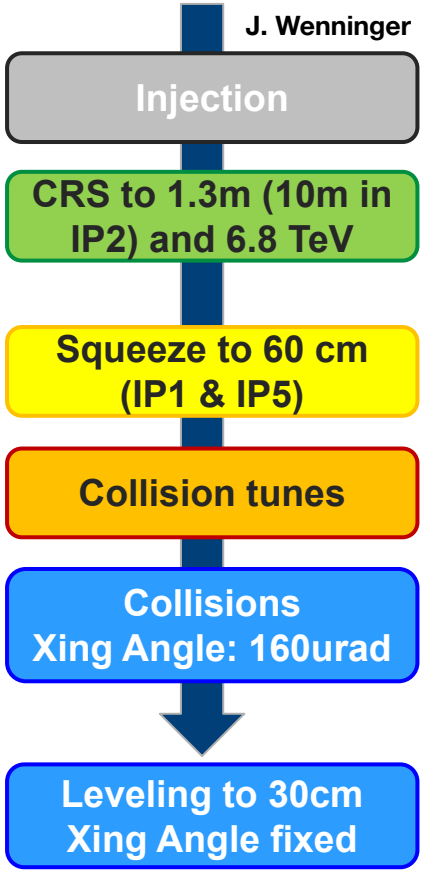
# 2022 LHC Operational Performance

Michi Hostettler for BE-OP-LHC

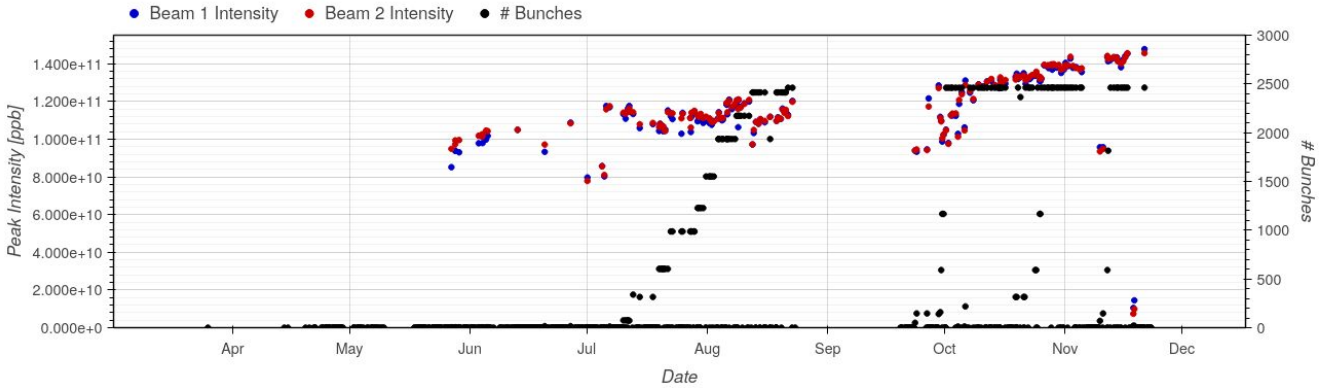
with thanks to LPCs, experiments, EiCs, BE-ABP, coordinators, and the injectors for all the protons

# 2022 operational cycle

- **"run 2 like" scenario to ease commissioning**
- **IP 1 / 5**
  - constant crossing angle: 160urad
  - **beta* levelling: 60cm → 30cm**
    - roman pots fixed during levelling
    - TCT positions, gaps & limits constant
- **IP 2 / 8**
  - crossing angle: 200urad
  - separation levelling
  - LHCb not rotated (ext. H crossing)

