6th Accelerator Reliability Workshop

Day 2 – Session 05 – Infrastructures

"LHC Cryogenic Infrastructure Reliability, towards High Availability"

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ARW2017
Accelerator Reliability Workshop

OUTLOOK

Introduction

- Operation scenarios
- Basic functional analysis and critical failure modes
- Availability definition and main downtime origins

Conclusion – Perspectives

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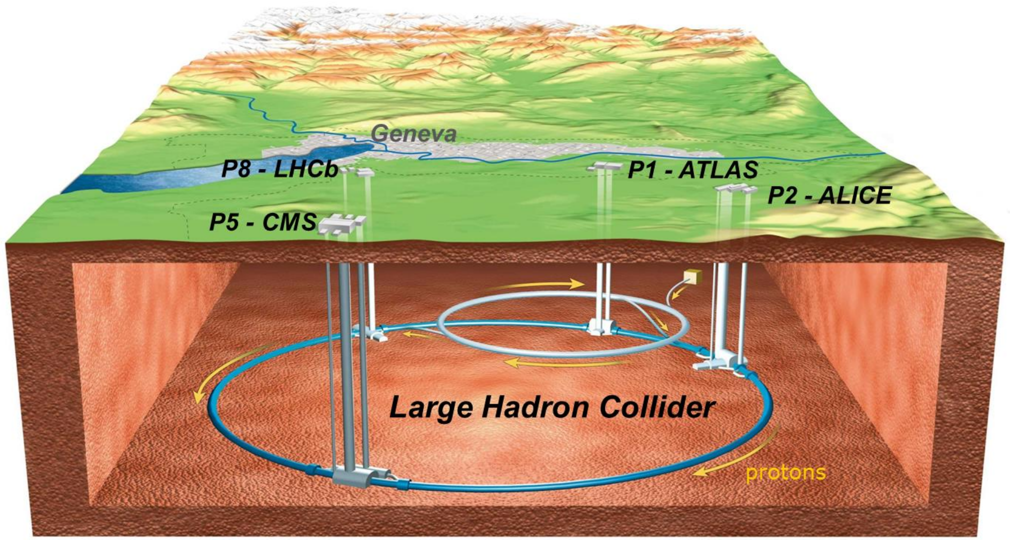
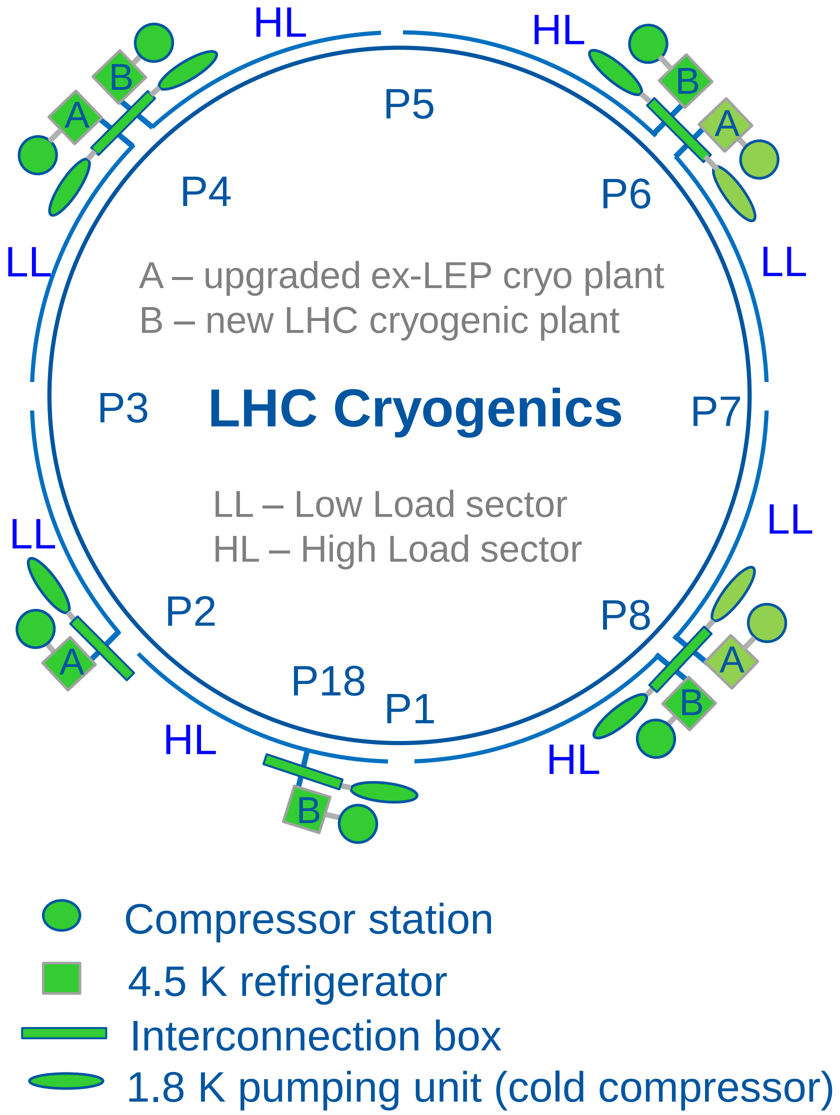
LHC Cryogenic System Architecture



- **circumference ➔ ~ 27 km,**
- **constructed at ~ 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



