LHC machine status

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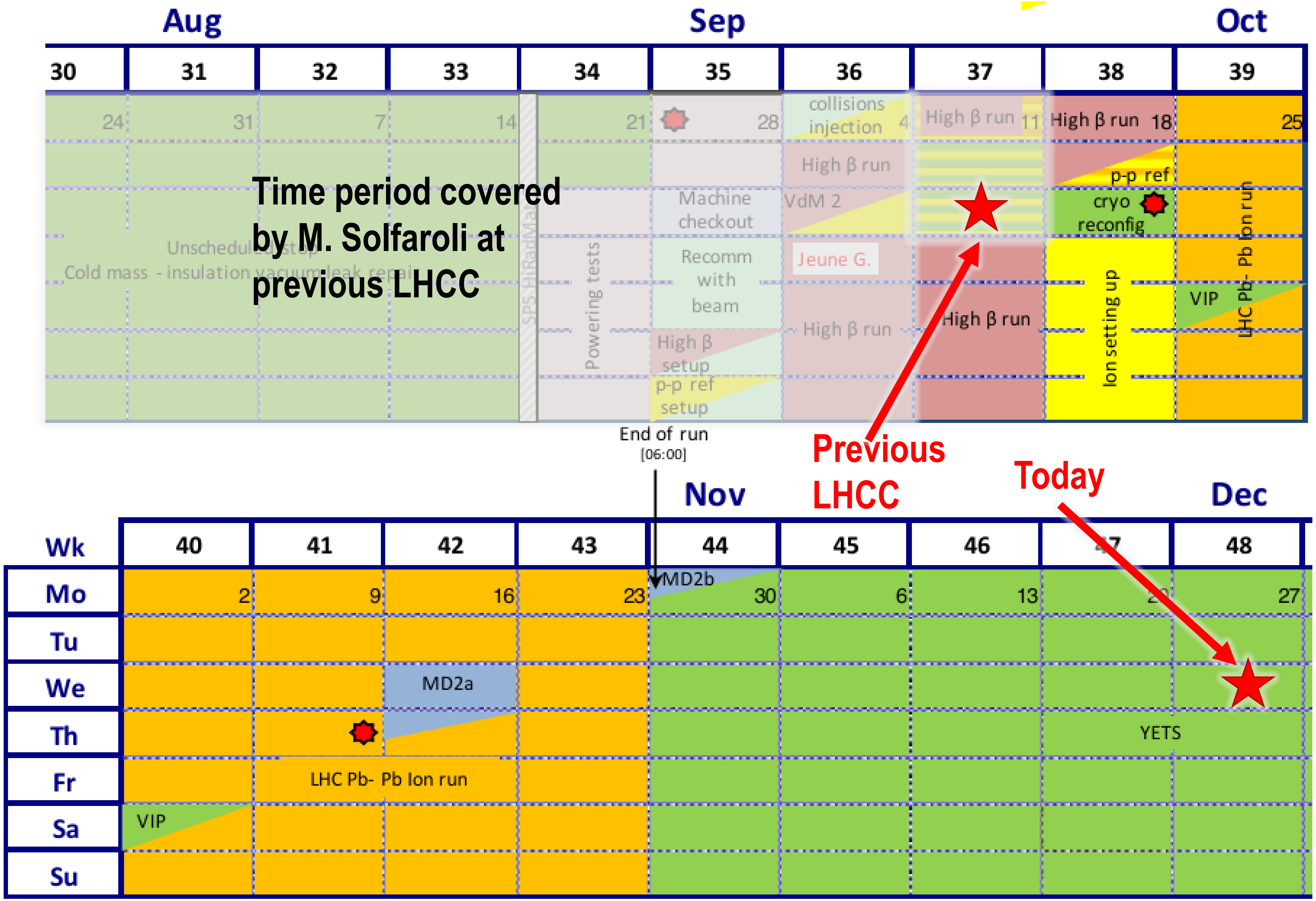
On behalf of the LHC team

Outline

- **Status at last LHCC and main program since then**
- **Summary of high-β run**
- **Constraints on injected intensity and schedule update**
- **Summary of Pb ion run**
  - Beams and machine configuration
  - Problems encountered
  - Luminosity production
- **Reversed polarity powering test and outlook on 2024**
- **Conclusions**

LHC schedule

- **Status at previous LHCC**
  - Coming out of recovery from IR8 triplet vacuum leak and re-scheduling
  - In the middle of the high-β run, going towards pp reference run and ion run
  - Vacuum leaks at TDIS in IR8 discovered – impact being evaluated
- **What has happened since September?**
  - End of high-β run
  - pp reference run postponed
  - Pb ion run, MDs
  - Now well into the YETS



