Maintenance and recommissioning of the LHC cryogenic system for the physics RUN3

October 17th, 2022

On behalf of CERN Cryogenics Group

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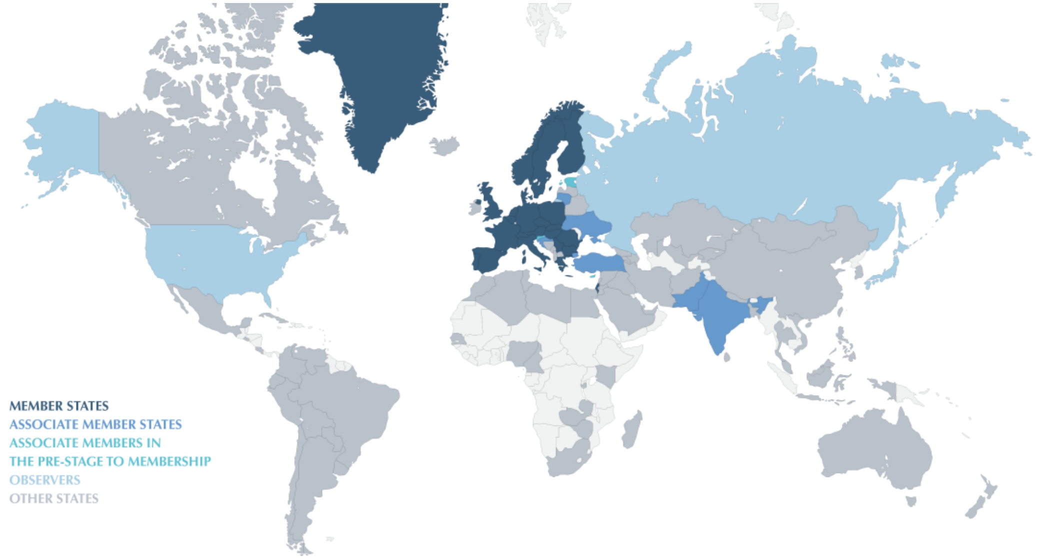
Outline

- CERN overview
- LHC cryogenics timeline and requirements
- Analysis of availability during previous running period
- Maintenance and consolidation strategies
- Expected improvements on reliability
- New challenges for current running period
- Preliminary availability results 2022

CERN, European Organization for Nuclear Research

An Intergovernmental Organisation for the High Energy Physics Research



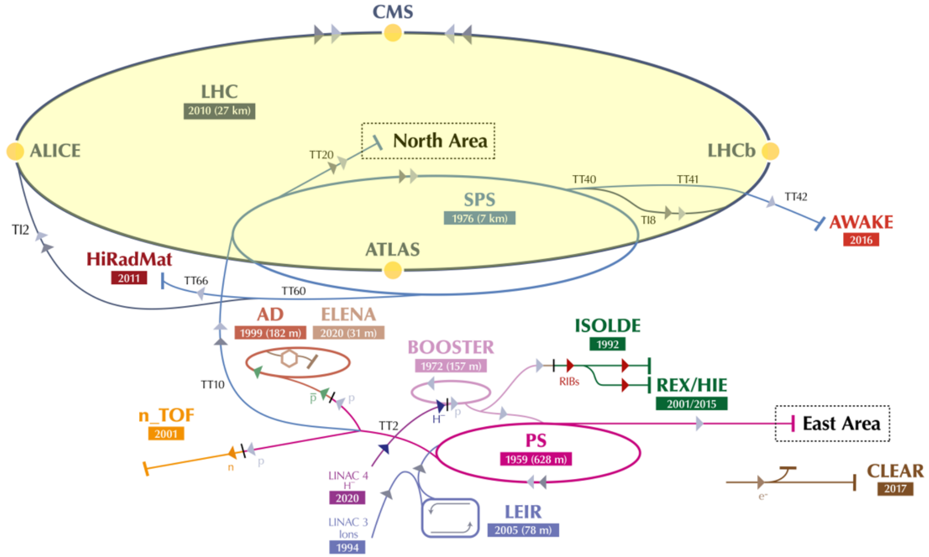
Today CERN has 23 Member States: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and United Kingdom

Cyprus, Estonia and Slovenia are Associate Member States in the pre-stage to Membership

Croatia, India, Latvia, Lithuania, Pakistan, Turkey and Ukraine are Associate Member States.

Japan and the United States of America hold Observer status with respect to the LHC, while the United States of America also holds Observer status with respect to the HL-LHC. The international organisations European Union and UNESCO currently have Observer status at CERN. The Observer status of the Russian Federation is suspended in accordance with the CERN Council Resolution of 8 March 2022. The Observer status of JINR is suspended in accordance with the CERN Council Resolution of 25 March 2022.Observer status has in the past been granted to States and international organisations.

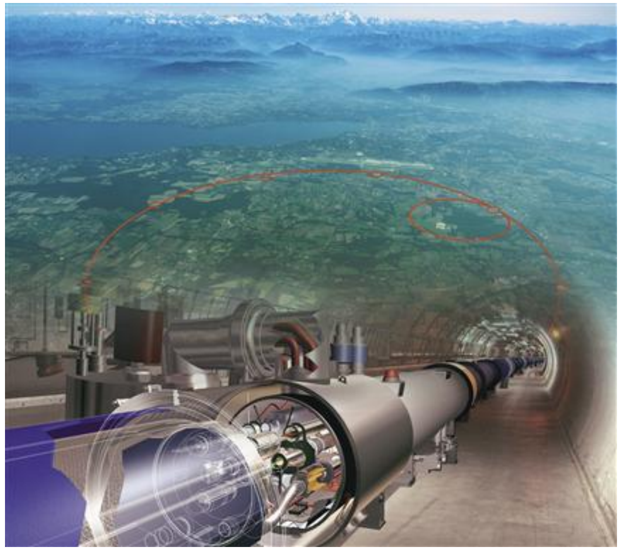
The accelerator complex at CERN is a succession of machines that accelerate particles to increasingly higher energies. Each machine boosts the energy of a beam of particles, before injecting the beam into the next machine in the sequence. In the Large Hadron Collider (LHC) – the last element in this chain – particle beams are accelerated up to the record energy of 6.8 TeV per beam. Most of the other accelerators in the chain have their own experimental halls where beams are used for experiments at lower energies.