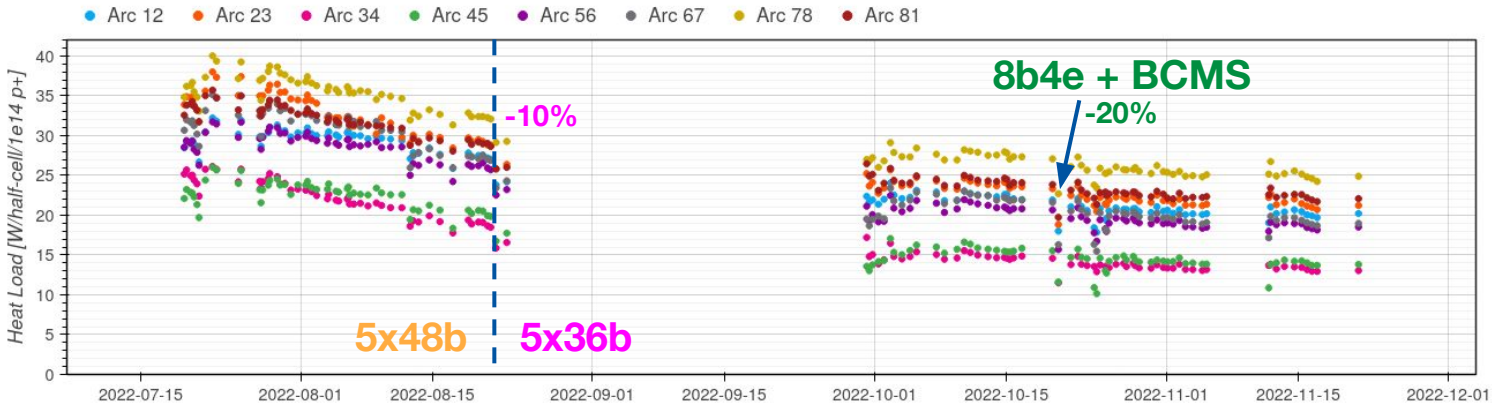


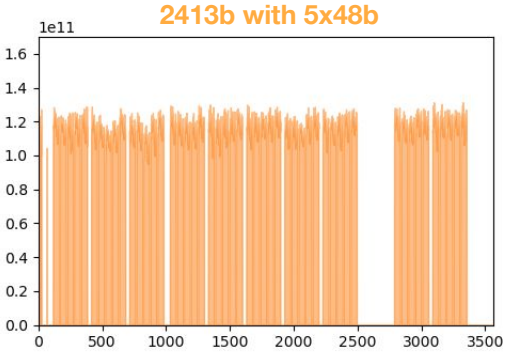
# 2022 LHC beams

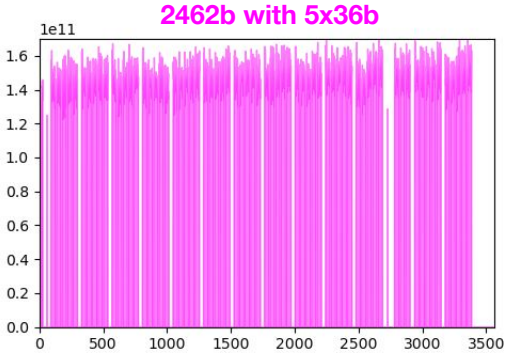


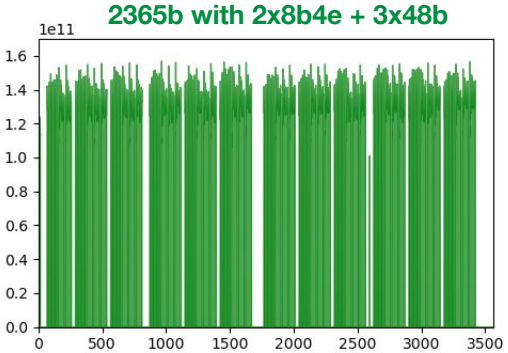

- **BCMS beams for physics**
  - up to **2462b** per beam with **~1.45 $10^{11}$ protons per bunch**
  - initially 5x48b - stepped back to **5x36b for heat-load / e-cloud**
- **mixed 8b4e + BCMS tested**
  - not applied in 2022: small gain in lumi, complications for experiments
  - preferred scenario for 2023
- **"standard" 25ns beams for scrubbing**

