LHC performance overview and highlights in 2024

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Content

Highlight of YETS upgrades

Summary of the protons run

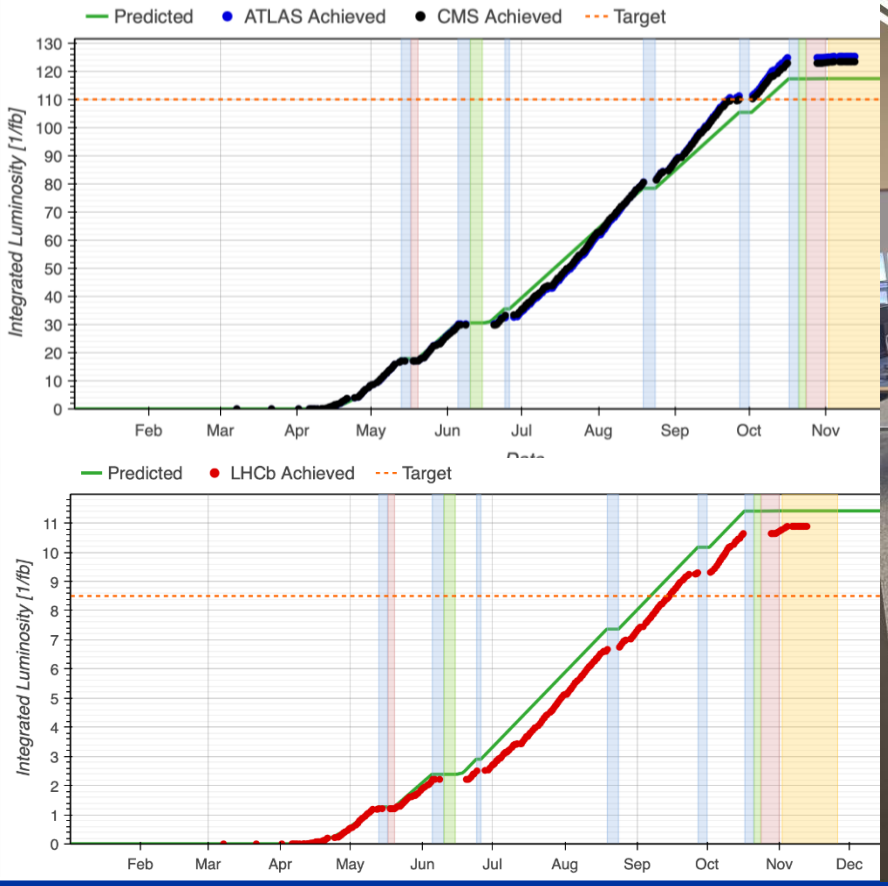
PP ref run in one slide

Summary of the ions run

This talk purposely omits some LHC issues that will be presented in a dedicated presentation tomorrow.

2024 : at last a very good year for physics

- PROTON RUN : above target for all experiments
- ION RUN : at target or above for all experiments

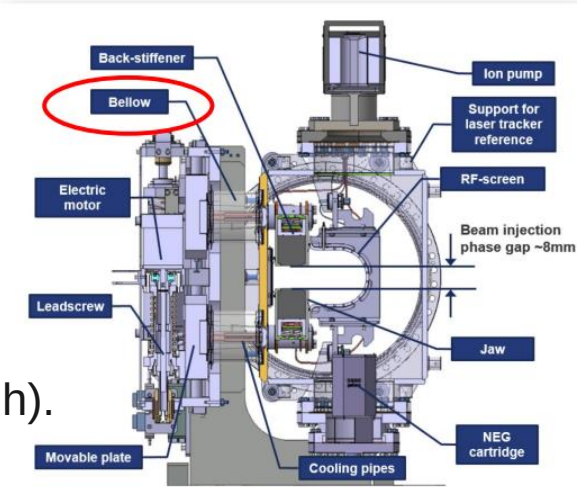


The biggest bottle ever, for the most productive year of LHC

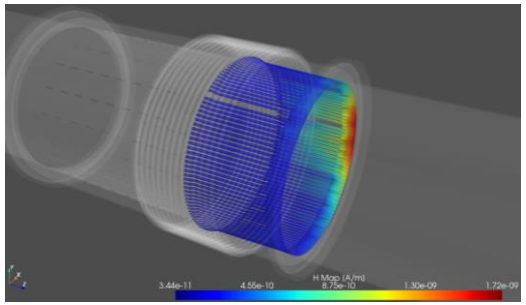
2024 success story…

… Started during the YETS 2023/2024

- **Mitigation for the downtime and limitation of 2023: equipment consolidation**
  - TDIS replacement (2023 vacuum leak du to bellow no conformity) :
    - With spare TDIS having the same bellow non-conformity (but should last long enough).
    - Prepare conform spares for August 2024
    - 2024 : reduce TDIS movement thanks to new parking settings



- Warm vacuum module consolidation campaign (degradation due to beam induced heat in 2023)
  - Plan to replace the modules in the recombination area around IPs
  - Partial in 23/24 : 47 modules replaced out of 71 to be completed in YETS 24-25



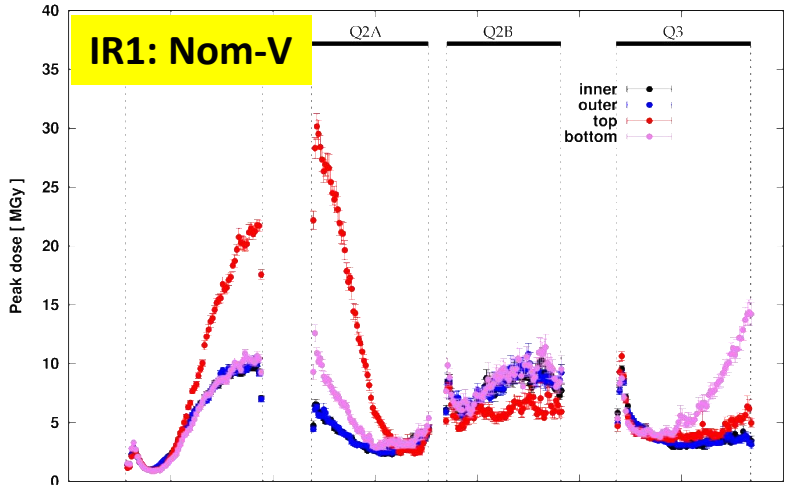
2024 success story…

… Started during the YETS 2023/2024

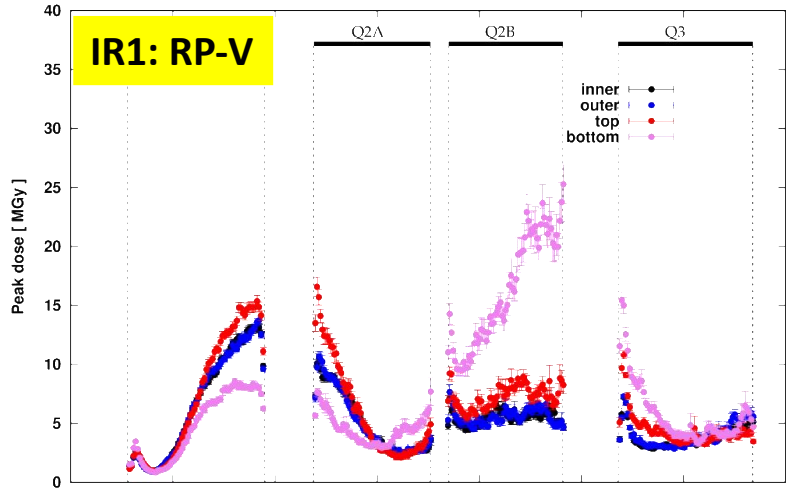
- **Mitigation for the downtime and limitation of 2023: equipment consolidation**
  - Consolidation of Quench detection boards (responsible for many dumps and magnet quenches during 2023 ions run) : radiation proof boards installed
  - Displacement of point 7 BLMs + replacement of SEM by LICs :
    - over-responsive at injection in 2023, SEM in saturation with high intensity beam
    - Should provide more tolerance for injection losses.
  - Cryo reconfiguration in point 8 to optimized cooling capacity in sector 78 and 81.

Reverse polarity optics at the high luminosity IPs

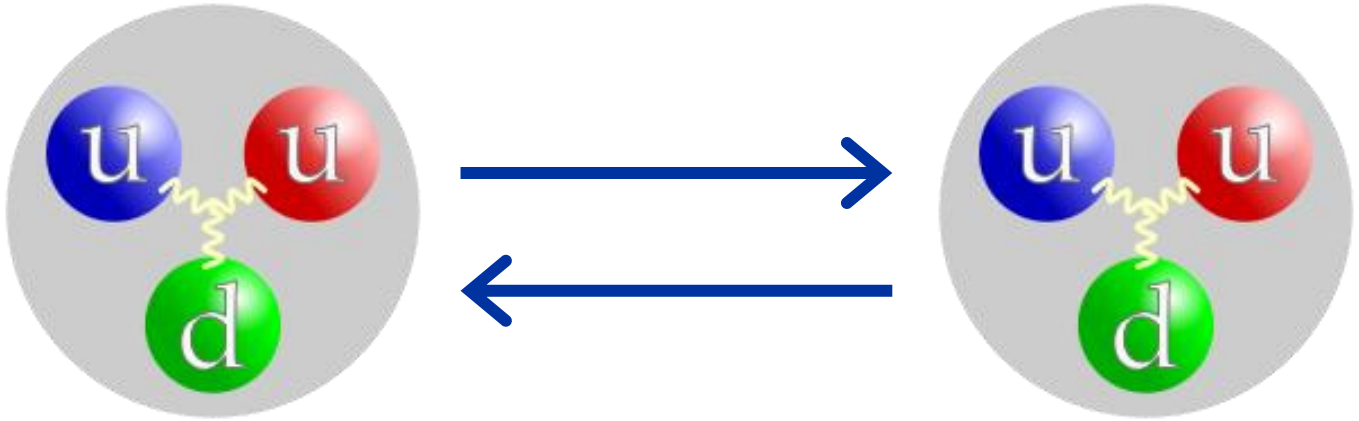
- **Inner triplet magnets closed to high luminosity interaction points (IR1/5) are reaching their life expectancy of integrated radiation.**
- **Inverting the polarity of the triplet quadrupoles, with a new local optic**
  - Redistribute the radiations to less irradiated part of the equipment
  - Therefore, preserve the equipment lifetime until end of run3 (magnets of interaction regions IR1 and 5 will all be replaced)
- **Implementation started with IP1 in 2024 (most critical IP)**



