5-year operation experience with the 1.8 K refrigeration units of the LHC cryogenic system

2015 IOP Conf. Ser.: Mater. Sci. Eng. 101 012141

(http://iopscience.iop.org/1757-899X/101/1/012141)

5-year operation experience with the 1.8 K refrigeration units of the LHC cryogenic system

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Abstract. Since 2009, the Large Hadron Collider (LHC) is in operation at CERN. The LHC superconducting magnets distributed over eight sectors of 3.3-km long are cooled at 1.9 K in pressurized superfluid helium. The nominal operating temperature of 1.9 K is produced by eight 1.8-K refrigeration units based on centrifugal cold compressors (3 or 4 stages depending to the vendor) combined with warm volumetric screw compressors with sub-atmospheric suction. After about 5 years of continuous operation, we will present the results concerning the availability for the final user of these refrigeration units and the impact of the design choice on the recovery time after a system trip. We will also present the individual results for each rotating machinery in terms of failure origin and of Mean Time between Failure (MTBF), as well as the consolidations and upgrades applied to these refrigeration units.

1. Introduction

The LHC commissioning started early 2007, with first beams circulating in September 2008 but with readiness for physics autumn 2009 after all early consolidations were performed to allow operation at the maximum possible energy for more than three years. This period is called Run 1. Considering time to cool-down and warm-up the magnets, it lasted five years and a minimum of 40’000 operating hours for all major technical systems including cryogenics. With 28 cold compressors running, the cumulated operating hours range is 1.1 million hours.

2. Short description of the arrangement for the 1.8K units.

2.1. Global arrangement for one sector

Figure 1 shows the global arrangement of the cryogenic system for one sector. The cryogenic system consists of one 18 kW plant at 4.5 K in charge of delivering super critical helium at 4.5 K and one 2.4 kW plant at 1.8 K. The super critical helium is distributed at 4.5 K and 3.5 bar to the final user via a valve box and a 3.3 km cryogenic line. This cryogenic line is also used to connect the 1.8 K pumping plant to the saturated heat exchangers distributed in the cold mass.

2.2 Detailed arrangement for the 1.8 K units

The arrangement of the 1.8 K refrigeration units is similar for our 2 vendors. This arrangement is based on combined cycle with warm volumetric screw compressors working with sub-atmospheric suction and centrifugal cold compressors. One vendor has chosen 3 stages of cold compressors while the other vendor has chosen a 4-stage arrangement as seen on Figure 2.

2.3 Technologies used for the cold compressors train

Regardless of the vendor, the cold compressor cartridges used all Active Magnetic Bearing system and Variable-Frequency Drive. Each set of cold compressor is driven by a dedicated PLC with complex software used to drive individually each compressor taking into account the global pumping request.

