Design, Procurement, Installation and Commissioning of the Cryogenic Infrastructure for a New Superconducting RF Test Facility with Beam at CERN

L Delprat, K Brodzinski, S Claudet, H Derking
CERN, Technology Department, Cryogenics Group, 1211 Geneva 23, Switzerland

Laurent.Delprat@cern.ch

Abstract. The High-Luminosity LHC project (HL-LHC), aiming at peak luminosity above $5.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, considers replacing the matching sections on both sides of the ATLAS and CMS experiments. To complement new focusing quadrupoles, this upgrade considers using the so-called superconducting crab cavities, never operated before with protons and therefore requiring qualification with beam. To this aim, a new cryogenic infrastructure for a superconducting RF test facility was initiated and recently installed at CERN SPS accelerator in 2018. From the early studies of heat load and design principles to the successful tests passed during late 2018, this paper describes the main cryogenic requirements for such a test facility, its design challenges, procurement, installation, and commissioning up to stable operation of the crab cavities module in superfluid helium at 2 K.

1. Introduction
In the frame of the High-Luminosity LHC project (HL-LHC), significant increase in the average luminosity is foreseen to around $5.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. To fulfill this objective, the cryogenic infrastructure for the magnets cooling will have to be adapted along several lines.

In particular, this significant upgrade will go through exploiting new inner triplets at interaction regions 1 and 5 around the ATLAS and CMS experiments.

To complement new focusing quadrupoles, this upgrade considers using the so-called superconducting crab cavities, never operated so far with protons and therefore requiring qualification with beam. To this aim, a new cryogenic infrastructure for a superconducting RF test facility was initiated and recently installed at CERN SPS accelerator in 2018 [1].

2. Design principles and key features
As the CERN SPS was not housing any cryogenic equipment as per conception, one completely new cryogenic facility had to be designed, ordered and installed in order to provide the necessary cooling power for the crab cavities to be tested at point 6 of the SPS. Figure 1 shows a view of this new cryogenic test facility.

This cryogenic facility consists of three main sub-systems complemented by cryogen storage tanks, which were procured separately from each other: the movable helium cryoplant @ 4.5 K, the cryogenic distribution system and the 2 K cryogenic sub-system together with its user interface.
2.1. Design of the 4.5 K cryoplant

The helium cryoplant is required to provide the necessary cooling capacity for the crab cavities at all temperature levels between ambient and 4.5 K. The cold box was designed to be movable: intended to work in SPS BA6 to allow cool down of the crab cavities cryo module during LHC beam runs and also to be operating for LHC point 4 Radio-Frequency Cavities (“RF cavities”) during LHC Long Shutdowns (“LS”). For this reason, it is designed for operation in liquefaction and refrigeration modes, as the SPS BA6 configuration is requiring a quasi-full liquefaction operation, whereas the LHC point 4 configuration requires refrigeration duty. Figure 2 shows the swap from liquefier mode to refrigerator mode for the helium cryoplant.
While the compressor station is installed at surface level, the cold box is located in a 60-meter depth underground cavern, at the same altitude as the final user – the crab cavities cryomodule – located inside the accelerator with two available positions, on-beam and off-beam.

The cryoplant was designed to be easily dismounted, transported without damage and re-installed in another location within five man-days. This requirement led to a two-skid design for the compressor station, based on iso-frame shapes to ease the handling and transportation phases, as shown on Figure 3. It also induced the regrouping of all interfaces to one location per skid.

Similarly, the cold box design was driven by four major constraints: timeframe of the supply, guarantee of the required performance for both liquefaction and refrigeration operation modes, accessibility of the installation location and movability requirement. This led to the choice for industrial standard products (including turn key control system) from Linde Kryotechnik AG® – supplier of the cryoplant – and added specific features inherent to the project constraints. In order to ensure the required performances, the cold box was designed on the basis of a LR280 refrigerator, with liquid nitrogen precooling and the possibility to swap turbines depending on the considered operation mode. The movability requirement was tackled by the implementation of a specific transportation frame attached to the cold box unit, together with heat exchanger fixation inside the vacuum chamber. The design criteria of tilting the cold box by 90° was directly driven by the dimensions of the access door of the installation location. Figure 4 hereafter shows final drawings of the cold box and a view of its handling during installation phase.
For the SPS BA6 installation operating in liquefier mode with corresponding turbines, the cryoplant can provide up to 7 g/s of liquid helium at 4.5 K (with permanent use of liquid nitrogen), while supplying 750 W of cooling capacity between 50 K and 80 K.

For the LHC point 4 and the refrigerator mode, the cryoplant can provide up to 700 W at 4.5 K of refrigeration duty, while supplying 300 W of cooling capacity between 50 K and 80 K.

In both cases, the cryoplant delivers supercritical helium at 3 bar abs / 5 K. Liquid helium phase separator for the cold box was supplied together with the cryo distribution system and is dealt with in section 2.2 of this paper.

