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 \(~1.45 \times 10^{11}\) 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

- 5x48b with 5x48b
- 2413b with 5x48b
- 2462b with 5x36b
- 2365b with 2x8b4e + 3x48b

8b4e + BCMS

-10%
-20%
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?

---

Fault dominated

mean = 10.5h  median = 5h  min = 1.8h
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?
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
  - \(\rightarrow\) *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: \(\sim\)15 minutes "inertia"
  - limit on the total triplet heat load
  - \(\rightarrow\) *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

- **2023+**: 1.2m ➞ 30cm (11+10 steps)
- **2022**: 60m ➞ 30cm (10 steps)

---

*S. Kostoglou, S. Fartoukh & Run 3 WG*
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: $\mu = 54 \pm 2.5\%$

- **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 \( \sim 2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) on IT L5
  - cooling capacity signal very non-linear
    - < 40% at \( 2.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
    - jump to > 80% at \( 2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

\[ \rightarrow \] limit total lumi to \( \sim 2.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

\( \sim 20\% \) higher than expected!

\[ \rightarrow \] 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 $\mu = 54 \pm 2.5\%$
    - bunch $\mu = 20-70!$ (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

> 40 fb$^{-1}$ delivered to ATLAS and CMS

> 1 fb$^{-1}$ delivered to LHCb

(conservative) target significantly exceeded!

efficiency was rather $\sim$50% than $\sim$30% at the end of the year
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, $\mu = 54 \pm 2.5\%$
  ○ triplet cooling not limiting, tested at $\sim 2.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
  ○ 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
arc heat load: a main limitation

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