Status of LHC Run 3 operation and lessons learned

R. Bruce, on behalf of the LHC team

Special thanks to J. Wenninger for material

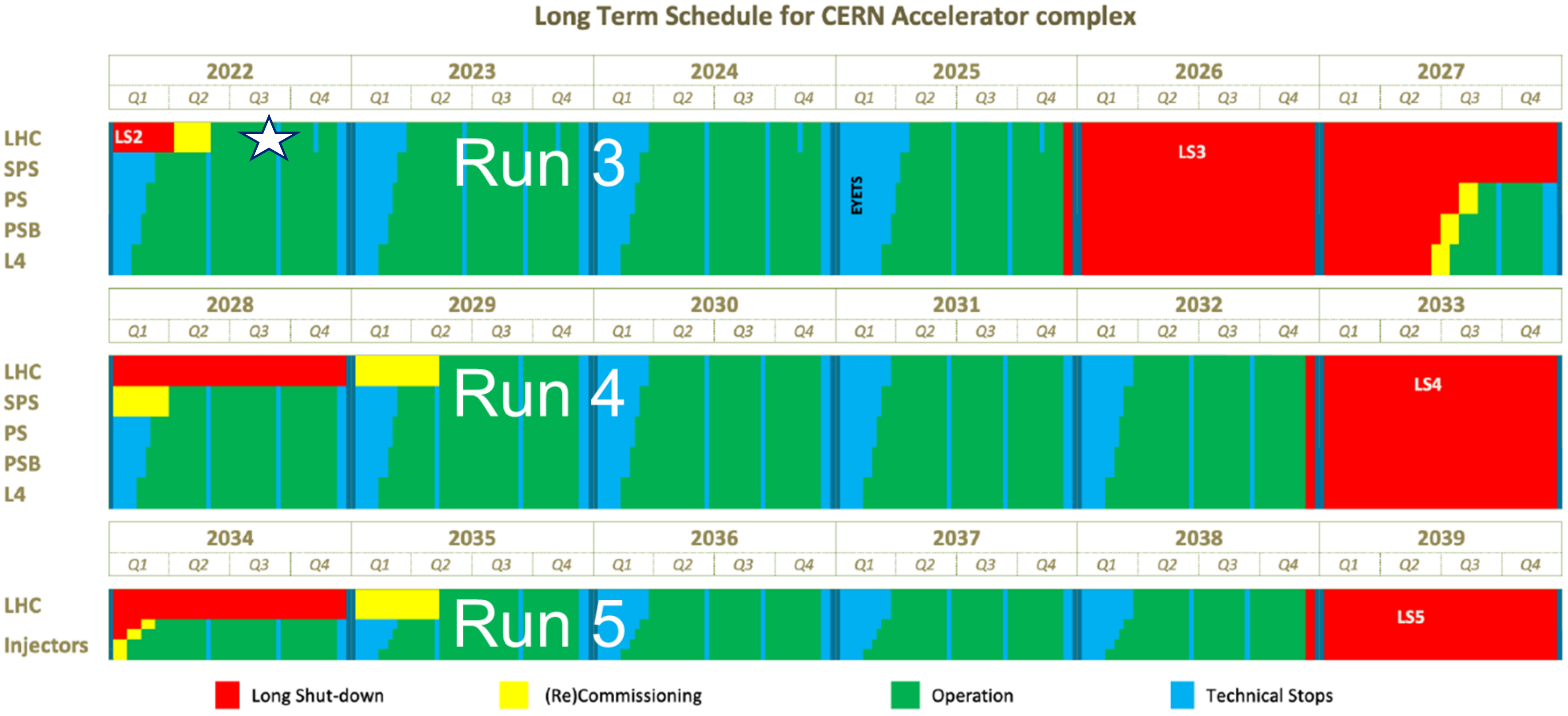
Based on inputs from: H. Bartosik, O. Bruning, A. Calia, M. D'Andrea, S. Fartoukh, L. Giacomel, P. Hermes, G. Iadarola, S. Kostoglou, M. Lamont, A. Lechner, E.H. Maclean, L. Mether, Y. Papaphilippou, S. Redaelli, G. Rumolo, M. Solfaroli, G. Sterbini, R. Tomas, A. Verweij, M. Zerlauth

Outline

- General plans and goals for Run 3
- 2022 startup and achieved performance
- Encountered limitations
- Commissioning and machine development for HL-LHC
- Conclusions

LHC long-term plan

- **LHC coming out of LS2**
  - consolidation works, e.g., on bypass diodes
  - New hardware installations for HL-LHC (injection protection, collimators, machine-detector interface)
- **Run 3 operation started in 2022**
- **Recent schedule changes:**
  - Extension of LHC Run 3 by one year until the end of 2025
  - Extension of Long Shutdown 3 (LS3) to 3 years (for LHC)



Reference: EDMS 2311633

Goals and constraints in Run 3 proton operation

- **Increased beam energy from 6.5 TeV to 6.8 TeV**
  - Initial magnet training to 7 TeV: bypass diode failure and an inter-turn short requiring thermal cycles in S23 and S78
  - Following risk analysis, target beam energy reduced to 6.8 TeV (limit quenches => limit risk for another thermal cycle)
- **Operational constraints:**
  - Limited triplet lifetime due to radiation dose – need to optimize energy deposition from luminosity
  - Need to level ATLAS/CMS luminosity at about 2×10^{34} $cm^{-2}s^{-1}$ due to cryogenic capacity, pileup <60
- **Max Run 3 LHC bunch intensity: 1.8×10^{11} p/bunch, ~2750 bunches (BCMS beam). Limitations:**
  - RF power at injection
  - the beam dump core/absorbers integrity – will be refined by observations during Run 3
  - heating of the injection kickers
  - Potential limit from cryogenic capacity and heat load

Run 3 operational scenarios

- **Optimized operational scenarios for 2022 and 2023-2025 worked out in dedicated Run 3 working group**
  - References: *S. Fartoukh et al*, *CERN-ACC-2021-0007*, *Chamonix* *talk* *S. Fartoukh*
  - Rely on β*-levelling and crossing angle anti-levelling in IR1/5 – will gain important experience for HL-LHC
  - Separation levelling in IP2/8

- **Predicted integrated luminosity:**

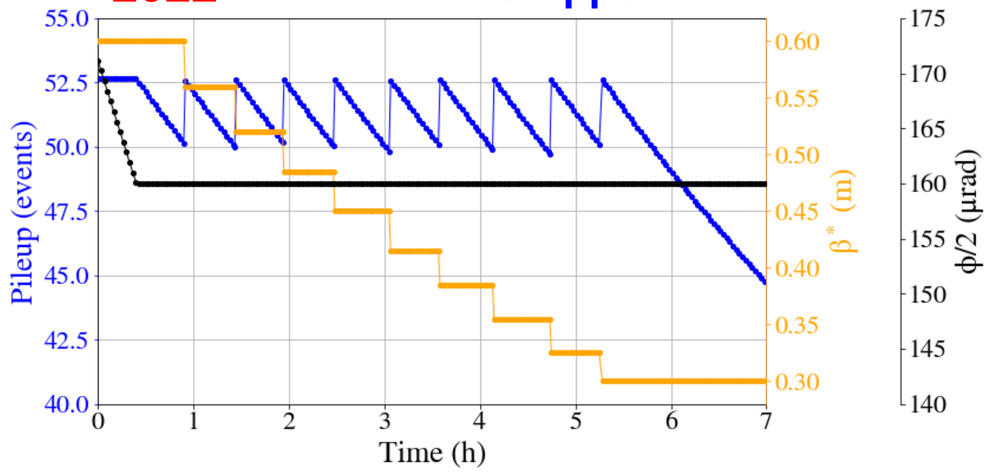
Year	Efficiency η_{eff} (%)	∫L (fb^{-1}) / year
2022	25%	≈30
2023-25	40%	85-90

$$\eta_{eff} = T_{SB} / T_{OP}$$

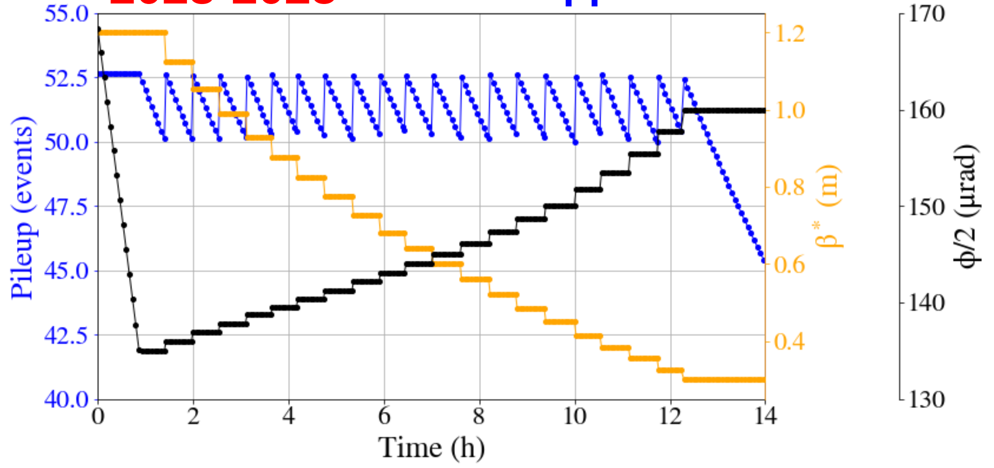
- **In total, could integrate ~290 fb^{-1} at ATLAS/CMS until the end of 2025**

Simulations; *S. Kostoglou*

2022 **1.4×10^{11} ppb**

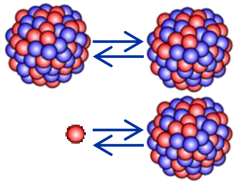


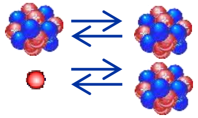
2023-2025 **1.8×10^{11} ppb**

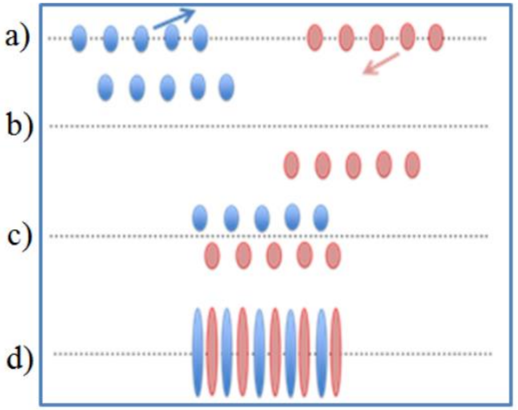


Heavy ions in Run 3

- **As in Run 1-2, about one month per year allocated to heavy-ion running.**
  - Pb-Pb in 2022, 2023, 2025
  - p-Pb in 2024
  - In addition, short (~1 week) pilot run with O-O and p-O. In 2024?
  - This planning is presently being reviewed – see later





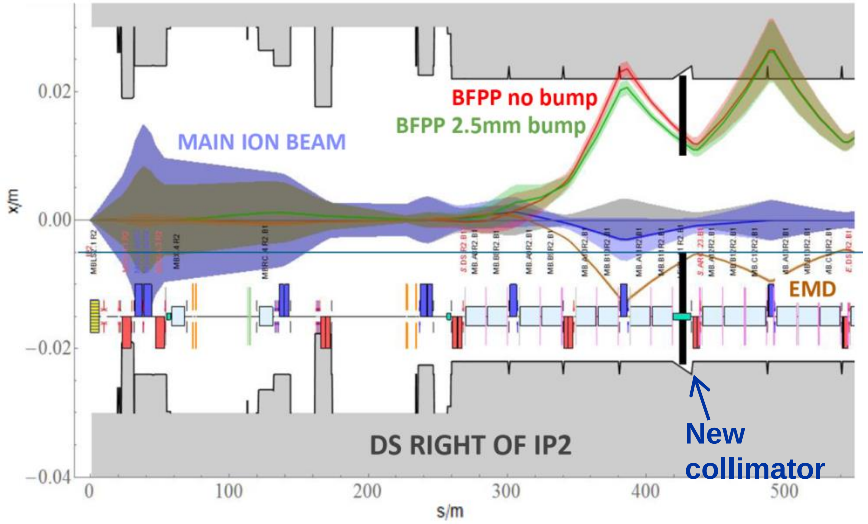


SPS slip-stacking

- **Foresee about 70% more Pb bunches in LHC than in Run 2, thanks to slip-stacking in the SPS**
  - Decreased bunch spacing of 50 ns (had 75 ns in 2018), relies on SPS RF upgrades done in LS2

