Status of the Accelerator

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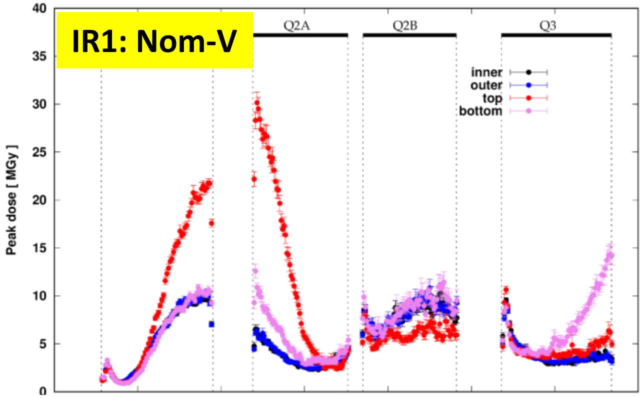
158th LHCC OPEN Session

May 29th, 2024

Outline

- **2024 run so far**
- “Limitations”
- Outlook for the rest of the year

Reversed Polarity (RP) optics

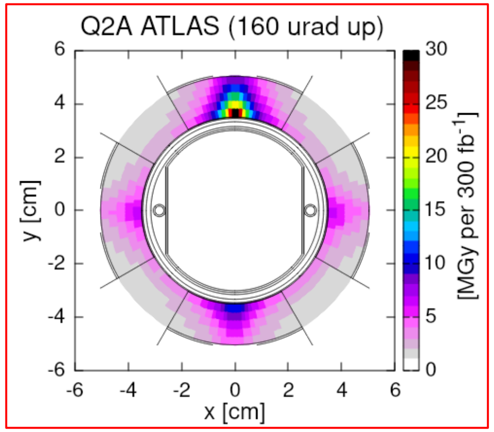


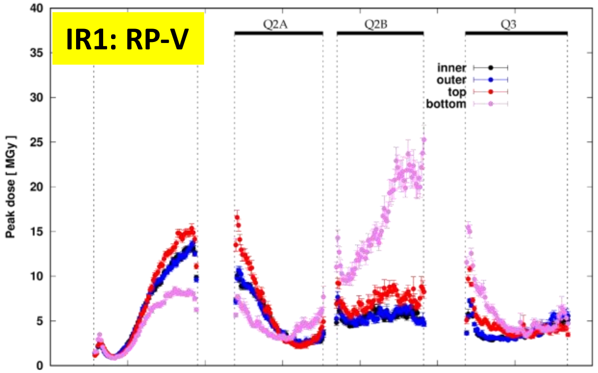
Excessive dose deposition on magnets of Inner Triplet region (close to interaction point) can lead to damage and failure

Solutions to **redistribute the radiation**, allowing for longer lifetime of the equipment:

- Local optics change (implemented in P1, as most critical)

Example for IP1



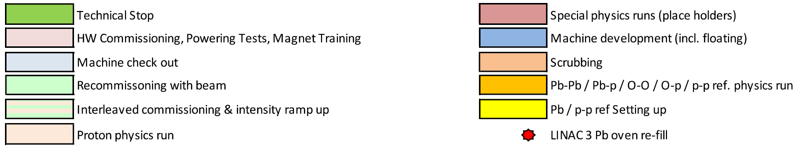


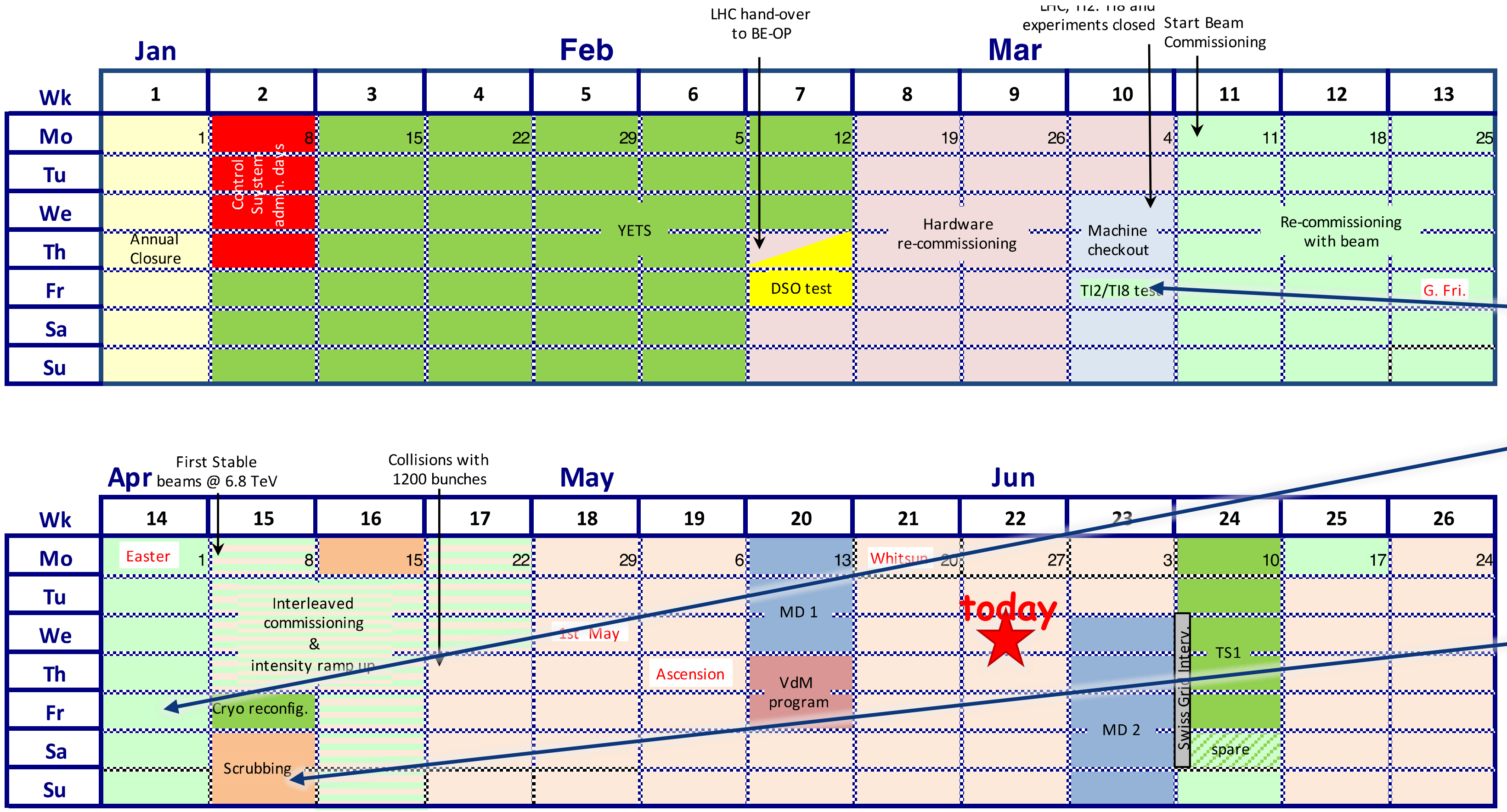
Configuration	Peak dose [MGy] at end of 2025 (430 fb^{-1})	
	IT	MBXA (D1)
NO change	26.5 (IR1) 26.5 (IR5)	**105** 70
2024 - **IP1**-RP 2025 - Full RP	20.5 (IR1) 22.5 (IR5)	70 60
2024 - **IP1**-RP 2025 – NO change	22 (IR1) 26.5 (IR5)	70 70

Estimated damage limit:

- 30 MGy for IT
- 90 MGy for D1

2024 LHC schedule v.2.0 - Q1+Q2

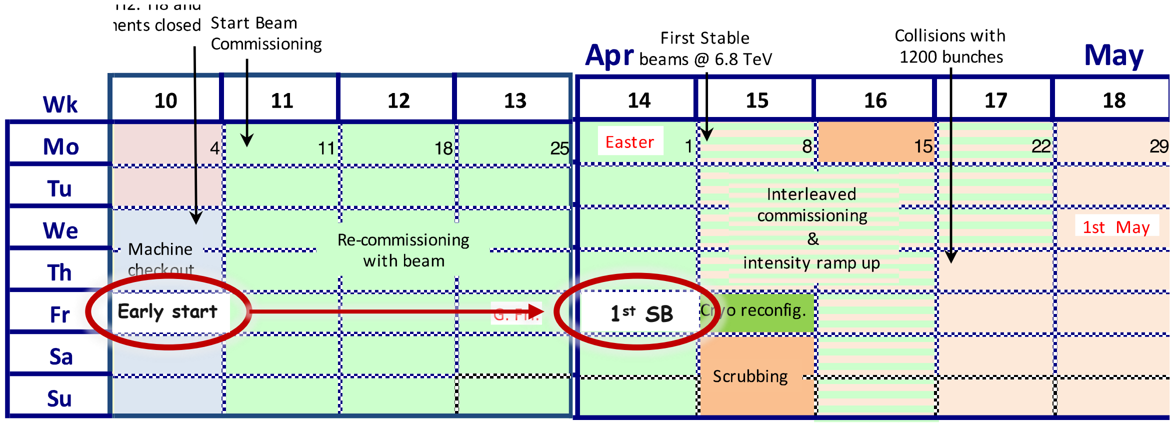




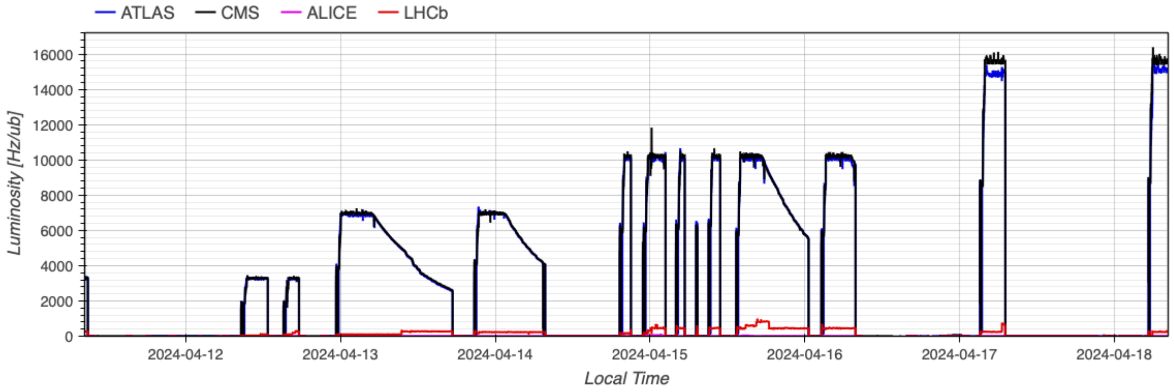
- **Hardware commissioning** completed in time
- **First injection** on 8th March (3 days ahead of schedule)
- **First STABLE BEAMS** at 6.8 TeV on 5th April (3 days ahead)
- **Scrubbing** succesful
- **Intensity ramp-up** completed in advance (1215b fill on 14.04)
- **MD#1 & VdM** successfully performed