# filling schemes & peak heat-load



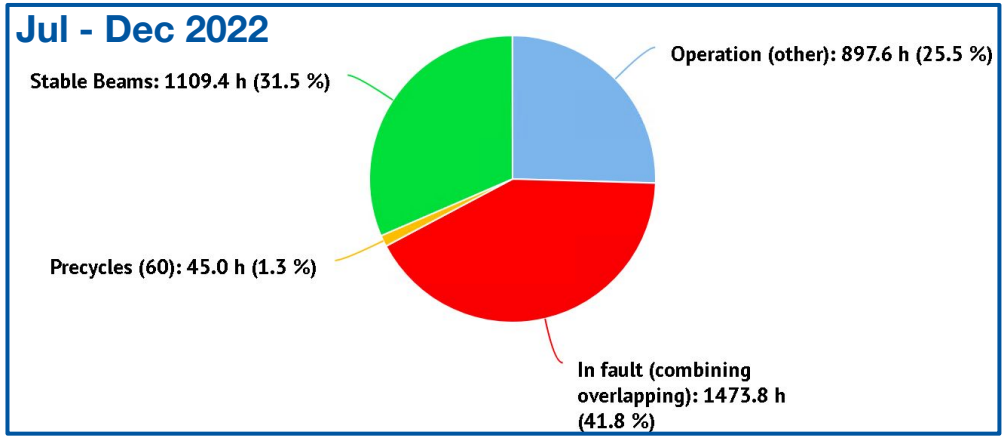



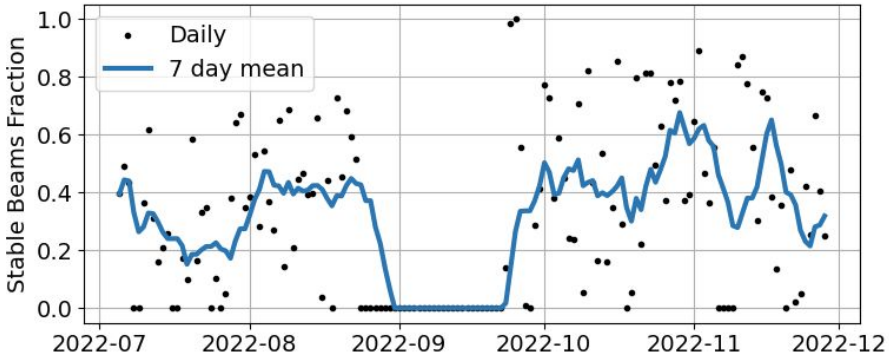



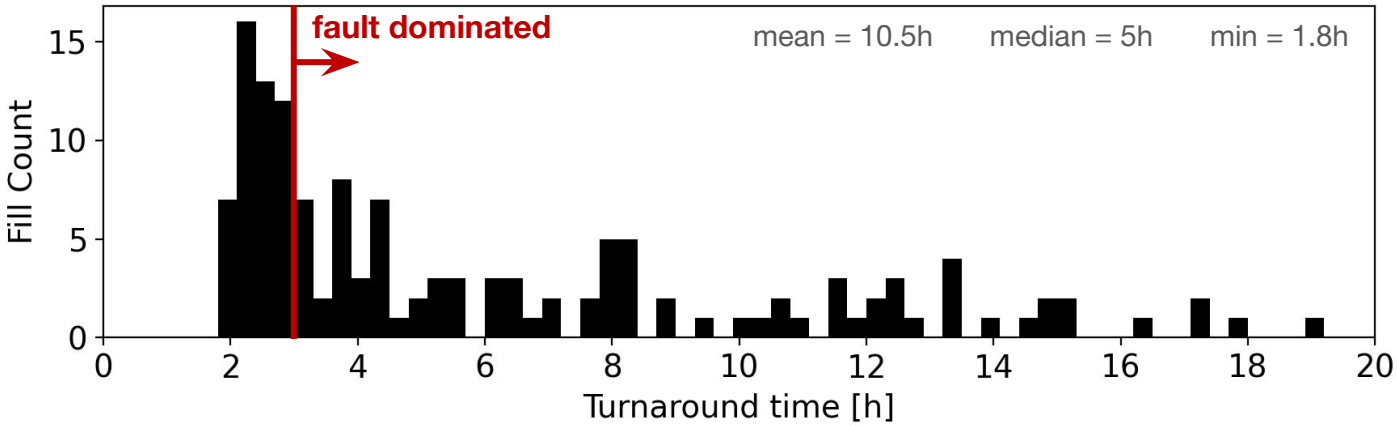
# operational efficiency

- **2022 main mission: recommissioning after LS**
- **~32 % stable beams over the full year**
- **average is not the full story!**
  - **long faults / downtimes**
  - September 2022!
- **towards the end of the year: weeks with > 60% SB**
  - comparable to 2018



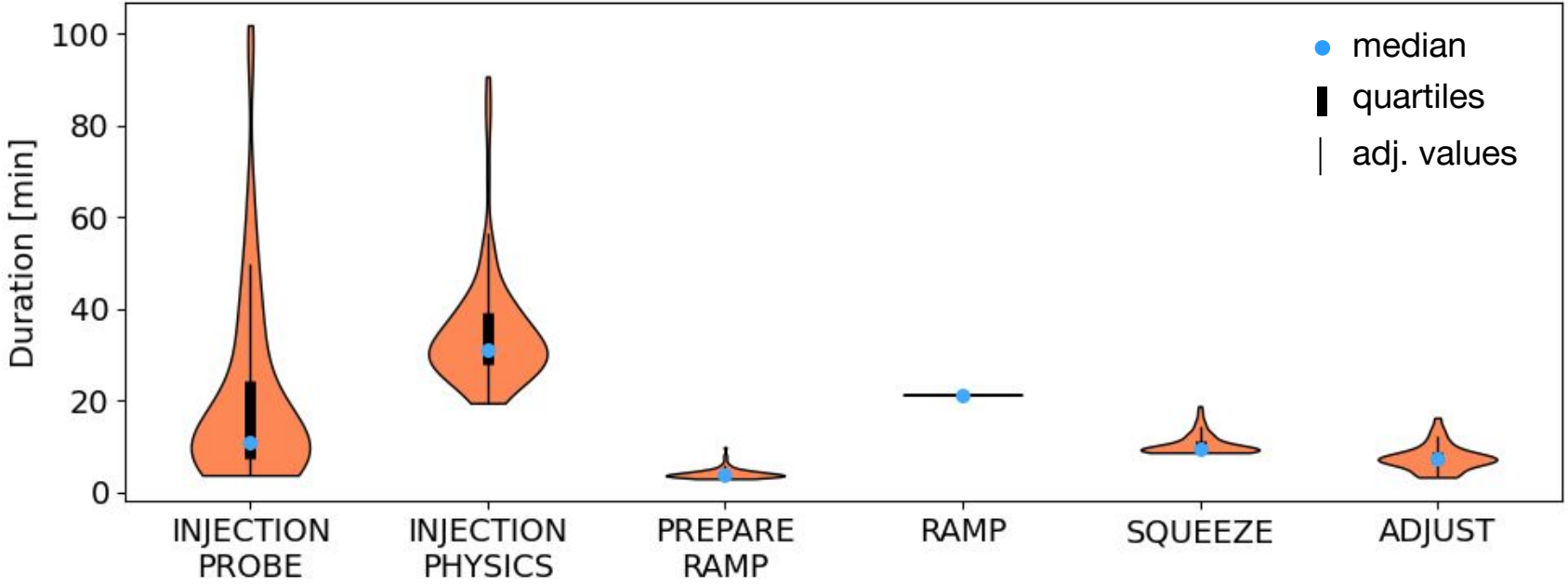



# turnaround time




- **dominated by faults**
  - turn-around times > 3h
  - "long tail" of the distribution
- **where did we lose time in "back-to-back" cycles?**
  - could sequences be optimized?
  - how much time we spend at injection?

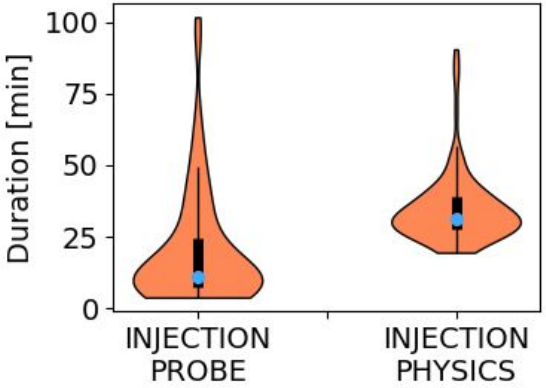
# where do we spend time?

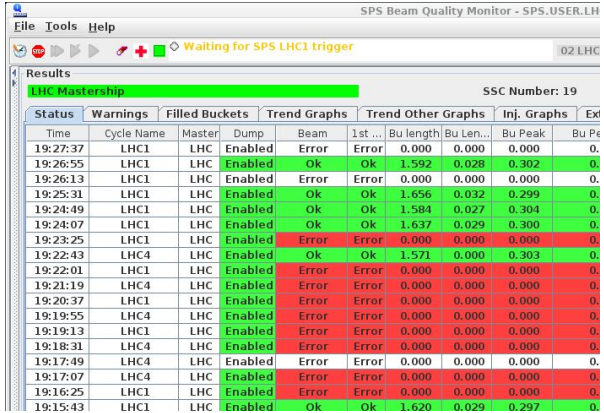



- **significant spread for injection**
- **cycle after very well optimized - potential gain < 10 min**

# injection time - can we improve?

- **long tails: dominated by faults**
  - LHC problems preventing injection
  - injector downtimes
  - not much we can do …
- **injection probe beam**
  - median close to minimum
  - dominated by LHC corrections
- **injection physics beam**
  - ~10 min from median to minimum
  - transfer line drifts & steering
  - missed injections: **setting up LHC beams earlier**?
  - **dedicated filling** could gain ~10 min
  - … at what price for other SPS users?