- **Higher luminosity and intensity – losses more critical**
  - Collisional losses – alleviation by TCLD collimators
  - Halo losses – rely on crystal collimation

HL-LHC upgrades implemented in LS2 and upcoming YETS 22/23



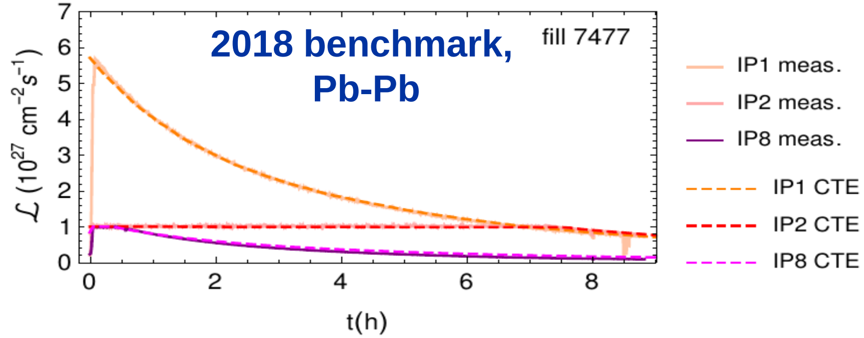
Operational scenarios for heavy-ions

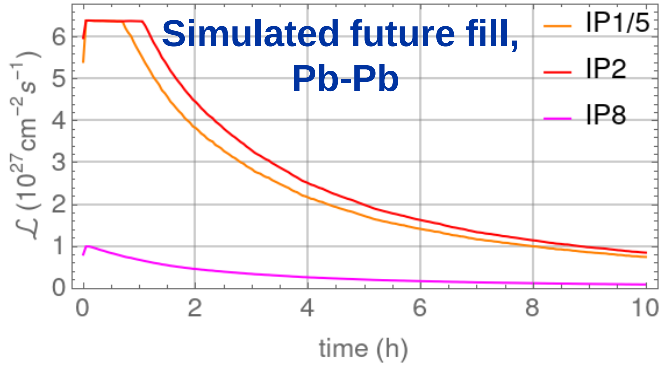
- **Significant performance improvements from Run 2**
  - Target: achieve more than a factor 6 higher luminosity at IP2 than in 2018

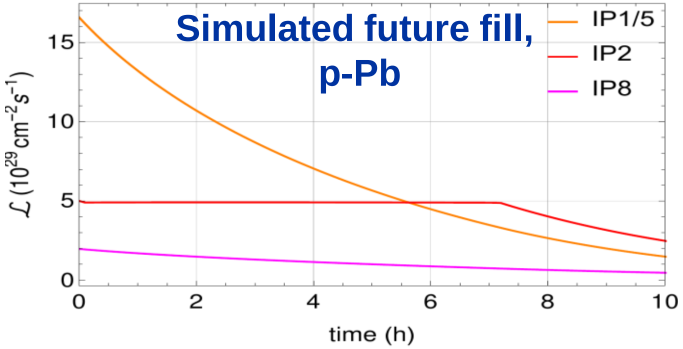
- **Predicted performance in a 1-month run with new 50 ns beams (assuming 19 days of physics)**
  - For Pb-Pb: (depending on filling scheme)
    - ~1.7-2.1/nb at IP1/2/5
    - Up to 0.4/nb at IP8
  - For p-Pb: (depending on filling scheme)
    - ~300/nb at IP2
    - ~375-620/nb at IP1/5
    - up to ~120/nb at LHCb

- **Main HL-LHC upgrades implemented in LS2 – the target is to reach HL-LHC performance for Pb operation already in Run 3!**

References:
Chamonix talk R. Bruce,
CERN-ACC- 2020-0011







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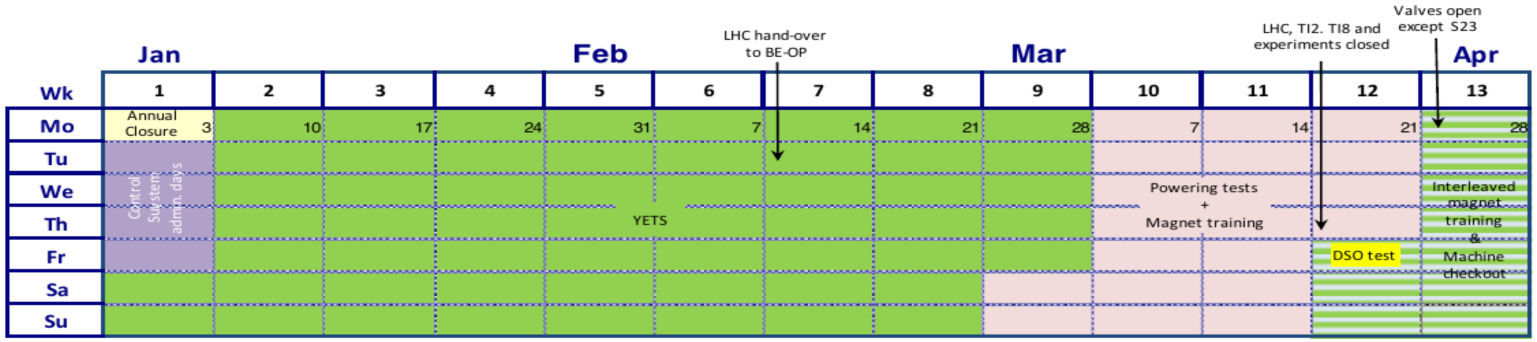
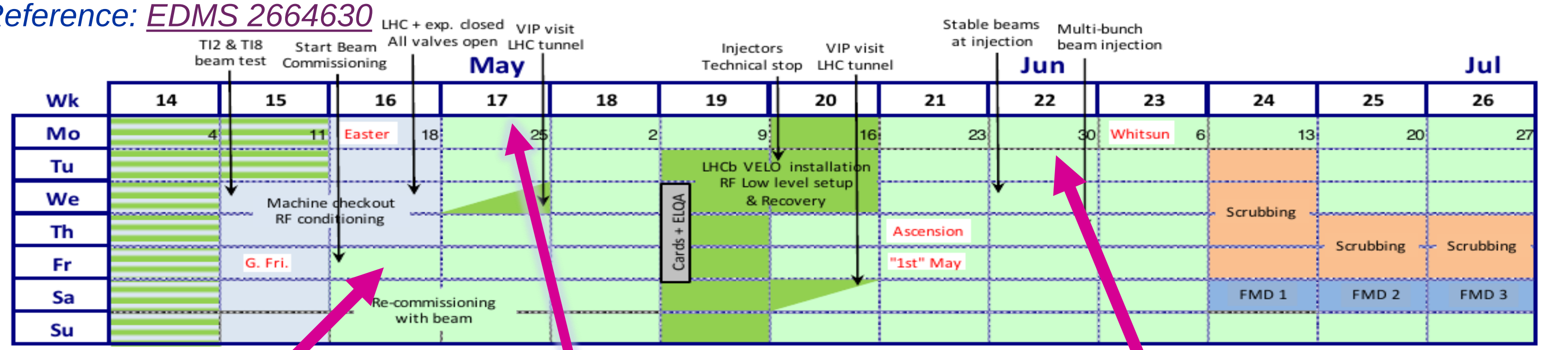
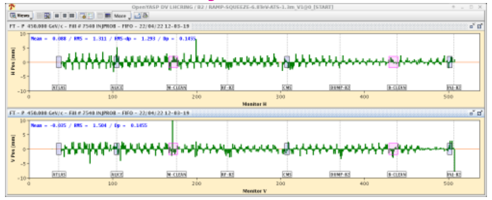
Beam commissioning 2022 – Q1 and Q2



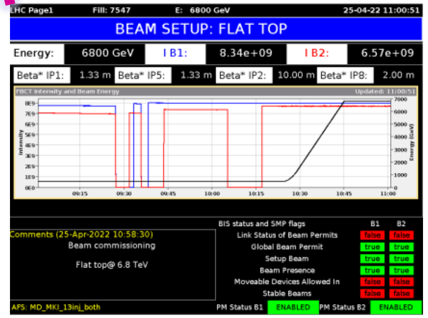
Reference: EDMS 2664630



April 22nd
First beam injection



April 25th
First protons at 6.8 TeV



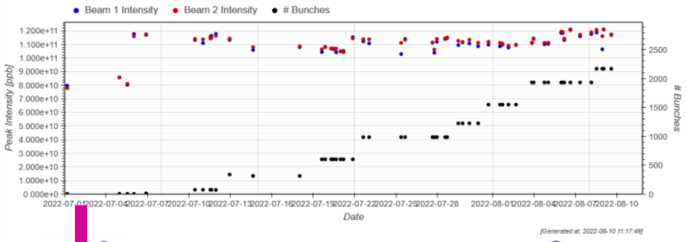
June 1st
Collisions at 6.8 TeV

- Initial delay: availability of LHCb VELO for installation, RF rupture disk failure following loss of cryo conditions
- Start of beam commissioning just after Easter
- Commissioning interleaved with scrubbing and machine development (floating MD)

LHC operation 2022 – Q2 and Q3

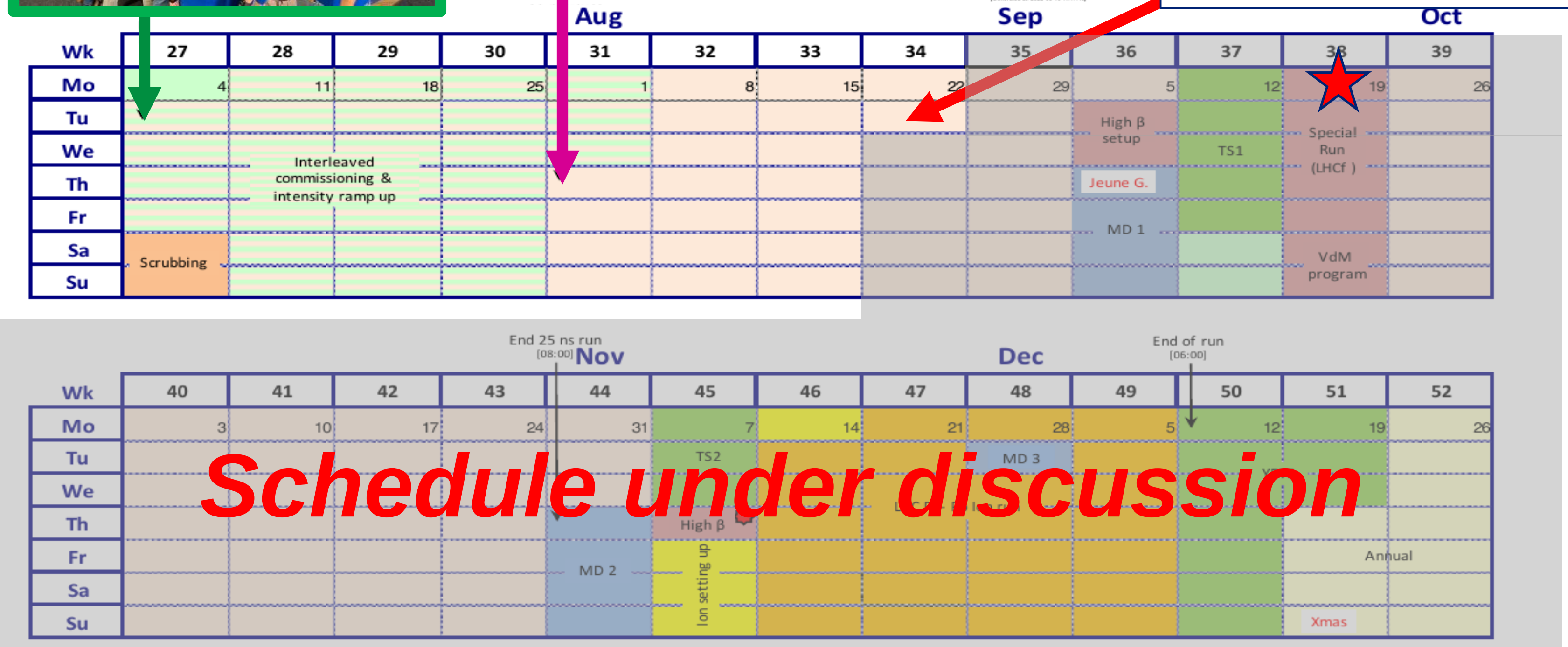
July 5th
Start of Run 3 physics

August 3rd
> 2000 bunches



August 23rd

Accidental cooling tower stop leads to helium release from RF cavities, failure of RF rupture disks – warm up and conditioning of RF cavities required – 3 weeks lost



