6th Accelerator Reliability Workshop

Day 2 – Session 05 – Infrastructures

“LHC Cryogenic Infrastructure Reliability, towards High Availability”

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On behalf of CERN Cryogenics Group
OUTLOOK

Introduction

Operation scenarios

Basic functional analysis and critical failure modes

Availability definition and main downtime origins

Conclusion – Perspectives
LHC Cryogenic System Architecture

- circumference $\rightarrow \sim 27$ km,
- constructed at $\sim 100$ m underground,
- the accelerator ring inclination is 1.4 \%

LHC cryogenics:
- 8 x 18 kW @ 4.5 K
- 1800 sc magnets
- 24 km & 20 kW @ 1.8 K
- 37 000 tons @ 1.9 K
- 130 tons of helium inventory

A – upgraded ex-LEP cryo plant
B – new LHC cryogenic plant
LL – Low Load sector
HL – High Load sector

Compressor station
4.5 K refrigerator
Interconnection box
1.8 K pumping unit (cold compressor)
LHC Cryogenics Operation Timeline

Beam-induced heat load
≈ 10 W / half-cell*

Beam Energy
7 TeV
8 TeV
13 TeV
13 TeV

Time

RUN 1
2008
2009
2010
2011
2012

RUN 2
2013
2014
2015
2016
2017
2018

LONG SHUT DOWN 1

Year End Technical Stops

1st cooldown

≈ 130 W / half-cell*

*half-cell: LHC cryogenic half-cell of 53 m housing (among others) one local beam-screen cooling loop
LHC Cryogenic System Configurations

RUN 1

RUN 2

- **Compressor station**
- **Interconnection box**
- **4.5 K refrigerator**
- **1.8 K cold compressor**
- **In operation**
- **Stopped**
Basic Functional Analysis

CRITICAL EQUIPMENTS

Gas He storage
- Compressors 4.5K
- Compressors 1.8K

Liquid He storage
- Compressors 4.5K
- Compressors 1.8K

Electrical Supply
- LN2 & GN2 supply

Water Cooling
- Vacuum pumping

Compressors
- HP 1'680g/s 18bar
- MP 880g/s 3.9bar GHe 20K
- LP 800 g/s 1.05bar ScHe 4.5K

Vacuum pumping
- Liquid He storage
- Gas He storage

Electrical Supply
- LN2 & GN2 supply

Condensers
- Cold Box 4.5K
- Cold Box 1.8K
CRITICAL failure modes involve a potential unavailability of cryogenics for LHC for weeks or months: breakdown of a critical equipment without an alternative scenario.

MEDIUM & HIGH failure modes are likely to happen with a potential unavailability of cryogenics for LHC for hours or days.

LOW failure modes are acceptable and will have no or very limited impact on LHC.

All identified failure modes shall raise this level after implementation of a mitigation plan:
- Operation Back-up Plan
- Critical spare parts
- Engineering change
- Maintenance strategy
- Detectability improvement
# 52 compressors for 4.5 K Refrigerators

## Screw Compressors

<table>
<thead>
<tr>
<th>Technology</th>
<th>Volumetric compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependencies</td>
<td>Electrical supply</td>
</tr>
<tr>
<td></td>
<td>Water Cooling</td>
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<tr>
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<td>Pressurized Oil Lubrication</td>
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<tr>
<td>Considered</td>
<td>1. Bearings/mechanical breakdown</td>
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<td>Failures Modes &amp; Expected Patterns</td>
<td></td>
</tr>
<tr>
<td>Failure Rate</td>
<td>Low to medium</td>
</tr>
<tr>
<td>Detection method</td>
<td>Off line vibration monitoring, Oil analysis</td>
</tr>
<tr>
<td>Maintenance Strategy</td>
<td>Preventive major overhaul 40'000h</td>
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<tr>
<td>Equipment Lead time</td>
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<tr>
<td>MTTR</td>
<td>1 to 3 months</td>
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<tr>
<td>Replacement Time</td>
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### Failure Rate
- Low to medium