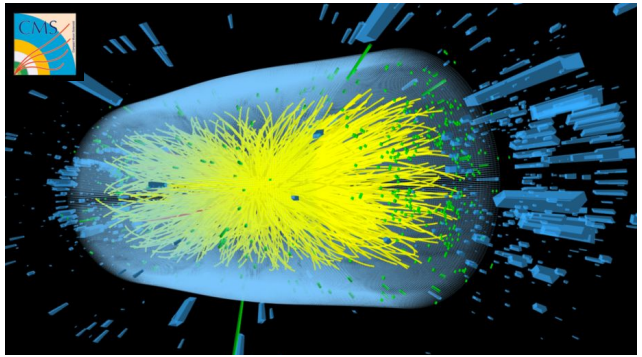




| Time | Cycle Name | Master | Dump | Beam | 1st ... | Bu length | Bu Len... | Bu Peak | Bu Pe |
|---|---|---|---|---|---|---|---|---|---|
| 19:27:37 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:26:55 | LHC1 | LHC | Enabled | Ok | Ok | 1.592 | 0.028 | 0.302 | 0. |
| 19:26:13 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:25:31 | LHC1 | LHC | Enabled | Ok | Ok | 1.656 | 0.032 | 0.299 | 0. |
| 19:24:49 | LHC1 | LHC | Enabled | Ok | Ok | 1.584 | 0.027 | 0.304 | 0. |
| 19:24:07 | LHC1 | LHC | Enabled | Ok | Ok | 1.637 | 0.029 | 0.300 | 0. |
| 19:23:25 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:22:43 | LHC4 | LHC | Enabled | Ok | Ok | 1.571 | 0.000 | 0.303 | 0. |
| 19:22:01 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:21:19 | LHC4 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:20:37 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:19:55 | LHC4 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:19:13 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:18:31 | LHC4 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:17:49 | LHC4 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:17:07 | LHC4 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:16:25 | LHC1 | LHC | Enabled | Error | Error | 0.000 | 0.000 | 0.000 | 0. |
| 19:15:43 | LHC1 | LHC | Enabled | Ok | Ok | 1.620 | 0.029 | 0.297 | 0. |

# instantaneous luminosity: why level IP1 & 5?

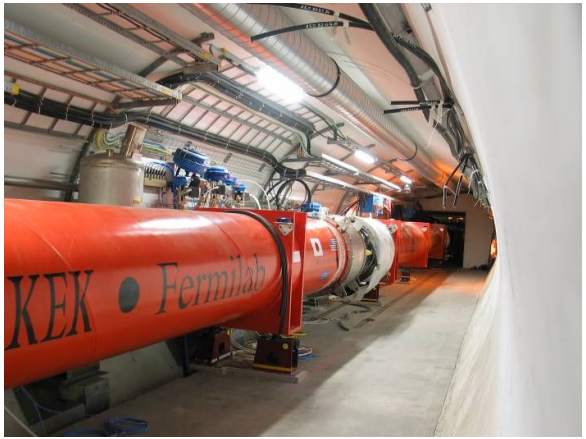
- **ATLAS and CMS pile-up**
  - processing power for event reconstruction
  - data taking efficiency & dead-time
  - limit on the average pile-up

    **➜ single-bunch instantaneous luminosity limit**



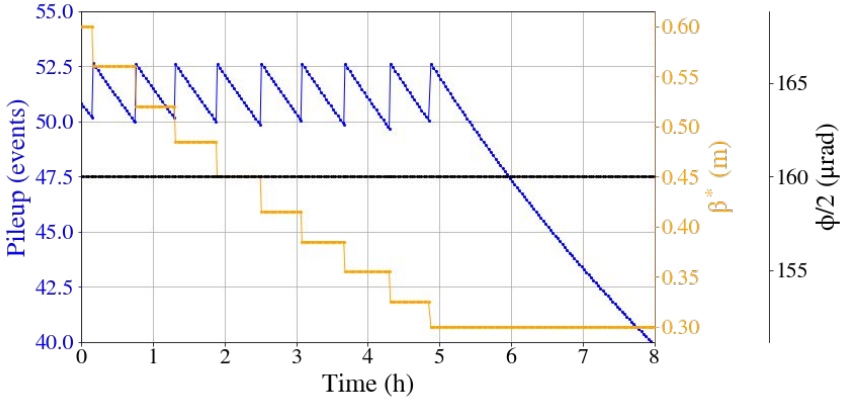

- **IR1 & 5 inner triplet cooling**
  - heating due to luminosity debris
  - cooling capacity different per triplet-side
    - risk of losing cryo conditions (helium overflow)
    - slow processes: ~15 minutes "inertia"
  - limit on the total triplet heat load

    **➜ total instantaneous luminosity limit**



# beta* levelling: the plan for run 3

- **pre-matched optics**
  - ➜ fixed steps
  - ➜ IP 1 / 5 fully coupled
- **number of steps is a compromise**
  - experiments
    - small, regular steps
    - max. ~5% lumi / pile-up jump
  - operation & commissioning
    - max. 1 step every ~30 min
    - 2022: max. 10 optics *(OMC at 60cm & 30cm)*
    - 2023: re-use 60cm ➞ 30cm part




