LHC cryogenics 2024 Performance, Limits and Outlook

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TE-CRG

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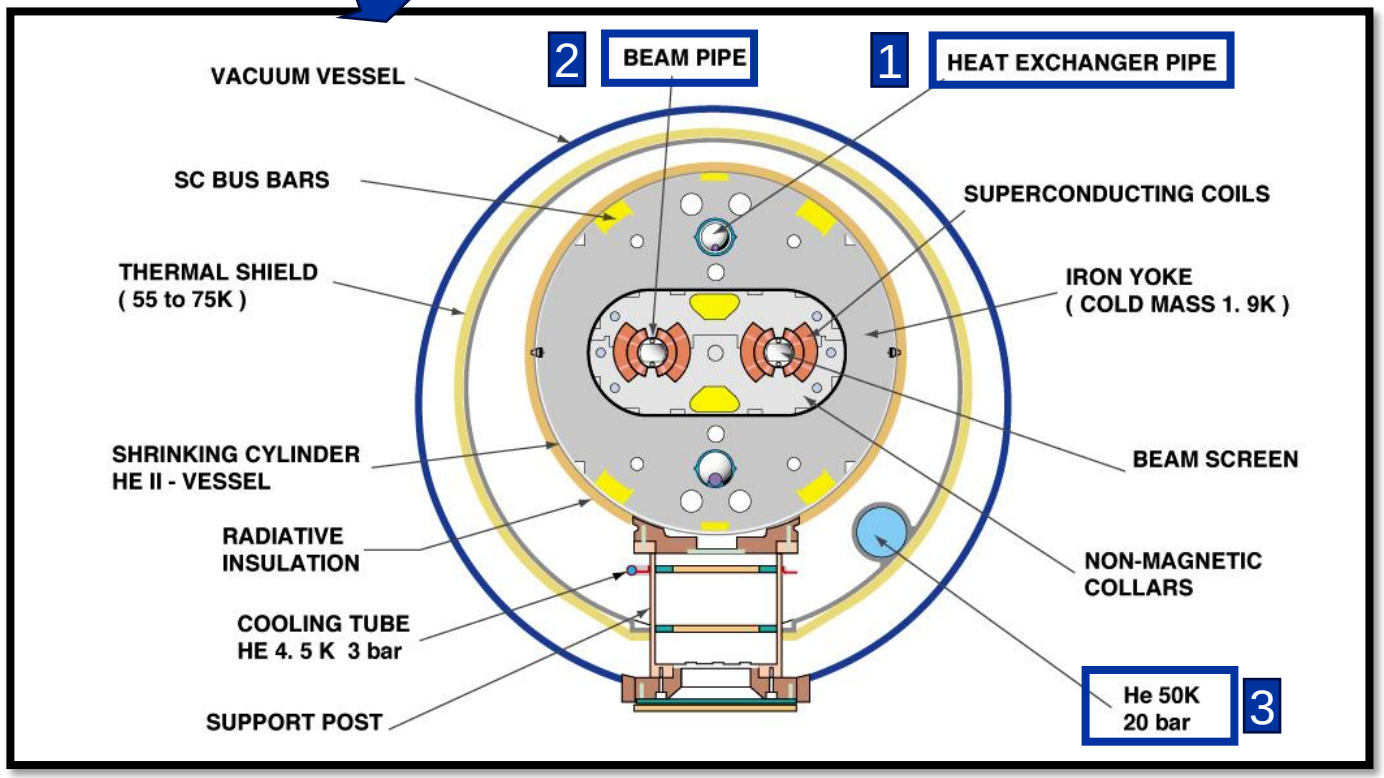
Introduction

LHC cryogenic system main task consists in keeping the required cryogenic conditions of the magnets, current leads and RF cavities.

1 - Bayonet HEX (~1.9K): Maintains the magnet under 2.05 K.

2 - Beam screen cooling (4.6-20 K): Protects the magnet from beam induced heat loads.

3 - Thermal shields (50-75K): Shields the magnets from outer heat inleaks.



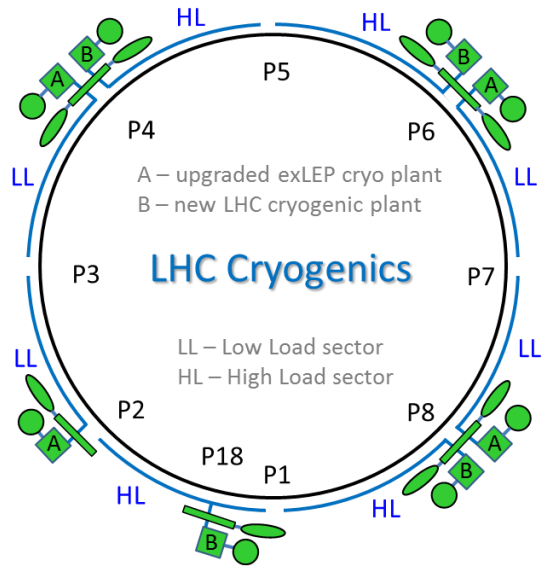
8 cryoplants, 1 per sector, are supplying the 3 circuits with Helium at the right conditions.

