First results of the cryogenics operation from the LHC physics Run 3 at the increased energy to 6.8 TeV

Laurent Delprat
CERN, Geneva, Switzerland

On behalf of the Cryogenics Group

With contributions from B. Bradu, K. Brodzinski and F. Ferrand

laurent.delprat@cern.ch

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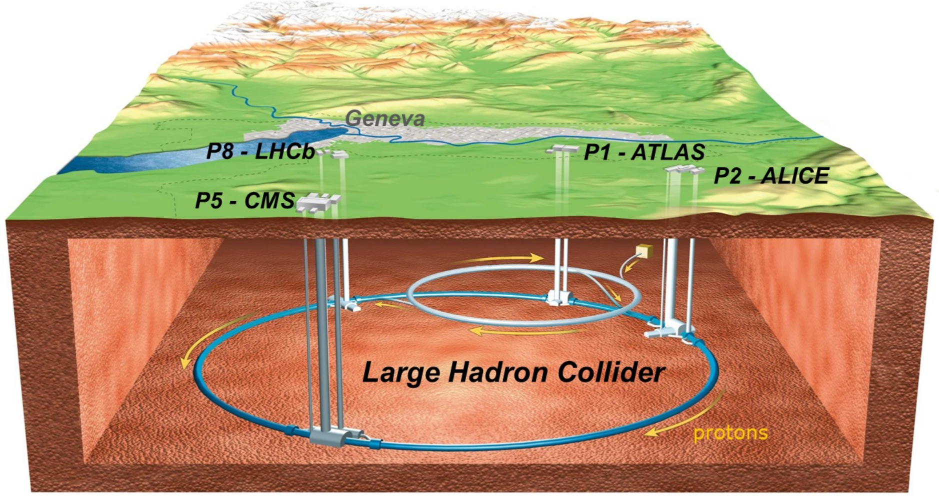
Compressor stations

4.5 K cold boxes

Liquid and gas helium storage

SURFACE



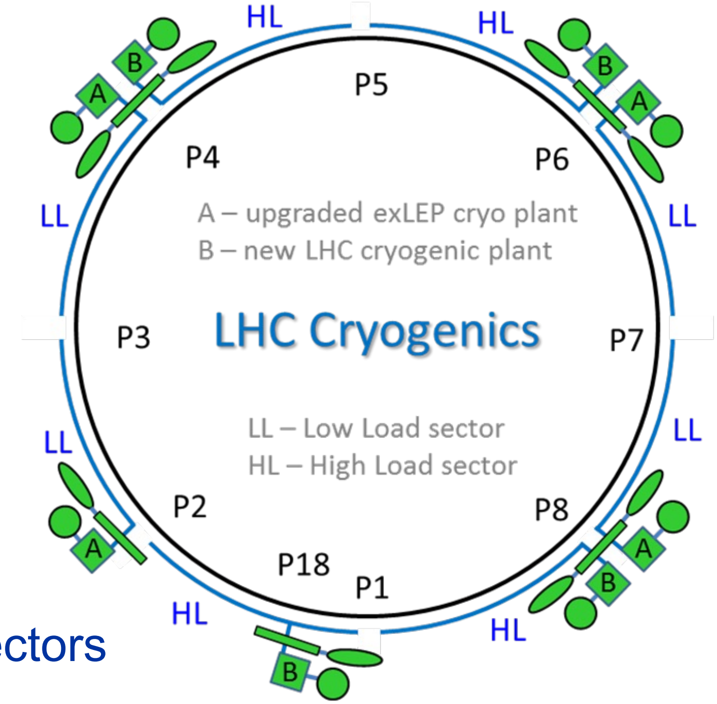
UNDERGROUND

4.5 K & 1.8 K cold boxes

Distribution Valve Boxes

Cryogenic distribution line

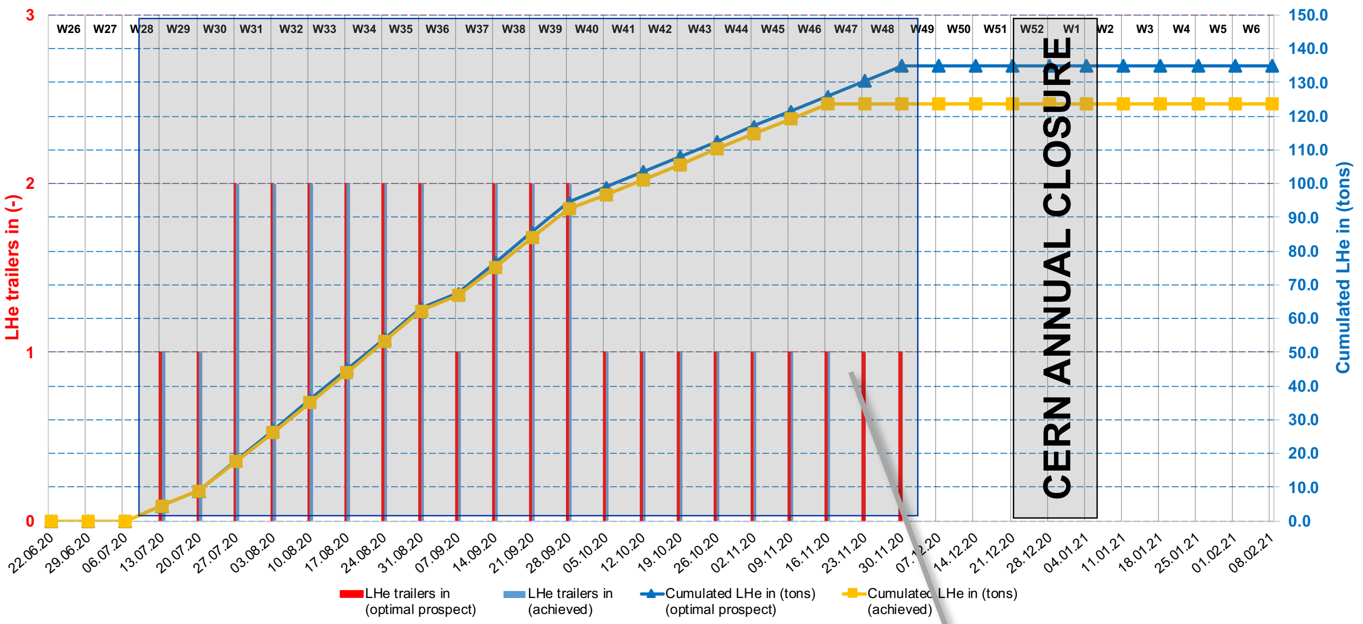
- Compressor station
- 4.5 K refrigerator
- Interconnection box
- 1.8 K pumping unit

