LHC Run 3: achievements and lessons learnt

Mike Lamont
7th October 2024

A walk on the good side 1/2

Good beam lifetime through injection, ramp, and squeeze with tight control of tune, chromaticity, coupling and closed orbit - operationally things are very well under control.

Great peak luminosity via exploitation of all available parameters (beta*, bunch population, bunch length, crossing angle, transverse emittance)…

Excellent luminosity lifetime in general with only moderate emittance blow-up in Stable Beams and minimal non-luminosity beam loss (!)

Well established and tuned magnet model, good compensation of persistent current decay and snapback, which coupled with a strict magnet cycling give excellent magnetic reproducibility.

The optics and huge parameter space of the machine has been measured and corrected to an impressive level, both linear and higher orders, BLM settings etc. and a superb level of understanding has been established.

Aperture is good, well measured and compatible with the collimation hierarchy (NB the “platinum mine”)

A walk on the good side 2/2

The magnets, circuits and associated systems are behaving impeccably at 6.8 TeV.

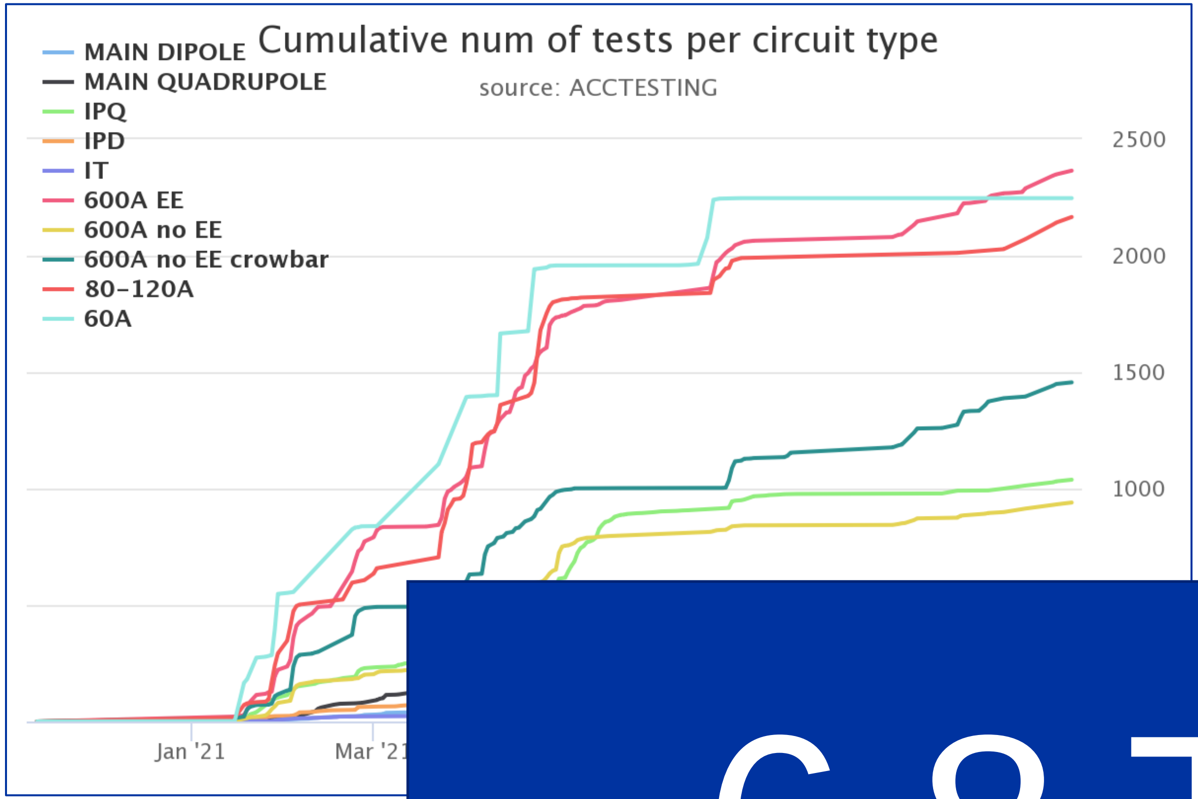
Robust and extended machine protection systems coupled with a rigorous culture has assured safe exploitation.

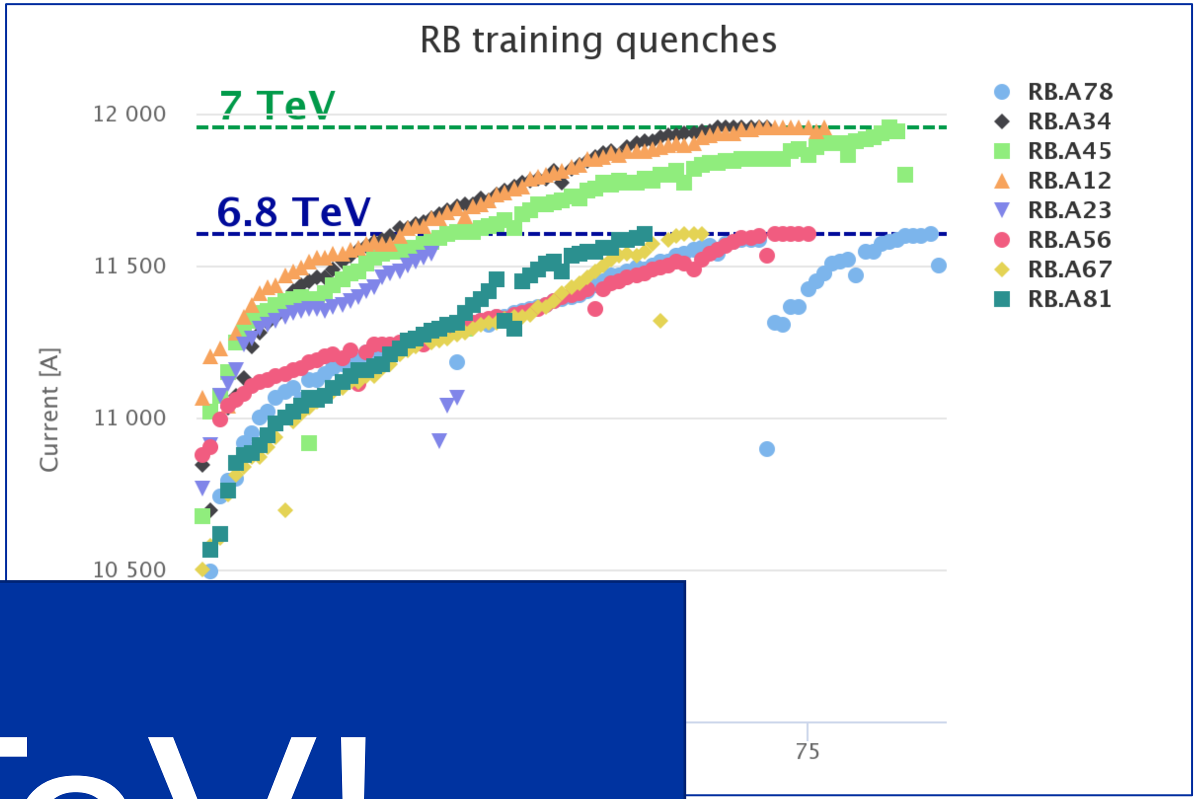
The collimation system has consistently demonstrated excellent performance and impressive robustness.

Stunning availability following sustained effort from hardware groups accompanied by effective fault tracking.

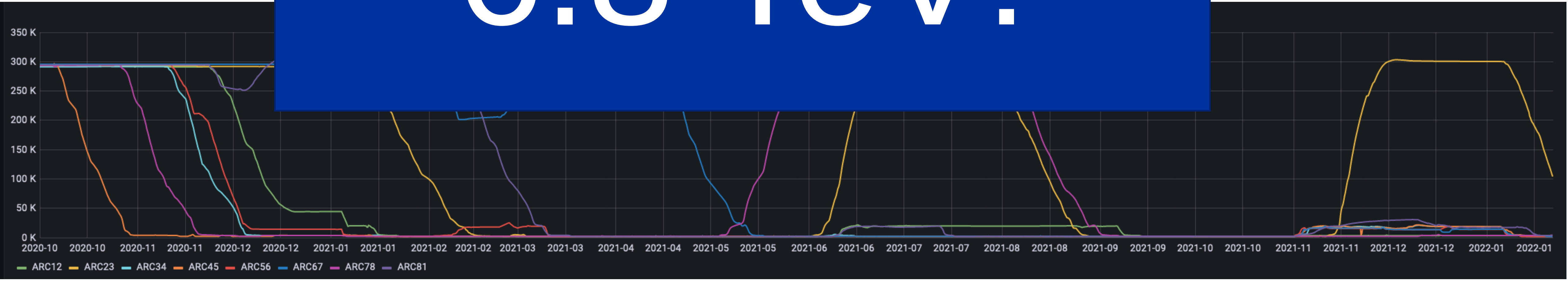
Few premature dumps allowing long fills: the UFO rate conditioned down and radiation to electronics effects have been largely mitigated after sustained and successful campaigns.

Excellent and improved system performance across the board, for example, transverse damper system; collimator alignment, improved injection kicker performance via hardware modifications, orbit feedback, cryogenics etc. etc. – more on this later


Cumulative num of tests per circuit type
source: ACCTESTING
MAIN DIPOLE
MAIN QUADRUPOLE
IPQ
IPD
IT
600A EE
600A no EE
600A no EE crowbar
80-120A
60A
2500
2000
1500
1000
Jan '21
Mar '21


RB training quenches
7 TeV
6.8 TeV
12 000
11 500
11 000
10 500
Current [A]
75
RB.A78
RB.A34
RB.A45
RB.A12
RB.A23
RB.A56
RB.A67
RB.A81

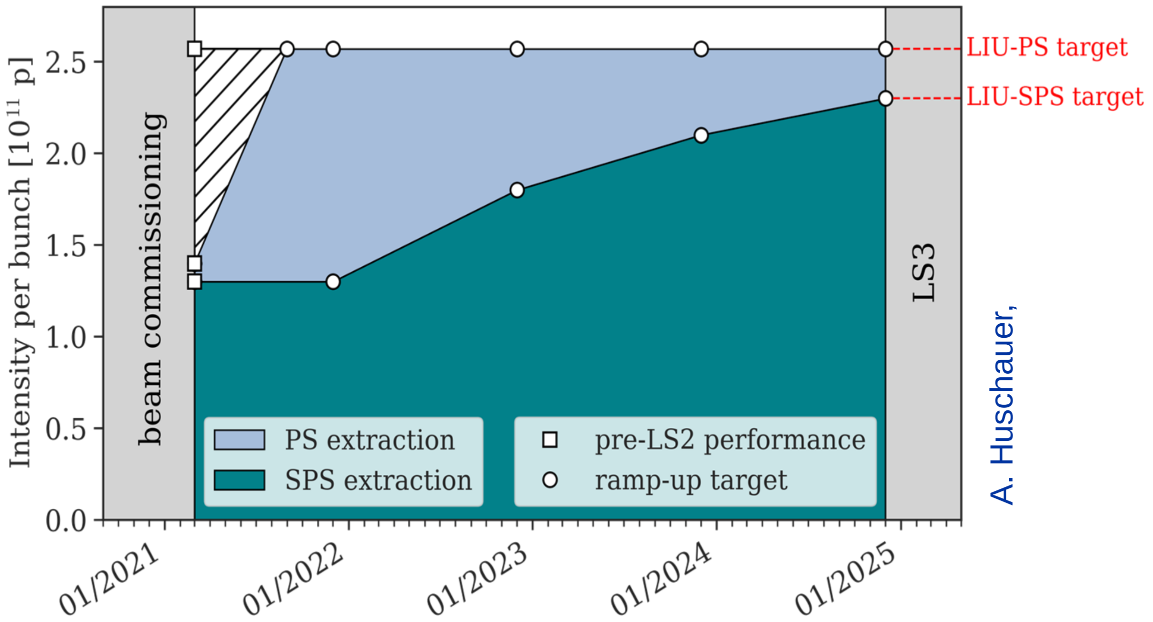
6.8 TeV!