Peak dose distribution profile along the triplet region

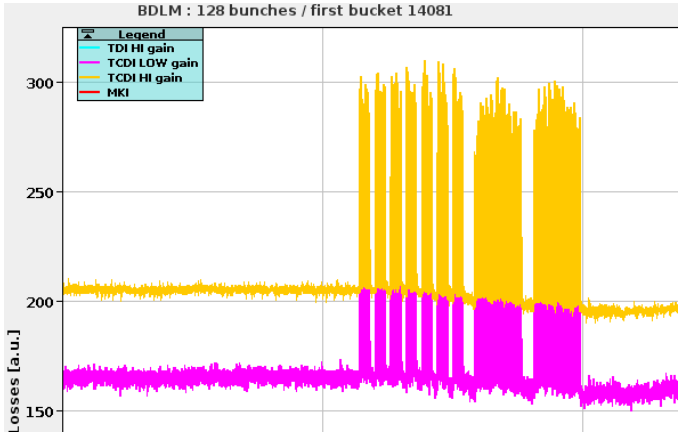


PROTON RUN

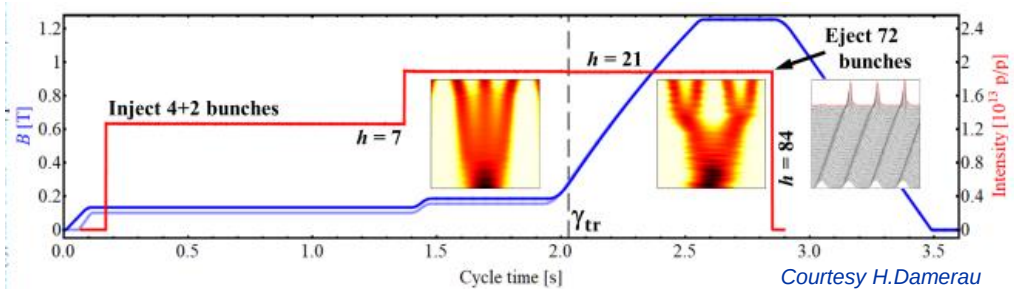


Proton beams

- **Get rid of the Hybrid (8b4e-standard 25ns)**
  - Hybrid kept the head load under control in 2023
  - But disliked by
    - **The experiments** (large bunch intensity distribution)
    - **The injectors** (set-up time doubled as 2 different cycles in PSB/PS)
    - **LHC OP**: less control on the losses

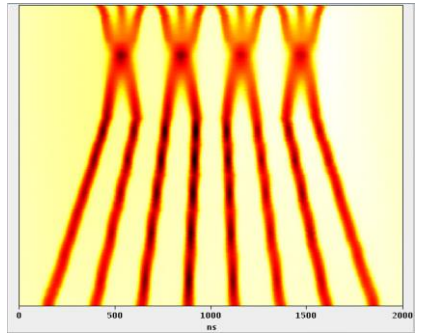


- **Decision to start with Standard 25ns**
  - Beam used in 2023 (part of the hybrid)
  - The one needed for scrubbing
  - Injector set-up of BCMS during this period

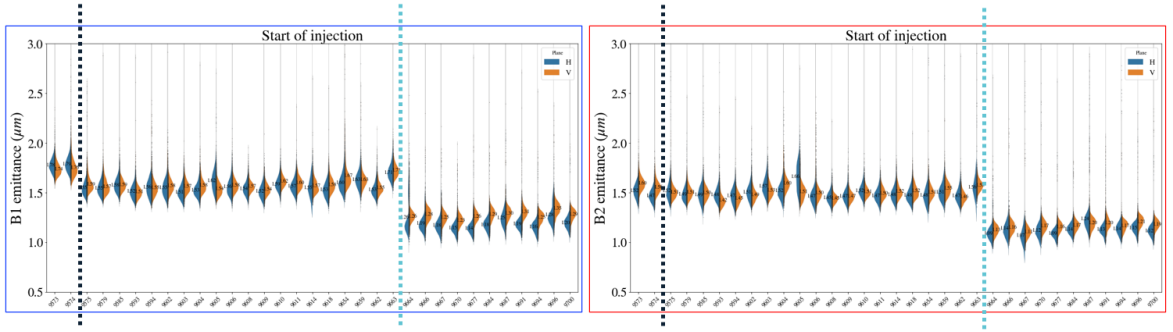


Courtesy H.Damerau

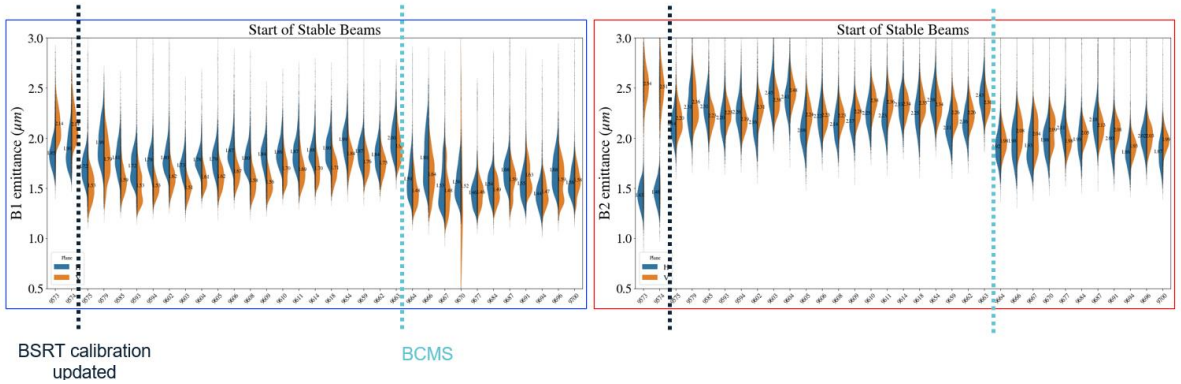
- **Switched to BCMS in May**
  - After 2 weeks, running with the same conditions (pattern, intensity), we could fairly compare the performances of the 2 beams in the LHC



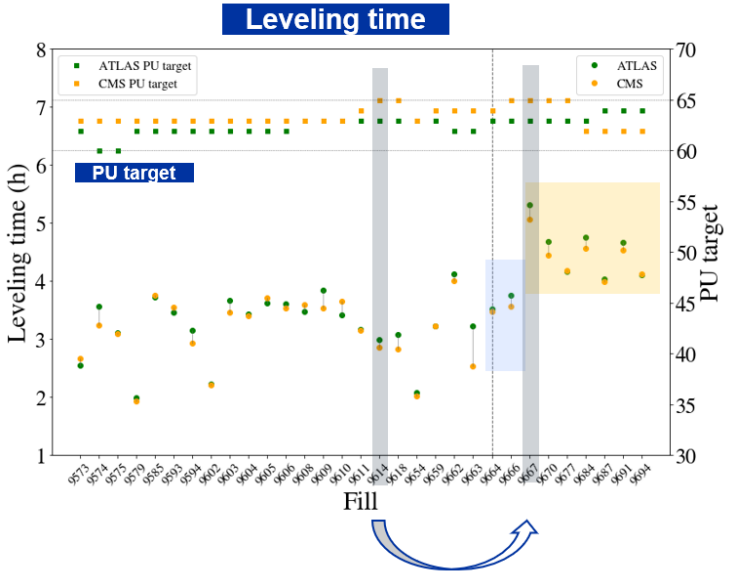
BCMS vs Standard performances analyzed by Sofia Kostoglou and reported in LBOC



Start of injection : BCMS 20% smaller emittances



Start of stable beam : BCMS 10% smaller emittances
(emittance preservation is better with the standard)



- Bunch intensity anyway limited to 1.6E11 for both beams.
- **Smaller emittance** is the parameter making BCMS more performant
- **Longer levelling time and integrated luminosity** with BCMS than standard

Decision confirmed by LMC to keep BCMS beam for the rest of RUN 3

Beam limitations : bunch intensity, bunch length

Warm vacuum modules consolidation not completed.

→ Decision to be conservative and limit intensity in 2024 to **1.6E11 p/bunch**

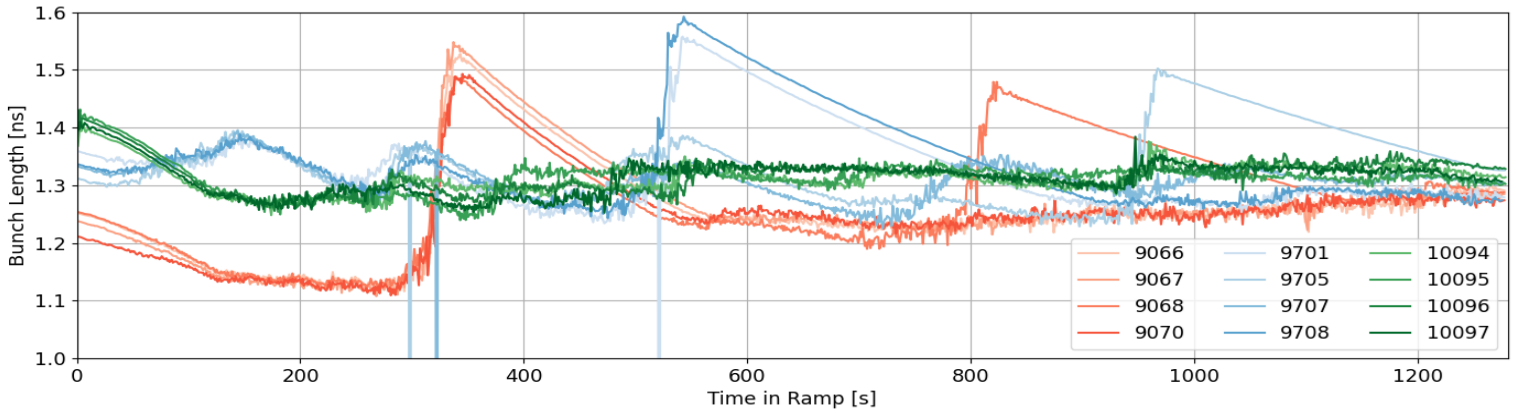
Energy deposition on the modules is strongly dependent of the bunch length.