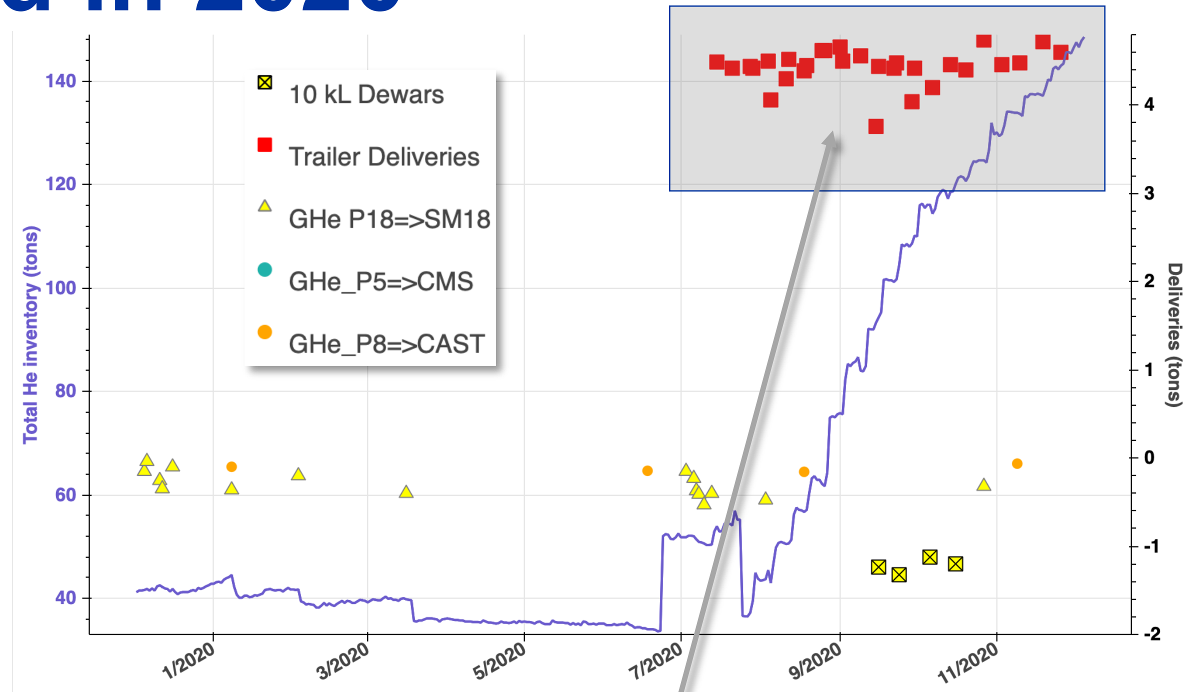


8 cryogenically independent sectors
8 x 18 kW @ 4.5 K
1800 sc magnets
24 km & 20 kW @ 1.8 K
37 000 tons @ 1.9 K
130 tons of helium inventory

- **circumference ➔ ~ 27 km,**
- **constructed at ~ 100 m underground,**
- **the accelerator ring inclination is 1.4 %**

LHC helium inventory rebuild in 2020





<u>Helium recovered at CERN from 13.07.2020 to 03.12.2020</u>:

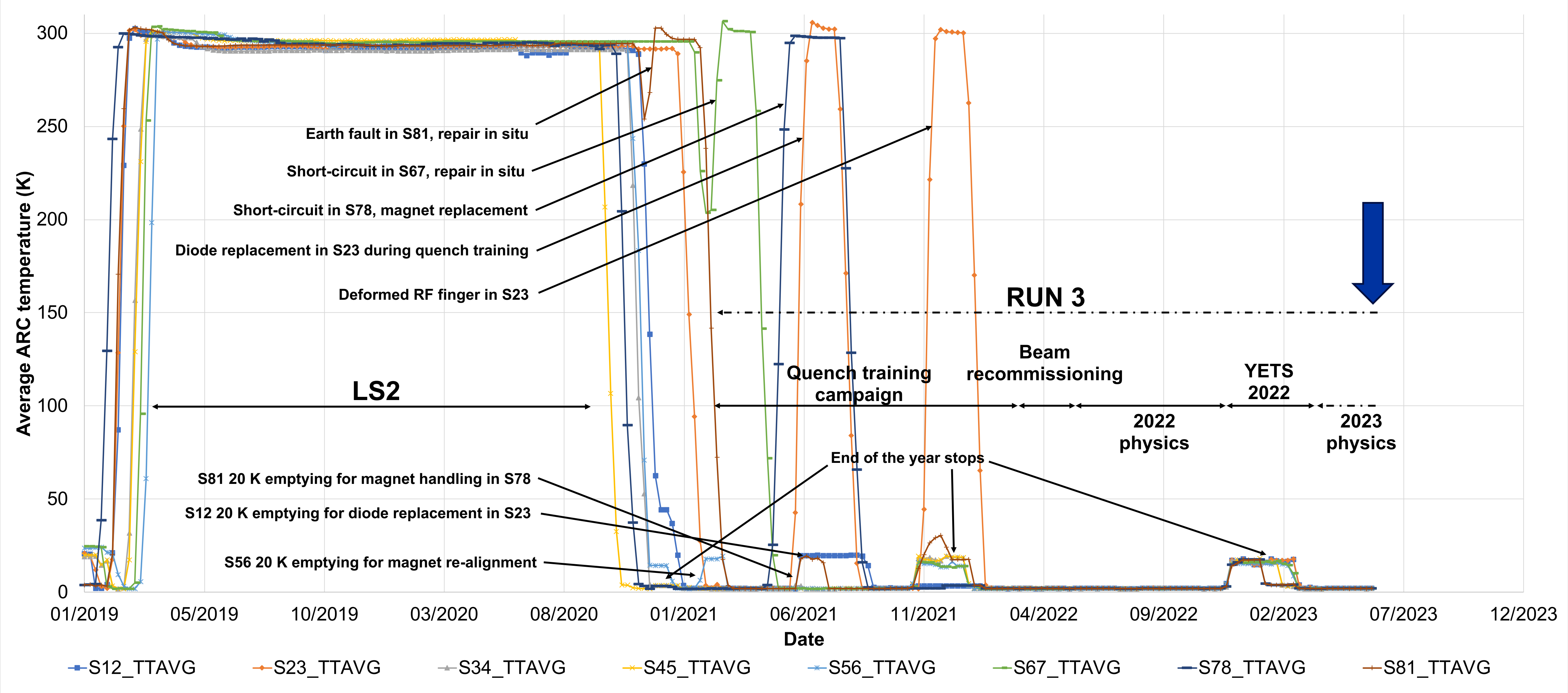
- 44.0 t / 10 trailers of new molecules
- 79.8 t / 18 trailers from externalized storage
- 9.3 t / 2 trailers for inventory build-up