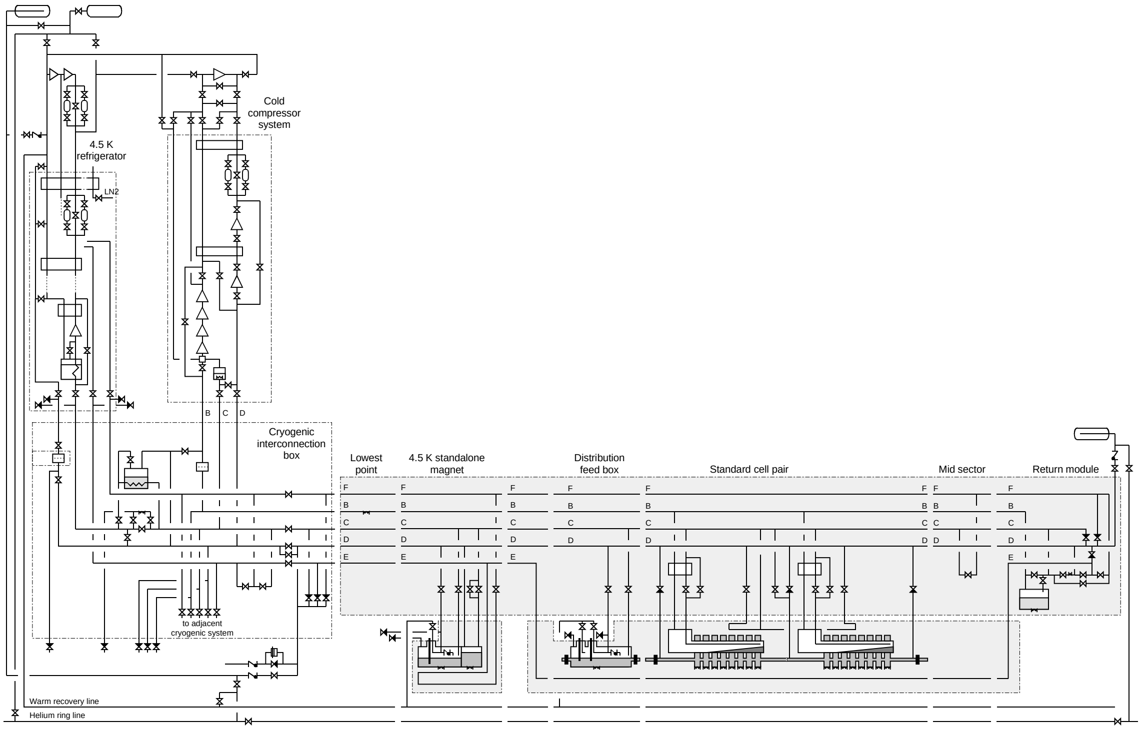

Figure 1 : Global cryogenic arrangement for one sector

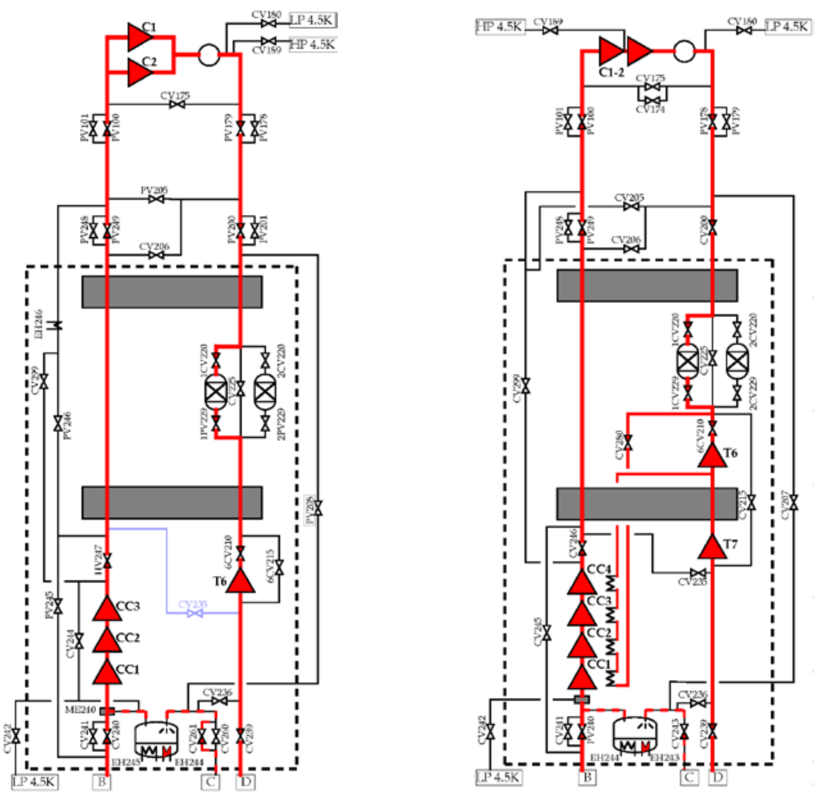

Figure 2 : The 2 different simplified schemes showing the arrangement chosen for the 1.8 K units

3. Availability for the final user.

The first analysis of reliability and origins of downtime has been presented by S. Claudet et al. [1]. This analysis shows for the reference year 2012, 18 stops of the cold compressors of which 2 are related to a total failure of the 4.5 K refrigerator. Going into more detailed analysis, the duration of the system trip should be broken down in sub-sequence detailed below.

3.1. Description of sub-sequence for recovery after a system trip

A system trip is mainly linked to a lack of utilities, a component fault or hydrodynamic loss of helium flow. Following this trip, the system must follow a strict path to recover the former nominal conditions.

The path, shown in Figure 3, consists first to recover the system without use of the cold compressor train. Then the cold compressor train is started to reach the pressure of the saturated pumping line (in average from 30 to 40 mbar [300 to 400 Pa]). This phase is followed by the connection to the saturated helium pumping line and finally by the pumping down to 15 mbar [150 Pa]. This will end this path and allow the recovery of the cryogenic conditions for the final user. The Figure 3 shows this sequence used to recover the nominal conditions after a system trip.

