ISSUES CONCERNING THE RELIABILITY OF THE LHC CRYOGENIC SYSTEM

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Abstract

The functionalities, redundancy and possible failure scenarios of the cryogenic system will be briefly presented based on components reliability and impact on beam commissioning. Requirements and problems related to accessibility and radiation issues for in-situ repair or exchange will be addressed. A list of possible interventions for repairs will be given together with the associated downtime for beam commissioning. Finally, the strategy for spares and maintenance policy (corrective against preventive) and the consequences on the system availability will be presented with the consequent shutdown scenarios.

INTRODUCTION

Large scale cryogenic systems have been already used at CERN for previous accelerators (SPS, LEP). Most of the primary cryogenic components of such systems (screw compressors, turbines, instrumentation, etc…) have been extensively used and a wide operational experience is available at CERN. Since 2001, additional operation experience on LHC cryogenic systems (first 18 kW @ 4.5 K refrigerator at PM18 and String 2 test campaign) has been cumulated. Based on this experience and the LHC cryogenic system architecture, reliability of components and sub-systems has been analysed focused on possible failures and availability affecting beam commissioning. Indicators such as mean time between failure (MTBF) and mean time to repair (MTTR) are given when possible.

Reliability being strongly related to maintenance policy, maintenance and shutdown scenarios are also presented as they will certainly have an influence on the availability of the cryogenic system.

LEP2 EXPERIENCE

A simplified layout of the LHC cryogenic system compared to the LEP2 one is shown in Figure 1. With more than 30.000 running hours, the LEP2 cryogenic system was very reliable with less than 1% downtime for the LEP machine due to cryogenics [1]. Figure 2 shows the cryogenic downtime rates for the LEP machine from 1996 to 2000.

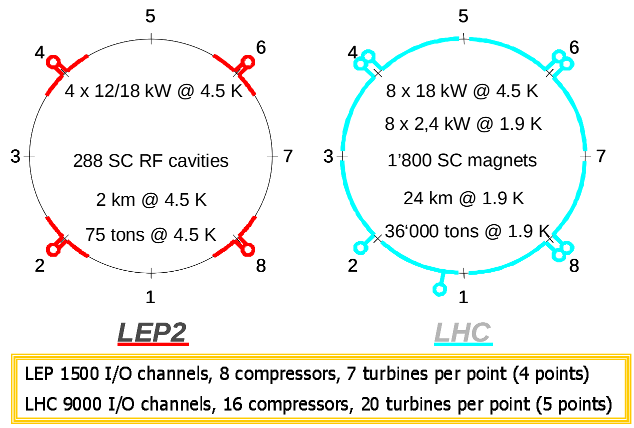

Figure 2: LEP2 and LHC simplified layouts

Main components failures appeared during commissioning or just after winter shutdown maintenance campaign (“post shutdown” effect). Predominant failures came from compressor stations (MTBF 0.1 year) due to aging of instrumentation or piping (high vibration levels). Cold boxes proved to be very reliable (MTBF ~years), in particular instrumentation and turbines. In any case, most of the corrective maintenance interventions were very efficient (average MTTR ~ 2-3 hours), mainly due to well trained operation teams and availability of spares.

Main issues concerning cryogenic distribution and cryomodules were beam related (heat load) and didn’t affect the availability of the cryogenic system but locally limited the cooling capacity [2, 3].

Gaseous impurity problems at warm turbines level (120 K and 90 K) were also an important issue [1, 3]. Although there was no direct downtime, interventions were regularly scheduled in order to recover the cooling capacity. This time was used for other machine interventions.