→ Recommendation to improve the bunch length control along the cycle to reduce the heat-load peaks on the modules

Bunch length control

Adiabatic shrinking of bunch length during the ramp and in collisions

- During stable beam, apply punctual longitudinal blow-up when the bunch length approaches the defined target (well under control, automatized, in place already in 2023)
- During the ramp, bunch length under controlled thanks to longitudinal blow-up with programmed settings
  - After several iterations of parameters optimization (OP + RF team), the control of the bunch length improved a lot, reducing over/undershoots significantly



H. Timko, A. Butterworth, N. Gallou, M. Jaussi, RF & LHC-OP teams

Factor 2 gained on the heat-load impact on the vacuum modules

Bunch length control

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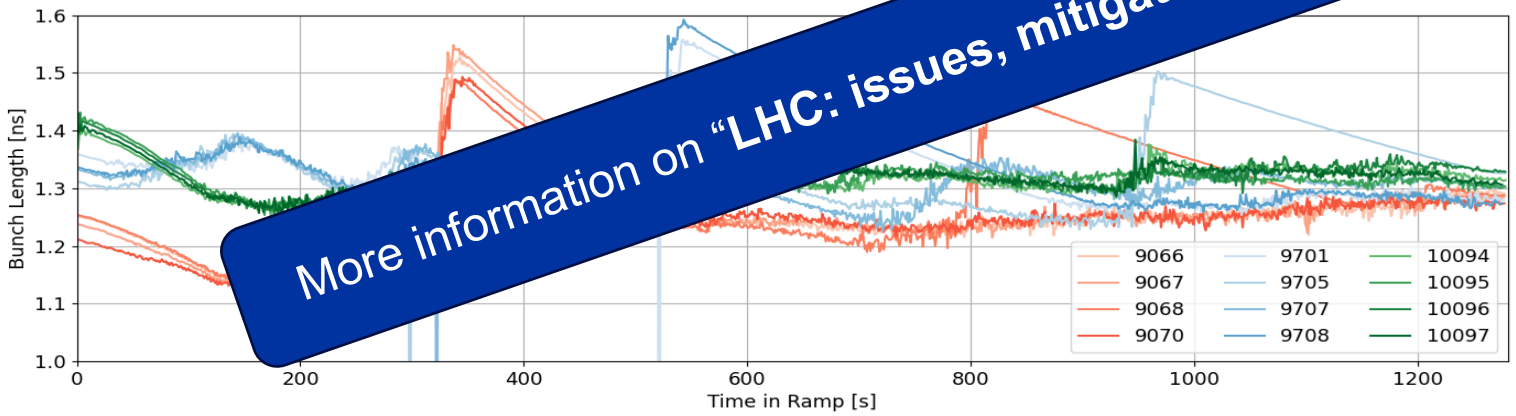
More information on "**LHC: issues, mitigations**" presentation tomorrow afternoon



H. Timko, A. Butterworth, N. Gallou, M. Jaussi, RF & LHC-OP teams

Factor 2 gained on the heat-load impact on the vacuum modules

Beam limitations : Heat load in sector 78

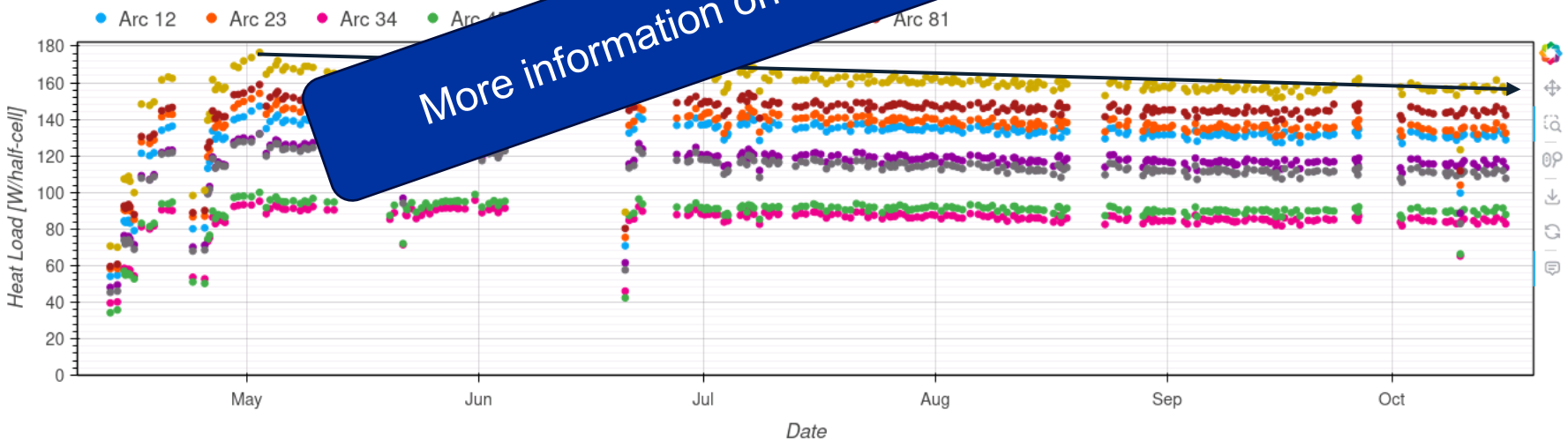
Optimization of cryo in point 8 + max intensity per bunch at 1.6E11 → confidence on the possibility to use 3x48b trains or 5x36b trains

Intensity ramp-up started with 3x48b trains, but cooling capacity of 7 as good as expected

Need to reduce e-cloud effect : decision to switch

- Total number of bunches limited to 2350 (3
ine with 3x48)

More information on “Cryogenic in LHC” presentation this afternoon

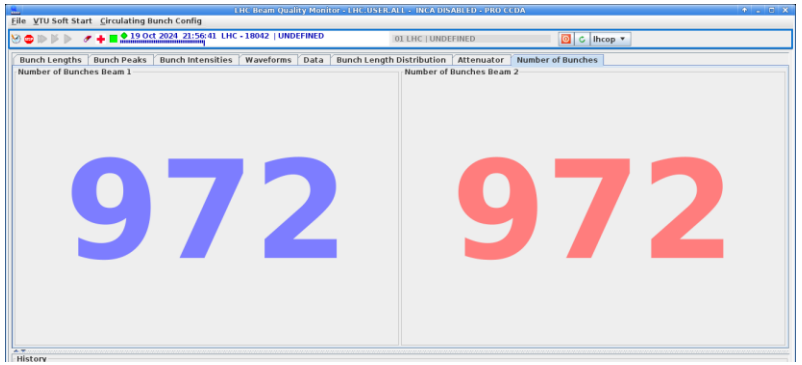


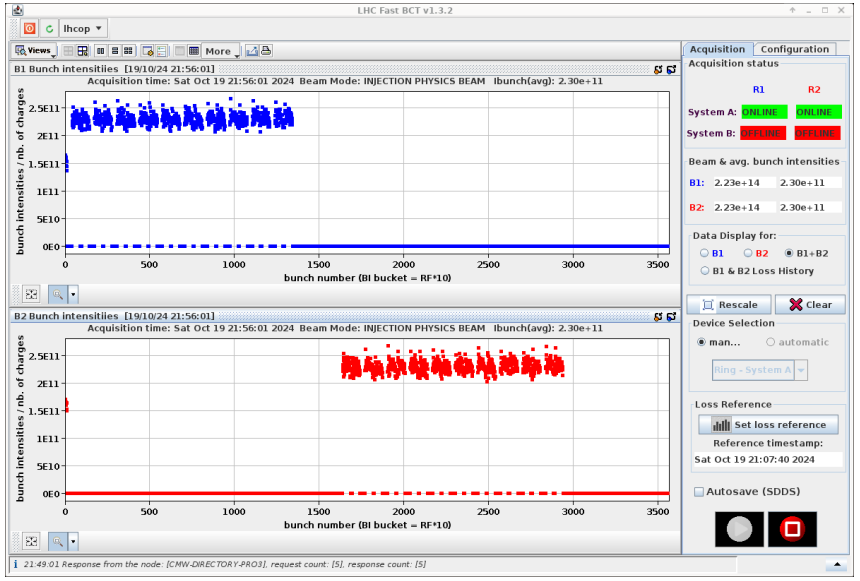
~10% margin gained by conditioning over 2024 (not enough for an additional full train)

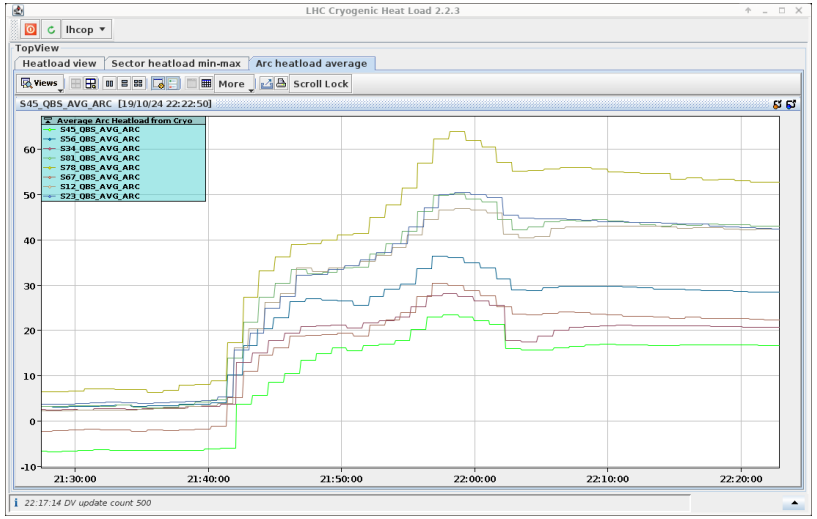
High intensity beam in LHC (MD only)

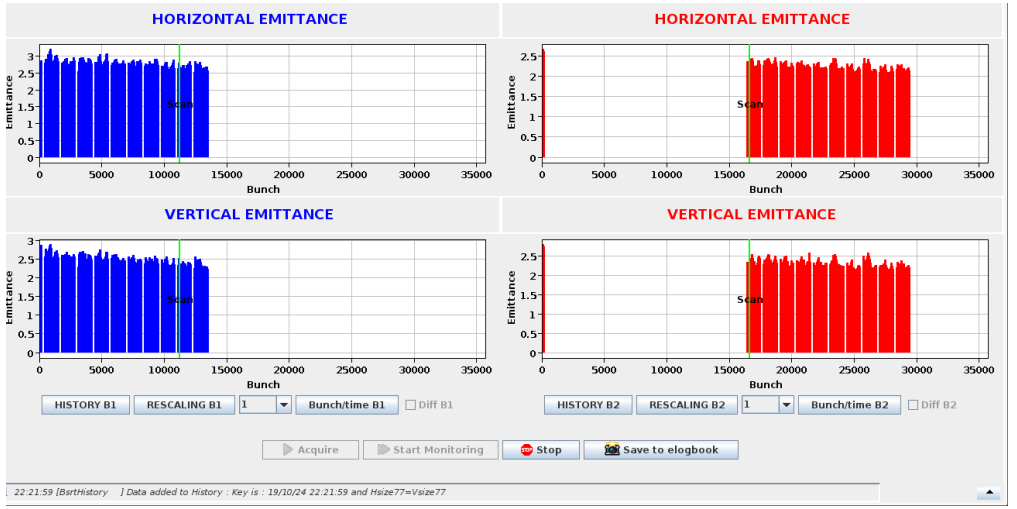
Record bunch intensity at injection : 2.3E11 p/b

