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Rotating machinery for LHC Cryogenics: first analysis of reliability and origins of downtime

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Abstract

The Large Hadron Collider (LHC) is cooled by eight independent helium cryogenic plants. Each cryogenic plant combines an 18 kW at 4.5 K refrigerator and a 2.4 kW at 1.8 K refrigeration unit totaling 64 oil lubricated screw compressors, 74 expansion turbines and 28 cold hydrodynamic compressors. Since the first cool-down of LHC in 2007, the large number of running hours and start-stop sequences accumulated allow to draw some tendency for reliability of such key components for present refrigeration technology. Statistics and origins of downtime will be presented, with possible typical failure rates.

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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 is called Run I. Considering time to cool-down and warm-up the magnets, it lasted four years. A minimum of 32'000 operating hours has been accumulated for all major technical systems including cryogenics. With several tens of rotating machinery of each type (screw compressors, expansion turbines, cold compressors), the cumulated operating hours range from 1 million to about 2.5 million hours. The global

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availability achieved has been 92.3 %, with each independent sector around 99 % or above, as presented by Delikaris et al. (2013) [1].

2. Methodology for failure analysis

Since beginning of run I, several methods and tools were tested to get statistics and tendencies for reliability. From the computer maintenance management system (CMMS), comparison between preventive and corrective work orders were started, with global evaluation of failure rates, as presented by Perinic et al. (2011) [2]. From the data logged by the operators in the e-logbook, a criticality analysis was then conducted in 2012 with the aim to identify critical components in terms of occurrence and severity, with failure rate functions and a Weibul analysis adapted to statistical treatment of large numerical data, as documented by Martin J. (2012) [3]. Both studies confirmed the tendency that could be guessed by the teams in charge of operation and maintenance, but suffered from the quality of the data collected that were not made for that.

The new operation scenario for run II will require more cooling capacity due to increased beam energy and luminosity, thus reducing the capacity margin with respect to run I. The availability and reliability of rotating machinery such as screw compressors, expansion turbines and cold compressors are key elements towards cooling capacity, and therefore important components in terms of criticality.

Before restarting for Run II, we wanted to analyze our failure statistics for these rotating machinery, evaluate the tools in place and draw some tendency. Other rotating machines were not evaluated yet, as built-in redundancy exists (oil pumps) or exchange could be made without perturbing operations (vacuum pumps).

Our field of investigation consisted of:

- understanding the origin of failures should allow us to focus our efforts on the domains that would help us increasing the global availability. Being the most representative of the criticality achieved after teething problems were cured, the data of 2012 were analyzed.
- evaluating the relevant criteria (operation time, number of starts or stops) would allow us to better monitor the parameters that would be appropriate for conditional checks and maintenance. This was again checked for 2012 data.
- reviewing our tracking tools and methods would identify if gained experience would be kept and consolidated. We must admit that without compilation of various files and independently stored data, it would not have been possible to get a complete picture of the situation. There is clearly room for improvement in this domain!

3. Screw compressors and associated electric motors

Oil lubricated screw compressors with their associated electrical motors are derived from standard industrial machines used in refrigeration or compressed air applications. They are the first machines to start, with only partial compensation of potential failures depending on their arrangement (2 to 5 in parallel), therefore critical for global availability. For around 2 million cumulated hours, two compressors suffered from a same failure mode and one electrical motor needed to be replaced, as can be seen on Fig. 1(a). Axial bearings of some high stage compressors suffered from too much efforts due to reduced force applied on a balancing piston to compensate for pressure difference. This problem could be considered as a “youth” issue that was cured on all similar machines during technical stops or Christmas breaks. The Electrical motor showed high vibrations due to a moving/missing shim and was replaced without operation loss before further consequences.

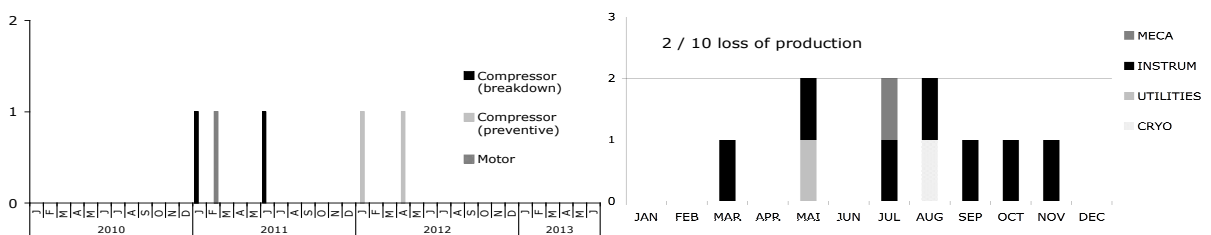


Fig. 1. Screw compressors (a) breakdowns during run I; (b) 2012 failures during operation per origin.