The cold box process is optimized for a continuous operation with liquid nitrogen precooling, in order to get the most out of the standard LR280 design, as the specified heat loads of the facility are at the limit of the cryoplant capacity operating without precooling. Liquid nitrogen facility used by the cryoplant was also supplied together with the cryo distribution system.

2.2. Cryogenic distribution system
The distribution system is composed mainly of two valve boxes (VB1 and VB2) with 80 m long distribution line in between.

The valve boxes are installed as interfaces to the cryoplant and to the Service Box on the user side. Geographical configuration of the cryogenic test facility with the cryomodule far from the cold box induced the choice of supercritical helium for the refrigerator output, and as a consequence the use of a sub-cooler in VB1 to recondition supercritical helium supply stream. The liquid helium at 4.5 K is produced in VB2 and then sent to the Service Box, where it is sub-cooled upstream J-T expansion valve – see section 2.3.1.

The distribution line is equipped with four main piping inside the vacuum envelope, housing the supercritical helium supply, the gaseous helium return, and the thermal shielding lines between 50 – 80 K needed to minimize losses over its 80-meter length. In addition, bellows free lines technology with thermal compensation centralized at the extremity of straight sections was used to avoid the potential risk of repair above the SPS beam line if needed.

Simplified flow diagram of the cryogenic system including the distribution is shown in Figure 5.

Figure 5. Simplified flow diagram of the cryogenic system in SPS BA6.

2.3. Design of the 2 K cryogenic sub-system and principle of crab-cavities cryomodule cooling
The first user of this new cryogenic infrastructure was a prototype of the crab cavities cryostat. Housing two deflecting cavities, the cryomodule was operated with 2 K saturated superfluid helium bath during
assigned testing period over 2018. The 2 K cryogenic sub-system is composed mainly of three modules: the Service Box, the water bath heater and the helium pumping unit. The principle of 2 K cooling system of the crab cavity cryomodule is presented in Figure 6.

2.3.1. Service Box. The Service Box main function is to provide adapted interfaces between 4.5 K distribution, client cryostat and the helium pumping system. The service box contains cool down and normal operation circuits equipped with flow control valves. The integrated subcooling heat exchanger allows for precooling of the supply helium stream and reduction of the gaseous helium phase produced during final expansion to the client cryostat. Moreover, the Service Box is equipped with safety devices for internal process lines and external envelope. The purge of the cryomodule internal circuits or individual warm up can be done using dedicated circuits of the Service Box.

![Diagram](image)

**Figure 6.** Simplified 2 K cryogenics flow diagram of the crab cavities cryomodule.

2.3.2. Water bath heater and helium pumping system. The return helium stream is warmed up in a water bath heater with a total installed power of 10 kW and pumped using two double stage helium pumping units delivered by Leybold Vacuum.

One pumping unit consists of a roots pump type WS 2001 with air cooled canned motor and a single-stage oil-sealed rotary vane vacuum pump type SV 630 with water cooling system. Both pumping units were recovered from another test stand at CERN and adapted for BA6 infrastructure. The pumping capacity of recovered units was checked prior to installation. The results of measurements are presented in Figure 7.

Considering Leybold design value of 1.3 g/s of flow given at 20 mbar as the suction pressure, pumping unit 1 performance gives 93 % of flow vs design value and pumping unit 2 gives 86 % of flow vs design value. The total real pumping capacity at 20 mbar can reach the value of 2.3 g/s.
Figure 7. Capacity test results for the two pumping units adapted for BA6.

2.3.3. **Cryomodule cooling and heat load – principles.** The helium level in the crab cavity cryomodule is controlled by the supply valve at the middle level of the bi-phase tube (see Figure 6).

The helium saturation pressure is regulated by the variable frequency drive (VFD) installed on roots helium pumps, adapting the pumping speed to the heat load of the cryomodule. According to measurements [2], about 1 g/s of the pumping flow is needed to compensate the static heat load of the cryomodule (18 W) and of the distribution system (that one being measured in the range of 4 W). Expected by design the dynamic heat load is equal to 13 W i.e. it will require additional 0.6 g/s of flow.

2.3.4. **Special requirements for integration.** The main reason for integration of the crab cavities in the SPS accelerator was to perform extended testing of this RF device with the same proton beam as injected to the LHC.

On the other hand, such a test was conducted for the first time, and presence of the cavities was not allowed to interfere with the LHC operation. Considering the above requirements, the cryomodule was installed on a mobile platform allowing for mechanical alignment of the crab cavities with the SPS beam. Displacement of the module out from the beam line allows for bypassing the test cryostat when SPS serves as the LHC injector. Such a solution required using specially designed beam vacuum “Y” chamber connected to the cryomodule and its bypass. The cryogenic Service Box was also installed on the mobile platform rigidly connected with the cryomodule. All other Service Box interfaces were designed as flexible to compensate 0.5 m distance of the platform displacement between two operation positions. Figure 8 presents the principles of the cryomodule and Service Box installation.

