VERTICAL CAVITY TEST FACILITY AT FERMILAB*

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Abstract

After a recent upgrade, the vertical cavity test facility (VCTF) for SRF cavities at Fermilab features a low level RF system capable of testing 325MHz, 650MHz, 1.3GHz, and 3.9GHz cavities, helium liquefying plant, three test cryostats, and the interlock safety system. The cryostats can accommodate measurements of multiple cavities in a given cryogenic cycle in the range of temperatures from 4.2K to 1.4K. We present a description of VCTF components. We also discuss cavity instrumentation that is used for diagnostics of cavity ambient conditions and quench characterization.

INTRODUCTION

Typically characterization of superconducting radio-frequency (SRF) cavity involves measuring intrinsic quality factor Q_0 as a function of accelerating field E_{acc} in a vertical test stand (VTS) [1]. Fermilab's VCTF was commissioned in 2007 [2] with a single cryostat referred to as Vertical Test Stand 1 (VTS-1). VCTF was originally designed for vertical testing of bare ILC 1.3 GHz superconducting RF cavities Between 2007 and 2012 the facility was mainly used for qualification of 1.3GHz 9-cell cavities for the ILC program, PIP-II and developing new cavity processing techniques. Starting from 2012, when effect of nitrogen doping was discovered at this facility [3] cavity testing was more focused on new cavity processing R&D as well as magnetic field expulsion studies. In 2014, two additional test stands (VTS-2 and VTS-3) were commissioned. These newer test stands were designed with testing of production cavities in mind. They are larger in diameter and longer than VTS-1. The larger cryostats contain about twice the volume of VTS-1. Since December 2014 regular cavity testing has been performed in two dewars, VTS-1 and VTS-2. Using two dewars routinely allows to minimize downtime due to warmup and to accommodate more efficiently testing of LCLS-II, PIP-II, and R&D cavities. With the start of LCLS-II project in 2014, Fermilab vertical test facility became the main location for qualifying cavities for this project. Qualification of a full set of cavities for Fermilab's LCLS-II prototype cryo-module is nearing completion. Cavity testing for LCLS-II production cryo-module is planned to commence in 2016.

CRYOGENIC SYSTEM

VCTF as well as other cryogenically cooled test stands located the same building are supplied from a 1500 watt helium refrigerator/liquefier. The vertical test stands are fed liquid helium from the liquid helium storage dewar. When only feeding the vertical test stands, the helium plant has a liquefaction rate of 350 Liter/hour (design value). This mode of operation of the helium plant will be addressed in this paper.

Helium Liquefier

There are four major components of the helium liquefier:

1. Compressor Skid
2. Cold Box
3. Liquid Helium Storage Dewar
4. Gas Helium Storage (Buffer Tanks)

A simplified block diagram of the helium liquifier is shown in Figure 1. The compressor skid contains two compressors,

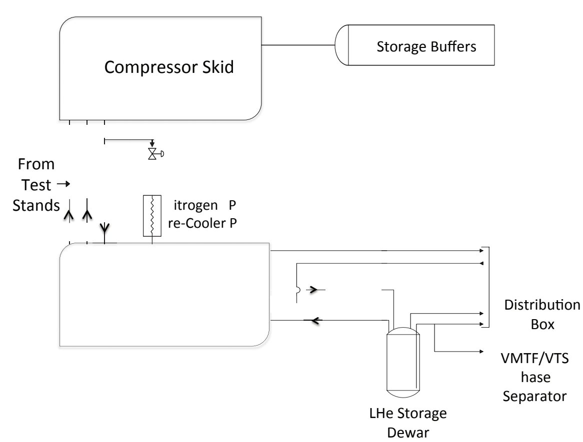

Figure 1: Simplified block diagram of the helium plant.