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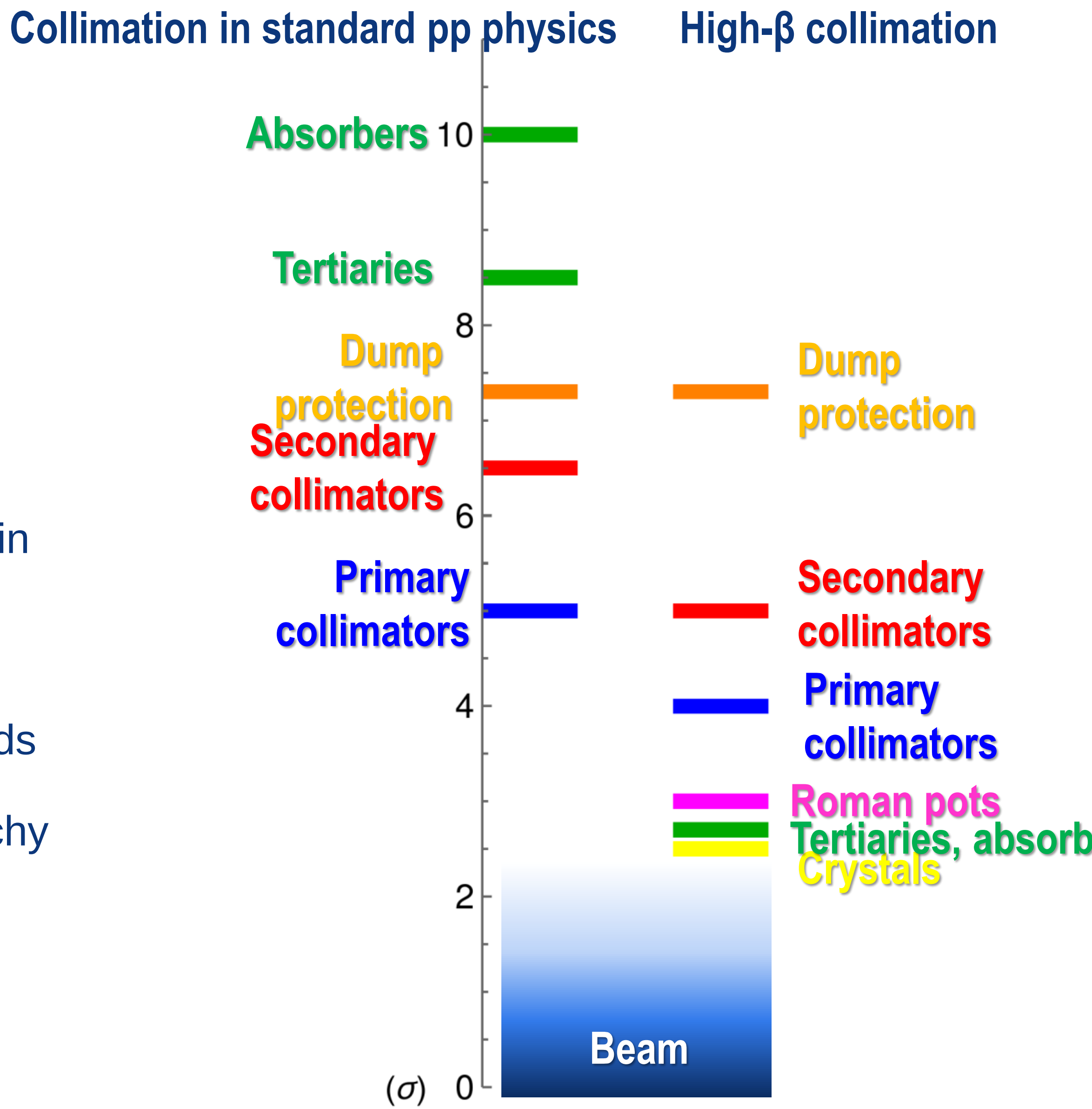
High-β run

- **Reminder**
  - High-β run done for forward physics at ALFA and TOTEM
  - Requirements:
    - Roman pots very close to the beam - around 3 σ half gap; low background; large β* at the collision point
  - De-squeeze of IR1 and IR5 to β_x*=3km, β_y*=6km
  - Low intensity – a few single bunches, staying below $3x10^{11}$ in total intensity

- **Very challenging collimation setup**
  - Need very efficient collimation to protect against backgrounds → **Relied on crystal collimation**
  - Must position collimators well below 3σ – super-tight hierarchy required
    - Some collimators with full gaps of ~1mm!
    - Margins between multi-stage hierarchy of ~ tens of μm
    - Very sensitive to orbit drifts

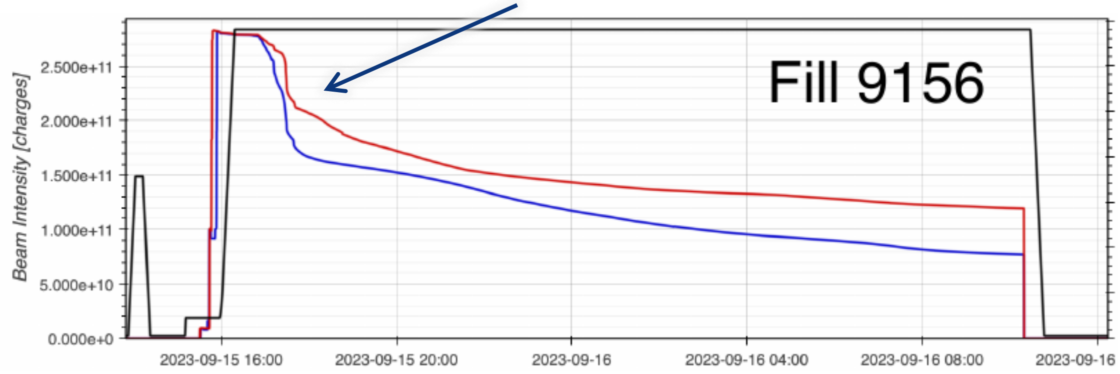


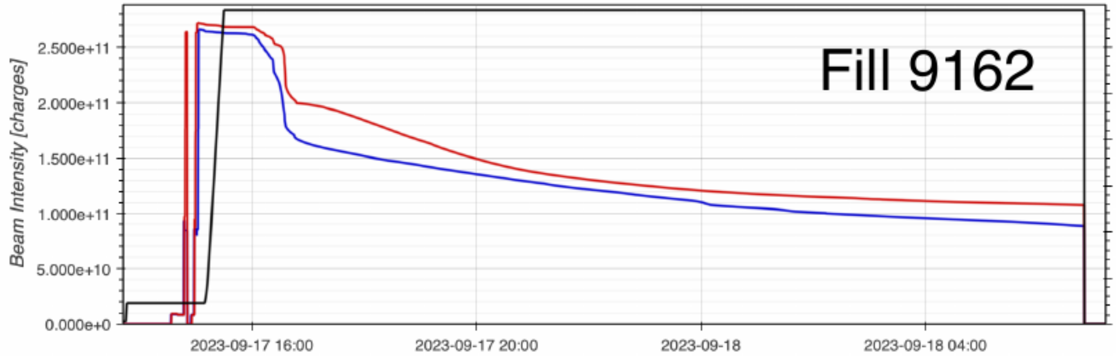
Operation in high-β run

- **Challenging beam scraping when moving in collimators**
- **In total, 9 fills with stable beams**
  - Total time 70 h
  - Average fill length 7.8h
  - Minimum turnaround ~3h