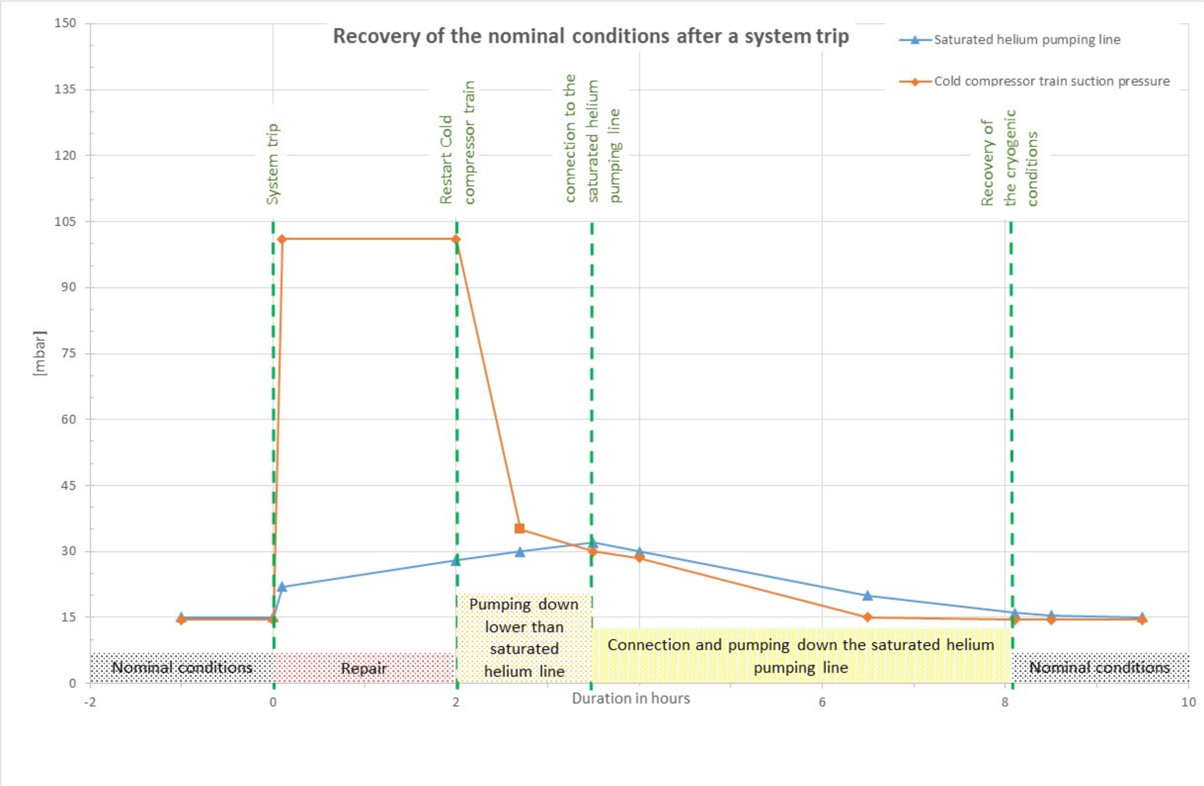

Figure 3 sequence used to recover a stable status after a system trip

3.2. Typical duration of sub-sequences for recovery after a system trip

The duration of the recovery after a system trip depends on the delay used to repair the faulty component. The lack of production was in average 12 hours.

For a short intervention with a repair lasting less than 3 hours the table 1 shows a breakdown of the different phases. The difference of duration between the configuration with 3 cold compressors and the configuration with 4 cold compressors is mainly linked to the lowest pressure reachable by the volumetric compressor. This pressure is in the range 100 mbar for 3 cold compressor to be compared to a pressure of 250 mbar for the configuration with 4 cold compressors. The other reason is a much more complex driving software for the 4 cold compressors that requires more time to restart the process.

		Average duration [hours], repair not included		
Configuration of the cold compressors units	**Repair**	**pumping down lower than saturated line**	**Connection and pumping down the saturated helium pumping line**	**Total duration to restore stable presurised temperature below 2.1 K**
All units	from 20 min to 3:00 h	1.25 h	4.75 h	6 h
configuration with 3 cold compressors	from 20 min to 3:00 h	0.75 h	3.25 h	4 h
configuration with 4 cold compressors	from 20 min to 3:00 h	2 h	7 h	9 h

Table 1 : Breakdown of the average duration necessary to recover the final stable status (repair shorter than 3 hours); repair duration not included.

