Functional analysis and design of the cryogenic system for the HL-LHC IT String test bench at CERN

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Abstract. The High Luminosity LHC (HL-LHC) is a project aiming to upgrade the LHC collider to maintain scientific progress and exploit its full capacity. In the HL-LHC configuration, the Inner Triplet (IT) magnets of the present LHC will be replaced by a new set of higher performance magnets. The collective behaviour of the new magnets and the related systems will be studied and validated in a dedicated cryogenic test facility, the IT String, currently under construction. This paper presents the results of the functional analysis performed to design the cryogenic system for the IT String. The required operation modes are identified and detailed together with the operational parameters and constraints used to define the cryogenic system. The layout of the cryogenic distribution system that fulfils the requirements of the IT String is presented and the characteristics of the main components are described.

1. Introduction

The High Luminosity Large Hadron Collider (HL-LHC) project aims at increasing by a factor five the luminosity available for the ATLAS and CMS experiments starting from 2025 [1]. In the framework of the project, the Inner Triplet (IT) magnets providing the final focusing of the proton beams at Interaction Regions (IR) 1 (ATLAS) and 5 (CMS) will be replaced with new larger aperture magnets [2]. The IT includes four Nb_3Sn quadrupoles (Q1, Q2a, Q2b and Q3), a recombination/separation dipole (D1) and several corrector magnets (CP) operating in pressurized (1.3 bar) He II at 1.9 K. To validate the design and assess the collective performance of the HL-LHC IT, a string of magnets (the HL-LHC IT String), will be installed in the SM18 cryogenic test facility at CERN [3].

In this paper, we present the requirements and the functional analysis performed to design the HL-LHC IT String cryogenic system. The IT String cryogenic system shall reproduce as far as possible the operating conditions of the magnets in the LHC tunnel, while integrating in the cryogenic infrastructure of the SM18 test hall. Existing equipment is to be re-used as far as possible to optimize project resources and schedule.

2. The HL-LHC IT String

2.1. Magnets and Cold Powering system

The IT String includes six magnets (Q1, Q2a, Q2b, Q3, CP and D1) housed in interconnected cryostats sharing a common He II bath at 1.9 K and a common vacuum vessel. The assembly has an overall length of about 60 m, a mass of about 120 tons and contains 1.5 m^3 of helium. As in the LHC, the heat load to the magnets is removed by conduction with a bayonet copper heat exchanger (HX) installed through all the magnets. To cope with the higher heat load expected in the HL-LHC magnets (up to 1.3 kW mostly due to particle collisions), each cold mass in the IT String will be equipped with a 70 mm diameter double bayonet HX. A detailed description of the magnet cryostat is found in [4].

In the LHC tunnel, the IT magnets will be remotely powered from power converters and current leads located in new underground areas excavated for the HL-LHC project through a Cold Powering system [5]. This is composed of:

- The DFX cryostat at the magnet connection side;
- A 100 m long superconducting (SC) link (DSHX) with an MgB_2 superconducting cable with a maximum operating temperature of 25 K;
- The DFHX cryostat at the current leads connection side;
- The current leads with current rating in the range 2 – 18 kA.

The superconducting splices between the NbTi busbars and the SC link are in a LHe bath in the DFX. The mass flow for cooling the SC link is generated by evaporating the LHe bath in the DFX.

The magnets and Cold Powering system are shown in the block diagram of the IT String cryogenic system in Figure 1 and in more detail in the IT String process flow diagram in Figure 2.

