ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPOGE09

STEADY-STATE CRYOGENIC OPERATIONS FOR THE UKRI-STFC DARESBURY SRF VERTICAL TEST FACILITY

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Abstract

A novel vertical test facility has been developed, commissioned, and entered steady-state operations at the UKRI-STFC Daresbury Laboratory. The cryostat is designed to test 3 jacketed superconducting RF cavities in a horizontal configuration in a single cool-down run at 2 K. 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 operational elsewhere. The facility is currently undertaking a 2-year program to qualify 84 high-beta SRF cavities for the ESS (European Spallation Source) as part of the UK's in-kind contribution. This paper reports on the steady-state operations, along with a detailed discussion of the cryogenic performance of the facility, including that of the cryoplant.

INTRODUCTION

The UKRI STFC Daresbury Laboratory Vertical test Facility (VTF) [1] has now been operating regularly for over a year. The VTF supports 2 K characterisation of three jacketed SRF cavities in a single cool-down run, with the 2-year ESS high-beta cavity testing program well underway. Measurements of HOMs and passband modes are made at low power. Q vs E field measurements are made at higher accelerating gradients (up to 200 W input power). A novel cryogenic architecture is used to significantly reduce the liquid helium (LHe) consumption compared with conventional facilities.

VTF CRYOSTAT DESIGN

The standard architecture for vertical SRF cavity testing is to fully submerge cavities in a large LHe bath, and then cool to ≤2 K using a vacuum pump/cold compressor to reduce the partial pressure over the bath. RF characterisation is then carried out. This method has been used successfully for many programs, including testing XFEL cavities at DESY [2]. Whilst well-proven, this technique requires both a large cryoplant and, for the activities at UKRI STFC, would require ~8500 L of LHe per test cycle.

Given the ever-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 [1,3]. 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 Fig. 1 which shows a photograph of an assembled insert. 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 (top and middle cavities dressed in MLI jackets).

The insert is mounted into a cryostat vessel which comprises the outer vacuum chamber, magnetic shielding, and thermal radiation shields. The cryostat was manufactured by Criotec[1].

SAFETY

In the operation of any cryogenic facility, safety is paramount. Accordingly, significant efforts have been devoted to understanding potential failure modes for the facility as described above, and introducing mitigation strategies in consideration of the relevant regulations. For a detailed report on the safety of this system, the interested reader is directed to Ref. [3].

CRYOGENIC INFRASTRUCTURE

An ALAT Hélial ML cryoplant, commissioned in 2018, supplies 50 K gaseous helium (GHe, produced by the first

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[1] criotec.com

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPOGE09

heat exchanger stage of the liquefier) and 4.2 K LHe. The first stage heat exchanger of the cold box is precooled using liquid nitrogen (LN_2) and is hence able to provide a cold gas supply rate of ~2 g/s and a liquefaction rate of ~130 L/hour. LHe is stored in a 3000 L capacity dewar. The plant is currently operated with a total helium inventory of 2700 L liquid equivalent.

The supply of liquid and gaseous cryogens to the shield and CSI circuits is managed by a 2 K valve box immediately adjacent to the VTF cryostat.

Pumping of the helium boil-off gas from the cryostat is provided by a single 2 K pump stack comprising a Leybold[2] RA7001 SO roots blower booster pump backed by an SV1200 rotary vane main pump.

The helium from the liquid and gas cooling circuits is recovered in a gas bag, compressed through to high pressure storage, purified by the cold box internal purifier, and then reliquefied, providing a completely closed-loop system.

CRYOGENIC PERFORMANCE

Following the commissioning of the facility [1], regular operations are well underway and facility is operating in steady-state. As of August 2022, 35 commissioning and cavity test runs have been carried out, with 73 cavity tests being conducted for the ESS high-beta cavities project.

The following section reports some of the observations, lessons learnt, and improvements from the transition from commissioning to steady-state.

Testing Cycles

Two identical cavity support inserts (CSIs) are operated to support high testing throughput; one can be prepared whilst the other is under test and then the two swapped to begin Run n+1 immediately following the completion of Run n. Test cycles are now reliably carried out on a two-week schedule; runs are divided into the following modes, each with clearly defined procedures and quality control 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
- **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
- **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 through-out of the facility.

Pressure and Temperature Stability at 2 K

The 2 K pumping system provides >1 g/s at 30 mbar (2 K). A PID control loop operates on a bypass valve in parallel with the pump stack (shown in Fig. 2) which has been demonstrated to provide pressure stability under static loading at the level of ±0.1 mbar in the CSI; this corresponds to a temperature stability of ±1 mK of the LHe. Planning is currently underway to install an additional pump set to provide additional pumping capacity as well as redundancy for the facility. The demonstrated cryogenic performance is sufficient to allow ~40 s of RF power dissipation up to 200 W during high-gradient testing.