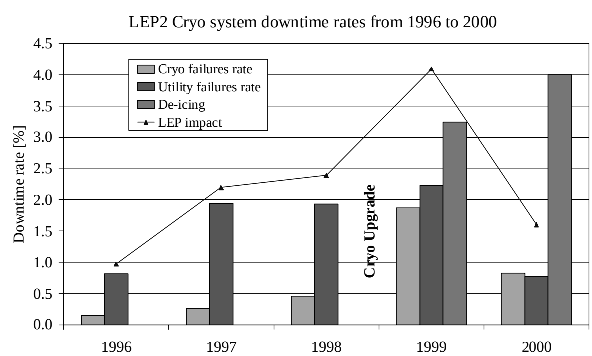

Figure 2: cryogenic downtime impact on LEP machine

THE LHC CRYOGENIC SYSTEM

The layout of the LHC cryogenic system (figure 2) already detailed in other specialised papers [4, 5] is based on eight cryoplants, each one composed of a 4.5 K refrigerator coupled to a 1.8 K refrigerator. As shown in figure 3, these cryoplants are grouped by two in LHC points 4, 6 and 8 where the interconnecting box (QUI) assures distribution to the two adjacent sectors through the respective cryogenic distribution line (QRL). This symmetry is not respected for the other two cryoplants, which have been installed separately in points 2 and 1.8.

The interconnecting boxes allow interconnection between cryoplants to assure distribution of the cooling capacity to the two adjacent sectors. This is not true for sector 2-3, where the cooling capacity can only be supplied from the cryoplant in point 2.

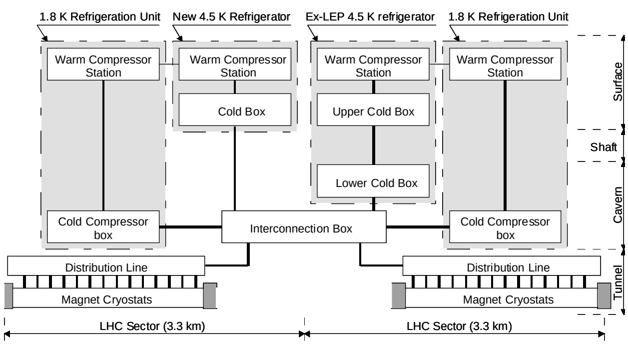

Figure 3: The cryogenic system architecture per point.

MAJOR AND COMPONENTS FAILURES

Major Failures (sub-systems)

We consider that a complete failure of a cryogenic sub-system (refrigerator, QUI, QRL, etc.) is possible but very unlikely to occur. The most probable failure would be the loss of insulation vacuum.

If one 4.5 K or 1.8 K refrigerator is stopped or not operational, the QUI allows to use the adjacent cryoplant to distribute sufficient cooling capacity to the two sectors for low intensity run. However, the estimated transition period to re-establish the flow and nominal conditions for beam would be more than 12 hours. As mentioned before, this option is not possible for sector 2-3.

Major failures of any of the other main sub-systems, QUI, QRL and electrical feed box (DFB), will lead to the total stop of the machine as no redundancy is available.

The following points summarize the failure analysis for the components of the different cryogenic sub-systems.

4.5 K and 1.8 K Refrigerators

There is no redundancy (or spares) for warm compressors (motor/compressor) but the spare capacity and/or connection to adjacent refrigerators would allow degraded mode (low intensity). Most likely failures to occur are breaking of compressor’s instrumentation (MTTR ~ 1-2 hours) or oil injection piping (MTTR ~ 1-2 days) due to vibrations.

Cold boxes instrumentation has proved to be very reliable and available spares would assure fast replacement (MTTR ~ 1-2 hours). For cold compressors (1.8 K refrigerators) spares are available as no degraded mode is allowed. Spares for turbines are not foreseen (1.8 K and 4.5 K refrigerators) as degraded modes allow continuation of tests. In any case, diagnosis and 5 hours intervention will be needed for replacement (in case of available spares).

The installation of dryers (H_2O removal) before the cold boxes and switchable adsorbers at 80 K (air removal) will prevent gaseous impurity problems. In case of insulation vacuum leaks, temporary solutions will allow running until winter shutdown when major interventions could be done.

In case of intervention in the cold boxes, access will be needed for underground areas. Special access to UX1.8, UX4, UX6 and UX8 will be needed for four 1.8 K cold boxes.

From the cooling capacity point of view component failures should not affect beam commissioning (spares, redundancy and connection to adjacent refrigerator) but the operational constraints and the recovery time will increase. Degraded modes might be a limitation for scrubbing run.