+133.1 t

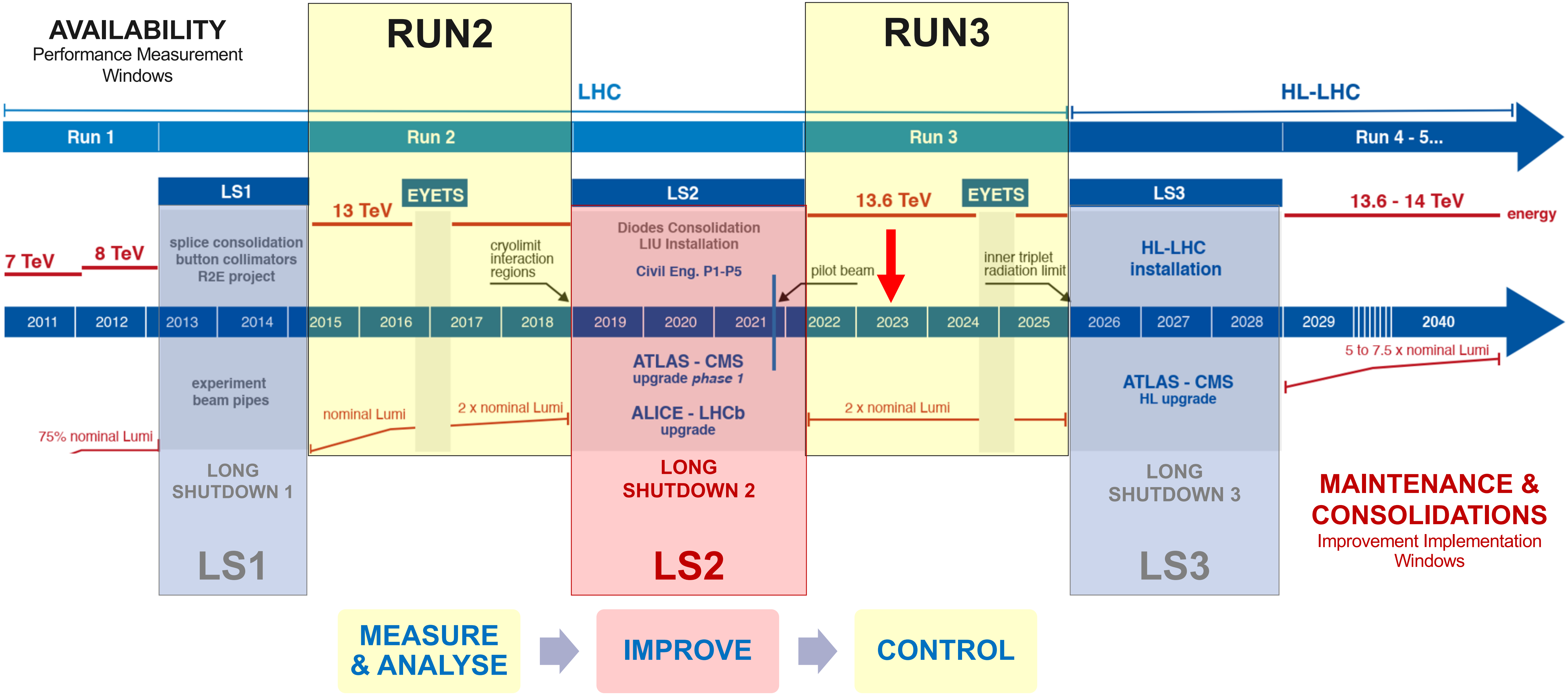
30 trailers

4.5 months

From LS2 into Run 3

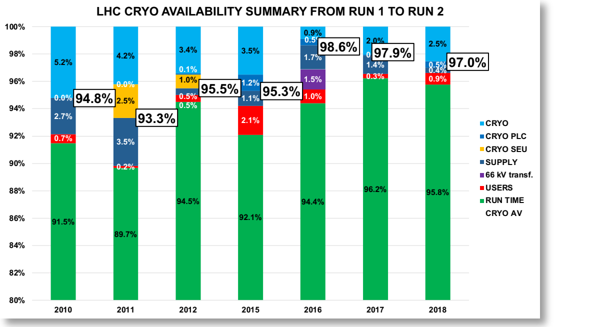


LHC cryogenics timeline and requirements



Building a comprehensive maintenance and consolidation program…

- Adopted methodology: data-driven/fault-tracking approach
- LHC cryogenic performance measured thoroughly during Run 2
- Listing and categorization of all occurred faults (with inter-dependencies)
- Prioritization of resulting maintenance and consolidation tasks, based on
  - RUN2 maintenance history
  - Previous technical stops lesson learned
  - Predictive maintenance data
  - Operation process data



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

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

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

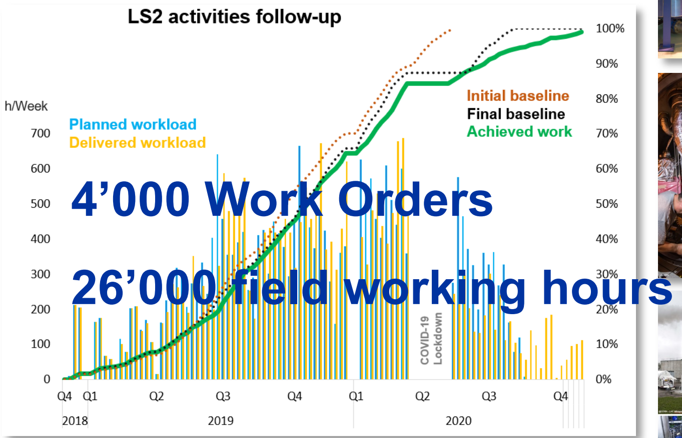
CONSOLIDATION
END OF LIFE PROGRAM
Replacement of control PLC and consolidation of CEM to reduce failure rate

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

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



…to ensure high availability of the system

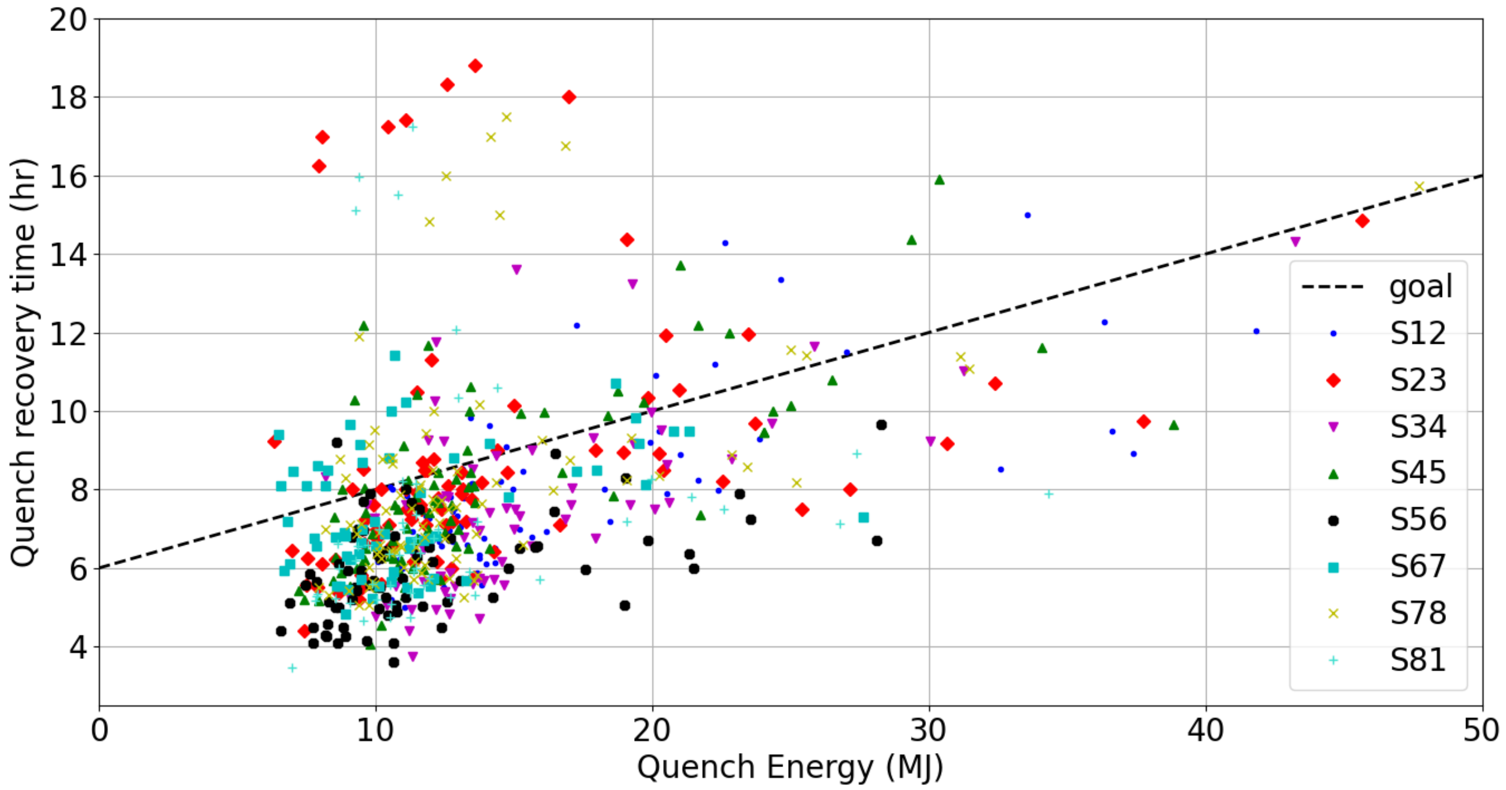
Maintenance/Consolidation *(not exhaustive)*	Budget	Results in 2022
[Meca] Warm screw compressors, 3.3 kV motors & Cold-Compressor major overhauling	4 MCHF	0% losses due to rotating machines
[Elec+instrum] Ex-LEP compression station electrical & instrumentation refurbishment (QSCA)	600 kCHF	0% losses due to QSCA elec/instrum
[Controls] Schneider PLC M580 upgrade (BE-ICS)	250 kCHF	0% losses due to PLC-CPU crash
[Instrum] New Cernox thermometers around turbine and cold compressors	180 kCHF	0% losses due to turbine & CC instrum + better efficiency control
[Meca+instrum] Turbine water circuit upgrade	35 kCHF	0% losses due to turbine water circuits