Typical fills

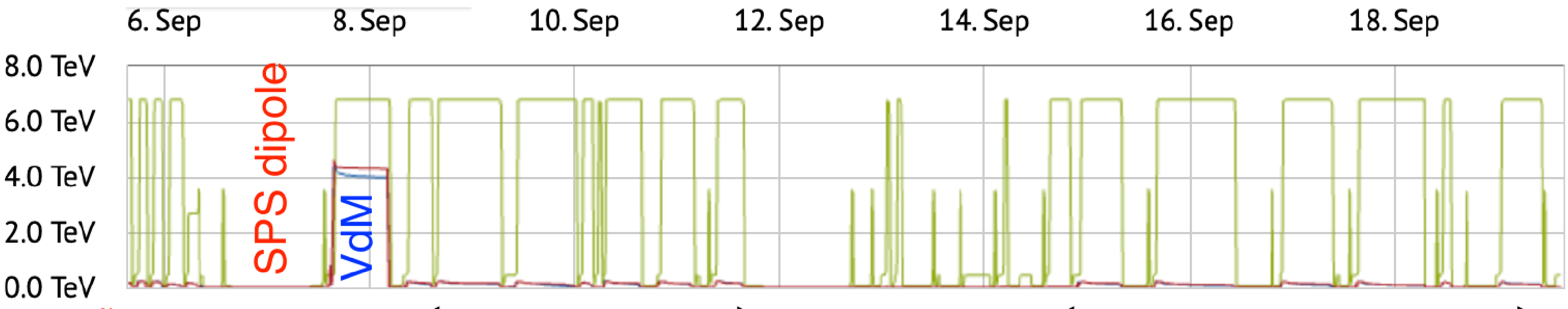
Collimator scraping to tight setting





Used different schemes with 1 pilot + 3 or 4 low-intensity INDIV

Results of high-β run



Initial setup: issues of losses and orbit reproducibility

Established operational robustness, converged on final settings for low-backgrounds. Evolving orbit setup procedure required a re-alignment
(IR7 orbit also affected because an orbit corrector was recovered that was faulty in the first alignment).

Regular operation (affected by several long faults)!

ATLAS magnet trip, water leaks…

Achieved luminosity:
ALFA = 329 μb^{-1} (target: 300 μb^{-1})
TOTEM = ~300 μb^{-1} (target: 400 μb^{-1})

From LMC talk S. Redaelli

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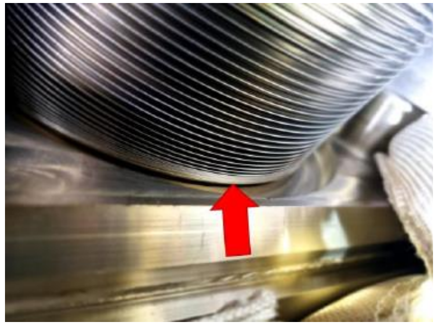
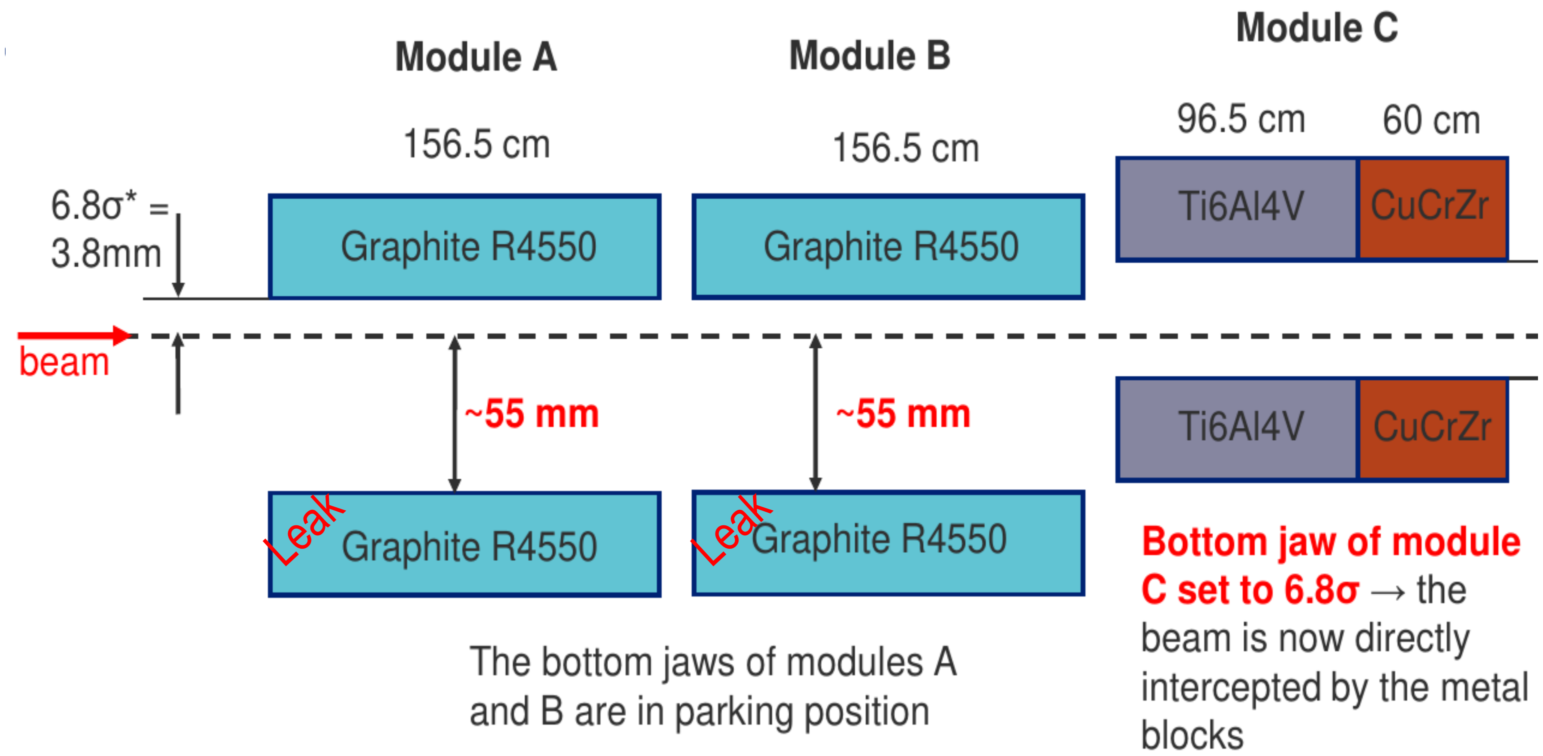
TDIS vacuum leaks

- **Vacuum leaks detected on bellows of two modules of TDIS.04R8 in September**
  - Injection protection device
  - Leaking bellows varnished and jaws blocked in parking position