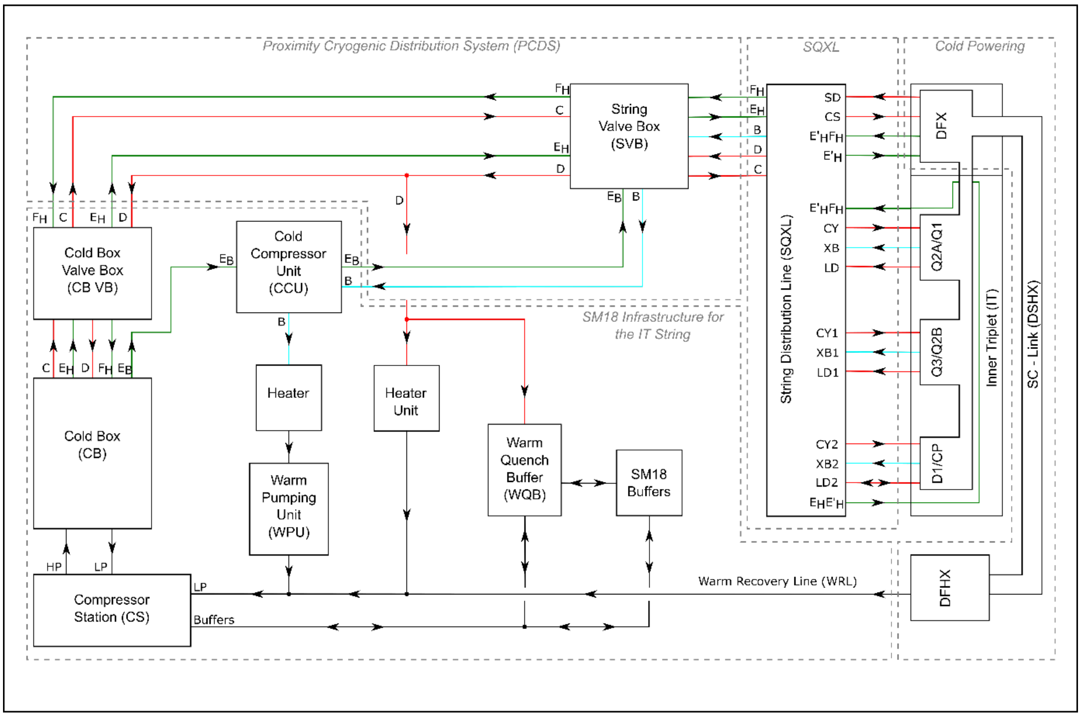

Figure 1. Block diagram of the cryogenic system for the IT String.

2.2. Operation modes and requirements of the cryogenic system

The main operation modes of the IT String and the corresponding requirements for the cryogenic system are summarized in Table 1. Additionally, the IT String cryogenic system shall:

- Supply up to 10 g/s of LHe to the Cold Powering system in nominal operating conditions;
- Supply up to 26 g/s of LHe for the bayonet HX test;
- Provide up to 26 g/s of low-pressure pumping capacity @ 1.9 K for the bayonet HX test;
- Provide a thermal shield circuit with temperature in the range 50 – 75 K;
- Recover the room temperature gas from the outlet of the current leads;
- Not interfere with the operation of the other cryogenic test benches in the SM18 test hall.

3. Functional analysis of the IT String cryogenic system

Following the outline of the architecture of the IT String cryogenic system shown in [6], a detailed study of the required operation modes was performed to validate the proposed layout and to size the different components.

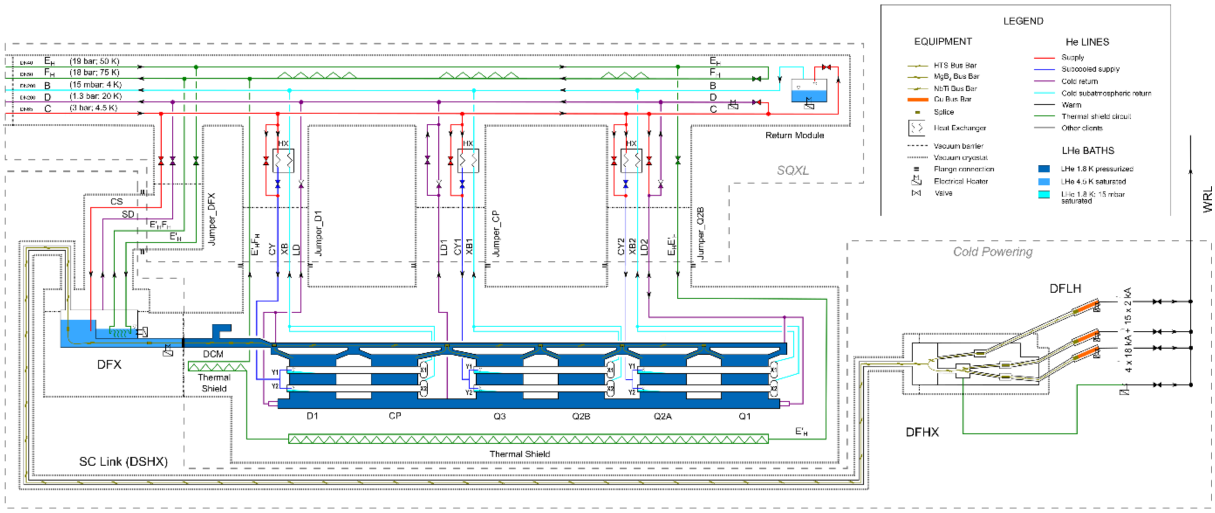

Figure 2. Process Flow Diagram of the IT String.