200 Hp and 1000 Hp, in series. These compress the gas from roughly atmospheric pressure to 38 psia and 150 – 300 psia, respectively. The heat due to compression is removed by cooling water on the compressor skid. The Cold Box is a series of heat exchangers, turbines and expansion valves. There are up to 3 flow paths in the heat exchangers: 1) High pressure helium inlet gas, 2) Medium pressure helium return gas and 3) Low pressure helium return gas. There is also a liquid nitrogen cooled helium pre-cooler that cools a portion of the high pressure helium inlet gas. Liquid helium from the Cold Box is stored in the 10,000 liter liquid helium storage dewar. Due to operational constraints, the current usable liquid capacity of this dewar is approximately 7,000 liters. Excess warm helium gas is stored in the Buffer Tanks until it can be processed into liquid. There are six 4,000 cu.ft. storage tanks in the Buffer Tank system. Due to the nature of

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portions of the facility operating below atmospheric pressure, air gets into the helium. When this air enters the Cold Box, it freezes out and reduces the performance of the liquefier. This eventually requires the warm-up of the Cold Box to scrub out the air from the helium system. Fermilab is nearing completion of a purifying system that will greatly reduce the amount of air from the helium gas thus increasing the time period between scrubbing cycles.

VCTF Support

Cooling down and filling of the cryostats with liquid helium can be performed from the helium plant storage dewar, transferring of liquid from one of the other two cavity test cryostats or from portable 500 liter dewars. The standard practice is to cool down and pre-fill the cryostat in the afternoon or evening before the test day. On the day of the test, additional liquid helium is added to the cryostat and pumped down to the operating pressure. During most of the pumping down of the cryostat, liquid helium continues to be flowed into the cryostat to ensure that there will be enough liquid in the cryostat to cover the cavities at the testing temperature. Tests are normally carried out at 2K, which requires that the pressure in the cryostat be reduced below atmospheric pressure. This is performed with the Kinney pumps. At 2K, a cryostat operating with two of these pumps can handle a cavity heat load of about 200 watts. Lower temperatures can be achieved. With two Kinney pumps operating and only the cryostat heat load, VTS-1 can achieve 1.5K and VTS-2 and VTS-3 can go to 1.4K or lower.

To increase the number of cavity tests per week, three cryostats can be used concurrently but with some limitations. For example, due to pumping capacity, only two of the three cryostats can be operating at or below 2K at the same time. With this capability, back-to-back tests can be performed. Typical recent practice, which allows to maximize the use of cryogenic system for cavity tests, has been to schedule cavity testing in VTS-2 while VTS-1 is warming up after previous cavity test completion. Since VTS-1 has only half the volume of VTS-2 it allows faster turnarounds between consecutive cavity tests. In this way, during the period of five days, three cryo-cycles can be performed, two in VTS-1 and one in VTS-2. VTS-3 is currently used for filling VTS-2 and, independently of routine cavity tests, for longer term cavity resonance control studies. Distributing cavity measurements among the three cryostats allows to address challenges associated with increased cavity testing demands of major accelerator projects such as LCLS-II and PIP-II and vigorous SRF research program at Fermilab.

During the past couple of years, cool down and operating conditions have been varied as requested to understand the impact on cavity performance. Although these cryostats have not been designed with varying the cool down rate in mind, ways were devised to provide for slower cool down rates needed for magnetic flux expulsion studies as described in Section INSTRUMENTATION AND EXPERIMENTS.

There have been a significant number of tests where the cavities needed to be temperature cycled within differing ranges for such studies. A typical set of 10 cycles may take about two 10 hour shifts to complete and may be performed on the weekend shifts allowing more time during the weekdays for RF testing.