350 K
300 K
250 K
200 K
150 K
100 K
50 K
0 K
2020-10
2020-11
2020-12
2021-01
2021-02
2021-03
2021-04
2021-05
2021-06
2021-07
2021-08
2021-09
2021-10
2021-11
2021-12
2022-01
ARC12
ARC23
ARC34
ARC45
ARC56
ARC67
ARC78
ARC81

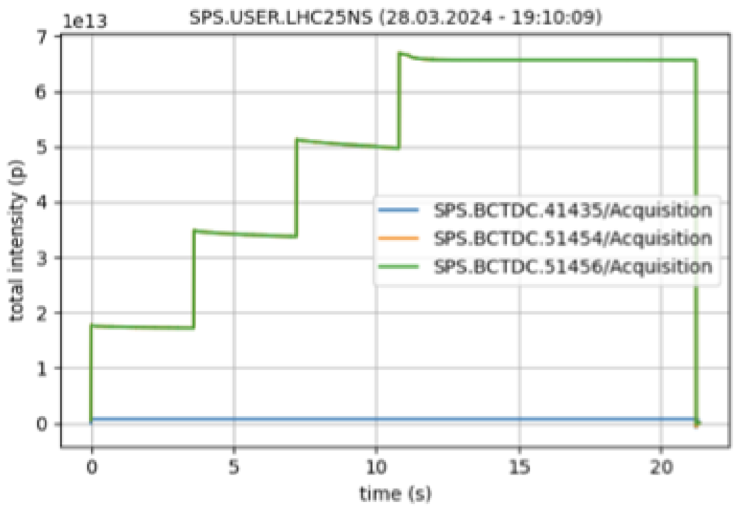
LHC injectors performance

Year-by-year intensity goals of the ramp-up at SPS extraction

- **2021**: **1.3e^{11} p/b** – Recover Pre-LS2 beam parameters
- **2022**: **1.8e^{11} p/b** – Set base for LHC 2023 operation
- **2023**: **2.1e^{11} p/b** – Toward LIU targets (HL parameters)
- **2024: 2.3e^{11} p/b** – LIU target for HL-LHC operation



A. Huschauer,



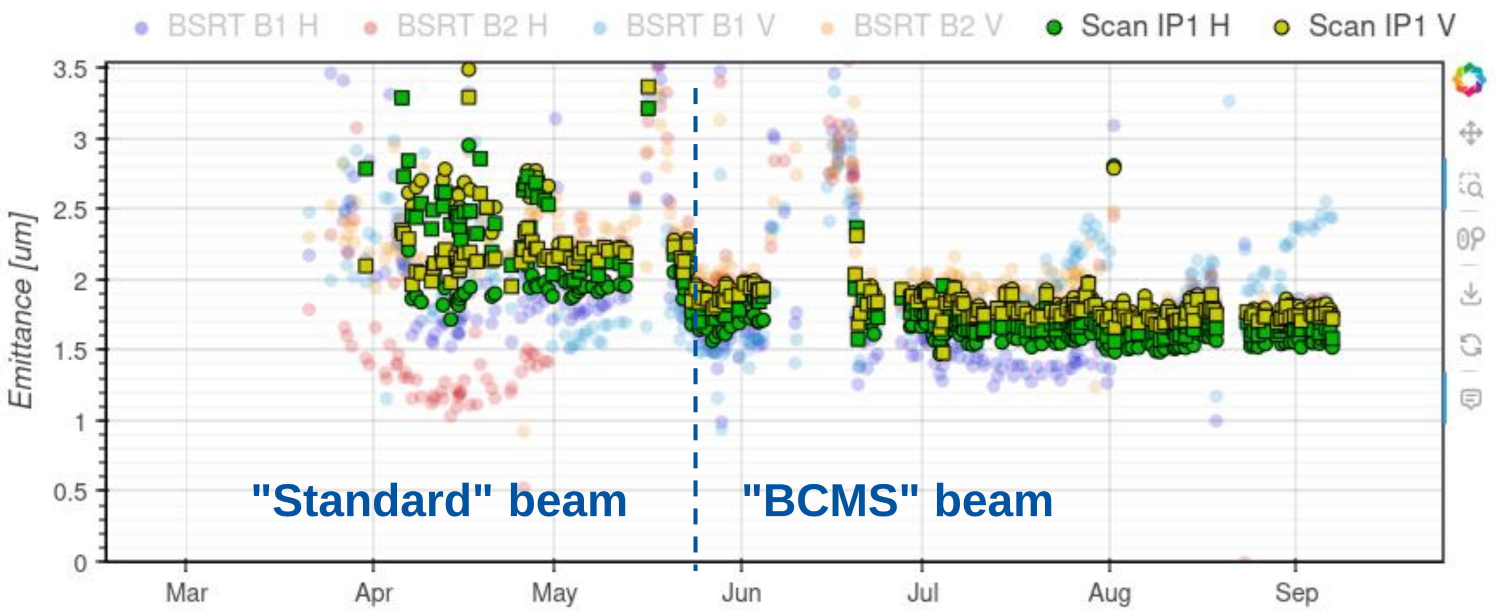
LIU intensity and bunch length at SPS extraction **achieved:**

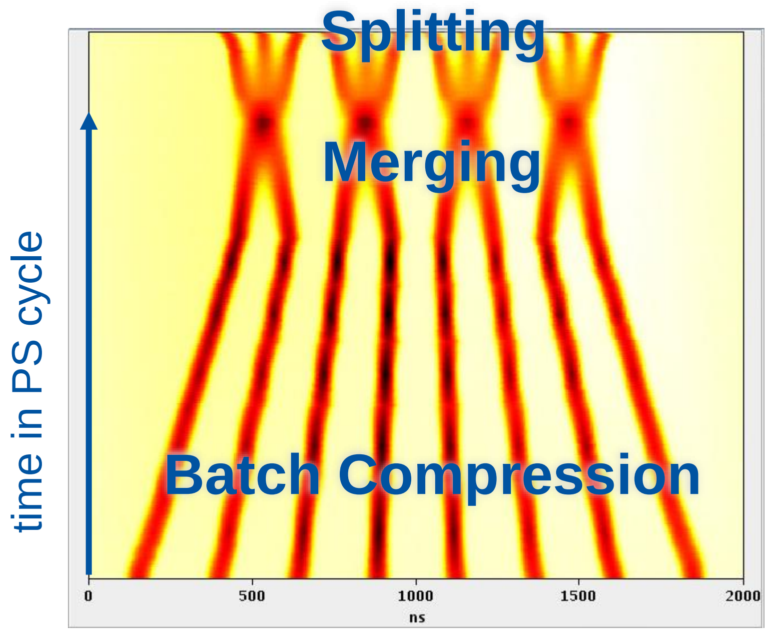
- 4x72 bunches at 2.3e^{11} p/b with bunch length of 1.65 ns
- Transverse emittances did not yet satisfy LIU specification (optimization will be done in the next high intensity sessions)

In the LHC during the last MD period!

Beams from injectors 2024: BCMS

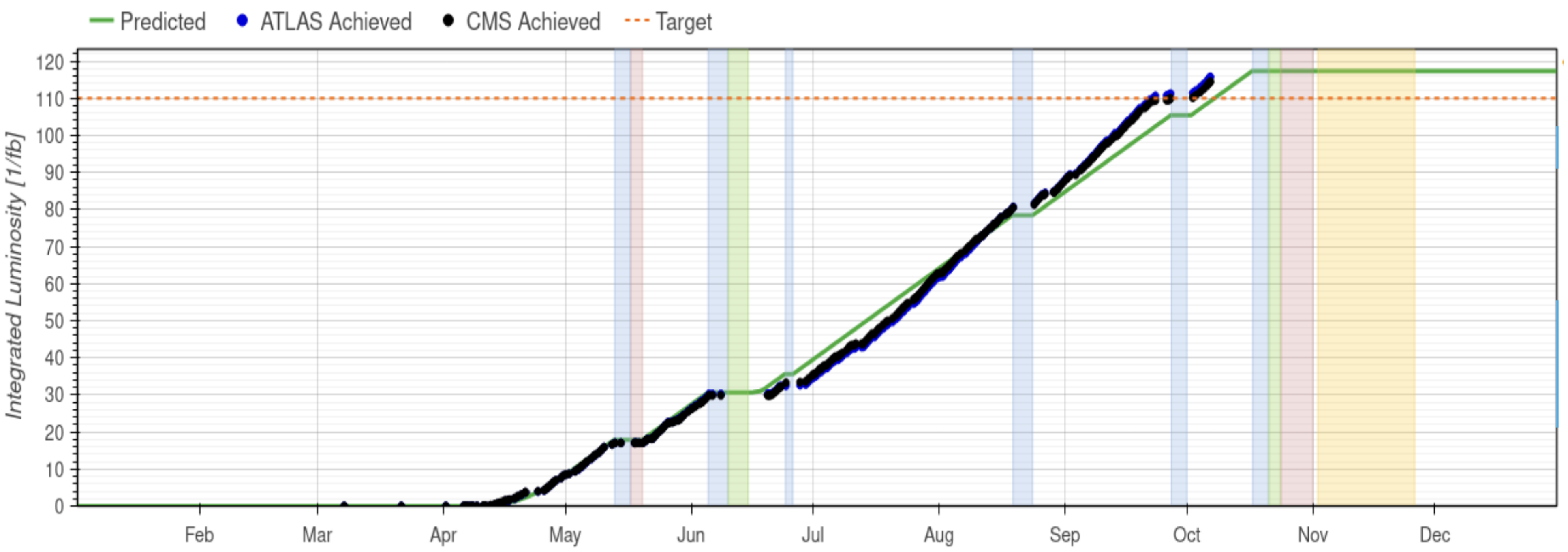
- **Batch Compression, Merging, Splitting ("BCMS") beam production scheme used since June**
  - use 8 instead of 6 bunches from PSB ➜ PS
- **~10% improvement in beam brightness**
  - ➜ gains ~1-2 hours of time levelled at peak luminosity