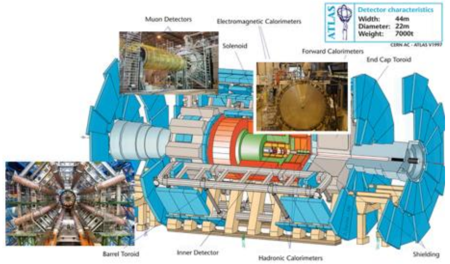
The LHC cryogenic system, among the most complex and powerful in the world, allows the cooling of the **superconducting magnets distributed over the 26.7 km of the accelerator's underground ring down to super fluid helium temperature at 1.9 K.** In the physics detectors, it will also cool down the large spectrometer magnets at their operating temperature of 4.5 K.

Helium cryogenics for LHC

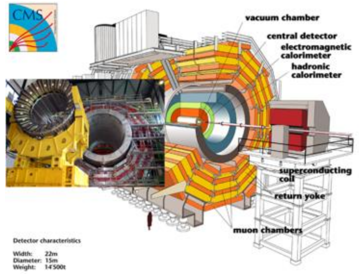
LHC accelerator and experiments
SERVICE SYSTEM



LHC 36'000 tonnes of cold mass distributed over the 26.7 km underground accelerator



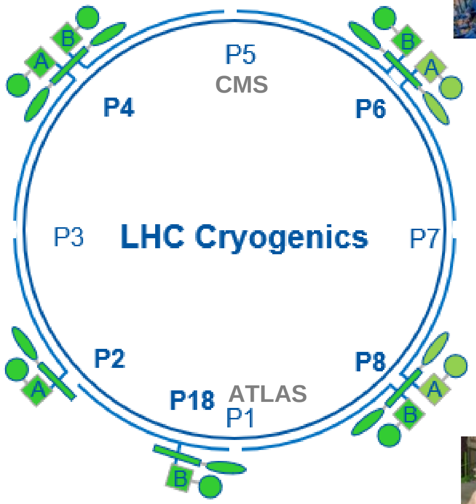
ATLAS 1'275 tonnes of cold mass



CMS 225 tonnes of cold mass

LHC accelerator 25 km @1.9 K of the superconducting magnets
ATLAS cooling @4.5 K of the superconducting magnetic system
CMS cooling @4.5 K of the superconducting solenoid

LHC cryogenics infrastructure

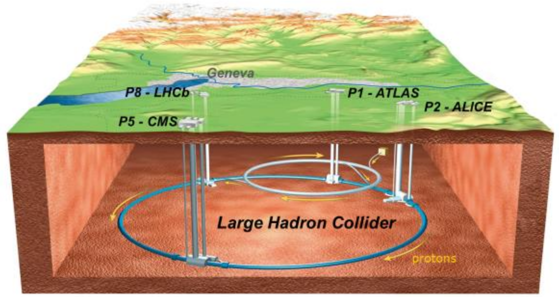


Compressor Stations

4.5K Cold Boxes

Liquid & Gas storages

SURFACE



UNDERGOUND

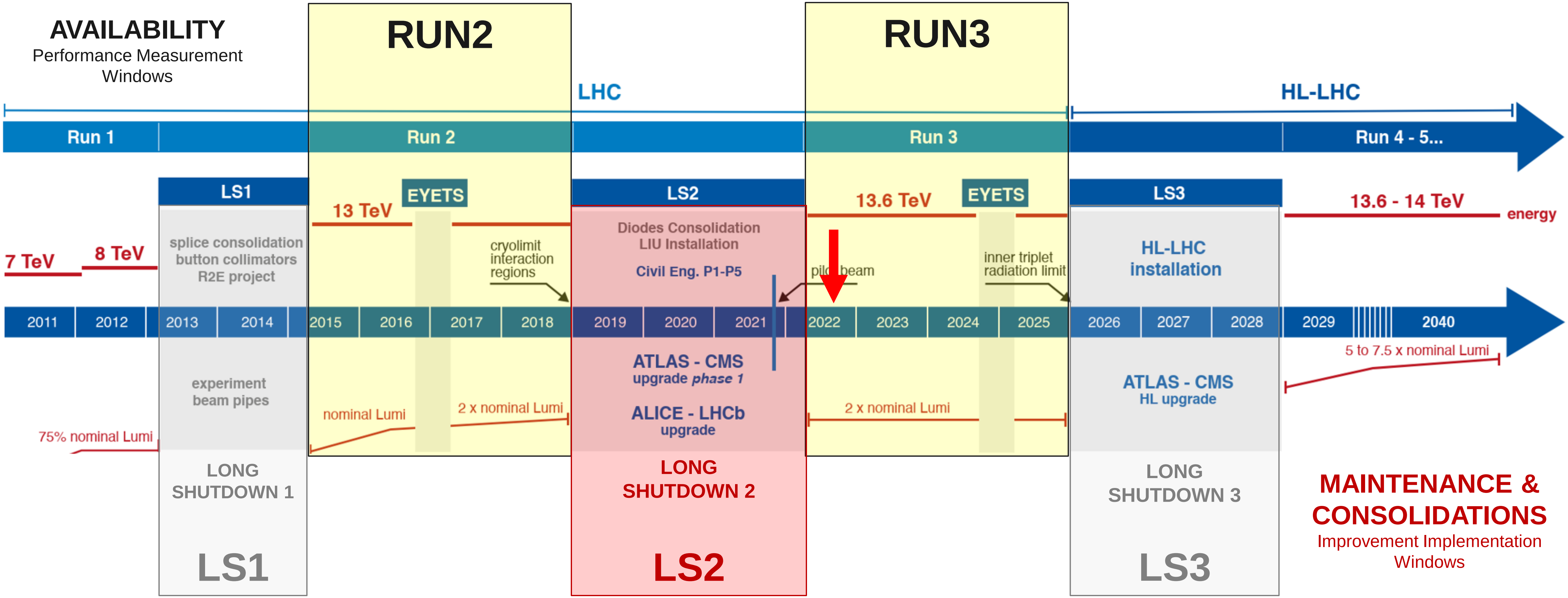
4.5K & 1.8K Cold Boxes

Distribution Valve Boxes

Distribution

Cryogenics Plants are **distributed around the LHC**
The accelerator cryogenics supply is **divided in 8 sectors**
Cryogenics plants are **interconnected**