Establishing physics production

- **Beam commissioning** completed in the 4 weeks allocated:
  - Well established baseline, effective knowledge and control: **early start** (3 days) -> **early stable beams** (3 days)
  - Optics change accounted for ~1 week (as expected)
- Step-wise approach for **intensity ramp-up**:
  - Monitor behavior during >15h in stable beams
  - Validate progressively correct functionality of machine-protection system and operational tools
  - Bunch intensity (in collisions) ~$1.55e^{11}$ p/b

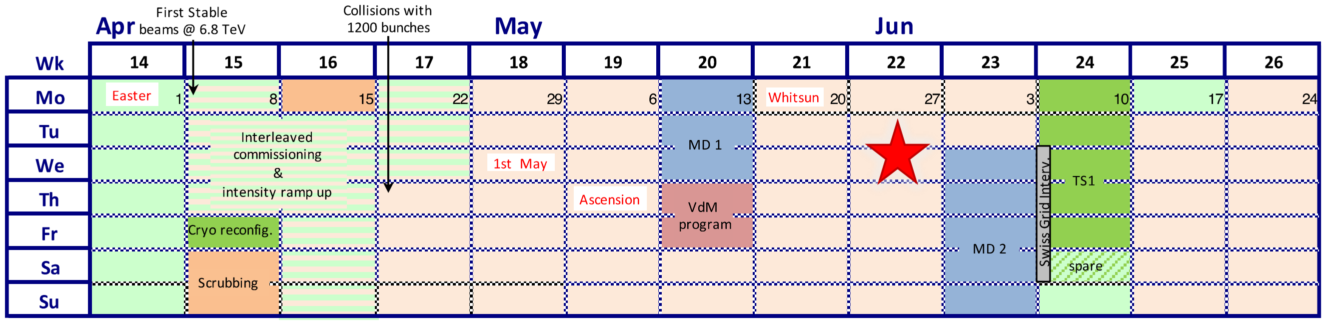


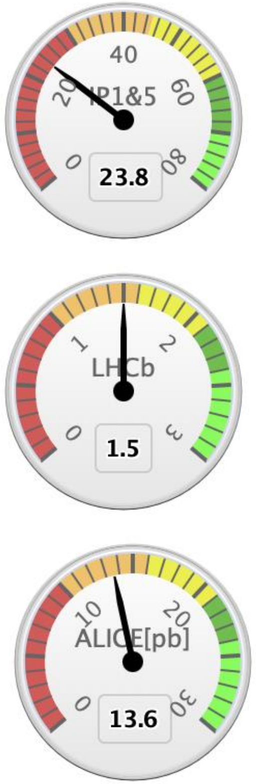
3/12 - 75 - 400 - 800 - 1200 - 1800 - 2400 - full machine*

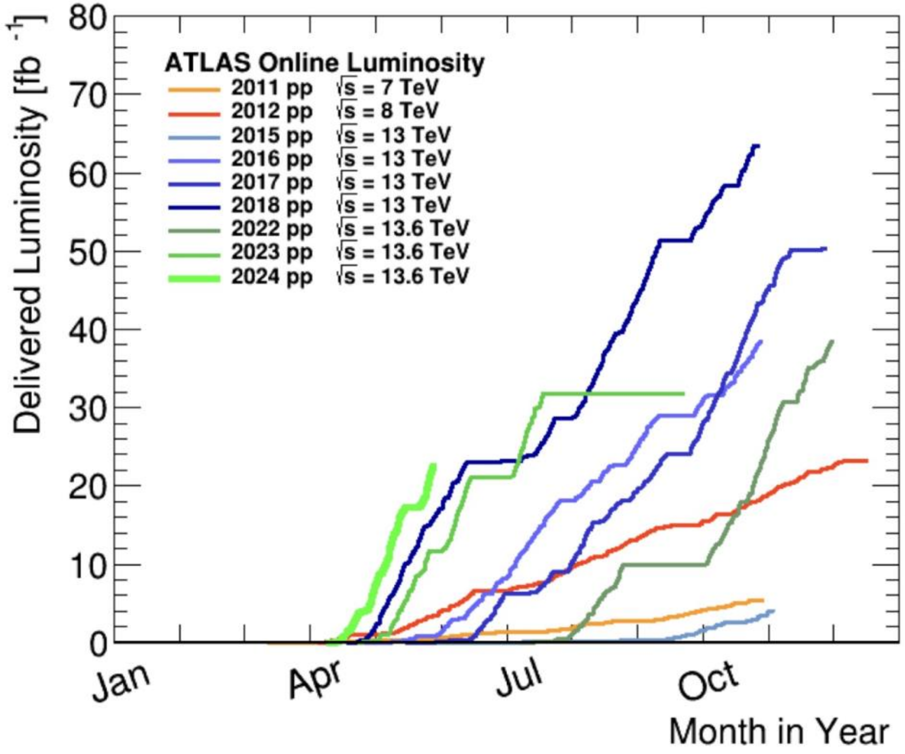


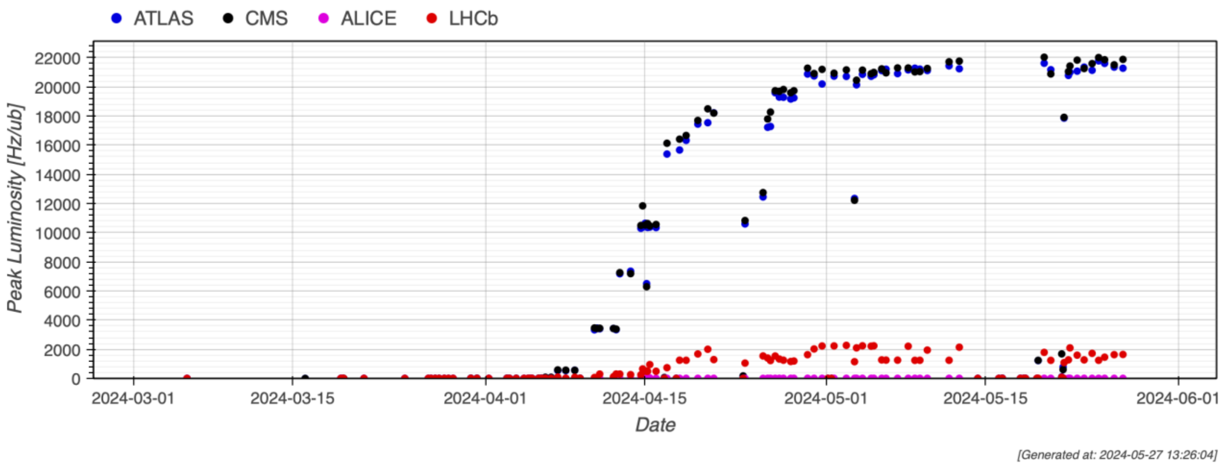
Physics production

- **Good availability** through the first part of the year
- **~24 fb^{-1}** in ATLAS/CMS
- Achieved **nominal rate** (as 2023)
- **Peak luminosity** at ~2.1e^{34} cm^{-1} s^{-1} (limited by cryogenic)
- **Pile-up** at 65





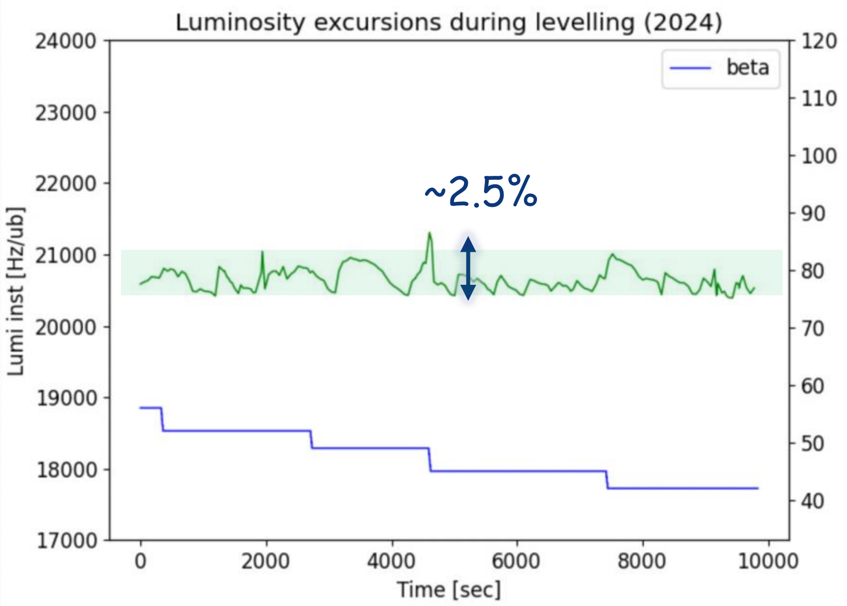


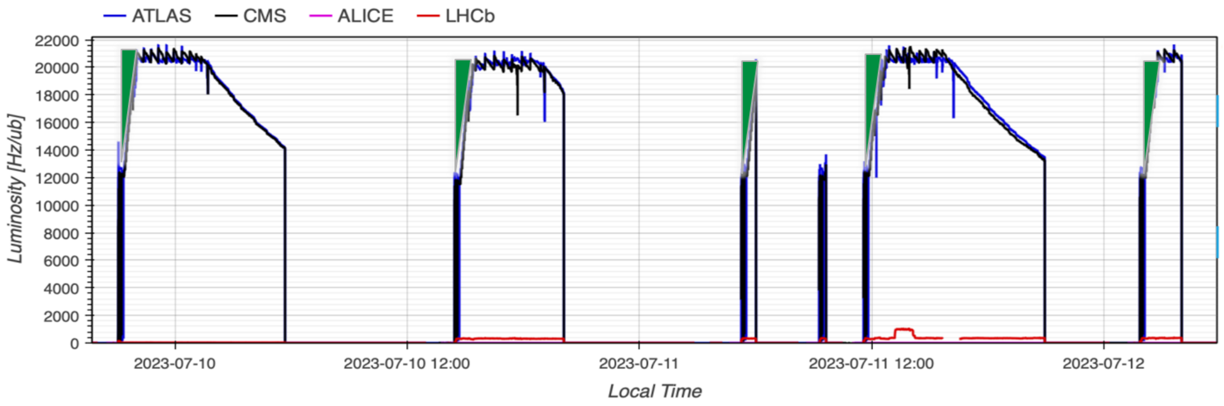


2024 operational improvements

“virtual lumi”: based on machine and beam parameters gives **theoretical luminosity**

