Report

Upgrade of the Cryogenic CERN RF Test Facility

O. Pirotte\textsuperscript{a}, V. Benda\textsuperscript{a}, O. Brunner\textsuperscript{a}, V. Inglese\textsuperscript{a}, T. Koettig\textsuperscript{b}, P. Maesen\textsuperscript{a}, B. Vullierme\textsuperscript{a}

\textsuperscript{a}CERN - European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
\textsuperscript{b}ESS - European Spallation Source, Box 176, 221 00 Lund, Sweden

Keywords: Cryogenic transfer line, Test Facility, SRF

Abstract

With the large number of superconducting radiofrequency (RF) cryomodules to be tested for the former LEP and the present LHC accelerator a RF test facility was erected early in the 1990’s in the largest cryogenic test facility at CERN located at Point 18. This facility consisted of four vertical test stands for single cavities and originally one and then two horizontal test benches for RF cryomodules operating at 4.5 K in saturated helium. CERN is presently working on the upgrade of its accelerator infrastructure, which requires new superconducting cavities operating below 2 K in saturated superfluid helium. Consequently, the RF test facility has been renewed in order to allow efficient cavity and cryomodule tests in superfluid helium and to improve its thermal performances. The new RF test facility is described and its performances are presented.

Presented at:

CEC/ICMC
Anchorage, Alaska
June, 2013
Upgrade of the Cryogenic CERN RF Test Facility

O. Pirottea, V. Bendaa, O. Brunnera, V. Inglesea, T. Koettigb, P. Maesena, and B. Vulliermea

aCERN - European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
bESS - European Spallation Source, Box 176, 221 00 Lund, Sweden

Abstract. With the large number of superconducting radiofrequency (RF) cryomodules to be tested for the former LEP and the present LHC accelerator a RF test facility was erected early in the 1990’s in the largest cryogenic test facility at CERN located at Point 18. This facility consisted of four vertical test stands for single cavities and originally one and then two horizontal test benches for RF cryomodules operating at 4.5 K in saturated helium. CERN is presently working on the upgrade of its accelerator infrastructure, which requires new superconducting cavities operating below 2 K in saturated superfluid helium. Consequently, the RF test facility has been renewed in order to allow efficient cavity and cryomodule tests in superfluid helium and to improve its thermal performances. The new RF test facility is described and its performances are presented.

Keywords: Cryogenic transfer line, Test Facility, SRF.

INTRODUCTION

The 7200 m² floor-space hall (SM18) at Point 18 was converted to the 1990’s in a large cryogenic test area for the tests of the main cryogenic components of the accelerators. It started early in the 1990’s with the installation of a large test facility for the series testing of superconducting radio-frequency (SRF) cavities and cryomodules devoted to the LEP collider upgrade (100 GeV per beam). The test facility consisted of 6 vertical test stands for single SRF cavities and one horizontal test stand hosted in a bunker for the SRF cryomodules. They were designed to operate at 4.5 K, with exceptional decrease in temperature down to 2.5 K. After the completion of the LEP upgrade in 1996, two vertical test stands were dismantled and transformed to an additional horizontal test stand. The SRF test facility was thenceforward mainly used for testing the LHC SRF cavities and cryomodules. Since then CERN has completed the cryogenic infrastructure of the SM18 with additional test facilities dedicated to the testing of cryogenic equipment for the LHC and its high-field superconducting magnets operating below 1.9 K [2] and also in view of a forthcoming LHC upgrade [3]. But no update or refurbishment was performed on the SRF test facility. The upgrade projects of CERN accelerator complex requires new types of accelerating cavities among which SRF cavities operating below 2 K in saturated superfluid helium. Consequently, the present SRF test facility needed to be upgraded in order to allow efficient SRF cavity and cryomodule tests in superfluid helium and to improve its thermal performances.