LHC cryogenics timeline and requirements



MEASURE & ANALYSE → **IMPROVE** → **CONTROL**

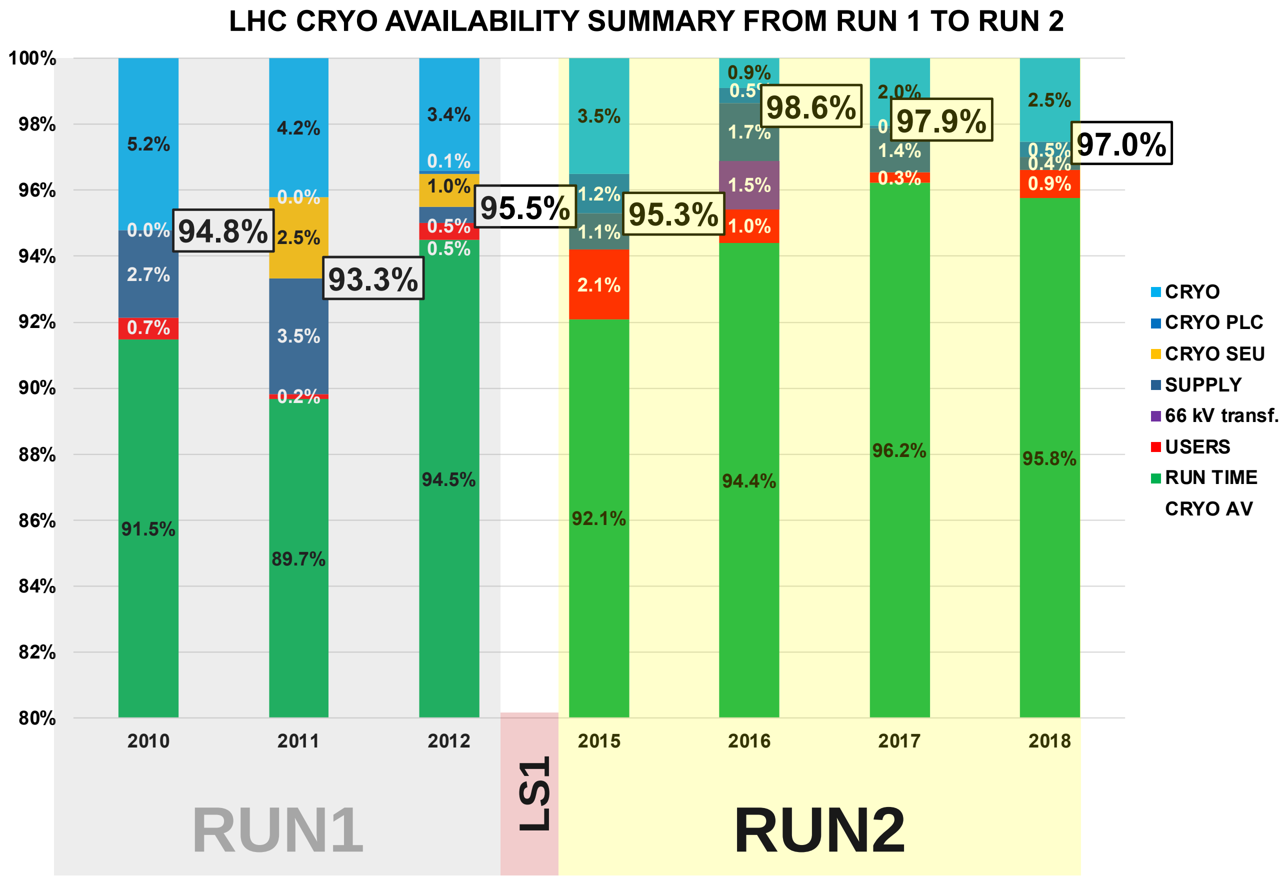
LHC RUN2 performance measurement

Cryogenics **Fault Tracking** categories & interdependencies

Sub systems used for statistics	Comments
CRYO-PROD-4.5K	Compressors, ORS, dryers, turbines, ADS - any mechanical failure
CRYO-PROD-1.8K	Compressors, ORS, turbines, ADS - any mechanical failure
CRYO-PROD-QUI	Any failure related to QUI
CRYO-PROD-VAC	Insulation vacuum of cold boxes and QUI
CRYO-PROD-INSTRUM	Valves, electrical heaters, sensors
CRYO-PROD-CONTROL	Software
CRYO-PROD-PLC	Surface installations PLCs
CRYO-PROD-SEU	Single event upsets in electronics due to radiation in operation environment
CRYO-PROD-OTHER	Other cryo production related issue
CRYO-TUNNEL-INSTRUM	Sensors, electrical heaters (except for EH893, under TE-MPE responsibility), valves
CRYO-TUNNEL-CONTROL	Software
CRYO-TUNNEL-PLC	Tunnel installations PLCs
CRYO-TUNNEL-SEU	Single event upsets in electronics due to radiation in operation environment
CRYO-TUNNEL-OTHER	Other cryo tunnel related issue
CRYO-OP-PNO-DFB	LHe level oscillation in a distribution feed box
CRYO-OP-PNO-SAM	LHe level oscillation in a standalone magnet
CRYO-OP-PNO-REF	Refrigerator tuning not optimized
CRYO-OP-PNO-BSCR	Beam screen regulation related issue
CRYO-OP-PNO-HF	Human factor in cryogenics operation, causing downtime (human or procedure)
CRYO-OP-PNO-OTHER	Other non-optimization leading to downtime

Technical Services → **Cryogenics Equipment** ← Users

LHC RUN2 performance measurement



Analysis of RUN2 unavailability

with root cause associated to Cryogenics

CRYO FAULT TRACKING SUMMARY

Year	CRYO Losses count	Cumulated Loss duration (h:m)
2015	166	259:20
2016	27	92:17
2017	27	107:20
2018	20	172:34
Total	**240**	**631:31**