**S. Kostoglou, S. Fartoukh & Run 3 WG**

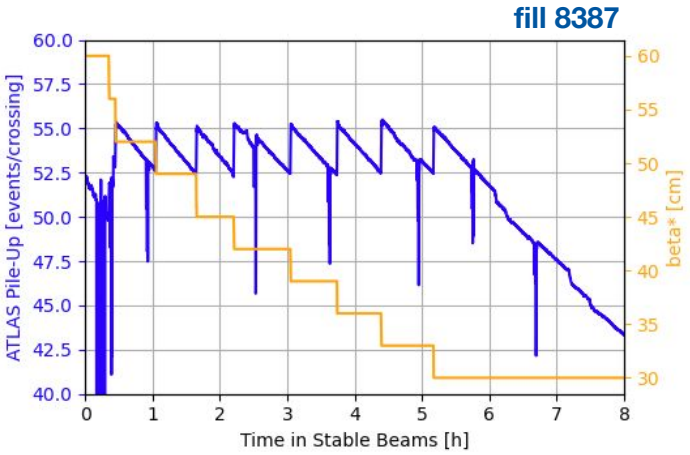
| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.200 | 1.125 | 1.055 | 0.990 | 0.930 | 0.875 | 0.825 | 0.775 | 0.725 | 0.680 | 0.640 | 0.600 | 0.560 | 0.520 | 0.485 | 0.450 | 0.415 | 0.385 | 0.355 | 0.325 | 0.300 |

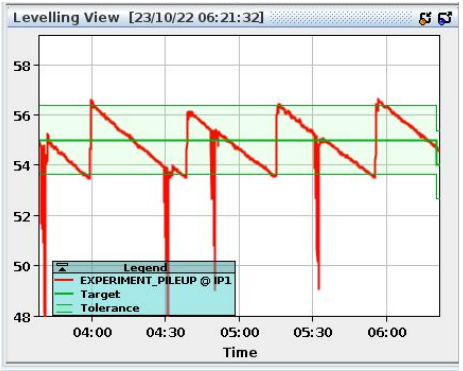
**2023+: 1.2m ➞ 30cm (11+10 steps)**

**2022: 60m ➞ 30cm (10 steps)**

# beta* levelling in operation: up to the plan

- **levelled on experiment pile-up**
  - limiting factor for 2022
  - signal from IP1 or IP5: CCC selection avoid dependency on both signals
  - target: **μ = 54 ± 2.5%**
- **fully automated!**
  - OP sets target, tolerance & signal to level on
  - LumiServer automatically takes steps
    - separation levelling in IP 2 & 8 automatically paused and resumed after the step
    - steps orchestrated with PCs, feedbacks, collimators (including limits) & PCInterlock
  - only OP action: re-optimize IP separation when necessary to compensate drifts



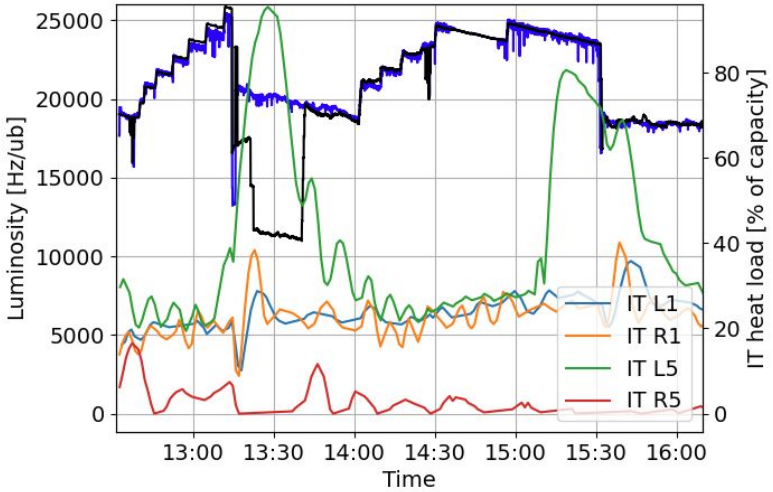
# beta* levelling & triplet cooling limits

- **"used cooling capacity" signal provided by cryo for each triplet-side**
  - at 70%: further beta* steps inhibited
  - at 100%: check with cryo, possibly apply separation
- **derived signal - not a direct observable**
  - signal ~30% for most of 2022
- **cryo limit test (Nov 2022)**
  - **hit limit at ~2.5 $10^{34}$ $cm^{-2}$ $s^{-1}$ on IT L5**
  - cooling capacity **signal very non-linear**
    - < 40% at 2.4 $10^{34}$ $cm^{-2}$ $s^{-1}$
    - jump to > 80% at 2.5 $10^{34}$ $cm^{-2}$ $s^{-1}$