LAYOUT AND FORMER SRF TEST FACILITY DESCRIPTION

The present cryogenic infrastructure of the SM18 hall relies on a 6 kW @ 4.5 K helium refrigerator [1] coupled to a 25 m³ liquid helium reservoir supplying the various test facilities for superconducting magnets and RF cavities, and two low-pressure pumping units [2]. The SRF test facility (Figure 1) consists of two horizontal bunkers M7 and M9 to test cryomodules up to 8 m length, and four vertical test cryostats (V3 to V6) to test individual cavities. The test cryostats are placed in pits and encapsulated with moveable concrete walls (mobile bunkers) for radiation protection. The high power RF equipment is placed in between the horizontal test stands or bunkers. The SRF test facility and its six test stands were connected to the liquid helium (LHe) reservoir and the refrigerator via three independent vacuum insulated transfer lines (Figure 2) : a supply saturated liquid helium line (P=1.6 bar), a cold gaseous helium (GHe) return line (T<80 K) and a warm gaseous helium return line (T>80 K). Each test stand was connected to each header via 3 single flexible transfer lines each including an in-line control valve. The operation of this infrastructure allowed purging of the cryostats, cool-down with saturated liquid helium, filling and refilling of the cryostats with liquid helium and warm-up with electrical heaters or by using the static heat load of the cryomodules. Pumping the helium bath to reach lower temperatures was realized sequentially by an additional vacuum pump station behind the common concrete wall in a refill and pump procedure. An alternative was to pump on the helium bath via the warm gaseous helium return line. This enables sub-atmospheric operation below 4.2 K for several hours depending on the overall heat load to the helium bath in the cryostats.
FIGURE 1. Layout of the SRF Test Facility.

FIGURE 2. Old Flow Scheme of the SRF Test Facility.

DESIGN OF THE NEW CRYOGENIC INFRASTRUCTURE

Requirements for the New Test Stands

In 2010 a functional specification for an upgrade of the CERN SRF test facility was issued [4]. It was based on the forthcoming projects requiring SRF cavities and internal reviews. The new layout focused on the SRF assembling facilities and is presented in reference [5]. The upgrade of the cryogenic infrastructure is driven by the operational needs of the associated forthcoming RF tests. The corresponding operation parameters and requirements for the six SRF test stands are summarized in Table 1.

TABLE 1. Operation parameters and requirements for the six SRF test stands

<table>
<thead>
<tr>
<th>Unit</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
<th>M9</th>
<th>M7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projects</td>
<td>SPL LHC Crab¹</td>
<td>SPL R&amp;D²</td>
<td>HIE-ISOLDE</td>
<td>LHC Spares</td>
<td>HIE-ISOLDE</td>
<td>SPL LHC Crab¹</td>
</tr>
<tr>
<td>Nominal operation</td>
<td>K</td>
<td>2</td>
<td>2</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Nominal heat load</td>
<td>W</td>
<td>92</td>
<td>92</td>
<td>15</td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>LHe inventory</td>
<td>Liter</td>
<td>2500</td>
<td>1500</td>
<td>100</td>
<td>2500</td>
<td>320</td>
</tr>
</tbody>
</table>

The test stands M7, V3 and V4 are dedicated to operate with saturated superfluid helium in continuous mode, whereas the sub-atmospheric operation will be occasional for the test stands M9, V5 and V6.

¹ The final operating temperature of the LHC Crab cavities is not yet confirmed.
² V4 test stand is used for research and development (R&D) program and to test specially designed cavity like quadrupole resonators.
Flow Scheme

General Distribution Flow Scheme

In order to meet the requirements of Table 1 and to allow a full flexibility in the future, each test stand has been equipped with a standardized service module permitting an independent and continuous operation at 4.5 K with normal saturated liquid helium or below 2 K with saturated superfluid helium (Figure 3). The three former vacuum insulated transfer lines have been replaced by a vacuum insulated combined cryogenic line (cryoline) comprising an additional gaseous very low pressure line (GHe Pumping VLP) connected to the low-pressure pumping units of the general infrastructure. To ensure a reliable, safe and continuous operation in sub-atmospheric conditions the vertical test stands V3 and V4 have been replaced with new redesigned cryostats permanently connected to their associated service module. As there are no more flexible cryogenic lines to be connected to the upper flange, it allows an easier and more reliable operation of these two cryostats.

FIGURE 3. General Flow Scheme of the Cryogenic Distribution

Test Stand Generic Flow Scheme

Each test stand includes a standard service module connected to the cryoline which allows independent operation of all the various required operating modes like purging, cool down, nominal operation with saturated liquid or superfluid helium, and warming-up. To this extent and for the handling of concurrent test phases, the necessary instrumentation and the bypass valves CV3 and CV4 to the two gaseous return lines of the cryoline have been integrated (Figure 4).

In order to cope with the unavoidable heat inleak to the helium supply line which increases the vapor fraction of the supplied helium, the service module comprises a phase separator (PS) to guarantee the liquid supply into the cryostat of each test stand. In the case of the sub-atmospheric operation a counter-flow heat exchanger (HX) allows an effective sub-cooling of the incoming liquid helium before the Joule-Thomson valve CV7 expands the helium to the saturation condition of the chosen temperature level. Additionally a bypass valve CV6 allows transferring high mass flows of liquid helium to cool down and fill the cryostat.