Loss of Cryo Maintain conditions

Prioritization of actions to improve availability

CRYO FAULT TRACKING

Sub System 1	Sub System 2	Events	Cumulated Loss duration (h:m)
PRODUCTION	1.8K	19	176:12
PRODUCTION	PLC	8	130:37
PRODUCTION	INSTRUMENTATION	13	73:37
TUNNEL	INSTRUMENTATION	38	67:09
PRODUCTION	4.5K	5	65:33
OPERATION	HUMAN FACTOR	8	56:45
OPERATION	DFB	121	27:11
PRODUCTION	CONTROL	1	12:52
OPERATION	PROCESS NOT OPTIMIZED	1	10:47
OPERATION	PROCESS NOT OPTIMIZED	3	4:07
PRODUCTION	VACUUM	2	2:56
TUNNEL	PLC	1	2:22
OPERATION	STAND ALONE MAGNET	12	1:05
Other		8	0:18
Total		**240**	**631:31**

CONSOLIDATION

RELIABILITY IMPROVEMENT PROGRAM

Refurbishment of Cold Compressor electrical cabinet and process control

CONSOLIDATION

END OF LIFE PROGRAM

Replacement of control PLC and consolidation of CEM to reduce failure rate

PROCESS REVIEW

Process review and measurement oil removal performance to identify deviations and adapt coalescing filters in some cases

PROCEDURE & TRAINING

Review of procedures used in Control Room for critical restarts and operator training

Consolidation programs at a glance

Table 3. Main cryogenics consolidation activities of the LS2.

Objective	Project	Volume
Reliability improvement	High stage compressors bearing size increase	11 compressors
	Oil pumps with magnetic couplings	12 pumps
	Refurbishment of Cold Compressor electronic	4 installations
	Switchable water-cooling filters	5 filters
	Cryogenic temperature sensors replacement	320 sensors
	Replacement of ATLAS MR compressor	1 compressor
End of life management	LHC old generation PLC upgrade	71 PLC
	Experiment cryogenics control electric upgrade	10 PLC
	Refurbishment of electrical cabinets	24 units
	Compressor set cable replacement	3’000 m of cable
	Instrumentation cable replacement	800 m of cable
	Oil pumps with magnetic couplings	16 pumps
New functionalities	LHC global mass flow measurement at cold	7 flowmeters

Cryogenics infrastructure maintenance plan

Compressor station & Oil Removal System

PREDICTIVE Maintenance program – Condition Based Monitoring

	Checked	Criteria
Vibration analysis	Monthly	Multiple : spectrum analysis, RMS
Oil analysis program	Yearly	Multiple : oxidation, particles
Electrical cabinets thermography	Yearly	Over heating temperature
Critical instrumentation checks	4-Yr	Deviating value

PREVENTIVE Maintenance program

Oil pumps Revision	8'000(minor) & 24'000(major) running hours
Activated charcoal load replacement	24'000 running hours
Coalescing filters replacement	None or 24'000 running hours
Screw compressor Major Overhauling	40'000 running hours
High Voltage Motors	30'000(bearings) & 40'000(sleeve bearings) running hours
Vacuum pumps revisions	8'000 to 40'000 running hours
Safety chain check	Yearly
Safety valves test bench test	2-Yr, 4Yr, 5-Yr
Water Heat Exchangers chemical cleaning	4-Yr
Critical instrumentation & valves check	4-Yr

Cold Boxes

PREDICTIVE Maintenance program – Condition Based Monitoring

	Checked	Criteria
Electrical cabinets thermography	Yearly	Over heating temperature
Critical instrumentation checks	4-Yr	Deviating value
Cold Compressors	4-Yr	Mechanical clearance
Heat exchangers	4-Yr	Tightness test
Turbine filters	Yearly	Delta P

PREVENTIVE Maintenance program

Safety valves test bench or local test	2-Yr, 4Yr, 5-Yr
Safety chain check	Yearly
Water Heat Exchangers chemical cleaning	4-Yr
Vacuum pumps revisions	8'000 to 24'000 running hours
Critical valves & instrumentation check	4-Yr
Turbine filters	4-Yr (when vacuum break required)

RUN to FAIL

- Turbines

Storage, Distribution & Cryostat

PREDICTIVE Maintenance program – Condition Based Monitoring

	Checked	Criteria
Line integrity test during warm-up	4-Yr	Pressure and vacuum tests
Critical instrumentation checks	4-Yr	Deviating value
Critical valves check	4-Yr	Leak tightness
Capacity legal pressure check	10-Yr	Pressure test according to EU

PREVENTIVE Maintenance program

Safety valves	2-Yr, 4Yr, 5-Yr
Safety chain check	Yearly
Vacuum pumps revisions	8'000 to 24'000 running hours
Critical valves check	4-Yr
Critical instrumentation check	1 to 4-Yr