Table 1. IT String operation modes and requirements for the cryogenic system.

Operation mode	Requirements
Cool down 293 K - 4.5 K	Max. duration: 15 days Max. temperature gradient over the string of magnets: 30 K
Magnet filling & cool down 4.5 K - 1.9 K	Max. duration: 40 hours
Steady state	Static heat load to cold masses at 1.9 K: 140 W
Current ramping	Additional dynamic heat load to cold masses 1.9 K: 350 W
Bayonet HX test	Extract up to 500 W per each double bayonet HX
Quench	Limit the pressure increase in the magnet cryostat Recover the helium expelled from the magnet cryostat
Quench recovery	Recover nominal operating conditions in max.12 hours
Warm up 4.5 K – 293 K	Max. duration: 15 days Max. temperature gradient over the string of magnets: 30 K

3.1. Cool down from 293 K to 1.9 K

The cool down of the IT String from room temperature to 4.5 K is performed with an existing helium cryogenic plant with a nominal refrigeration capacity of 6 kW @ 4.5 K and a maximum liquefaction capacity of 25 g/s.

The cold GHe supplied by the cold box is circulated via line C, it enters the magnet cryostat via line LD2 to exit at the opposite end of the String through line LD and returns to the cold box via line D. Circulation through the thermal shield is started when the cold mass temperature reaches 50 K. No circulation of cold GHe in the Cold Powering system is foreseen during the initial cool down phase.

Cool down of the 84.2 tons cold mass from room temperature to 4.5 K with a maximum GHe mass flow of 100 g/s requires 8.5 days (see Figure 3) and results in a maximum temperature gradient over the String of magnets of less than 23 K.

The cold box available in the SM18 hall for the usage of the IT String is equipped with a LN_2 pre-cooling system. However, the study shows that LN_2 pre-cooling is not required to meet the target of cooling the IT String from 293 K to 4.5 K in less than 15 days.

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The next cool down phase consists in the filling of the magnet cryostat with LHe. The saturated GHe initially in the cryostat is progressively condensed by extracting heat via the bayonet HXs. As the GHe turns to liquid, the pressure in the cryostat decreases below the set value of 1.3 bar, which triggers the opening of the LHe supply valve.

The magnet filling phase relies on the 25 g/s liquefaction capacity of the cold box, which is shared between the bayonet HXs and the magnet cryostat. The optimal mass flow distribution between the two is independent of the initial level of LHe in the cryostat and corresponds to 20 g/s for filling the cryostat and 5 g/s for pumping. Assuming conservatively that the 1.5 m^3 cryostat is initially full of saturated GHe at 4.5 K, the filling of the IT String magnets requires 2 hours.

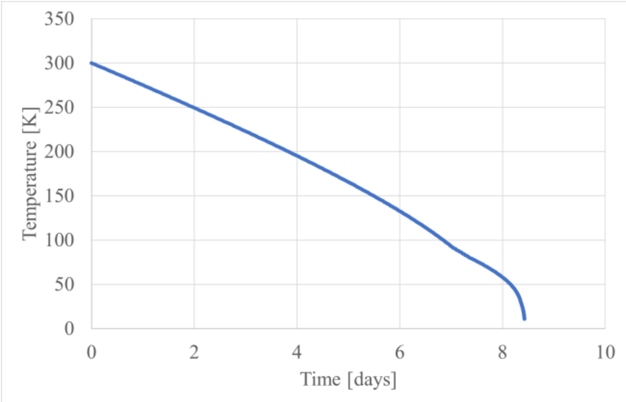

Figure 3. Cool down time of the IT String magnet from room temperature to 4.5 K.

In the final phase of cool down, the cold mass temperature is further lowered from 4.5 K to the nominal operating value of 1.9 K by pumping on the bayonet heat exchangers. The cool down speed is limited by the available pumping capacity for the IT String in SM18, which corresponds to the maximum mass flow of a single Warm Pumping Unit (WPU). Although the SM18 cryogenic infrastructure has two WPUs, each with a pumping capacity of 18 g/s at 30 mbar, only one of them will be permanently dedicated to the IT String. The second WPU will be shared among the other SM18 cryogenic test benches. With this constraint, the cool down from 4.5 K to 1.9 K requires 2.3 hours. During this phase, a LHe mass flow of about 6.6 g/s is needed to re-fill the cryostat. The total LHe mass flow required during the cool down from 4.5 K to 1.9 K does not exceed the cold box liquefaction capacity of 25 g/s.