972 bunches per beam





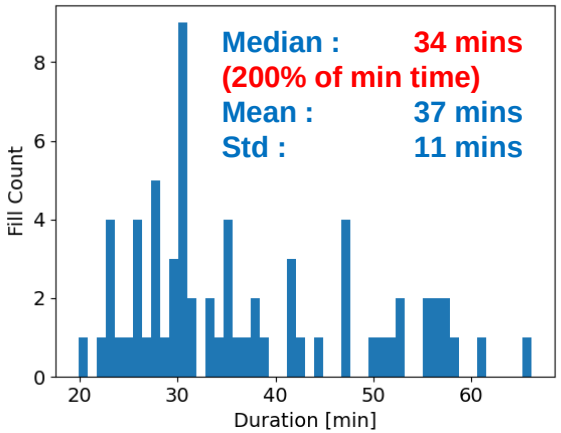




Operational efficiency : injection

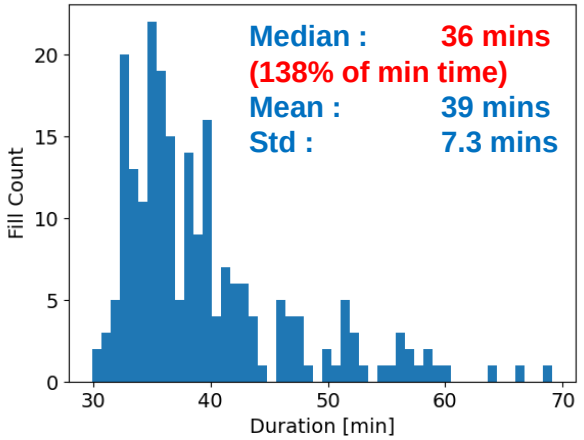
Time spent in “Injection physics beam” mode

2023 : Hybrid, 236b x 1.6E11



Minium achievable time : 17 mins
(41s SPS supercycle, 24 inj total)

2024 : BCMS, 108 x 1.6E11

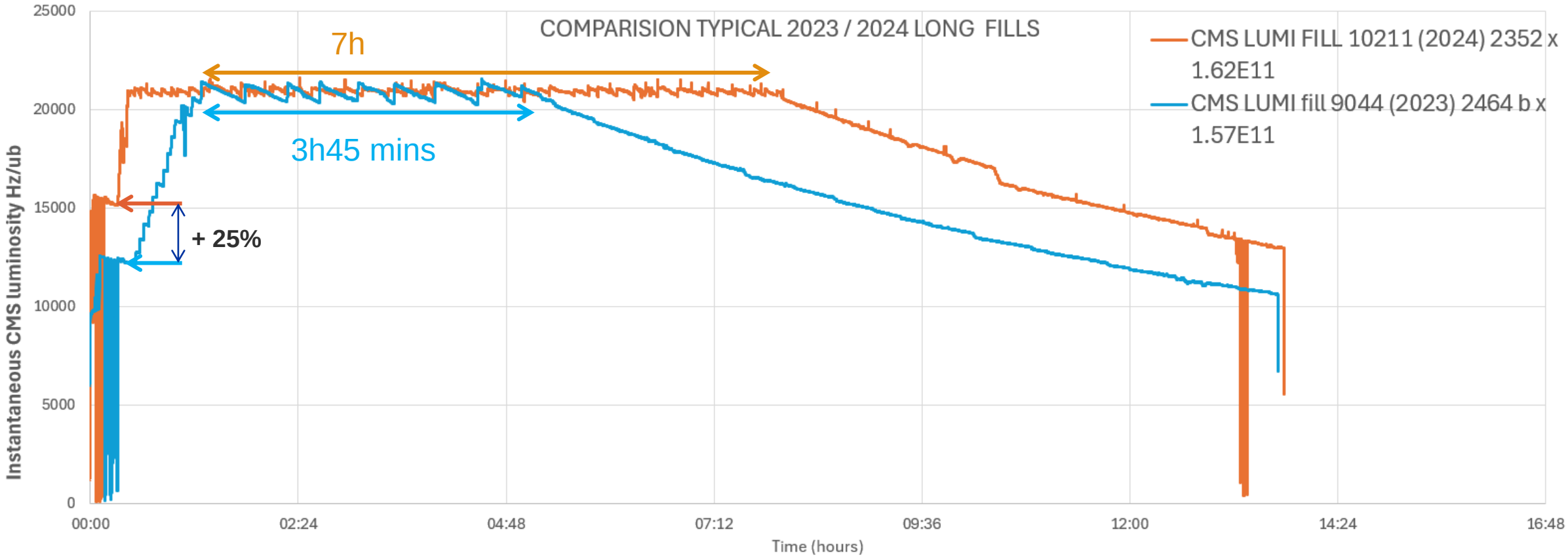


Minimum achievable time : 26 mins
(33s SPS supercycle, 48 inj total)

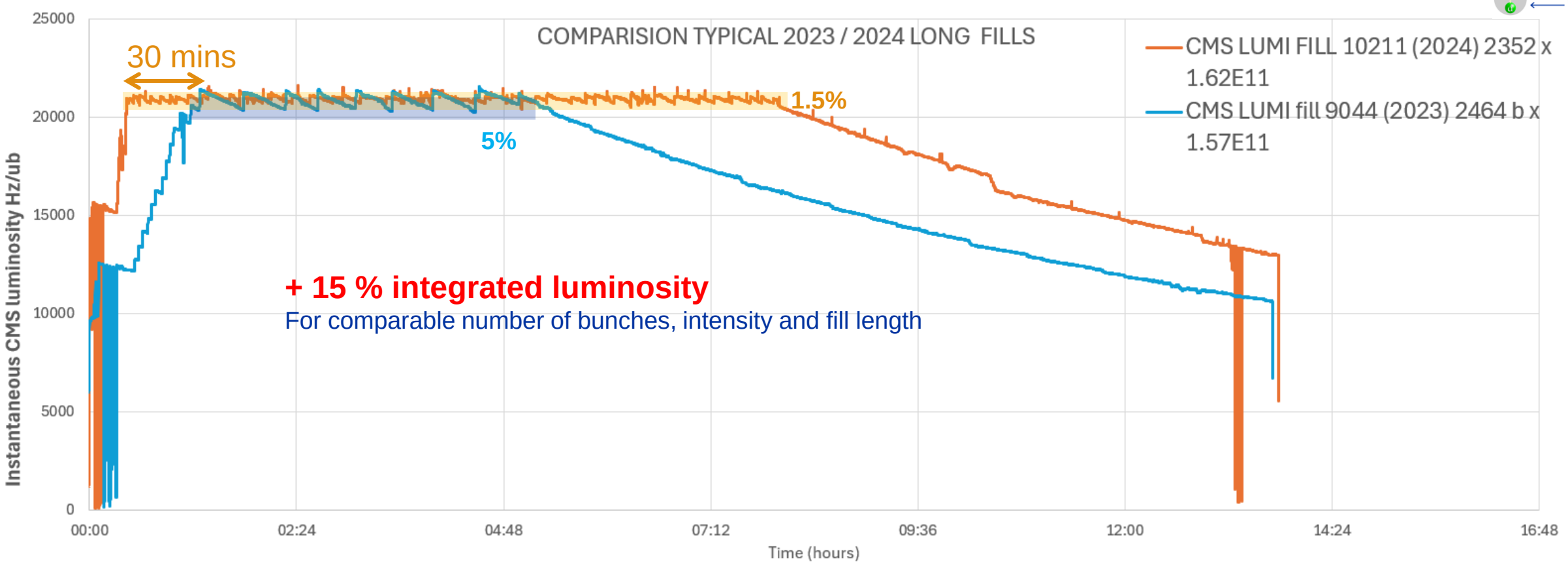
Injection process : clear benefit to be back to BCMS, and with unchallenging intensity.

- Very reproducible and stable
- Steering very smooth
- Losses at injection : less losses than hybrid + margin retrieved with BLMs displacement during YETS

Operational efficiency : levelling



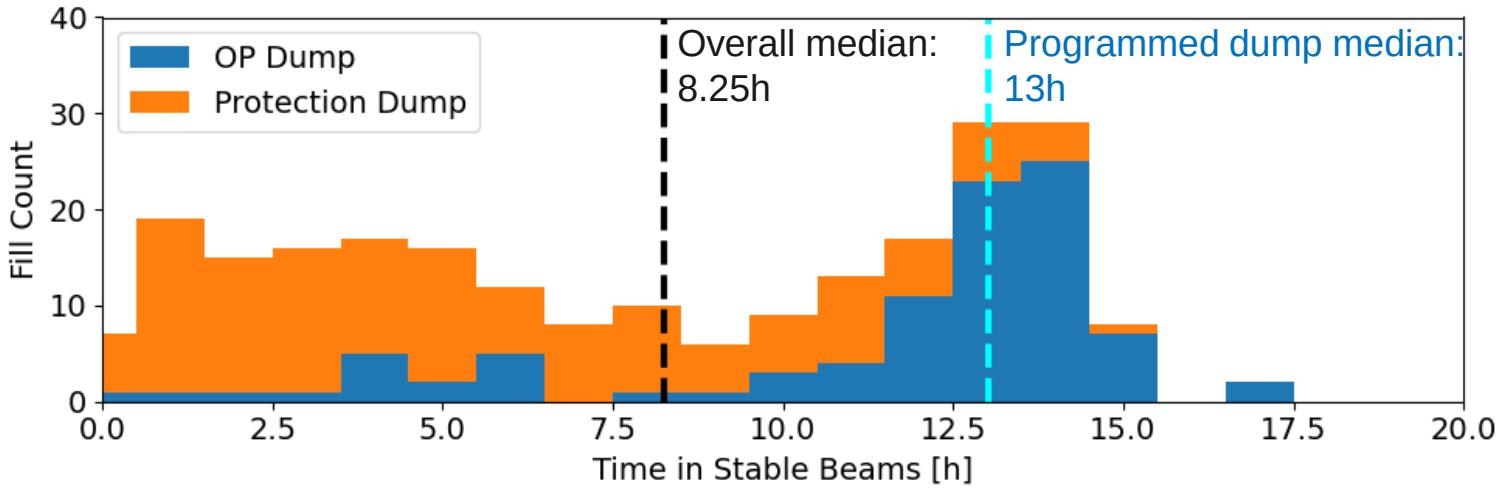
- **Direct gain from the higher brightness of the BCMS beam**
  - Lumi at 1.2m β* 25% higher in 2024
  - Levelling time significantly increased (+86%)