- Used **for β* levelling**
- **2024 improvement:** Luminosity oscillations in 2.5% range (Run3 request was 5%)





Fast(er) reach of desired β*

- LHC cycle (i.e. β* at collision) **optimised for $1.8x10^{11}$ p/b ➔ ~45 min** to reach target levelling luminosity
- Few % gain (depending on fill length)

Outline

- 2024 run so far
- **“Limitations”**
- Outlook for the rest of the year

Vacuum module

IMPACT in 2023

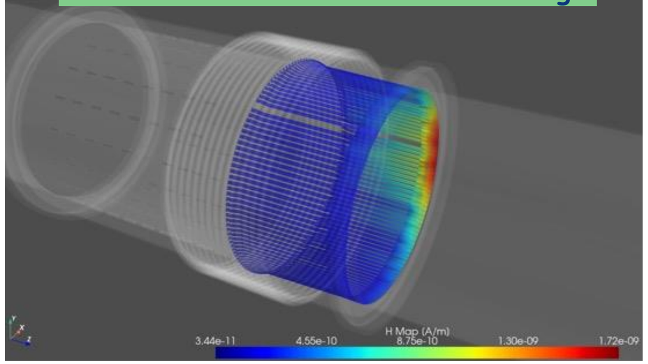
- ~5 days lost
- Bunch intensity limited to $1.6e^{11}$ p/b

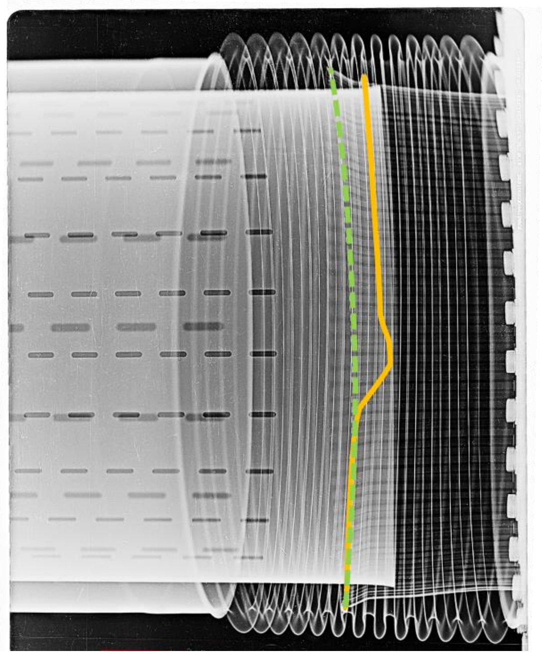
- Difficult to identify **intensity limitation** (strong dependence on contact quality)
- **2024 LHC operation** presently limited to $1.6e^{11}$ p/b
- **Simulations ongoing** to assess impact of beam parameters on power deposition

LMC 479: limit bunch intensity at $1.6e^{11}$ p/b, while maximizing the bunch length throughout the cycle

VISUAL INSPECTION
annealed/plasticised spring on the 212 mm vacuum module due to localized temperature increase to more than 500°C

EM simulations show localized heating





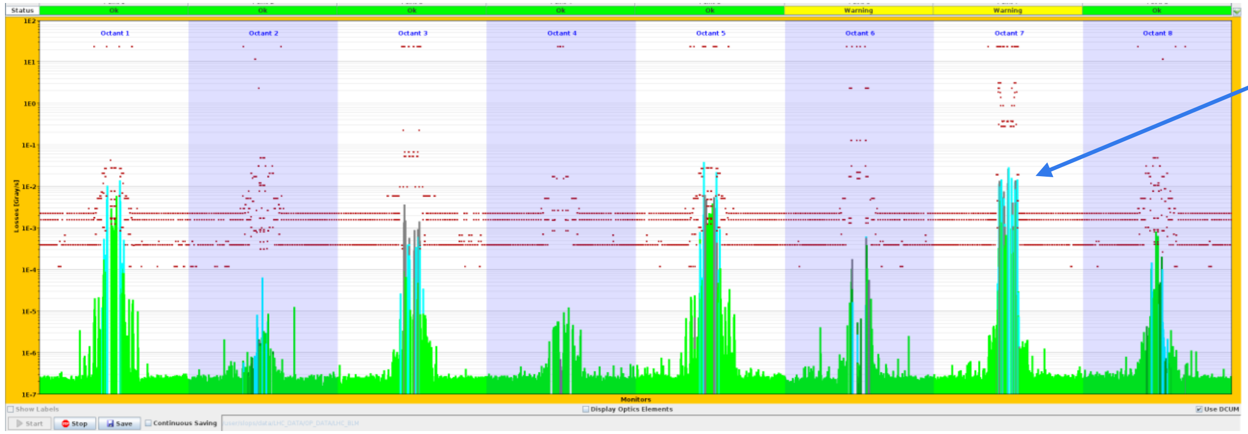
Consolidation plan:

- 47 replaced during 23/24 EYETS
- 24 foreseen in 24/25
  - No failure expected with ideal contact

Improved control of bunch length provides a **safety factor** of ~2 or more in power deposition

Beta* limitation (36 cm)

First observation: significant losses on secondary collimator (TCSPM.B4R7.B2) in fill 9530 (17th April)
300-400 um orbit shift needed to induce observed hierarchy breakage



Highest losses in the **middle of insertion,** instead of extremities, where primary collimators are located!

*Signature of **broken collimation hierarchy (protection at risk)***

No issue observed during machine **validation (low intensity):**

- Quite **some differences** between validations fills (single bunches) and physics fill with long trains (non-linearities, beam-beam effect, BPM response,…)

Beta* limitation (36 cm)

- **Studies, tests and simulations** to identify the origin of the problem
- **Various contributions,** no clear “smoking gun” identified:
  - **Centres** of suspected **collimators** within **0.1-0.2 sigma from nominal settings (<20 um)**
  - **No significant orbit change** at collimators as function of filling scheme
  - **Optics stable** within <5% (45-30 cm)
  - Observed dependency on **bunch intensity**
  - Impact from **non-linearities** (octupoles, chromaticity)
  - **Two-beams effect**

Produced by **halo** (not primary beam), hitting only one collimator jaw

- could match off-momentum halo, due to non-linearities (beam-beam), combined with a somehow large dispersion

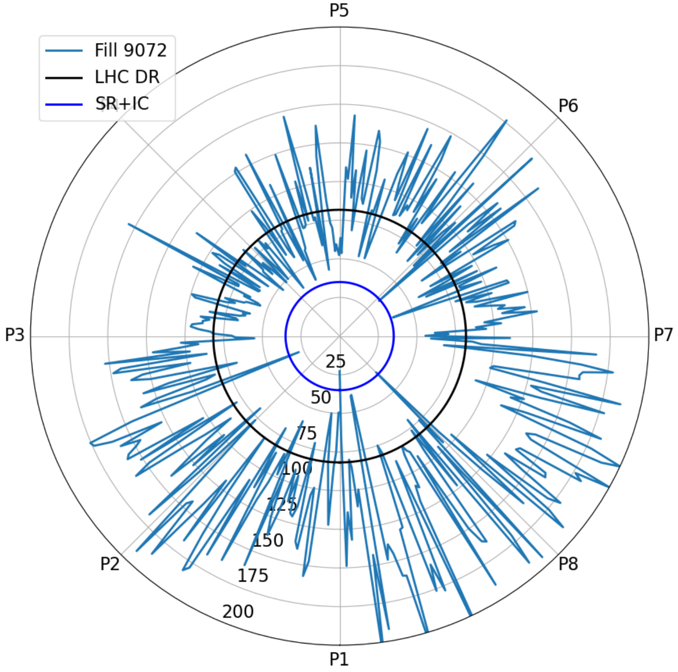
Test planned for this week

Physics production **limited to 36 cm** (about 1-2% loss), until the origin of the problem and possible mitigations are identified

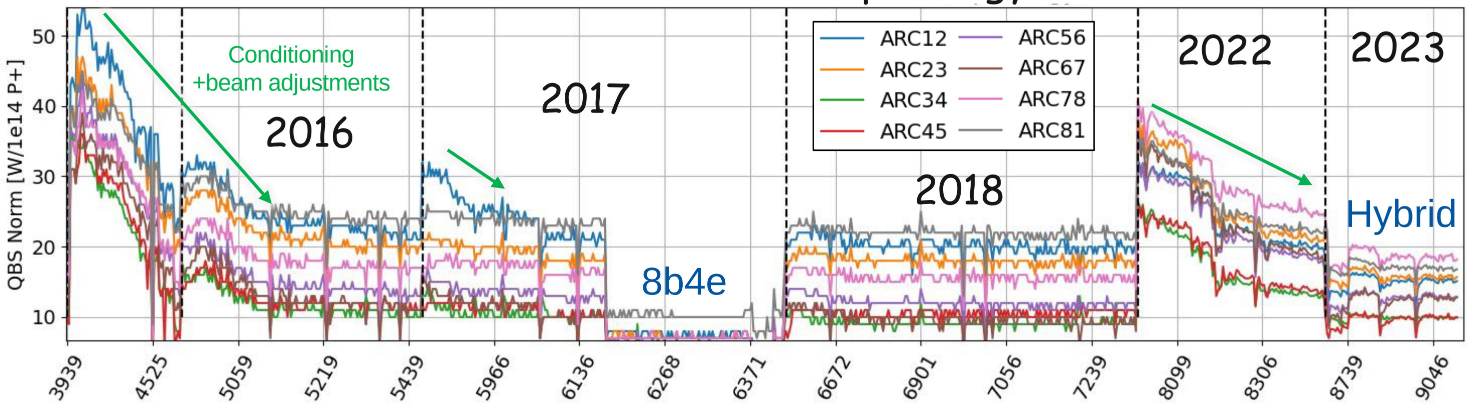
Heat load

- Heat load (HL) deposited by the beams **can become a limitation** when not enough cryo capacity is available (presently well beyond the Design Report value)
- **Degradation observed** when sectors are vented to air (LS)
- **Non-homogeneous distribution** across the machine
  - Sector 78 is the highest sector in Run3
- **Gradual conditioning** helps to increase the beam intensity