➜ **limit total lumi to ~2.4 $10^{34}$ $cm^{-2}$ $s^{-1}$**

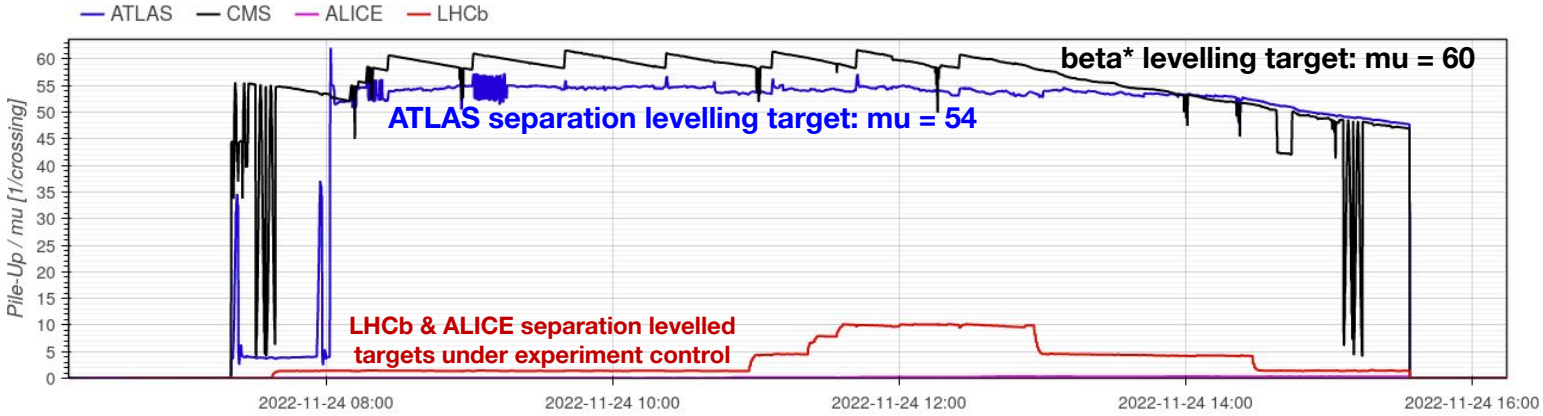
***(~20% higher than expected!)***

➜ **no automatic feedback…**



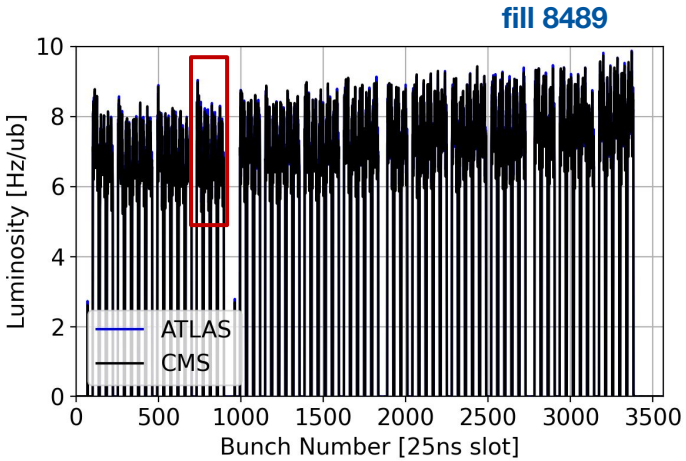
# levelling: "à la carte" options

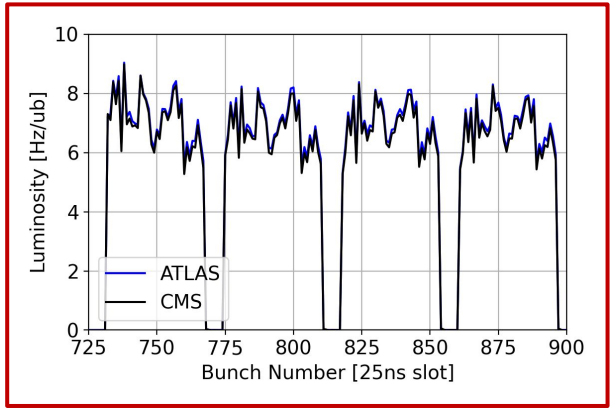
- **separation levelling in IP 1 & 5 still an option**
  - if initial luminosity is above target
  - if ATLAS & CMS targets are different
- **separation levelling in parallel to beta* levelling**
  - **possible!**
  - ~5% transients during beta* levelling steps

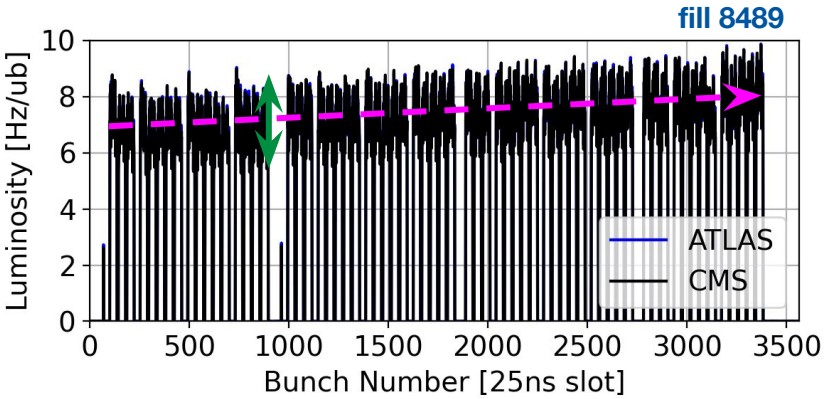
# luminosity: bunch-to-bunch spread

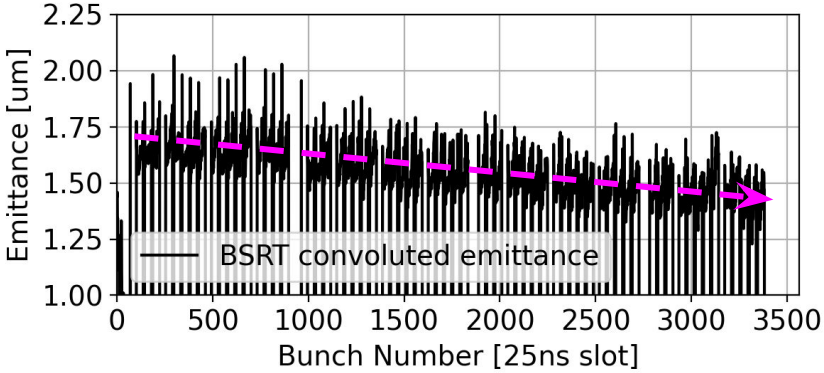
- **significant bunch-to-bunch lumi spread**
  - 10-15% r.m.s.
  - up to 50% peak-to-peak!
- **spread in lumi = spread in pile-up**
  - e.g. target average μ = 54 ± 2.5%
    ➜ bunch μ = 20-70! (r.m.s. ~6)
- **no big issue for experiments**
- **where does it come from?**
  - intensity
  - emittance