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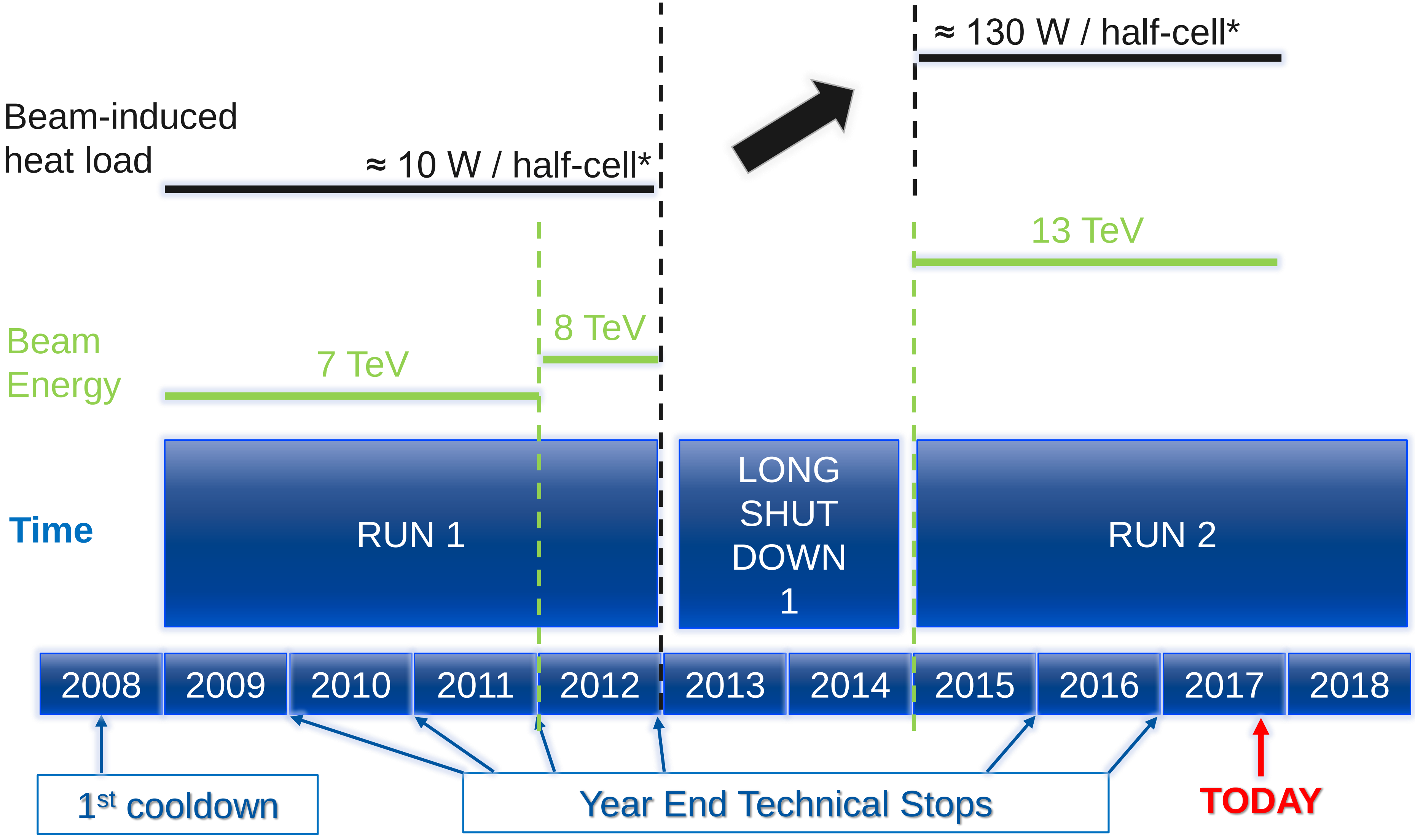
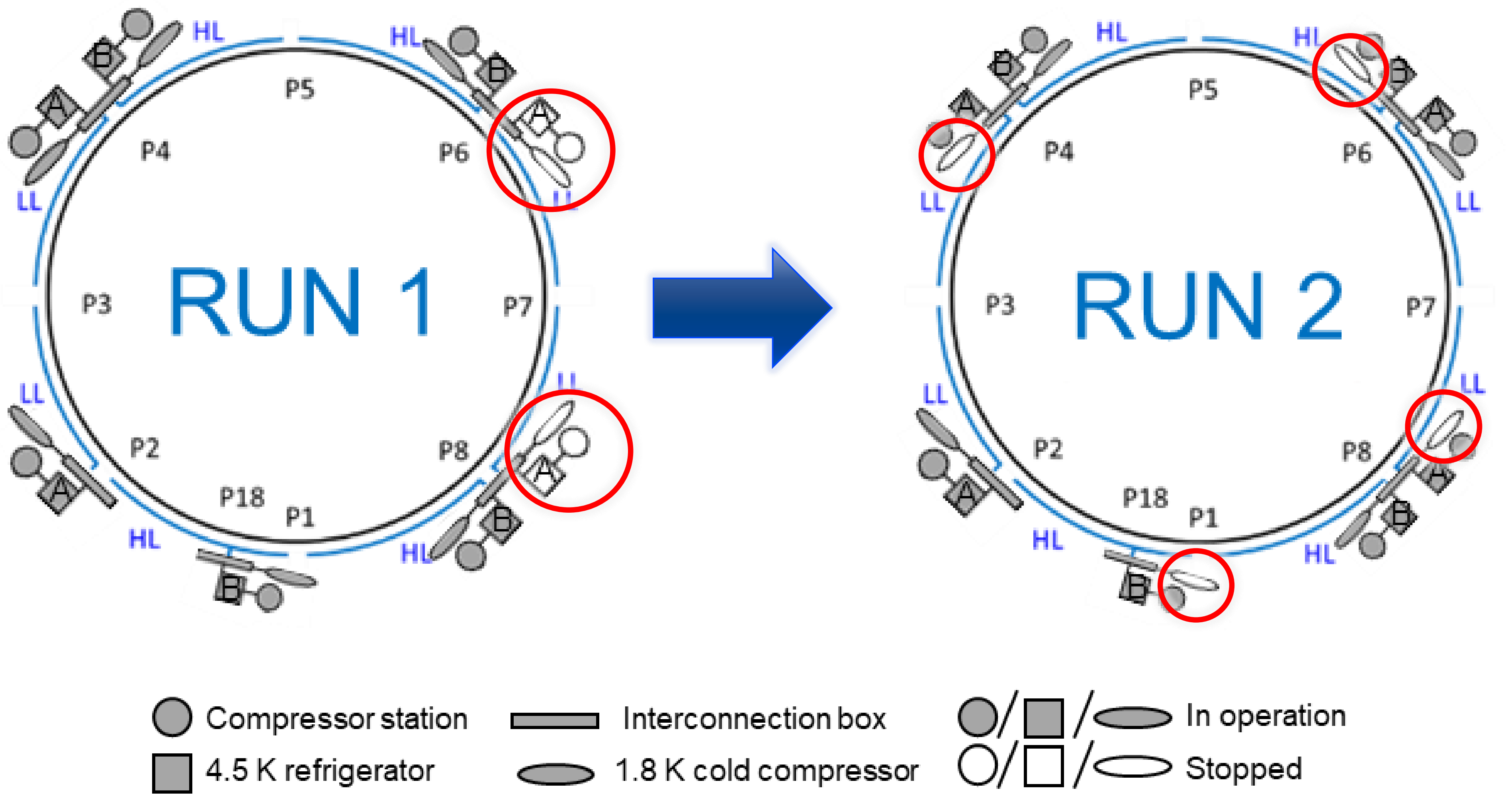
LHC Cryogenics Operation Timeline