- First stable beams and media event on July 5th
- Intensity ramp-up with good luminosity production in spite of some issues
- Beam expected back tomorrow after incident and RF conditioning
- In addition, 2022 run to be shortened by 2 weeks due to energy crisis
- **Schedule for the rest of the year, as well as coming years in Run 3, being re-discussed**

Injector status

- **Protons: excellent progress on LIU / HL-LHC beams in the injector chain**
  - PSB and PS have completely fulfilled LIU specifications - ramp-up now only concerns the SPS
  - Presently on track for LIU ramp-up schedule; dump kicker vacuum behaviour being studied for further ramp-up
    - Present limitations being worked on: vacuum spikes in SPS dump and injection kickers; beam tails; losses at LHC injection

Reference: IPP talk C. Zannini

Intensity [p/b]	Emittance H/V at FB end [µm]	#bunches	Bunch length [ns]	Beam type
1.4e11	1.4/1.2	5 x 48	1.65	BCMS
1.52e11	1.8/1.7	4 x 72	1.65	Standard
1.85e11	1.9/1.7	1 x 72	1.65	Standard
1.7e11	1.6/1.5	5 x 48	1.65	BCMS
1.8e11	1.7/1.6	2 x 48	1.65	BCMS
1.8e11	1.7/1.6	5 x 48	1.9	BCMS

Operational (first row)

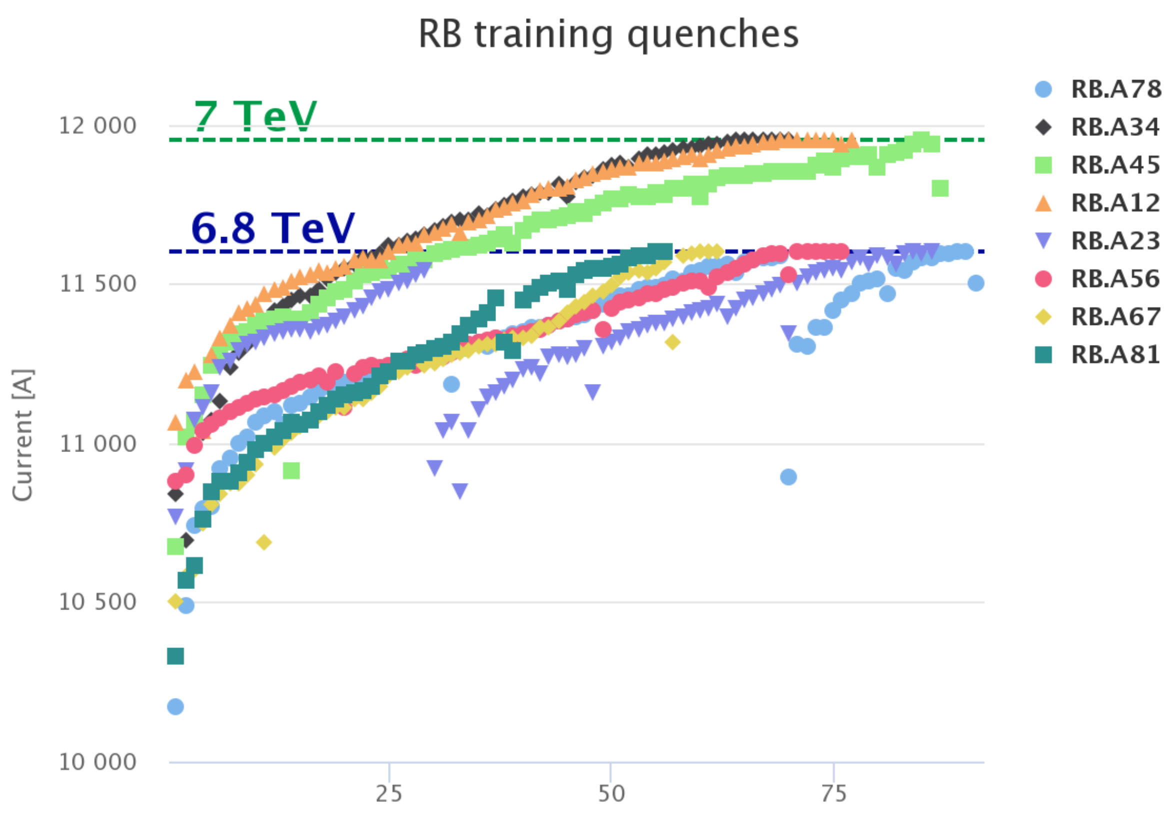
Perspective for high intensity MDs (remaining rows)

- **Achieved beam performance is more than what the LHC can presently take – see later**

- **Pb ions: Beams on track – commissioned to the end of the PS in 2022; pending SPS commissioning**

Magnet training campaign

- **Magnet training in 2021 and 2022**
  - 605 primary training quenches on dipole circuits
  - 3 sectors trained to 7 TeV
  - 5 sectors trained to 6.8 TeV
- **Some circuits showed much longer training than in previous campaigns – to be monitored**
  - RCBCH/V (likely due to radiation),
  - RQSX3 (possibly due to radiation),
  - RQ5 and RQ6 circuits operated at 4.5 K and containing MQM-type magnets
- **During beam operation, 13 training quenches occurred at flat-top in the main dipole magnets**
- **Additional powering, 100 A above nominal current, done in last weeks during beam stop**

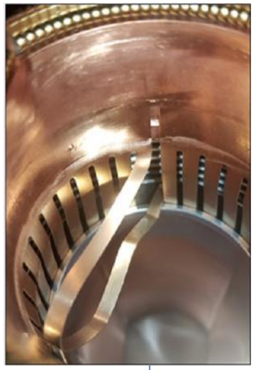


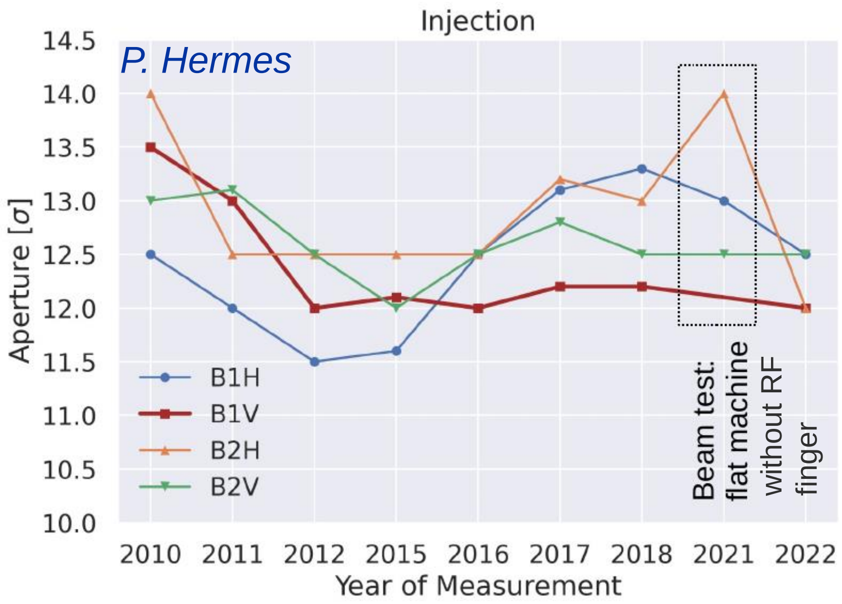
Reference: LMC talk by A. Verweij

Beam aperture

- **Reminder: 2021 beam test at injection showed high losses in cell 21L3**
  - Turned out to be a buckled RF finger, warm-up and intervention required

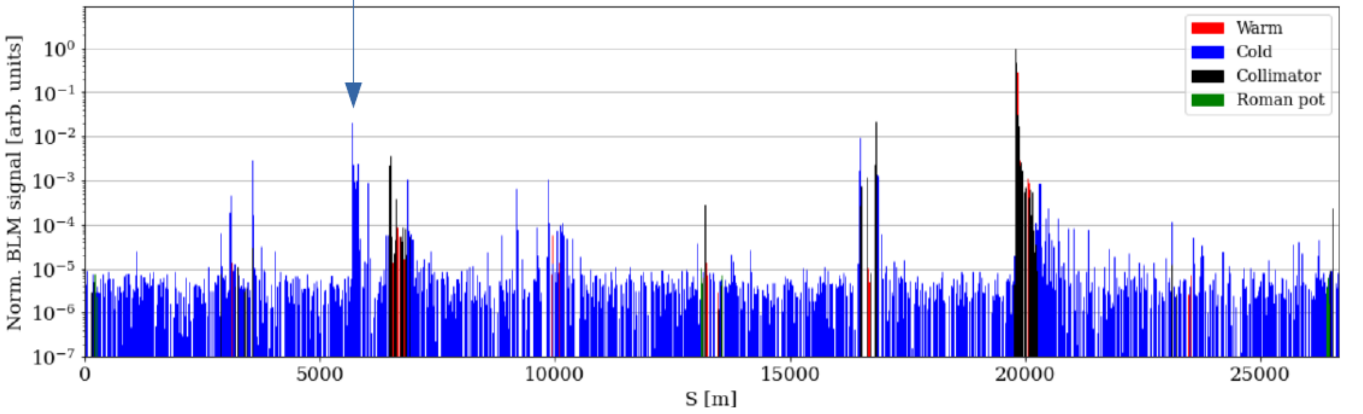
- **Loss maps and aperture measurements in 2022 commissioning: all looks good**