Compressor preparation for shipment

Heat exchanger mechanical cleaning

Oil pumps maintenance

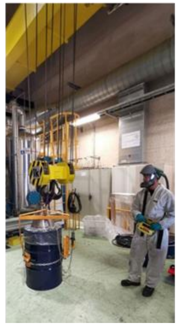
Dryer molecular sieve replacement

Calibration of instrumentation

Coalescer replacement

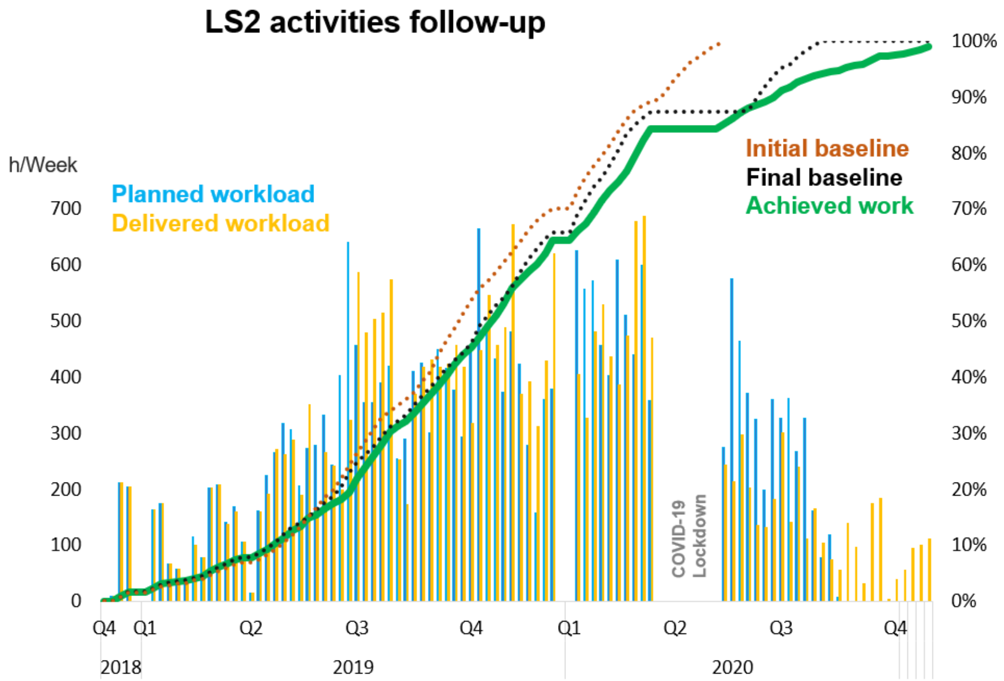
Confined space intervention in adsorber

Charcoal replacement



Motors reinstallation

Data driven prioritization of maintenance



4’000 Work Orders preventive and corrective

26’000 field working hours

Prioritization of maintenance based on:

- RUN2 **maintenance history**
- Previous technical stops **lesson learned**
- **Predictive maintenance data**
- Operation **process data**

Table 2. Examples of technical decisions for maintenance during LS2.

Domain	Decision	Result
Instrumentation	Sensor’s calibrations reviewed by criticality	20% of 8’669 sensors
	Deployment of instrumentation calibrator	2’000 sensors
Vacuum	Review of vacuum criticality & accessibility	28% of 566 devices
	Vacuum gauges check and calibration	45% of 411 devices
Mechanics	Replacement of coalescing filters reference	32 coal stages
	Conditional maintenance for instrumented filters	47% of 262 assets
	Water cooling exchangers analysis and cleaning	40% of assets
Logistics	Anticipated shipping of rotary machines	126 assets

RUN3 has now started since beginning 2022

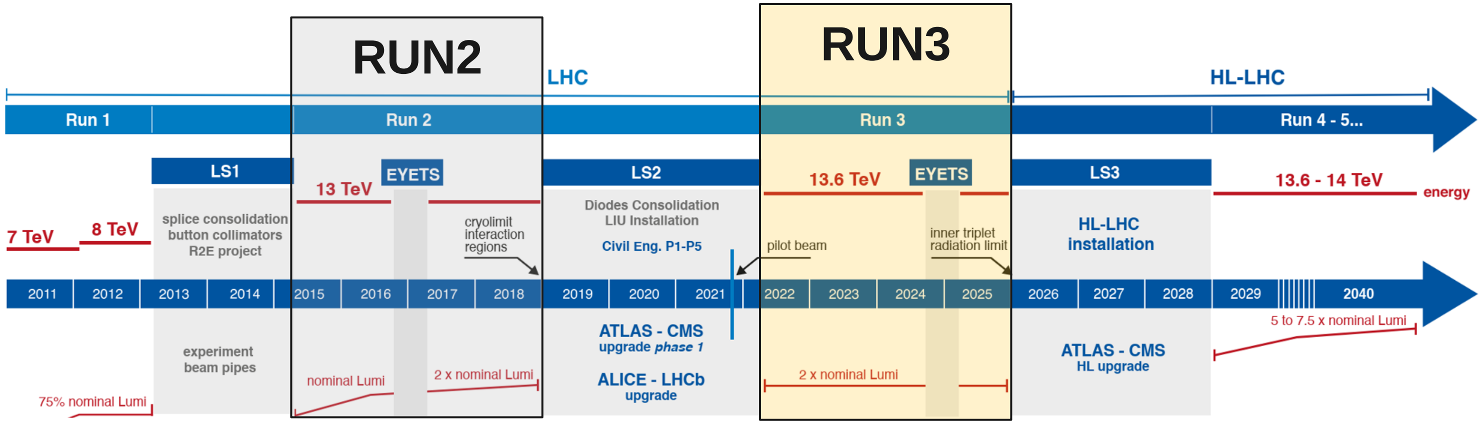
New challenges

- LHC **heat load evolution**
- CERN commitment for **energy preservation**
- LHC cryogenics operation in a context of **helium shortage**

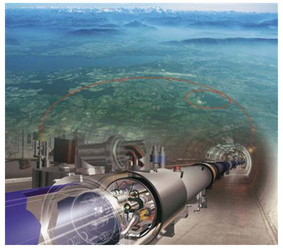
Closing the loop

- Availability preliminary results 2022

LHC heat load evolution



COLD MASS



LHC 36'000 tonnes *of cold mass distributed over the 26.7 km underground accelerator*

Heat load ***at 1.9K and 4.5K +*** *Thermal Shield* ***in between 50 and 70K***

BEAM SCREEN

Screen to ***intercept the beam-induced heat loads*** *inserted into the cold bore*

Dynamic Heat load ***in between 5 and 20K***

10 W / half-cell

130 W / half-cell

180 W / half-cell

ELECTRON CLOUD induced heat load

half-cell *= LHC cryogenic half-cell of 53 m housing one local beam-screen cooling loop*
Maximum average value of all half cells measured on one sector