Compressor station

4.5 K refrigerator

Interconnection box

1.8 K pumping unit (cold compressor)



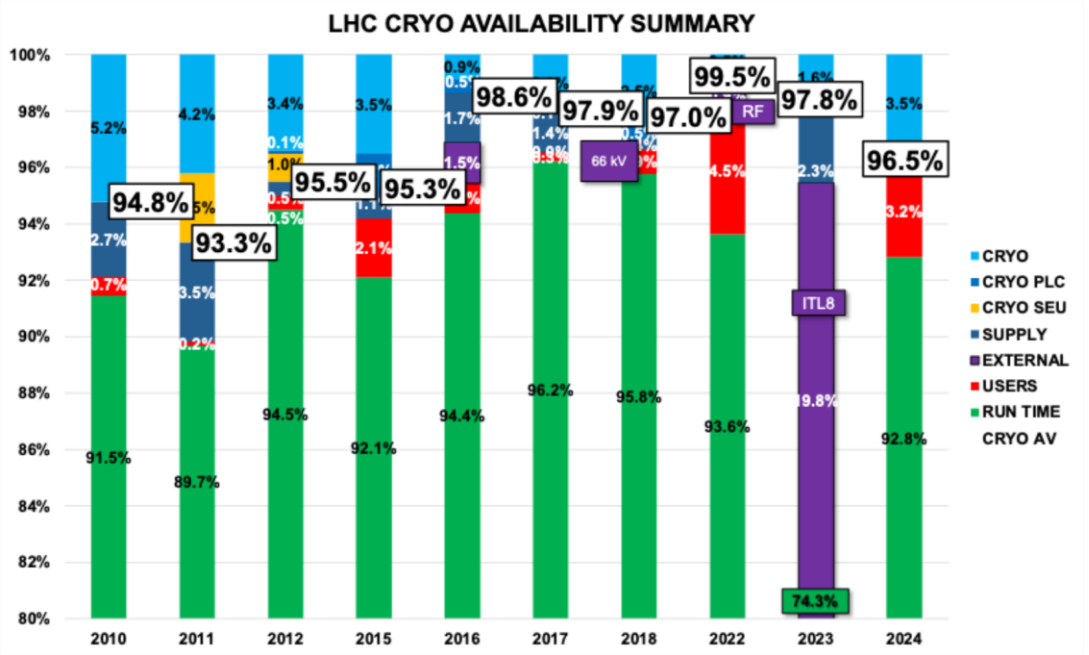
LHC Cryogenic System 2024 Performance

2024 Run was the highest integrated luminosity run so far.

It lasted **6026** hours, disturbed by **432** hours of downtime, by events:

- 35 Users (192 hours):
  - 30 quenches
- 7 Technical Services (31 hours):
  - 400 V glitch P6 (18h)
  - Trip SVC P8 (6h)
- 33 Cryo-related (209 hours or 3.5%):
  - 5x QURCA8 stops (~165h):
    - 2 Magnetic bearing controller trips (R2E).
    - 1 VFD trip (SVC).
    - 2 instrumentation failures.
  - 1x 400V perturbation trip.
  - 16x DFBMI loss (~3h).