- **Consequences:**
  - Risk to damage Module C of the TDIS itself in case of failure – need to limit injected intensity





From LMC talk, A. Lechner

Implications of TDIS vacuum leaks

- **Limits on maximum intensity per injection** (see LMC talk, A. Lechner)
  - Protons: 8 bunches (1.4×10^{11} ppb) per injection
    - Excluded to do high-intensity pp reference run – postponed to 2024
    - OK to finish high-β run – injection of single p bunches only
  - Pb ions: nominal Pb beams (1.9×10^{8} Pb/bunch, 56 bunches per injection) acceptable
    - Interlock implemented to limit intensity per injection to 9×10^{11} charges
    - OK to go ahead with Pb ion run

- **TDIS vacuum leaks now understood** (see LMC talk, M. Calviani)
  - Non-compliant bellows with respect to real operational requirements on number of cycles
  - Confirmed by recent tests on other TDIS bellows

- **Strategy put in place for mitigating intensity limits in 2024-2025** (see LMC talk, M. Calviani)
  - Remove both TDIS (IR2 and IR8) this YETS and replace with operational spares for 2024
    - Spares have also non-conform bellows, but not used in operation yet so should survive 2024
    - TDIS.4R8 already replaced!
  - Repair removed TDIS and install compliant bellows – both TDIS to be re-installed in YETS 24-25
    - Re-using present TDIS jaws → should not be damaged, motivates the intensity limits above
  - Backup options pursued in parallel (new TDIS tanks)

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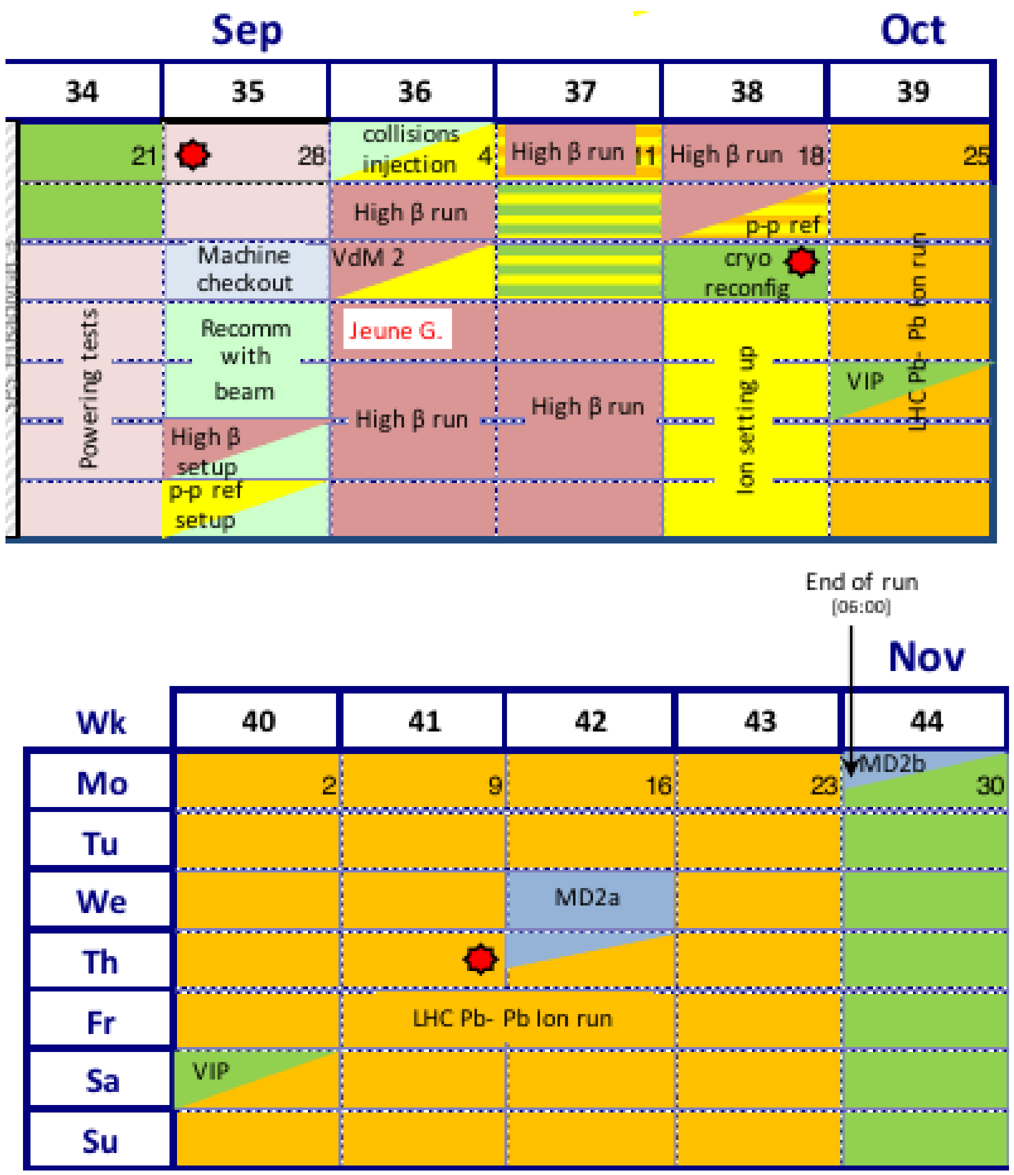
Overview of Pb ion run

- **Schedule for Pb-Pb run**
  - 4 days for commissioning, 32 days for physics
  - Breaks for VIP visits, MDs, VdM
  - Initially planned pp reference run postponed - one pp reference fill done at low intensity while waiting for ion injectors

- **Ion run relied on several new concepts**
  - **Slip-stacked 50 ns beams** from the injectors to provide higher intensity
  - **Crystal collimation** to handle the higher intensity without beam dumps or quenches
  - **TCLD collimators + BFPP orbit bump** in IR2 to allow full luminosity for ALICE
  - **New BFPP orbit bump in IR8** to increase quench margin and luminosity levelling target
  - **Full squeeze in ramp**