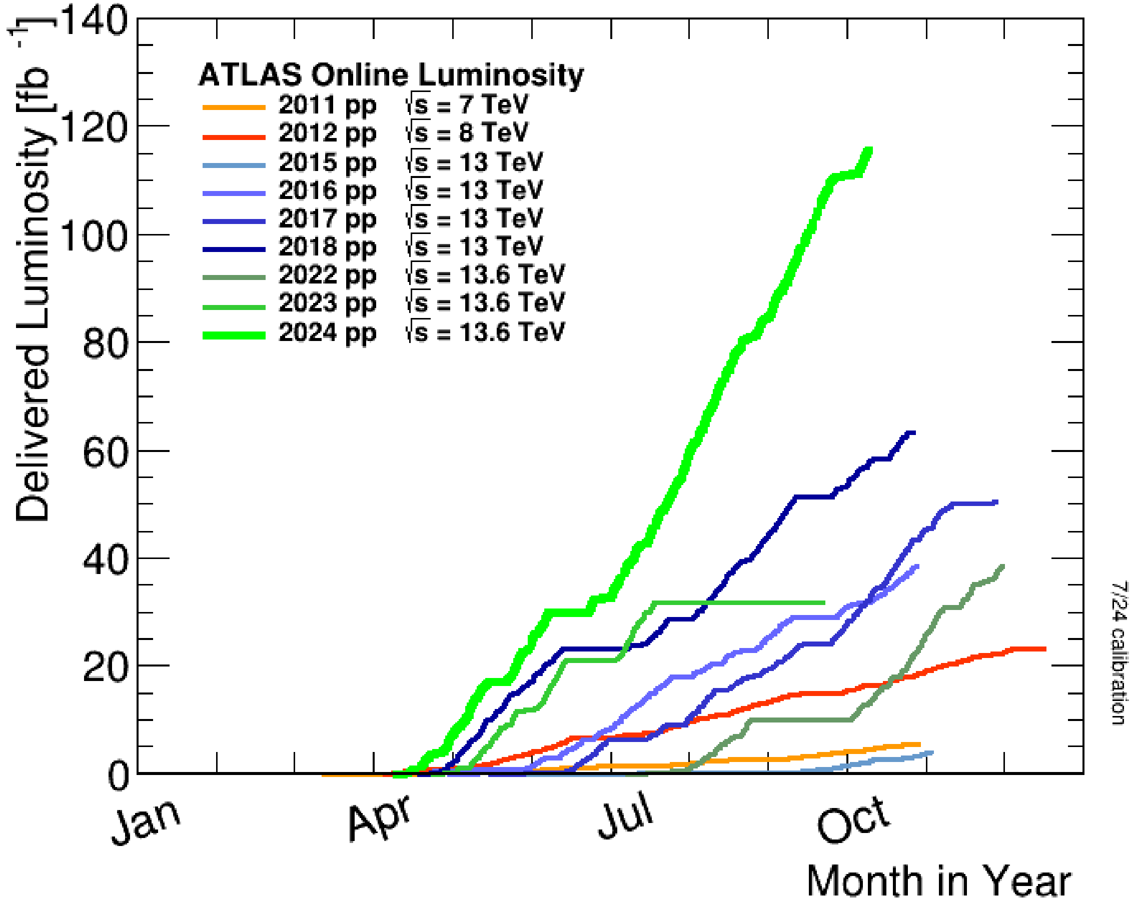
A. Lasheen, H. Damerau and the PS OP team

LHC 2024 – ATLAS and CMS just passed 115 fb^{-1}



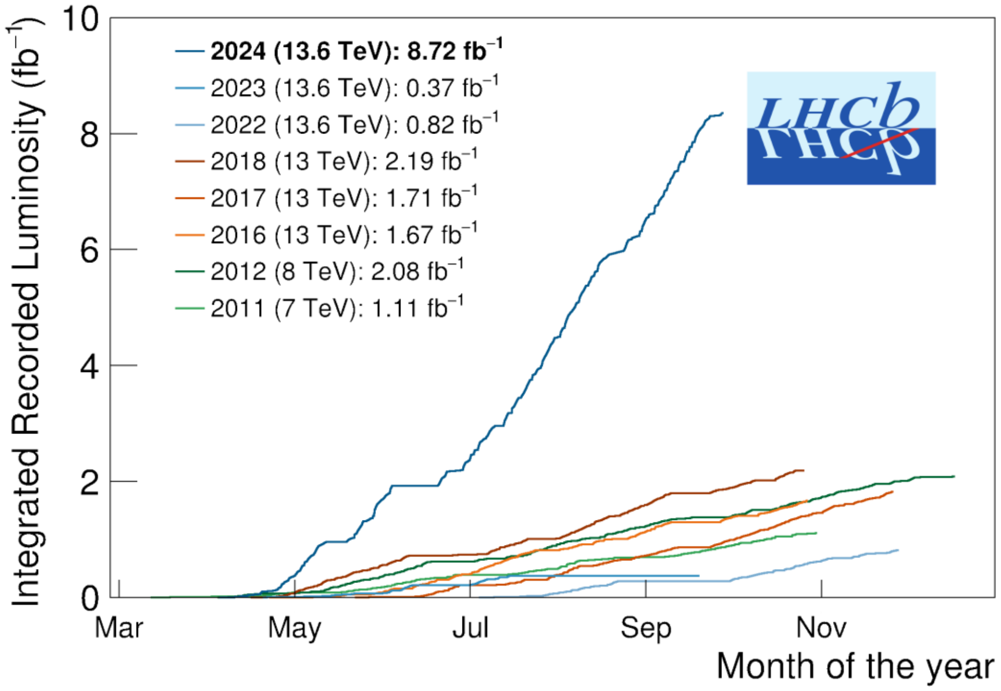
- ~1.4 fb^{-1} / 24h in ATLAS / CMS possible with good availability
- ~7.5 fb^{-1} / week achieved on average in "good" weeks

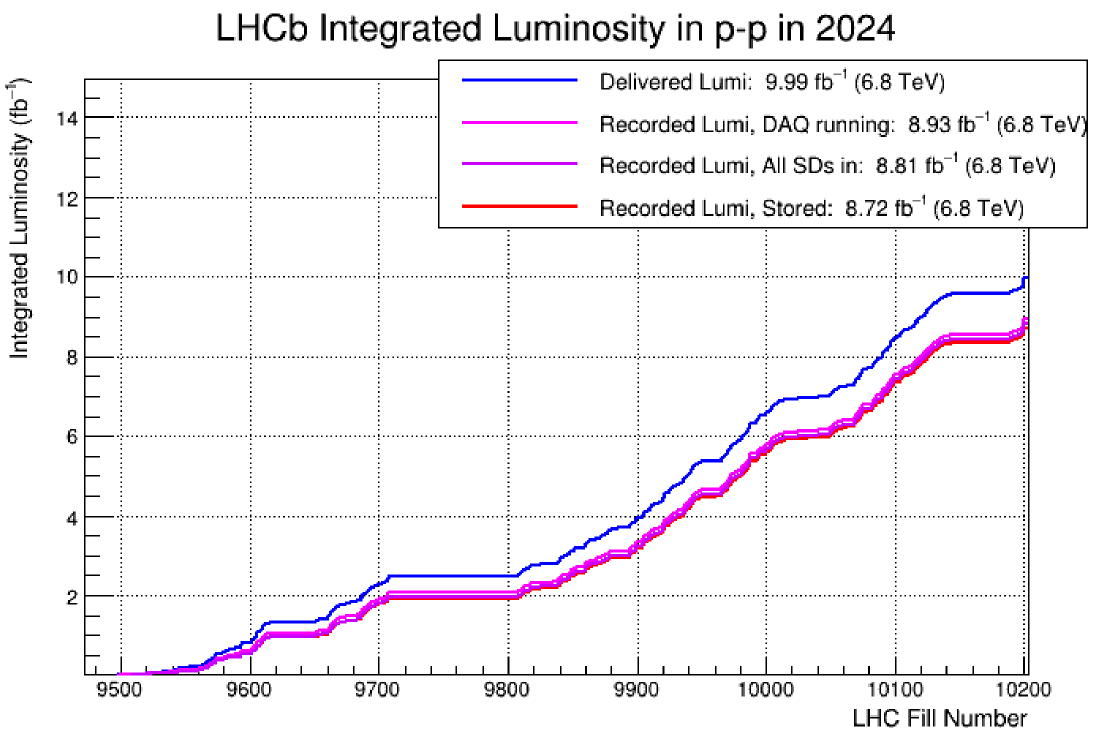
ATLAS



Peak Luminosity	2.33e34 $cm^{-2}s^{-1}$
Max. Luminosity in one day	1.525 fb^{-1}
Max. Luminosity in 7 days	8.342 fb^{-1}
Longest time in Stable Beams for 7 days	5 days 3 hr 35 min
Max. Charge per bunch	1.64e11

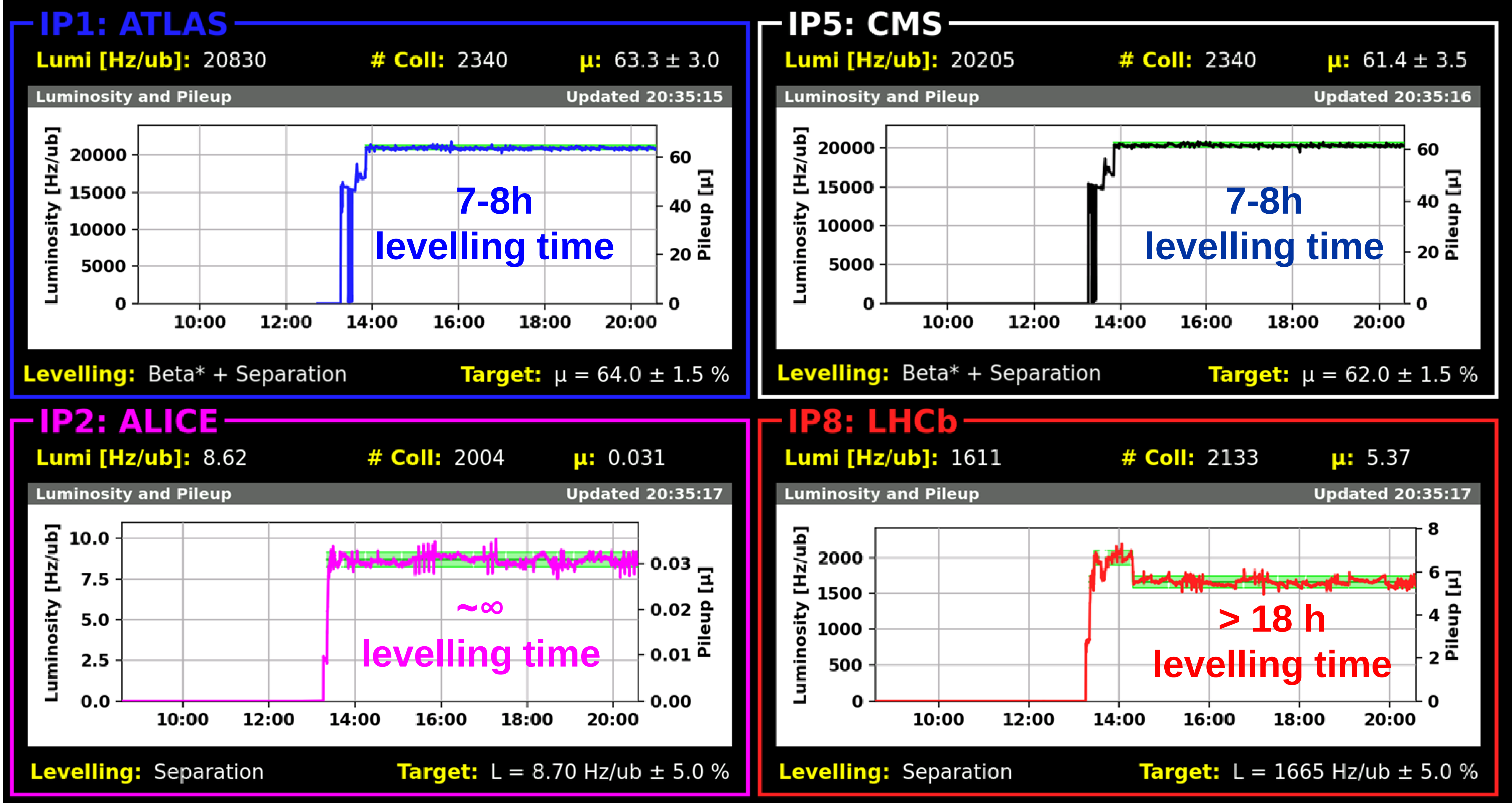
Astounding!!!





