Cryogenic safety considerations for Vertical Test Facility for qualifying high-$\beta$ SRF cavities for the European Spallation Source

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Abstract. A dedicated cryogenic infrastructure has been installed at STFC Daresbury Laboratory to qualify and deliver 84 high-$\beta$ SRF cavities for the ESS (European Spallation Source) under construction in Lund, Sweden. In order to meet the delivery schedule and optimise the test process efficiently, a large 1.6 m diameter, 3.5 m tall liquid helium cryostat has been developed. RF tests are conducted on 3 cavities at 2 K in one cool-down. There are 3 cryogenic circuits operating at 50 K, 4.2 K and 2 K designed to handle a maximum helium mass flow rates of 4 g/s. Considering the large internal beam pipe and external surface areas of the cavities under test, the pressure relief system has been designed very carefully. Various limiting scenarios and associated safety schemes are presented in detail in this paper.

1. Introduction

The European Spallation Source (ESS) is an accelerator-driven neutron spallation source currently under construction near Lund, Sweden. On completion, the ESS will be the world’s most advanced neutron spallation source. The first neutrons are scheduled to be delivered in 2019, with the full user program beginning in 2023 [1].

A key component of the ESS is the linear accelerator. The linac creates protons at the ion source, accelerates them to an appropriate energy, and then steers them onto the target. Here, neutrons are created via spallation for use by a suite of research instruments. As shown in Figure 1, the beam is accelerated to progressively higher energies by a sequence of normal and superconducting RF cavities. The SRF cavities are fabricated from niobium and operated at 2 K in pumped helium baths. An individual helium tank surrounds each cavity.

The high-$\beta$ cavities which accelerate the beam from 628 MeV to 2500 MeV are a five cell design operating at 704.42 MHz, designed at CEA-Saclay. As part of the UK’s in-kind contribution, STFC is responsible for the fabrication and testing of 84 high-$\beta$ niobium cavities including management of eddy current scanning and 2 K RF qualification of cavities with $Q = 5 \times 10^9$ [2]. In order to support this activity, a Vertical Test Facility has been designed and is currently undergoing commissioning at the STFC Daresbury Laboratory.
Figure 1. Block diagram of the ESS accelerator; orange items are normal conducting and blue items are superconducting [1]

2. Vertical Test Facility Cryostat Design

The conventional method for Vertical Test Facility (VTF) SRF cavity testing is to fully immerse the cavities in a large liquid helium (LHe) bath, and then pump the entire bath down to 2 K using using a cold compressor/vacuum pump. RF testing is then carried out with the cavities at 2 K. This approach has been used successfully for many programs, including cavity testing for XFEL at DESY [3]. Whilst well-proven, this technique requires both a large cryoplant and, for this activity, would require $\sim 8500$ L of LHe per testing run.

In order to significantly reduce both the amount of LHe required and the cryoplant throughput, an alternative cryostat architecture has been developed [4]. The cryostat has been manufactured by Criotec\(^1\) and is being commissioned presently. An ALAT\(^2\) Héial 100 cryoplant supplies 50 K gaseous helium (GHe) and 4.2 K LHe and has completed commissioning.

The cryostat is based on a cavity support insert (CSI) where three cavities are mounted horizontally inside LHe jackets, each fed by a common fill/pumping line as shown in Figure 2. By using this design approach, far less LHe will be required per run ($\sim 1500$ L) compared with the conventional design. A CAD model of the CSI and photograph of an assembled insert are shown in Figures 3 and 4 respectively.

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1. [criotec.com](http://criotec.com)
2. [advancedtech.airliquide.com](http://advancedtech.airliquide.com)
The insert is mounted into a cryostat vessel which comprises the outer vacuum chamber, thermal radiation shields, and magnetic shielding.

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.

3. Operational procedure
After the cavities and their helium jackets are assembled, the insert is mounted into the cryostat vessel. The vacuum space is evacuated and the lines to the cryoplant are connected.

A pump and purge procedure of the helium circuit shown in Figure 2 is then carried out with GHe to minimise contamination and the possibility of ice blockages in the circuit during the subsequent cooldown.