Interconnecting Box (QUI)

Redundancy will be available for control loop and QRL interfaces instrumentation. Cryogenic valves are not redundant as they are considered as highly reliable (MTBF ~ years). The main issue concerning availability of the QUI will be the clogging of line D filter (on each sector) by solid impurities. This would mainly happen during cool down and first quenches provoking a stop of the cooling flow. Intervention will require 1-2 days to replace the filter and reach nominal conditions. Alternative solutions to increase reliability and reduce the MTTR are under study

In case of insulation vacuum leaks, temporary solutions will allow running until winter shutdown when major interventions could be done.

Any intervention will need underground access to the UX and US for point 2.

From the functionality point of view, the QUI assures the redundancy of the cryoplants to supply the cooling capacity to two adjacent sectors (except for sector 2-3).

QRL and Ring components

Insulation vacuum issues for QRL and ring components are described in [6].

- QRL: instrumentation is redundant or allows degraded modes. Most of the cryogenic valves are redundant allowing degrade modes (higher helium flows and less control). In case of in situ exchange, 1 week intervention will be needed depending on the valve position. Quench valves filling functionality is not redundant (typically once/year operation), but the safety functionality is fully redundant.

- Beam screen: clogging of circuits (very small diameter pipe) might be an issue, provoking perturbations on the cooling flow and loss of beam screen temperature control. Failure of electrical heater and temperature sensors (no redundancy) will result in degraded mode (no temperature control and higher helium flow) but could be a limitation for scrubbing run.
- Current Feed Boxes (DFB), superconducting links (DSL) and Standalone magnets: level gauges are redundant and easily to repair (except for some D2's and D3's). Concerning current leads, temperature control valves are easy to replace and temperature sensors are redundant or can be replaced by other control options (valve characteristics). More detailed analysis on the DFB and its components is available in [7].
- Dipoles and Inner Triplets: magnet temperature sensors are redundant (only electronics replacement needed). Other control options such as opening valve characteristics or copying valve position of adjacent cells (only for dipoles) will be also possible. Failure of the bayonet heat exchanger level gauge could provoke liquid in the pumping line B with the consequent magnet temperature perturbation.
- Radiofrequency cavities: previous considerations about instrumentation and cryogenic valves apply. Main issues concerning cavities are pressure stability and protection during quench [8].

From the functionality point of view, reliability of most of the primary components is high. Replacement or degraded modes will avoid impact on beam commissioning. Any intervention will need access to the tunnel.

Utilities Failures Recovery

As already described in [9], cryogenics availability is highly dependent on utilities (electrical power, cooling water, compressed air and controls). Figure 4 shows the estimated recovery time for the LHC cryogenic system together with results from LEP operation during 1998-2000 and few points of mains failures during operations of the LHC Test String.

The cryogenic recovery acts as a time amplifier of the utility stop, the recovery time being equal to 6 hours plus 3 times the utility stop length.

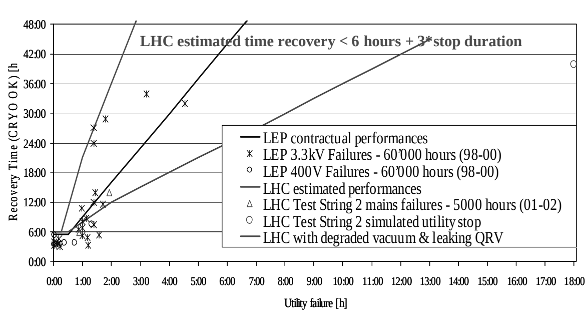

Figure 4: Mains failure recovery performances.

Recovery predictions and performances have still to be validated for the global cryogenic system during hardware commissioning, as only individual sub-systems functional tests have been done until now. In any case, degraded modes will certainly increase recovery time.

During commissioning of the first LHC cryogenic sub-systems, an increasing dependence on controls have been noticed. The control system for cryogenics being itself under commissioning, the reliability of this system is not up to expectations and clearly needs to be improved.