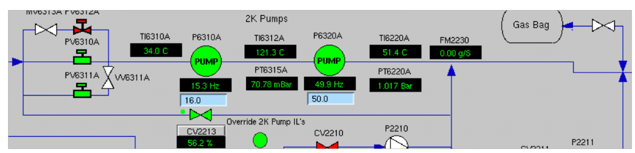

Figure 2: Bypass valve (CV2213) shown operating on PID control in parallel with 2 K main pump (P6320A) and booster pump (P6310A) (NB: direction of flow is left to right through pumps and right to left through bypass valve).

Shield Cooling

The thermal shields are cooled by ~50 K GHe from the coldbox, which is fed from the clean gas buffer. When the liquefier is running, there is an additional demand on the clean gas buffer which the purifier throughput cannot match and so it is not possible to run both the shield cooling with gas and liquefier simultaneously for periods in excess of a few hours.

As such, a scheme has been developed whereby GHe is is used to cool the shields from room temperature down to ~100 K, and then switching to cooling with LHe boil off <100 K which is run during cold testing.

Plant and VTF Reliability

During the move from commissioning to steady-state operations, a range of interlocks have been added and a number of engineering controls have been implemented to substantially improve the reliability of the system.

As shown in Fig. 3, the number of out-of-hours interventions required to support continuing operations has steadily decreased since August 2019.

[2] leybold.com

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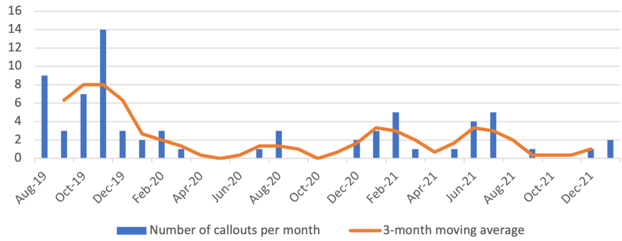

Figure 3: Call-out statistics for the cryogenic team supporting VTF operations.

Impact of COVID-19

Commissioning of the system and the move to steady-state operations was successfully completed despite the COVID-19 pandemic. Site-wide measures were implemented to minimise the risk of transmission, with most systems set up to allow remote operation.

Maintenance

A comprehensive maintenance plan has been developed and fully implemented to support continuing reliable operation of the facility. The following fall under the responsibility of the cryogenics team:

- **Weekly** Oil removal system drained, Kaeser compressor[3] shaft seal leak rate measured, recovery compressor filter drained
- **Monthly** Plant-wide leak check, cryoplant helium inventory analysis
- **Quarterly** Coldbox warmup, conditioning of HP lines, LP lines, and purifier
- **Annually** Cryoplant maintenance by Air Liquid Cryogenic Services[4], vacuum equipment maintenance by Leybold[5], pressure equipment inspections

Thermal Modelling and Comparison with Experimental Data

Details of hand calculations and finite element analyses of the steady-state static heat loading on the system along with a comparison to experimentally-determined values are reported in Ref. [4].

RF TESTING

As described in detail elsewhere [1, 5], measurements of HOMs and passband modes are made at low power (fixed temperature), measurements of Q against temperature are made by allowing the temperature of the LHe bath to drift and sampling the Q periodically at low power, and Q vs E field measurements are made at higher accelerating gradients (up to 200 W input power).

[3] kaeser.com
[4] advancedtech.airliquide.com
[5] leybold.com

During operation in the accelerator, the RF input coupler will be cooled directly by LHe; in this setup however, copper straps are used to thermally anchor the input flange (described in detail in Ref. [1]). The 2 K pump is sufficient to allow ~40 s of RF power dissipation during high-gradient testing; several minutes are required between applications of RF power to allow the input coupler flange to cool as a result of this lack of direct cooling.

CONCLUSION

The Vertical Test Facility (VTF) at the UKRI STFC Daresbury Laboratory has entered steady-state operations. The VTF reliably supports 2 K characterisation of three jacketed SRF cavities in a horizontal configuration in a single cool-down run lasting 2 weeks. Measurements of HOMs and passband modes are made at low power. Q vs E field measurements are made at higher accelerating gradients (up to 200 W input power). Cavity data obtained is entirely consistent with those from collaborating facilities. A novel cryogenic architecture is used to significantly reduce the LHe consumption compared with conventional facilities. Excellent pressure and temperature stability has been demonstrated at 2 K and cryogenic performance validated for high-power testing at 2 K.

The facility is well into 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. 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.

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