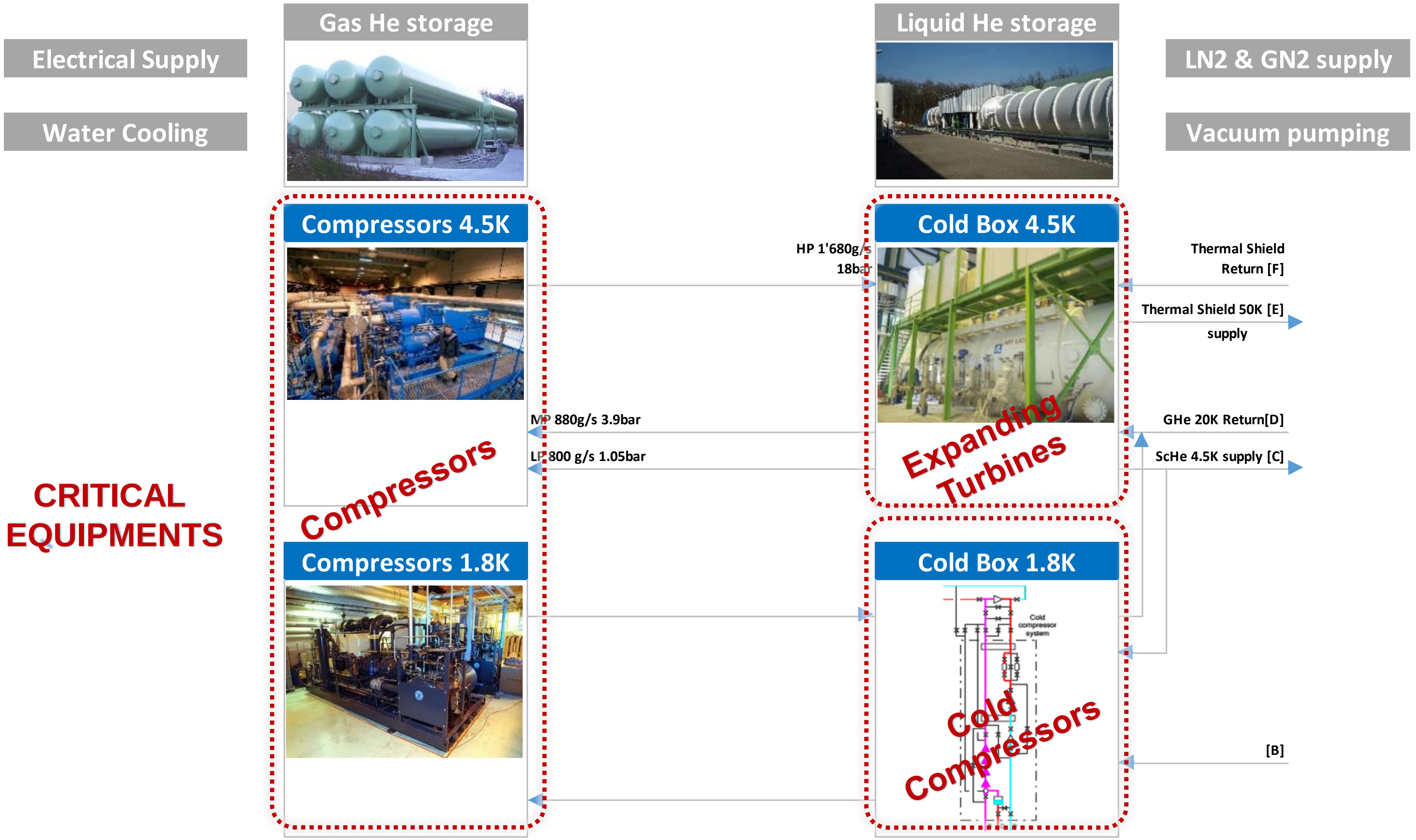


*half-cell: LHC cryogenic half-cell of 53 m housing (among others) one local beam-screen cooling loop

LHC Cryogenic System Configurations



Basic Functional Analysis



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Critical Failure Modes

SEVERITY \ PROBABILITY	Remote	Uncommon	Occasional	Frequent
Catastrophic	Critical	Critical	Critical	Critical
Major	Low	Medium	High	High
Moderate	Low	Low	Medium	High
Minor	Low	Low	Low	Low

CRITICAL means a potential unavailability of cryogenics for LHC for **weeks or months**: breakdown of a critical equipment without alternative scenario.

MEDIUM & **HIGH** means that failure is likely to happen with a potential unavailability of cryogenics for LHC for **hours** or **days**.

LOW means that risk of failure is 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

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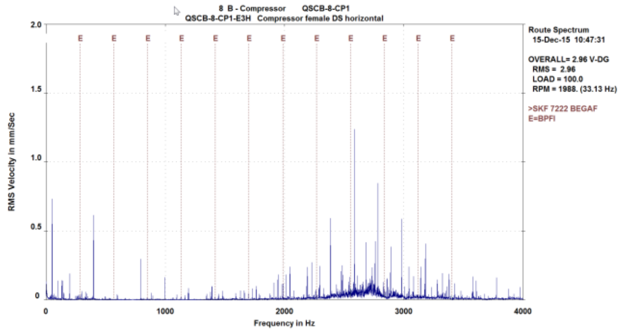
52 compressors for 4.5 K Refrigerators



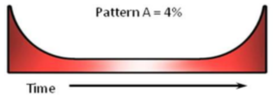
Screw Compressors	
Technology	Volumetric compression Industrial standard adapted to helium
Dependencies	Electrical supply Water Cooling Pressurized Oil Lubrication
Considered Failures Modes & Expected Patterns	**1. Bearings/mechanical breakdown** 
Failure Rate	Low to medium
Detection method	Off line 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

Fig. 2: The inner ring with 2 flaked areas. One flaked area is identified by the arrow.

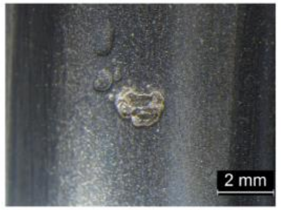
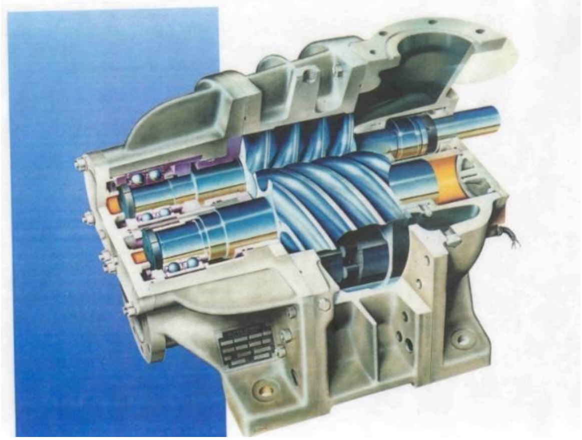
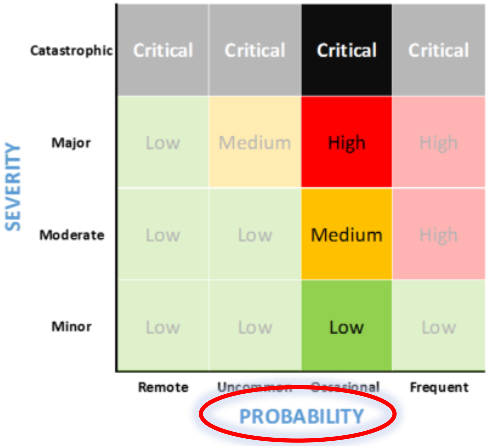


Fig. 3: Detail photo of the flaked area from Fig. 2.





