FROM STRING 2 TO THE SECTOR TEST: THE TUNNEL CRYOGENIC SYSTEM

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Abstract

Following a description of the tunnel cryogenic system, its circuits and its operation modes (transients, quench recovery, etc.), the cryogenic system of String 2 is shown to be an exact replica of the tunnel cryogenic system of an arc full-cell. The objectives of the planned experiments are detailed.

1 INTRODUCTION

The design and construction of accelerator systems unprecedented in size and complexity requires careful selection and testing of components. Furthermore, operational and full-scale models, where all components can be operated altogether, become even more necessary tools to verify and improve the overall performances and limitations.

For this purpose a first version of the LHC Test String, representing a half-cell of the machine lattice, was assembled, operated and extensively tested for more than 4 years [1]. Various cryogenic components as well as the overall cryogenic distribution scheme were not only validated but also improved and/or simplified to increase the reliability of the system and decrease investment and operational costs [2].

Following the first half-cell operational model (String 1) a new full-cell operational model (String 2) has been designed and assembled to become operational during 2001 [3]. It incorporates all modifications following the testing of its predecessor and it represents a full-scale model of the tunnel cryogenic system for the LHC as well as other accelerator systems. It will be used to finally check all systems altogether and in particular to verify and improve the process and operation of the cryogenic system as well as to train the future operation crew in view of the full sector test in 2004 and subsequent full machine operation later in 2006.

2 COOLING SCHEME OF A SECTOR

2.1 General Layout

The LHC cryogenic system is based on a five-point feed scheme (see Figure 1) with one cryogenic plant dedicated to each of the eight 3.3 km-long sectors [4].

In the underground tunnel, as shown in Figure 2, a separate cryogenic distribution line feeds the different clients and the elementary cooling loops extending over the length of a full-cell (107 m).

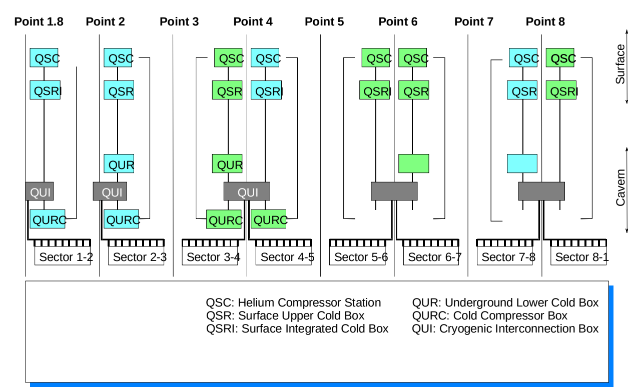

Figure 1 : The LHC cryogenic system layout

Cryogenic power is distributed as supercritical helium at 3 bar and 4.6 K, and gas is recovered or pumped at various temperatures. The thermal screens are separately cooled in series between 50 and 75 K to intercept radiation loads.

The cryogenic distribution line is interconnected to the Cold Compressor System for Very Low Pressure Pumping, the 4.5 K refrigerator and the helium gas storage via a Cryogenic Interconnection Box situated in the underground cavern.

The Cryogenic Distribution Line (QRL) supply the local cooling loops of

1) the arc full-cells
2) the DFBs (electrical distribution feed boxes) for electrical powering of the sector
3) the superconducting cavities
4) the inner triplet
5) non standard cryostats

2.2 The Cryogenic Distribution Line

A Cryogenic Distribution Line is used to transport from the refrigerators cooling power to the local cryogenic clients and to recover cold gas at the required pressure and temperature levels [5].

This distribution line houses the helium supplies and recovery headers at the required pressure and temperature levels (Table 1). It runs inside the machine tunnel parallel to the superconducting magnets and it interconnects to them every 107-m.