Machine and beam configuration

- **Optics similar to 2018**
- **ALICE polarity reversal in the middle of the run**
- **First full Pb-Pb physics run at 6.8 Z TeV**
- **New 50-ns filling schemes relying on slip-stacked beams from injectors**
  - Design case: 1240 bunches, with mix of 56 and 40-bunch trains
  - During the run, introduced schemes relying only on 40-bunch trains
  - In Run 2: Had up to 733 bunches, 75 ns spacing

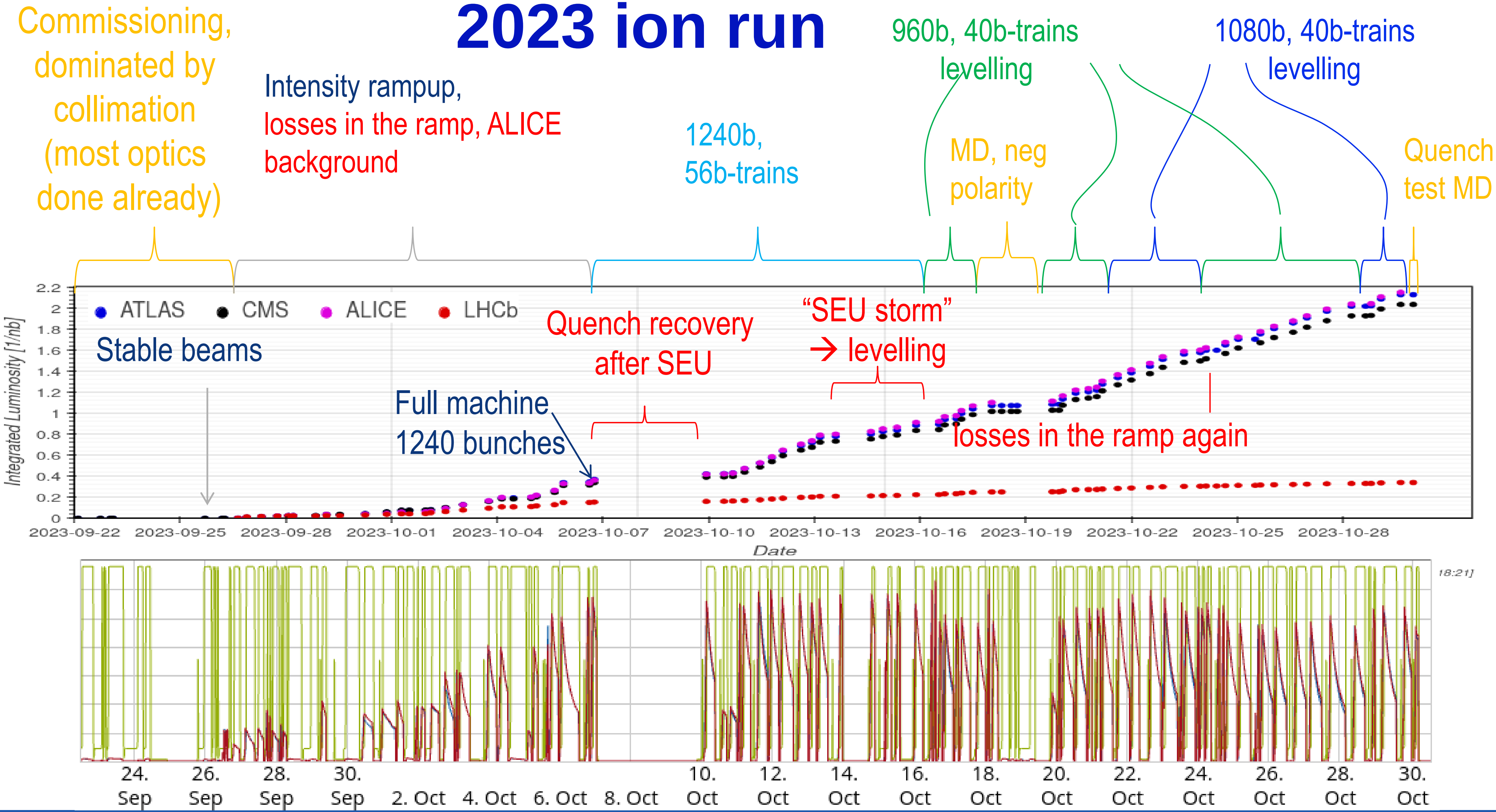
	IP1/5	IP2	IP8
β* (m)	0.5	0.5	1.5
Spectrometer half crossing (μrad)	0	±72	-139
External half crossing (μrad)	170	±170	-135
Net half crossing (μrad)	170	±98	-274

	Run 3 design
Beam energy	6.8 Z TeV
Bunch spacing	50 ns
Bunch intensity (start of collision)	1.8×10^8 Pb
Normalized transverse emittance	1.65 μm

Main operational schemes

N.o. bunches	Bunches/train	Collisions IP1/5	Collisions IP2	Collisions IP8
1240	56 / 40	1088	1088	398
1080	40	960	960	288
960	40	875	875	218

2023 ion run



Commissioning, dominated by collimation (most optics done already)
Intensity rampup, losses in the ramp, ALICE background
1240b, 56b-trains
960b, 40b-trains levelling
MD, neg polarity
1080b, 40b-trains levelling
Quench test MD
ATLAS
CMS
ALICE
LHCb
Stable beams
Quench recovery after SEU
"SEU storm" → levelling
Full machine 1240 bunches
losses in the ramp again
Integrated Luminosity [1/nb]
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2023-09-22
2023-09-25
2023-09-28
2023-10-01
2023-10-04
2023-10-07
2023-10-10
2023-10-13
2023-10-16
2023-10-19
2023-10-22
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12. Oct
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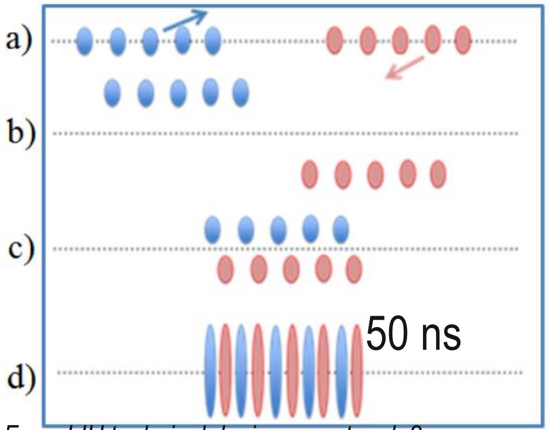
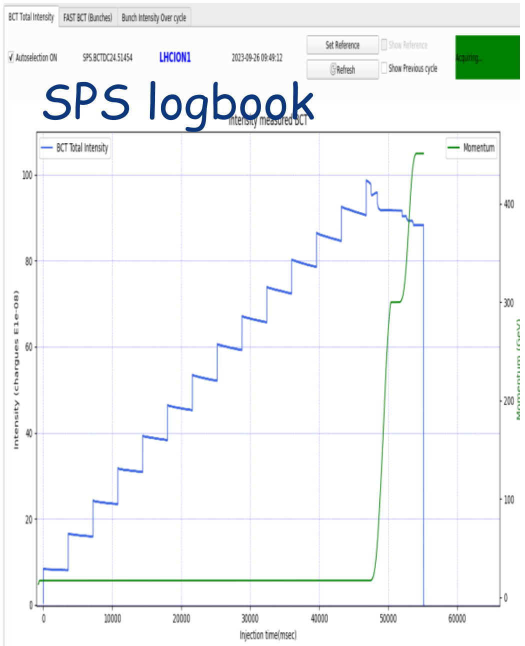
30. Oct