To deal with the sub-atmospheric operation conditions and the associated risks of atmosphere to helium leaks, the associated instruments have been collected and placed in a vessel (helium guard) where the pressure is monitored and kept slightly above atmospheric pressure. In addition, each helium circuit interface with the cryoline includes two isolation valves in series.

Figure 4 shows the flow scheme of a vertical test stand equipped with the interface to one of the new test cryostats (V3 or V4). For V5 and V6 that re-use the old cryostats equipped with bayonet interfaces, flexible vacuum insulated transfer lines have been accommodated to replace the rigid connection. The interface for the M7 and M9 test stands are still under study in parallel with the various cryomodules.
Design

In addition to the low heat inleak requirements for cryogenic distribution systems the design had to take into consideration two other constraints:

- all the work concerning the upgrade had to fit into a two-month exceptional shutdown period of the SRF test facility at the end of 2012;
- no major civil engineering modification of the present layout was allowed.

To satisfy the first requirement, emphasis was made in the design to produce a maximum of prefabricated subassemblies leading to the minimum of interconnecting works during the final assembly.

Cryoline

In order to reduce the heat inleak due to the thermal radiation and to allow a more compact design in order to fit into the trench diameter, the three former independent vacuum insulated transfer lines have been replaced by a vacuum insulated combined cryogenic line where the liquid helium supply pipe is shielded by an aluminum profile cooled by the cold gaseous GHe return line (Figure 5).

Special mobile supporting systems have been accommodated inside the cryoline in order to cope with the different operation modes and the associated thermal shrinkages of the inner pipes which need to move independently from each other. The LHe supply pipe is wrapped with 10 layers of multilayer insulation (MLI) and the aluminum profile of the thermal shield with 30 layers. The GHe Pumping VLP pipe is wrapped with 15 layers of MLI while the warm GHe return pipe is left without MLI.

The total length of the cryoline is about 60 m. In the neighboring of the 25,000 liter Dewar the cryoline is split into four independent vacuum insulated transfer lines connected to the general infrastructure. These lines are only a few meters long except the GHe pumping VLP line which has an additional length of 40 m.

To design the LHe supply and GHe return lines the maximum liquefaction flow delivered by the refrigerator has been considered (25 g/s). To design the pumping VLP line the maximum pumping capacity (18 g/s at 30 mbar) of one pumping unit has been taken into account. For an average temperature and pressure of 5 K and 25 mbar respectively, the pressure drop of the pumping VLP line is estimated at 4 mbar.
Service Module

One of the major challenges in the design of the service module was that it had to fit into a reduced volume compatible with the mobile bunkers. A solution has been found with a cross-shape design based on a standard DN350 pipe fixed against the rear of the bunker wall (Figure 6.b). The phase separator is located in the top part and the heat exchanger in the bottom part. A vacuum barrier is accommodated between the cryoline and the service module.

The design was not only focused on the compactness of the service module but had also to take into account the continuous operation mode at 2 K with saturated superfluid helium and to include some margin on the refrigeration capacity. In agreement with the reference [4] a minimum refrigeration capacity of 100 W @ 2 K was defined. In the final design, the pressure drop of the GHe pumping VLP circuit in the service module is estimated at 8 mbar for a flow of 10 g/s at an average temperature of 4 K and pressure of 25 mbar, which results in a refrigeration capacity of 230 W @ 2 K.

New Test Cryostat for Saturated Superfluid Helium Operation

For the continuous operation in saturated superfluid helium of the V3 and V4 test stands, two new test cryostats were purchased. As the size of the cavities can vary significantly one of the cryostats (V4) was designed shorter in order to conserve helium volume when not needed. The main design requirements for these new cryostats have been defined in order to optimize the heat inleaks with respect to the operating conditions: they are equipped with an actively cooled thermal shield insulated from the inner vessel and a ring welded to the inner vessel to intercept the conduction heat loads from the upper flange. This ring acts as a gas heat exchanger and is connected in series with the inlet of the thermal shield circuit. Additionally the cryostats can be fed by the top or the bottom inlet. As these cryostats will be operated at a sub-atmospheric pressure, the top flange is equipped with a double O-ring joint and the interspace fed with gas helium slightly above atmospheric pressure. The schematic layout is presented in Figure 6.a and the design parameters in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner useful diameter</td>
<td>m</td>
<td>1.1</td>
</tr>
<tr>
<td>Useful height long cryostat (V3)</td>
<td>m</td>
<td>4.2</td>
</tr>
<tr>
<td>Useful height short cryostat (V4)</td>
<td>m</td>
<td>2.6</td>
</tr>
<tr>
<td>Thermal shield circuit maximum pressure</td>
<td>bar</td>
<td>5</td>
</tr>
<tr>
<td>Inner vessel maximum pressure</td>
<td>bar</td>
<td>3.5</td>
</tr>
<tr>
<td>Max heat load to shield circuit @ 50 K</td>
<td>W</td>
<td>20</td>
</tr>
<tr>
<td>Max heat load to inner vessel @ 2 K</td>
<td>W</td>
<td>2</td>
</tr>
</tbody>
</table>