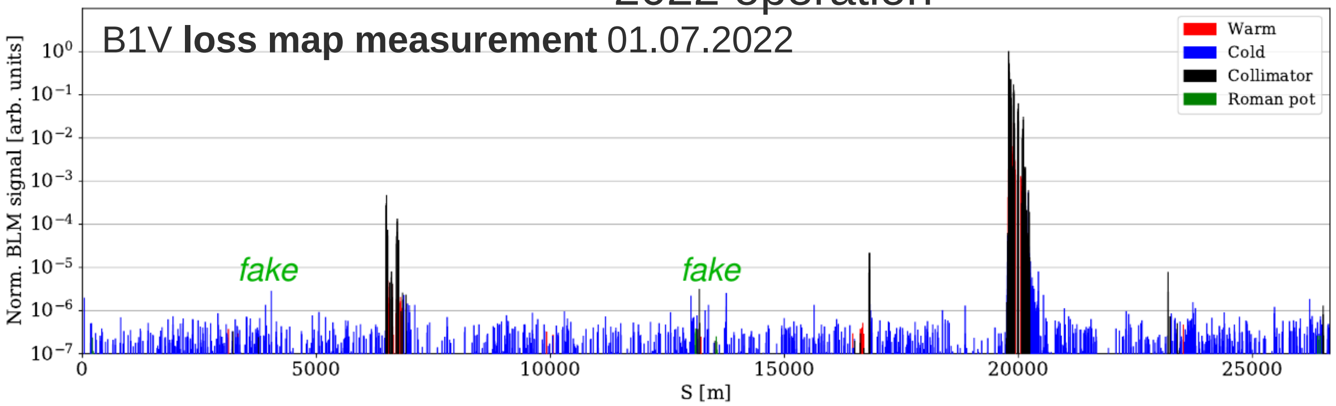


2021 Beam test

B1V **loss map measurement** 26.10.2021 22:22:01



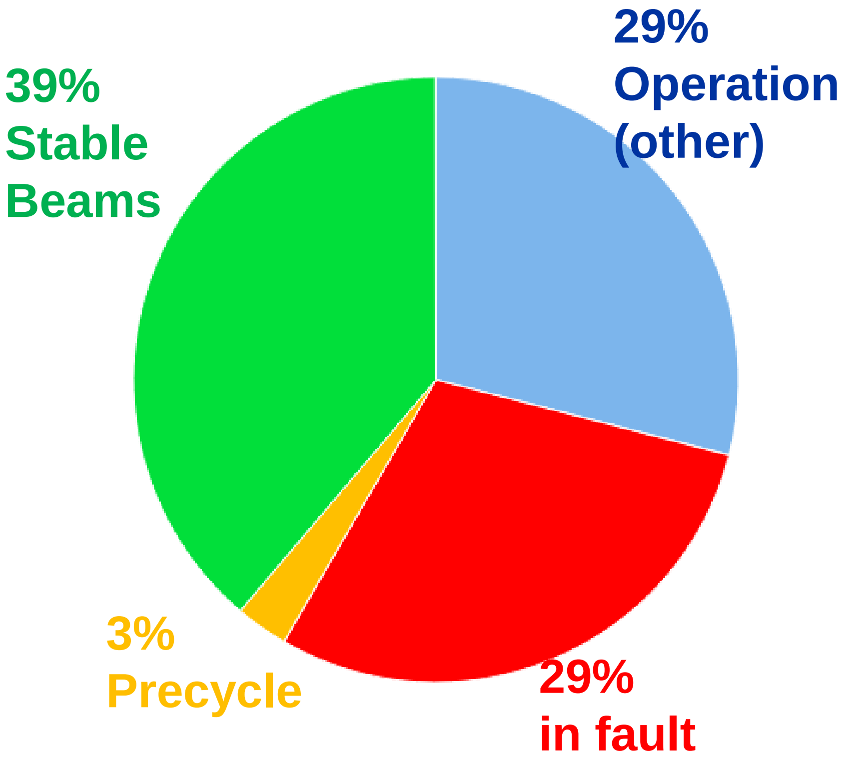
2022 operation



LHC availability

- **In the four weeks before the incident on 23/8:**
  - 71% availability
  - spent 39% of the time in stable beams
- **Sometimes excellent turnaround – just over 2h in many cases**
- **Some faults and causes of downtime:**
  - Cryogenics and cooling tower incident on 23/8/2022
  - Injector complex
  - UFOs
  - Training quenches in operation
  - RF trips, klystron replacement
  - Electric perturbations
- **Beam lifetime statistics to be followed up by end of 2022**

LHC availability 23/07/2022 – 23/08/2022
Source: aft.cern.ch

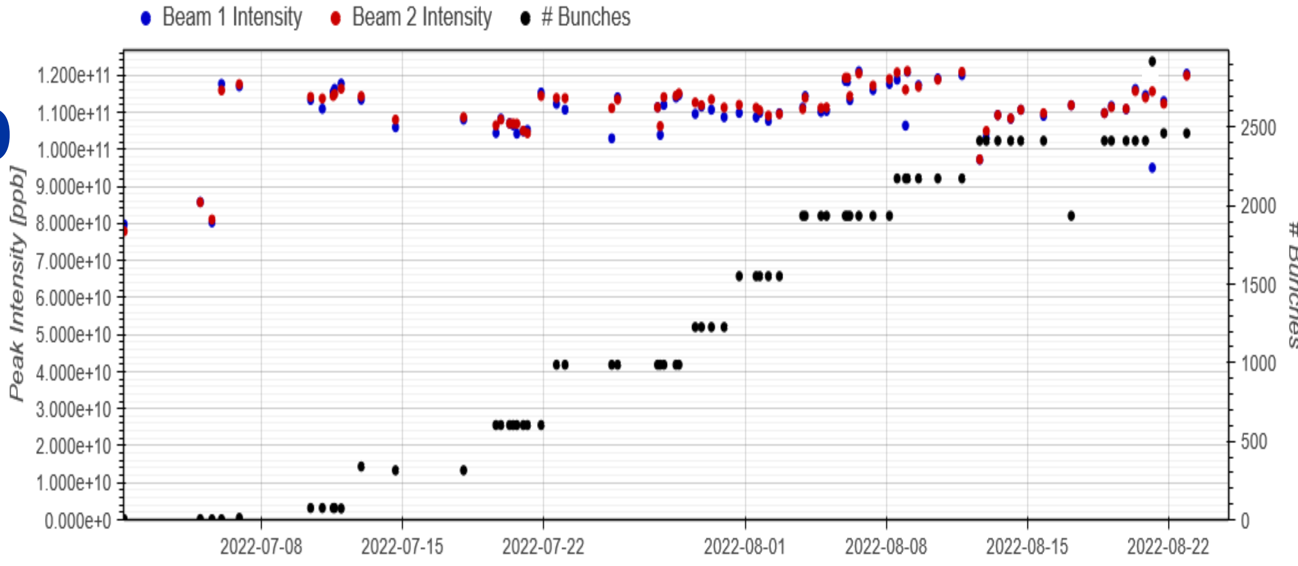


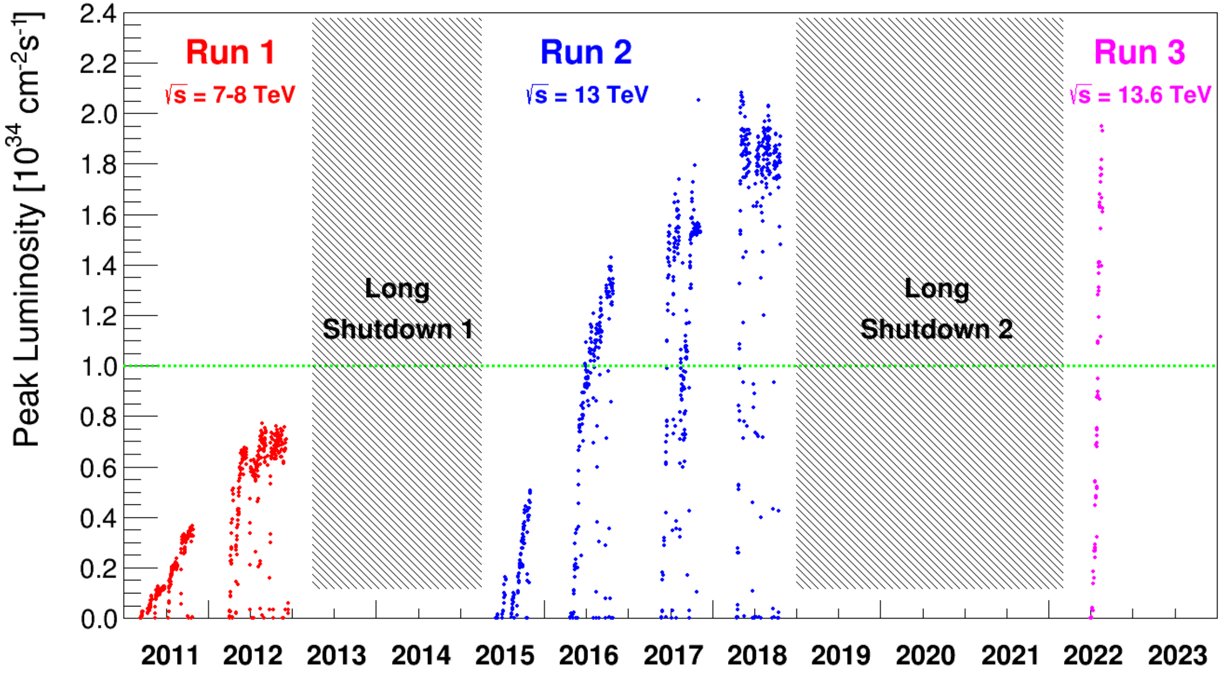
LHC performance ramp-up

- **Startup strategy: increase number of bunches at 1.2×10^{11} p/bunch until machine is full, then push bunch intensity towards 1.4×10^{11} p/bunch**

- **Very steep ramp-up of intensity and peak luminosity**
  - Not far from 2018 performance only after 1.5 months
  - Peak luminosity almost within target already
  - Reflects the excellent understanding of how to optimize and operate LHC

- **Intensity presently limited by electron cloud – see later**

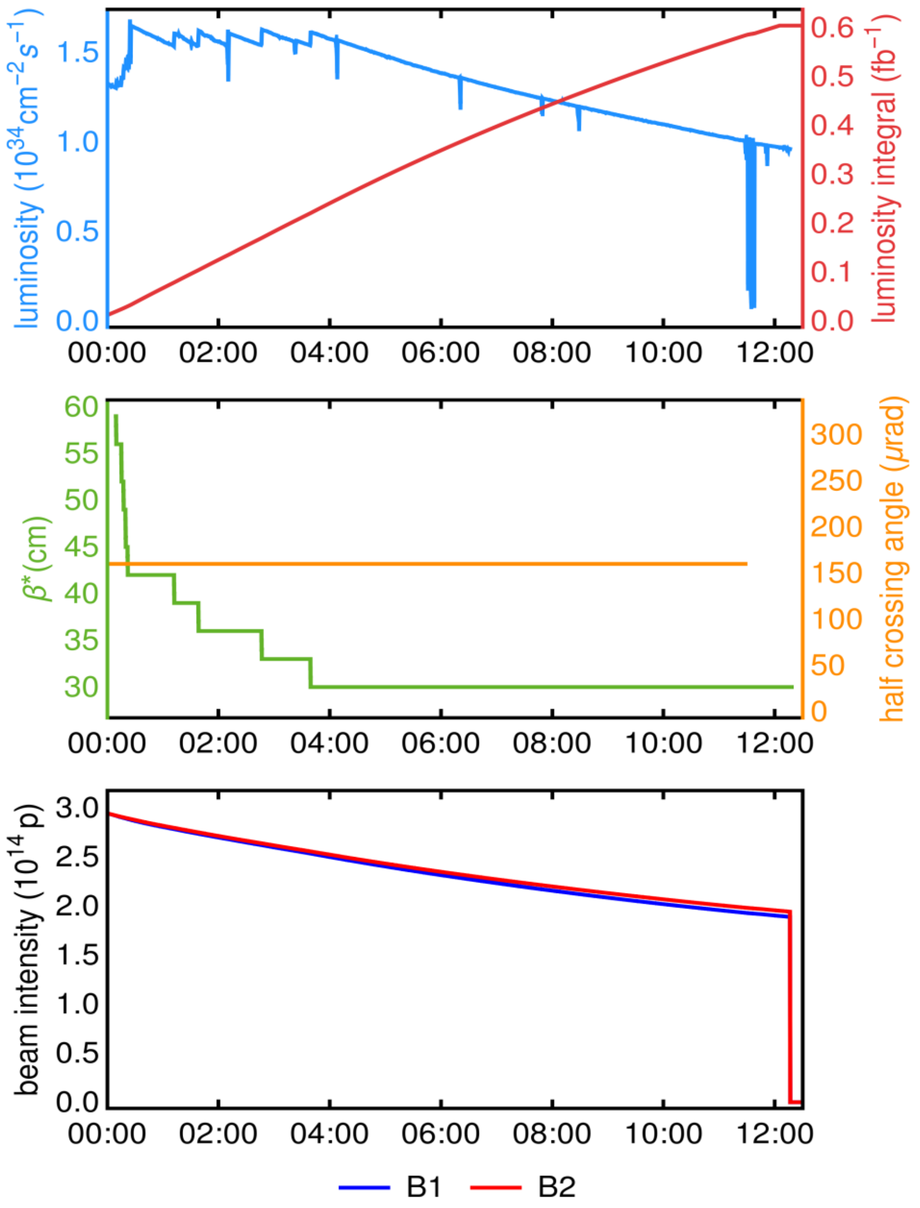




LHC performance in recent fills

- **In spite of limitations, very good performance demonstrated**
- **Could regularly collect 0.5 fb^{-1} or more per fill**
- **β*-levelling used very successfully**
  - Levelling over 30 cm range, compared to 5 cm in 2018
  - Telescopic optics used in levelling – also larger than before
  - Very important milestone for HL-LHC