Geographical HL distribution



Normalised HL at top energy

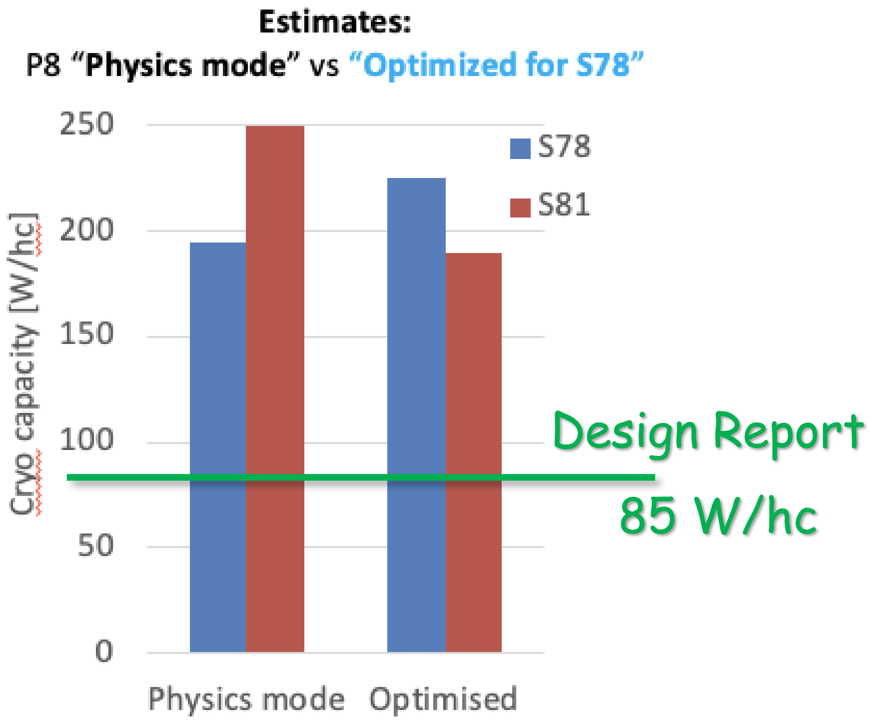


Heat load in Run3

2023: HL kept under control thanks to **hybrid filling scheme** (8b4e and 36 bunch trains) – e-cloud suppressed at price of total number of bunches

2024

- Test with modified cryogenic configuration (capacity rebalanced between S78 and S81) hinted at possibility to operate LHC <u>without hybrid scheme</u> at 1.6e^{11} p/b, allowing for:
  - **Larger number** of bunches
  - Better beam quality
- **Beam generated HL,** higher than expected, limits further the number of bunches (~100b less than in 2023)



Hybrid vs 48b vs 36b (today)

Beam type	Max number of bunches
Hybrid	2464
48b trains	2355 (HL limited)
36b trains	2352 (HL limited)

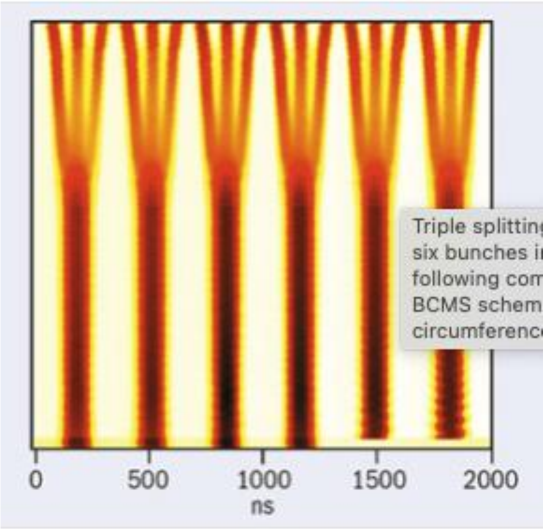
- **Hybrid vs pure 25 ns beam**
  - **PROS**: e-cloud free beam, NO heat load
    - Higher number of bunches (~100b)
  - **CONS**: mixed beam type (8b4e + 36b)
    - Continuous setup in the injectors (2 beam types to be maintained), with increased risk of availability limitations
    - Lower beam quality with less homogeneous bunch distribution
    - More difficult control, increased losses across LHC cycle
- **48b vs 36b trains**
  - No (significant) difference in number of bunches
  - 36b means more injections (longer LHC flat-bottom), but allows to exploit BCMS (next slide) -> potential gain up to 10% in brightness
  - 36b generates less HL, allowing for larger cryogenic operational margin

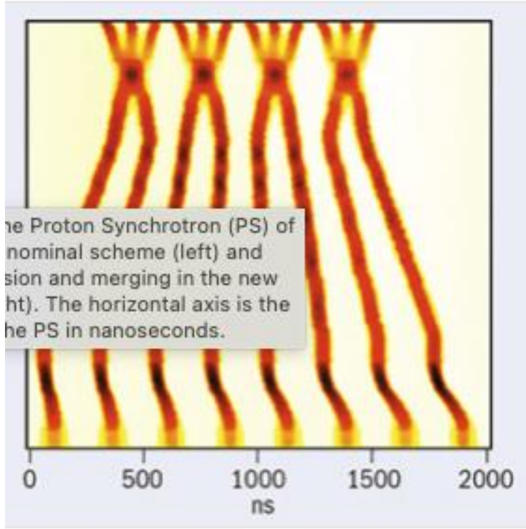
BCMS vs 25 ns beam

With a filling scheme based on 3x36b patterns, the standard 25 ns and Batch Compression and (bunch) Merging and (bunch) Splitting (BCMS) beams are **interchangeable** transparently

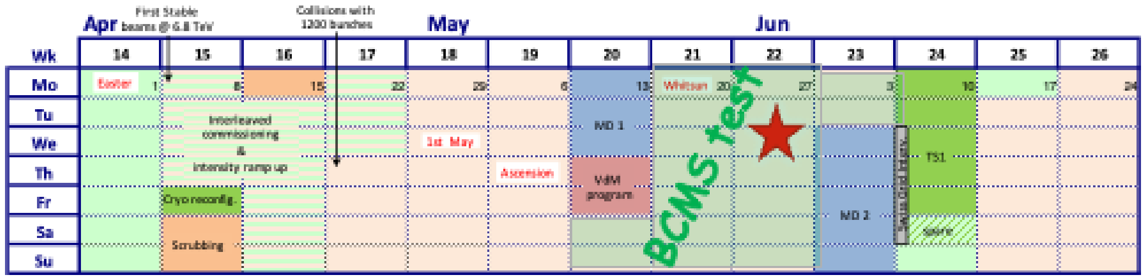
Test with **optimized BCMS** beams in the LHC is ongoing (brightness theoretical **10% higher):**

- Smaller emittance is beneficial for **losses reduction**, especially at injection
- If smaller emittance preserved through the LHC cycle, **better equivalent cross-section**