Abstraction made from heat loads due to the top plate.
CRYOLINE THERMAL PERFORMANCE TEST

Measurement Setup

In 2009 a thermal performance measurement of the former cryogenic distribution system was executed. A heat load corresponding to 7.5 g/s was measured on the LHe supply line when operated up to the V4 test stand (reference [6]).

The farthest service module M7 has been used to characterize the cryogenic performance of the cryoline by measuring the heat inleak into the saturated LHe supply line and the cold GHe return line (Figure 7). The return line acts as an actively cooled thermal radiation shield of the liquid supply line.

To measure the heat inleak into the liquid supply line, liquid helium is taken from the main 25 m³ helium Dewar at saturation condition. The helium evaporates partly on the way towards the service module M7 and arrives in two-phase flow conditions in the phase separator PS of M7. The overall heat inleak is determined by keeping the liquid level in this phase separator constant. In doing so, the enthalpy difference between the saturation liquid condition in the main Dewar \( h_{\text{in}} (p_{\text{Dewar}}) \) and the saturation vapor condition in the service module phase separator \( h_{\text{out}} (p_{\text{PS}}) \) multiplied with the mass flow rate results in the overall heat inleak into the supply chain. This liquid helium supply chain consists of the following parts shown in Table 3 that are integrally measured during this test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension/number</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction pipe from 25 m³ Dewar</td>
<td>2 m</td>
<td>30 layers of MLI</td>
</tr>
<tr>
<td>Cryogenic control valve CV10</td>
<td>1</td>
<td>Estimated heat load 1 W</td>
</tr>
<tr>
<td>Bayonet (600 mm long)</td>
<td>2</td>
<td>Estimated heat load 2.51 W each</td>
</tr>
<tr>
<td>Saturated LHe supply Dewar - cryoline connection</td>
<td>4.5 m</td>
<td>30 layers MLI. Independent partly flexible vacuum insulated transfer line (no active shield)</td>
</tr>
<tr>
<td>Saturated LHe supply pipe (cryoline)</td>
<td>60 m</td>
<td>10 layers MLI + aluminum shield + 30 layers MLI</td>
</tr>
<tr>
<td>Vacuum barrier</td>
<td>1</td>
<td>Length of the extension pipe 600 mm</td>
</tr>
<tr>
<td>Inlet cryogenic control valve CV1</td>
<td>1</td>
<td>Estimated heat load 0.8 W</td>
</tr>
<tr>
<td>Service module piping</td>
<td>2.4 m</td>
<td>30 layers MLI</td>
</tr>
<tr>
<td>Phase separator in M7</td>
<td>0.012 m³</td>
<td>30 layers MLI, partly actively shielded, add. Level gauge + connection.</td>
</tr>
<tr>
<td>GHe return T &lt; 80 K cryoline - refrigerator connection</td>
<td>10 m</td>
<td>30 layers MLI. Independent partly flexible vacuum insulated transfer line including one bayonet.</td>
</tr>
</tbody>
</table>
FIGURE 7. Schematic of the set-up of the cryoline performance measurement. The saturated liquid is taken from the 25 m³ Dewar under controlled flow rate conditions towards the phase separator PS. The level LT is kept constant. The return cold gas flow temperature (TT1) is adjusted in the service module and actively cools the thermal shield. The return flow outlet temperature is measured with TT3. The mass flow rate is measured at ambient temperature conditions after the heater EH2.

The calculation of the heat inleak is dependent on the saturation pressure in the Dewar (saturated liquid at the inlet of the transfer line) and in the PS (saturated vapor at the outlet). The respective enthalpy values are taken from the Hepak® program. To measure the mass flow as precise as possible an ambient temperature gas mass flow meter FI from Hastings® is chosen and calibrated in the expected flow range of 0-3 g/s for helium at 295 K. The return flow is connected to the helium recovery system of the cryogenic infrastructure.