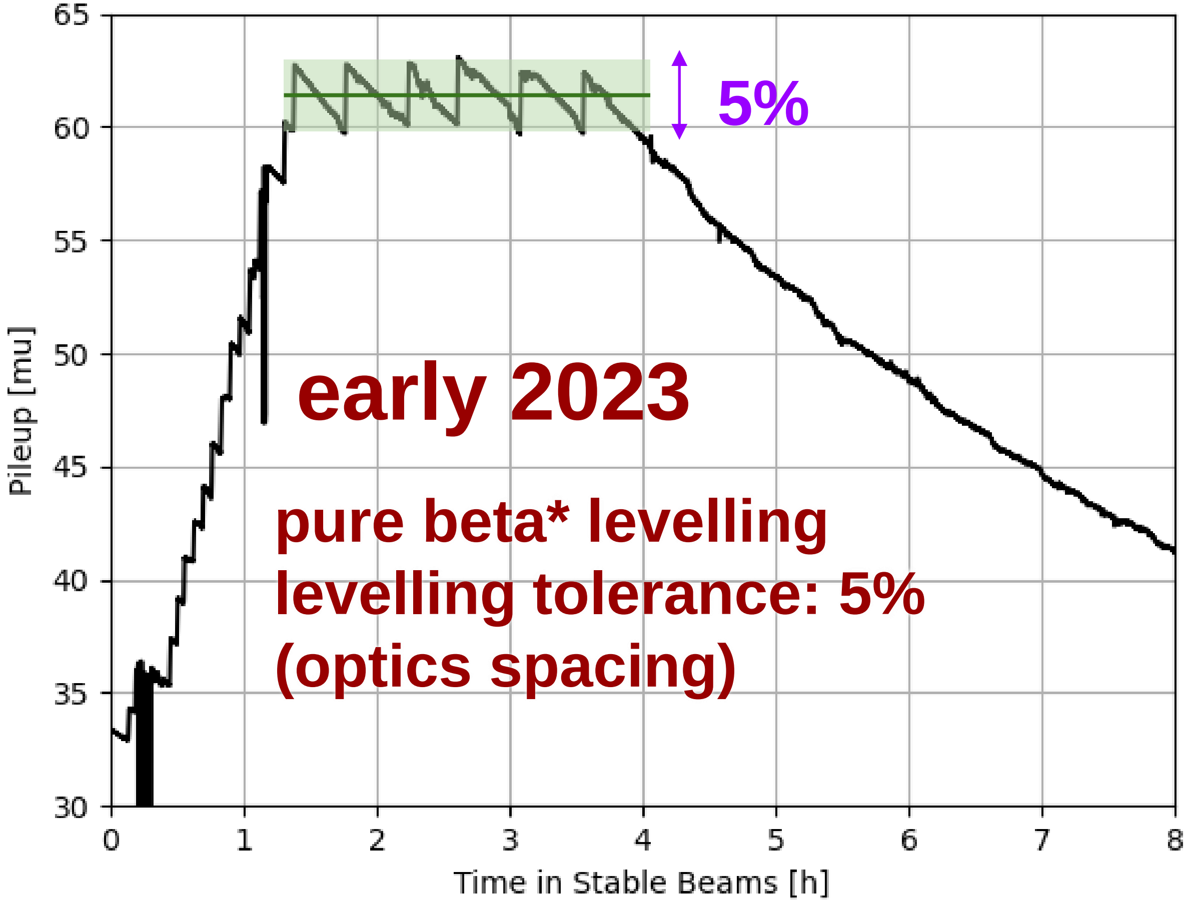
9.99 fb^{-1} delivered to LHCb

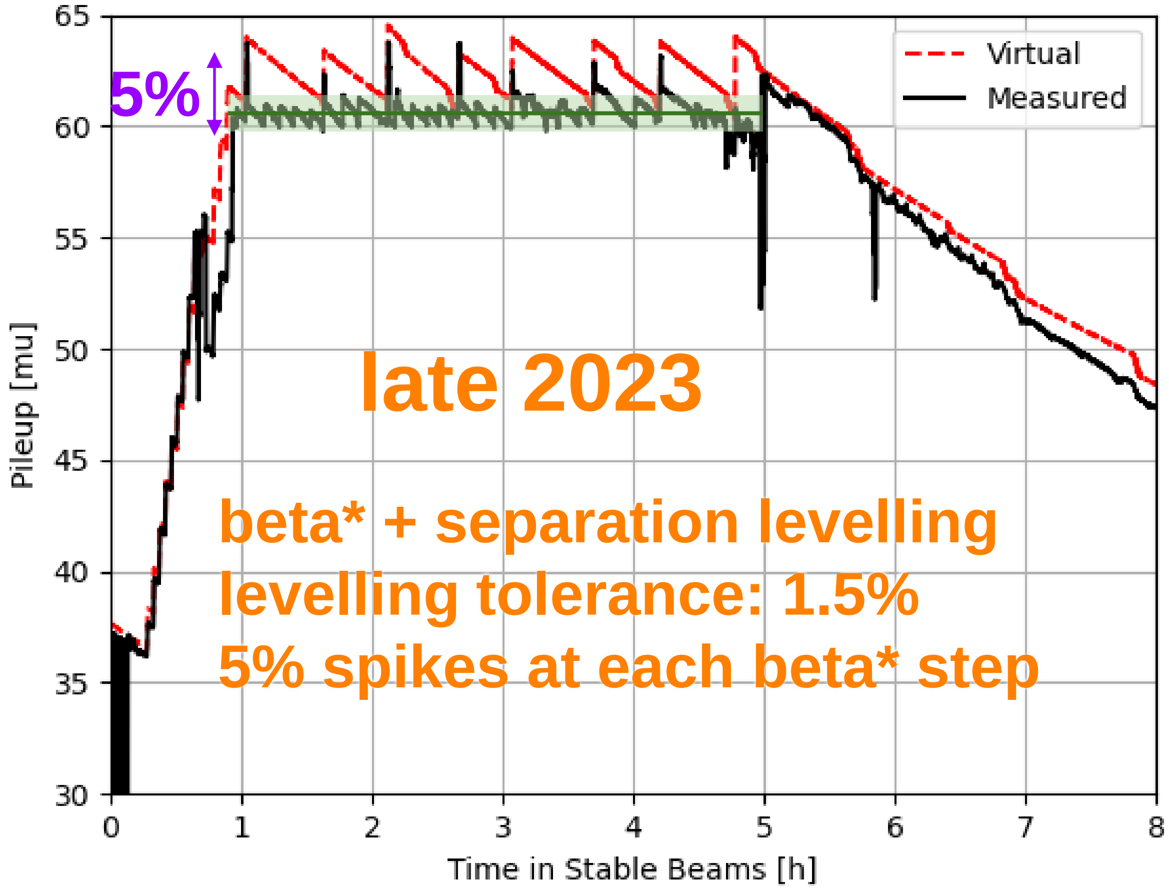
Pretty good as well!!!



IP1: ATLAS
Lumi [Hz/ub]: 20830
Coll: 2340
μ: 63.3 ± 3.0
Luminosity and Pileup
Updated 20:35:15
7-8h
levelling time
Levelling: Beta* + Separation
Target: μ = 64.0 ± 1.5 %
IP5: CMS
Lumi [Hz/ub]: 20205
Coll: 2340
μ: 61.4 ± 3.5
Luminosity and Pileup
Updated 20:35:16
7-8h
levelling time
Levelling: Beta* + Separation
Target: μ = 62.0 ± 1.5 %
IP2: ALICE
Lumi [Hz/ub]: 8.62
Coll: 2004
μ: 0.031
Luminosity and Pileup
Updated 20:35:17
~∞
levelling time
Levelling: Separation
Target: L = 8.70 Hz/ub ± 5.0 %
IP8: LHCb
Lumi [Hz/ub]: 1611
Coll: 2133
μ: 5.37
Luminosity and Pileup
Updated 20:35:17
> 18 h
levelling time
Levelling: Separation
Target: L = 1665 Hz/ub ± 5.0 %
Luminosity [Hz/ub]
Pileup [μ]
10:00
12:00
14:00
16:00
18:00
20:00