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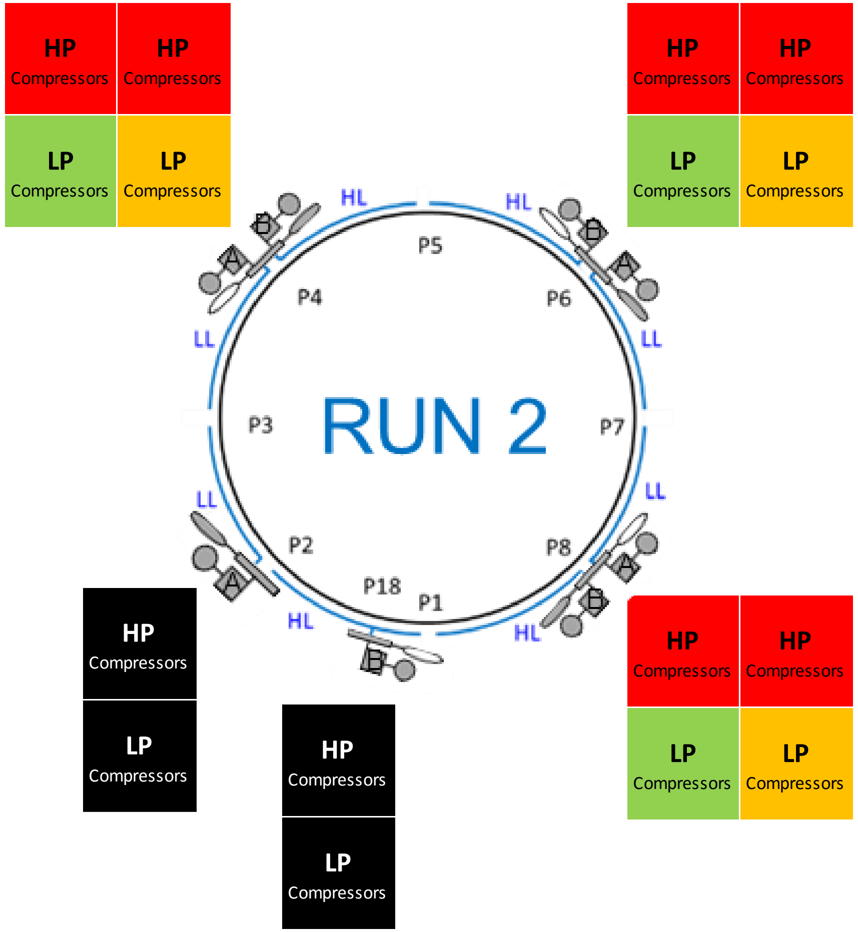
52 compressors for 4.5 K Refrigerators



	Remote	Uncommon	Occasional	Frequent
Catastrophic	Critical	Critical	Critical	Critical
Major	Low	Medium	High	High
Moderate	Low	Low	Medium	High
Minor	Low	Low	Low	Low

SEVERITY / PROBABILITY

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 cyoplants 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

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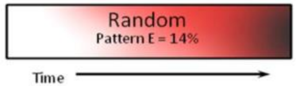
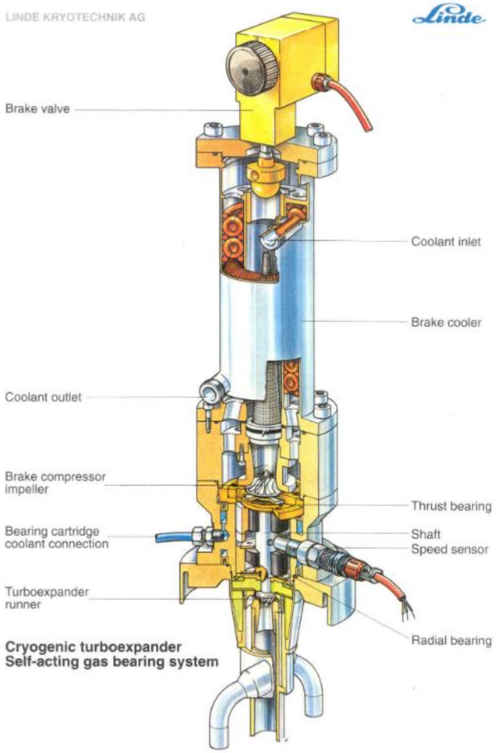
64 expansion turbines for 4.5 K Refrigerators

Cryogenic Expansion Turbines	
Technology	Gas bearing, rotating frequencies from 500Hz to 3kHz Specific but wide spread in the gas industry
Dependencies	Water Cooling Vacuum insulation
Considered Failures Modes & Expected Patterns	**1. Breakdown caused by gas/charcoal pollution** 
Failure Rate	Low to medium
Detection	None
Maintenance Strategy	No Preventive maintenance Run to fail
Equipment Lead time	Standard 8 to 12 months
MTTR	Standard 6 to 8 months
Replacement Time	1 day

SEVERITY	Remote	Uncommon	Occasional	Frequent
Catastrophic	Critical	Critical	Critical	Critical
Major	Low	Medium	High	High
Moderate	Low	Low	Medium	High
Minor	Low	Low	Low	Low

PROBABILITY



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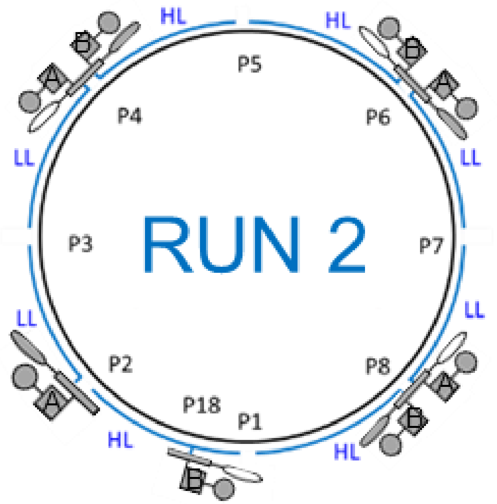
64 expansion turbines for 4.5 K Refrigerators

Above 80K	
Down to 40K	Down to 40K
Down to 4.5K	Down to 4.5K



SEVERITY	Remote	Uncommon	Occasional	Frequent
Catastrophic	Critical	Critical	Critical	Critical
Major	Low	Medium	High	High
Moderate	Low	Low	Medium	High
Minor	Low	Low	Low	Low

PROBABILITY

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.