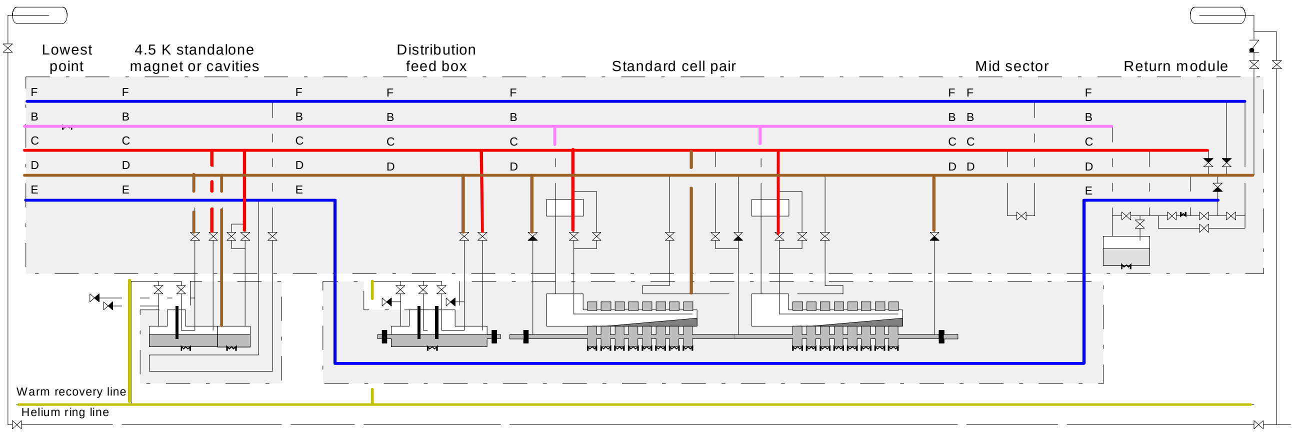

Figure 2 : The tunnel cryogenic system layout for a typical sector

Table 1: Supply and recovery

	Feed / recovery Temperature	Feed / recovery Pressure
Supply	4.5 K SHe	3 bar
Recovery	20 K GHe	1.3 bar
Supply Thermal screen	50 K GHe	19 bar
Recovery Thermal screen	75 K GHe	18 bar

2.3 The Elementary Cooling Loops

There are about 27 arc full-cells in a machine sector, which are fed in parallel from the QRL. During cooldown, line C supplies helium at progressively lower temperatures to each pair of full-cells and the helium flow is discharged into line D and returned to the refrigerator [6]. Two weeks are necessary to cool the 4500 t of the magnets down to 4.5 K. Feed and discharge valves are closed to evenly distribute the cooling flow depending on the cooldown speed of each full-cell.

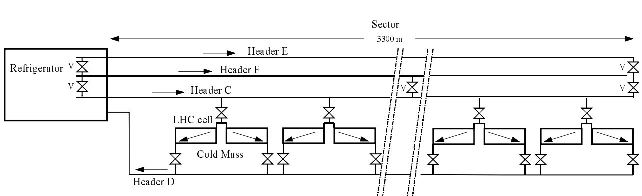

Figure 3 : Cooling flow distribution of a sector

Once at 4.5 K, liquid helium is distributed to the cells to fill the magnet cold masses. Once filled to 70 % the inlet and outlet valves are closed and the cold masses filled by condensation of gas pockets and further filling via the feeding valve.

The bayonet heat exchanger inside the pressurised liquid helium bath in the cold mass cools the magnets down to superfluid helium temperatures by vaporisation of a saturated liquid helium flow [7]. The superfluid saturated helium flow comes from the subcooling in a counterflow heat exchanger and further expansion in a Joule-Thomson valve of supercritical helium at 4.5 K and 3 bar supplied via line C in the QRL.

The Electrical Distribution Feed Boxes [8] are several meters long liquid helium cryostats which support and cool 13 kA, 6 kA and 600 A current leads. They are used to power the LHC main dipole and quadrupole superconducting magnets, together with their correctors. The DFBs are fed, via a Joule-Thomson expansion valve, with 4.5 K liquid helium from line C to cool the bottom part of the HTS current leads and the LTS busbars. The heat exchanger (classical) and the top part of the HTS of the current leads are cooled with 20 K gaseous helium forced flow from the return of line D. Gas recoveries from the DFB are sent to the warm recovery line.

Superconducting cavities and non-standard cryostats cooling loops are directly fed with liquid helium from the main feed line C. Cold gas at/or below 20 K is recovered via line D.

3 COOLING SCHEME OF STRING 2

3.1 General Layout

The cryogenic flow-scheme for String 2 is based on the proposed design of the cryogenic system for the LHC.

Its layout is based on a full-cell of the machine arc together with cryogenic and powering feeds and makes use of the existing cryogenic utilities in SM18.

To interface the components representing the machine sector , dedicated systems have been designed