Luminosity levelling: beta* and separation

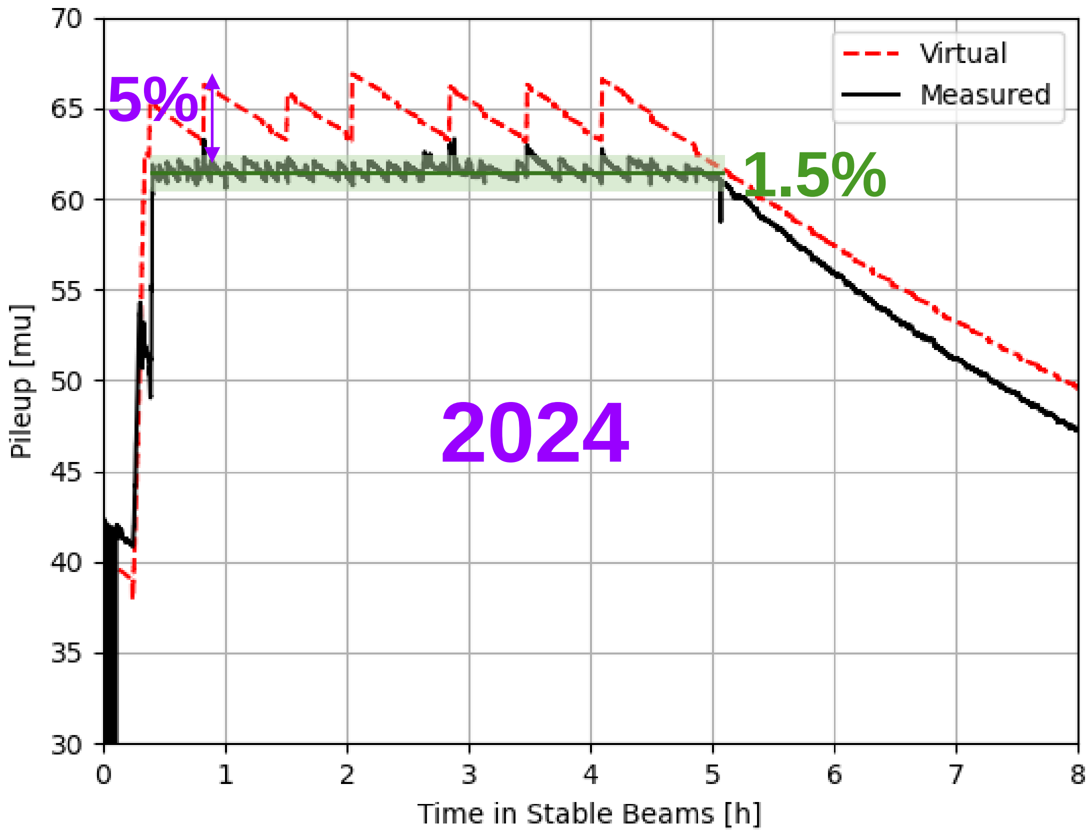


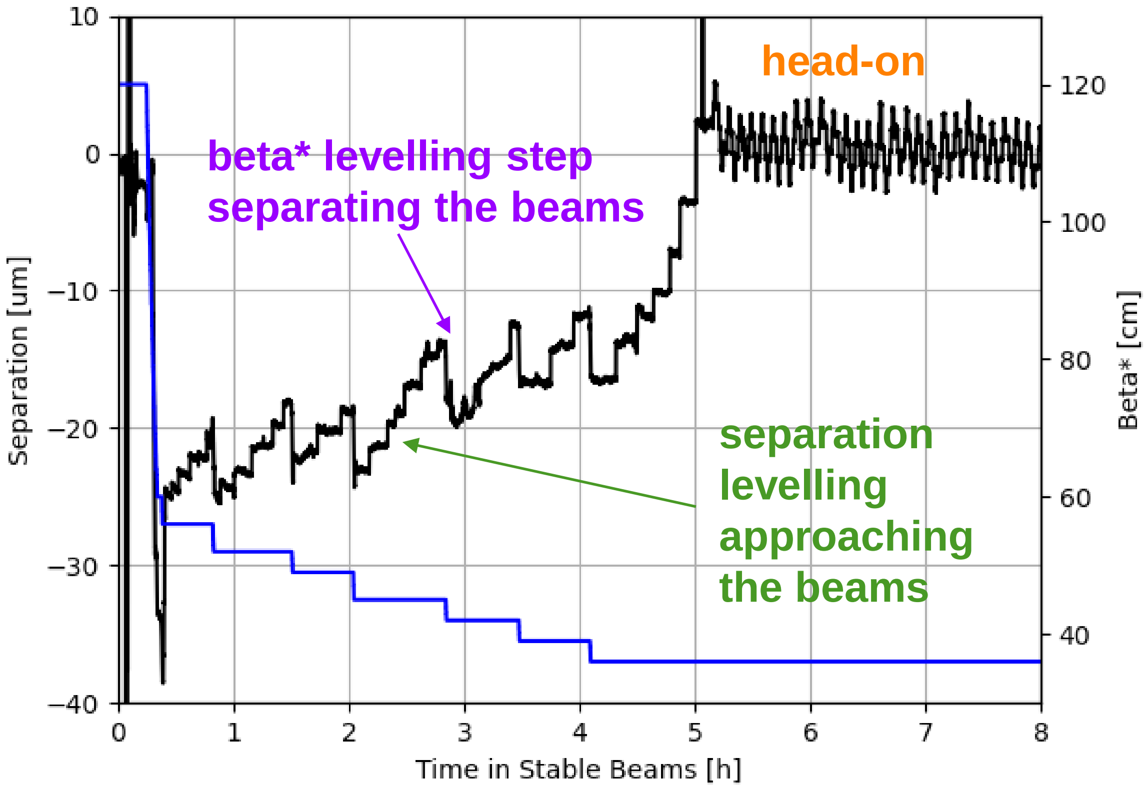


Luminosity levelling: beta* and separation

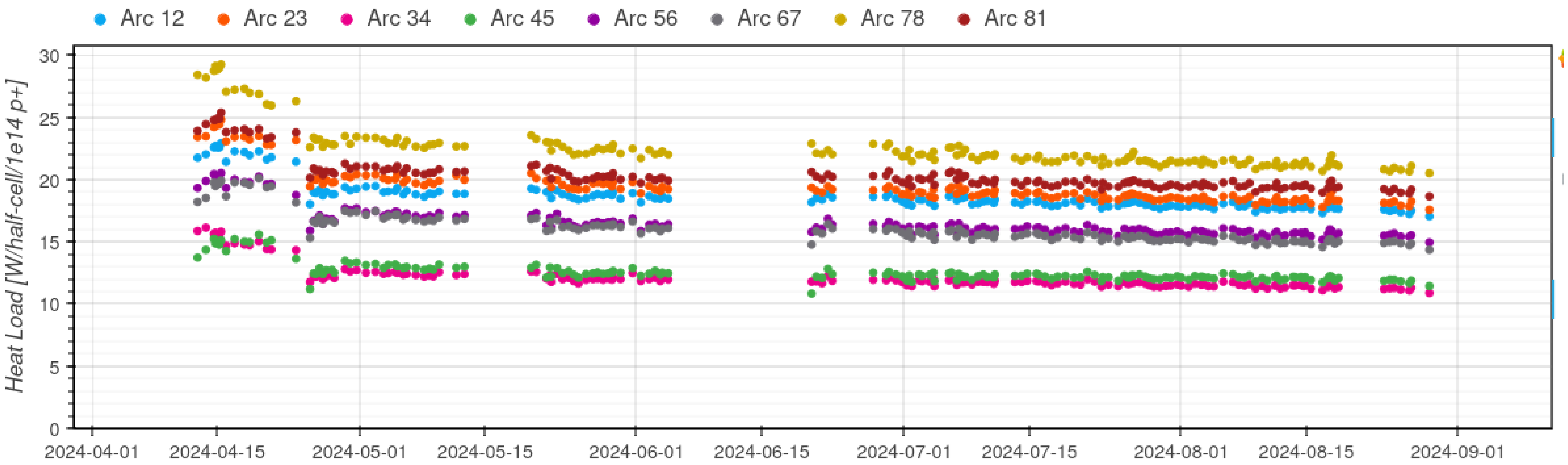
- 5% spikes flattened by increasing separation in parallel to beta* steps

→ experiments can approach pile-up limit – no trigger issues due to spikes





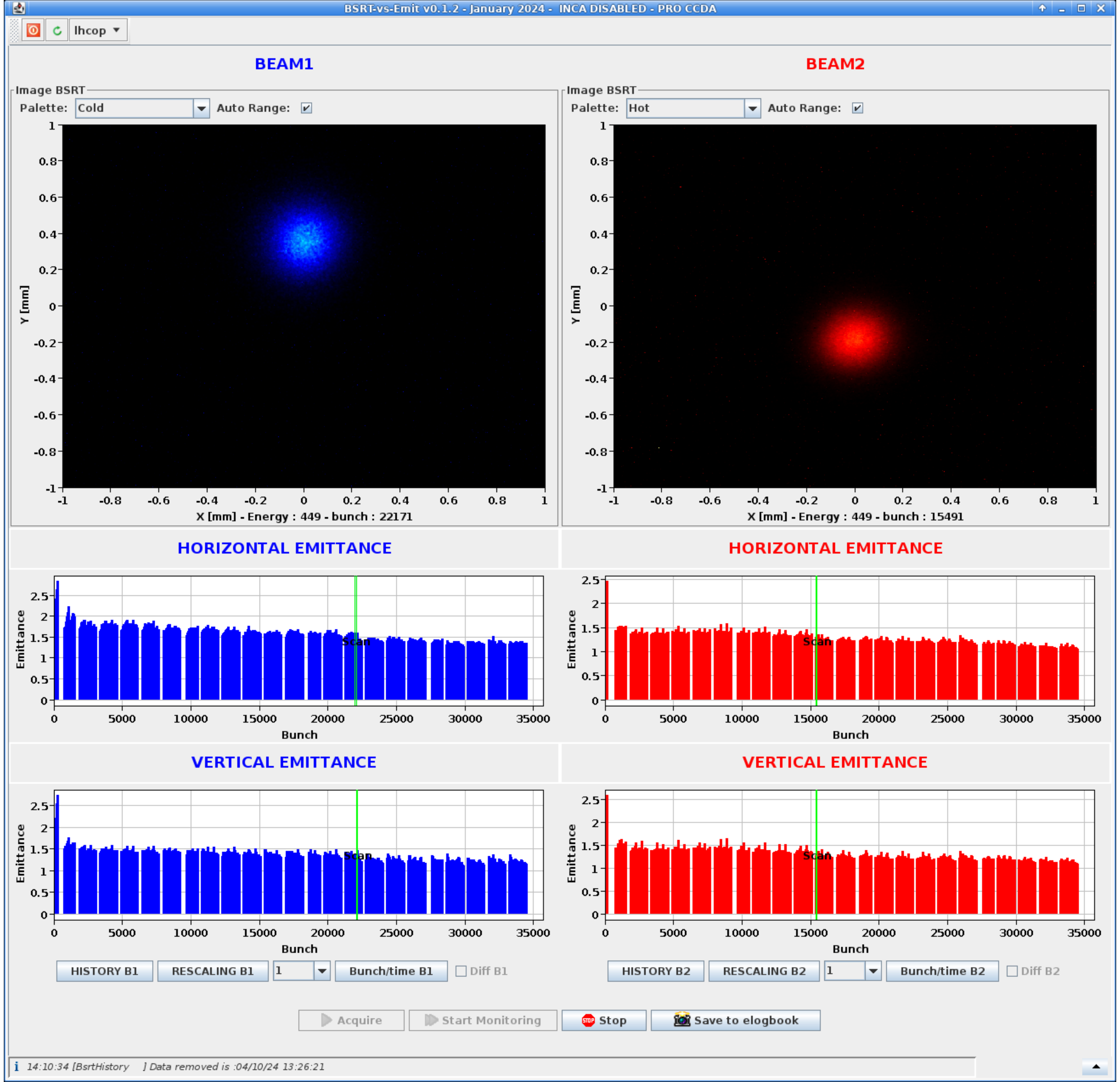
Electron cloud and heat load



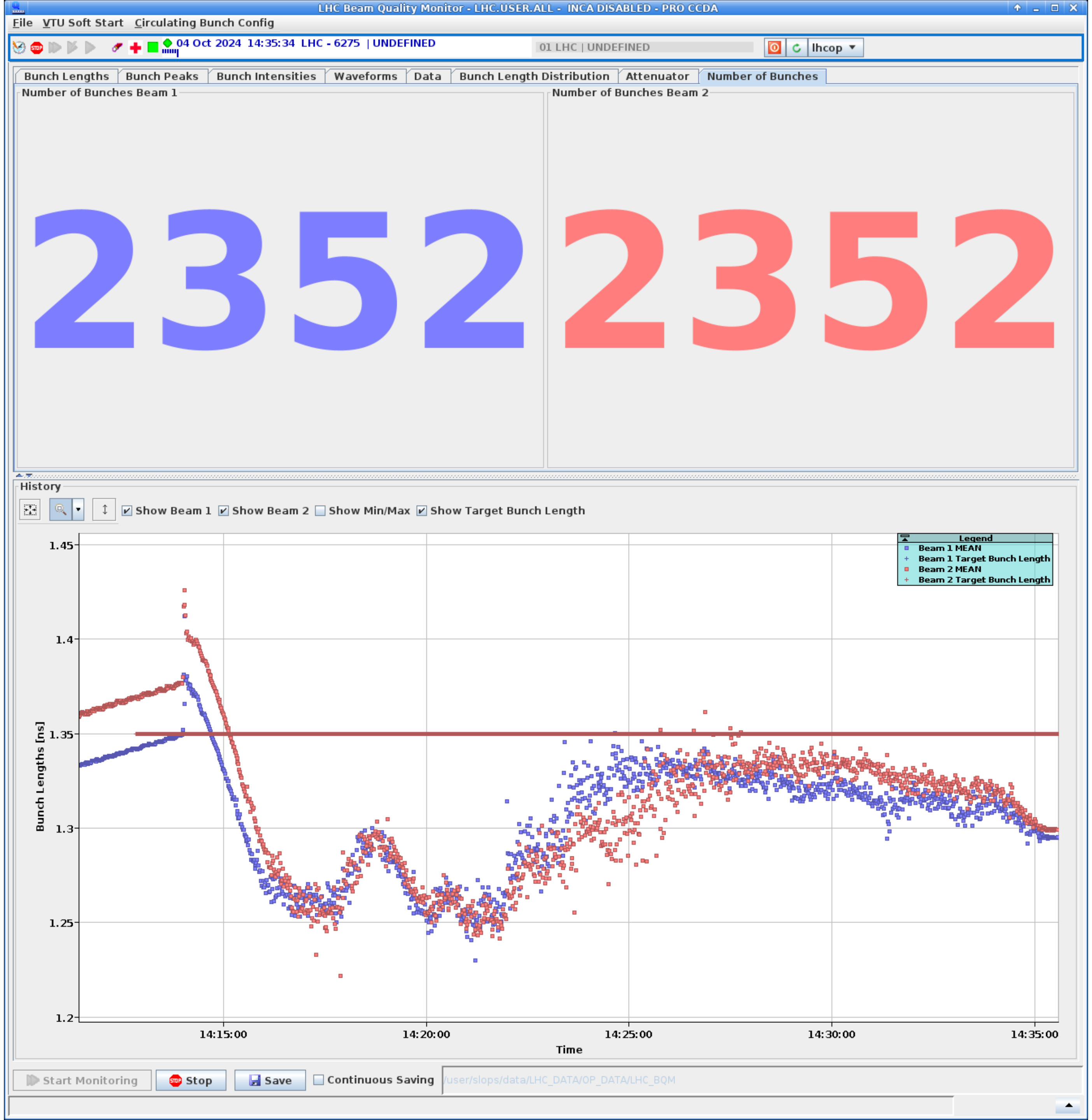
- **electron cloud induced heat-load: sector 7-8 limiting**
  - limits the train length and total number of bunches
  - 2024: 3x36b trains, 2352b total

