.

Processing

All eight manufactured cavities passed coordinate measuring machine (CMM) and RF measurements, 20 µm outside and 80 µm inside Buffered Chemical Processing (BCP), high temperature 800C hydrogen degasification bake, and RF tuning. Additional 20 µm BCP and High Pressure Rinse (HPR) were done prior to cold tests. All cavities have passed through this stage of the process. Total time for cavity processing (from completion of fabrication until ready to test) is of order 25 working days.

Cavity center measurements

Alignment of the cavity according to beam center line is important for minimizing of high order modes excitation and providing beam stability. Cavity can be deformed in each step of processing: production, BCP, RF tuning and especially during the welding to helium vessel. A CMM mechanical measurement of the cavity center takes 1-2 days and sometimes needs additional waiting time. Also it is not possible to do CMM for a dressed cavity at all. Alternative technique based on bead-pull measurements was developed, which usually takes 2-3 hours. To exclude bead–pull positioning error two sets of measurements are required: in the initial position and rotated by 180^0. This technique allows controlling of the cavity alignment after welding to helium vessel, when CMM measurements are impossible.

CMM and RF cavity center measurements are in good agreement. Difference between them for just arrived cavity usually less than 0.2 mm.

VERTICAL TEST RESULTS

Each cavity was successfully cold tested several times in the A0 Vertical Test Station. Cavities 2÷8 have been tested to date – a total of about 30 tests. All cavities have achieved accelerating gradients of 22-25 MV/m (see Figure 1).

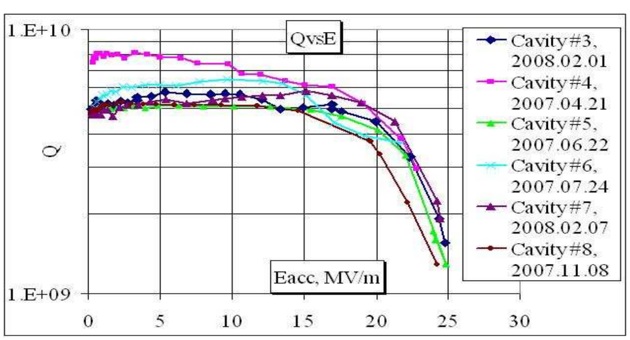

Figure 1: Vertical test results of the cavities #3-8. Cavity #4 was 120C 48hours baked.

If the bare cavity reaches gradients more than 22 MV/m, we test cavity with two HOM coupler antennas and one regular field probe installed. In these cold tests accelerating gradient usually was limited by thermal breakdown quench on HOM antenna tip (see Figure 2). One can see that all cavities with 2-leg trimmed HOM design reached 12-19 MV/m and with 1-leg design [2] reached 21-22 MV/m. This limitation is correct only for a CW operation (see horizontal test results).

Cavity is backfilled with clean Nitrogen during adjustment of notch filter of the HOMs. This was done to eliminate notch frequency shift due to difference of the pressure on internal and external surfaces of the cavity. The goal is to reach external Q factor more than 10^{11} for each HOM coupler at 3.9 GHz.

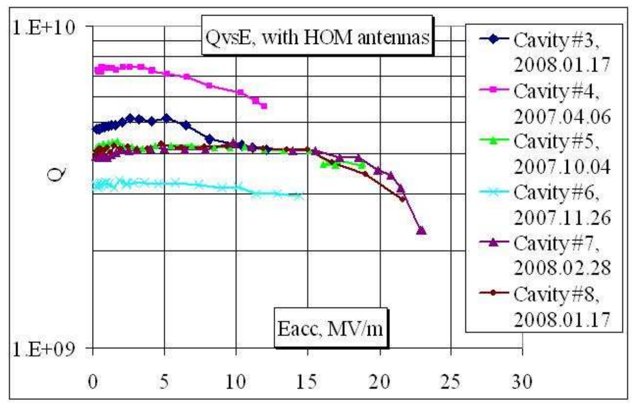

Figure 2: Vertical test results of the cavities #3-8 with HOM antennas installed.

HORIZONTAL TEST RESUTS

Cavity #5 was chosen for the first horizontal cold test. The cold part of the power coupler was installed in the class 10 A0 clean room and the cavity was sealed and backfilled with clean argon gas. After installation of magnetic shielding and Blade Tuner (BT), cavity #5 was brought to the ILCTA_MDB Horizontal Test Stand (HTS) [3]. Its helium vessel was successfully tested at HTS to pressure of 2.3 bar. Then it was installed in the HTS test cryostat and the outer part of its input coupler was mounted.

Room Temperature Operation

At room temperature the cavity's resonance frequency was about 8 MHz less than the nominal 3900 MHz operating frequency. This allows for off-resonance conditioning of the input coupler using pulsed high RF power. The conditioning sequence is performed at 1 Hz repetition rate and begins with a pulse length of 20 µs. The RF power is gradually increased from zero until the maximum klystron power (~60 kW) is reached. This power level is sustained for one hour and then the process repeats with ever-increasing pulse lengths (50, 100, 200, 400, 800, and 1300 µs). If at any point in the sequence the pressure in the cavity or coupler exceeds $2 \cdot 10^{-7}$ Torr, or if electron emission in the coupler (as measured by two coupler electron pickups) exceeds 1 mA, the RF power is reduced for a short period of time. The process is illustrated in Figure 3; a small amount of vacuum activity was observed during the conditioning sequence but tended to decrease with conditioning time.

