

# COMMISSIONING OF THE UKRI STFC DARESBUURY VERTICAL TEST FACILITY FOR JACKETED SRF CAVITIES

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## Abstract

A novel vertical test facility has been developed at the STFC Daresbury Laboratory. The VTF is designed to test 3 jacketed SRF cavities in a horizontal configuration in a single cool-down run at 2 K. Cavities were tested at low power levels for HOMs and passband modes, and  $Q$  vs  $E$  field measurements at high power levels. The specification requires an unloaded  $Q$  of 5E9 at a field gradient of 19.9 MV/m. The cavities are cooled with superfluid helium filled into their individual helium jackets. This reduces the liquid helium consumption by more than 70% in comparison with the conventional facilities operated elsewhere. The facility will be used to conduct a 2-year program to qualify 84 high-beta SRF cavities for the European Spallation Source as part of the UK's in-kind contribution. This paper reports on the commissioning program, along with a detailed discussion of the RF and cryogenic operations and performance of the facility.

## INTRODUCTION

A new Superconducting Radio Frequency Lab (SuRF Lab) which includes a Vertical Test Facility (VTF) and Re-processing Facility (Cleanroom and High Pressure Rinse) is currently in the commissioning phase at the UKRI STFC Daresbury Laboratory. An internal operational readiness review has been completed for the requirements of the ESS High Beta Cavity Project.

The VTF supports 2 K characterisation of three jacketed SRF cavities in a single cool-down run. Measurements of HOMs and passband modes are made at low power.  $Q$  vs  $E$  field measurements are made at high power levels (up to 200 W). A novel cryogenic architecture is used to significantly reduce the liquid helium (LHe) consumption compared with conventional facilities.

## VTF CRYOSTAT DESIGN

The conventional method for VTF SRF cavity testing is to fully immerse the cavities in a large LHe bath, and then cool to 2 K using a cold compressor/vacuum pump to reduce the vapour pressure over the bath. RF testing is then carried out with the cavities at 2 K. This approach has been used successfully for many programs, including XFEL cavity testing at DESY [1]. Whilst well-proven, this technique

requires both a large cryoplant and, for this activity, would require ~8500 L of LHe per test cycle.

Given the diminishing global supply of He, and associated rise in cost, an alternative cryostat architecture has been developed for vertical testing of jacketed SRF cavities which requires significantly less LHe and a much smaller cryoplant throughput [2–4]. The cryostat is based on a cavity support insert (CSI) where three cavities are mounted horizontally inside LHe jackets below a header tank, each fed by a common fill/pumping line; this may be seen in Figs. 1 and 4 which show a photograph and a CAD model of an assembled insert respectively. By using this design approach, far less LHe is required per testing run (~1500 L, all of which is recovered) compared with the conventional designs.



Figure 1: Photograph of CSI on stand with three jacketed cavities installed (top and middle cavities dressed in MLI jackets).

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The insert is mounted into a cryostat vessel which comprises the outer vacuum chamber, magnetic shielding (see below), and thermal radiation shields. The cryostat was manufactured by Criotec<sup>1</sup>.

An ALAT<sup>2</sup> Hérial ML cryoplant, commissioned in 2018, supplies 50 K gaseous helium (GHe, produced by the first heat exchanger stage of the liquefier) and 4.2 K LHe. Sub-atmospheric pumps provide cooldown of the liquid to 2 K. Helium is recovered from the shield and CSI cooling circuits, stored at high pressure, purified, and then reliquefied, providing a completely closed-loop system.

## CAVITY TESTING PROGRAM

As part of the UK's in-kind contribution to the European Spallation Source (ESS), STFC is responsible for the procurement, qualification testing, and delivery to CEA Saclay of 84 high-beta Nb cavities. The high-beta cavities, which accelerate the beam from 628 MeV to 2500 MeV, are a five-cell bulk Nb design operating at 704.42 MHz, designed at CEA Saclay. 2 K RF qualification of cavities with  $Q \geq 5 \times 10^9$  at 19.9 MV/m will be required [5].

In total, 115 tests are anticipated; given the project timeline and a 2 week testing duration, this required the infrastructure and work flow to be developed for testing 3 cavities simultaneously. To facilitate this, two CSIs have been manufactured which can be used alternately in a single vacuum vessel. This will allow simultaneous testing of three cavities and preparation of the following three on the other insert, reducing down time between runs.