### Detection method
- Off line vibration monitoring, Oil analysis

### Maintenance Strategy
- Preventive major overhaul 40'000h
- Condition Based Monitoring

### Equipment Lead time
- Standard 4 to 8 months

### MTTR
- 1 to 3 months

### Replacement Time
- 2 to 3 days

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**Screw Compressors**

- **Technology**: Volumetric compression
- **Dependencies**: Electrical supply, Water Cooling, Pressurized Oil Lubrication
- **Considered Failures Modes & Expected Patterns**: 1. Bearings/mechanical breakdown
- **Failure Rate**: Low to medium
- **Detection method**: Off line vibration monitoring, Oil analysis
- **Maintenance Strategy**: Preventive major overhaul 40'000h, Condition Based Monitoring
- **Equipment Lead time**: Standard 4 to 8 months
- **MTTR**: 1 to 3 months
- **Replacement Time**: 2 to 3 days
52 compressors for 4.5 K Refrigerators

RISK ANALYSIS
At Point 4, 6 and 8:
- Low Pressure compressors capacities can be shared between cryoplants within margins of operation
- High Pressure compressors capacities can be shared between cryoplants but requires cryoplants configuration change and use of nitrogen pre-cooling

At Points 18 and 2:
- There is no operational margin for compression capacity
- Compressor stations cannot be interconnected

MITIGATION PLAN
- Critical spare parts:
  - 7 different types of compressors
  - 8 spares for 52 compressors in operation for LHC machine
  - 16% of the financial replacement asset value.
- Maintenance strategy includes major overhauling and vibration analysis to anticipate complete breakdown for compressors and motors
64 expansion turbines for 4.5 K Refrigerators

Cryogenic Expansion Turbines

<table>
<thead>
<tr>
<th>Technology</th>
<th>Gas bearing, rotating frequencies from 500Hz to 3kHz Specific but wide spread in the gas industry</th>
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<td>Dependencies</td>
<td>Water Cooling Vacuum insulation</td>
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<tr>
<td>Considered Failures</td>
<td>1. Breakdown caused by gas/charcoal pollution</td>
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<tr>
<td>Modes &amp; Expected Patterns</td>
<td></td>
</tr>
<tr>
<td>Failure Rate</td>
<td>Low to medium</td>
</tr>
<tr>
<td>Detection</td>
<td>None</td>
</tr>
<tr>
<td>Maintenance Strategy</td>
<td>No Preventive maintenance</td>
</tr>
<tr>
<td>Equipment Lead time</td>
<td>Standard 8 to 12 months</td>
</tr>
<tr>
<td>MTTR</td>
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Technology: Gas bearing, rotating frequencies from 500Hz to 3kHz
Specific but wide spread in the gas industry

Dependencies:
- Water Cooling
- Vacuum insulation

Considered Failures:
1. Breakdown caused by gas/charcoal pollution

Failure Rate: Low to medium
Detection: None
Maintenance Strategy: No Preventive maintenance
Equipment Lead time: Standard 8 to 12 months
MTTR: Standard 6 to 8 months
Replacement Time: 1 day
64 expansion turbines for 4.5 K Refrigerators

**RISK ANALYSIS**
- **Above 80K**: operation without turbines is possible with nearly no loss in refrigeration power as it can be compensated with LN2.
- **Down to 40K**: Turbines produce cooling power for screens and most of them are critical for LHC results in a considerable loss in refrigeration power.
- **Down to 4.5K**: Turbines produce cooling power for magnets, leads and cavities. Most of them are critical for LHC results in a considerable loss in refrigeration power.

**MITIGATION PLAN**
- **Turbine automation protection** in the process.
- **Service contract** to reduce MTTR below 4 weeks and avoid buying spare for turbines above 80K.
- **Critical spare parts:**
  - 27 different types of turbines.
  - 21 spares for 64 turbines in operation for LHC machine.
  - 32% of the financial replacement asset value.
28 cold compressors for 1.8 K Pumping Units

**Cryogenic Cold Compressor**

<table>
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<tr>
<th>Technology</th>
<th>Magnetic bearings, rotating at high frequencies Confidential technology</th>
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<tr>
<td>Dependencies</td>
<td>Electrical Supply Water Cooling Vacuum insulation</td>
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<tr>
<td>Failures Modes</td>
<td>1. Breakdown caused by rotor/welding fatigue</td>
</tr>
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<td>2. Stop or breakdown cause by electronic</td>
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<td>Considered</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Rate</td>
<td></td>
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<tr>
<td>Detectability</td>
<td>Clearance and diagnostic of magnetic bearing Fast landing bearings</td>
</tr>
<tr>
<td>Maintenance Strategy</td>
<td>Condition Based Monitoring</td>
</tr>
<tr>
<td>Equipment</td>
<td>Standard 12 to 18 months</td>
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<tr>
<td>Lead time</td>
<td></td>
</tr>
<tr>
<td>MTTR</td>
<td>6 to 12 months</td>
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**SIL RATING**

