1.3 GHZ SUPERCONDUCTING RF CAVITY PROGRAM AT FERMILAB*

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Abstract

At Fermilab, 9-cell 1.3 GHz superconducting RF (SRF) cavities are prepared, qualified, and assembled into cryomodules (CMs) for Project X, an International Linear Collider (ILC), or other future projects. The 1.3 GHz SRF cavity program includes targeted R&D on 1-cell 1.3 GHz cavities for cavity performance improvement. Production cavity qualification includes cavity inspection, surface processing, clean assembly, and one or more cryogenic low-power CW qualification tests which typically include performance diagnostics. Qualified cavities are welded into helium vessels and are cryogenically tested with pulsed high-power. Well performing cavities are assembled into cryomodules for pulsed high-power testing in a cryomodule test facility, and possible installation into a beamline. The overall goals of the 1.3 GHz SRF cavity program, supporting facilities, and accomplishments are described.

INTRODUCTION

FNAL is engaged in a program to provide 9-cell 1.3 GHz cavities for assembly into CMs in support of Project X, an ILC, or other future projects. The cavities are fundamentally of the Tesla design [1], made of high RRR niobium with elliptical cell shape, for superconducting operation at 2K in TM010 mode. Six CMs will be built at FNAL in the next few years, each may contain eight or nine 9-cell cavities. The first CM, CM1, was built from a kit of parts supplied by DESY. The next CM built will be CM2, using cavities processed and tested at FNAL and JLab. This paper describes the overall goals of the FNAL 1.3 GHz SRF cavity program, the supporting facilities and accomplishments.

BARE CAVITY SEQUENCE

Cavities are purchased from outside vendors and are built to print from FNAL drawings. Incoming inspection of a production cavity involves a visual inspection, a CMM measurement, vacuum leak check, and a room temperature field flatness and frequency measurement. Cavity surface processing follows the general scheme of the ILC RDR [2], and includes electropolishing. The bare cavity RF qualification test consists of a measurement of cavity unloaded quality factor, Q_0, as a function of gradient, E_{acc}, at 2K. The x-ray dose rate at the cryostat top plate is also monitored, to provide an estimate of field emission (FE) in the cavity. The cavity residual resistance and performance at other temperatures may also be measured. Depending on cavity performance, one or more steps of surface processing may be repeated.

A facility at ANL for 1-cell and 9-cell cavity surface processing and assembly [3], designed, built and operated jointly by FNAL and ANL staff, is in full operation. The facility houses an EP and an HPR tool, cleanrooms of class 10, 100, and 1000, an ultrasonic rinse tank, and a cavity vacuum system for post-assembly evacuation.

Other facilities used for cavity preparation are located at FNAL. A high-temperature vacuum furnace was installed and commissioned in 2010 for 800C furnace treatment. An automated cavity tuning machine [4] built in collaboration with DESY and KEK, was installed and commissioned in 2010. Internal optical inspection using an automated KEK/Kyoto inspection tool [5,6] is frequently used as an intermediate diagnostic tool at various stages in the cavity processing procedure. A low-temperature baking system using heaters and blankets is integrated with the mechanical support structure and vacuum system at the vertical cavity test facility (VCTF).

The VCTF at FNAL [7] has been in operation since 2007 for bare cavity performance qualification. One radiation shielded and magnetically shielded test cryostat is currently in operation, and typically operates at 2K. Performance diagnostics available for tests now routinely include thermometry [8] and second sound sensors [9,10] for quench location. Two additional larger cryostats are currently under construction [11], and are expected to more than triple the current throughput.

The goal for FNAL bare cavity performance is the ILC performance specification: E_{acc}>35 MV/m, and $Q_0>8x10^9$ at 35 MV/m. The FE requirement is less precise: x-ray dose rate must be as low or lower than that for typical well performing cavities. A summary of bare cavity gradient performance for all 1.3 GHz 9-cell cavities owned by FNAL is shown in Fig.1.

DRESSED CAVITY SEQUENCE

Once cavities have been qualified in vertical test, typically to the ILC specification, they are dressed and prepared for dressed cavity test. The dressing process includes welding the cavity into a helium vessel. In addition, mechanical tuners, a high-power input coupler, and magnetic shielding are installed. During dressing, the cavity field flatness and straightness are measured and if out of tolerance, the cavity is tuned and/or straightened. The frequency is monitored during the welding. The dressed cavity is then tested to the same performance specification as the bare cavity, confirming the quality of the dressing procedure and cavity operation under conditions similar to operation in a CM without beam.