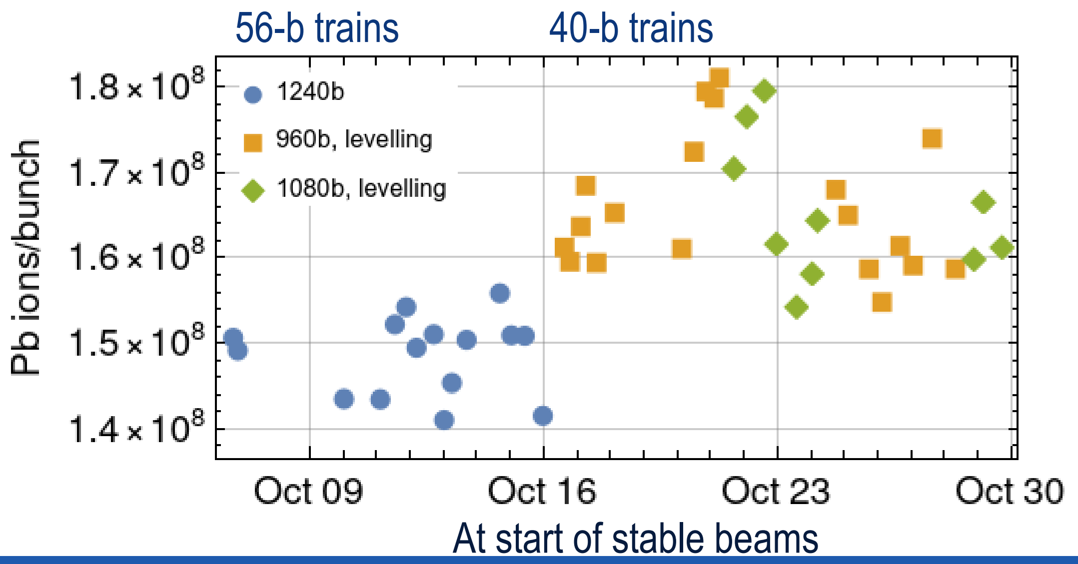
Beams from injectors

- **Slip-stacking successfully set up in the SPS, just in time**
- **Observed degradation in injected intensity over time**
  - Recovered by injector optimization, then degrading again
  - Initially limited injected intensity due to TDIS, later not needed
- **Average bunch intensity at start of stable beams**
  - 56-bunch trains: 1.49x10^8 Pb/bunch
  - 40-bunch trains: 1.66x10^8 Pb/bunch
  - Compare target: 1.8x10^8 Pb/bunch – reached only in a few fills with 40b-trains
- **Stored beam energy up to 17.5 MJ**



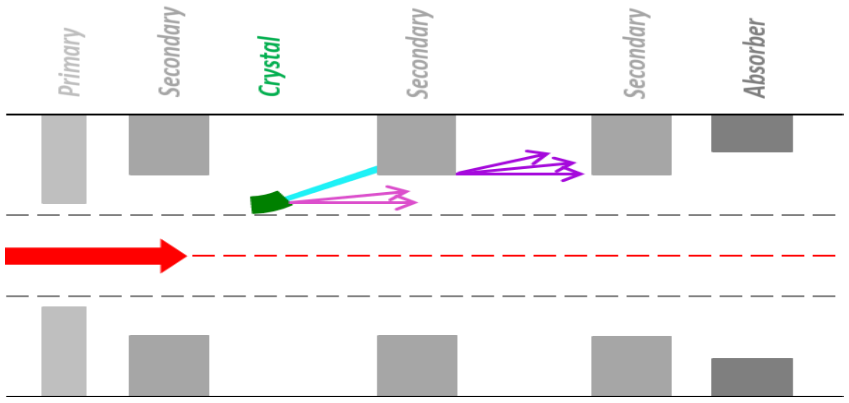
From LIU technical design report, vol. 2