During the reference year 2012, at least one of the screw compressors stopped at 10 occasions during operation, inducing two loss of production, one being relatively long (20 hours) as the entire cryoplant was stopped with the need to be restarted from scratch after diagnostic and intervention. It is clearly visible from Fig. 1(b) that instrumentation surrounding the compressors is the dominant mode of failure. Efforts in understanding and treating this category will be required for availability as the capacity margin will be reduced in the future.

For this type of machines, the number of starts and stops is now relatively low, and does not show a correlation with the machine breakdowns nor failure during operation. Preventive maintenance should be kept according to the integrated running hours and predictive maintenance based on periodic vibration measurement campaigns.

4. Expansion turbines

Expansion turbines rotate on gas bearings, and can be by-passed in case of stop with a drop of capacity that could be smoothed by the heat exchangers and depends on the temperature level (the lowest the most critical). For cumulated hours around 2.4 million hours, eight turbines had to be replaced and sent back for repair. For most of the cases, the bearings were damaged without deterioration of the aluminum wheels. It is always difficult to identify a-posteriori the original cause of the failure, but impurities were found, ranging from liquefied gases to dust of various size and nature. About a third of the cases was linked to degraded fine filters at the outlet of activated charcoal 80 K absorbers that were suspected but could not be replaced during run I. Two cases were due to repeated process oscillations or failure on the inlet valve control.

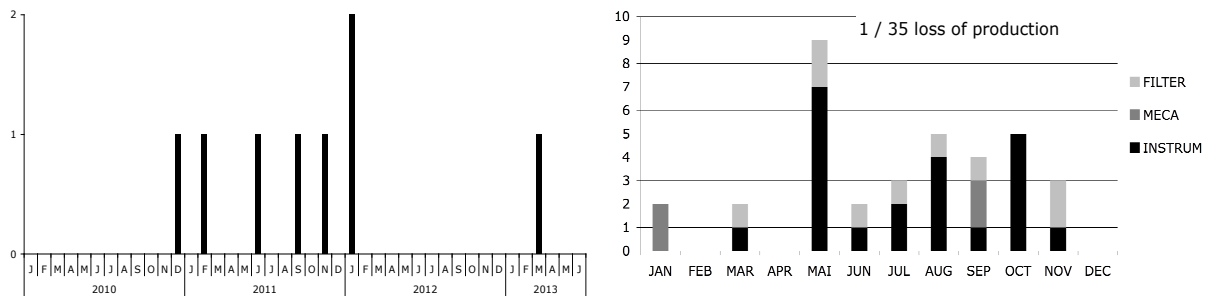


Fig. 2. Expansion turbines (a) breakdowns during run I; (b) 2012 failures during operation per origin.

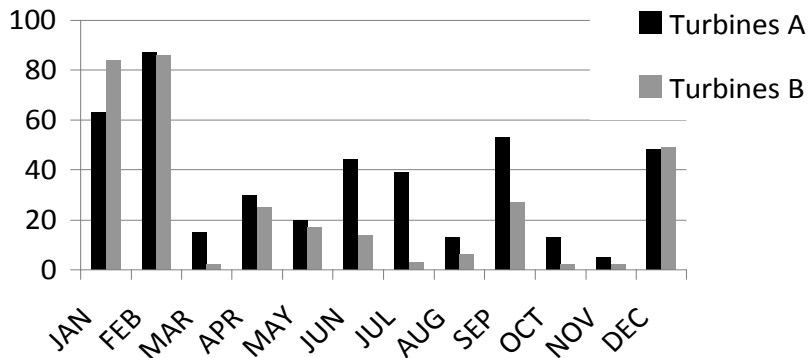


Fig. 3. Restart and stop of expansion turbines in 2012.

During the reference year 2012, single expansion turbines stopped at 35 occasions during operation, inducing only one minor loss of production of few minutes. As illustrated on Fig. 2(a), two third of the failures were due to faulty instrumentation and one third due to clogged filters. A nitrogen to helium leak was found on a heat exchanger of the pre-cooling circuit during the long shut-down and all filters were cleaned, with a specific case for which damaged filters were exchanged and the root cause of the damage identified and tentatively cured (pressure front during periodic regeneration of the absorbers). Efforts in understanding and treating the root cause of instrumentation failures will be as well required for availability as the capacity margin will be reduced in the future.