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The cavity E_{acc} and Q_0 are measured, as is the FE level. In addition, the cavity Lorentz force detuning is measured, operation of the tuners confirmed, and couplers conditioned both at room temperature and at 2K. Details about the recent dressed cavity tests are described elsewhere [12,13]. A sample comparison between vertical and horizontal cavity performance is shown in Fig.2.

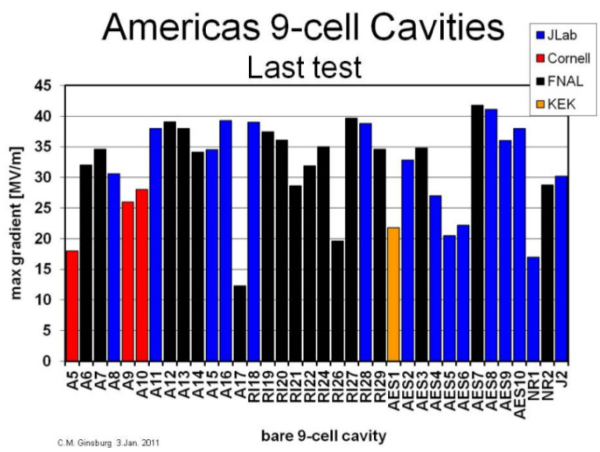

Figure 1: Bare cavity gradient performance in the most recent qualification test as of Jan.3,2011. Tests performed at FNAL are shown by the black bars. Surface processing location is typically, but not solely, the test lab shown.

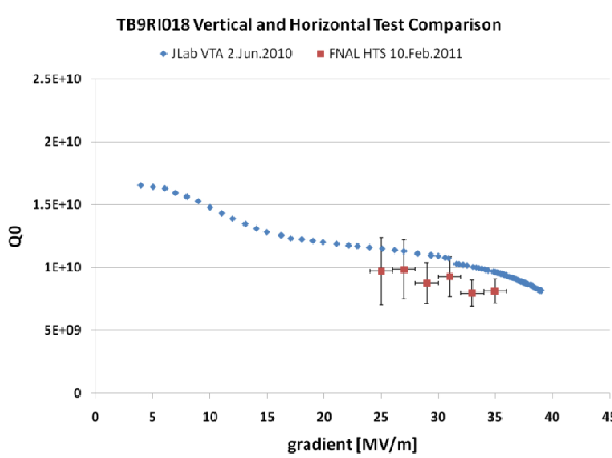

Figure 2: An example Q_0 as a function of E_{acc}, showing both bare cavity (blue) and dressed cavity performance. The bare cavity test data are courtesy of JLab.

The horizontal cavity test facility at FNAL [14], capable of holding one 1.3 GHz cavity, has been in operation since 2007 for dressed cavity performance qualification. So far, ten 1.3 GHz cavities have been tested; two have been tested twice. One of the tested cavities went to the S1-Global CM at KEK. Upgrades under development include an additional horizontal test cryostat which would hold two cavities, RF tested separately, or one cavity and a magnet/BPM package.

CRYOMODULE ASSEMBLY

Once eight cavities have been qualified in horizontal test, they will be assembled into CMs at the Cryomodule Assembly Facility (CAF). First, the dressed cavities are assembled into a cold string in a class 10 cleanroom. Alignment of the string and assembly of the cold mass is completed before final assembly into the vacuum vessel. CM1 was assembled at CAF, and the infrastructure is ready for CM2 assembly as soon as the cavities are qualified.

CRYOMODULE TEST

Completed CMs will be installed at the NML SRF accelerator test facility [15]. This facility is currently undergoing extensive expansion in anticipation of future FNAL projects. NML will be capable of accelerating an ILC-like electron beam using one CM, three, and then up to six CMs, as well as providing a state-of-the-art R&D facility for accelerator components. Dedicated CM test stands without beam are also planned. CM1 is currently being tested at NML without beam.