Next, the thermal shield is cooled to $\sim$50 K with GHe supplied by the cryoplant (produced by the first heat exchanger of the helium liquefier) and the cavities and other CSI components precooled to $\sim$100 K via helium convection with the thermal shield. LHe is then supplied to the circuit, completely immersing the cavities and filling the circuit (as shown in Figure 2), cooling the cavities to 4.2 K. These stages of the cooldown are shown in Figure 5. The duration of this cooldown stage is $\sim$22 hours.

The LHe bath is then pumped on to reduce the pressure to $\sim$30 mbar, bringing the liquid temperature to $\sim$2 K. Approximately half of the helium inventory evaporates from self-cooling losses during this process, as shown in Figure 6. The duration of this stage is $\sim$1.5 hours. 2 K RF testing may then be carried out.

As shown in Figure 6, the 2 K pumping rate required for this cooling stage is $\sim$4 g/s. This is significantly less than the $\sim$20 g/s required by the conventional VTF approach, thus reducing the size of the 2 K pumps, safety devices, valves and transfer lines.

4. Safety Considerations
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.

The Pressure Equipment Directive (PED) 2014/68/EU defines the standards for pressure equipment over 1 L in volume and having a maximum pressure more than 0.5 bar(g). However, as
volumes inside the cryostat only contain gas below 0.5 bar(g), design, fabrication and operation are instead governed by Local Safety Schemes and Good Engineering Practices.

In order to avoid unsafe pressure build-up in case of a valve failure, it is necessary to identify any potentially closed volumes and ensure pressure relief devices are located and designed accordingly. All of these devices are shown on the piping and instrumentation diagram in Figure 7. Extensive consideration has been given to the “worst case” failure scenarios, as detailed in following subsections.

4.1. Cryostat vacuum failure
A catastrophic loss of vacuum inside the cryostat vessel would lead to an immediate leak of room temperature air onto the cold surfaces. With bare cavity jackets, this would give rise to a loading of $\sim 3.8$ W/cm$^2$ to the 2 K stage. However, the use of MLI on this stage, as well as reducing the radiative loading during normal operation, also reduces the resultant loading of air on the 2 K stage to $\sim 0.6$ W/cm$^2$ by retarding heat transfer from the gas. This in turn reduces the required sizes of safety valve and burst disc as shown in Table 1.

| Loss of vacuum heat load (kW) | Diameter safety valve required (mm) | Cross section burst disk required (mm$^2$) |
|-----------------------------|-----------------------------------|-----------------------------------------|
| Without MLI on cavities    | 170                               | 64                                      | 17680                                   |
| With MLI on cavities       | 42                                | 32                                      | 4368                                    |

The minimum flow discharge area $A$ for critical flow is given by

$$A = \frac{Q_m}{0.2883\kappa \sqrt{P_0/v_0}}$$

where $Q_m$ is the mass flow rate (found by dividing the total loading on the 2 K stage by the latent heat of LHe), $\kappa$ is the discharge coefficient, $P_0$ is the absolute flowing pressure and $v_0$ is the specific volume of the gas.

4.2. Beam pipe vacuum failure
A leak into the UHV circuit for the cavity beam pipes would load the inside surfaces. Three independent UHV systems are used for the cavities; it is considered extremely unlikely that all three would fail simultaneously. As such, the loading from room temperature air incident on the full inside area of a single cavity and beam pipe has been calculated. However, as the loading in this case is found to be less than that in the case of cryostat vacuum failure as described in Section 4.1, this is not considered to be the limiting scenario.

4.3. Contamination of helium circuit
If the safety valve described in Section 4.1 does not close correctly after helium boil off from a transient loading event, ingress of air to this circuit is possible. In order to mitigate this, a low pressure helium guard (LPHG) is used, as shown in Figures 8 and 9 and highlighted by the blue box in Figure 7. By surrounding PRV1180 with a buffer chamber containing helium gas at 0.1 bar(g) and sealed by a second valve PRV1182, the malfunction of PRV1180 would cause only the ingress of helium to the circuit.
5. Conclusion

In order to meet the RF testing requirements for the ESS high-β cavities to be delivered by STFC, a novel VTF cryostat has been designed, manufactured and is currently undergoing commissioning at the the Daresbury Laboratory. Commissioning of the cryoplant has been completed. Analysis of the cryogenic safety requirements for the facility has been carried out, along with detailed analysis of the “worst case” scenarios. Mitigation strategies have been reported.

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