Under consolidation during current YETS

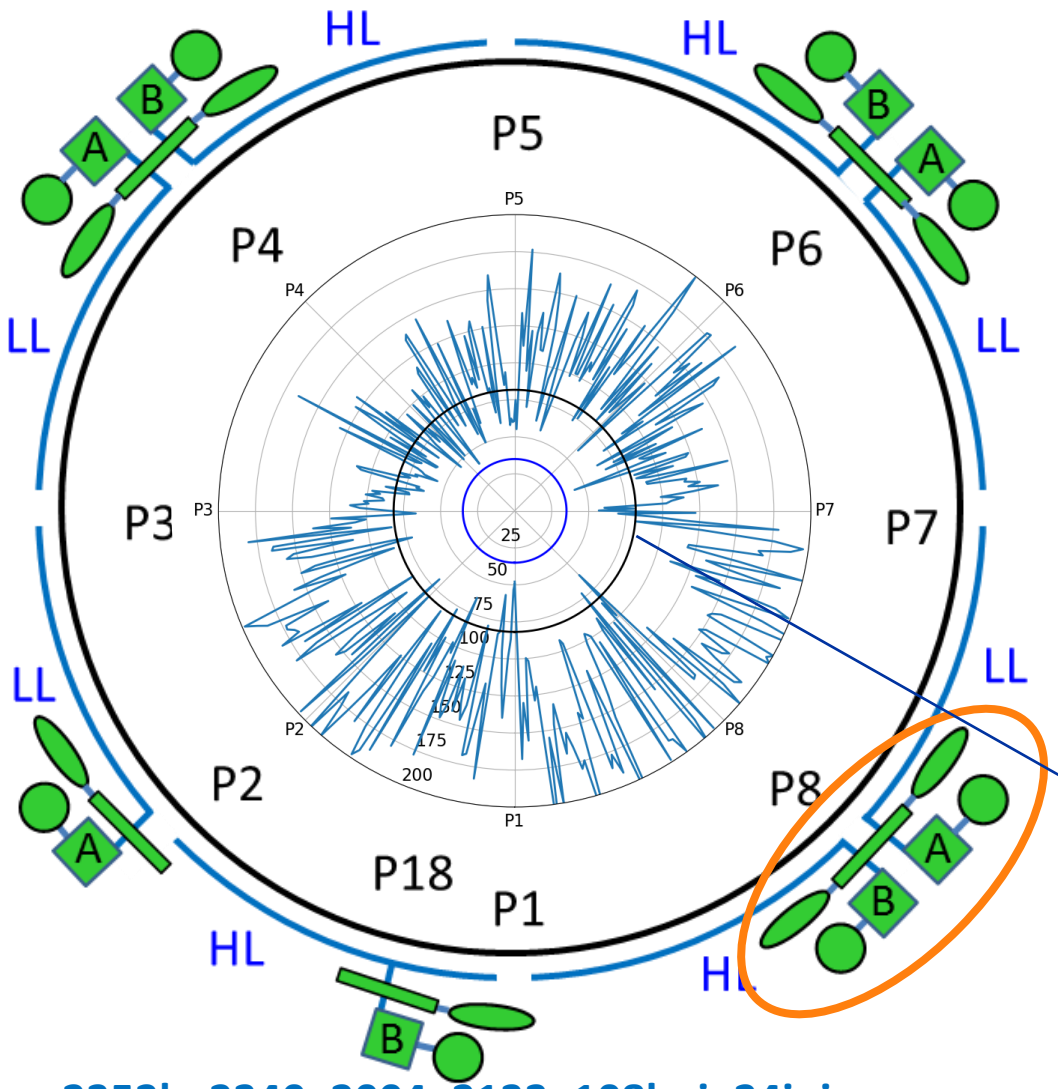


LHC 2024 cryogenics availability – **96.5%**.

Focus on P8

What is special about P8?

- Since LS2, Beam screen heat loads are the highest on sector S78 and S81.
- Cryoplant-LHCA at P8 is an ex-LEP plant which has lower cooling capacity.

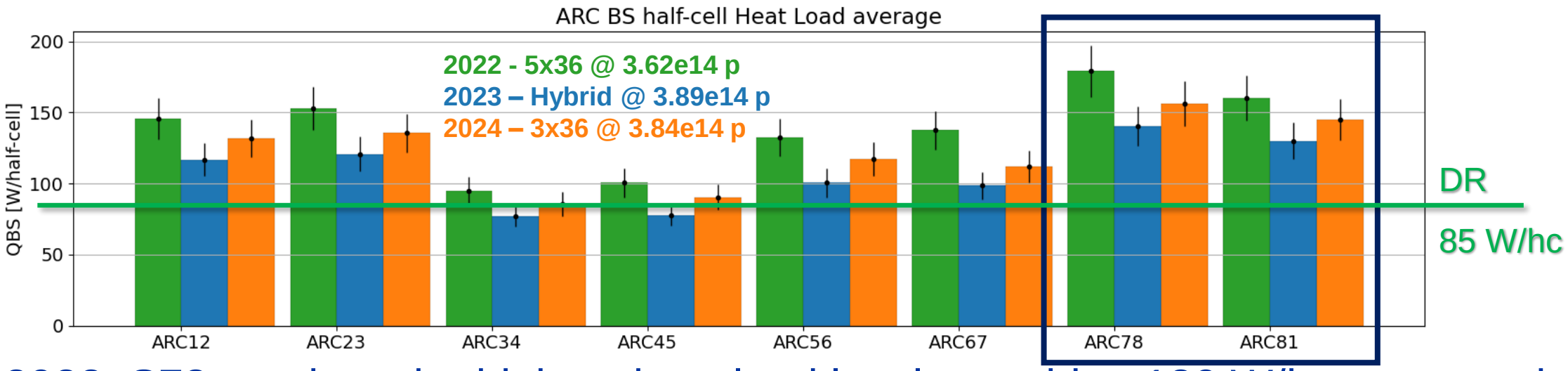


The 416 ARC half-cells are represented on the ring (53m each)