RF SYSTEM

The design of the RF Control and DAQ systems at Fermilab's vertical test facility closely followed that of Thomas Jefferson National Laboratory (JLab) cavity vertical test stand [2, 4]. The RF Control and DAQ systems, originally built in 2007, have been upgraded and commissioned in 2014 for LSLS-II and PIP-II project cavity testing [5]. Additional instrumentation and systems have been added recently to expand cavity RF testing capabilities and magnetic flux expulsion measurements. A block diagram of the RF Control and DAQ system shown in Figure 2. The system consists

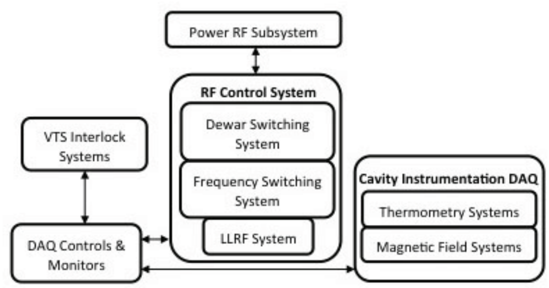

Figure 2: VCTF Control and DAQ system.

of the following components:

- Interlock Subsystem
- Cavity Instrumentation
- RF Control System
- Power RF Subsystem
- DAQ Controls and Monitors Subsystem

Interlock System provides personnel and equipment protection for the whole test facility. The Interlock System issues permit to power device under test only when all interlocks (radiation monitors, shielding block position switches, RF leak detector etc.) set into safe mode.

RF Control system includes LLRF System, Frequency Switching System and Dewar Switching System. LLRF System employs an analog phase-lock loop (PLL) to track the resonant frequency of the cavity.

Frequency Switching System operates mechanical RF switches to include or exclude frequency converters from the RF path. In this way cavities with frequencies 1300MHz, 650MHz and 325MHz can be tested. Recently the system has been upgraded to include 3.9GHz frequency band converter to accommodate LCLS-II 3.9GHz cavity testing. First RF test of 3.9GHz cavity is scheduled soon after this conference. Photograph of a single cell 1.3GHz cavity can be seen, for example, in Figure 4. Nine-cell 1.3GHz dressed

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and bare cavities are shown in Figure 6. Two types (β=0.61 and β=0.9) of 650MHz single cell cavities can be seen in Figure 7. Photographs of 325MHz and 3.9GHz cavities are shown in Figure 8.

Dewar Switching System is the set of mechanical RF switches that perform operational dewar selection between the three dewars. Since 2014 upgrade two of the three dewars, VTS-1 and VTS-2 are used routinely for cavity testing. Normally dewar switching between the two dewars takes place several times a week.

Power RF system include the set of low power and high power amplifiers, high power cables, high power bi-directional coupler. Low power wide-band amplifier is used for calibration and cavity measurements at low accelerating fields. Set of high power narrow-band amplifiers is used for cavity measurements at high accelerating fields.

DAQ Controls and monitors subsystem includes instrumentation for monitoring RF signals from the cavity under test and allows users to control operation and measure the performance of the cavity. This subsystem controls and communicates with other subsystems (see Fig. 2). Users communicate with DAQ system through LabVIEW-based software interface [5].

Cavity instrumentation DAQ is the set of measurement and control equipment typically used for variety of measurements. These will be detailed in the next section.

INSTRUMENTATION AND EXPERIMENTS

Cavity instrumentation include fast thermometry [6, 7], temperature mapping system [8, 9], temperature monitoring, quench detection systems, as well as radiation detectors, quench heaters and pressure measurement systems. Fig. 3 shows T-map system on a 1.3GHz single cell cavity. T-map system has been used to study quench mechanisms as well as