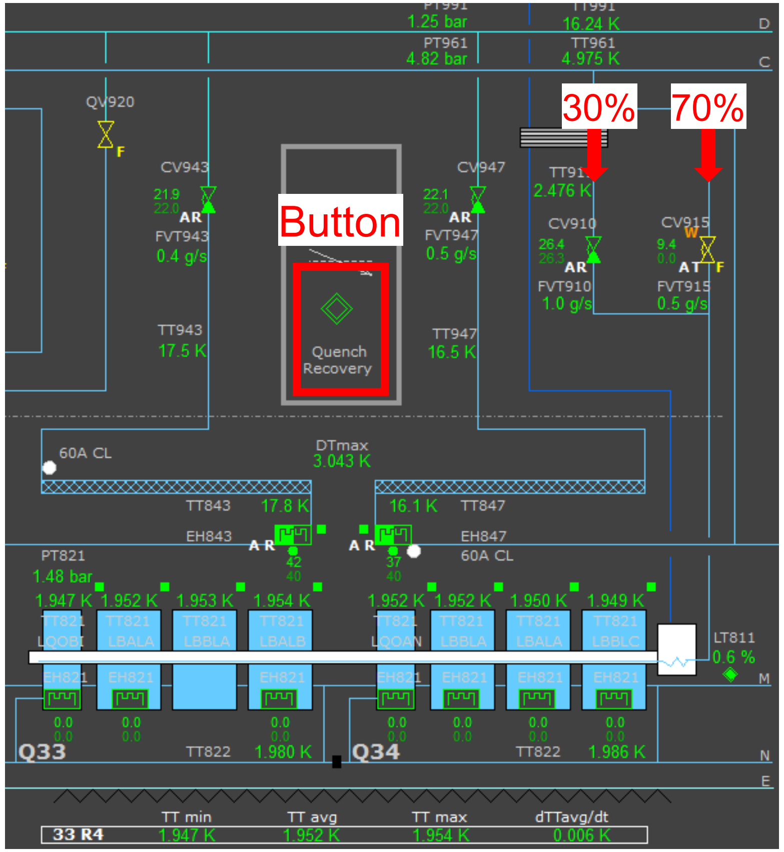
Software/Training *(not exhaustive)*	Applications	Results in 2022
Control logic/interlock improvements (TE/CRG+BE/ICS)	~100 logic modifications treated in refrigerators & tunnel	0% losses due to control logic issue
Daily signal analysis algorithms for automatic diagnostics	~5 000 signals analysed each day	Many issues anticipated and corrected before having a cryo loss
Optimized operator training	80 hr of cryo operation training +50 hr of cryo simulator training	0% losses due to human errors

Run 3 will last 5 years for cryogenics (*1st time since LHC start*)

Ensuring high availability after 2024 will require the anticipation of major overhauling for compressors/motors during YETS 24/25.

A new logic tool for magnets training to 6.8 TeV

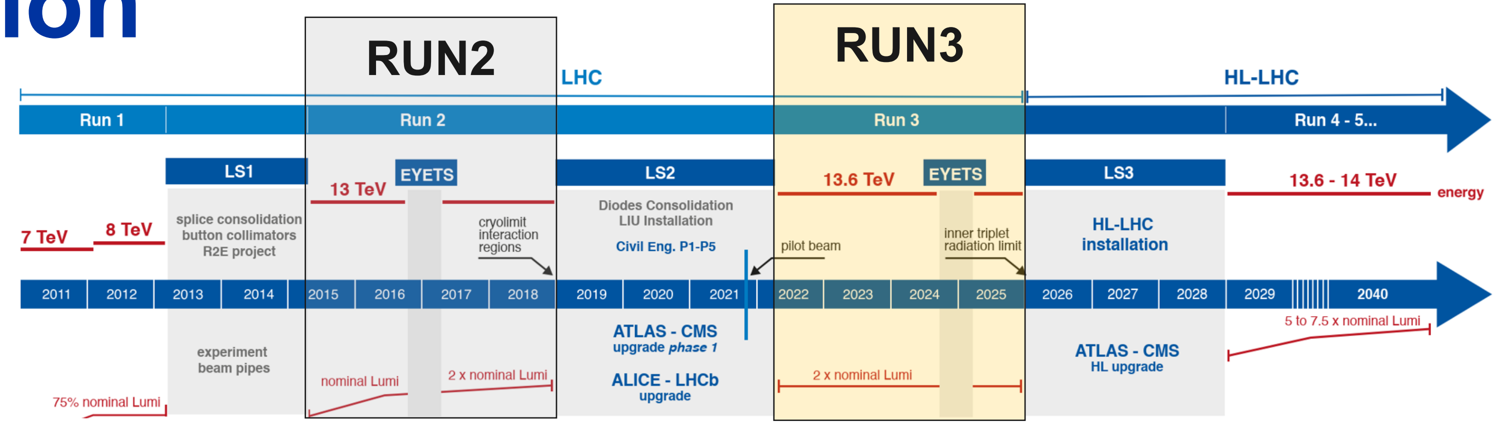




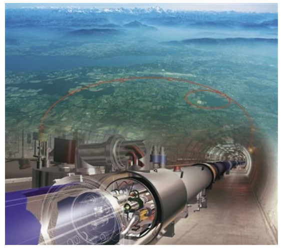
- 1 year of training from March'21 to April'22
- ≈ 600 quenches on LHC main dipoles
- 3 sectors qualified to the nominal energy of 7.0 TeV (sectors 12, 34 and 45)
- 5 sectors qualified to operate at 6.8 TeV