85 W/hc design load

Fill #10137 (22nd September 2024): 25ns_2352b_2340_2004_2133_108bpi_24inj

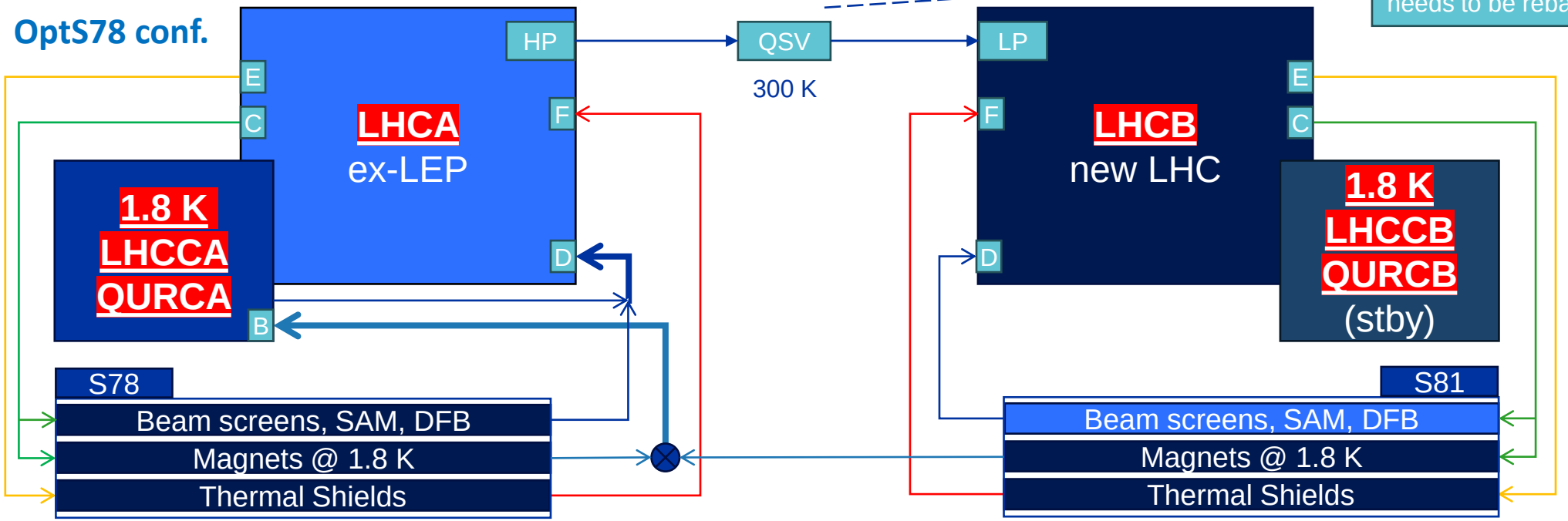
P8: Asymmetry of heat loads



- In 2022, S78 receives the highest heat load levels reaching 180 W/hc compared to 160 W/hc on S81.
- In 2023, Hybrid scheme (8b4e) + 5x36b reduces considerably the total induced heat load.
- In 2024, a higher beam intensity was reached at lower induced heat loads thanks to filling scheme and beam conditioning.

P8: Asymmetry of cryoplants

Because a cryoplant is based on a thermodynamic cycle (Claude), all asymmetry needs to be rebalanced.



- Cryoplants were designed for 85 W/hc on the beam screen, and higher loads at 1.8 K.
- Due to lower loads at 1.8K, only one cold compressor (LHCCx) is needed for both sectors and more BS loads can be taken.

- LHCA is an upgraded ex-LEP plant with a lower refrigeration capacity.
- LHCB is newer plant with higher refrigeration capacity.

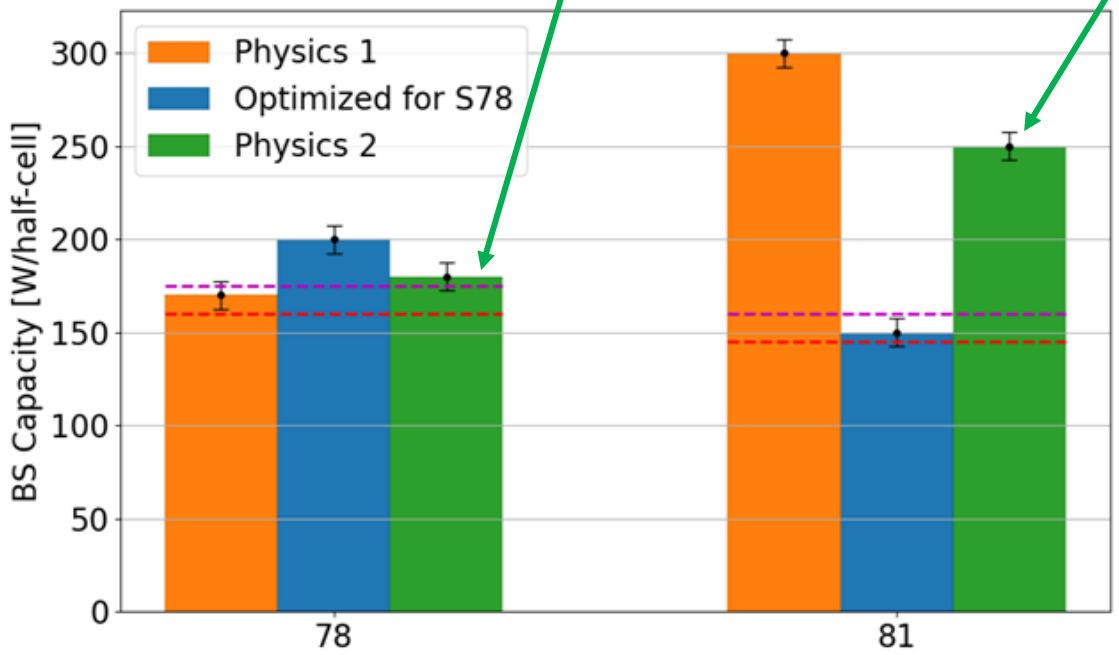
LHCCA is used.
LHCCB is kept in STBY.

LHCA as **economiser**
LHCB as **liquefier**

P8: Capacity tests

	Cryo config.	S78 capacity	S81 capacity	Comments
Test 1	**Physics 1** (with line F return)	170 W/hc	**300 W/hc*	LHCA limited on LP LHCB TU4 inlet pressure delicate to operate
Test 2	**Optimized for S78** (shields decoupled)	**200 W/hc*	150 W/hc	LHCB suffering a lot with ADS80K at 120 K
Test 3	**Physics 2** (with RM81 return)	180 W/hc (limited by LHCA LP)	**250 W/hc*	LHCA & LHCB OK [Almost at the LP limit on LHCA]

Selected configuration for 2024 operation



-- begin 2024
-- end 2024

NB: there is no contingency in these numbers and cryogenic needs margin to handle properly the transients and the unexpected disturbances.