For a long intervention with a repair in the range from 3 hours to 24 hours, the recovery of the system is linked to the cooling down of cold mass. The recovery duration should go up to 24 hours.

3.3. Effect on the global availability of the 1.8 K units

During the reference year of 2012, the global availability of the cryogenic system for LHC has been 94.8 % [2]. On the total failure duration (5.2 %) the main contributor has been the 1.8 K units (3 %). The remaining 2.2% of failure was shared between 18 kW refrigerator, users and unexpected stops of utilities.

4. Mean time between maintenance of the cold compressor cartridges.

According to the formal definition, the Mean Time Between Maintenance (MTBM) is equal to the sum of the operational periods divided by the number of observed failures.

At CERN the quantity of Cold Compressors used is 15 cartridges for one vendor and 20 cartridges for the other vendor.

Seven of them (3 from one vendor, 4 from other vendor) are used as spare parts during maintenance and are also used on a test bench developed to validate Active Magnetic Bearing (AMB) and Variable-Frequency Drive (VFD) upgrades.

The cold compressor cartridges have a cumulated operation time higher than 1.1 million hours during the run 1, ended in 2013 regardless of the vendor.

Some cartridges were maintained during this run and some were maintained during the following long shut down (period 2013/2014). A total of 13 cartridges had been sent for maintenance at supplier workshop. One of this cartridge has been damaged during specific tests done on the test bench and will not be considered in the following calculations.

Taking into account these data, we could estimate the Mean Time Between Maintenance (MTBM) of our cold compressor cartridges equal to 100000 hours for one vendor and 90000 hours for the other vendor.

4.1. Replacement during operation phase

Three cartridges had to be replaced and sent back for repair, with one during operation and two as a preventive measure. Twice, the Emergency Touch-Down Bearings (ETDB) were out of tolerance and twice, connecting issues were identified, with one machine having both.

4.2 Replacement during long shut down

During the long shut down, a systematic check of all cartridges has been done. Ten cartridges were identified as requiring a maintenance. For eight of them, ETDB were out of tolerance, two shows damage on rotor shaft and three of them shows also some electrical insulation issues.

5. Consolidations and upgrades applied to 1.8 K refrigeration units.

5.1. Consolidations

Consolidations applied to the 1.8 K refrigeration units consists mainly in four parts.

The first part has been to improve the stability during the operation of the system. That means than a better control of the process, mainly of the thermodynamics parameters at the inlet of the first compressor and a smooth drive of the pumping parameters gives better results in term of availability.

The second consolidation consists to improve the availability of the utilities such electrical powering (include 24 VDC) and cooling water flow.

The third consolidation consists to avoid perturbations of electronics components such as AMB & VFD, linked to unexpected losses of beam generating some secondary particles shower and associated single event upset (SEU). This consolidation has been done by moving electronic cabinet to a more protected area.

The last element needed to improve the global availability of the 1.8 K units was the permanent follow-up of electrical and electronic devices by our support team. By this way each issue was detected and solved rapidly. This active follow-up also allows to prepare smooth improvements compatible with requested global availability.

5.2. Upgrades

The first installation of this material had started in 2005. As consequence, all electronic components are now close to their MTBF duration (aging effect). On the other hand, some electronic components had necessitated new development to be compatible with the displacement of electronic cabinets. Consequently, it has been decided to upgrade all VFD & AMB units. The adaptation of the new industrial components to our specific use has been done by our control and electrical support team. The upgrade scheme is applied gradually. Around 65% of these components have already been exchanged with their upgraded component. This upgrade is foreseen to be ended end of 2016.

6. Conclusion

The 1.8 K refrigeration units are fully integrated in refrigeration architecture and already at a level of availability above 99% per installation with excellent overall reliability of the cold compressors cartridges technology operated above 500 Hz. Some improvements are identified for a further increase and a stabilisation of the overall availability.

7. Acknowledgment

The authors wish to warmly thank their colleagues from the operation, technical and industrial support teams, performing the operation, maintenance and consolidation activities at CERN, each member of these teams being co-responsible of the good results obtained.

8. References

[1] Claudet S et al 2014 Rotating machinery for LHC cryogenics: first analysis of reliability and origins of downtime *Proceeding of ICEC25-ICMC 2014*

[2] Delikaris D et al 2013 The LHC cryogenic operation availability results from the first run of three years *CERN-ACC_2013-0098*