INNER TRIPLETS

Final ***focusing quadrupoles before ATLAS and CMS*** *experiments*

Dynamic Heat load ***at 1.9K***

Up to **120 W** / inner triplet

Up to **250 W** / inner triplet

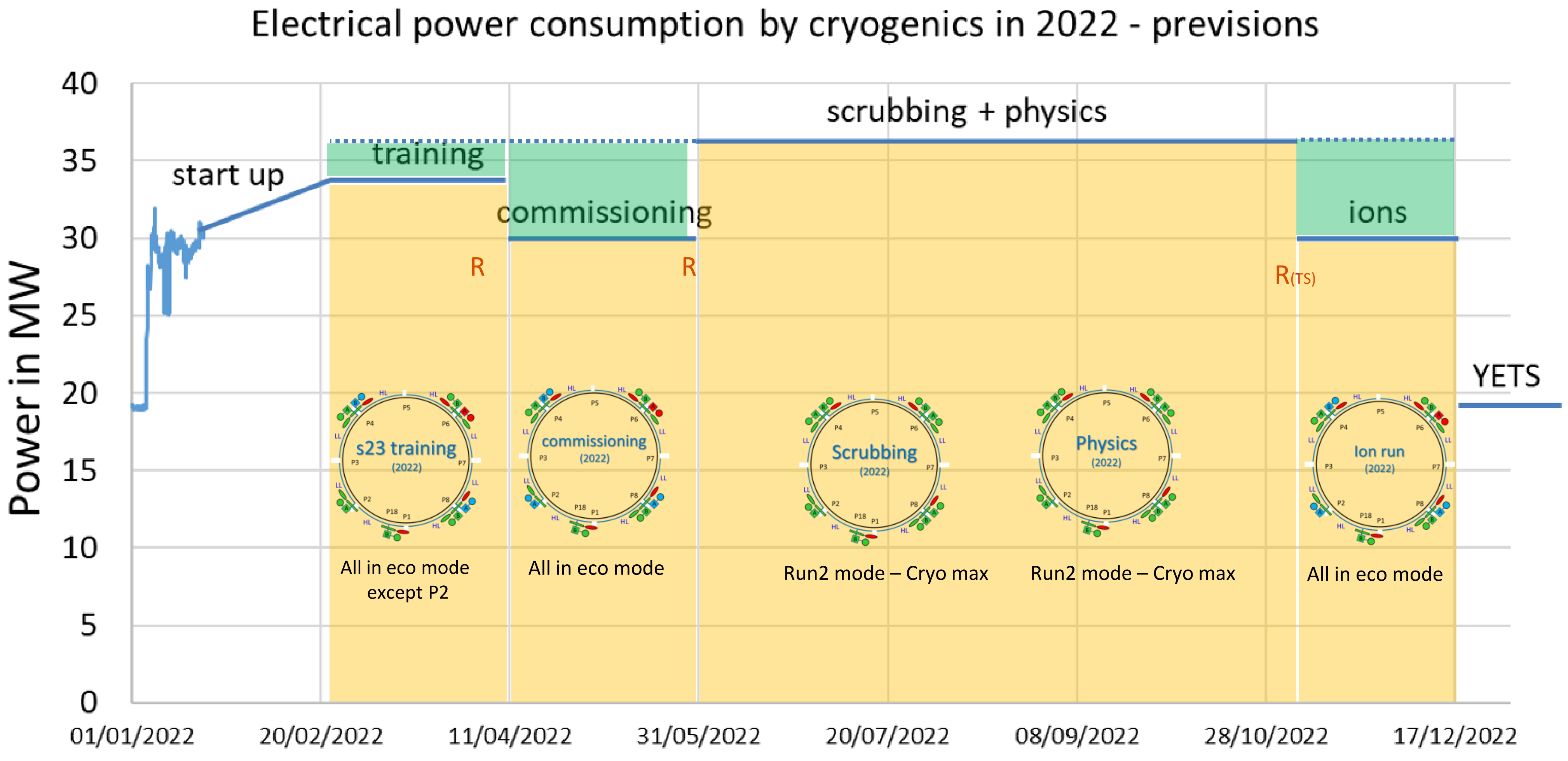
~1 kW / inner triplet

RUN4

COLLISION induced heat load

LHC energy preservation configuration for 2022

Cryogenics energy consumption can be optimized depending on required heat load compensation

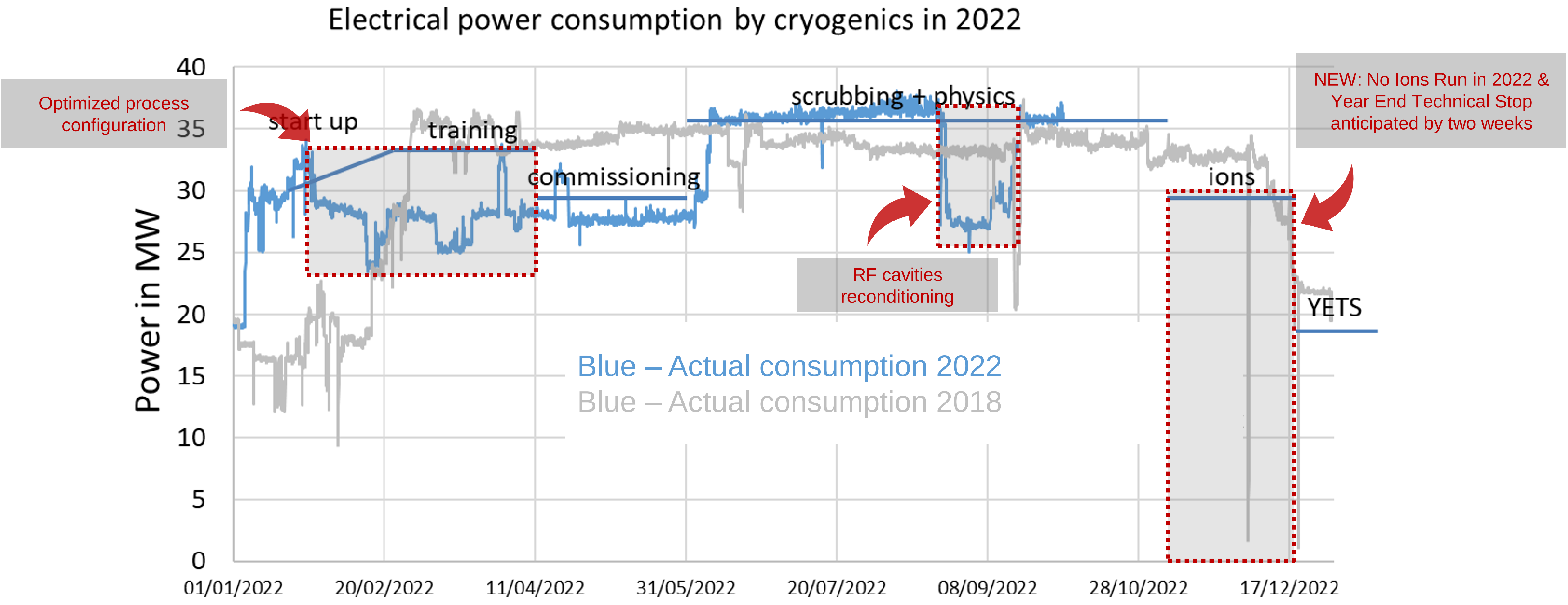


Run 2022 over 9 months, cryogenics electrical consumption should stay at ~185 GWh instead of 235 GWh in cryo max