→ **conditioning over 2024 gained ~5-10% margin**

Beam size at injection



Bunch length control in the ramp

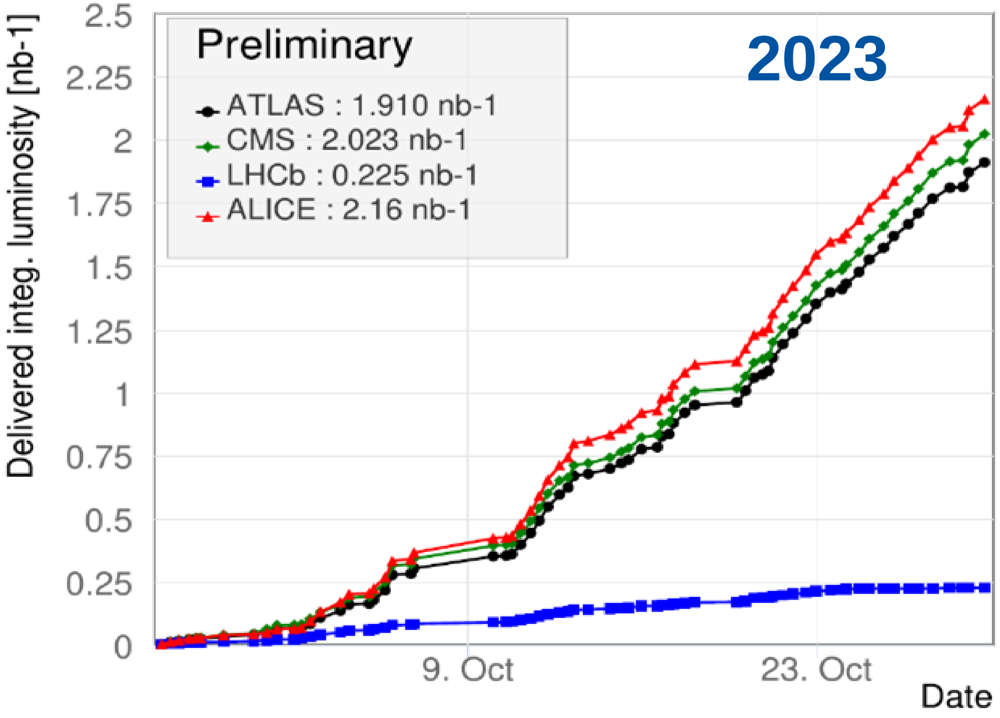


Lifetime in collisions above 30h for both beams

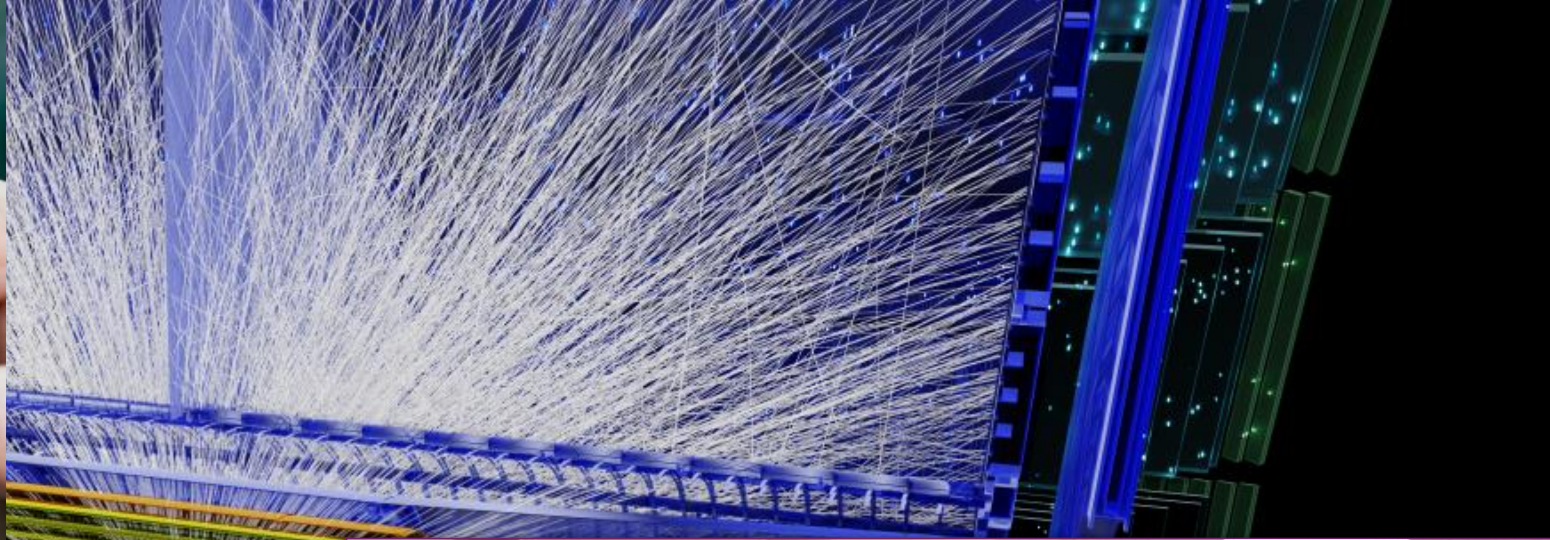
2024 heavy-ion run

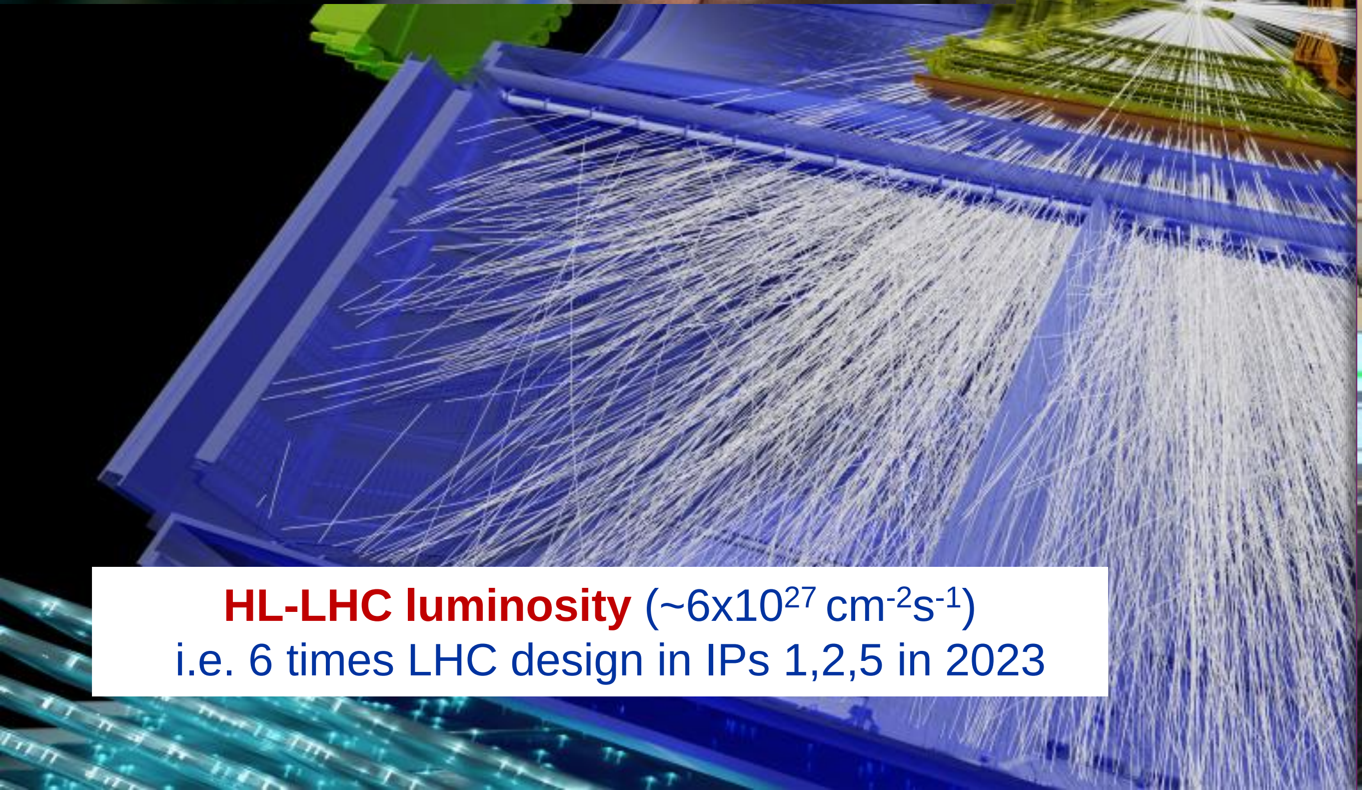
- **6 days of proton-proton "reference run"**
  - 2.68 TeV per beam, equivalent of 6.8 Z TeV Pb-Pb
  - luminosity targets:
    - ATLAS / CMS: ~300 pb^{-1}
    - ALICE: 4.5 pb^{-1}
    - LHCb: 100 pb^{-1}
- **17 days of Pb-Pb heavy ion run**
  - 6.8 Z TeV per beam - same configuration for Run 3
  - luminosity target:
    - 5.3 nb^{-1} in all Run 3 (2 nb^{-1} collected in 2023)
    - ~1.5 nb^{-1} in 2024
  - LHCb: full heavy-ion program
  - mitigations in place for 2023 issues (“10 Hz” losses, QPS)

→ challenging targets - challenge accepted!



R. Alemany, R. Bruce, F. Alessio, C. Young et al.

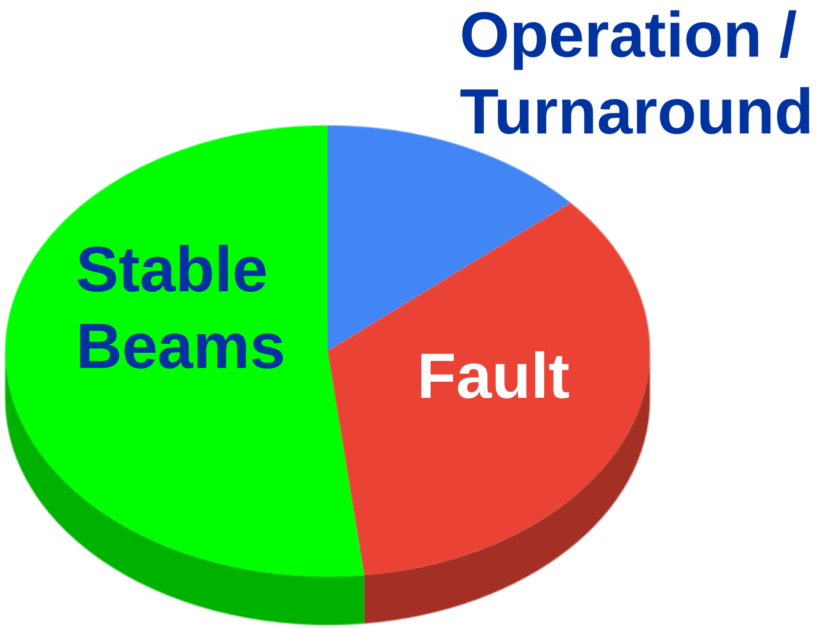


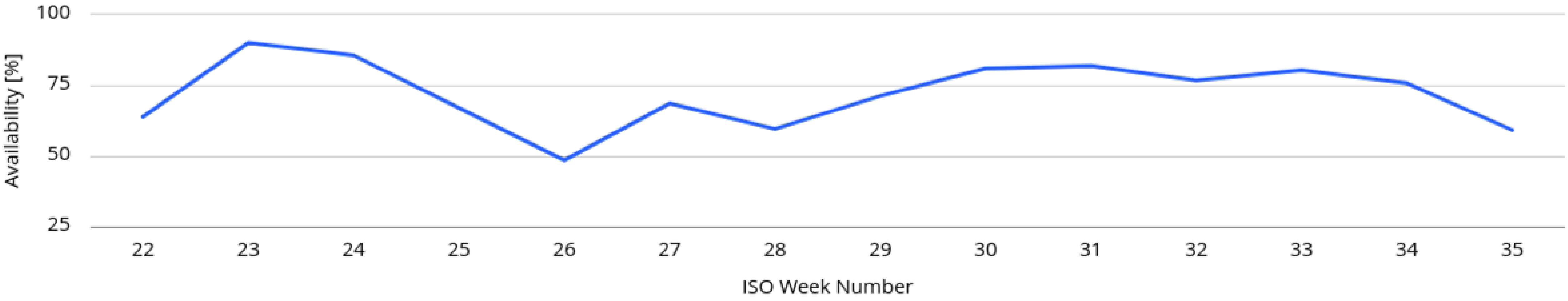


HL-LHC luminosity ($\sim 6x10^{27}\ cm^{-2}s^{-1}$)
i.e. 6 times LHC design in IPs 1,2,5 in 2023