- New automatic quench recovery sequence using the sub-cooling HX bypass valve when needed (TT_{MAG} > 2.5 K and ΔT_{SHX} < 1 K)
- 70% of the flow is bypassed (using virtual FTs)

LHC heat load evolution



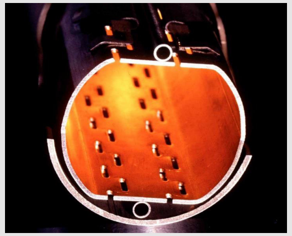
COLD MASS



***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***

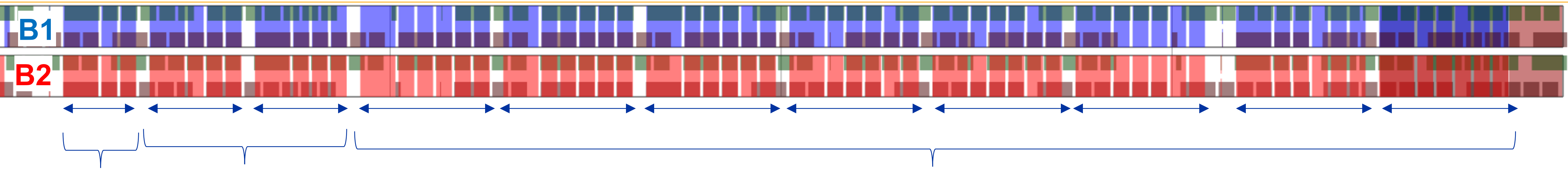
Up to **120 W** / inner triplet → Up to **250 W** / inner triplet → **~1 kW** / inner triplet

RUN4

COLLISION induced heat load

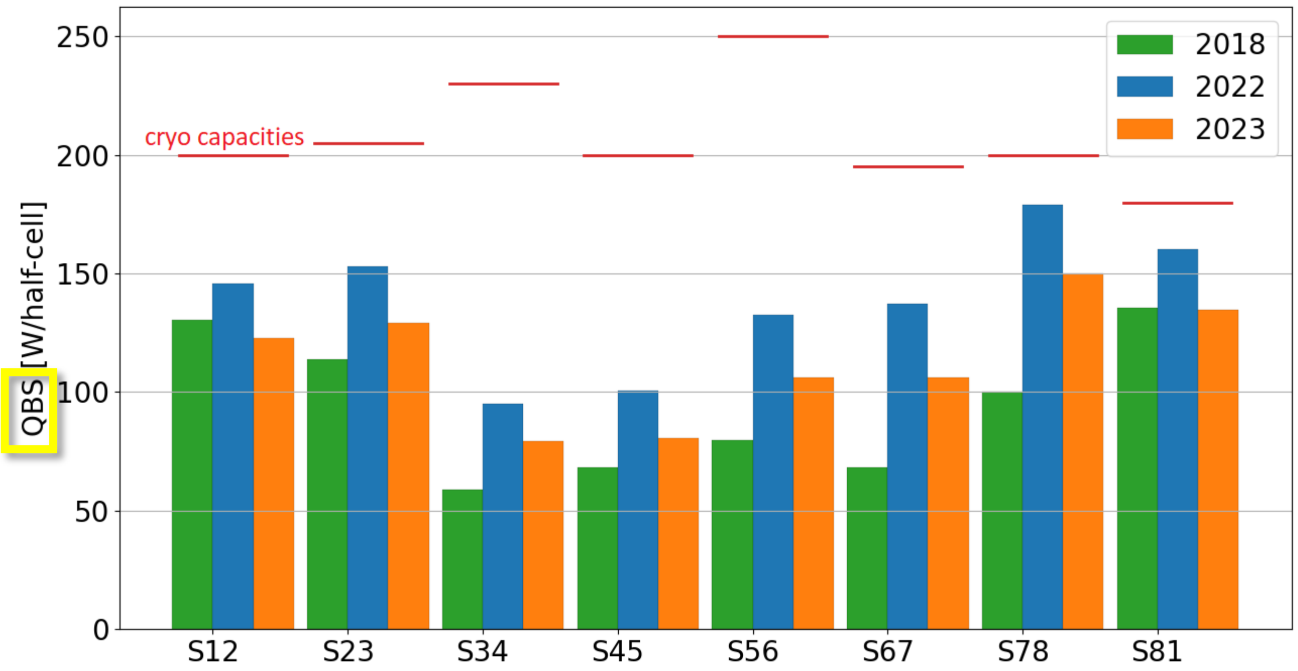
New hybrid filling scheme based on “8b+4e”

- Goal: mitigate the electron-cloud effect without impacting too much the beam & luminosity performances
- How: injectors use a “hybrid” filling scheme for LHC, where 25% of the bunches are presenting empty buckets
  - 25% of “8b+4e beam”: trains of 56 bunches, where every 8 bunches are followed by 4 empty bunch slots
  - 75% of “Standard 25ns beam”: trains of 36 bunches



➔2 358 bunches in total with 25% of 8b+4e

Beam screen heat loads vs cryogenic capacities



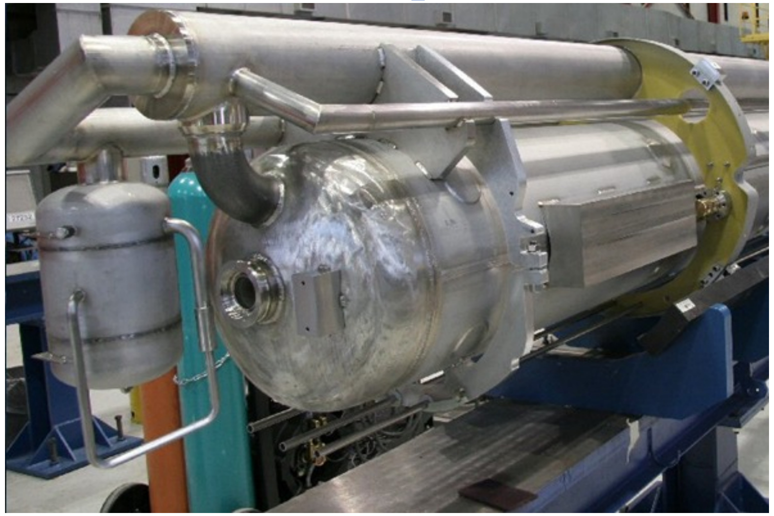
Heat load monitoring

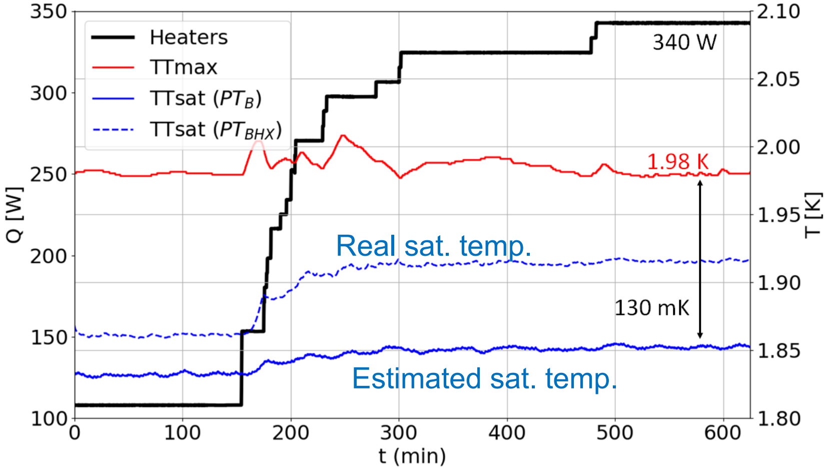
- Energy balance on each of the 485 beam-screen cooling loops with the use of available instrumentation
- Plotted as **Q**(heat) – **B**(beam) – **S**(screen) per sector