The analysis shows that the existing cryogenic infrastructure in the SM18 hall allows to cool down the IT String magnets from 293 K to 1.9 K in less than 9 days.

3.2. Steady state and current ramping

In steady state conditions the estimated heat load to be removed by the IT String cryogenic system is 140 W, corresponding to a pumping capacity of about 7 g/s that could be provided by a single WPU at an inlet pressure of 12 mbar.

During current ramping, the total heat load on the cryogenic system increases to almost 350 W mostly due to the large hysteresis losses in the Nb_3Sn magnets amounting to 6.6 W/m [7]. The pumping capacity required to cope with the dynamic heat load is nearly 18 g/s, corresponding to the maximum flow of a WPU at 30 mbar suction pressure. Considering the pressure drop along the 90 m-long pumping line and the estimated power dissipation the cold mass temperature would exceed 2 K during the current ramp.

To keep the magnet temperature at the nominal value of 1.9 K during current ramps, it is planned to use a cold compressor unit with a capacity of 18 g/s at 10 mbar suction pressure. Operation of a cold compressor requires the inlet gas having a maximum temperature of about 5 K, which implies that the pumping line (line B in Figure 1) must have an actively cooled shield.

3.3. Bayonet HX test

The bayonet HX test goal is to validate the heat removal capacity of the double bayonet heat exchangers. During the test, up to 500 W shall be removed by a double bayonet heat exchanger, which corresponds to a pumping capacity of 26 g/s. Since the pumping capacity of a single WPU is limited to 18 g/s, both WPUs available in the SM18 hall will be needed for the test. This will interfere with the operation of the other SM18 test benches requiring low pressure pumping. However, since the test is expected to last a couple of days, the disruption is compatible with the expected test program of the other test benches.

The mass flow needed for the bayonet HX test (26 g/s) exceeds the nominal liquefaction capacity (25 g/s) of the cold box dedicated to the IT String. The liquefaction capacity of the cold box can be temporarily boosted by supplying a cold (4.5 K) GHe mass flow to the Low Pressure (LP) line of the cold box. The cold flow can be generated by evaporating part of the liquid helium stored in the 25 000 l dewar, connected to both the helium cryo-plant supplying the IT String and the recently installed 35 g/s cold box supplying the other SM18 cryogenic test benches. The heater installed in the 25 000 l dewar allows the generation of up to 40 g/s of GHe at 4.5 K. More details about the SM18 cryogenic infrastructure can be found in [8].

3.4. Quench

During a quench, up to 39.1 MJ of energy initially stored in the magnetic field are dumped into the He bath [9]. The pressure increase in the magnet cryostat is limited below the design pressure of 20 bar by three quench relief valves located on quench lines LD, LD1 and LD2 that release the expanding helium to line D.

Line D (GHe return to the cold box) has an overall volume of about 2 m^3 and, during quenches, effectively acts as a cold quench buffer. A large cold buffer volume is useful to boost the cold box liquefaction capacity if sufficient liquid or cold gas at 4.5 K can be recuperated during the quench, that is, if significant amounts of liquid is expelled from the magnet cryostat and can then be evaporated. This was the case of the String 2 of LHC, which included a 2 m^3 cold quench buffer in addition to the buffering volume of line D [10].

To assess the need of an additional cold quench buffer for the IT String, a 1-D thermohydraulic model of the quench recovery system detailed in [9] was developed. In the analysis the magnet cryostat is modelled as two connected volumes corresponding to magnets Q1 to Q3 and CP and D1, respectively. Since more than 90% of the quench energy is released by magnets Q1 to Q3, the full quench energy is released into the cryostat volume Q1 to Q3 for the sake of the simulation. Conservatively, it is assumed that the quench relief occurs only through the quench valve on line LD connected to the CP and D1 volume. The simulation shows that a maximum of 34 kg of LHe would be expelled to line D during a quench. Given the small amount of helium that could be potentially used to boost the following quench recovery phase, the option of adding a cold quench buffer to the IT String cryogenic system has been discarded.