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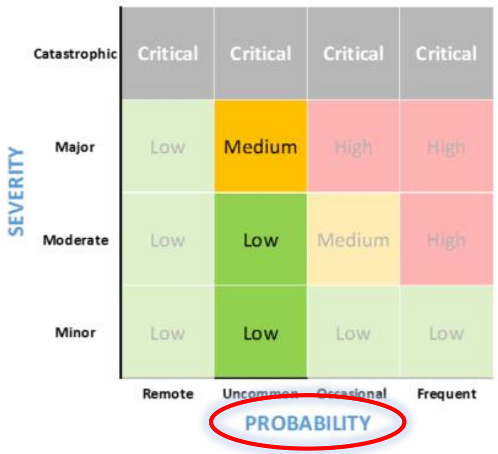
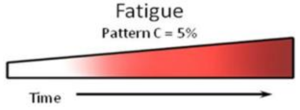
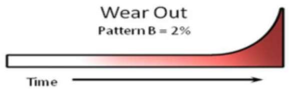
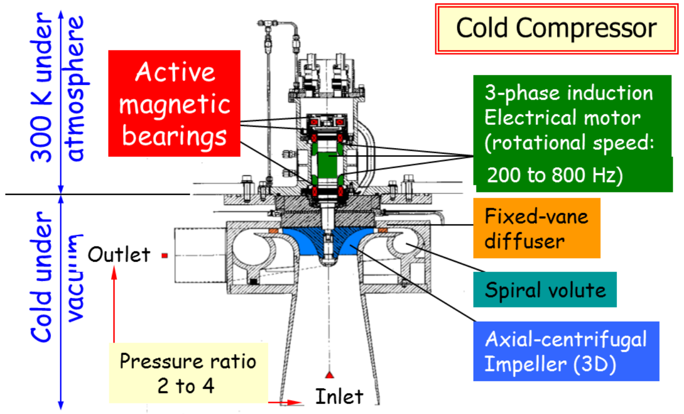
28 cold compressors for 1.8 K Pumping Units



Cryogenic Cold Compressor	
Technology	Magnetic bearings, rotating at high frequencies Confidential technology
Dependencies	Electrical Supply Water Cooling Vacuum insulation
Considered Failures Modes & Expected Patterns	1. **Breakdown caused by rotor/welding fatigue**  2. Stop or breakdown cause by electronic 
Failure Rate	
Detectability	Clearance and diagnostic of magnetic bearing Fast landing bearings
Maintenance Strategy	Condition Based Monitoring
Equipment Lead time	Standard 12 to 18 months
MTTR	6 to 12 months
Replacement Time	1 to 2 days



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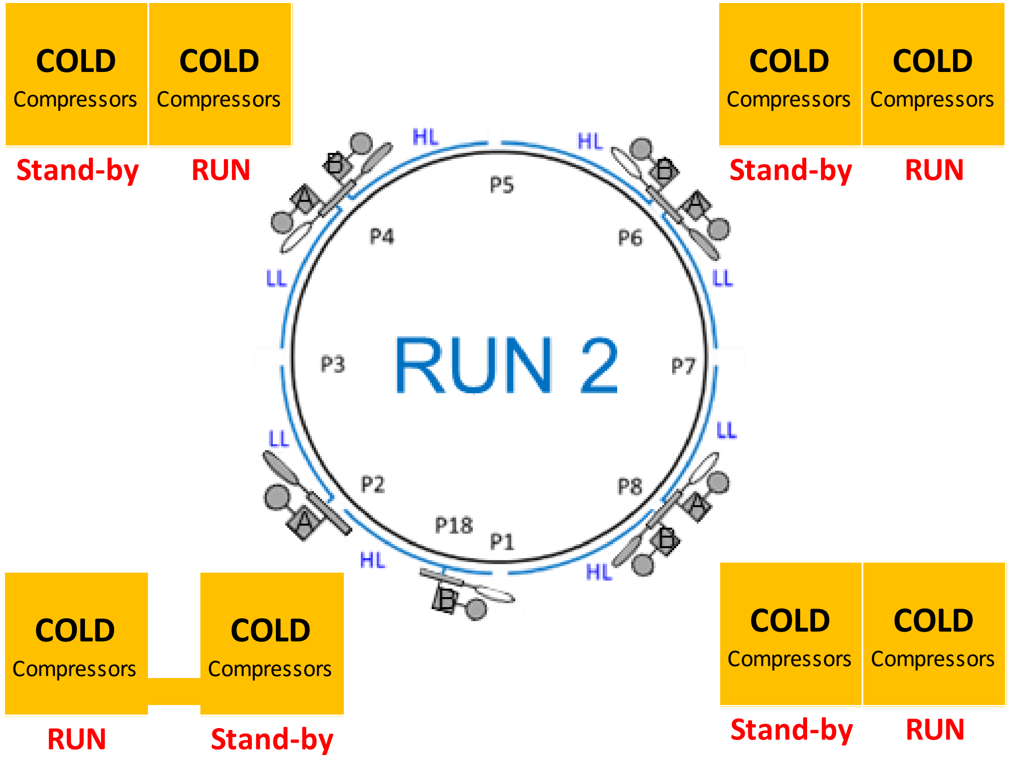
28 cold compressors for 1.8 K Pumping Units



SEVERITY				
Catastrophic	Critical	Critical	Critical	Critical
Major	Low	Medium	High	High
Moderate	Low	Low	Medium	High
Minor	Low	Low	Low	Low
	Remote	Uncommon	Occasional	Frequent
	PROBABILITY			