Beam parameter	Run 1	Run 2	Run 3 (*ongoing*)	Design (*memo*)
Energy	4 TeV	6.5 TeV	6.8 TeV	7 TeV
Intensity	2.7×10^{14} protons/beam	3.2×10^{14} protons/beam	3.8×10^{14} protons/beam	3.2×10^{14} protons/beam
Luminosity	0.8×10^{34} $cm^{-2}.s^{-1}$	2.2×10^{34} $cm^{-2}.s^{-1}$	2.5×10^{34} $cm^{-2}.s^{-1}$	1×10^{34} $cm^{-2}.s^{-1}$

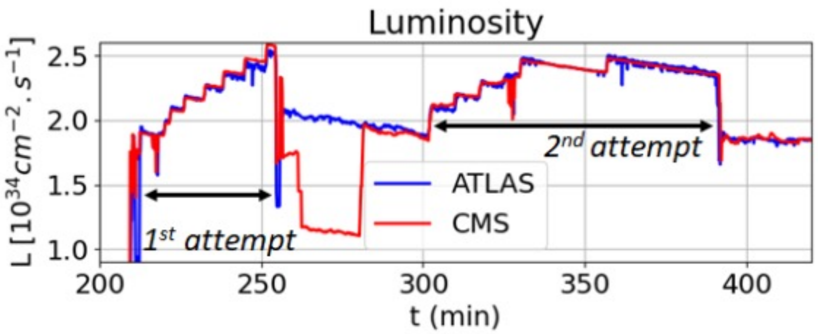
What's next: increase beam intensities up to reaching the limits of the cryogenic system

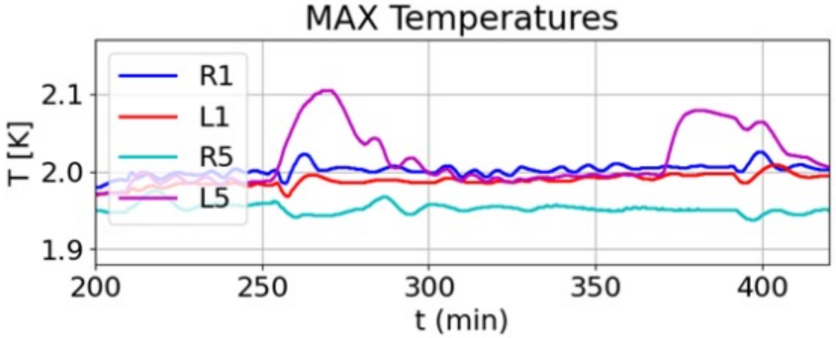
Inner triplets heat loads





Inner Triplet capacity test in April 2021 (left triplet of ATLAS)





High luminosity test in November 2022

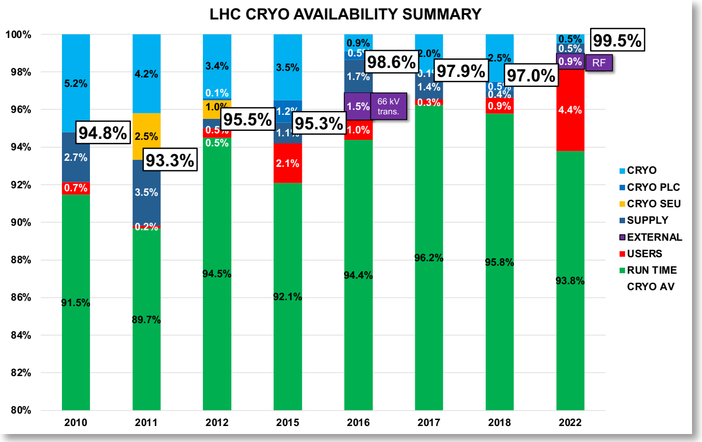
Heat extraction capacity in inner triplets

- Re-evaluated from 270 W to 325 W @ 2 K
  due to extra pressure drop in sub-cooling heat exchanger inducing a wrong TTsat estimation
  ➔ Operation of triplet at ~2 K instead of ~1.95 K
- Updated achievable in steady state operation, peak luminosity: 2.2e^{34} cm^{-2}.s^{-1}
- Maximum achievable luminosity validated at 2.4e^{34} cm^{-2}.s^{-1}
- Confirmed with a real test in ATLAS and CMS in November 2022

Highest availability of the cryogenics since 2010

- Run 3 restart main failures clearly dominated by the occurrence of quenches (direct consequence of the increased beam energy)

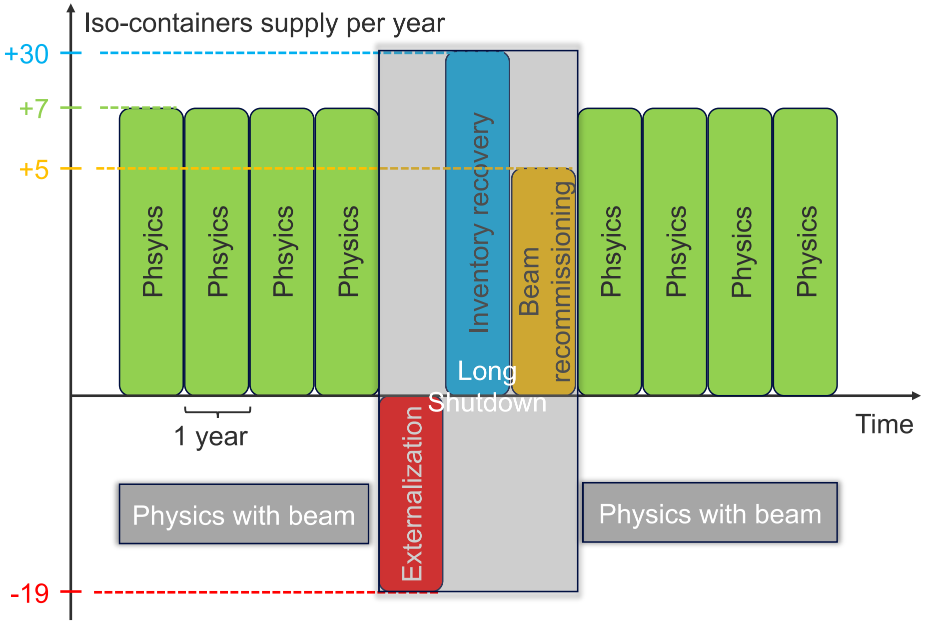
- 2022 run lasted 4 465 hours, disturbed by 277.7 hours of downtime
  - Users: 194.5 hours of downtime
    - 30 quenches on LHC magnets (mainly dipoles)
  - Technical services: 62 hours of downtime
    - 1 major water-cooling failure on a LHC point => 38 hours of downtime
    - 2 failures of static VAR compensators (SVCs) => 18 hours of downtime
    - 2 other minor faults on distribution electrical feedboxes => 6 hours of downtime
  - Cryo-related: 21.2 hours of downtime
    - 1 stop & go on a 1.8 K pumping unit (inlet filter regeneration) => 8 hours of downtime
    - 2 stops of compressors (minor instrum issues) => 7 hours of downtime
    - 2 instrum faults in the tunnel => 6 hours of downtime
    - 7 very minor other faults => > 1h of downtime