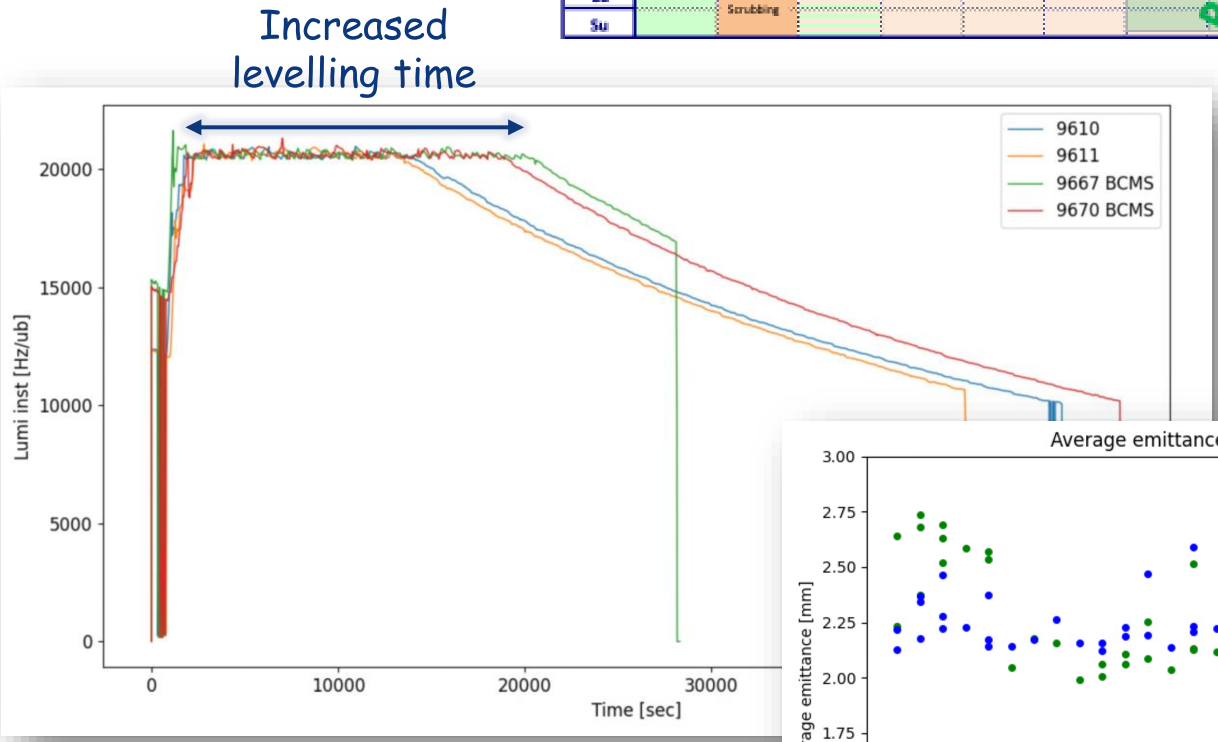


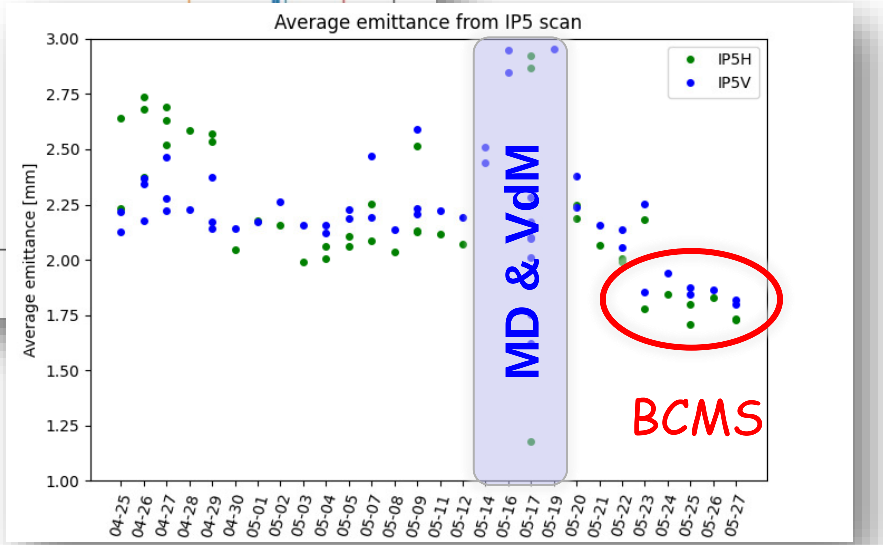


BCMS vs 25 ns beam



- Test operation with **BCMS beam** until TS#1 (unless major problems come out) to establish performance difference
- Few fills needed to **adjust the working point** (fight emittance growth at injection)
- Once set, clear increase of **25-30% in levelling time**
- Potential gain of **6-8% in integrated luminosity**

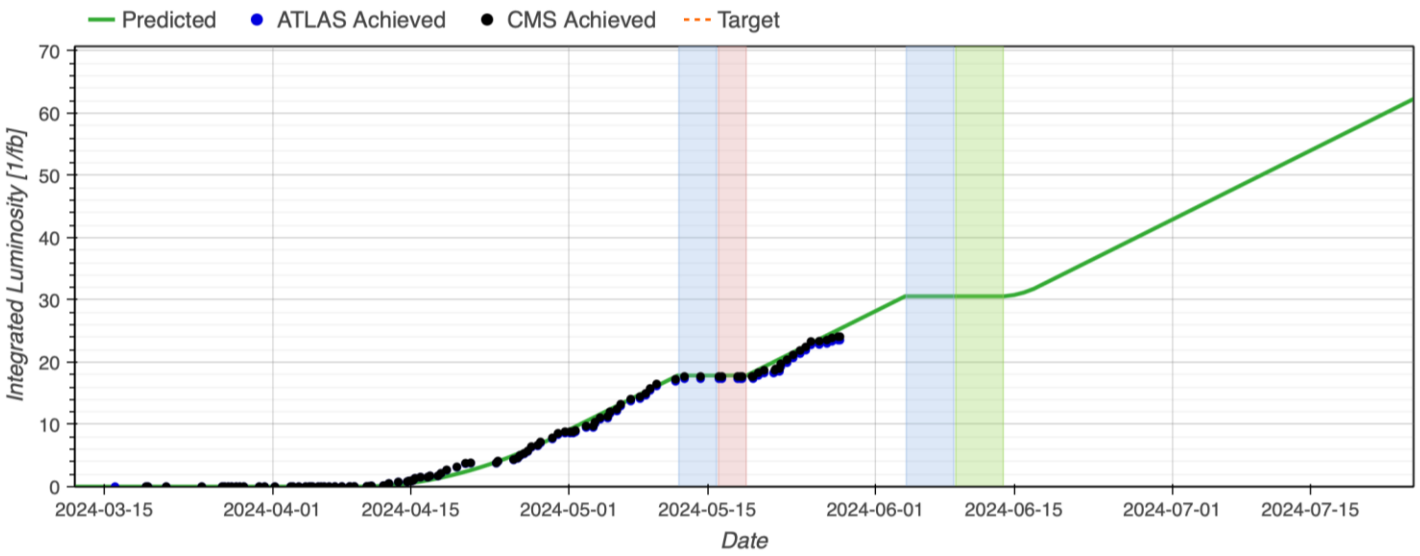


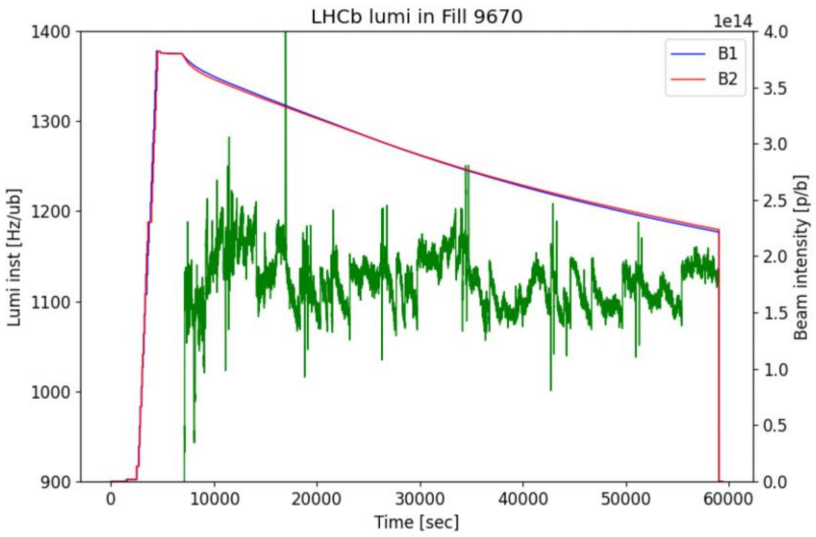


Preliminar observations

Performance reach

- Despite the above-mentioned “limitations” (beta*, number of bunches and bunch intensity), physics production is **nicely following expectations** and target is in reach
  - LHCb levelling >=15h
- **2024 operational configuration** allows performance similar to 2023 with more homogeneous beam and better operational control
- **Some improvements** still possible

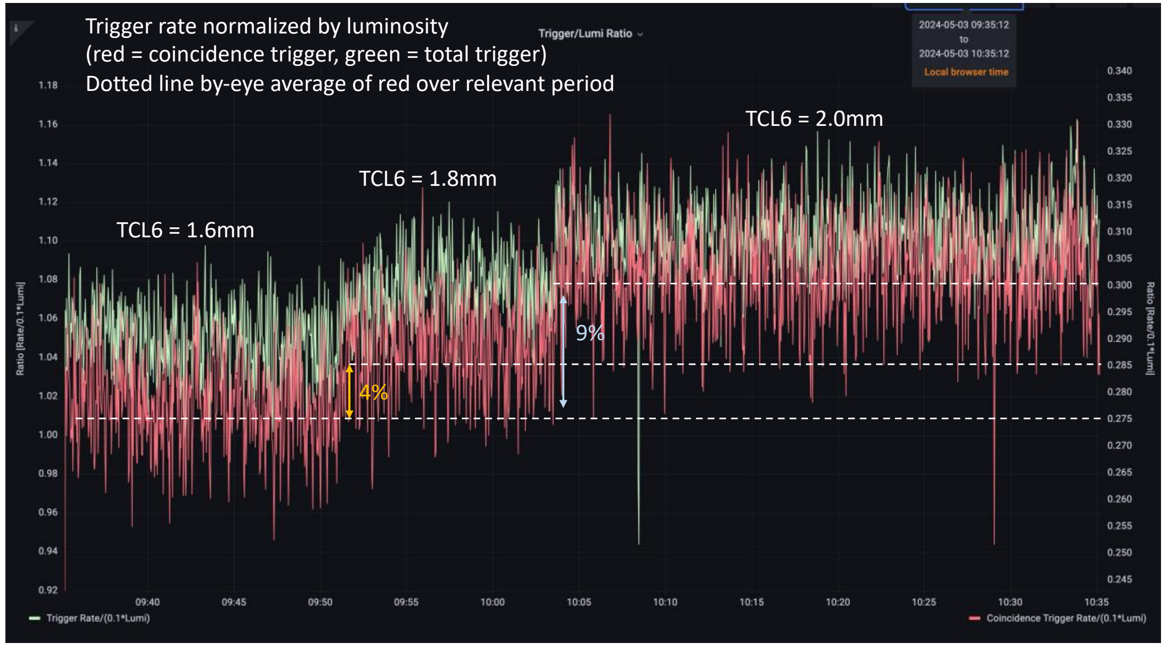




FASER/SND background

- **FASER and SND background rates** significantly higher (~double) wrt 2023 (non-RP optics)
  - Implies more frequent emulsion exchanges (if available!)
- Background tests for FASER demonstrated **little impact of collimation system** on background:
  - increase driven by TeV-scale muons, originating from IP

TCL6 scan (3/5/24)



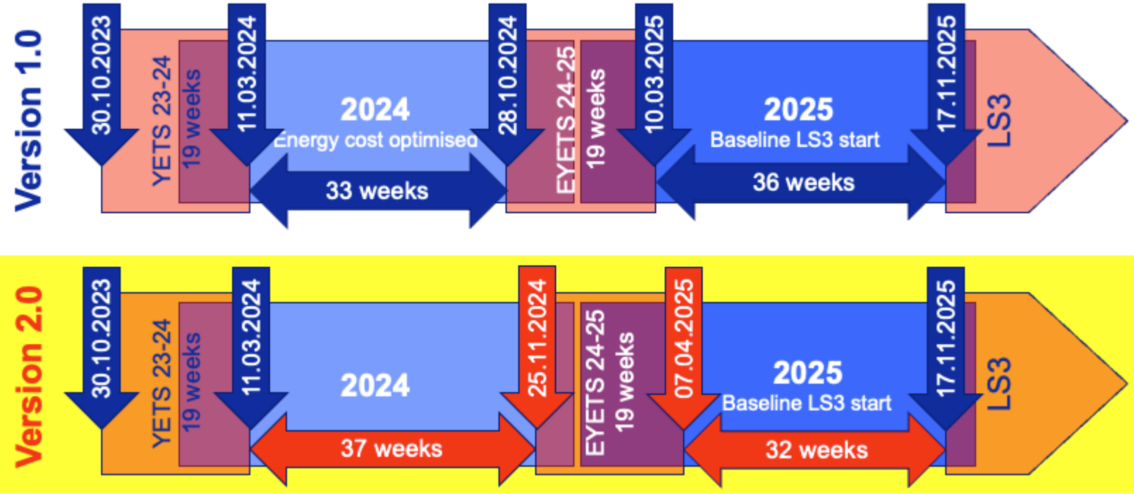
Coincidence trigger rate about 4% higher with 1.8mm and 9% higher with 2.0mm: OK for FASER for periods with no emulsion