*estimates

Run 3 summary and outlook

	2022	2023	2024
Type	BCMS 5x36	56b (8b4e) + 5x36b	BCMS 3x36
N_{bunch}	2462	2464	2352
Bunch population	1.47e11	1.58e11	1.63e11
I_{tot}	3.62e14	3.89e14	3.84e14
Cryo config @ P8	OptS78	OptS78	Physics 2
$W_{hc_{s78}}$ [W] (max/mean)	182 / 164	150 / 127	177 / 161
$W_{hc_{s81}}$ [W] (max/mean)	163 / 146	135 / 116	159 / 147

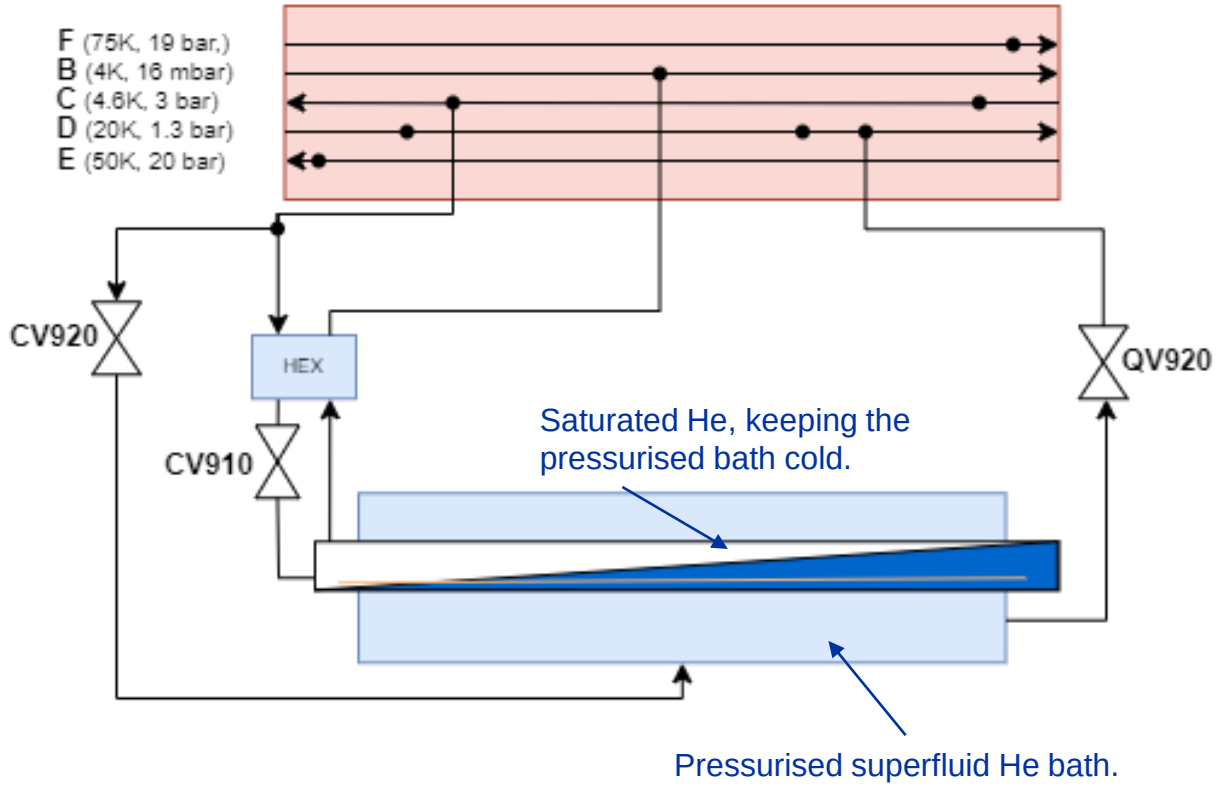
- Opt78 mode was used during 2022 and 2023, adding strong operational constraints.
- Physics2 mode was successfully introduced during 2024 after a 'CryoMD' test window in Feb 2024.
  - S78 heat loads are still the most constraining. Max limited to 170 W/hc, considering operation.
  - Wrt to end of 2024, P8 should be compatible with an extra 10 W/hc of heat load in S78 for 2025.
- Degraded mode with QURCB would limit the capacity to ~100 W/hc.

CV920 vibration induced beam dumps – follow up

- CV920 keeps the magnet bath at 1.25 bar.
  - Because of small leaks, pressure descends and **it needs to open periodically**.
  - Mixture of warm He and superfluid He creates vibrations.
- Perturbations correlated with a growing beam orbit oscillation during the ion run.

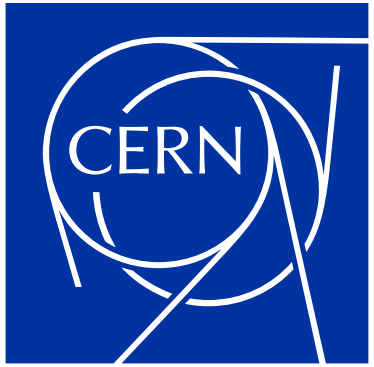
- New control logic has been added to address the issue:
  - During ion beam, selected critical cells (13L8 and 13L2) CV920 stay closed.
  - After beam dump, CV920 repressurises the cells.

- **<u>The solution was proven during the 2024 ion run.</u>**



CONCLUSIONS

- Successful 2024 run has been completed with 96.5% availability.
- Issues generating downtime have been identified, analysed, and mitigation measures are put in place during the current YETS.
- 2022 was very complicated to operate with high loads and OptS78 P8 configuration.
- P8 cooling capacity has been tested in different configurations during a “CryoMD”. A new mode was found with good performance-operability balance – Physics2.
- P8 limits have been identified for all modes. A margin of ~10 W/hc at S78 is still available for 2025/2026 run (leading to 170 W/hc).
  - Exact beam configuration should be validated during the beam commissioning phase.
- Cryogenic valve induced orbit oscillations has been resolved with a new simple control logic condition.