Green – fully in operation
Blue – “new”, run in reduced mode for thermal screen
Red – out from process, in cold stand-by

LHC energy preservation configuration for 2022

Cryogenics energy consumption can be optimized depending on required heat load compensation



Green – fully in operation
Blue – "new", run in reduced mode for thermal screen
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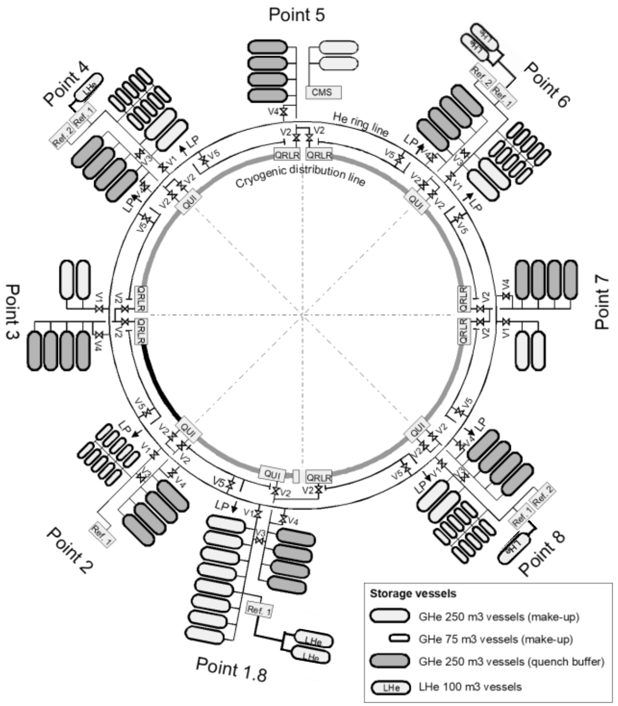
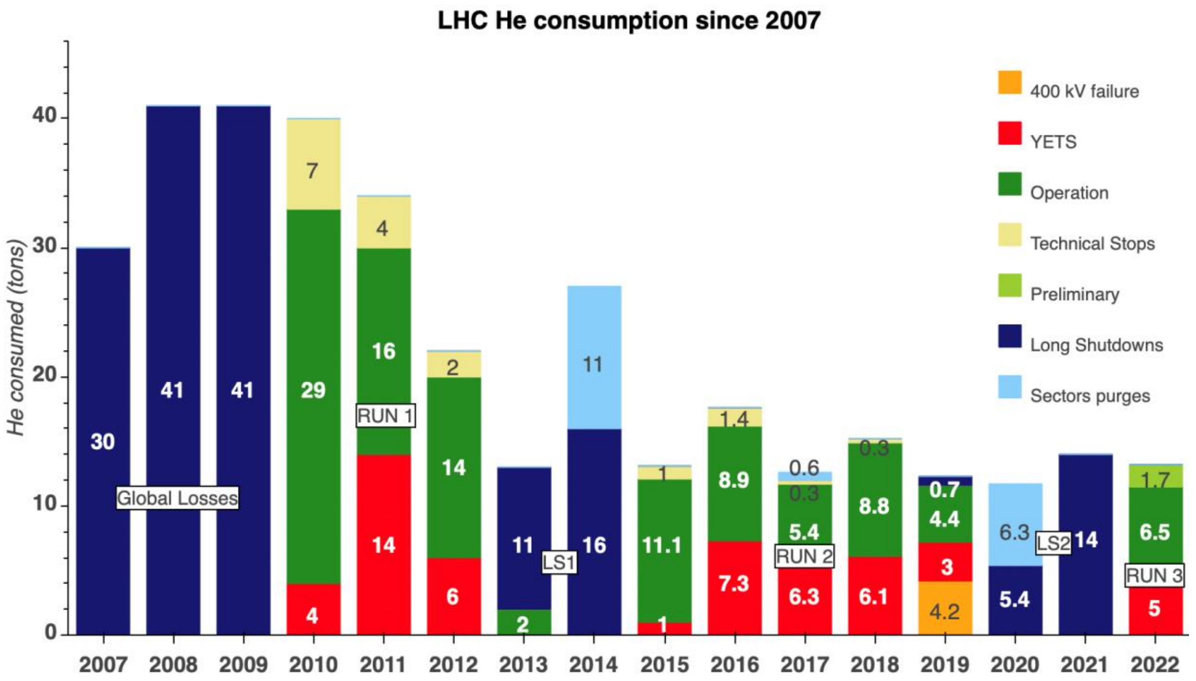
Feedback on helium management