Outline

- 2024 run so far
- “Limitations”
- **Outlook for the rest of the year**

LHC schedule - changes

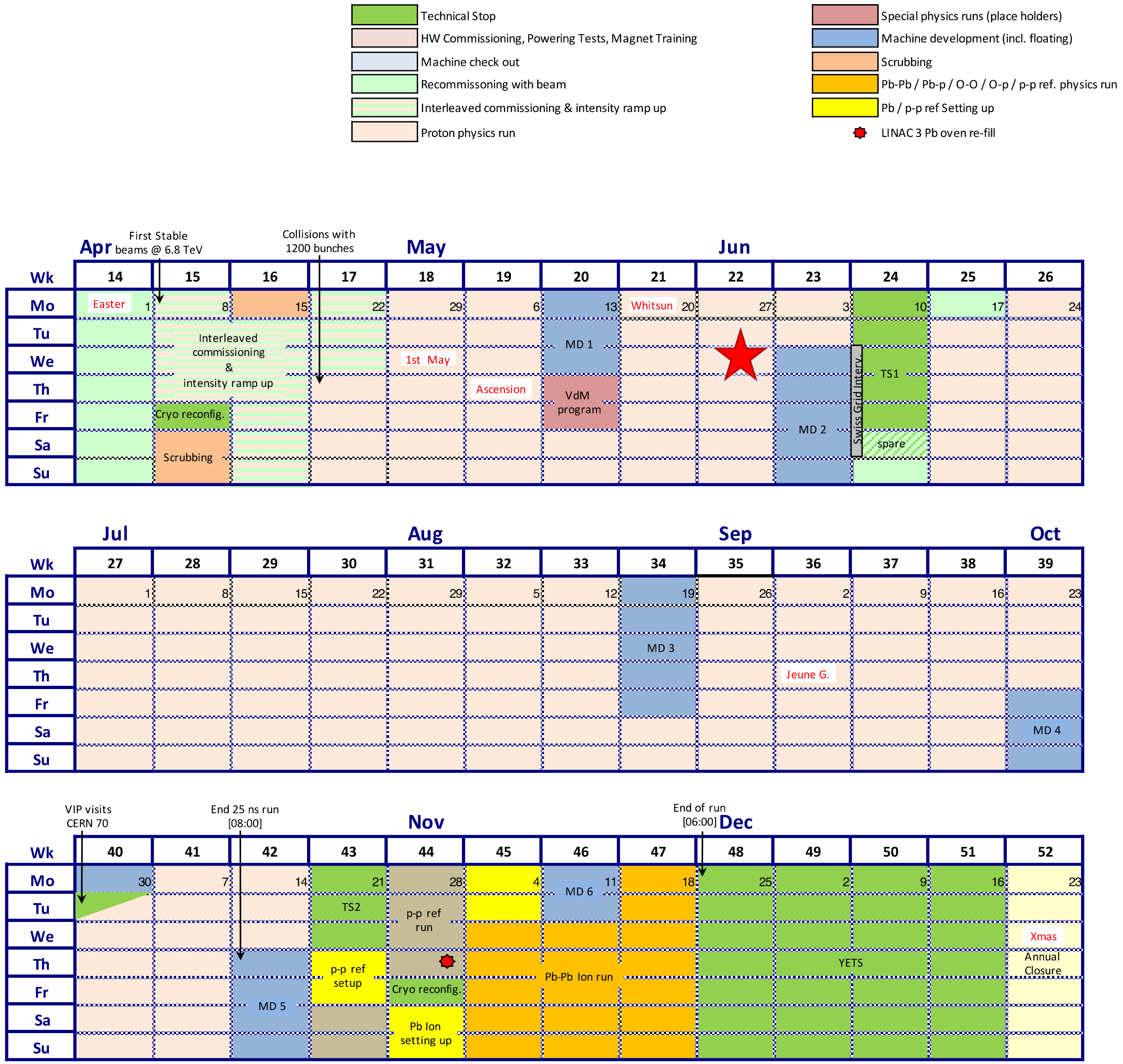
- **Injectors YETS** shifted by 5-weeks
  - 3-weeks reduction, more physics
- **LHC YETS** shifted by 4-weeks (Start date 28.10 -> 25.11)
  - 19 weeks length (beam-to-beam) maintained
  - Extended time used for proton physics
- **2025 run** shortened by 4 weeks -> one Technical Stop removed
- NO additional technical stop for **2024 run**



Activity	2024+2025 v1.0 [days]	2024+2025 v2.0 [days]	Diff [days]
Proton physics	269	274.5	**+5.5**
Ion physics & p-p ref. run (Oxygen included)	44.5	45	**+0.5**
Scheduled stops & recovery	28.5	22.5	**-6**

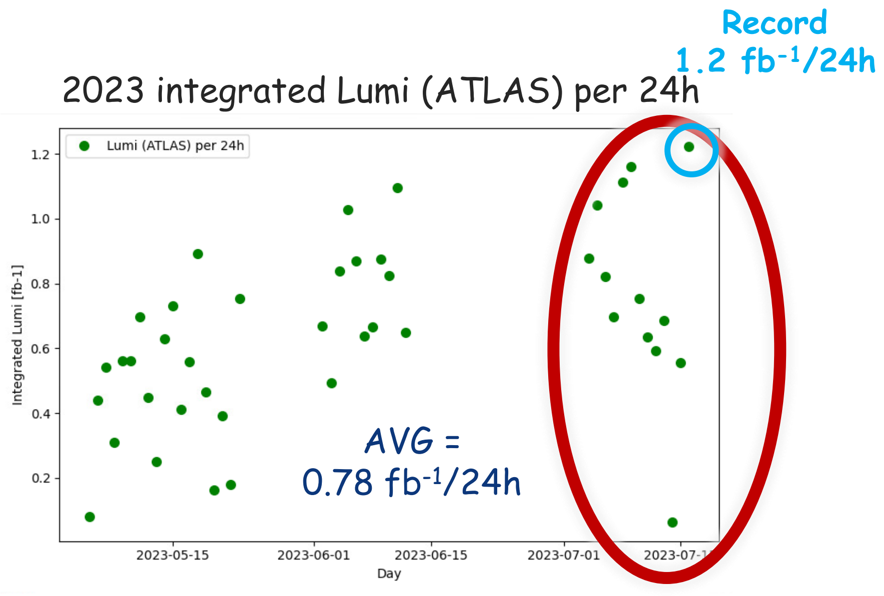
2024 LHC schedule

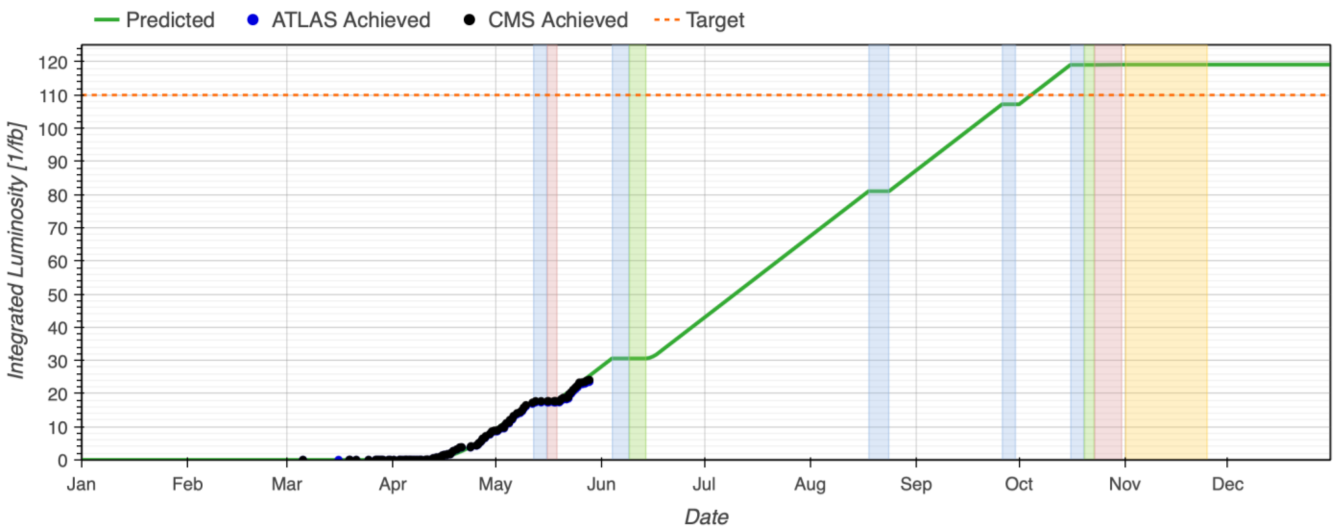
Activity	Duration [days]	Ratio [%]
Beam Commissioning & Intensity ramp-up	41	15.8
Scrubbing	3	1.2
25 ns physics (>1200 bunches)	**147.5**	**56.9**
Special physics runs (incl. setting-up)	**2**	**0.8**
Pb-Pb ions & p-p ref. setting-up	6	2.3
Pb-Pb ions physics & p-p ref. run	**23**	**8.9**
Technical stop	9	3.5
Technical stop recovery	2	0.8
Other scheduled stops	2.5	1.0
Machine Development	23	8.9
Total:	**259**	**100**