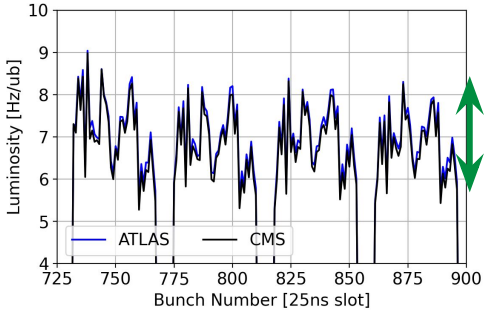
# luminosity: bunch-to-bunch spread

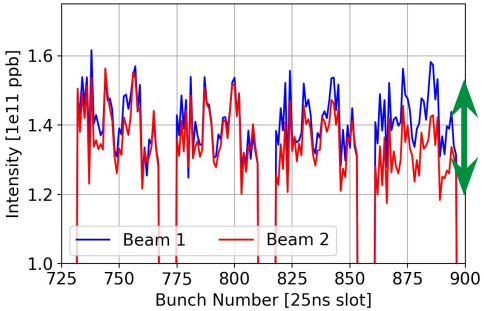



- **structure within trains**: mainly intensity, from injectors
- **trend over the ring**: emittance growth at injection (IBS in LHC)

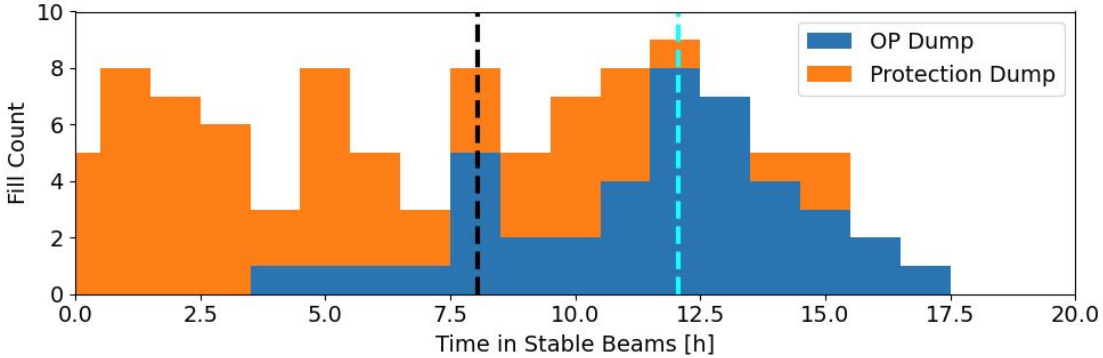
➜ reducing filling time would help!