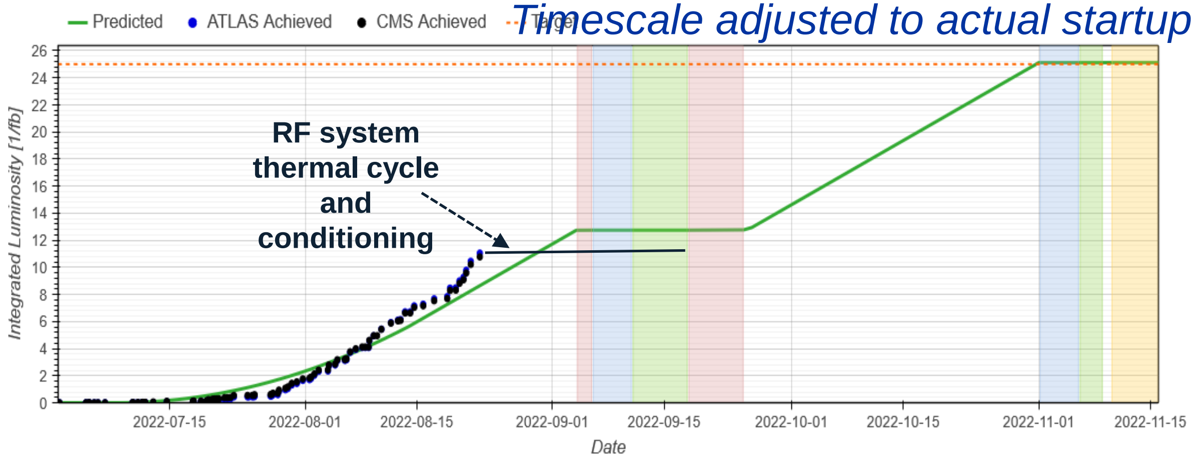
Recent fill (8151) – August 23rd

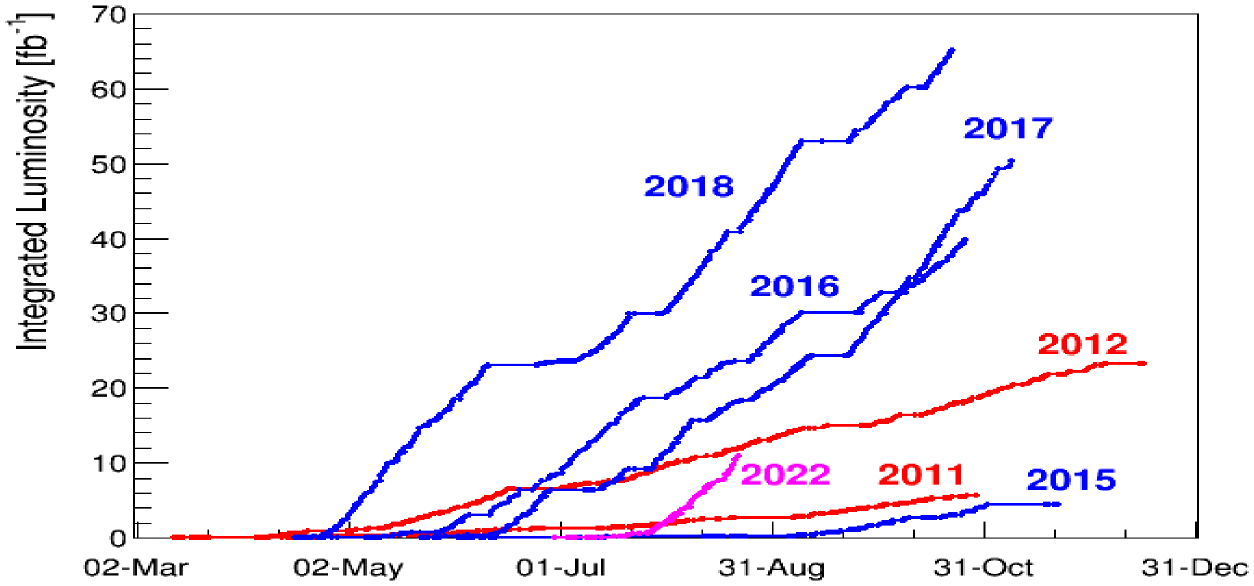


Status of 2022 luminosity production

- **Luminosity production started to exceed the planning before the incident on 23/8**
- **Slope close to the best Run 2 periods**
- **So far collected about 11 fb^{-1} at ATLAS / CMS**

Timescale adjusted to actual startup





J. Wenninger

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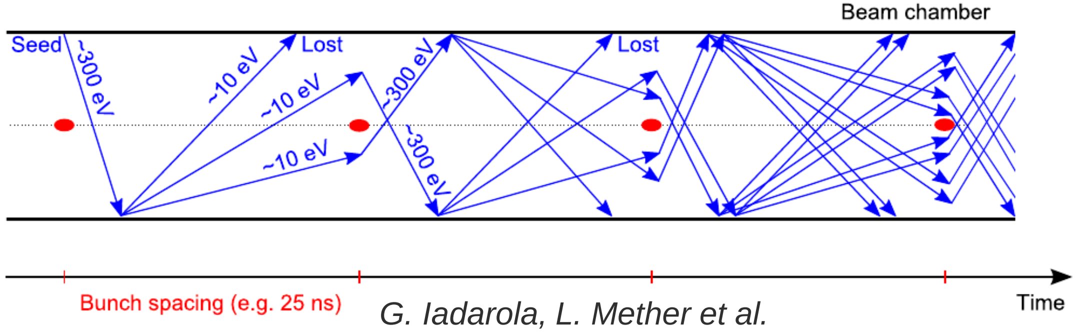
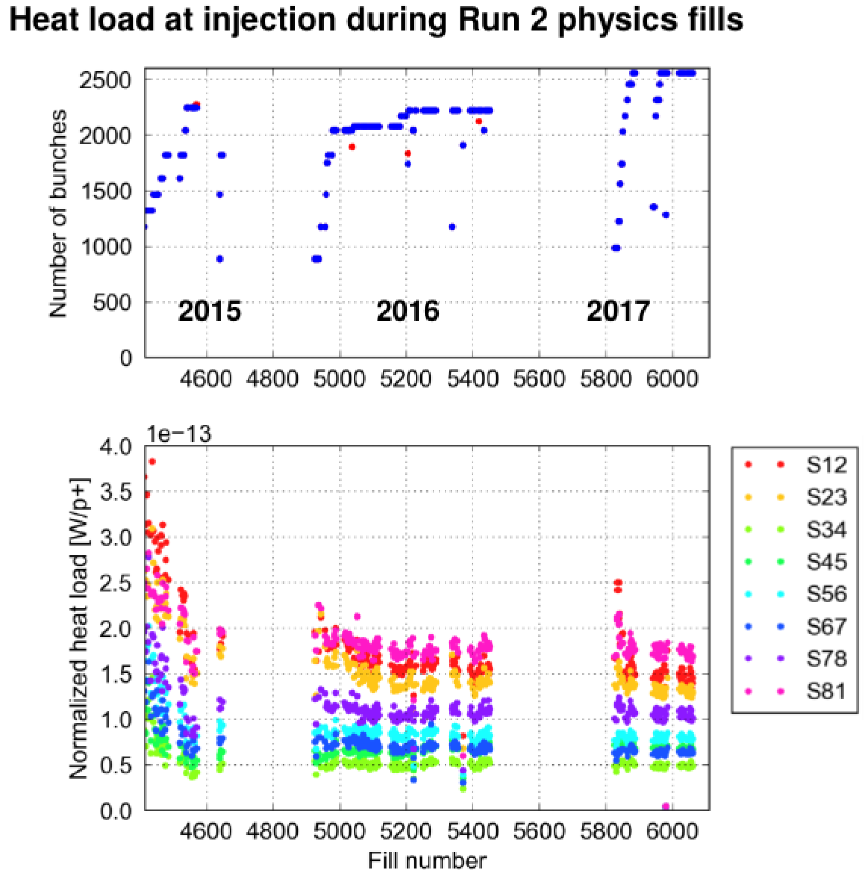
Electron cloud and heat load

- **Electron cloud**
  - Electrons accelerated by the beam, hitting the chamber and in turn releasing new electrons => avalanche effect
  - Consequences: heat load on chamber wall (main limit), instabilities, vacuum degradation, emittance blowup …

- **Run 2**
  - Conditioning over the run
  - Significantly higher heat load observed in some LHC sectors: S12, S23 and S81 => degradation from Run1 to Run 2.
  - Studied by dedicated task force. Found chemical alterations in beam-screen surface at high-heat load locations (see LMC talk V. Petit)



G. Iadarola, L. Mether et al.

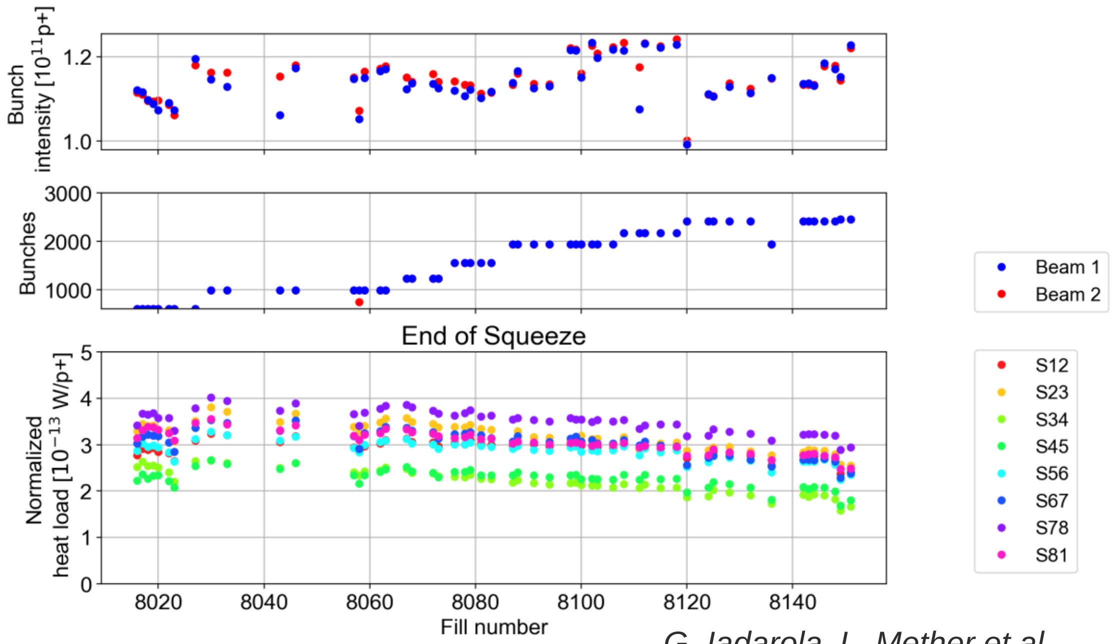


Electron cloud and heat load in 2022

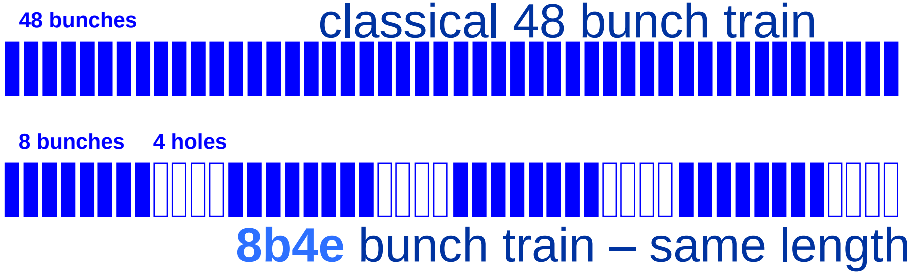
- **2022**
  - Scrubbing run and intensity ramp-up: S78 is now the worst, with significantly higher SEY than in Run 2
  - Presently limited by heat load at 1.25×10^{11} p/bunch and 2461b
    - Had to reduce train length (now at 36b trains).
  - For more info, see LMC talk L. Mether and talk K. Paraschou