CAVITY R&D

The cavity R&D at FNAL in support of the 1.3 GHz cavity program may be divided into three broad groups: manufacturing and quality assurance optimization, cavity surface repair and surface processing optimization, and basic SRF R&D[16]. The majority of this R&D is performed using single-cell 1.3 GHz cavities. To optimize niobium sheet quality, investigations are ongoing on the benefit of eddy current scanning; typically scanning a fraction of sheets within an order is considered sufficient. To confirm cavity manufacturing quality, studies are ongoing with x-ray tomography of electron-beam welds. Many bare cavity processes and tests are done in support of qualifying new vendors. Quality assurance studies are done in close collaboration with vendors. A new cavity tumbling machine at FNAL [17] shows promise for both the repair of cavities with limiting features and as a basic preparation for unprocessed cavities. An example of this is a 9-cell cavity that was recently improved from 19 to 35 MV/m after a tumbling and electropolishing sequence. Studies of cavity performance as a function of tumbling surface finish are also underway. Basic SRF R&D issues include understanding medium- and high-field Q-slope and especially correlations of Q_0 with process type, the materials science of hot and cold spots using cut-outs from single-cell cavities, and the optimization of RF surface properties.

ACCOMPLISHMENTS

Currently fifty 9-cell 1.3 GHz cavities are at various stages in the production process. Forty more were ordered using ARRA funds, with delivery expected in the next two years. The FNAL/ANL cavity processing facility performed 44 electropolishing processes on 1.3

GHz cavities in 2010, of which 23 were for 9-cell cavities and 21 for 1-cell cavities. The facility has also performed 64 test preparations in 2010: 32 for 9-cell bare cavity tests, 23 for 1-cell (bare) cavity tests, and 9 for dressed cavity tests. A 25-30% increase in bare cavity process cycles is anticipated for the calendar year 2011. The VCTF has performed 81 cavity tests in 2010, of which 38 were for 9-cell cavities and 39 for 1-cell cavities. Although the throughput of bare cavity tests is expected to be high for 2011, the installation of one new cryostat during this period is likely to impact operations.

Currently there are fourteen cavities which have been identified as candidates for CM2[18], thirteen of which pass the ILC performance specification in vertical test. The horizontal tests of these cavities are in progress at FNAL[12]. The cavity performance is summarized in Fig.3. Three of the cavities shown in the figure, TB9RI029, TB9RI024 and TB9RI020, were processed and vertically tested at FNAL/ANL facilities; the remainder were processed and vertically tested at JLab. Note that an administrative gradient limit of 35 MV/m was imposed for horizontal tests after the degradation of TB9ACC013 by an arc event in the input coupler, and that TB9ACC013 and TB9ACC016 could not be tested with ILC pulse length because of FE. Most instances of cavity degradation can be traced to FE. The vacuum practices in all facilities are currently under review, with improvements expected.

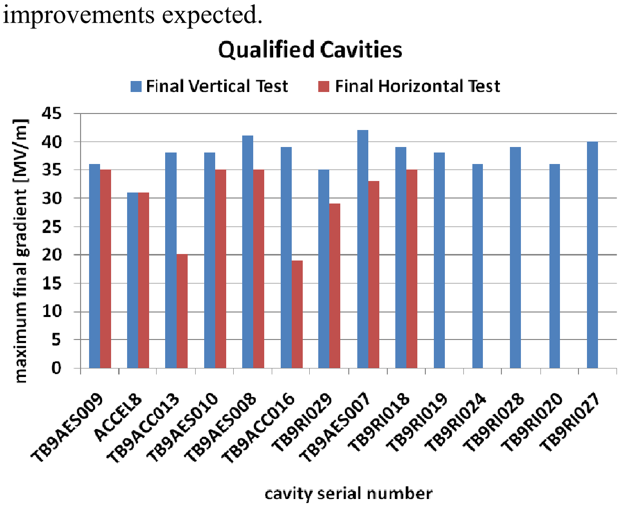

Figure 3: Comparison of final results from bare (blue) and dressed (red) cavity tests, ordered by horizontal test date.

The first 1.3 GHz CM, CM1, is now under evaluation. The CM was installed and cooled down to 2K in 2010. So far, three cavities have been tested; two retain their previous performance as measured at DESY, whereas one shows performance degradation as evidenced by an increased cryogenic heat load with increasing input power above a gradient of ~14 MV/m.

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