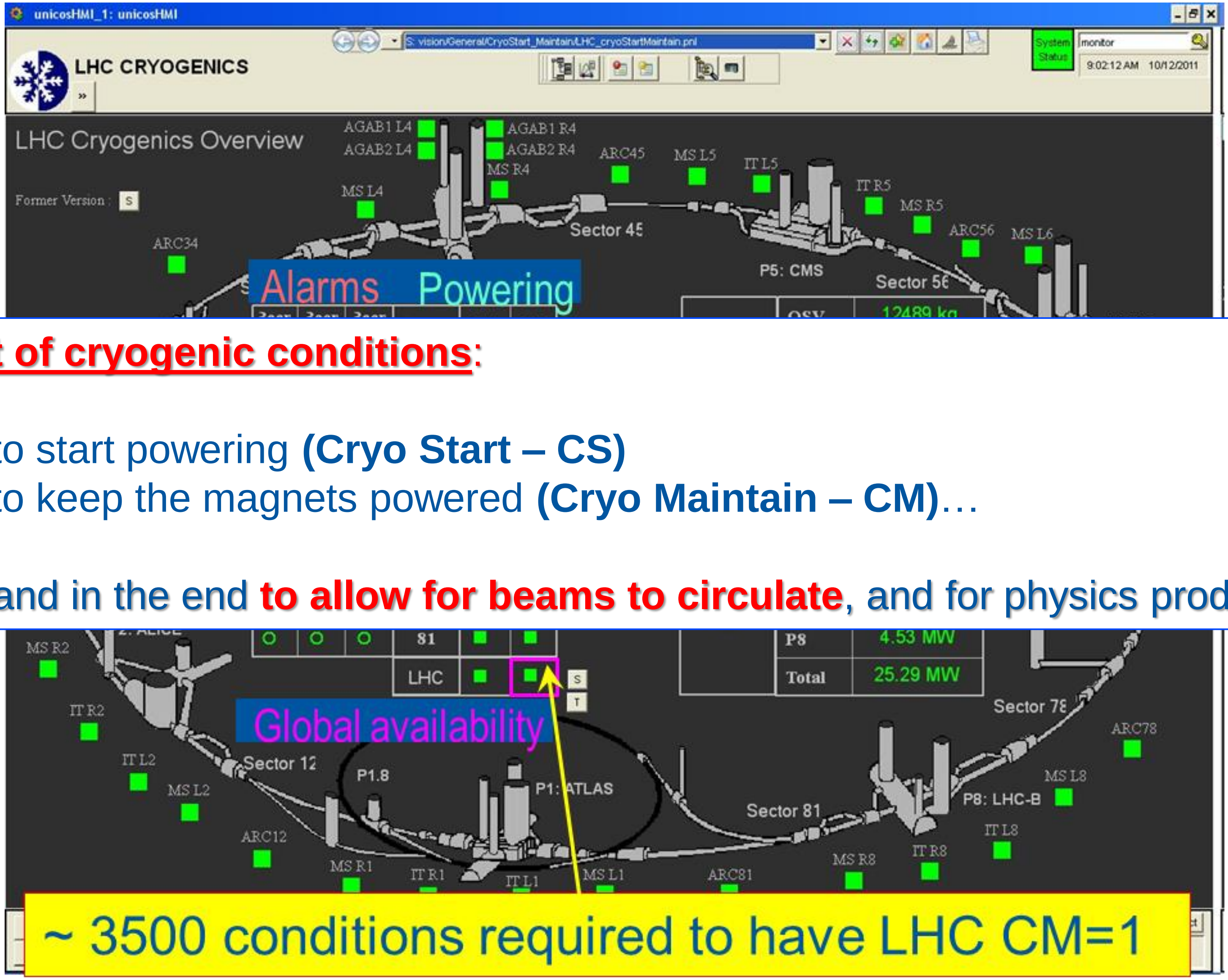
RISK ANALYSIS

- 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:

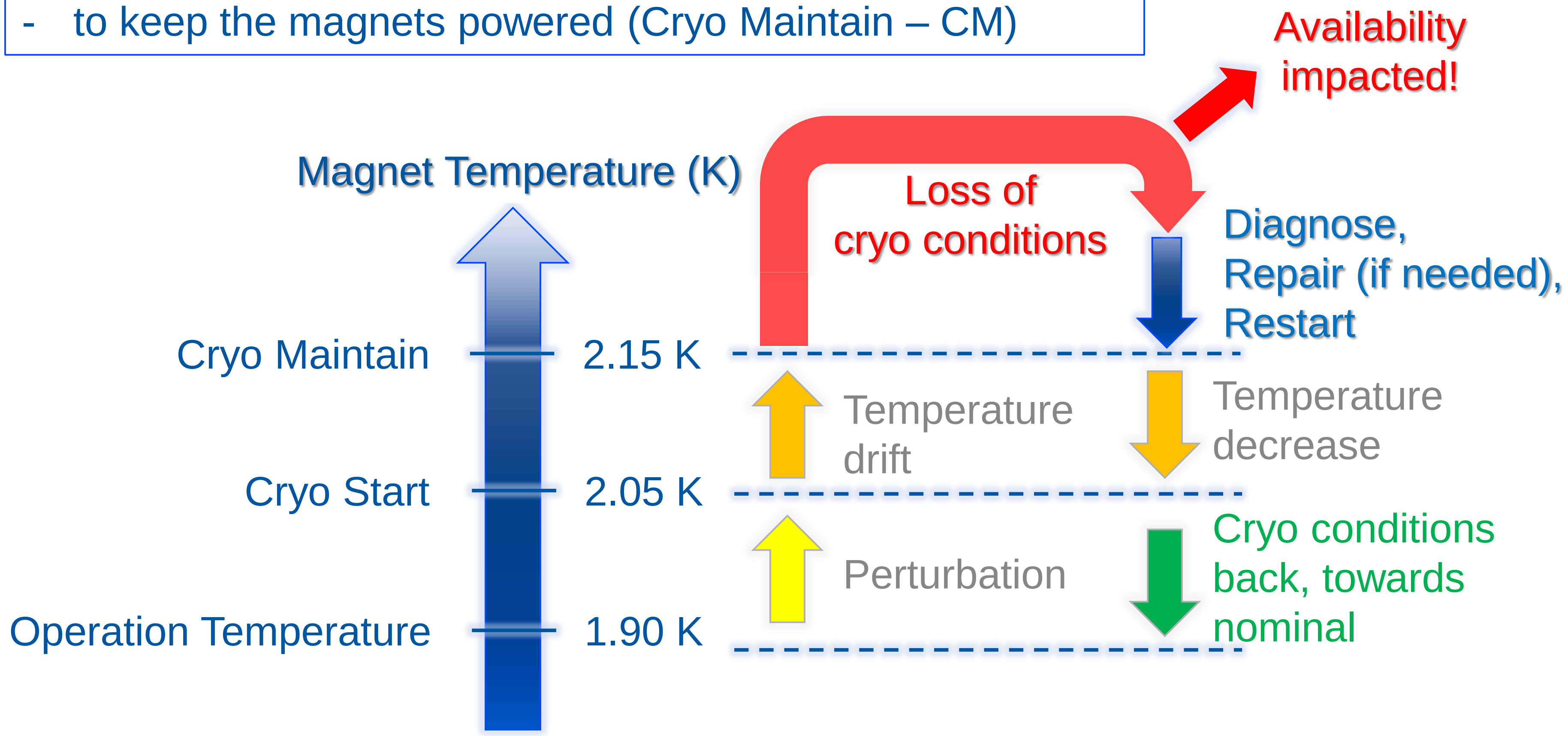
- to start powering **(Cryo Start – CS)**
- to keep the magnets powered **(Cryo Maintain – CM)**…