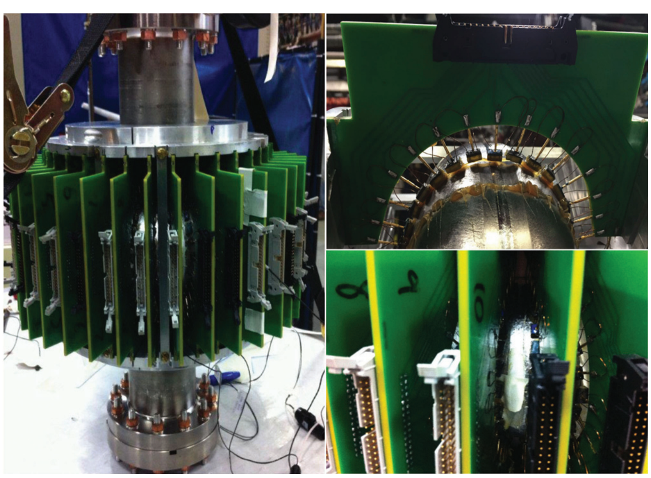

Figure 3: Left: T-map system on 1.3GHz single cell cavity. Top right: single board with resistors along the cavity. Bottom right: view of adjacent boards installed along the equator.

dynamics of cavity transitioning though the superconducting critical temperature during the cool-down. Oscillating Superleak second-sound Transducers (OST) [10, 11] have been used for determining quench location in a multi-cell cavities. There are also plans to implement cold X-ray monitors as a routine test equipment.

Recently magnetic field systems were added for studies of magnetic flux expulsion under different cooling dynamics and its effects on cavity performance [12–14]. In what follows these systems and experiments will be described in some more detail. First, flux expulsion experiments require probing different cavity cooling rates that lead to different temperature gradients across the cavity during the cool-down. In one of the methods of reducing the cooling rate of the cavity, the temperature of the inlet helium is adjusted by reducing the liquid helium flow rate and adding warm gas. As the cavity cools down, the helium temperature is reduced by decreasing the warm gas flow. Another way is to use the top fill valve instead of the bottom fill valve and supplying just liquid helium. The rate is also influenced by the source of liquid helium used (storage dewar vs portable dewar vs transfer from another cryostat). This is due to the difference in the flow rates and liquid fraction that can come from each source.

Instruments used in flux expulsion studies include magnetic field sensors, Helmholtz coils to apply or compensate magnetic field during operation, and a set of power sources and PID controllers to control magnetic field through Helmholtz coils. Magnetic filed is measured with single-axis Barrington Mag-01H cryogenic fluxgate magnetometers. Fluxgate magnetometer signal is also used in a control loop feedback mechanism to compensate ambient magnetic field with externally applied magnetic field. External magnetic field is typically applied via a pair of Helmholtz coils placed around the cavity as shown in the picture in Fig. 4. In some experiments Helmholtz coils are used to produced a desired amount of magnetic field at the cavity to study the expulsion during cavity cool-down as it undergoes superconducting transition. Typical remnant magnetic fields in the cryostats are between 1mGauss and 10mGauss in the axial direction at 9K depending on the cryostat and the position in the cryostat. With active compensation, fields below 1mGauss, as measured on the equator of the cavity, can be achieved. Fluxgate sensors installed on the equator of the cavity can be also seen in Fig. 4.

In special experiments to mimic cool-down conditions of the cavity in an accelerator cryo-module and in a horizontal test cryostat, the cavity was suspended on the insert in the horizontal orientation [15] (Fig. 5). For this experiment two sets of coils were used for producing magnetic fields in two orthogonal directions: along the cavity in the horizontal orientation and along the cool-down direction. In the latter case custom-made magnetic coils were used. Such experiments where conducted in both VTS-2 and VTS-1 dewar. Since VTS-1 dewar has a smaller diameter, cavity assembly hardware was modified in order to reduce the total length of cavity assembly and fit into the dewar diameter.

Other measurements performed at VCTF include measurements of cavity frequency as a function of temperature during special slow warmup through the superconducting critical temperature. In order to improve the precision of this measurement, dewar pressure measurements are used to compensate for microphonic effects. Measurement of quality factor as a function of temperature are performed simultaneously with the frequency measurement. These two measurements allow independent determination of the critical temperature [16].