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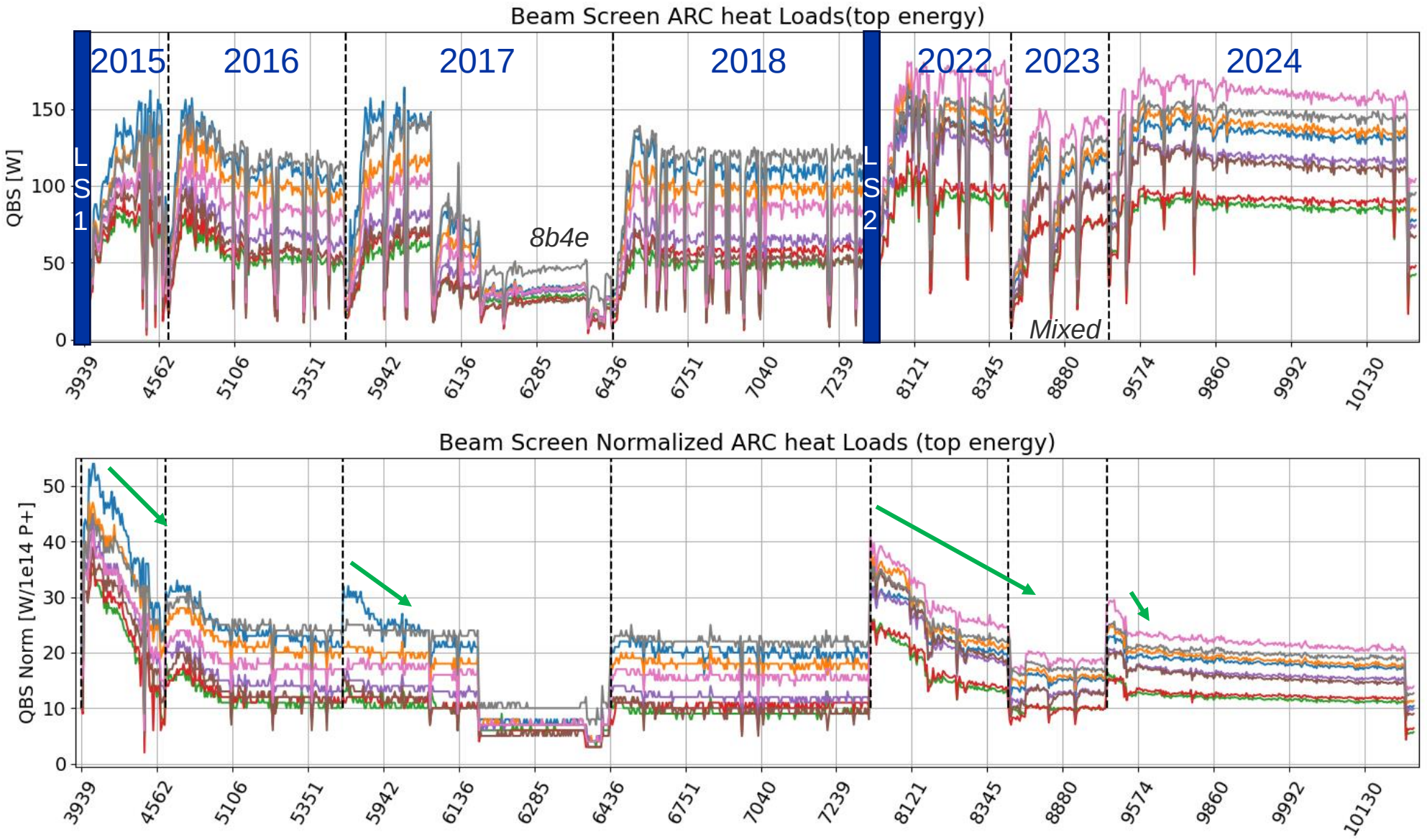
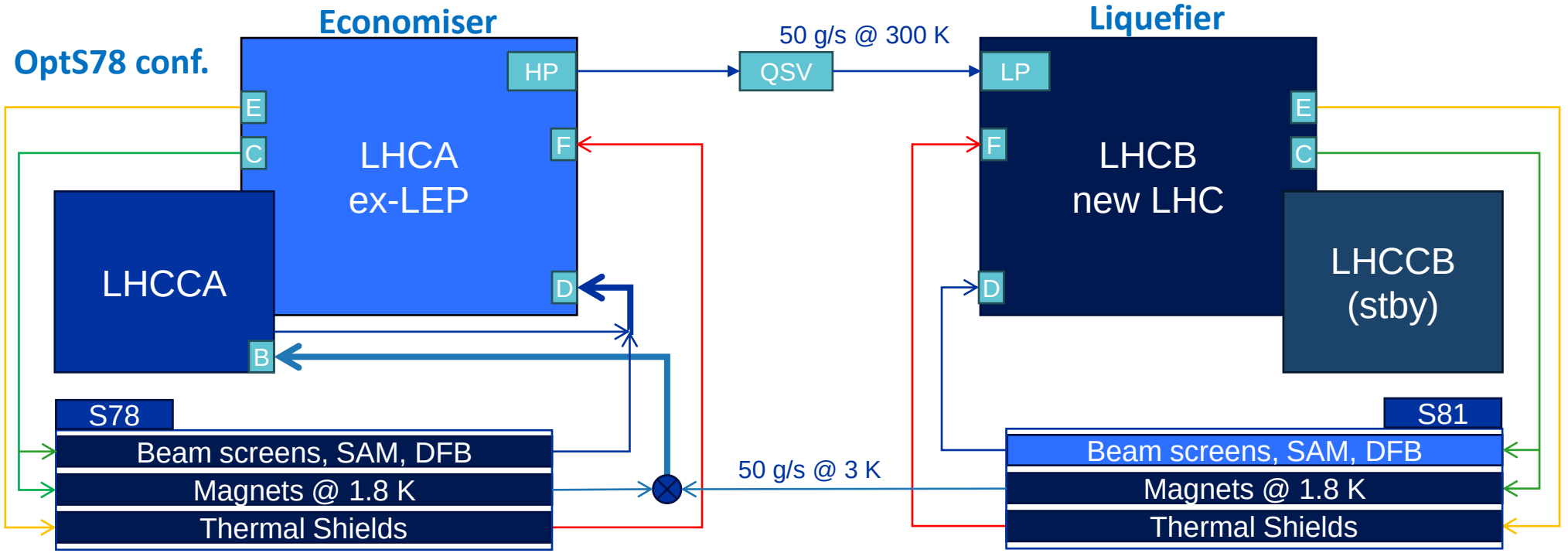
Beam screen heat loads Heat loads history @ top energy