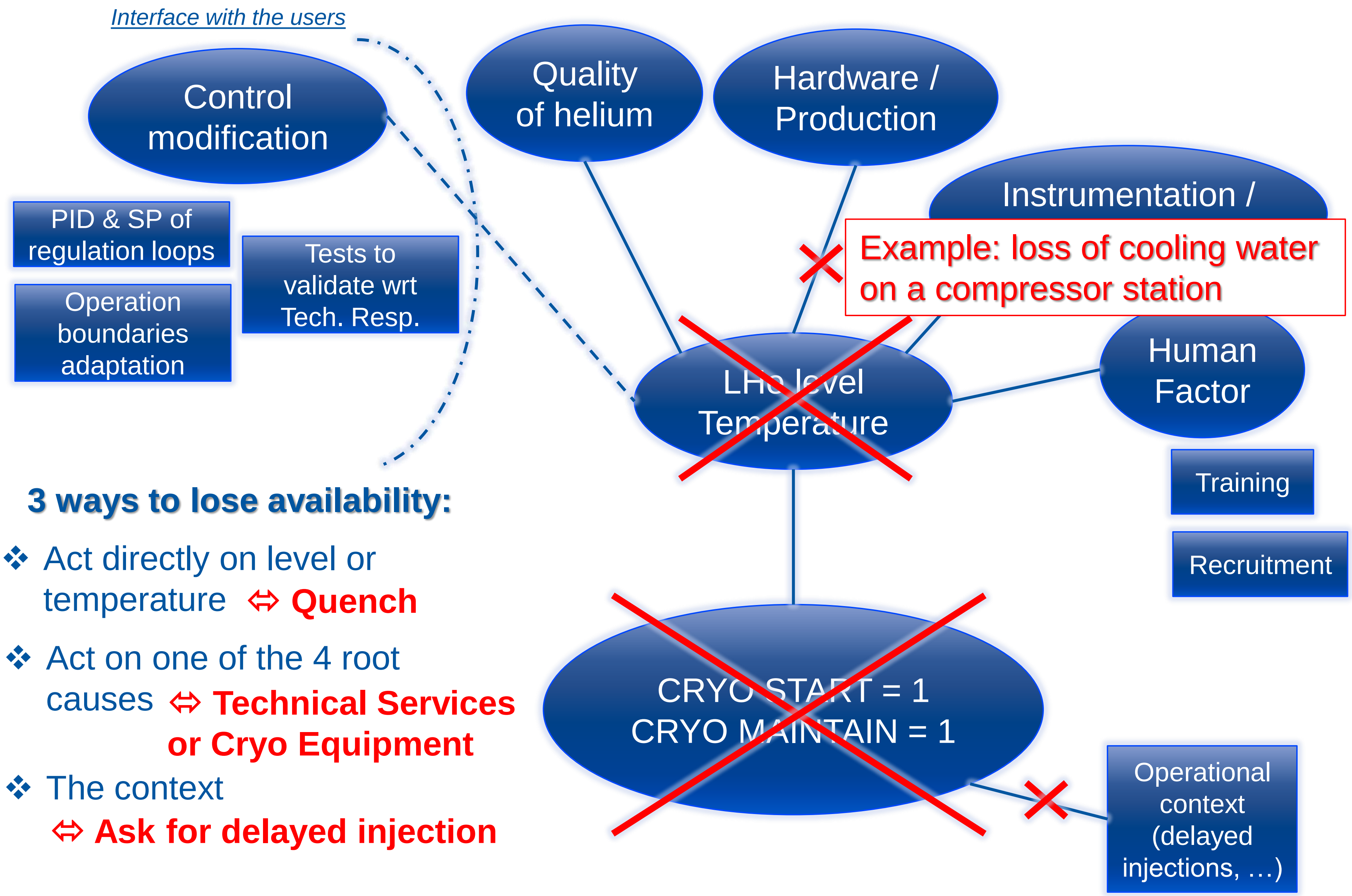
… and in the end **to allow for beams to circulate**, and for physics production !

~ 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)





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**

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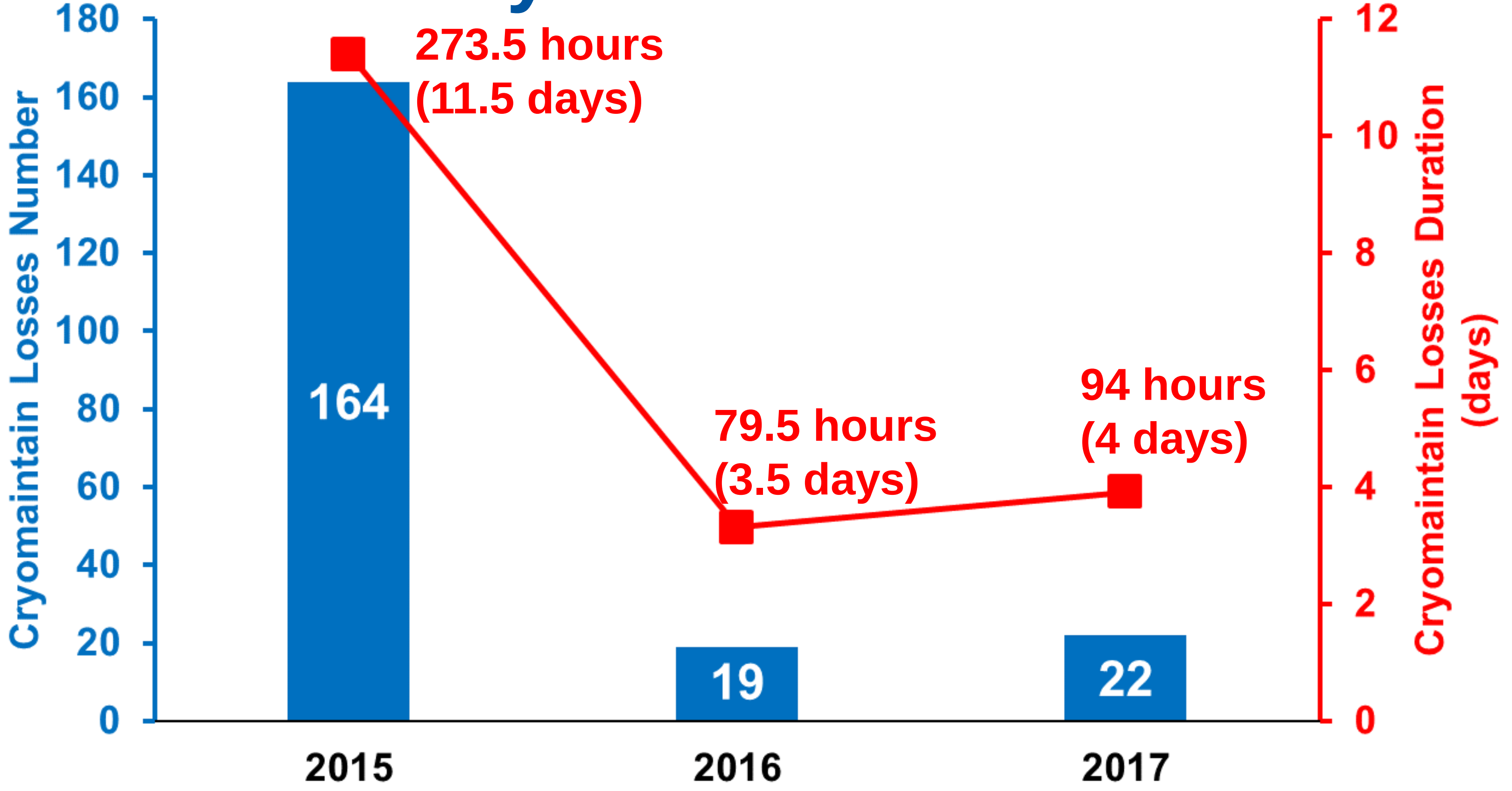
Run 2 CryoMaintain Downtime