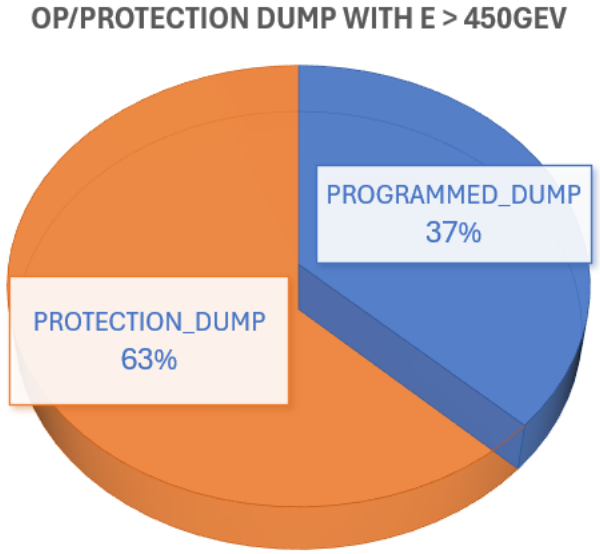
- **Optimization of the levelling process**
  - Direct step to 60cm, 30 mins more at max luminosity
  - Mix separation and β* levelling for a smoother luminosity
    - From **5%** levelling tolerance (with pure β* levelling) to **1.5%** levelling tolerance (feasible with separation levelling)
    - No luminosity spikes, no risk for overshoots

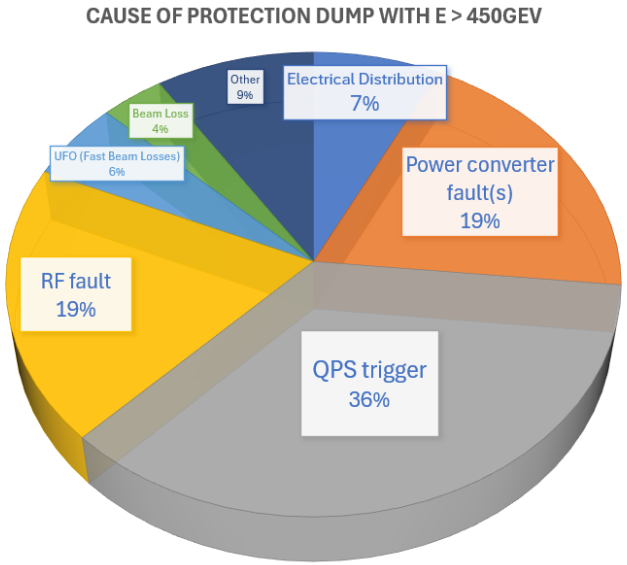
Stable beam durations and causes of dump

Optimal fill length established to 13h considering the average turnaround



Usual ratio of 60% of protection dump



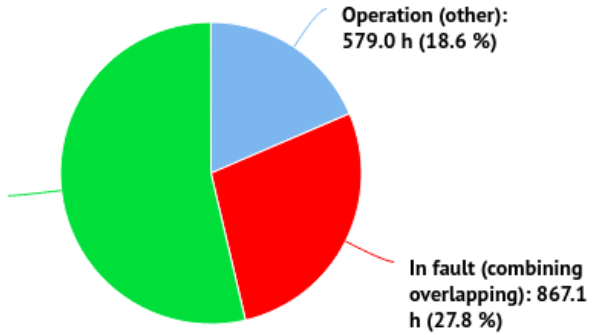


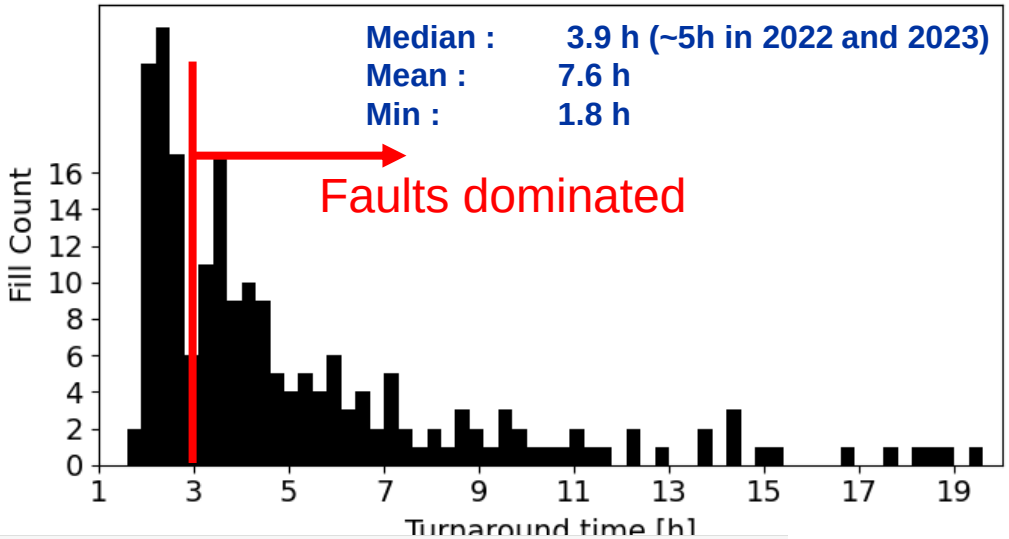
Availability

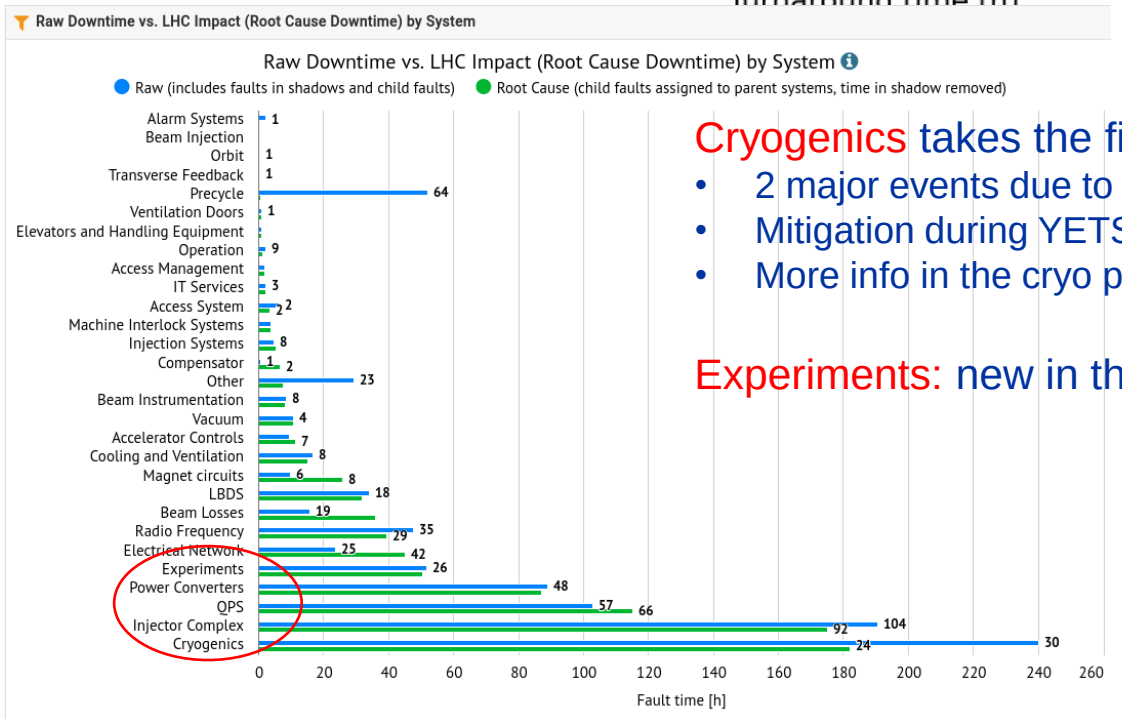
Availability	Stable beams (SB)
72.2%	53.7%

From proton physics period – MD, TS and commissioning days removed

Fault versus operation time distribution







Best year so far in run 3!

More than any operational improvement, **availability is the key** to accelerator performance

No long faults implying to drastically change the accelerator schedule!

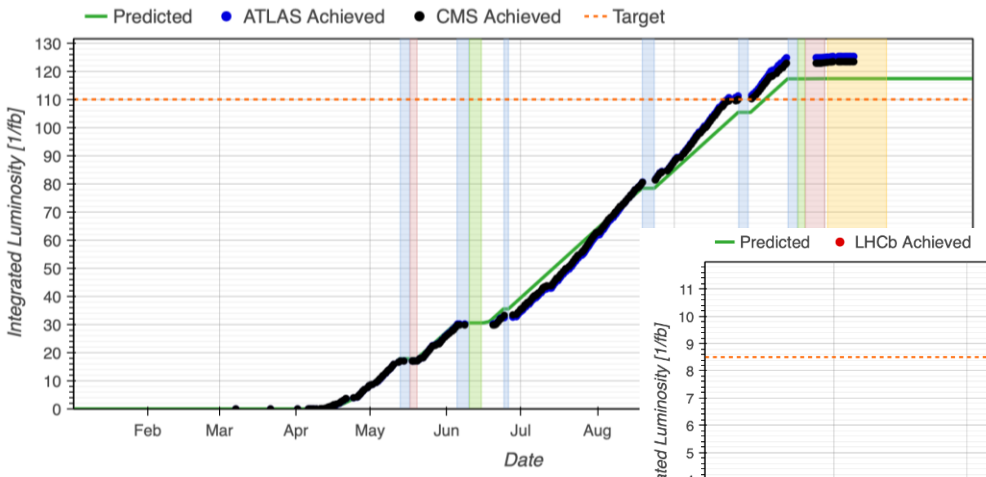
Cryogenics takes the first position

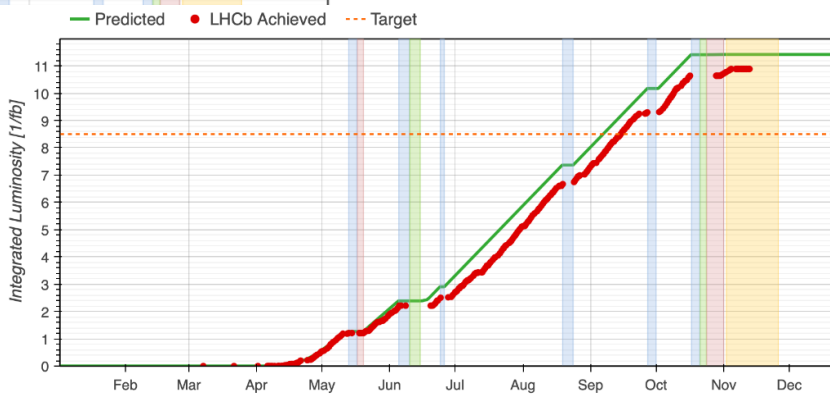
- 2 major events due to SEU
- Mitigation during YETS
- More info in the cryo presentation

Experiments: new in the top 5!