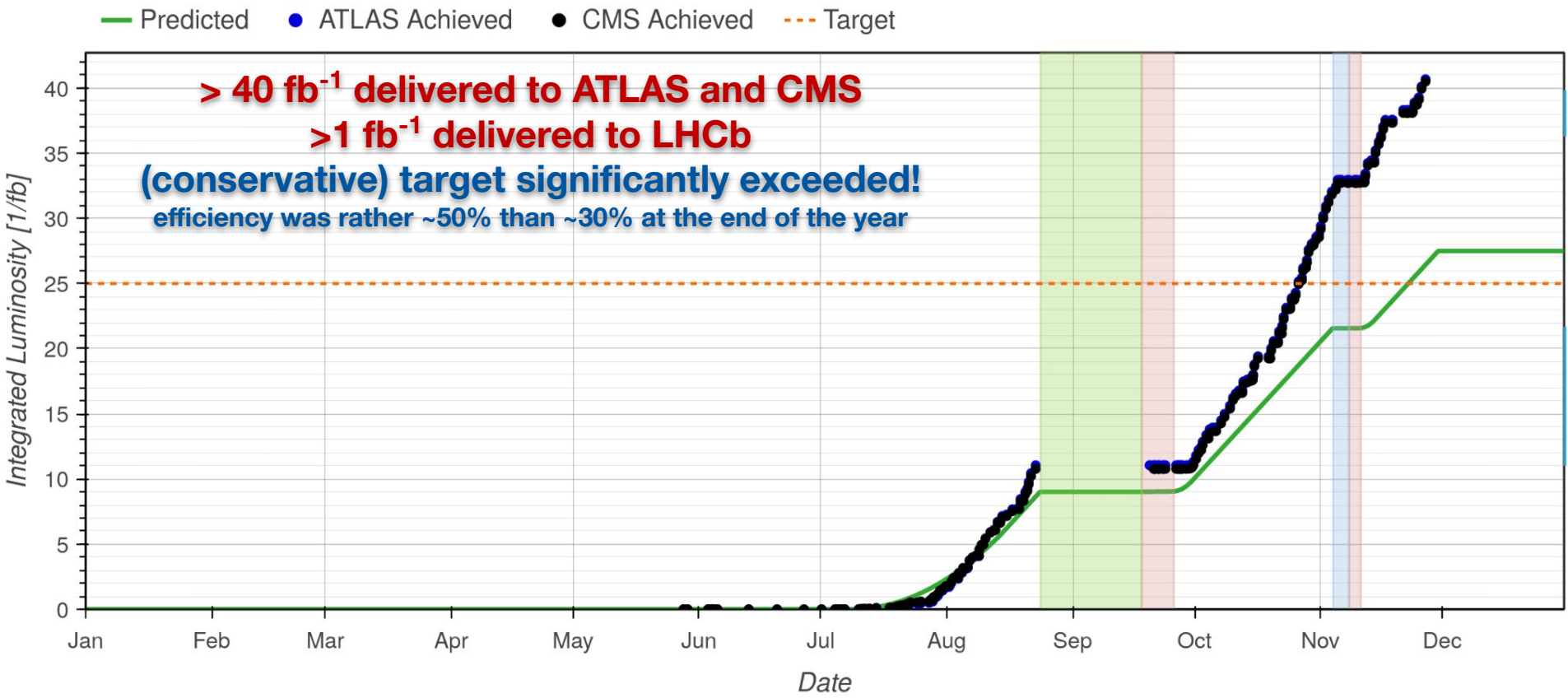



# fill length & dumps

- **optimum fill length: ~12h in Stable Beams**
  - ~5h median turnaround
  - < 3% integrated luminosity lost when stretched to 15h
- **42 OP dumps, 60 protection dumps of production fills**
  - OP dumps include "forced" dumps for access (e.g. chimney heaters, …)
  - median fill length: ~8h in Stable Beams



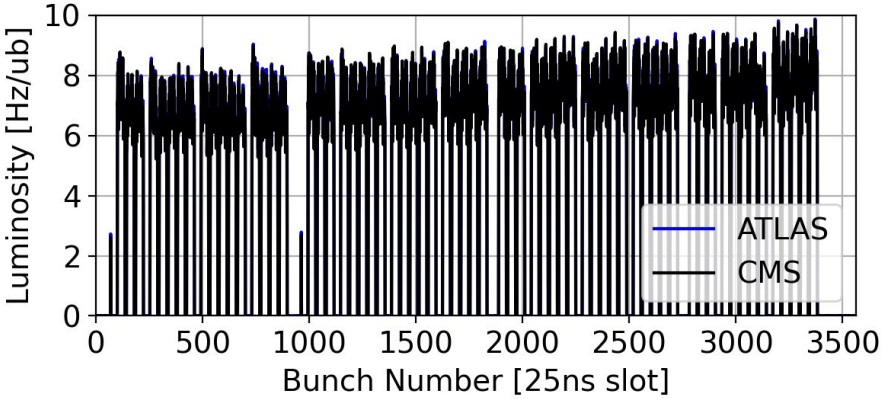
# integrated luminosity

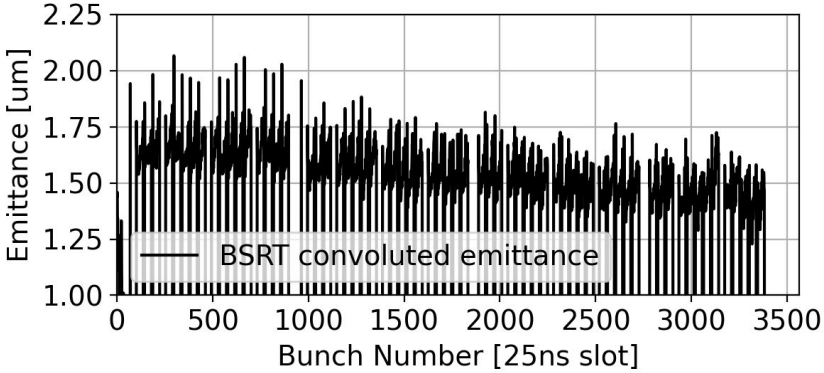


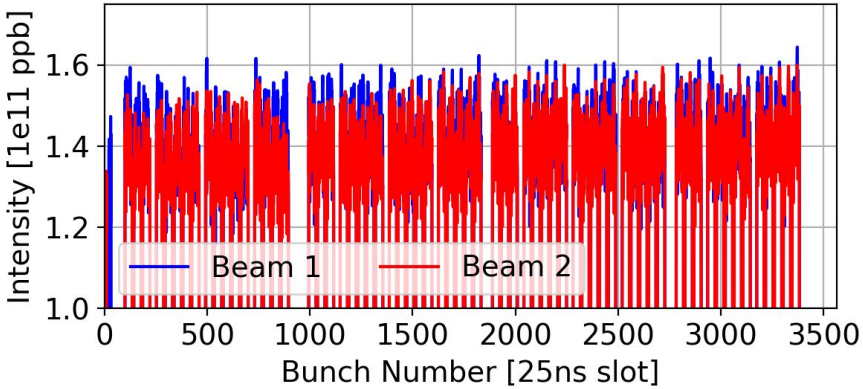
# conclusions

- **2022 - a very successful commissioning year for LHC**
- **cycle similar to run 2 to ease commissioning**
- **cycle efficiency: good, potential gains at injection**
  - dedicated filling & earlier preparation of LHC beams could help
  - impact on other physics users to be considered!
- **new: beta* levelling from 60cm → 30cm**
  - limited by experiment pile-up, **μ = 54 ± 2.5%**
  - **triplet cooling** not limiting, tested at **~2.5 $10^{34}$ $cm^{-2}$ $s^{-1}$**
  - levelling is fully automated & used in every physics fill
- **luminosity targets significantly exceeded**
  - > 40 fb-1 in ATLAS and CMS
  - > 1 fb-1 in LHCb

# thanks for your attention


Luminosity [Hz/ub]
10
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
3500
Bunch Number [25ns slot]
ATLAS
CMS


Emittance [um]
2.25
2.00
1.75
1.50
1.25
1.00
0
500
1000
1500
2000
2500
3000
3500
Bunch Number [25ns slot]
BSRT convoluted emittance


Intensity [1e11 ppb]
1.6
1.4
1.2
1.0
0
500
1000
1500
2000
2500
3000
3500
Bunch Number [25ns slot]
Beam 1
Beam 2

# arc heat load: a main limitation

- arc 7-8 average heat load ~190 W/half-cell
- cryo limit at ~200 W/half-cell