Surface storage & distribution



Gaseous helium storage 250m^3

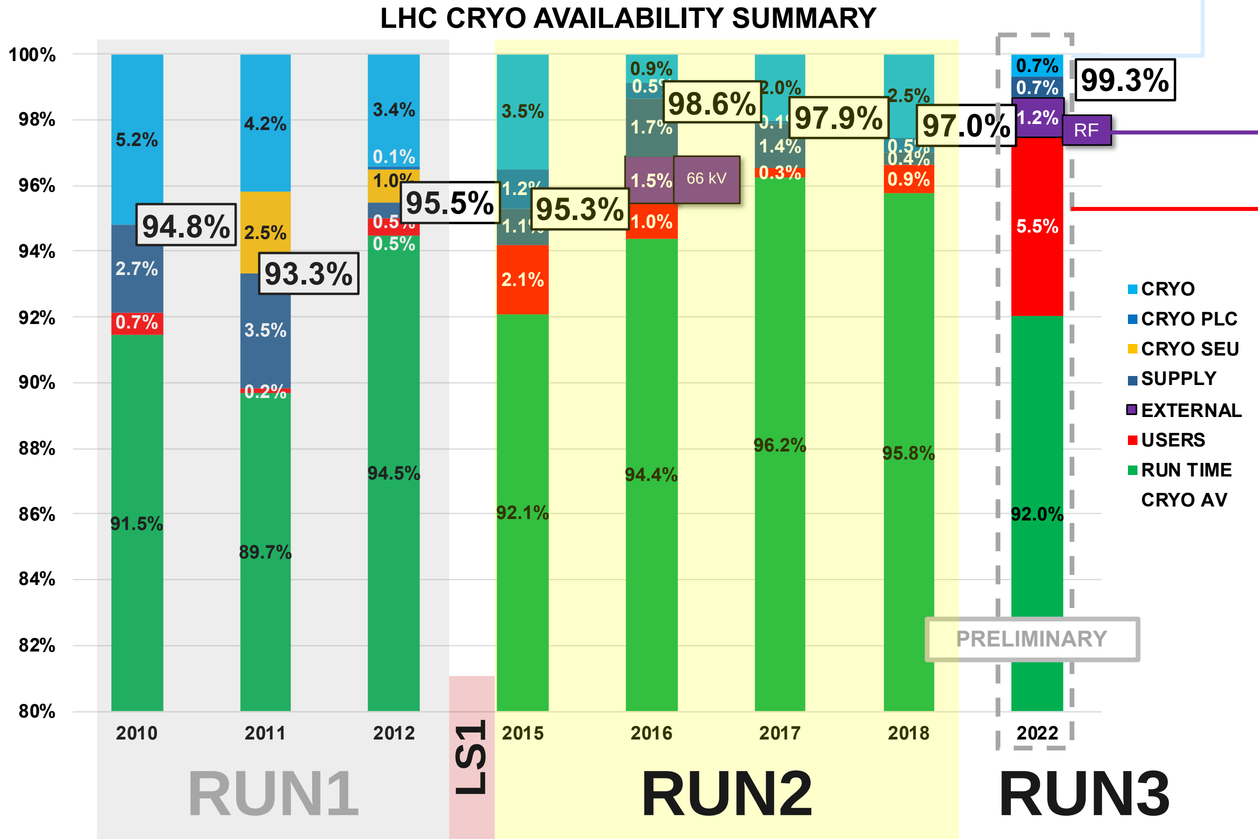
Liquid helium storage 250m^3



- Total inventory at CERN up to 175 tonnes including **130 tonnes minimum for LHC**
- Yearly helium **losses shall be compensated** to ensure continuous operation
- **Special attention given to helium management in 2022 in a context of worldwide shortage**

Closing the loop, availability preliminary results 2022

Until end of September 2022



CRYO category

- Unavailability at **0.7%**
- No PLC downtime

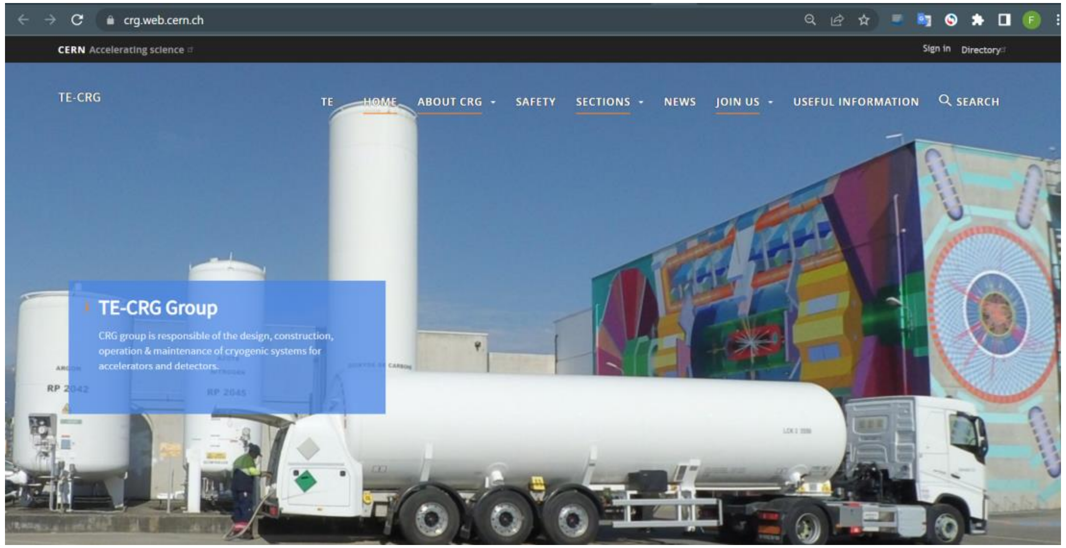
USERS category

- **RF cavities** stop caused by external source requiring reconditioning
- **Quenches** during magnet training:
  - Replacement of magnets during LS2
  - LHC up to 6.8TeV per beam

Conclusion

- Cryogenics is a **critical service system** of the LHC Machine
- **Systematic analysis of availability measurement** during RUN2 gave us vital inputs for the prioritization consolidations and maintenance
- Cryogenics team has implemented an improvement action plan, and performed **major consolidations during Long Shutdown 2**
- The **operational constraints have significantly increased** for operation of cryogenics during RUN3
- **First result show a reduction of the cryogenics unavailability** to be confirmed in the coming years

Check out our website & related publications !



CEC 2022, **Overview of the maintenance and consolidation activities for CERN cryogenics during LHC Long Shutdown 2**, April 2022

ARW 2019, **CERN LHC Cryogenics: availability calculation tool improvement and new helium balance monitoring tool development**, 2019

CEC 2019, Cryogenic Engineering Conference, **Experience from the outsourcing of the Cryogenic Operation & Maintenance at CERN**, July 2019, LINK

Cryo Ops 2018, **General cryogenic maintenance policy and recent update for CERN assets**, June 2018, LINK

ARW 2017, **LHC Cryogenic Infrastructure Reliability, Towards High Availability**, October 2017

ABSTRACT

Maintenance and recommissioning of the LHC cryogenic system for the physics Run3

CERN operates and maintains several large cryogenic systems with complex architecture necessary for the operation of the Large Hadron Collider (LHC). Continuous operation of the accelerator during Run2, and the implementation of availability calculation tools as well as the use of a fault tracking system on cryogenics equipment, has allowed the CERN cryogenics team to gain valuable experience and data to drive maintenance and consolidations. Major maintenance tasks and a comprehensive consolidation program have been planned during the Long Shutdown 2 based on a data driven approach. In this talk we will review the methodology, approach and main issues addressed to improve reliability of the cryogenic infrastructure aiming at maintaining the cryogenic system availability for the accelerator complex above 98% for the coming years. We will report on the initial operation results achieved and we will also give some perspective on the new timeline for cryogenics operation during the extensive Run3 including impact of energy preservation scenarios.