Production

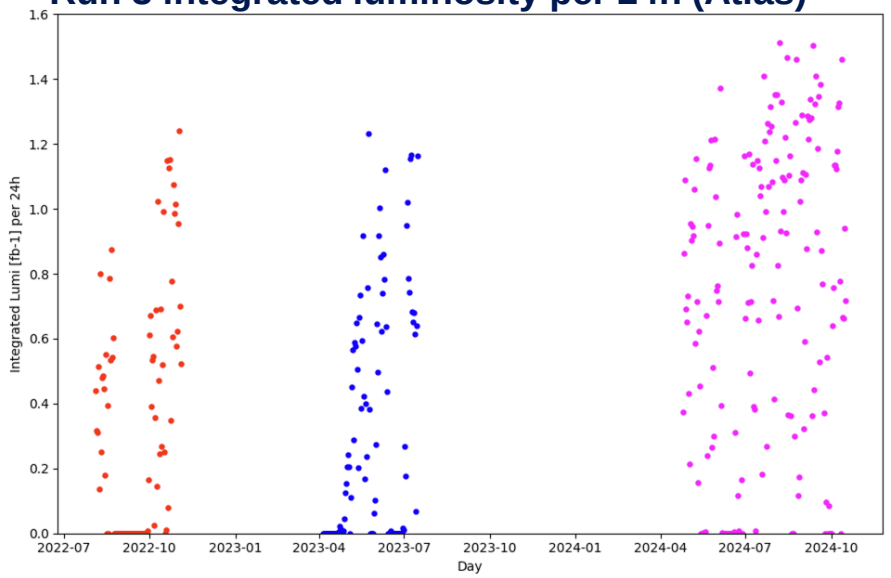
- **124 fb^{-1}** in ATLAS/CMS
- **11 fb^{-1}** in LHCb
- **67.5 pb^{-1}** in ALICE
- Highest production **rate ever**
- **Peak luminosity** at ~2.1e^{34} cm^{-1} s^{-1} (limited by cryogenic)



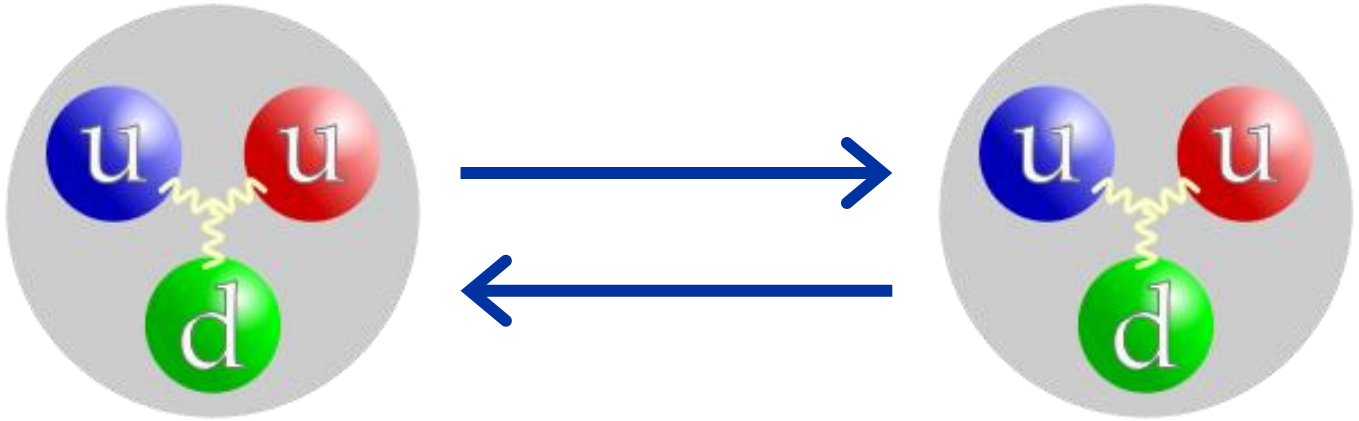


- **2024 AVG** rate = 0.83 fb^{-1}/24h
- **2024 highest** rate = 1.5 fb^{-1}/24h (midnight to midnight)

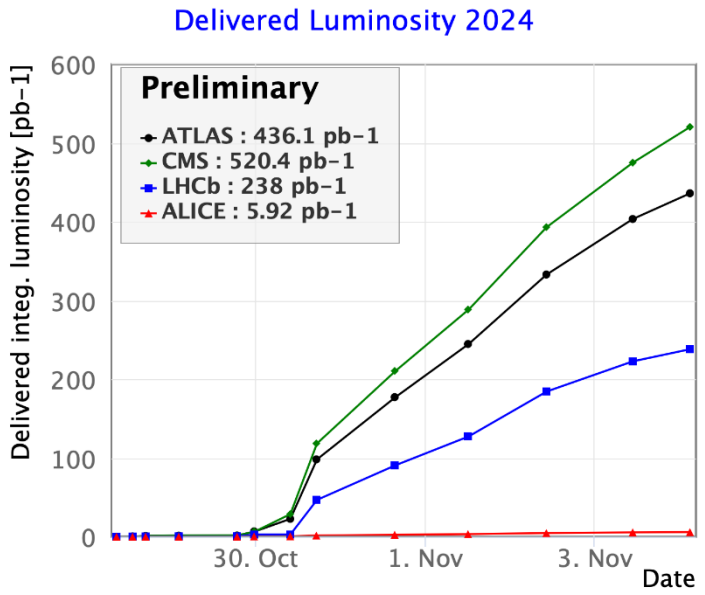
Run 3 integrated luminosity per 24h (Atlas)

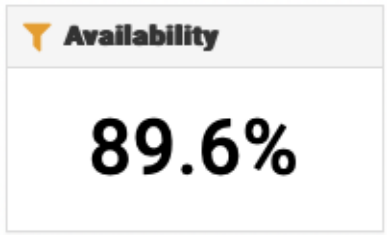


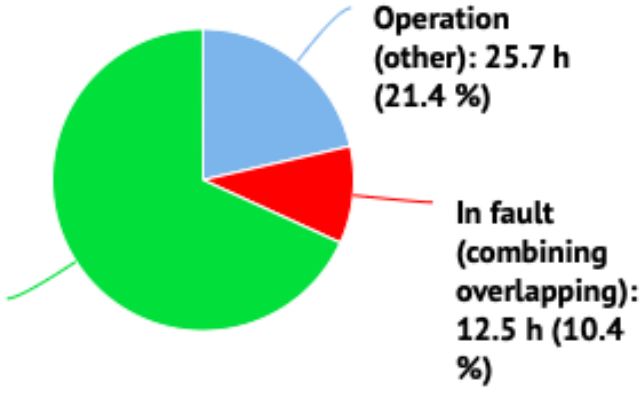
PPREF RUN



Luminosity production for pp ref run

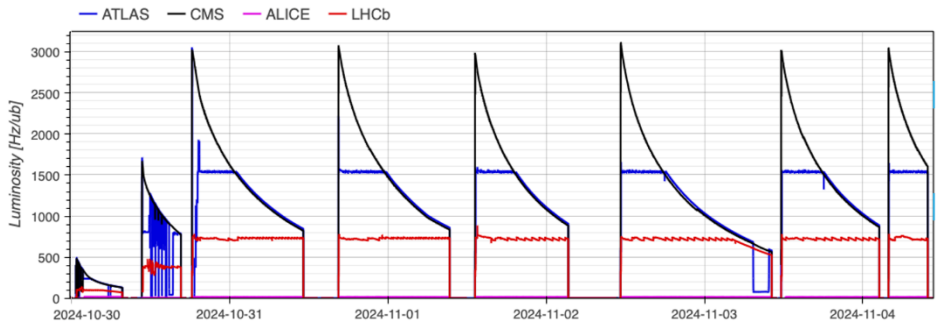






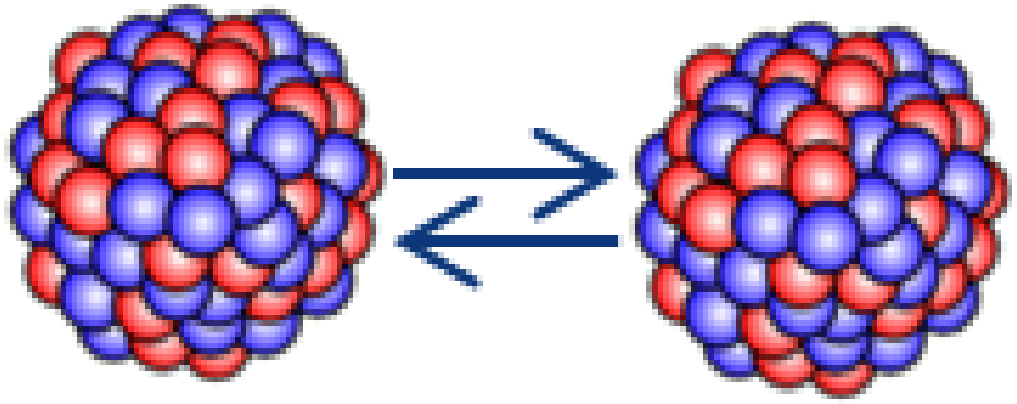
7-day run (extended by one day to satisfy higher targets, as a consequence of the Run3 extension), results only possible as blessed by **excellent machine availability!**

Exp	Requested lumi	Delivered/recorded lumi [pb^{-1}]
ATLAS	350	**436 (390)**
ALICE	5.5	**5.9 (5.5)**
CMS	350	**520 (~520)**
LHCb	>100	**246 (~240)**



Courtesy Matteo Solfaroli

Ion run



2023 challenges, issues and mitigation

New systems commissioned in 2023

- Slip stacking for 50ns beam
- Crystals
- New TCLD collimator
- BFPP orbit bump in all IR