2022 LHC cryogenics availability

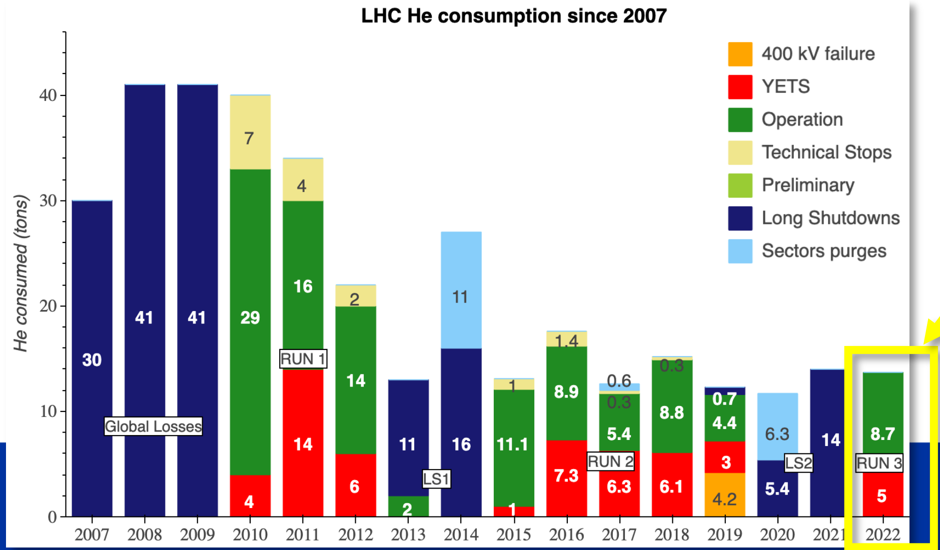
99.5%

Helium management strategy reaching maturity

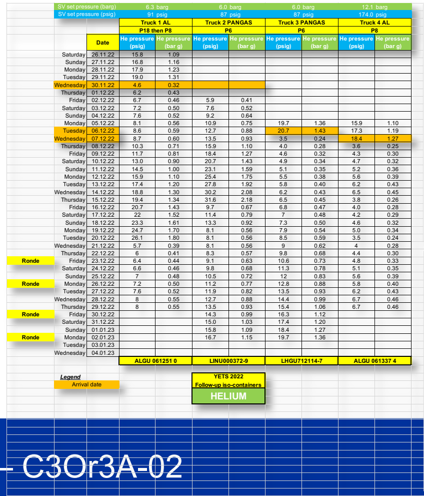


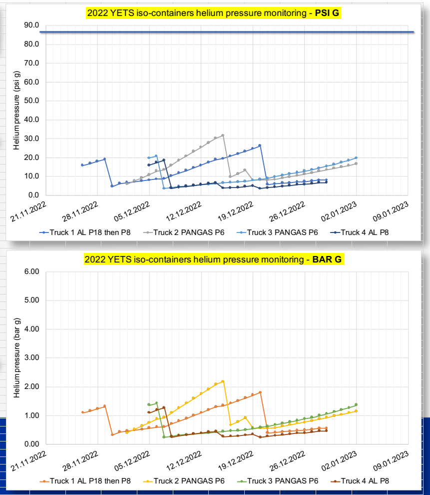
- **Repetitive scheme** around the alternance of maintenance and operation periods

- Systematization of LHC sectors emptying and maintaining at 20 K **during YETS** with validation of a new strategy for **on-site storage** in ISO-containers