FIRST LHC EXPERIENCE

The first LHC 18 kW at 4.5 K refrigerator has been in operation for the LHC magnet test bench since 2002. With more than 20000 cumulated running hours the availability of this refrigerator has been about 99%. Apart from the post-commissioning period, the reliability of components has confirmed LEP experience, although the high performance is partly explained by the possibility of running with degraded modes and the spare cooling capacity.

In spite of being a prototype and test facility, String2 experience (2002-2003) also confirmed the positive predictions. The availability was 98.5% for about 6000 running hours and main downtime was due to tuning, quench recovery and controls validations. No major problems were detected concerning instrumentation or beam screen circuits.

MAINTENANCE AND SHUTDOWN STRATEGY

Maintenance Policy

The reliability of the cryogenic system is highly dependent on maintenance. Maintenance policy is based on a complete maintenance plan: equipment lists and their criticality, spare parts list, preventive routines and corrective follow up actions, historic of interventions and performance indicators. This maintenance plan has to be upgraded (old LEP installations), completed (new LHC installations) and implemented in CERN CAMMS before getting the sub-systems into operation [10].

The key factors of this maintenance plan are:

- Preventive maintenance: extensive maintenance campaign during winter shutdown (baseline, 13 weeks)
- Spare parts: a criticality analysis method is used in order to establish a first batch of spare parts just after the commissioning (~2.2% of cryoplant cost). This allows a fast capacity reaction in case of component failure and assures MTTR of few hours.

However, for some main components such as turbines, warm compressors and associated electrical motors there will be no spares.

Executive maintenance resources are completely outsourced and no competences are available at CERN. In view of LHC operation, all cryogenic maintenance will need to be based on CERN CAMMS and the cryogenic maintenance management will need to be reinforced.

Shutdown Strategy

Based on a 16 weeks shutdown [11] and a maintenance policy as presented, two shutdown scenarios are envisaged.

Scenario1: full stop and maintenance campaign on all the cryogenic sub-systems, keeping the magnets at floating temperature (~200 K). This option is based on the present maintenance philosophy and will assure the same availability rates. However, due to the large number of installations to be maintained the "post shutdown" effect might have a more important impact during start up (cold check-out, beam?). Thermal cycling of components will increase the risk of helium leaks and materials (welding) stress. In addition, magnet temperatures above 80 K will require additional 5 weeks during machine cold check-out for electrical reconditioning (ELQA).

Scenario 2: partial maintenance on 1 cryoplant per point keeping sectors cold. In this case "post shutdown" effect will be reduced although availability rate for the non maintained cryoplant will certainly decrease. Thermal cycling and additional time for ELQA will be suppressed. This scenario is not possible for sector 2-3, although cooling capacity at 80 K from point 1.8 cryoplant might solve the problem.

Utilities availability during shutdown will be driven by the cooling water towers maintenance. The present baseline is 4 weeks per LHC point (2 points in parallel) so a total of 10 weeks. Scenario 2 would require to review this baseline.

In any case, warm up could be needed for ring components replacement.

CONCLUSIONS

In principle, the cryogenic system should have a very low impact (except for sector 2-3) on beam commissioning because of:

- Redundancy of systems.
- Available spare cooling capacity for low intensity mode.
- Reliability of components and instrumentation

However, failure of sub-systems and components cannot be ruled out completely and could result in few days' delays to switch to redundant sub-system or component and to adapt to the new configuration:

- Worst failure would be loss of insulation vacuum in the QUI or QRL as well as the refrigerator in point 2 or DFB's for magnet powering.
- Most likely failure would be filters blockage in the QUI during or after the first cool down and magnets quench due to accumulation of impurities.
- Recovery time after major failure (cryo or utilities) will be approximately 6 hours plus 3 times the stop length (15 times in case of bad vacuum or quench valve leaks).

The cryogenic sub-systems will be individually tested, but the overall cryogenic system will certainly require complex and extensive commissioning prior and during powering in order to validate the collective behaviour and optimize operating modes. The availability or quench recovery performances of the LHC cryogenic system:

- Could be reduced by additional heat loads or non conformities from commissioning magnet powering.
- Strongly depend on a correct and effective maintenance management: it has already started and needs CERN dedicated resources.

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