Figure 8. Principle of the cryomodule and Service Box integration on a mobile platform in SPS (STL – supply transfer line, RTL – return transfer line, PTL – pumping transfer line).
3. Timeline of procurement and installation

Overall tight planning together with a completely scratch start – initially no cryogenics at all in SPS BA6 – did have a real impact on the timeline. Year 2016 was used for studies focusing on all interfaces and key features to launch procurements. 2017 was dedicated to detailed engineering and the fabrication, with a strict deadline and time-window for the end of the work and strong constraints on the underground and accelerator facilities accessibility during normal operation. The installation was done during Q1 – 2018, while the SPS was in shutdown period. The commissioning started end of Q1 in spring 2018.

3.1. Procurement of the cryogenic test facility

Procurement of the cryogenic test facility was conducted through three main packages: the helium cryoplant, the cryogenic distribution system and the 2 K cryogenic sub-system.

Separately from them, gaseous helium buffers for the compressor station were refurbished and recommissioned from already existing installation at CERN. Liquid nitrogen facility to be used for the helium cryoplant precooling was procured through an independent contract. The cryo-module itself, as the final user, was handled separately as well. In total, 7 different contracts handled in less than 18 months (Q4 2016 to Q1 2018) were necessary to procure this new test facility. Figure 9 shows the main procurement phases for the cryogenic test facility at CERN SPS and related timelines.

| Phase                  | 2016 | 2017 | 2018 | 2019 | 2020 |
|------------------------|------|------|------|------|------|
| Studies & Requirements |      |      |      |      |      |
| Tendering              |      |      |      |      |      |
| Engineering & Fabrication |    |      |      |      |      |
| Installation           |      |      |      |      |      |
| Commissioning          |      |      |      |      |      |
| Operation              |      |      |      |      |      |
| Consolidation          |      |      |      |      |      |

Figure 9. Procurement phases for the cryogenic test facility at CERN SPS.

3.2. Installation of the cryogenic test facility

Major constraint for the installation work was the necessity to access the CERN SPS accelerator area, whereas it is used for physics operation and production almost all along the year. Therefore, some specific time-window – the 2017/2018 winter accelerator shutdown – had to be foreseen to be granted access with no beam. Some of the core infrastructure work (installation of the 80 m cryoline in the SPS tunnel and cabling between surface and underground levels) could be anticipated and realized one year ahead during 2016/2017 winter shutdown. Most of the installation work required close coordination to fit the allocated three-month period from January to March 2018 and was achieved successfully in time thanks to clear interface definition and management as well as excellent availability of both industrial and CERN internal support teams.

4. Commissioning and operation

The very intensive period of activities at BA6 imposed to divide commissioning period into three main phases: test and acceptance of all supplies and basic tuning altogether, to allow first operation phase at 4.5 K to gain experience before operation in 2 K saturated liquid helium conditions and LN\(_2\) storage consolidation.

During 4.5 K operation period control software for 2 K was finalized and issues with liquid nitrogen precooling of the cold box could be identified. The operation with superfluid helium started from September 2018 and was resumed beginning of December 2018. The overview with main milestones of the operating conditions during commissioning period are presented in Figure 10.
Cryoplant was commissioned together with the VB1 and the VB2 using the phase separator of VB1 for cold box stable operation, and circulating through the thermal shielding circuit for turbine string stabilization. Due to severe time constraints, cryoplant was operated only in liquefaction mode, as per installation requirement in SPS. However, turbines were tested and validated in situ in both modes. Required liquefaction capacity for operation of the crab cavities cryomodule at 2 K – 30 mbar abs with beam was successfully delivered by the cryoplant with no particular issue to be reported.

Meanwhile, liquid nitrogen (LN$_2$) facility for cold box precooling was suffering from periodic blockage. A complete warm-up and drying of LN$_2$ storage tank were performed and since then, continuous operation including refill is possible without any problem.

Besides several investigations on RF side, the static heat load of the cryomodule was finally assessed by means of natural boil off method [2]. Knowing the helium volume of the system and emptying time the static heat load of 2 K part was recalculated at 18 W, which is in very good agreement with calculated value of 20.1 W. This result gave more confidence for the design of final HL-LHC cryomodules to be installed in the final configuration in the LHC.

5. Conclusions and perspectives
The complete 2 K cryogenic infrastructure was designed and built from scratch between 2016 and beginning of 2018 in the SPS BA6. The reception test was conducted during Q1 of 2018 with direct operation period afterwards.

First stable operation of crab cavities in liquid helium was successfully achieved in spring 2018 (in superfluid helium from September 2018) thanks to strong collaboration of all involved teams.

Upcoming Long Shutdown 2 period, which started in December 2018, induced the necessary stop of the cryogenic test facility, to allow for required maintenance and consolidations.

Restart of the whole facility, scheduled for the time being during 2020, shall allow for completing performance assessment and further testing of the cavities with proton beams in SPS, pushing the RF related values to nominal operating level.

References
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