Following the completion of the ESS high-beta testing program, the facility will be used for testing of HB650 cavities for the PIP-II project. Work is currently ongoing to study the modifications to the facility that will be necessary to support this activity.

## CRYOGENIC PERFORMANCE

During the commissioning of the VTF, 15 cooldown runs have been carried out. These have been done to validate and improve the thermal performance with zero, one, two, and three cavities in a combination of cradle positions. Extensive radiation surveys have been carried out. Mechanical operations for removing and reinstalling UHV components have been validated by comparing cavity performance before and after the procedures. Both inserts have now been fully validated.

A given run is divided into the following modes, each with clearly defined procedures and QC checks:

**Mode-1** Cavity assembly on CSI

**Mode-2** CSI loading into bunker cryostat

**Mode-3** Shield and cavity cooldown to 50 K using cold GHe; typical cooldown time is 48 hours

**Mode-4** Cavity cooldown with LHe to 4.2 K; typical cooldown and fill time is 6 hours

**Mode-5** RF operations at 4.2 K (see following Section)

**Mode-6** Cavity cooldown to 2 K utilising sub-atmospheric pumps; typical fill and cooldown time is 5 hours

**Mode-7** RF operations at 2 K (see following Section); following a LHe top-up, hold time to keep all three cavities immersed for testing is typically 8 hours, during which time sufficient pressure stability under static loading is maintained to give temperature stability at the level of 1 mK (this is done by utilising a valve in parallel with the 2 K pumps operated by a PID controller)

**Mode-8** Warmup to 300 K; here, heaters along with recirculation pumps on each cryogenic circuit are used to increase the warm up speed, typically 72 hours

**Mode-9** CSI removal from bunker

**Mode-10** Cavity disassembly on CSI stand (then return to mode-1)

It may be seen that overlap is possible between modes 2-8 and modes 9-1 on the alternate CSI, improving the throughput of the facility.

## RF TESTING

RF power is carried down from the lid of the cryostat via SiO<sub>2</sub> stainless steel cables purchased from Times Microwave<sup>3</sup>. The SiO<sub>2</sub> dielectric and stainless steel outer of the cable reduce conductive heat flow to the cold stage.

Daresbury LLRF (DaLLRF) v0.1 is a hardware project aimed at prototyping a new, simplified and improved Low Level RF (LLRF) system for particle accelerators. The PCB is designed using free software Kicad 4.x<sup>4</sup>. DaLLRF v0.1 has two identical RF output channels (TX0 and TX1) and two identical RF input channels (RX0 and RX1). Clocking has to be applied to each of the four converters externally using MCX connectors. Each of the RF input channels is implemented using Linear Technologies<sup>5</sup> LTC2145-14 14 bit 125 MSps dual ADC, and a Texas Instruments<sup>6</sup> TRF371109/TRF371125/TRF371135 quadrature demodulator with a frequency range of (0.3 to 1.7) GHz / (0.7 to 4.0) GHz / (1.7 to 6.0) GHz. When set to Self Excited Loop (SEL) mode the LLRF will lock on to the incoming signal. The output will track the incoming signal phase but will maintain constant amplitude. A phase offset can be set inside the loop. The system reports the instantaneous frequency.

The high power testing system was fairly standard with a high power switching network and a solid state 500 W amplifier. Input, reflected and transmitted power were monitored by directional couplers which can be calibrated so that these values are referenced to the connectors on the cavity. The cavity decay was measured at low power levels so as to calibrate the system and then cavity parameters are derived from a knowledge of the incident, reflected and transmitted power. The transmitted power was monitored using a pick up probe which was very loosely coupled to the cavity.