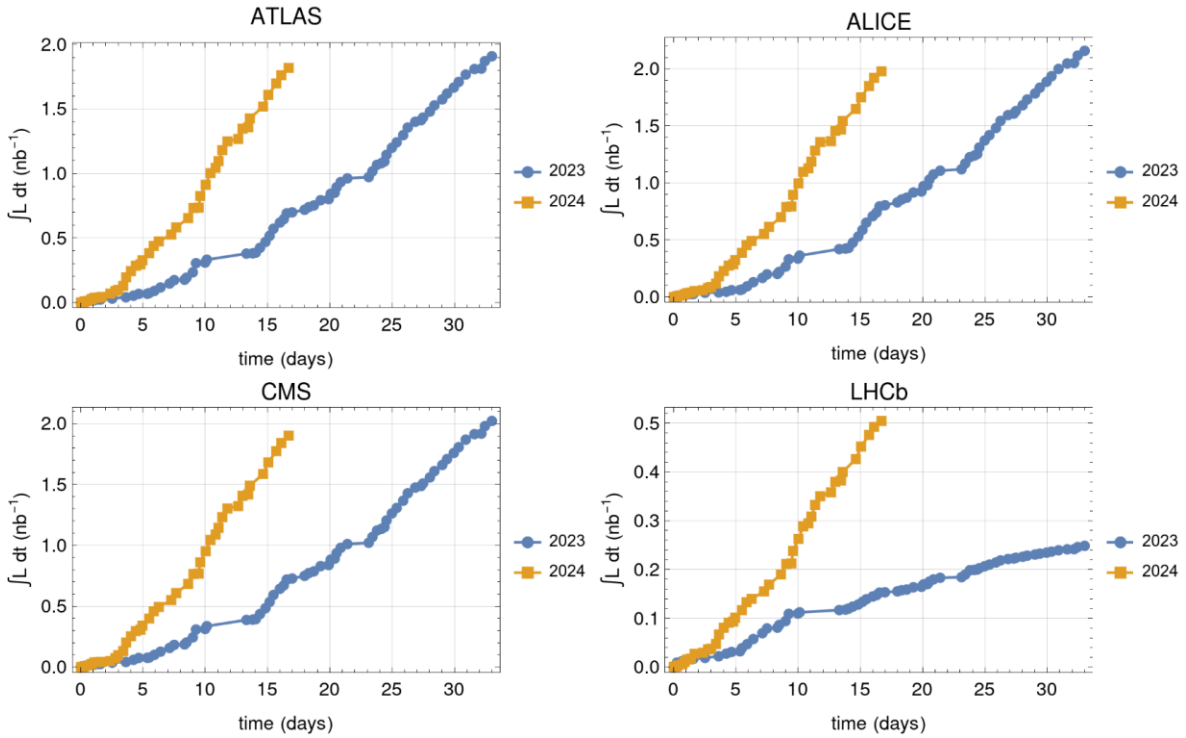
2023 challenges, issues and mitigation

Unforeseen issues : understood and mitigated

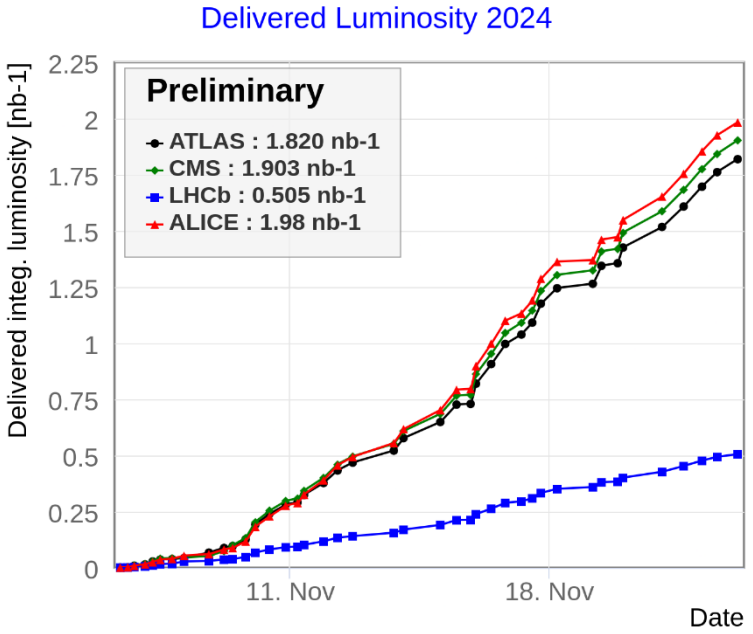
- Radiation on the QPS boards : dumps and quenches, luminosity had to be reduced
  - consolidated during YETS
- 10Hz horizontal orbit oscillations provoking beam dumps :
  - analysis showed that it came from cryo valves opening. Mitigated by delaying the opening of the valves during NO BEAM periods
- Transverse losses during ramp provoking beam dumps
  - More relaxed collimator strategy
  - Less aggressive ramp settings (squeeze partially separated from ramp, smoothing of orbit corrections)
- Drift of the crystal orientation (reducing the cleaning efficiency)
  - Reason not fully understood
  - New application for automatic optimization of the channelling along the cycle
- Strong background in Alice
  - IP1 dispersion correction reduced the background significantly

2024 : reaping the fruits

all 2023 issue were mitigated in 2024, allowing for excellent performance!



Integrated luminosity 2023 and 2024 by experiment



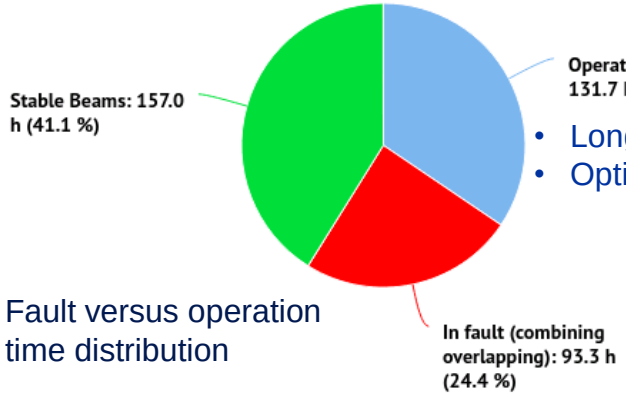
- Lumi expected by the experiment : 1.9 nb^{-1}
- Looked at that time very very challenging
- It was reached even with 1 day less for ion physics

from R.Bruce presentation in LMC#499 04/12/24

2024 : availability

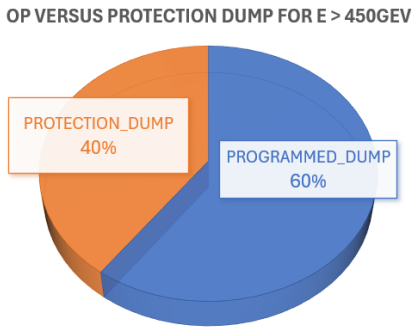
Availability	Stable beams (SB)
75.6%	41.1%

From 6/11 to 24/11 - Planed MD period removed

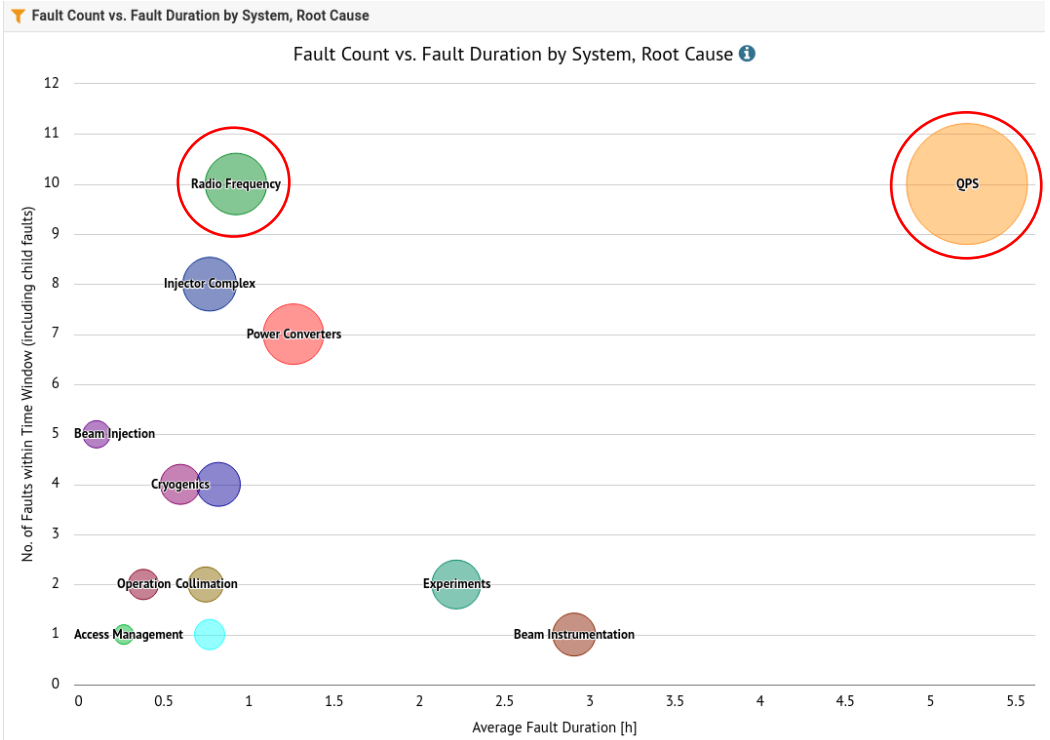


Fault versus operation time distribution

- Long filling time (median 1h12mins)
- Optimal SB time ~7h



Major part of the fills dumped by OP!



QPS : issue in the new boards installed last YETS : quenches provoked after fast abord received.

- 3 events during the ions run
- Last event : quench of 15 magnets and anticipation of the end of run and MD-quench test cancelled.