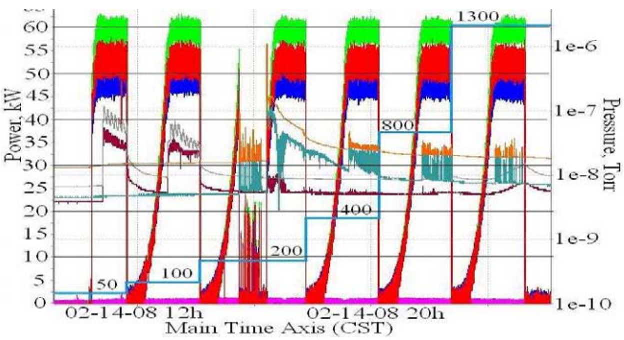

Figure 3: Off-resonance conditioning of C5's input coupler at HTS. The horizontal axis is a time span of about 18 hours. The green (red) trace is the klystron (cavity) forward power. The blue trace is the cavity reflected power. The grey and maroon (orange and blue-green) traces are monitors of the coupler (cavity) pressure. The magenta trace indicates coupler electron emission and the light blue trace indicates the pulse length. The "hole" during the 200 μs step is the result of instrumentation debugging).

Cold Operation

After cooling the cavity to 1.8 K, its mechanical blade-tuner (BT) was used to adjust its resonance frequency to 3900 MHz (Figure 4). A loaded Q (Q_L) of $8.9{\cdot}10^5$ was measured from an exponential fit to the transmitted power decay curve. The cavity field pickup calibration factor k_t = $3.8{\cdot}10^6$ V/ [m·$W^{1/2}$] was determined by calculating the expected gradient from the cavity forward power and Q_L.

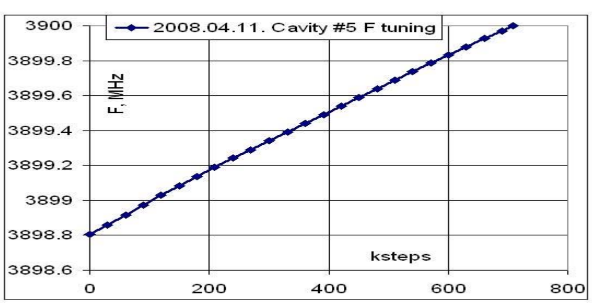

Figure 4: Tuning of C5 at 1.8 K. The horizontal axis shows the number of motor steps taken; the vertical axis shows the cavity resonance frequency.

The cavity was then powered to a quench at a gradient of 24.5 MV/m using a 1.3 ms pulse length and a repetition rate of 1 Hz. When running at a repetition rate of 5 Hz, excessive heating of the HOM coupler antennas was noted for gradients above ~20 MV/m. At lower gradients the temperature would plateau, see Figure 5. It is expected that improving the HOM couplers' heat sinks to the cryo system will provide sufficient cooling to run the cavity at high gradient at 5 Hz At 2K the cavity reached 23 MV/m at a repetition rate of 1Hz.

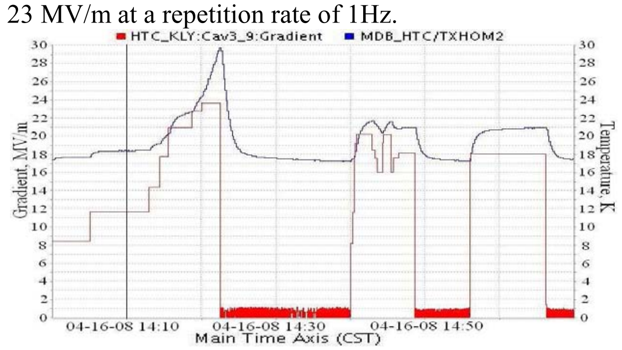

Figure 5: Runaway HOM coupler heating observed at 5 Hz for gradients > ~20 MV/m. The horizontal axis is a time span of about 1.5 hours. The red trace is the cavity gradient and the blue trace is a HOM coupler antenna feedthrough temperature.

The unloaded Q (Q_0) of the cavity at 18 MV/m and 5 Hz repetition rate was determined by measuring the dynamic heat load to the cryo system. This measurement was limited by some instrumentation uncertainty, but an initial estimate yielded a heat load of 0.5 ± 0.3 W, resulting in $Q_0 = 5.6 \pm 3.9{\cdot}10^9$. This measurement will be refined and extended to other gradients in the future.

SUMMARY

Fermilab are finishing of a 3.9 GHz cavity string for use in DESY's TTF/FLASH facility. Eight cavities have been manufactured and six have gone through vertical testing. All six have now achieved the necessary design parameters and have operated at gradients in excess of 22 MV/m. Three cavities have been welded to helium vessels, and one dressed cavity has already been tested in HTS. Critical steps remain: welding into helium vessels of three more, horizontal testing of five cavities, assembly into a 4-cavity string, final assembly, and shipping to DESY. The expectation is to provide the final product in the end of 2008.

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