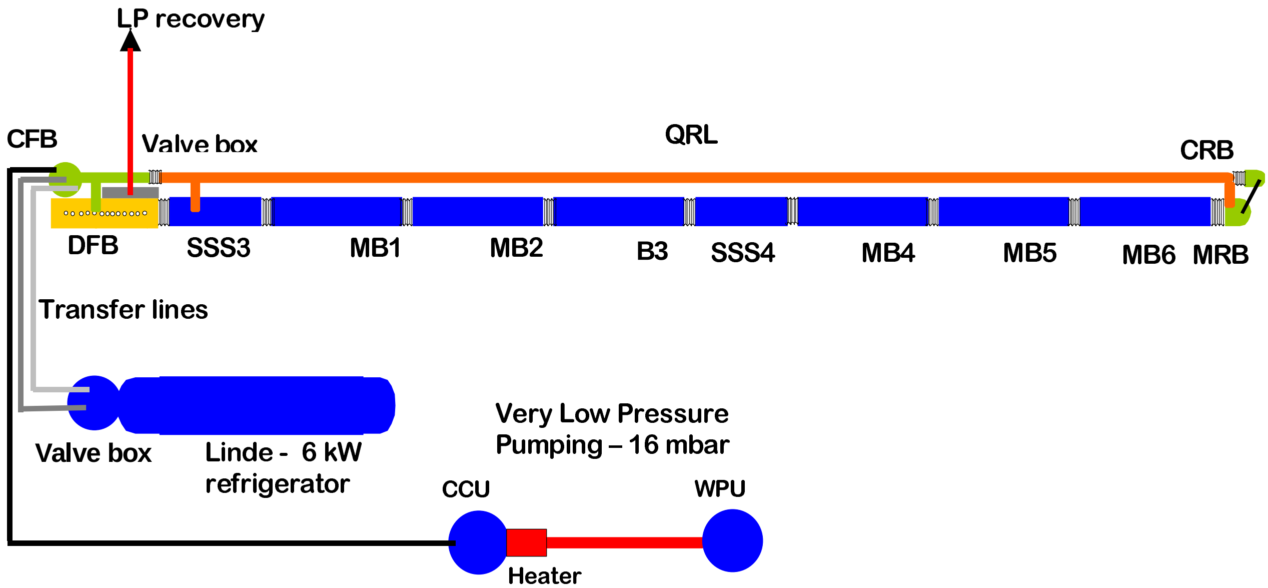

Figure 4 : String 2 layout

which are peculiar of String 2, although components with similar functions can be found in each LHC machine sector.

3.2 Components

The String 2 cryogenic system is representative for the basic component of a LHC machine arc sector: a full-cell.

The magnet cold masses, the DFB and the QRL represent a part of the LHC machine arc.

The arc full-cell components are: the magnet String with the bayonet heat exchanger and the QRL.

The DFB, situated at both ends of an arc, is part of the system to allow powering of the full-cell.

Other components such as the feed and return boxes (CFB and CRB), the quench buffer vessel (QBV), the refrigerator and ancillary systems (Cold Compressor Unit, Warm Pumping Unit, etc.) are peculiar of String 2 although components with similar functions can be found in each sector of the LHC machine.

Details on String 2 cryogenic components can be found in [9].

3.3 Circuits

Two main loops are fed by the CFB, each extending over the 100-m length of the String:

– The thermal screen and heat interception at 50 K loop with line E and F;
– The supercritical helium loop (line C) together with the low-pressure recovery (line D) and the very low pressure pumping (line B).

Line C provides supercritical helium (SHe - 3 bar and 4.5 K) to the superfluid helium circuit, the two beam screen and feet heat interception circuit, and the cold mass cooling and filling loops.

The superfluid helium loop feeds the cold mass heat exchanger with superfluid helium created by the heat exchanger subcooling and the Joule-Thomson valve expansion of supercritical helium and provides cooling of the pressurized superfluid helium inside the cold mass. Superfluid helium is fed to the far end of the String via the heat exchanger inner tube. Line B provides very low pressure pumping of the superfluid helium loop. Line D recovers gases from the beam screen and cold mass cooling loops. Furthermore, it acts as quench recovery line where helium expelled from the cold mass, via the Quench Relief Valves at each end of the String, is buffered, and transported to the low pressure recovery and the Warm Buffer via the Quench Buffer Vessel.

Further details on String 2 cryogenic circuits can be found in [9].

3.4 Operation Modes

After the String is assembled or following an opening of a cryogenic circuit during a shutdown, the cryogenic circuits are evacuated and flushed before connection to the refrigerator and then pressure and leak tested prior to cool-down. At the same time all systems (components, actuators, instrumentation, etc.) are checked in warm conditions.

The process of the cryogenic system is divided in five main operational phases:

1. Cool-down
2. Normal operation (with or without current)
3. Quench recovery
4. Cold floating (only the temperature screen are actively cooled)
5. Warm-up

Once all circuits and components are verified the system is ready and the cooldown phase may start. From this phase, it can either go to cold floating, via an operator action that stops the cool-down, or reach normal operation once the coldmass magnet temperature is below 1.9 K and the HTS current leads are at operating conditions (i.e. HTS are below 50 K and liquid helium in DFB covers the HTS/LTS joints).

The magnets, and therefore the HTS leads, can only be powered in the normal operation phase.

When a magnet undergoes a quench in normal operation, the system will go to quench recovery. It will start warm-up if instructed by an operator. It can also go to cold floating via an operator action. In cold floating all cooling with the exception of the thermal screens is stopped.

From the cold floating phase the system can be cooled-down again or warmed-up via an operator action.

Once the coldmass temperature is above 293 K the warm-up is finished and the system ready for intervention or idle for another cool-down.