- **Expect continued conditioning in physics fills – situation should slowly improve**
  - End point to be seen in 2023 - experience from the 2023 run will be extremely important to identify limitations for HL-LHC

- **Mitigations under discussion – see LMC talk L. Mether**
  - Could change filling scheme to include "holes" (8b4e) – limited to about 1900 bunches in total
  - Could use mix of 8b4e and standard 25 ns beams
  - Task force in place, studying different surface treatments for SEY reduction

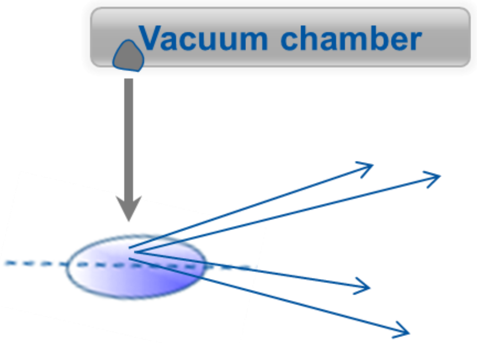


G. Iadarola, L. Mether et al.

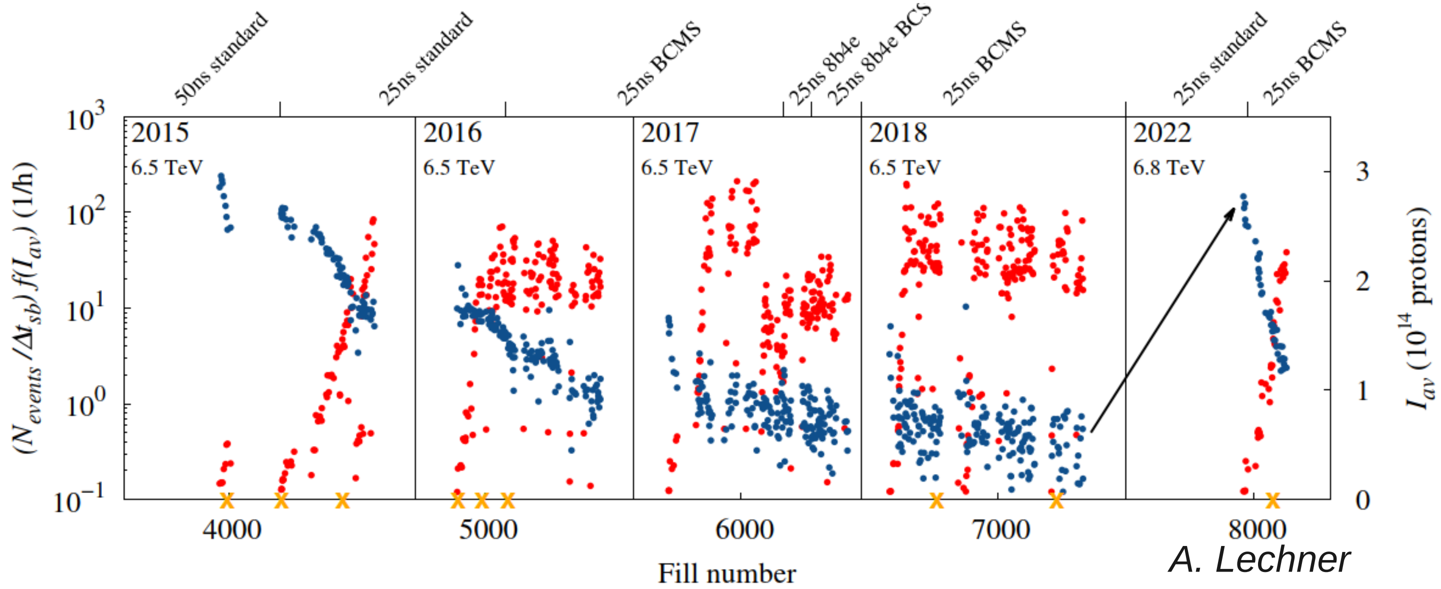


UFO events

- **UFOs = Unidentified Falling Objects**
  - Likely negatively charged dust particles attracted by and hit by the beam
  - Inducing fast beam losses, could cause beam dump or quench
- **Shows conditioning with time, but “reset” after long shutdown**



- **In 2022, 23 beam dumps (1 quench) due to UFOs**
- **Important impact on availability this year, but the worst should be over by the end of 2022**



A. Lechner

Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

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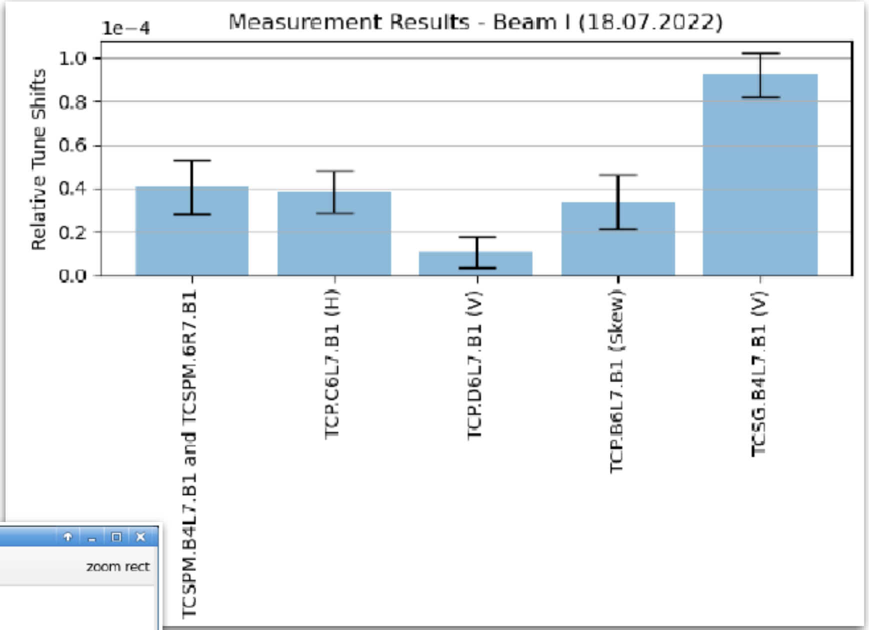
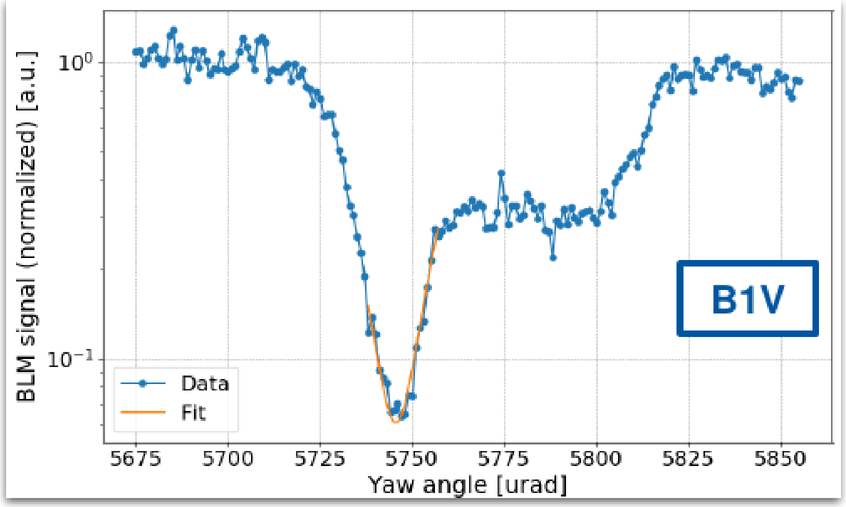
Operational tests and machine development

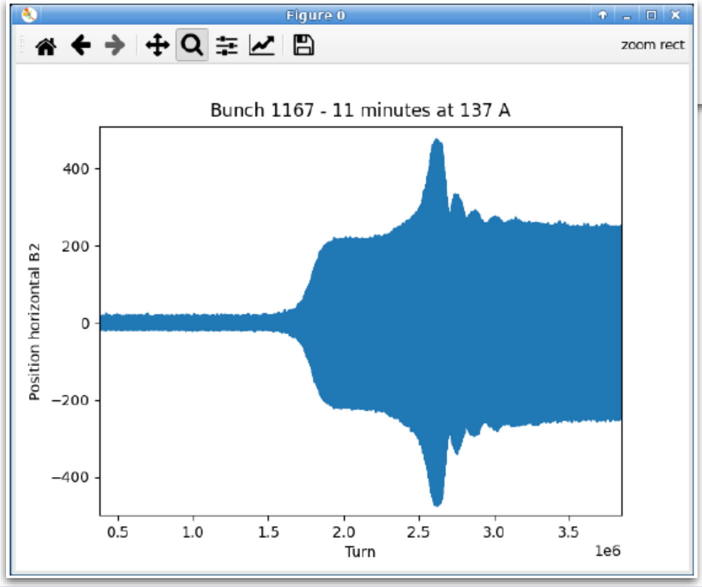
- **LHC tests in Run 3 are extremely important input for HL-LHC**
- **Detailed list of machine development for HL-LHC in 2022 – see talk G. Iadarola at WP2**
  - Dedicated talk on collimation MDs at this meeting by P. Hermes on Wednesday
  - Main areas: Halo and collimation, Impedance and beam stability, Optics correction, Electron cloud, RF power limitations, Incoherent effects
- **September MD block not done due to beam stop – re-scheduling underway**
  - Some important tests in the pipeline – electron cloud, collimation quench test, RF power limitations…
- **Some experience already collected in commissioning, operation, and floating MDs**
  - Caveat: limited bunch intensity reached so far in operation (with 25 ns trains)
  - Brief snapshots on following slides
  - Full details of floating MDs – see LSWG meeting

Results from commissioning, machine development

- **Measurements of low-impedance collimators** (see talk L. Giacomel)
- **Stability threshold measurements - octupole scans show no bad surprises** (see talk L. Giacomel)
- **Commissioning with protons of crystal collimators for ion run** (see LPC talk M. D’Andrea)