Availability 2024

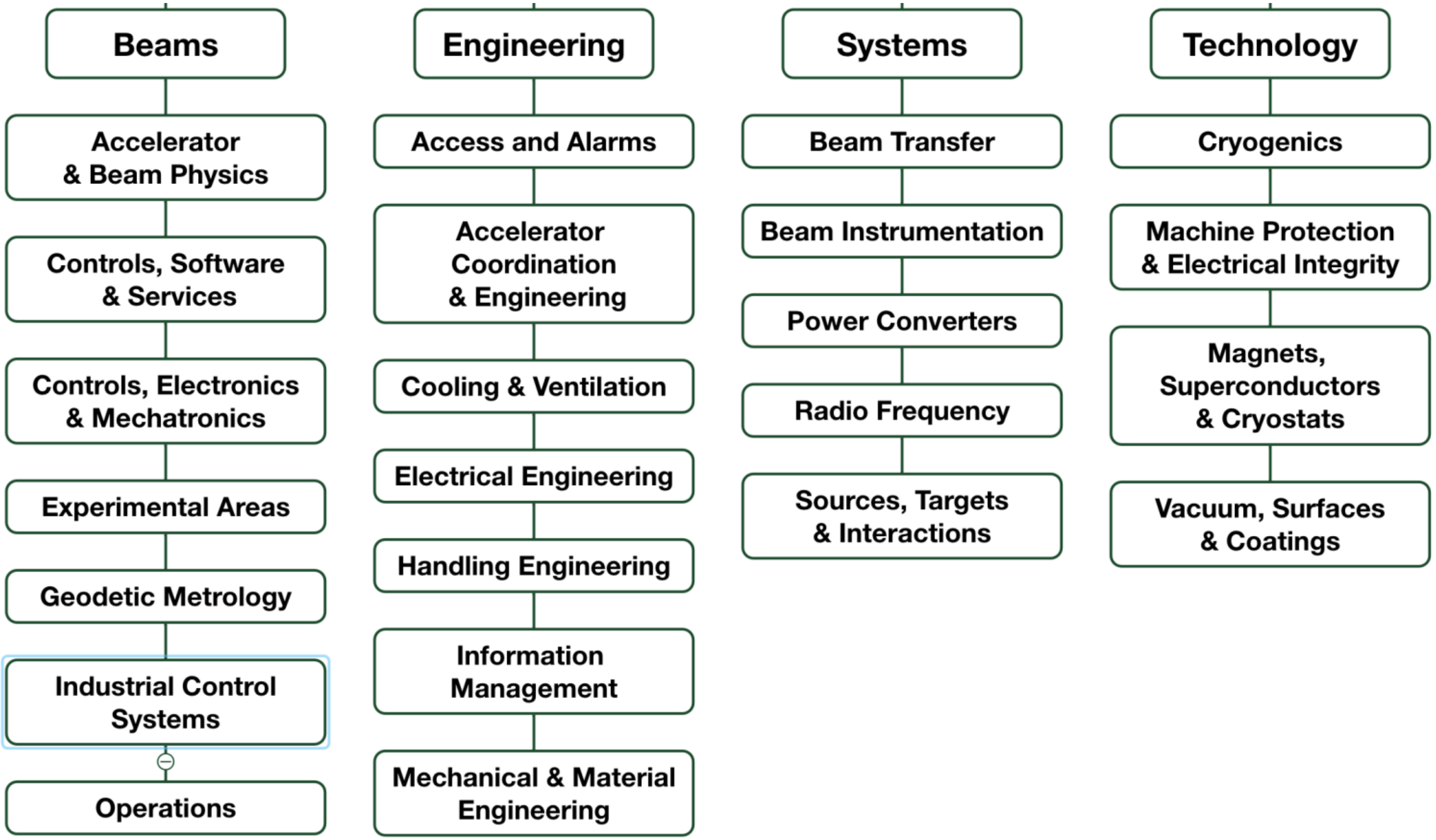
- **Availability is key!**
- **2022 & 2023 dominated by long faults**
  - 2022: RF burst disks
  - 2023: vacuum modules & triplet L8
- **2024: "good" weeks availability > 75%, stable beams > 60%**





2023 LHC cardiogram in the AFT tool

System performance



RF, power converters, collimators, beam dump system, projection devices, injection system, transverse feedback, machine protection

Cryogenics, Vacuum, Magnets, quench protection system & associated systems

Beam instrumentation and beam based feedbacks

Controls, network, servers, front-ends, middleware, databases, high level software

Survey, technical infrastructure, access system, radiation protection

Mature performance following sustained operations, issue resolution, technology advances deployed, functionality enhanced

Difficult to do justice to the commitment and effort that's gone in to getting, and keeping, the complex operational at the highest level

The challenge …

6084 Quench heater discharge power supplies

202 600 A energy extraction systems

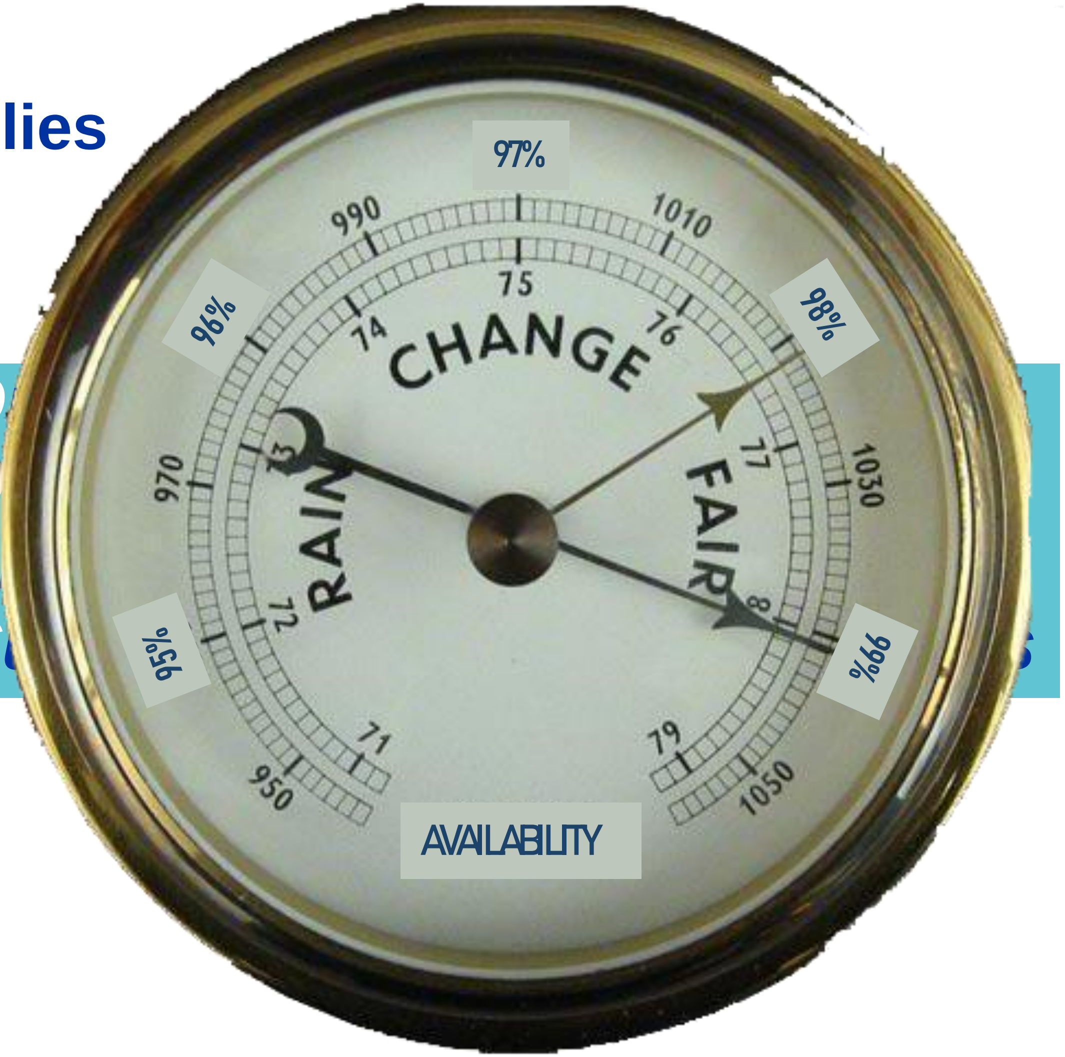
32 13 kA energy extraction systems

2282 Quench detection crates

9436 Quench detection systems

2582 Communication boards

1352 CLHS systems



12908 Hardwired interlocks to stop LHC at any time …

AFT call signs: QDS: QPS-CONTROLLER (TE-MPE-EP)
QPS&EE: QPS-HARDWARE (TE-MPE-MP)
CLHS: MAGNET CIRCUITS / CLHS (TE-MPE-PE)

Machine Development

Last week

G. Iadarola, G. Trad, J. Uythoven – LHC MD coordination

Many thanks to:
Injectors teams for preparing several challenging beams
LHC OP teams, machine coordination, equipment experts for their support
LHC Experiments for their collaboration
MD teams for the excellent preparation work and for their flexibility