<sup>3</sup> timesmicrowave.com

<sup>4</sup> kicad-pcb.org

<sup>5</sup> analog.com

<sup>6</sup> ti.com

<sup>1</sup> criotec.com

<sup>2</sup> advancedtech.airliquide.com

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Testing initially began with a measurement of the decay curve of the cavity and the  $Q_{ext}$  of the pick up probe. After this, power was gradually increased to the cavity in a series of CW pulses lasting ~20 to 30 s at low power. During this initial period of testing, the phase was also optimised for each pulse to minimise the amount of power reflected from the cavity. At the very highest power levels, the phase optimisation was not performed, due to thermal issues. This reduced the length of the pulse down to ~10 to 20 s. In this system, the input flange, where RF power is applied, tends to warm at the highest power levels. This is because such flanges are typically stainless steel and there were some conductor losses on the metal. During operation in the accelerator, the RF input coupler is cooled directly by LHe; in this setup however, copper straps were used to thermally anchor the input flange, as shown in Fig 2.



Figure 2: Thermal strap used to provide cooling of the input coupler flange.

The plot in Fig. 3 shows the measured data for ESS high-beta cavity H016. Two separate data sets were taken on separate days, showing very good repeatability. Measured radiation levels for H016 were very low. It may be seen that the cavity easily met the ESS requirement of  $Q \geq 5 \times 10^9$  at 19.9 MV/m. Typical error values were on the order of 10 to 15% which is consistent with standard measurement errors found by other authors [6]. Further understanding of both the repeatability and accuracy of the data will be the subject of ongoing efforts throughout the testing program.

Measurements of  $Q$  against temperature (not shown) were also made by allowing the temperature of the LHe bath to drift and sampling the  $Q$  periodically at low power.

In this system, the radiation dose rate detectors were much closer to the ends of the cavities than in most other systems in use around the world. The separation was ~20 to 30 cm. In most other laboratories, the distance is typically on the order of 2 to 3 m. This means that the dose rate measured at Daresbury was expected to be on the order of 100 times greater than that measured at other labs, purely from the effect of  $1/r^2$ . Work is ongoing to characterise this in greater detail, including both geometrical and instrumentation effects.

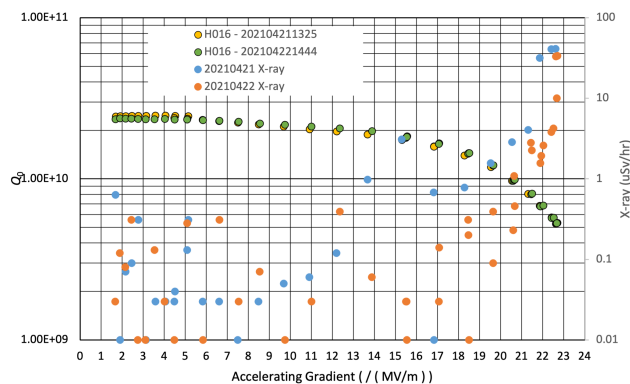


Figure 3: Measured  $Q$  and radiation levels against accelerating gradient for ESS high-beta cavity H016.

## MAGNETIC SHIELDING

Stray field attenuation at the cavities to  $< 1.4 \mu\text{T}$  is achieved by a static Mu-metal magnetic shield<sup>7</sup> surrounding the cryostat. Further attenuation to  $< 1.0 \mu\text{T}$  is achieved through the use of two active coils located at the top and bottom of the cryostat as shown in Fig. 4. Coils are energised to ~6 A and ~8 A respectively to provide the desired attenuation. Field measurements in the centre of each cradle showed  $0.231 \mu\text{T}$  for the top cavity,  $0.767 \mu\text{T}$  for the middle cavity, and  $0.346 \mu\text{T}$  for the bottom cavity.

## UHV SYSTEM

A custom slow pump slow vent (SPSV) ultra-high vacuum system has been designed and built as part of each CSI. Pumping through a SPSV system allows cavities to be actively pumped during RF testing with minimal risk of particulate transfer from the internal surfaces of the pumping system to cavity. All components used for the build were processed for cleanliness and particulate control before final assembly under ISO 4 cleanroom conditions. The SPSV system comprises three separate pumping lines, one for each cavity that can be tested on the CSI, and each pumping line can be linked if required to protect against hardware failures. The SPSV system is controlled remotely via PLC and each line comprises a number of control valves, Pirani gauges, cold cathode gauges, and RGAs that allow cavity acceptance data to be recorded before and after RF testing. All gauge and RGA data is logged and stored during RF testing.