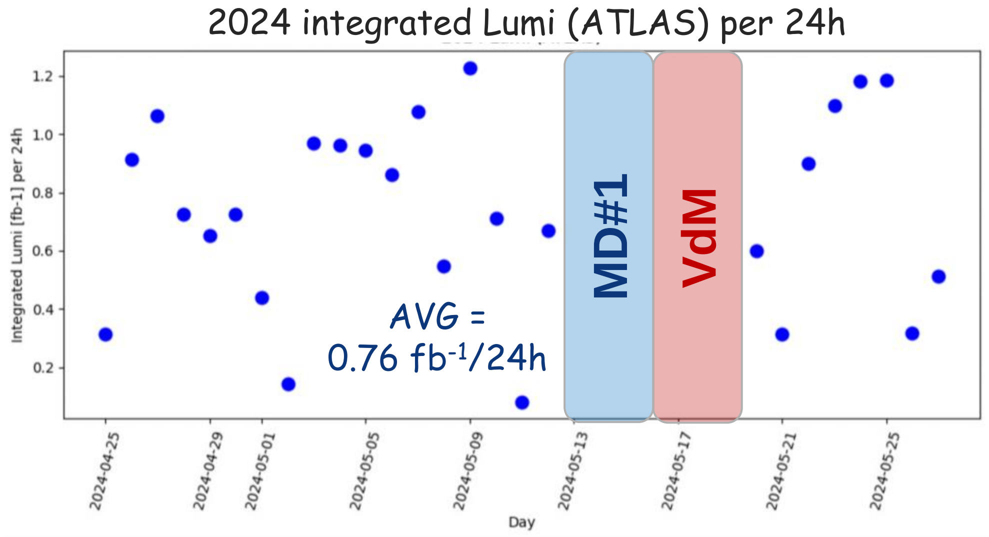


Performance

- 2024 **production rate** reached 2023 values (~0.8 fb^{-1}/24h)
  - Peak record of 1.2 fb^{-1}/24h
- Scaling the target by the increased number of pp physics days, **110 fb^{-1}** should be **in reach**







Availability is key

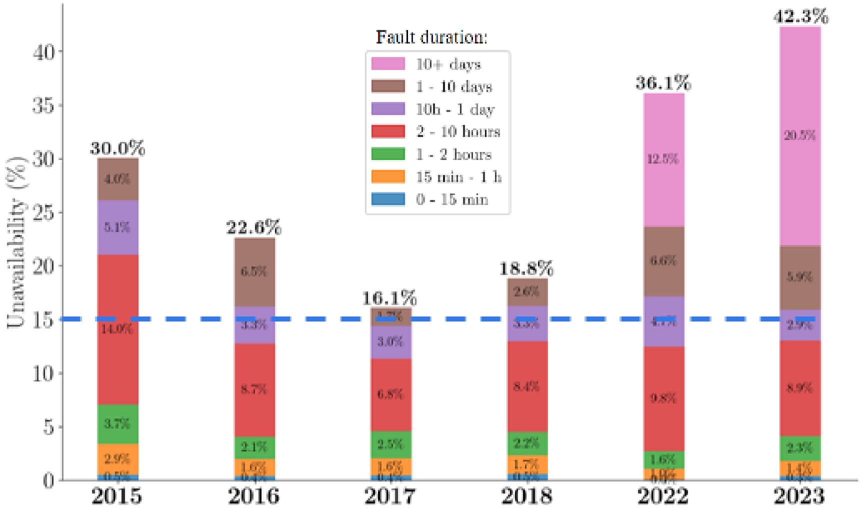
- Availability is THE key factor for accelerator performance
- **Accelerator Fault Tracking** (AFT) systems allows for analysis and cataloguing of down time
- **Availability factor** was constant through Run2 and Run3 for small (<24h) faults
- **"Long faults" have been so far** dominant for Run 3

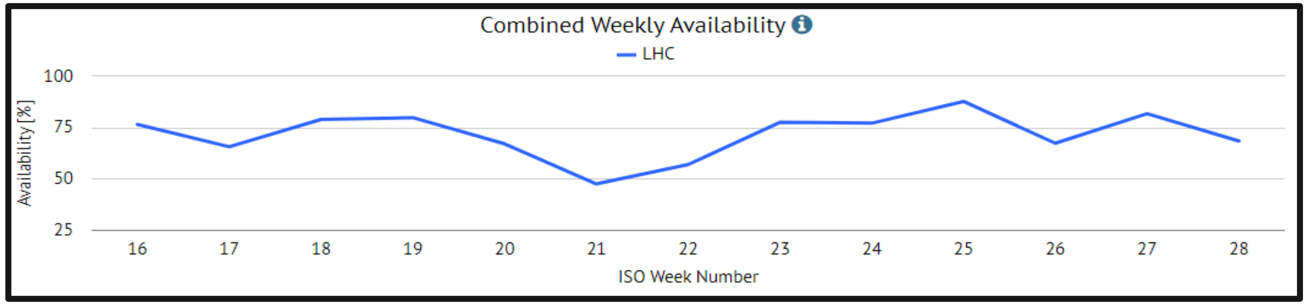
2023 availability during production period

Availability	Stable beams (SB)
75.9%	51.6%

2024 availability during production period

Availability	Stable beams (SB)
70.5%	52.3%





Conclusions

- **2024 Run** is progressing well
  - Some improvements still possible (BCMS optimised, lower beta*)
- Despite of a few “limitations”, **production rate** is in line with expectations
  - **Bunch intensity** limited to 1.6e^{11} p/b for risk mitigation
  - Beta* (temporarily) limited to 36 cm, until problem identified
  - Heat load limits number of bunches
- 2024 LHC schedule v2.0 allocates **23.5 additional days** to pp physics
  - 110 fb^{-1} should be in reach (provided good availability)

Thanks for your attention

SPARE

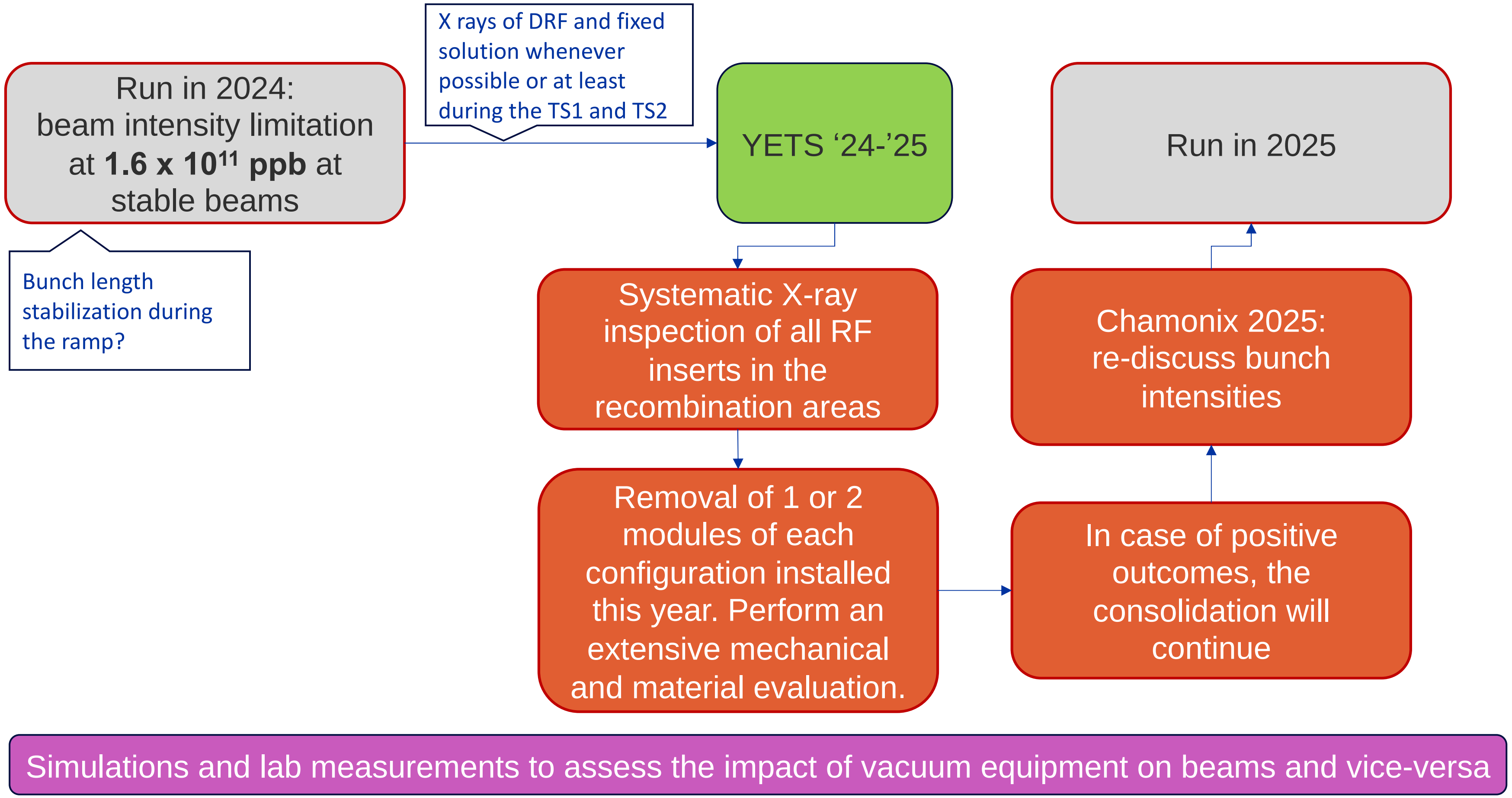
2024 LHC schedule

	Version 2.0		Version 1.0		Gains & Losses
Activity	Duration [days]	Ratio [%]	Duration [days]	Ratio [%]	
Beam Commissioning & Intensity ramp-up	41	15.8	42	18.2	=
Scrubbing	3	1.2	3	1.3	=
25 ns physics (>1200 bunches)	**147.5**	**56.9**	**124**	**53.7**	**+ 23.5**
Special physics runs (incl. setting-up)	**2**	**0.8**	**2**	**0.9**	**=**
Pb-Pb ions & p-p ref. setting-up	6	2.3	6	2.6	=
Pb-Pb ions physics & p-p ref. run	**23**	**8.9**	**22.5**	**9.7**	**+ 0.5**
Technical stop	9	3.5	9	3.9	=
Technical stop recovery	2	0.8	2	0.9	=
Other scheduled stops	2.5	1.0	0.5	0.5	=
Machine Development blocks (incl. floating MDs)	23	8.9	20	8.7	+ 3
Total:	**259**	**100 %**	**231**	**100 %**	**+28**