The maximum pressure in line D will be limited to 10 bar, which is achieved by releasing the gas from line D into a Warm Quench Buffer (WQB) with a volume of 80 m^3 initially at room temperature. Since the WQB is made of carbon steel, its minimum operating temperature is limited to –30°C. A 150 m long non-vacuum insulated quench recovery line is used to connect line D to the WQB, which allows to heat up the cold helium so that the WQB wall temperature does not decrease below the allowed limit during a quench. A detailed discussion and validation of the sizing of the IT String quench recovery system, including the assessment of the mechanical integrity of the WQB, is presented in [9].

The present operation strategy foresees that during a quench the cold box is isolated from the IT String and switches from liquefaction to refrigeration mode. However, this approach is currently under review to include the request of avoiding interruptions of the LHe supply to the Cold Powering system, which would result in partial thermal cycles of the SC link due to the limited autonomy of the system in case of disconnection from the cold box.

3.5. Quench recovery

Following a quench, nominal operating conditions shall be recovered within maximum 12 hours. Two quench recovery strategies have been considered in the functional analysis of the cryogenic system:

- Re-cool down by pumping;
- Depressurization and re-cool down via the cold box.

Re-cool down by pumping is the quench recovery strategy used in the LHC. The magnet cryostat remains closed at the end of the quench and the helium is re-condensed through the bayonet heat exchanger. This quench recovery mode presents several advantages:

- It requires little intervention by the cryogenic operators;
- It minimizes the volume of liquid helium to be supplied to re-fill the magnet cold masses;
- Depending on the temperature of the helium at the end of the quench, the GHe expelled to line D can be potentially used to boost the liquefaction capacity of the cold box.

The main bottleneck of re-cool down by pumping is the available pumping capacity for the IT String in SM18, which for a single WPU is limited to 18 g/s and 6 g/s at 30 mbar and 10 mbar suction pressure, respectively. Quench recovery by pumping includes 3 stages:

- Isochoric cooling from the state after the quench to 4.5 K through the bayonet HX. In this phase, the maximum flow of a WPU (18 g/s at 30 mbar suction pressure) is used;
- Isobaric re-filling of the magnet cryostat (see Section 3.1);
- Isobaric cool down from 4.5 K to 1.9 K. This phase is performed with decreasing mass flow as the suction pressure of the WPU is lowered to reduce the cold mass temperature to 1.9 K.

Table 2 summarizes the re-cool down time by pumping for different quench energies.

Table 2. Re-cool down time of the IT String by pumping for different quench energies.

	Quench energy		
	39.1 MJ	22 MJ	6.3 MJ
GHe temperature at the end of the quench [K]	28.2	19.6	8.5
Cool down to 4.5 K [h]	20.4	9.4	2.4
Magnet filling [h]	1.9	1.6	0.1
Cool down from 4.5 K to 1.9 K [h]		2.3	
Total time [h]	24.6	13.3	4.8

Quench recovery by pumping exceeds the maximum required time of 12 hours for both 39.1 MJ and 22 MJ quench energies. The strategy is applicable only to recover from low energy quenches.

Alternatively, re-cool down following a quench can be achieved by depressurizing the magnet cryostat and line D down to 3 bar and then resuming circulation from the cold box as described in Section 3.1. The depressurization phase is limited by the power of the electrical heater used to warm up to room temperature the cold GHe before recompression. A heater unit with a power of 30 kW, allowing the warmup of about 20 g/s, is selected for the IT String cryogenic system.

Table 3 summarizes the re-cool down time by depressurization and circulation from the cold box for different quench energies. A fixed cold box re-configuration time of 3 hours is also included, which can occur, if required, in parallel to the depressurization phase.

The maximum depressurization time is 1.7 h for the 22 MJ quench while it is 1.2 h for the 39 MJ quench. This is because after a medium energy quench, more helium remains in line D and the cryostat compared to a high energy quench, when a larger fraction of the initial helium inventory is in the warm quench buffer.

Even including a fixed cold box reconfiguration time, the time required to recover from a quench by depressurization and re-cool down with the cold box is well below the limit of 12 hours.

The present operation strategy foresees the depressurization of the magnet cryostat to line C, through the control valve regulating the liquid helium supply to the cryostat, and then to line D, through a by-pass between line C and line D. Direct depressurization of the magnet cryostat to line D when a significant pressure difference is present is not selected as a rapid full opening of a quench valve with a large Kv would result in very high flow speeds. An alternative strategy is currently being developed to allow continuous LHe supply to the Cold Powering system during quench and quench recovery, as discussed in Section 3.4. This solution requires by-passing of one of the quench valves with a control valve with flow coefficient adapted to the system conditions during quench recovery.