For this type of machines, it was noticed that breakdowns were more likely to happen outside of the beam operation periods, especially during possibly numerous restarts that could occur during transients (re-cooling or re-fill) that usually takes place around the Christmas breaks, as shown in Fig. 3. Moreover and when analyzing the data for monthly numbers of start and stop of the turbines, we found luckily mostly zero or one stop and restart. Looking at the monthly maximum numbers, they range from a minimum of 1 and a maximum of 14 times. A simple counter should be added in the control system, with the possibility to define warnings thresholds and periodic and systematic review of these indicators, as it could as well illustrate an abnormal situation deserving appropriate investigations.

5. Cold compressors

The LHC Cold compressors are centrifugal cryogenic compressors arranged in trains of 3 to 4 units in series, rotating on active magnetic bearings at room temperature. As they built-up pressure, they cannot be by-passed in case of stop, with compulsory impact on production. For cumulated hours around 1.0 million hours, three cartridges had to be replaced and sent back for repair, with one during operation and two as a preventive measure. Twice, the touch-down bearings (to support the rotating part during stop phase when magnetic bearings are no longer active) were out of tolerance and twice connecting issues were identified, with one machine having both. As the sensitivity of these machines to severe stop conditions was known, a systematic analysis of all stops of cold compressors was put in place, with a predefined classification considering: process stop with nominal magnetic bearings, intermediate stop with assisted landing, emergency stops on touch-down bearings. The tolerance to the later type of stop depending on the manufacturer (in any case a maximum with only one digit), this became a conditional criteria for preventive maintenance to be organized at the next possible occasion while the spare cartridge would be put into service. Furthermore, criteria to assess the status of the touch-down bearings are being investigated together with the manufacturers for periodic assessment.

During the reference year 2012, trains of cold compressors stopped at 20 occasions during operation, inducing all the time a lack of production of about 13 hours in average. The cumulated time to recover from these operation failures amounted for some 60% of the total cryogenic downtime, dominating by far! As this sensitivity had already been identified, efforts to understand the origin of these operation failures were conducted with appropriate corrections implemented (process, tolerance to utility failures) or prepared for the long shut-down No1 (cabling, protection of sensitive electronics from high energetic neutrons coming from beam collisions).

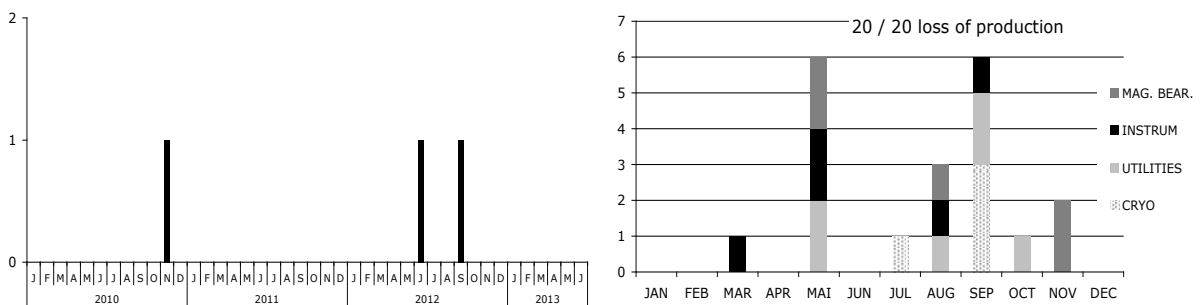


Fig. 4. Cold compressors (a) breakdowns during run I; (b) 2012 failures during operation per origin.

6. Conclusion

With continuous efforts from the operation and support teams, the global downtime of the cryogenic system for beams was divided by 2 in 2012 with respect to previous years, giving a global availability of 94.8%. fully compatible with the LHC physics program This corresponds to better than 99.3% availability for each of the eight cryogenically independent sectors. However, the foreseen increase in energy and luminosity of LHC will be less tolerant to failures of rotating machinery that induce temporary lack of capacity. The analysis of the breakdown and operation failures of rotating machinery during run I has been performed. It demonstrates already a good level of reliability, with a mean time between failures (MTBF) in the order of 0.3 to 1.0 million hours. This confirms that on-the-shelves spares for rotating machinery is enough, with low probability to be required regularly. Having now one spare per type of machine, it will be possible to apply preventive exchange at a moment that will not disturb operations. The analysis of the origin of operation failures has identified domains where efforts should be continued. Relevant criteria for preventive and conditional maintenance are identified and should be considered, together with a more systematic analysis and documentation in order to keep tracks of the potentially decreasing number of failures.

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