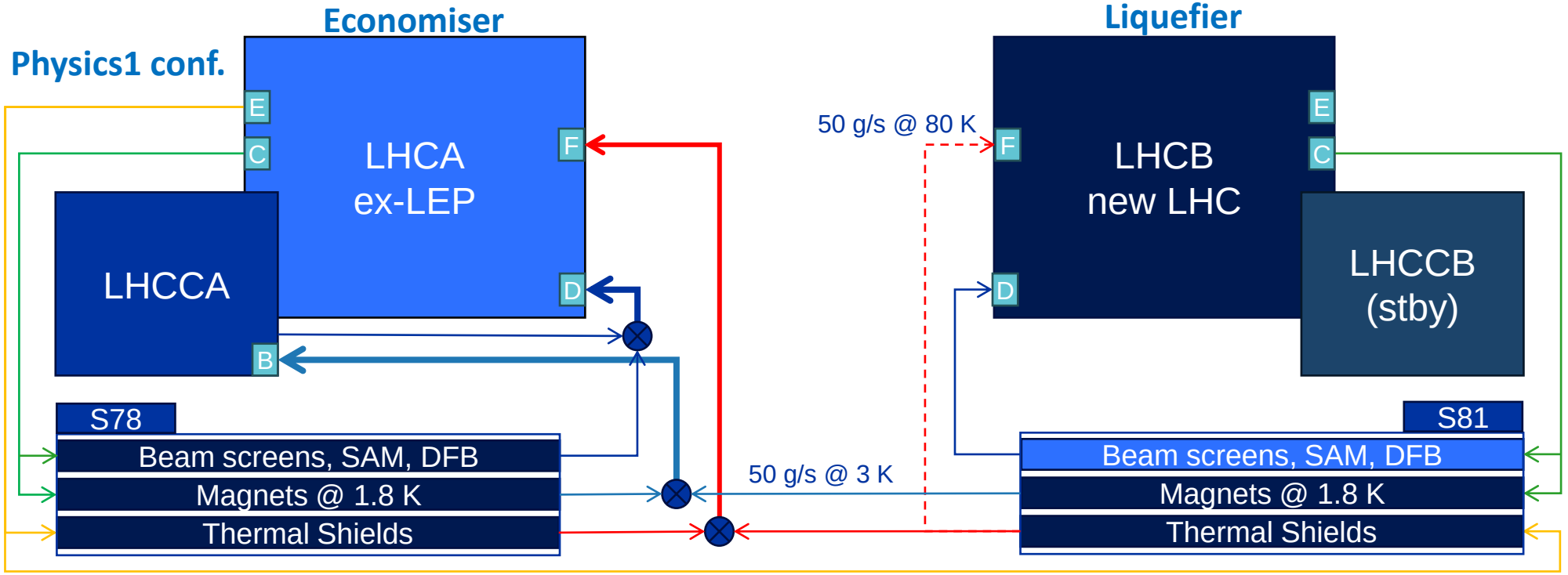


P8: Possible configurations – OptS78



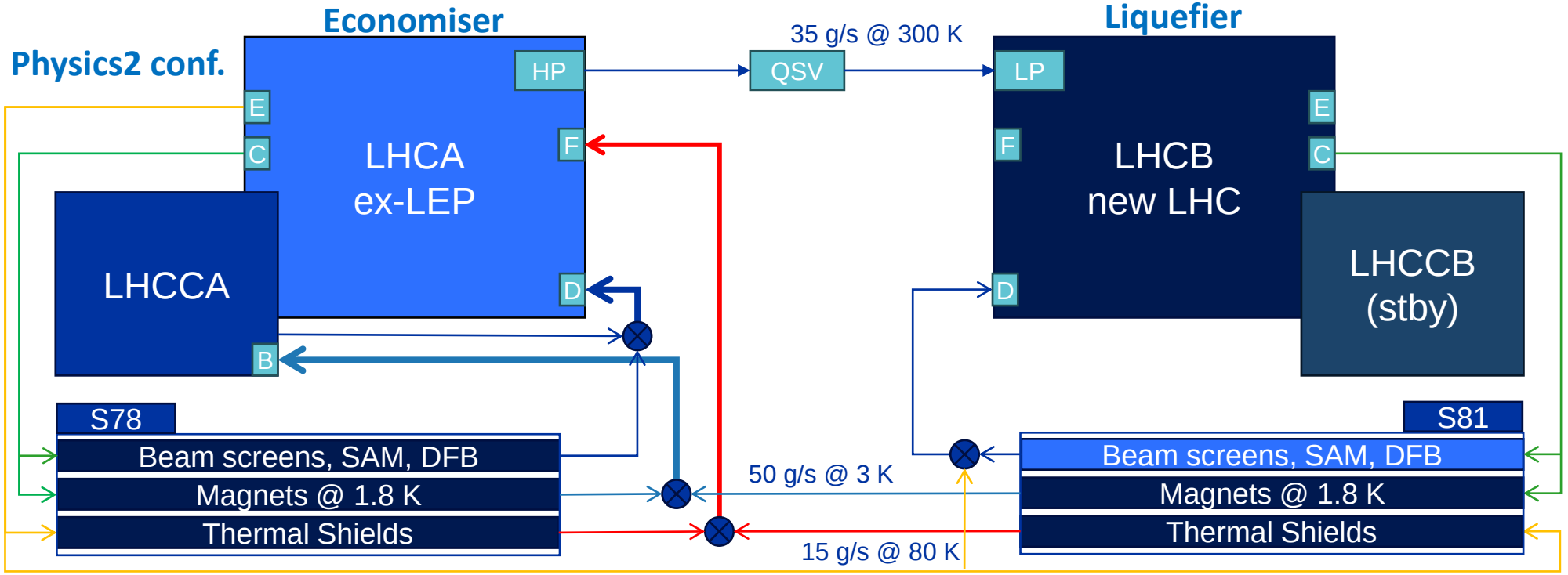
- Operation mode of P8 during 2022 and 2023.
- LHCB is in liquefaction as line D collects less than what line C supplies (due to LHCCA usage).
- Rebalance LHCA-LHCB done at 300 K.
- Uncertain performance and **difficult** operability.

P8: Possible configurations – Physics 1



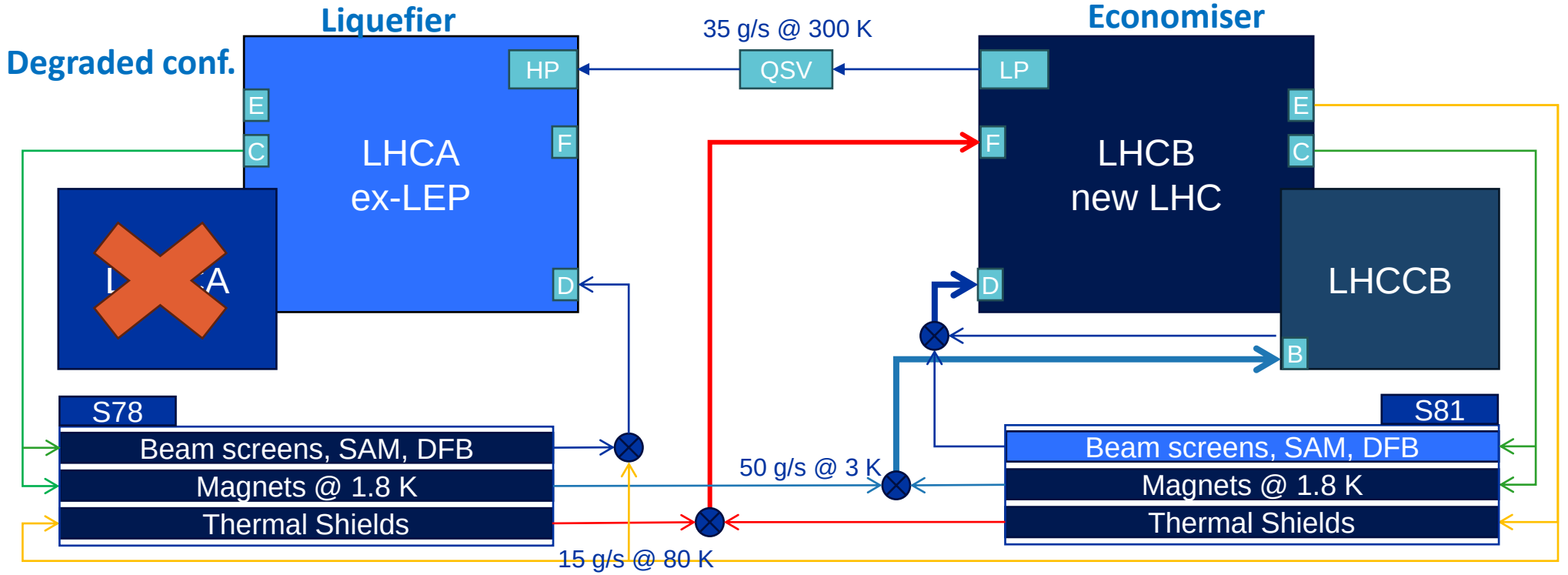
- Standard mode currently used for all other LHC points.
- Economiser/liquefier asymmetry appears due to usage of LHCCA.
- All thermal shields supplied by LHCA. Rebalance of the two sides at 80 K.
- Difficult to operate at P8 due to the absence of isolation valves in line F return. Hard operation constraint.
- Good performance but constraint operability.

P8: Possible configurations – Physics 2



- New mode used at P8 during 2024.
- LHCB still in liquefaction.
- Rebalance LHCA-LHCB done at partly at 80 K and partly at 300 K.
- Good performance-operability balance.

P8: Possible configurations – Degraded



- Degraded mode to be used if extended LHCCA downtime is expected.
- LHCA is now in liquefaction – limited capacity.
- Rebalance LHCA-LHCB done partly at 80 K and partly at 300 K.
- Poor performance.