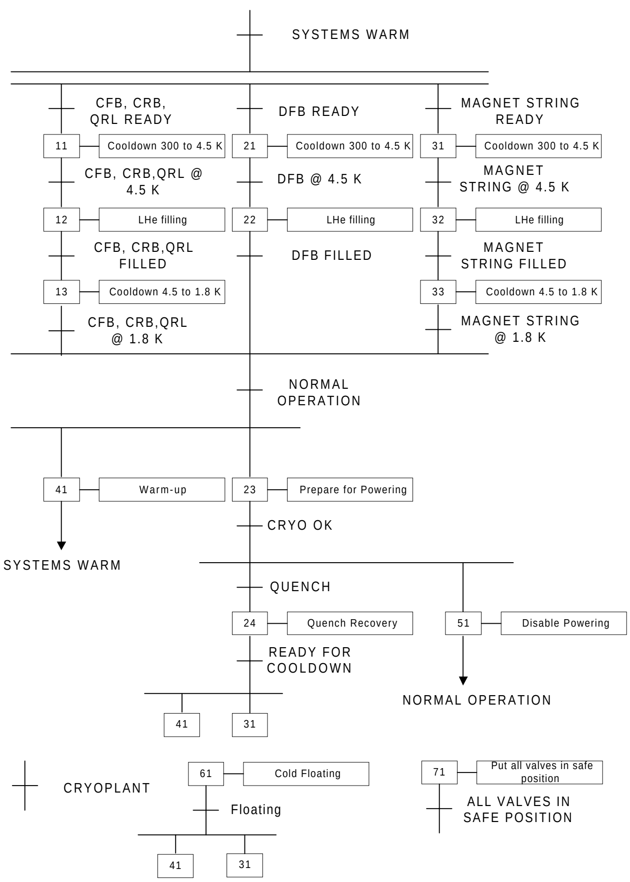

Figure 5 : String 2 Cryogenic System State Diagram

The cool down of each subsystem can be, if needed, in parallel or after a complete cool down of other subsystems. In general all components and subsystems are cooled down and warmed up together with the refrigerator.

The cool down to 1.8 K or the filling operation can not be started prior to cooling below 5 K of the CFB, CRB and QRL.

Details on the process for each subsystem are described in [10].

The nominal operating conditions are reached when:

1. the String cold mass is below 1.9 K
2. the upper part of all the current leads is below 50 K
3. the lower part of all current leads are in liquid helium
4. the liquid helium level in Quench Buffer Vessel is below 15 %
5. the pressure in the Warm Buffer Vessel is below 2.5 bar.

The magnets can be powered only in nominal operating conditions. The operator delivers the CRYO OK signal to the Interlock System of String 2 upon request. In turn, the Interlock System of String 2 delivers the authorisations for powering. Whenever any of the nominal operating conditions fail the CRYO OK is withdrawn and the Interlock System of String 2 takes the appropriate action.

This phase is terminated when a quench occurs or the operator orders a transition to warm-up or stops the cooling.

4 STRING 2 EXPERIMENTS

The String 2 experimental program has been defined to verify the basic design technical choices of the cryogenic and other systems of the LHC machine.

The superfluid and supercritical helium loops will finally be validated after being tested on dedicated test set-up or on shorter length models (String 1).

String 2 will also allow to evaluate the process control and the instrumentation performance under machine–like conditions, while dedicated tests will ensure the compatibility with radiation levels during the LHC lifetime operation.

The facility will permit to investigate advanced control techniques for the accurate control of the cold mass temperatures.

For the first time a DFB with HTS leads will be tested and the overall performance and limitations of a sector full-cell, directly coupled to a refrigerator, will be assessed.

The quench recovery procedures will be finalised and quench propagation tests will improve the forecast of the machine downtime after a quench.

In general String 2 will allow checking and finalising the process and operation of the cryogenic system and can be used as a training facility for future operation crews.

Unfortunately not all the tests will be completely representative of a full sector. In particular it will not be possible to study: the distribution of cooldown flow for several full-cells, the influence on the temperature control of adjacent cells cooling via superfluid helium, the possibility of propagating a quench not only from magnet to magnet but also from cell to cell and the complexity of commissioning and operating a 3.3 km full sector. Furthermore, the sector test will be the only facility to verify design and sizing of the quench recovery system for the accidental scenario of a full sector quench.

5 CONCLUSIONS

String 1 and now String 2 are valuable full scale models for assessing performance and validate basic technical choices. Nevertheless the sector test will be the only facility were final validation over the distributed 3.3 km length of the sector can take place.

Furthermore String 2 and later the sector test will permit not only to assess the process, operation modes, capabilities and limitations of the cryogenic system but also to reduce the commissioning time of the LHC machine.

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