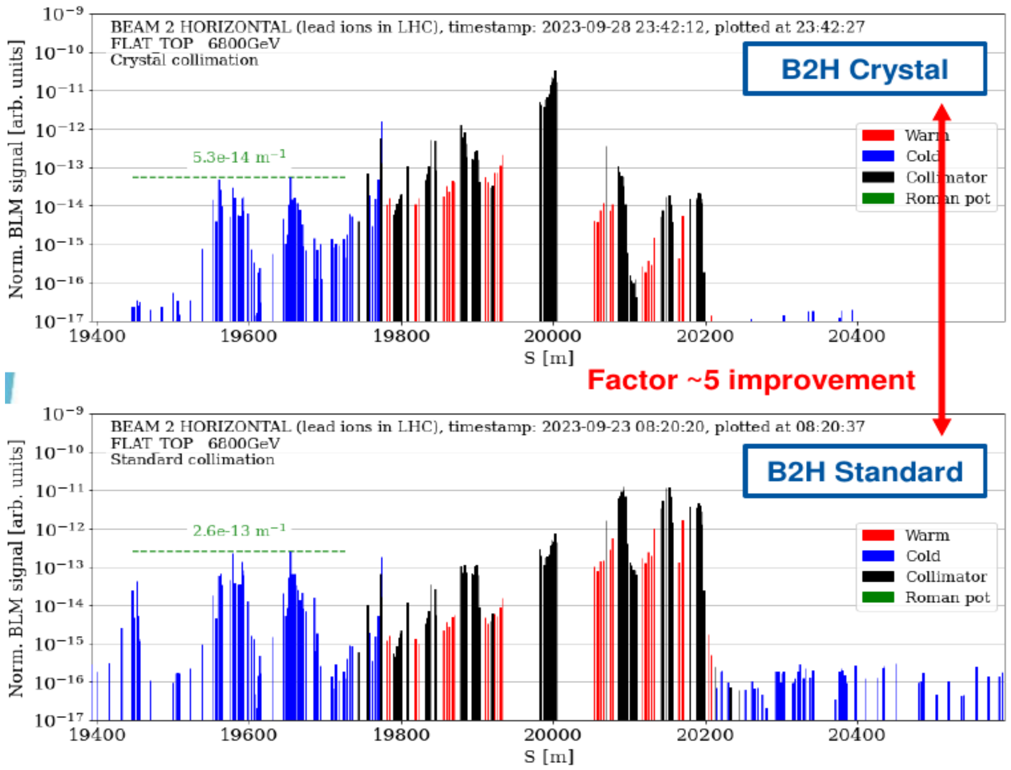




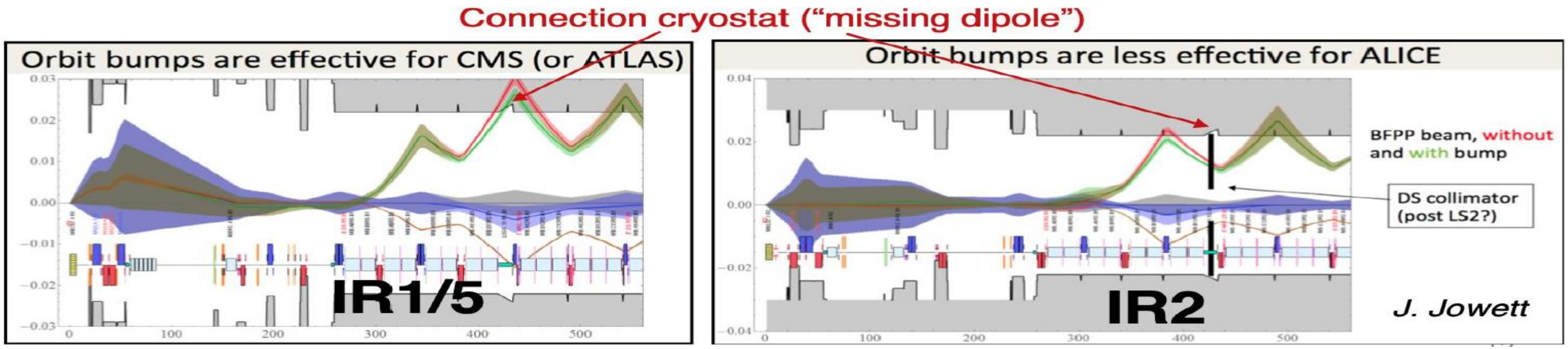
Crystal collimation

- **Principle**
  - Halo particles trapped in potential well between crystalline planes
  - Angular kick from crystal bending → Halo particles hit deeply in downstream absorber (standard collimator)
  - Crystalline planes must be precisely aligned with respect to the beam with tolerance of O(μrad) at top energy
- **First high-intensity physics run relying on crystal collimation**
  - Four new devices installed recently
  - Setup non-trivial: alignment of both position and angle
- **Observed drifts of optimal orientation for channeling**
  - Not yet fully understood
  - Flat top mitigated by automatic re-optimizations; Not mitigated in ramp
  - Possible correlation to temperature under investigation
- **Cleaning performance**
  - Excellent performance demonstrated in channeling orientation
  - Not performing well in amorphous, as expected





Alleviation of collisional losses



- **Alleviation techniques for bound-free pair production used successfully in operation**
  - **IR1/5: Orbit bumps** successfully deployed already in Run 2 to steer losses into empty connection cryostat
  - **IR2:** bumps alone do not work – **need bumps + new dispersion suppressor collimator (TCLDs)** → **new in 2023**
  - **IR8: bumps steer losses from cell 10 to cell 12**, where they are more spread out and BLM threshold is higher → **new in 2023**

- **Thanks to new mitigation, demonstrated factor 6 higher ALICE peak luminosity than in Run 2**

- **Quench test MD in last fill of the run**
  - without alleviation techniques, quenched in 11L1 at L=2x10^{27} $cm^{-2}s^{-1}$, factor ~3 below achieved peak luminosity
  - final unambiguous confirmation that the BFPP alleviation is essential to reach target the luminosity

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Single event upsets on quench protection system (QPS)

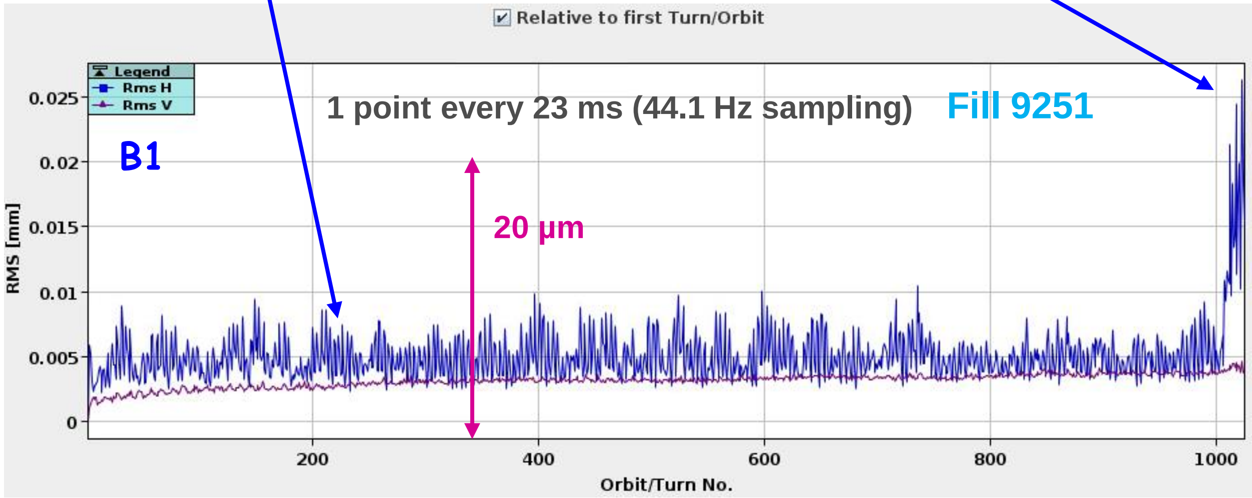
- **Had several issues with quench protection system likely due to single-event upsets (radiation-induced)**
  - Causing beam dumps, sometimes magnet quenches due to spurious firing of quench heaters
  - One event quenched 5 magnets, another one caused a 3-day downtime
  - Follow-up: reconfigured full cryogenic power around IR2 for faster recovery
- **Decided to level luminosity at 3.5×10^{27} $cm^{-2}s^{-1}$ at IP2, IP1, IP5**
  - Situation calmed down, could get back to steady operation, but some further events still observed
- **In total, 13 events on quench protection system**
  - 10 fills dumped in stable beams
  - In total, 9 events in IR2, 3 in IR1, one in IR5
  - In several cases, needed access to replace the electronics board
- **Follow-up studies to identify mitigation measures are ongoing**