MDs rescheduled from MD3

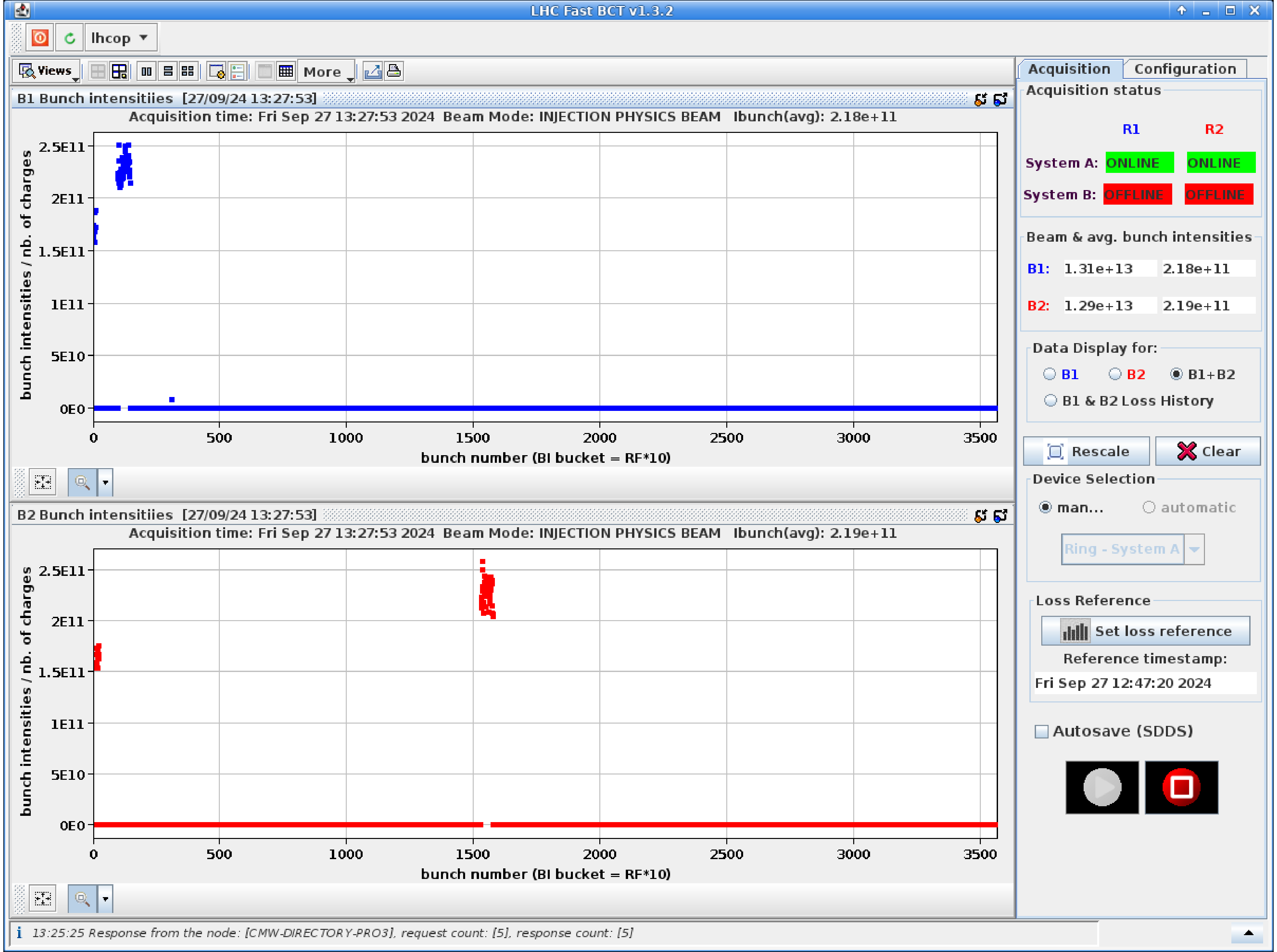
MD	Title	Topic
MD12743	**RF power limitations for high-intensity batches** • Inject and capture trains $2.3x10^{11}$ p/bunch (using max 350b per beam)	RF
MD6925	**Electron cloud coupled-bunch tune shifts at injection** • Characterize bunch-by-bunch tune shift from e-cloud up to HL-LHC intensities	e-cloud
MD12663	**Wire compensation during the beta*-levelling** • Test the use of wire compensation at different stages of the b* levelling (in operation wires are only powered at end of levelling)	Beam-beam

MD4 block – selected MDs

By way of illustration

MD	Title	Topic
MD13723	**Injection study: B1 mismatch mitigation with new QTL TFs** • Characterize injection mismatch with improved transfer function on transfer line quadrupoles (QTL)	Injection
MD9543	**Failing IR correctors and novel method to find local errors** • Test strategies to handle possible triplet corrector failures	OMC
MD11843	**Collimation performance with HL-LHC settings** • Characterize cleaning performance with collimation settings foreseen for the HL-LHC era	Collimation
MD12723	**HL-LHC optics cycle development (cont'd)** • Deploy optics corrections and remeasure • Characterize aperture and collimation performance	Optics dev.
MD13144	**Coronagraph resolution study** • Development of halo monitoring with synchrotron light	Instrument.
MD13463	**Chromaticity measurement in physics conditions with BTF and ADT-AC dipole** • Develop non-invasive chromaticity measurements for physics fills	Stability
MD13583 (in parallel with 13144)	**Improved tune-shift measurements at flat-top** • Investigating unexpected behaviour of tune-shift measurements vs collimator gaps observed in B1 (H plane) • Compare measurements from ADT kick vs ADT AC-dipole excitation	Stability
MD11789 & MD13403	**Optimized ramp** • Improve setup of longitudinal blow-up on PPLP ramp • Test optimized strengths interpolation between matched points	OP - Cycle optimization

2.3e11 ppb


LHC Fast BCT v1.3.2
lhcop
Views
More
B1 Bunch intensitiies [27/09/24 13:27:53]
Acquisition time: Fri Sep 27 13:27:53 2024 Beam Mode: INJECTION PHYSICS BEAM Ibunch(avg): 2.18e+11
bunch intensities / nb. of charges
bunch number (BI bucket = RF*10)
B2 Bunch intensitiies [27/09/24 13:27:53]
Acquisition time: Fri Sep 27 13:27:53 2024 Beam Mode: INJECTION PHYSICS BEAM Ibunch(avg): 2.19e+11
Acquisition
Configuration
Acquisition status
R1
R2
System A: ONLINE ONLINE
System B: OFFLINE OFFLINE
Beam & avg. bunch intensities
B1: 1.31e+13 2.18e+11
B2: 1.29e+13 2.19e+11
Data Display for:
B1 B2 B1+B2
B1 & B2 Loss History
Rescale
Clear
Device Selection
man... automatic
Ring - System A
Loss Reference
Set loss reference
Reference timestamp:
Fri Sep 27 12:47:20 2024
Autosave (SDDS)
13:25:25 Response from the node: [CMW-DIRECTORY-PRO3], request count: [5], response count: [5]

Watch out for…

2.3e11 ppb

Electron Cloud, mitigation foreseen - Beam Screen Treatment

Latent weaknesses (non-conformities or inadequate specifications) e.g. edge welded bellows, PIMs…

Impedance, beam induced heating etc.

Radiation to electronics (increased luminosity, intensities)

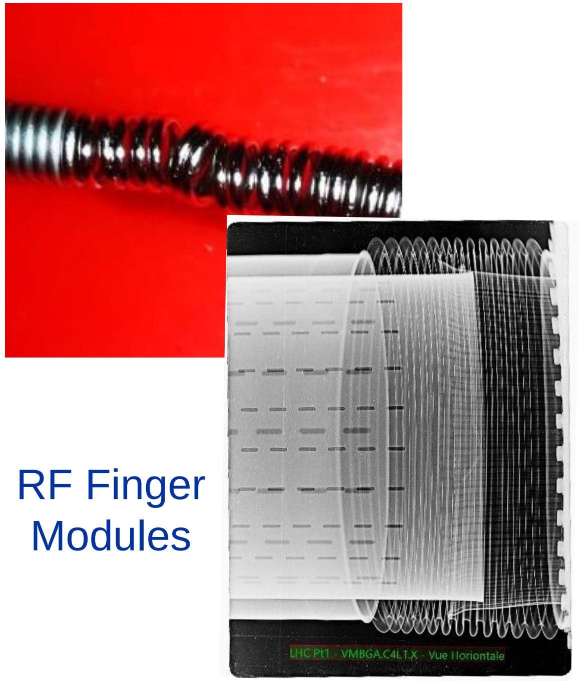
Injection losses, losses at start of ramp, RF power limitations

Energy management

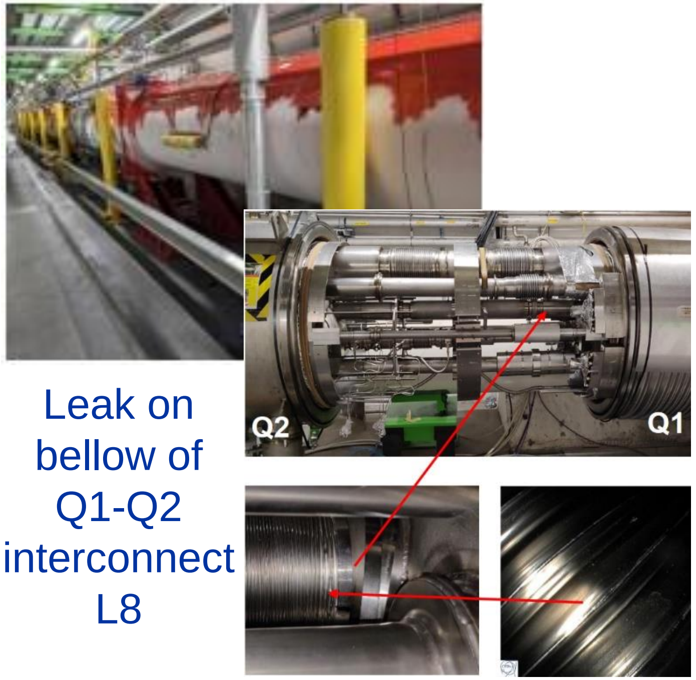
Weasels

Is the LHC Falling Apart?

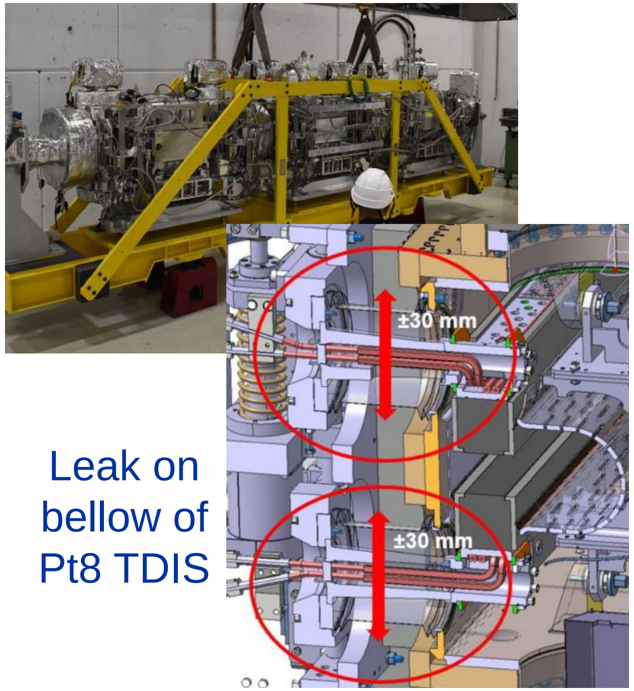
RF Burst Disks



RF Finger Modules



Leak on bellow of Q1-Q2 interconnect L8



Leak on bellow of Pt8 TDIS

- **2023 long faults caused by latent weaknesses (non-conformity or inadequate specifications)**
  - No direct link to long-term ageing of components
  - 2 of the 4 issues were on equipment installed or changed in LS2
- **Mitigation strategies now defined & implemented**
- **Crucial to ensure current (& future) hardware is fit for the HL-LHC era**
  - In particular that they can cope with the higher beam intensities foreseen


Weasel Patè
Delicious and soft
Cooked with 88KV
Perturbingly good!

LHC Performance 2024

Fantastic achievement, highlighting the outstanding performance of the LHC and the entire accelerator complex and its technical infrastructure. This goes deep.

- Back to original design and construction, and installation
- 19th September 2008 and the collective response
- Extensive consolidation in the LSs that followed: LS1 SMACC (splices, magnets, feed-boxes, R2E); LS2 DISMAC++, LIU…

And on the back of all the work that goes into maintenance, consolidation, upgrades, improvements, monitoring, and everything that is done in the LS, and technical stops

The operational mastery of the machines and facilities themselves and all their many systems - modern technology and engineering advances being leveraged - truly impressive across the many domains of expertise.

Things inevitably go wrong, but there is remarkable reactivity and commitment to problem resolution when it does.

Summary

The LHC has moved into a mature exploitation phase and is enjoying the benefits of the decades long international design, construction, installation, commissioning effort - it's clear that the foundations are good.

Its present performance is worthy reflection of this effort and the huge amount of experience and understanding gained and fed-forward over the last years.

Progress represents a sustained effort by all the teams involved.

Not only can you operate a 27 km superconducting collider, but you can do it spectacularly well.

This is rather special!!!