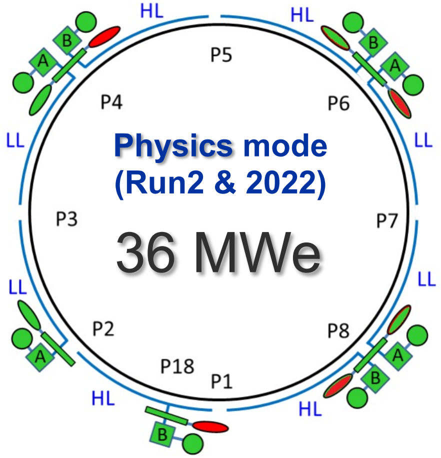


10% of the total LHC helium inventory as regular annual consumption

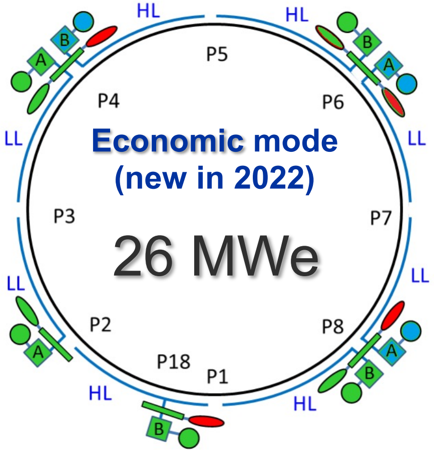


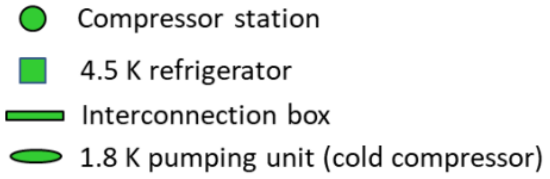


Cryoplants operation & energy savings

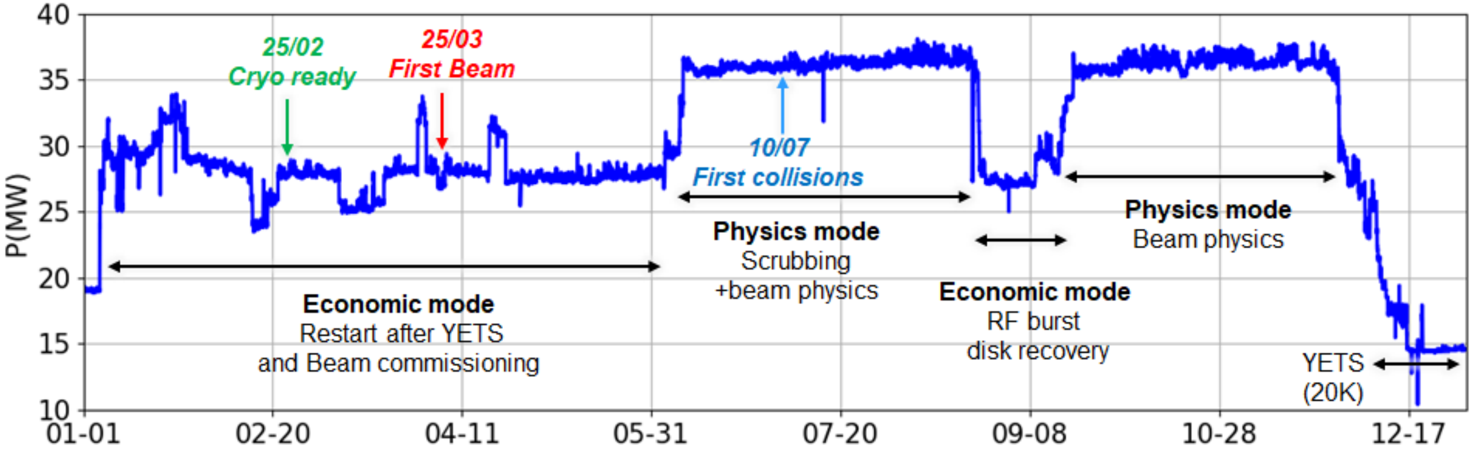


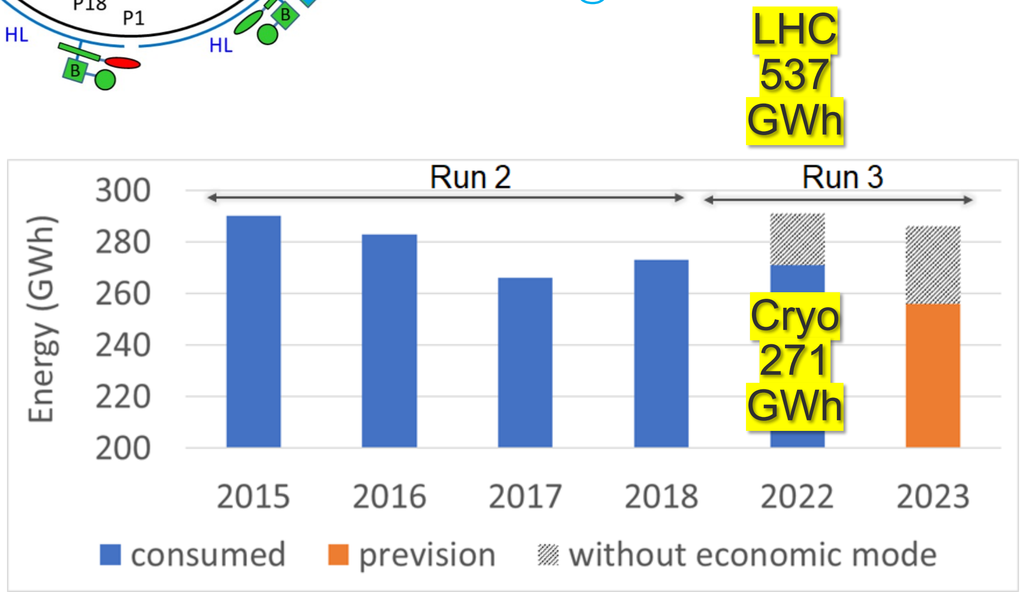
- 24 hours without beam needed for reconfiguration of the cryoplants
- 28% of energy saving





Green – in operation
Red – stopped
Blue – @ 50 K for thermal shields





With the implemented strategy, in 2022 run, power savings from cryogenic operation reached 20 GWh/y

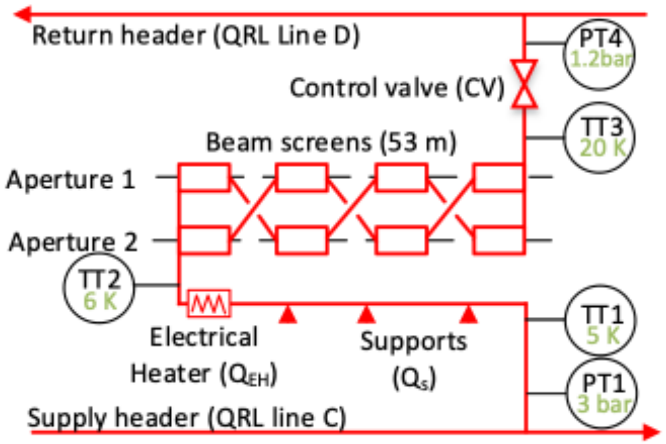
Conclusions and perspectives

- LS2 allowed the restoration of the full potential of LHC cryogenic infrastructure
- Successful quench training campaign paved the way to operation at 6.8 TeV
- A new hybrid filling scheme was implemented to tackle increased beam induced heat loads
- First results of Run 3 with 2022 operation showed a high cryogenic availability (99.5%)
- Helium management strategy has reached maturity
- A new cryoplants operation configuration allowed for significant electrical power saving
- There is still some margin for increasing the beam intensities before reaching cryo limits

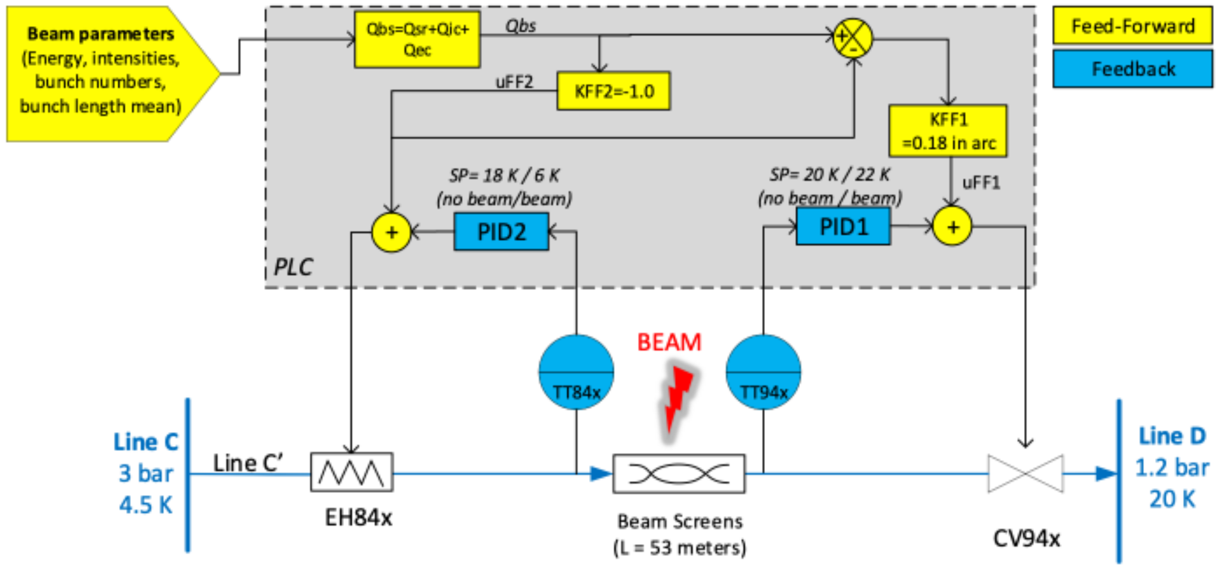
!!! Fully ready for physics production !!!

SPARES

Beam-screen cooling loop



Beam screen cooling scheme with its associated instrumentation



Beam screen control scheme

One beam-screen local cooling loop = one half-cell (hc) *

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