To check the influence of the thermal shield temperature the saturated vapor flow at the outlet of the PS is adjusted using a special designed heater cartridge EH1 that controls in this way the inlet temperature of the cold gas return flow. The respective temperature of the GHe return pipe is calculated as the average value of the inlet and the outlet of the GHe return line connected to the general infrastructure via a vacuum insulated transfer line \( \left( T_{\text{shield}} = (T_{T1} + T_{T3})/2 \right) \). The temperature is measured with PT100 sensors class B/10 and the resistance offset between the sensors is compensated at liquid nitrogen temperature around 80 K beforehand.

The measurement accuracy is estimated for the saturated LHe supply line and the GHe return line, separately. For the LHe supply line, measurements include both saturation pressures and the mass flow rate. Typical values of the saturation pressures are 1.6 bar absolute (PT10) and 1.05 bar absolute in the PS (PT1). The measurement range of both pressure sensors is 4 bar absolute with a combined measurement error of \( \pm 0.04 \) % of full scale (FS) and the sum of the relative, long term stability and temperature errors of \( \pm 0.175 \) % FS. This results in a total accuracy of \( \pm 8.6 \) mbar for each sensor.

The accuracy of the mass flow meter is stated to be \( \pm 0.63 \) % FS with a full scale of 6.4 g/s, which results in a total deviation of \( \pm 40 \) mg/s. Additionally, temperature influences are considered with \( \pm 0.035 \) %/K FS plus \( \pm 0.05 \) %/K Rdg. and a repeatability accuracy of \( \pm 0.05 \) % FS. The overall measurement accuracy is estimated as \( \pm 68 \) mg/s. The reached measurement accuracy for the heat inleak of the saturated LHe supply line is \( \Delta Q/Q_{\text{LHe}} = \pm 3.6 \) %.

The measurement deviation for the GHe return line considers the deviation of the mass flow meter and the errors of the differential measurement of the temperature at the inlet (sensor TT1) and the outlet flow temperature (sensor TT3), compare Figure 7. Respecting the comparison of the temperature sensors the accuracy of the temperature difference measurement is estimated to be \( \pm 2 \) K in the temperature range between 30 K and 80 K. Including the deviation of the mass flow measurement the overall accuracy for the heat inleak of the GHe return pipe is estimated to \( \Delta Q/Q_{\text{shield}} = \pm 12.7 \) %.

Results and Discussion of the Heat Inleak Measurement

Two different tests are carried out in different time spans and after the cooldown of the line. Figure 8 summarizes the resulting heat loads. First in the short-term test, the cryoline was cooled to liquid level condition in the phase separator and 30 K return inlet temperature (TT1) and kept running over 5 hours. During the following 4 hours the test has been performed at three different successive GHe return line inlet temperatures 30 K, 40 K and 50 K. The total timespan in which the transfer line has been cooled to liquid inlet conditions is 9 hours. The overall heat inleak into the liquid supply chain for TT1=50 K is 43.7 W (2.54 g/s) and for the GHe
return line is 214 W. The heat inleak into the liquid supply line also drops slightly, which indicates that the thermal equilibrium of the whole transfer line is not reached after 9 hours of cold operation.

Second a long-term cold run has been performed to measure the inleak in case the cryoline is kept cold (liquid conditions in the supply line and TT1 = 30 K for 7 days). The overall heat load to the liquid supply chain is then 23.5 W (1.36 g/s) and 256 W for the GHe return line.

These figures can be used to define the best strategy of operation of the SRF test facility with respect to the great variety of measurement tasks and the global energy consumption of the whole SM18 infrastructure.

**FIGURE 8.** Short- and long-term performance test of the cryoline. The overall cold time at liquid conditions in the supply chain is 9 hours (short term) and 7 days (long term). Values at the x-axis correspond to the average temperature of the GHe return pipe (shield) between the inlet and the outlet temperature.

**CONCLUSION**

The cryogenic infrastructure of the SRF test facility has been redesigned in order to allow optimum testing capacity and flexibility with respect to the test program based on the forthcoming and various projects requiring SRF cavities. Each test stand can be operated independently and continuously with normal saturated liquid helium or below 2 K with saturated superfluid helium. The thermal performances of the distribution system have been measured and improved by a factor 5.5.

**ACKNOWLEDGMENTS**

The authors would like to express their warmest thanks to the industrial support in charge of the manufacturing and installation of the new equipment at CERN, and particularly to J. Mouleyre and N. Veillet who designed and supervised technically the entire project.

**REFERENCES**

6. V. Benda (private communication, 2009).