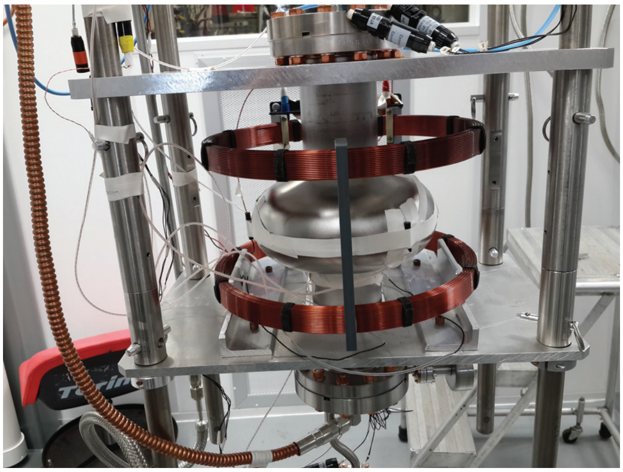

Figure 4: Helmoholtz coils for creating axial external magnetic field for vertical test of a 1.3GHz single cell cavity in a typical vertical test orientation of the cavity.

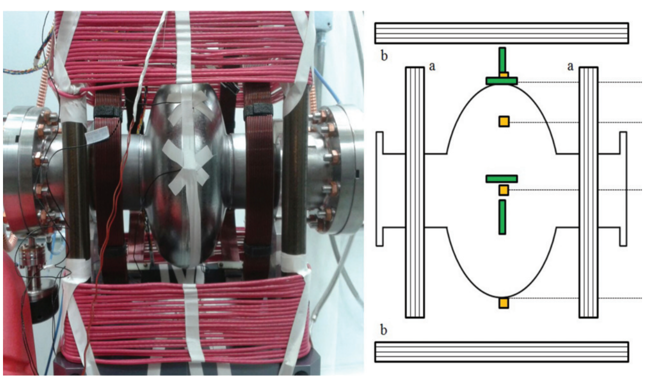

Figure 5: Left: vertical test setup in the horizontal cavity orientation with two pairs of Helmoholtz coils, fluxgate magnetometers, and Cernox temperature sensors. Right: schematics of the vertical test setup. Coils for producing cavity axial and cavity transverse fields are labelled a and b respectively. Fluxgate magnetometers are shown as green rectangles. Cernox temperature sensors are shown as yellow boxes.

Fig. 6 shows LCLS-II dressed cavity on the dewar insert in preparation for the vertical test. The cavity is equipped with two higher order mode couplers and internal instrumentation (6 Cernox temperature sensors and three fluxgate magnetometers).

Figure 6: Left: LCLS-II dressed cavity with internal instrumentation and higher order mode couplers installed on the dewar insert at the staging area in preparation for installation into the VTS-2 dewar. Right: two bare 9-cell 1.3GHz cavities on the insert before installation into VTS-1 dewar.

Figure 7: Left: two 650MHz β=0.61 single cell cavities in support frame on the cart. Right: two 650MHz β=0.9 single cell cavities are being instrumented in vertical test staging area.

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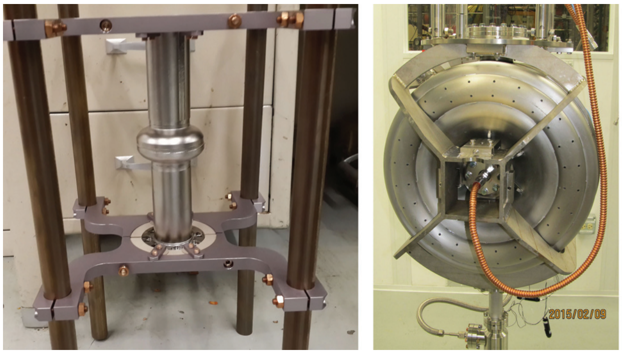

Figure 8: Left: 3.9GHz single cell cavity on a newly fabricated VTS support structure. Right: bare 325MHz single spoke cavity on the insert in the staging area with RF connections for vertical test.

SUMMARY

Brief overview of Fermilab's vertical cavity test facility, recent additions and activities have been presented in the this paper.

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