<table>
<thead>
<tr>
<th>Category</th>
<th>Critical</th>
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</tr>
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<tbody>
<tr>
<td>Major</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
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<tr>
<td>Minor</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
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</tr>
</tbody>
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**PROBABILITY**

- Remote
- Uncommon
- Occasional
- Frequent

**Cold Compressor**

- 3-phase induction Electrical motor (rotational speed: 200 to 800 Hz)
- Fixed-vane diffuser
- Axial-centrifugal Impeller (3D)

**Cryogenic Cold Compressor**

- 28 cold compressors for 1.8 K Pumping Units
- Magnetic bearings, rotating at high frequencies Confidential technology
- Electrical Supply Water Cooling Vacuum insulation
- 1. Breakdown caused by rotor/welding fatigue
- 2. Stop or breakdown cause by electronic
- Clearance and diagnostic of magnetic bearing Fast landing bearings
- Condition Based Monitoring
- Standard 12 to 18 months
- 6 to 12 months
- 1 to 2 days

**ARW2017 – Infrastructures – LHC Cryogenics**
RISK ANALYSIS

- In current configuration 1.8K is redundant on all points with one unit in operation and the second unit in cold stand-by

MITIGATION PLAN

- Power Supply and electronic design change to improve reliability
- Predictive maintenance with mechanical clearance and bearings check to validate service intervention on time
- Critical spare parts:
  - 7 different types of Cold Compressors
  - 7 spares for 28 units in operation for LHC
  - 25% of the financial replacement asset value.
Cryogenic Conditions Definition

Set of cryogenic conditions:

- to start powering (Cryo Start – CS)
- to keep the magnets powered (Cryo Maintain – CM)…

… and in the end to allow for beams to circulate, and for physics production!

~ 3500 conditions required to have LHC CM=1
Example for magnet temperature

Set of cryogenic conditions:
- to start powering (Cryo Start – CS)
- to keep the magnets powered (Cryo Maintain – CM)

Magnet Temperature (K)

- Cryo Maintain: 2.15 K
- Cryo Start: 2.05 K
- Operation Temperature: 1.90 K

Loss of cryo conditions

Diagnose, Repair (if needed), Restart

Temperature drift

Temperature decrease

Perturbation

Cryo conditions back, towards nominal

Availability impacted!
3 ways to lose availability:

- Act directly on level or temperature ⇔ Quench
- Act on one of the 4 root causes ⇔ Technical Services or Cryo Equipment
- The context ⇔ Ask for delayed injection

Example: loss of cooling water on a compressor station

Operational context (delayed injections, …)
Run 2 CryoMaintain Downtime

Average due operation time for Run 2:

5600 hours per year (\( \Leftrightarrow 233 \text{ days} \))

One should act both on:
- Most frequent losses
- Most time consuming losses
Run 2 CryoMaintain Downtime Origins

- Electrical feedboxes helium level oscillations: 58 losses, 68% of all losses, 72% of total cryo downtime
- Supercritical helium degradation: 56 losses
- Beam screen temperatures evolution: 25 losses, 139 out of 205 losses
- PLCs failures: 106 hours
- Cryoplants stops: 164 hours
- Tunnel instrumentation: 53 hours, 323 out of 447 hours

68% of all losses
72% of total cryo downtime
139 out of 205 losses
323 out of 447 hours
Conclusion – Perspectives

- Run 1 operation at lower than designed beam intensity gave cryogenic teams extensive experience with the complex LHC cryogenics system.
- Run 2 operation with increased beam-induced heat loads allowed for maintaining high level of availability while for the first time taking into account the beam feedback.
- Adapted maintenance and spare parts strategy based on equipment criticality is a key factor to maintain high availability.

- Extensive follow-up of the downtime origins together with close discussions with technical services allow for proposing adequate mitigation solutions to encountered problems, thus improving hardware reliability and finally availability.
- Optimization of the cryogenic performance is still ongoing, with work to collect more detailed failure data and use data-mining analysis to use early-warning signals.

Thank you for your attention!