## CLEANROOM AND HIGH PRESSURE RINSE FACILITY

Data from previous cavity testing programs such as XFEL [7] suggest that ~30% of cavities may be expected to fail to meet specification on the first test. The standard approach to improve the performance to meet specification is for these cavities to undergo a high pressure rinse (HPR) of their RF surface. A bespoke cleanroom has been designed and com-

<sup>7</sup> magneticshields.co.uk

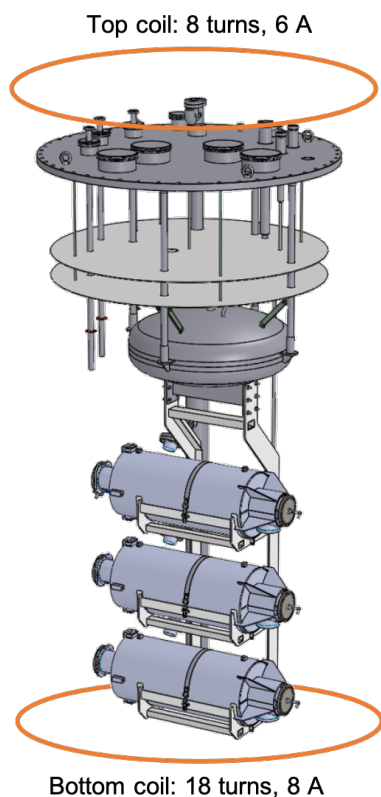


Figure 4: CAD model of CSI with three jacketed cavities installed showing position of active coils.

missioned, and houses the HPR facility which is currently being commissioned.

The HPR machine was designed by Auredom<sup>8</sup> (formally ACMEI Industries) with key input from STFC technical staff and contracted SRF technical expert.

Cavities follow a staged cleaning process. First, they enter the ISO 7 area where they are cleaned and loaded onto an inspection table for the assembly of the bespoke alignment cradle, giving concentricity along the full length of the cavity (~1300 mm) of  $\leq 1$  mm. They then undergo additional cleaning procedures where they are finally prepared in the main cleanroom (operating under ISO 4 conditions), and then connected to the TORROS 500 lifter<sup>9</sup> where they can be rotated into a vertical position. The UHV beam line flange is then removed in preparation for loading on the HPR machine, in readiness for treatment in the wet cleanroom. Following the HPR cycle, a designated drying room is utilised.

An ultra-pure water system has been designed and is currently being commissioned to support a pre-rinse cycle proposed at ~20 minutes, followed by a full rinse cycle proposed at ~6.5 hours. The wand features a nozzle providing ultra-pure water at 100 bar through 6 outlets oriented radially with even spacing, along with a nitrogen purge circuit. All cavities are mounted vertically, with the aforementioned concentricity allowing for a highly uniform spray pattern.

<sup>8</sup> auredom.fr

<sup>9</sup> torros.net/

All processes are to be validated initially using a prototype high beta cavity followed by a full vertical test, then finally moving onto rinsing a series cavity with known performance and repeating the vertical test.

During initial testing of the HPR machine, it was found that the ultra-pure water became contaminated by particulates from the steel bearing; a new ceramic bearing has been ordered, with full commissioning to be carried out in the next few months.

## CONCLUSION

A new Superconducting Radio Frequency Lab (SuRF Lab) which includes a Vertical Test Facility (VTF) and Re-processing Facility (Cleanroom and High Pressure Rinse) is currently in the commissioning phase at the UKRI STFC Daresbury Laboratory. An internal operational readiness review has been completed for the requirements of the ESS High Beta Cavity Project.

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Commissioning of the associated cleanroom has been completed and for the HPR facility is well underway.

The facility has now begun a 2-year testing program for the high-beta cavities being provided by the UK as part of its in-kind contribution to the ESS project. Performance so far appears consistent with plans to test cavities in 2-week runs.

Work is currently ongoing to study the modifications to the facility that will be necessary to support HB650 cavity testing for PIP-II.

## ACKNOWLEDGEMENTS

The authors would like to thank collaborators from ESS, DESY, CEA, and INFN, as well as industrial partners. They also would like to thank T. Powers for his help in designing the test system as well as the use of the LabVIEW software from JLab, and A. Matheisen for sharing technical knowledge for the design and commissioning of the SuRF Lab infrastructure.

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