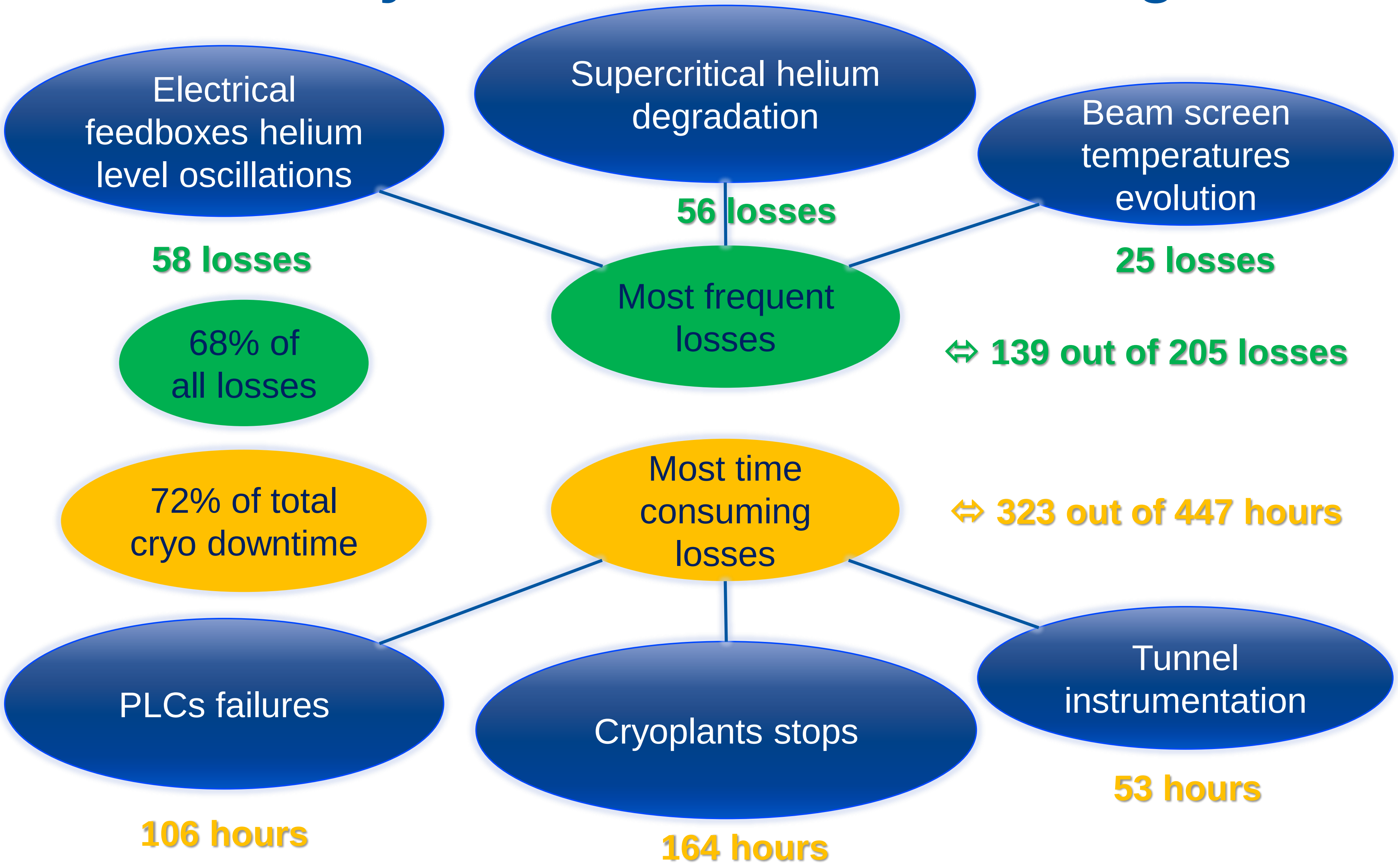
Average due operation time for Run 2:

5600 hours per year (⬄ 233 days)

One should act both on:

- Most frequent losses
- Most time consuming losses

Run 2 CryoMaintain Downtime Origins



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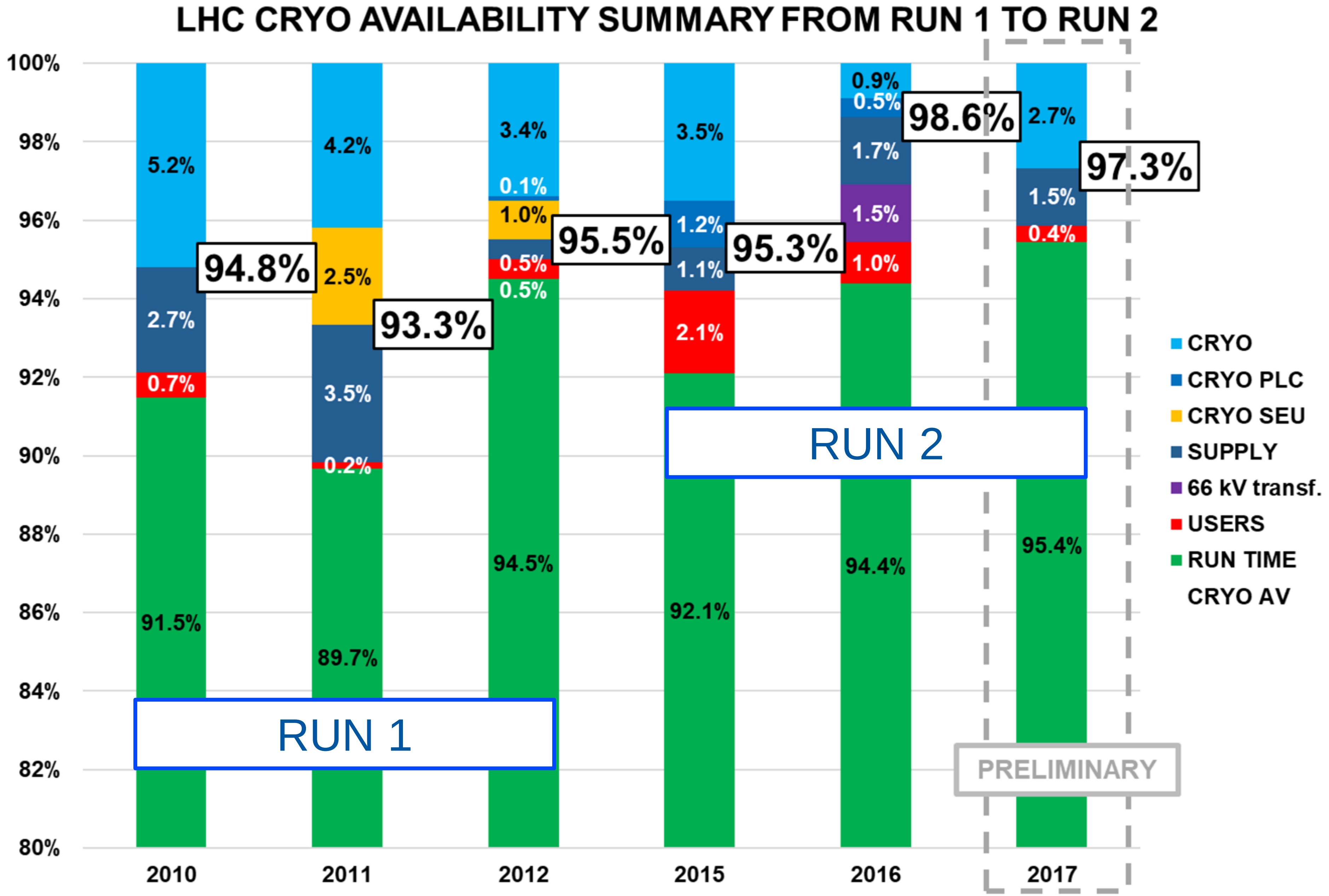

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Conclusion – Perspectives

- 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!

Questions ?

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