Should be fully mitigated during YETS + new step in HW commissioning

RF : 2 types of recurrent faults

- Line 3B2 HOM coupler over-heating
- M1B2 cryomodule quench

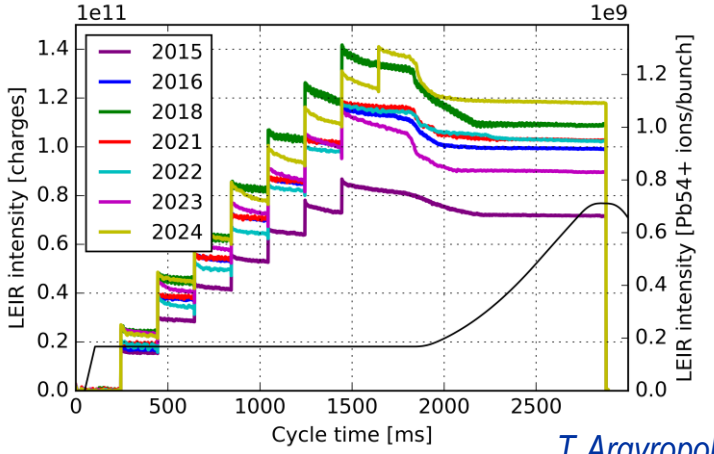
Tests and mitigation measures foreseen in YETS

More details by Y.Uythoven and K.Turaj in the LMC #499 04/12/2024

Beam quality

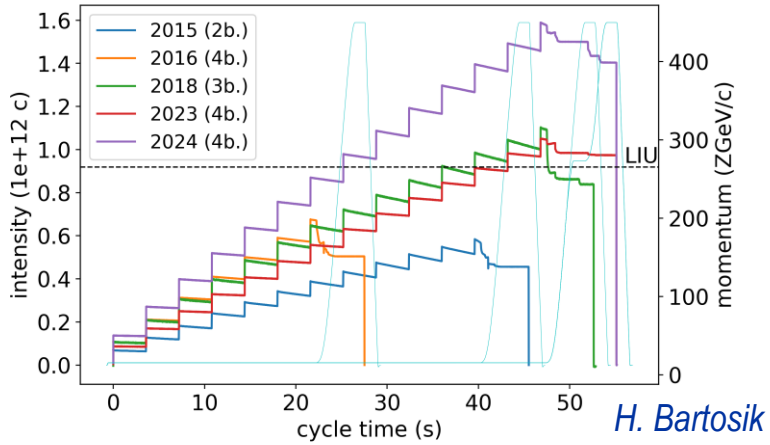
Impressive improvement of beam intensity in the injectors

- Careful, continuous optimization of the intensity in LEIR and the injector chain
- Improved transmission between LEIR, PS and SPS
- Improved transmission in SPS with 50Hz compensation



T. Argyropolous

On average 2.6E8 Pb/b injected in LHC (30% above LIU spec)



H. Bartosik

Improvement of the transmission in LHC: 88% (84% in 2023 with less intensity)

- Thanks to RF voltage optimization at flat bottom

from R.Bruce presentation in LMC 04/12/24

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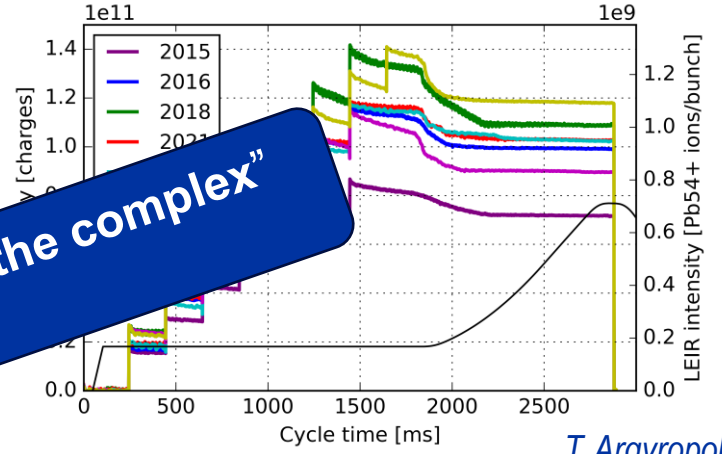
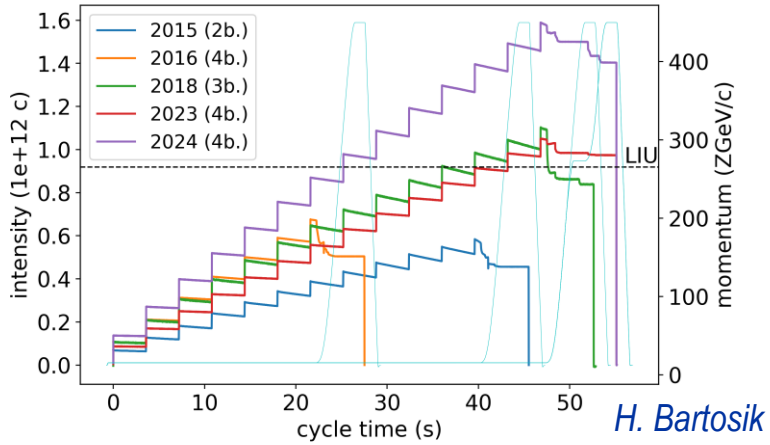
On average 2.6E8 ; in LHC (30% above LIU spec)

More information on "**Ions: overview and outlook across the complex**" presentation tomorrow afternoon



T. Argyropolous



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Improvement of the transmission in LHC: 88% (84% in 2023 with less intensity)

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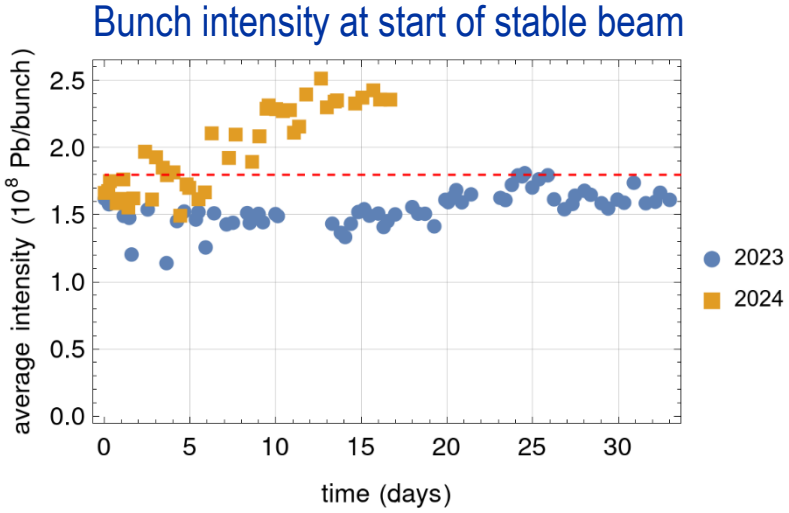
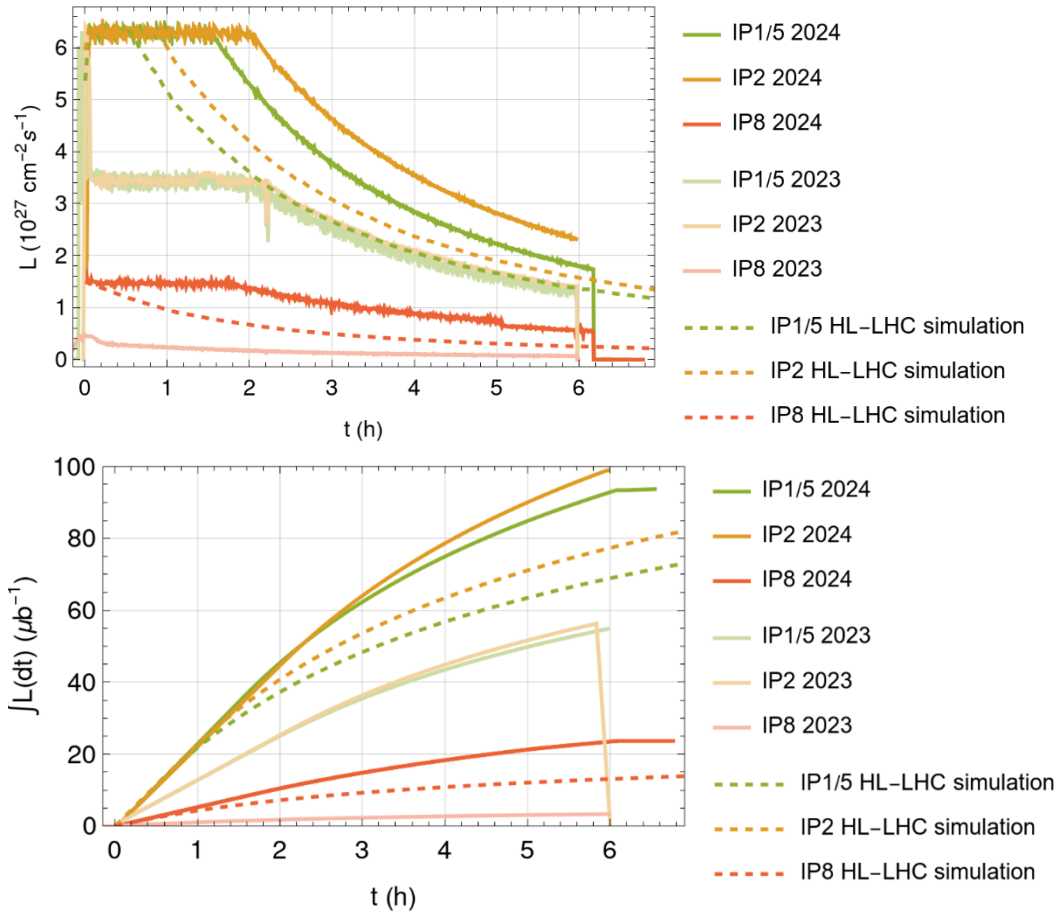
from R.Bruce presentation in LMC#499 04/12/24

Beam quality : fill luminosity



2024: fill 10400; 2023: fill 9285 (among the best fills each year)



Bunch intensity at start of stable beam much improved in 2024 :

- **average 2.3E8 Pb/bunch** (1.6E8 in 2023) +40%

2024 lumi production far better than in 2023.

- Up to 2h levelling time in Alice
- Average daily production :
  - 0.144 nb^{-1}/day in IP1/2/5
  - 0.036 nb^{-1}/day in IP8

from R.Bruce presentation in LMC#499 04/12/24

Conclusions

Ions: 1.9nb^{-1} in 18 days : challenge accepted and met!

- Fantastic work in the injector to deliver record bunch intensity
- In the LHC, after the struggle of 2023, the main issues have been solved allowing for a good lumi production in 2024
- **HL-LHC performance for ions largely surpassed**

Conclusions

Proton : Stability, reproducibility and good availability

- Conservative choices helped for availability and were beneficial to luminosity production
- It was not without issues as it will be presented tomorrow by Andrea.

We can do even better next year if limitations are lifted or at least relaxed

And so can the experiments….

THE WORLD'S LARGEST CHAMPAGNE BOTTLE WAS FLOWN IN
BY HELICOPTER TO UNIVERSAL STUDIOS, HOLLYWOOD, CA 12/28/1999

MARILYN MONROE LOOK-A-LIKE POSES WITH THE 23 FEET, 4 1/2 TON BOTTLE

PHOTO BY NINA PROMMER/GLOBE PHOTOS INC.©1999 K17520NP