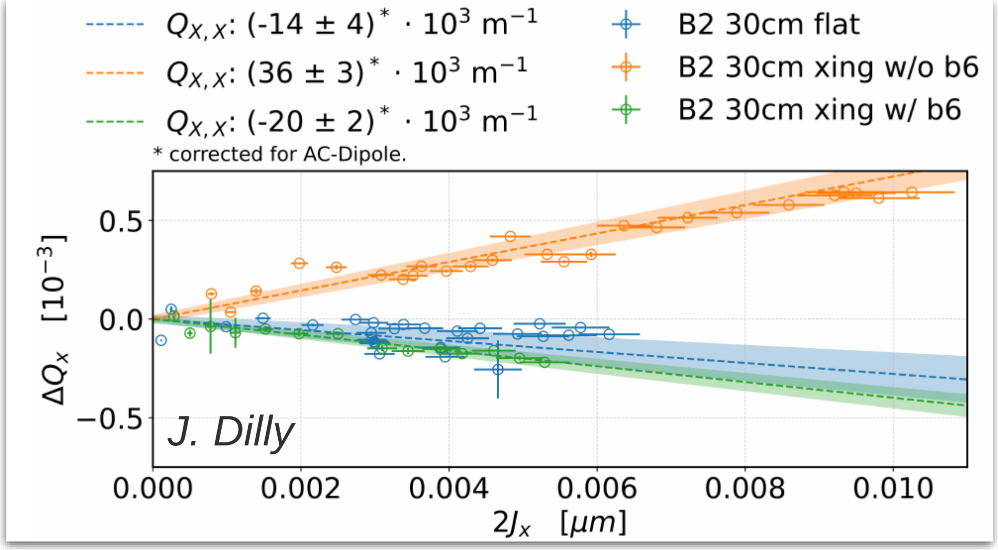


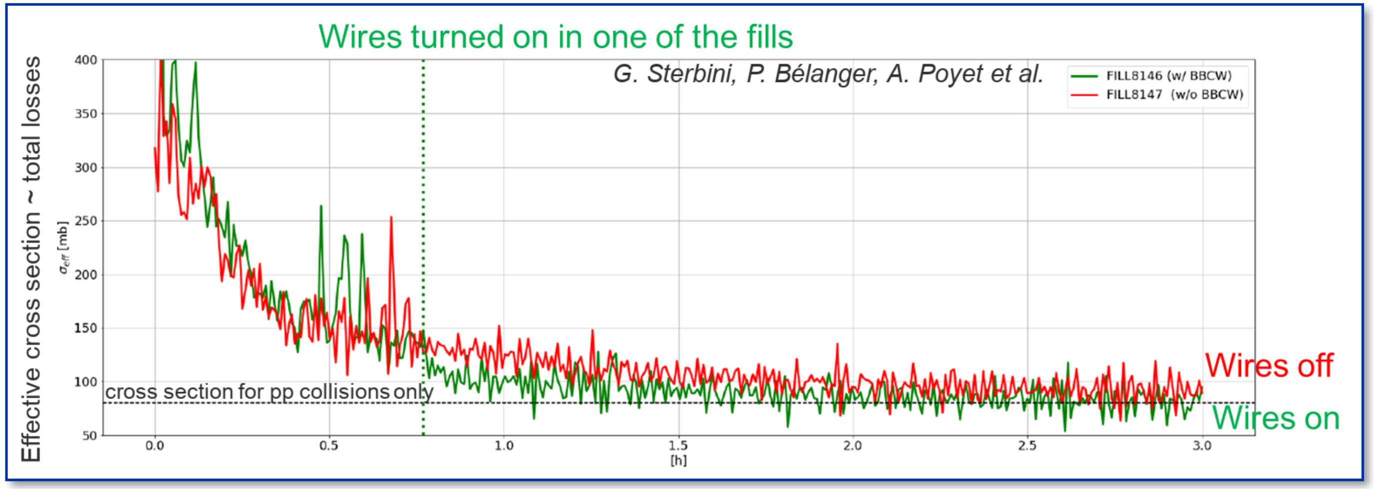


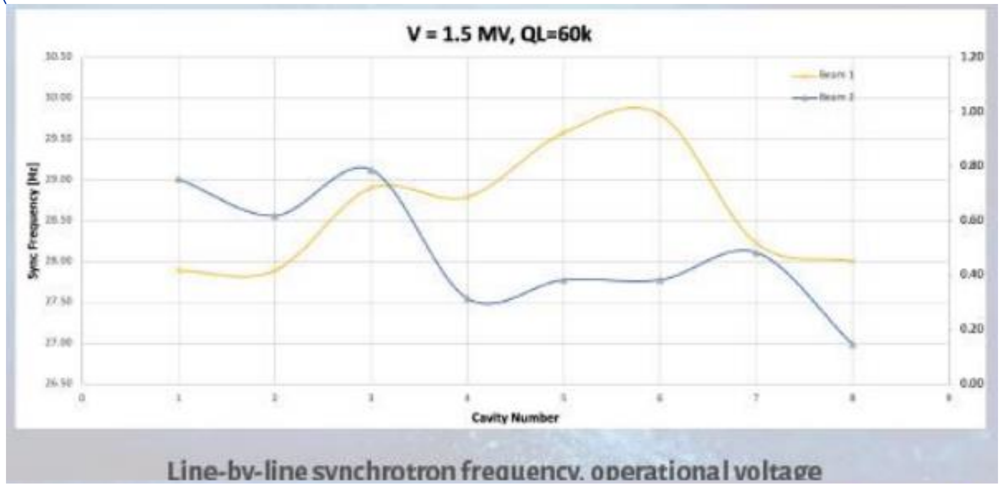


Results from commissioning, machine development

- **Optics correction: Correction of b6 error, non-linear optics corrections with low excitation amplitudes** (see LMC talk E.H. Maclean)
- **RF voltage calibration** (see talk B.E. Karlsen-Baeck)
- **Beam-beam wire compensation used regularly in physics fills at end of levelling** (see beam-beam wire workshop in Uppsala on Friday)







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- **The LHC injector chain is in excellent shape – good progress with the high intensity LHC beams for Run 3**

- **LHC commissioned successfully, Run 3 physics operation started on July 5th**
  - Steep increase in intensity and luminosity despite UFOs and electron cloud
  - The complex luminosity levelling mix of Run 3 (and HL-LHC) was implemented in a record time – now fully operational

- **Intensity currently limited by electron cloud (at 1.25×10^{11} p/bunch and 2461 bunches)**
  - Mitigations under discussion - bunch trains with holes (8b4e)
  - 8b4e interesting also because of energy saving considerations (lower cooling power needed)

- **The lessons learned in 2022 to be analyzed – impact on 2023 run is under study**

- **Schedule updates under discussion, following beam stop due to incident on 23/8, and 2-week shorter run due to energy crisis**
  - Longer term energy crisis driven schedule changes and their implications also under consideration

Thanks for the attention!

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BACKUP

Targets from the injectors

- **Injectors will push intensity towards HL target of 2.3×10^{11} ppb at extraction from the SPS in 2023-2025 – but the LHC cannot 'swallow' such beams in pp production in Run 3.**

	2022	2023	2024	(2025)	Comment
Number of bunches	2748 (BCMS) → 2492 (Mixed)				Starting with pure BCMS in 2022 and monitor the heat load in LHC
Bunch charge [10^{11}]	**1.4 → 1.8*)**	**1.8 → 2.1*)**	**2.1 → 2.3*)**	**2.3**	*) Max. intensity reach at the end of each year, **operational only the following year**
Norm. emittance [μm]	1.30	1.30→1.55	1.55→ 1.70	1.70	Intensity ramp up at constant emittance in 2022

From Run 3 WG meeting, with latest update

Slide from S. Fartoukh, Chamonix 2022

Performance (1/4)

- Main assumptions

(i) Schedule for pp Run3

→ **T_{OP}~ 105 *effective* days in 2022** (5 weeks for the intensity ramp up, counted half, and 88 days of production)

→ **T_{OP} =130 days in 2023-2024-(2025)**

(ii) Effective cross-section of 100 mb (81 mb for the in. X-section)

(iii) Turn around time of τ_0=4.5 h (vs. 4.7 h and 7.2 h for the median and average τ_0 achieved in 2018)

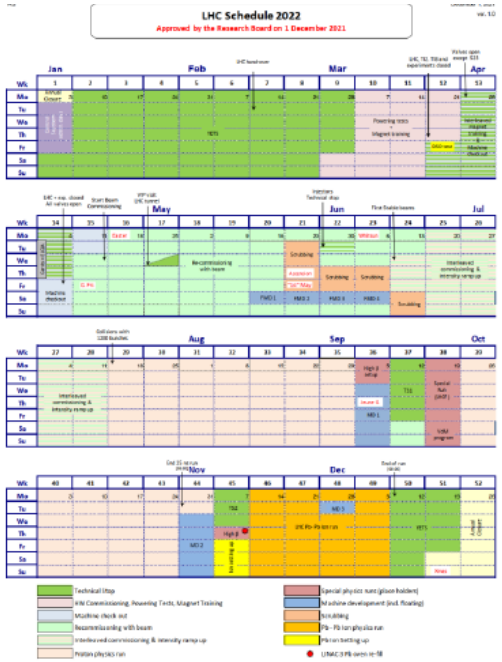
→ Optimal fill length of **τ_{Opt}~11 h in 2022** (1.4e11 p/b)
and **τ_{Opt}~ 15 h in 2023-2024-…** (1.8e11 p/b)

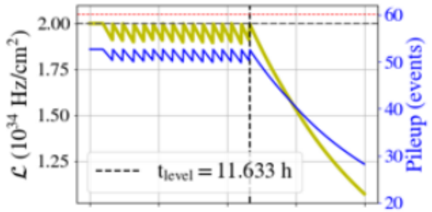
(iv) Machine efficiency η_{eff} = T_{SB}/ T_{OP}

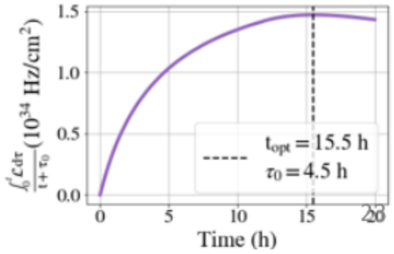
→ 50% reached in 2018, but still no data for high intensity …

→ **η_{eff} = 25% in 2022** and **η_{eff} = 40% for the rest of Run3**

$$\int_{Year} L\,dt \equiv \eta_{eff} \times T_{OP} \times \left(\int_0^{\tau_{opt}} L\,dt \;/\tau_{opt} \right)$$







26/04/2021 S. Fartoukh, LHC Performance workshop 2022

Origin of high heat loads

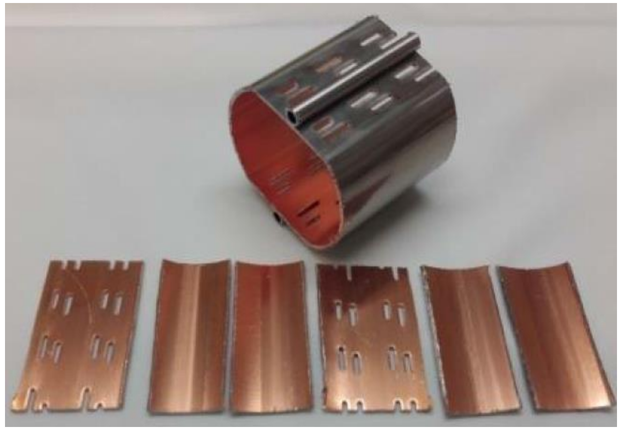
Slide from J. Wenninger

Vacuum chamber samples **were analysed to identify** differences in surface properties **between high and low load magnets.**

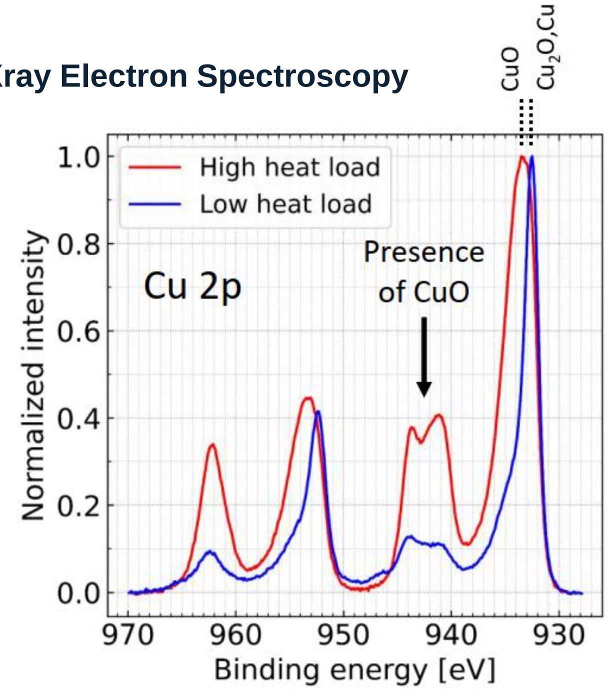
High heat load sector are characterized by:

Large concentrations of CuO,

Low Carbon content.