Table 3. Re-cool down time of the IT String by depressurization and circulation from the cold box for different quench energies.

	Quench energy		
	39.1 MJ	22 MJ	6.3 MJ
Cold box re-configuration [h]		3	
Depressurization to 3 bar [h]	1.2	1.7	0.3
Cool down to 4.5 K [h]	1.6	0.7	0.1
Magnet filling [h]		2.0	
Cool down from 4.5 K to 1.9 K [h]		2.3	
Total time [h]	8.9	8	7.6

3.6. Warm up

The liquid helium in the magnets is evaporated with heaters located in the cryostat. The maximum speed at which the cryostat can be emptied is set by the power of the heater unit. The evaporation of the total LHe mass stored in the cryostats with a 30 kW heater requires 3 hours.

The cold mass is then actively warmed up by circulating temperature controlled GHe from the cold box, similarly to the procedure followed during cool down, and by-passing part of the return flow through the 30 kW heater. The same duration and temperature gradient constraints of the cool down phase are valid during warm up.

4. Layout of the IT String cryogenic system

Figure 1 shows the layout of the IT String cryogenic system as it results from the functional analysis described in this paper. The IT String cryogenic system consists of three sub-systems:

- The String cryogenic distribution line (SQXL);
- The SM18 infrastructure for the IT String;
- The Proximity Cryogenic Distribution System (PCDS).

The SQXL is the section of transfer line that connects to the magnets and reproduces the characteristics of the QXL to be installed in the LHC tunnel. The SM18 infrastructure includes all the equipment in the SM18 hall required to perform the different operation modes of the IT String. Finally, the PCDS includes several cryogenic transfer lines and the String Valve Box (SVB) needed to connect the IT String and the SQXL to the SM18 infrastructure. The PCDS also supplies the helium guard system for the sub-atmospheric instrumentation, medium pressure helium system and the purge system.

The SQXL and the PCDS are new equipment and they are currently in the final design and manufacturing phase, respectively. Installation in the SM18 hall is expected by the end of 2021.

The SM18 infrastructure includes a combination of existing and new equipment:

- An existing helium cryogenic plant providing 6 kW @ 4.5 K of refrigeration power and a maximum liquefaction capacity of 25 g/s and its valve box;
- An existing volumetric compression unit (WPU) with a capacity of 6 g/s at 10 mbar and 18 g/s at 30 mbar suction pressure;
- An existing cold compressor unit with a capacity of 18 g/s at 10 mbar suction pressure / 30 mbar outlet pressure and its downstream heater. The cold compressor unit will be refurbished in the framework of the IT String project as it was unused since the completion of the LHC magnets test campaign;

- An existing 80 m^3 buffer and quench line that will be adapted for the IT String project;
- A new heater unit including 2 x 15 kW electrical heaters;
- A new Warm Recovery Line (WRL) for the warm GHe at the outlet of the Cold Powering system.

5. Conclusions

This paper presents the functional analysis of the IT String cryogenic system. The study confirms that the refrigeration and liquefaction capacity delivered by the cold box available for the IT String meet the operating requirements of the test bench.

A single WPU in combination with a refurbished cold compressor unit can provide the required low pressure pumping capacity, with the exception of the bayonet HX test.

The analysis shows that since in the IT String all magnets will lose the superconducting state during quenches, the mass of helium in a cold quench buffer is expected to be relatively small and would not allow boosting the successive quench recovery phase.

Due to the limited available pumping capacity in the SM18 hall, quench recovery from 39.1 MJ and 22 MJ energy quenches needs to follow a different approach from the one used in the LHC. Depressurization of the magnet cryostat followed by circulation of a cold flow from the cold box are required to meet the target of recovering the nominal operating conditions in less than 12 hours.

The IT String cryogenic system is currently in the final design and manufacturing stage. The installation is foreseen over one year starting from August 2021.

The commissioning of the IT String cryogenic system will be divided in two phases. In the course of 2021, the cryogenic system (with the exclusion of the quench recovery system) will be commissioned without magnets. Following the installation of the magnets foreseen in the first quarter of 2023, a second commissioning phase will take place starting from the end of May 2023.

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