2025 LHC schedule

	Version 0.6		Version 0.4		Gains & Losses
Activity	Duration [days]	Ratio [%]	Duration [days]	Ratio [%]	
Beam Commissioning & Intensity ramp-up	36	16.1	37	14.7	=
Scrubbing	2	0.9	2	0.8	=
25 ns physics (>1200 bunches)	**123**	**54.9**	**141**	**56**	**-18**
Special physics runs (incl. setting-up)	**2**	**0.9**	**2**	**0.8**	**=**
Oxygen ion setting-up	4	1.8	4	1.6	=
Oxygen ion physics	**4**	**1.8**	**4**	**1.6**	**=**
Oxygen ion recovery	0.5	0.2	0.5	0.2	=
Pb-Pb ions & p-p ref. setting-up	6	2.7	6	2.4	=
Pb-Pb ions physics & p-p ref. run	**18**	**8.0**	**18**	**7.1**	**=**
Technical stop	8	3.6	13	5.2	- 5
Technical stop recovery	2	0.9	4	1.6	- 2
Other scheduled stops	1.5	0.7	0.5	0.2	+1
Machine Development blocks (incl. floating MDs)	17	7.6	20	7.9	- 3
Total:	**224**	**100%**	**252**	**100**	**- 28**

Recommendations based on a precautionary approach



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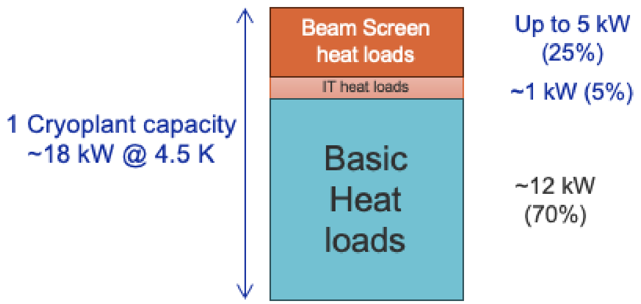
P. Chiggiato @ LMC #479

Heat load expectations

Beam screen cryo capacities during HL-LHC era

- **LHC cryoplants are supplying many devices in parallel at different temperatures**
  - ➢ Thermal shields between 50 K and 75 K
  - ➢ Main superconducting magnets at 1.9 K (ARC dipoles/quadrupoles)
  - ➢ Stand Alone superconducting magnets at 4.5 K (D2, D3, Q4, Q5, Q6)
  - ➢ RF cavities at 4.5 K
  - ➢ DFB at 4.5 K with their current leads and superconducting links
  - ➢ Inner Triplet at 1.9 K around experiments (dynamic heat loads, depending on luminosity)
  - ➢ Beam Screens (BS) between 4.5 K and 20 K (dynamic heat loads, depending on beams)



- **All LHC cryoplants are slightly different and have different capacities & loads (RF, SAM, DFB, triplets, etc.)**

Expected changes in Run 4++	Helium massflow	Q @ 1.9 K [per sector]	BS Capa 4.5 K - 20 K [per ARC]	BS Capa 4.5 K - 20 K [per half-cell]	Concerned sectors
Removal of IT at P1 & P5 in LS3 (Run4)	-12 g/s	-280 W	+1.3 kW	+25 W/hc	S12, S81, S45, S56
Increase of Lumi at P8 with LHCb++ after LS4 ? (Run5)	+11 g/s	+260 W	-1.2 kW	-23 W/hc	S78, S81

➔ **The available beam screen cryogenic capacities will change from Run 4**

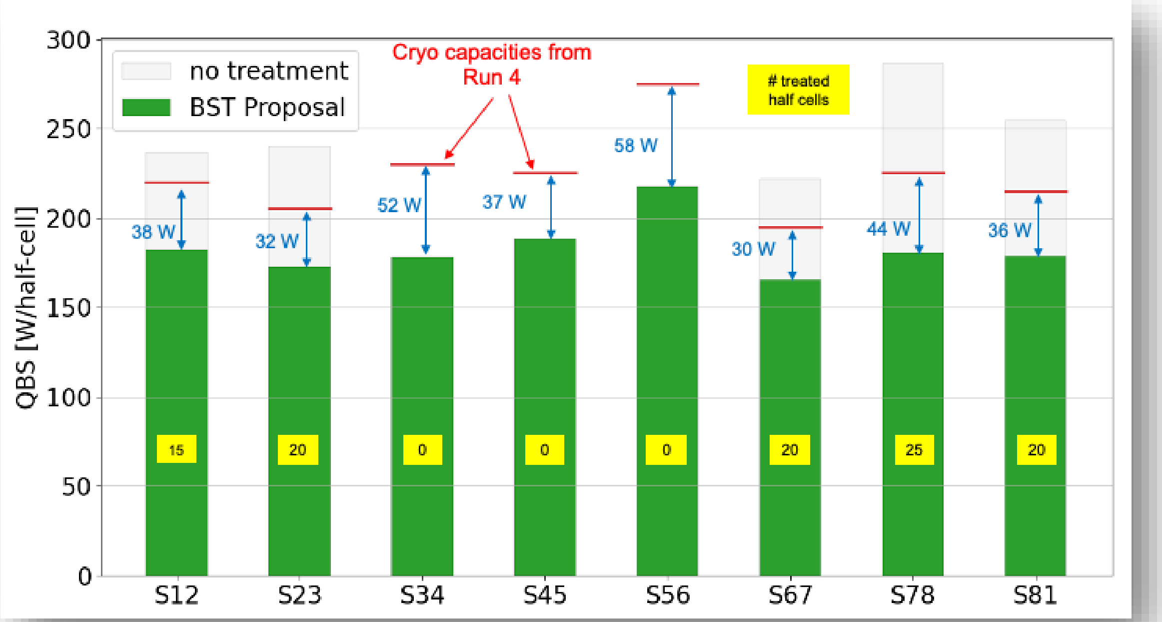
Beam screen treatment

Risks:

- **Degradation** of un-treated half-cells during future LS
  - Extremely difficult to quantity and impossible to localize
- **Higher than expecter heat loads** of treated half-cells
- **Low(er) number** of treated half-cells in LS3

OBJECTIVES

- Remove CuO and/or increase surface carbon concentration on selected BS
- Beam Screen (BS) surface passivation (robustness against re-oxidation)

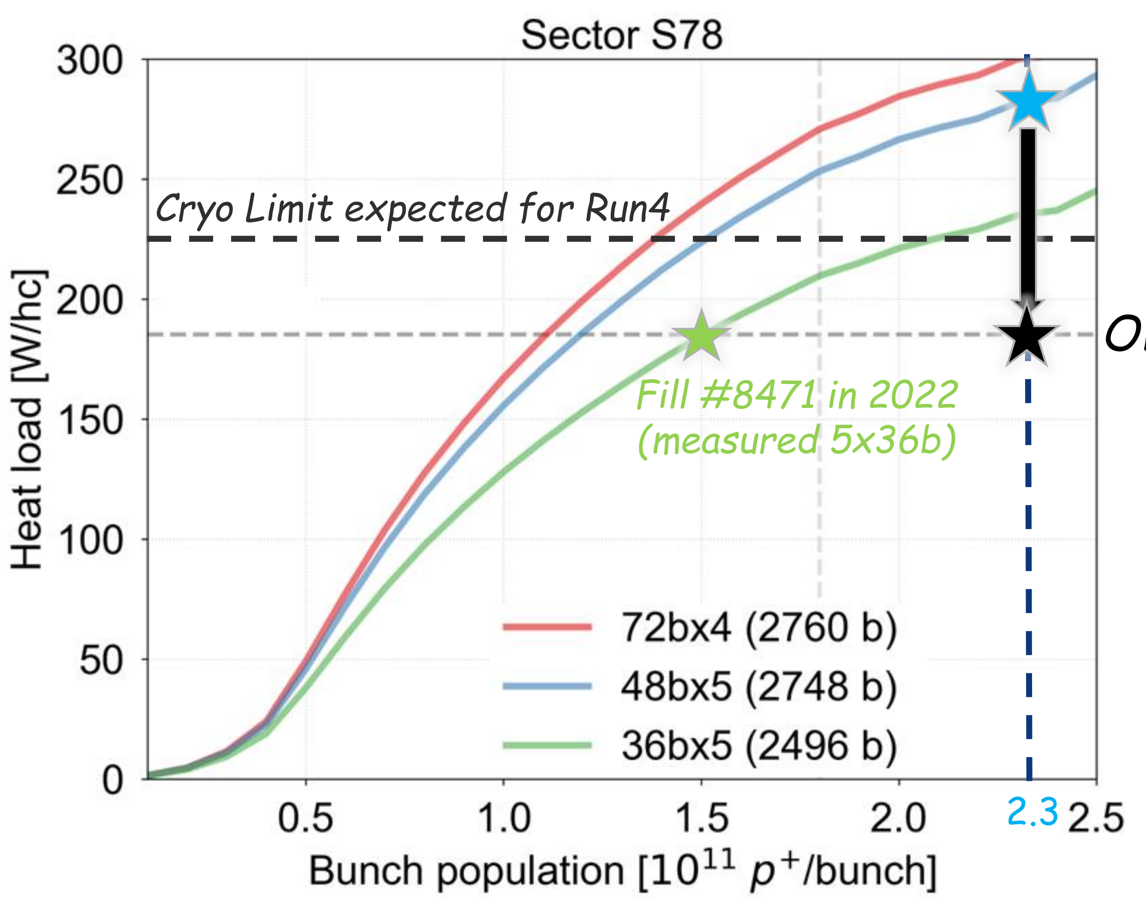


Possible mitigations?

- Treat **larger number** of half-cells (more margins)
- Produce **less e-cloud**
  - Filling scheme (36b/48b (2022), hybrid (2023))
  - Continue the beam screen treatment in future LS

A scenario treating **100 half-cells** looks realistic

Heat load expectations



HL-LHC prediction in S78
for 5x48b @ 2.3x10^{11} ppb & 7 TeV
➔ 280 W/hc > Cryo limit [225 W/hc]

Simulations performed for **main beam injection schemes** without any Beam Screen treatment

- 4x72b, 5x48b and 5x36b