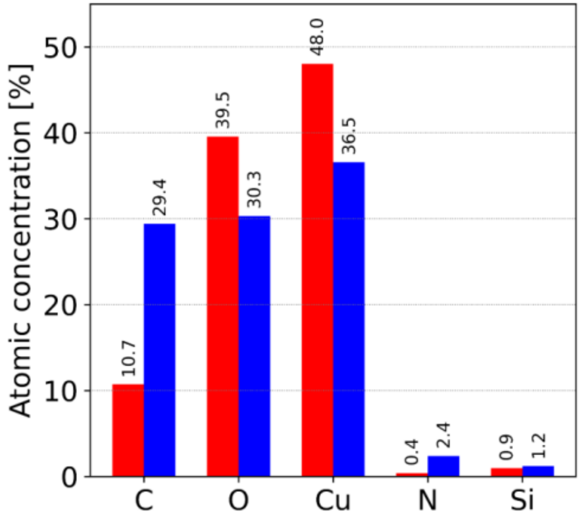
Xray Electron Spectroscopy



Laboratory tests show **much slower conditioning** of the high heat load surface samples under e- bombardment.

More work to understand the surface alteration in progress at a new cryogenic laboratory.

In-situ treatments of the vacuum chamber during a future long shutdown are **under evaluation**.



23rd August incident

- ~ 18:00 lost communication SF4 cooling water flow PLC
  - Cryo compressor stopped in P4
  - RF cryo went in safe mode → controlled He release
- ~ 22:00 cryo system back online, start of recovery
- Fast response time of all involved teams !

- RF cavities pressure release disks ruptured
  - Cold He release lowered the burst disk rupture threshold
  - Disks replaced during the night by RF and Fire Brigade
  - Warm up to 300K is needed due to contaminated atmosphere in the RF cryo module

- **Expected downtime ~4 weeks**

More info LMC #446 - https://indico.cern.ch/event/1190674/

Slide from A. Calia, LHCC meeting

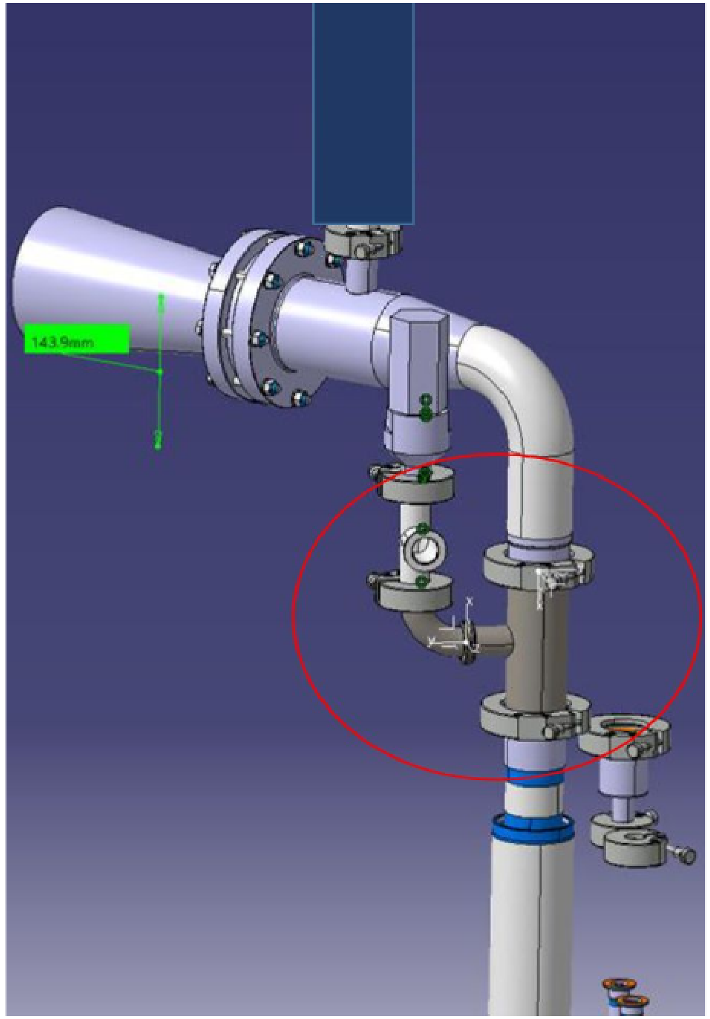
23rd August incident: mitigations

Slide from A. Calia, LHCC meeting

- SF4 cooling tower controls
  - PLC consolidations project underway EDMS 2256896
  - Incident cause under investigation with PLC manufacturer
  - Reliability being addressed but is only one mechanism to cause a loss of cryo cooling

- Immediate measures (RF burst disk task force)
  - Safety valves recalibrated to open at a slightly lower pressure
  - He release mechanism modified to ensure that burst disks are not cooled down significantly during He release
  - Should improve margin between safety valve opening and burst disk rupture → lab results showed no cooling of the burst disks

- Longer term solutions being studied by a dedicated task force with the aim of implementation during the YETS



Some key areas for HL-LHC measurements in Run 3

- Quantify and mitigate potential limitations in the latest HL-LHC baseline, in particular on intensity
  - Heat load and e-cloud
  - Beam stability and impedance
  - RF-related intensity limits
  - Collimation cleaning, beam losses and halo
  - Machine protection
  - Beam-beam, dynamic aperture
  - Emittance blowup, noise

- Demonstrate new concepts or hardware
  - Telescopic round optics (ATS)
  - Optics corrections (OMC)
  - Beam instrumentation
  - Damper (ADT)

- Demonstrate backup scenarios
  - Filling schemes for reduced e-cloud
  - Flat optics (ATS)
  - Beam-beam wire compensation
  - New optics for reduced impedance in IR7

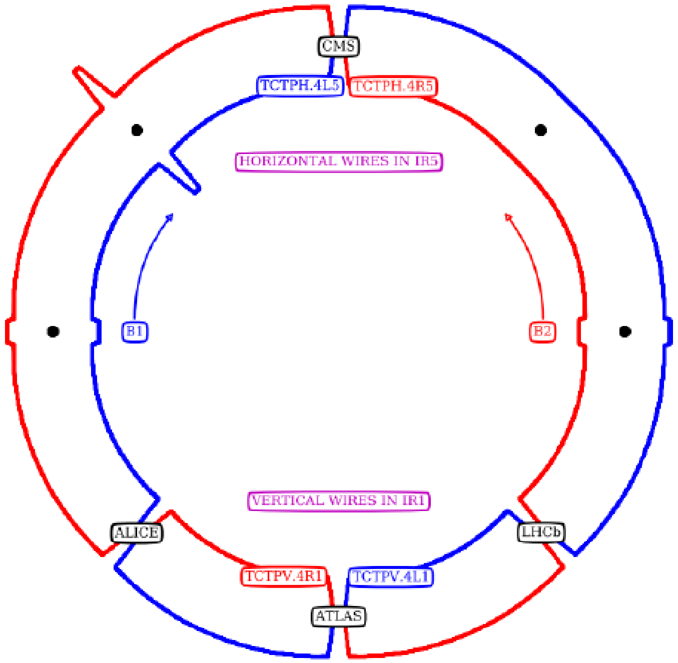
Possibly not an exhaustive list – potentially to be reviewed and updated.
Detailed list of MDs discussed in 2019 WP2 talk by R. Tomas and in 2020 MD day

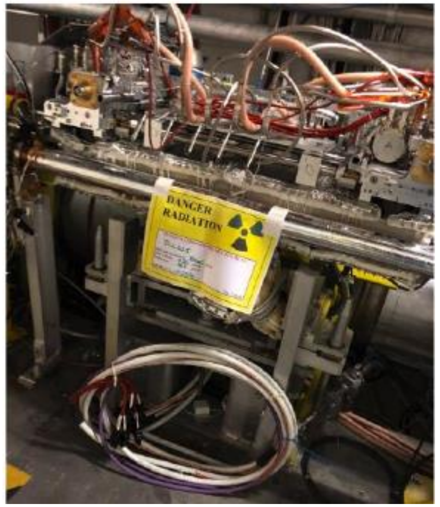
Run3 MD program discussed by the LSWG with input from the HL project

Beam-beam wire compensators

- **Idea: compensate long-range beam-beam effect through current-carrying wires**
  - Wires integrated in collimator jaws close to experiments - initial promising tests in Run 2
  - Benefits: improved dynamic aperture and decreased losses, potential to decrease crossing angle.
  - Run 3: two wires per beam per IP, installed in tertiary collimators on incoming beam

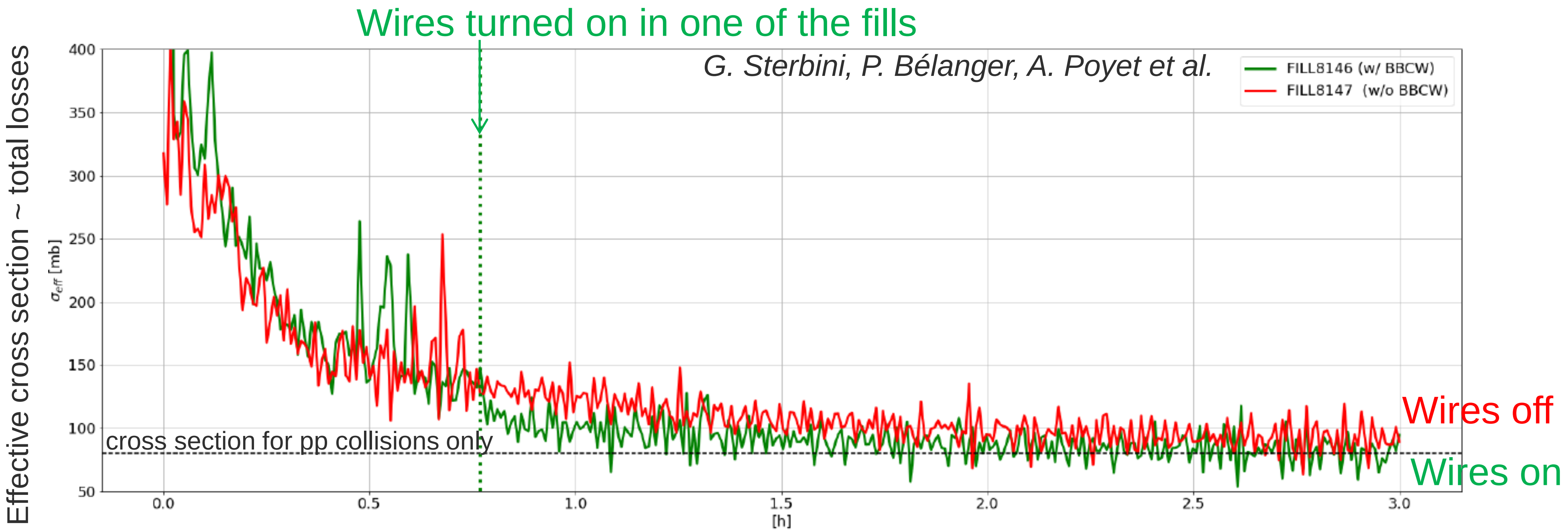
- **Further tests and operational use during regular Run 3 operation**
  - Wire installation commissioned and validated for operation in 2022
  - Plan: turn on wires in every fill at end of β*-levelling (β*=30 cm) – so far done in 20 fills
  - Earth fault occurred in one of the last fills – wire operation on hold, repair planned for technical stop





2022 experience with beam-beam wire compensation

- **Preliminary observations show beneficial effect**
  - Comparing to equivalent fills, less non-collisional losses are seen with the wire on
  - Tune optimization very important
  - Plot of B2 – B1 shows a less evident effect of the wire



- **For future studies for HL-LHC see beam-beam wire workshop on Friday**