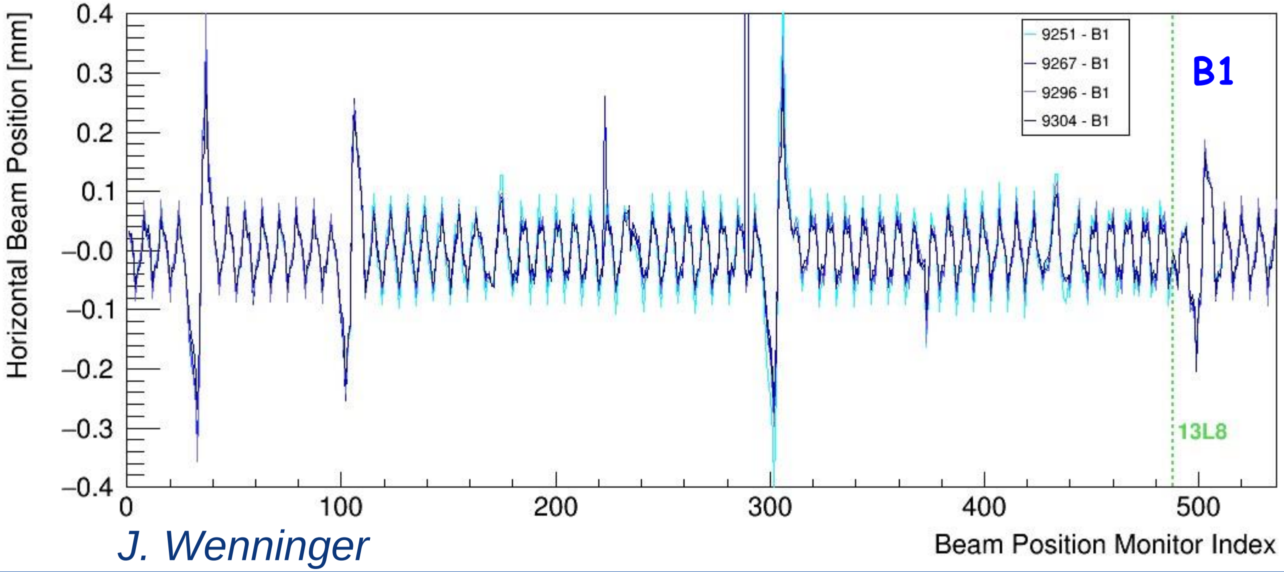
10 Hz losses

- **Growing horizontal orbit oscillations in B1 at around 10 Hz caused sudden losses and beam dumps**
  - In 2023, 7 fills dumped (+1 unclear dump)
  - Not new - had 7 10 Hz dumps also in 2018
- **Source of oscillation:**
  - Reconstructed orbit consistent with motion of quadrupole magnet
  - Points to kicks in quadrupole 13L8 or 13L2
- **No real mitigation found yet**
  - Successive optimizations (BLM thresholds, collimator settings) → dumping "later" but the increase of losses did not stop
  - Further optimizations may be possible, but unclear when/if the amplitude increase would stop
  - **Ongoing discussions and studies on mitigations**

"Noise" in H plane is activity around 10 Hz.

Increased activity → dump

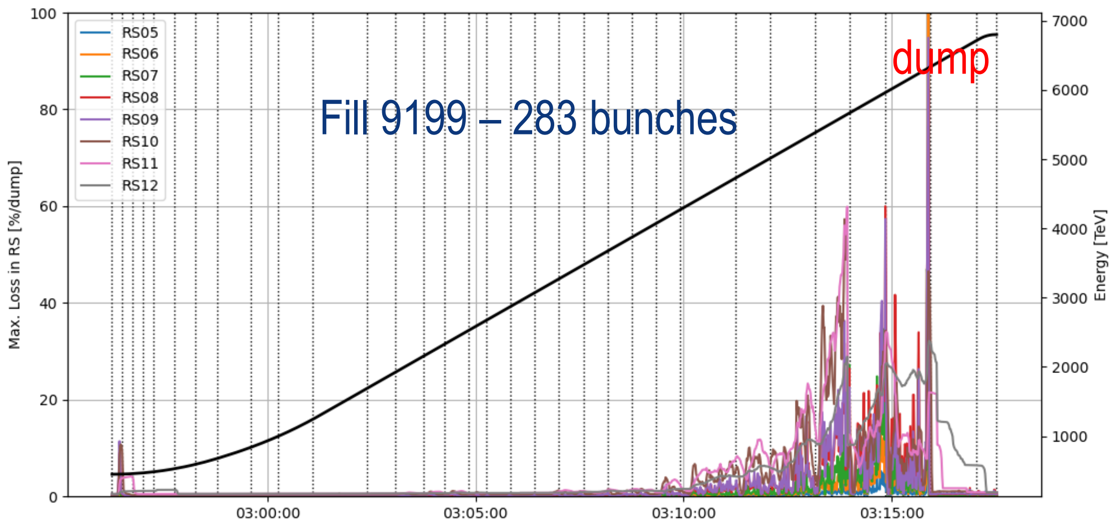


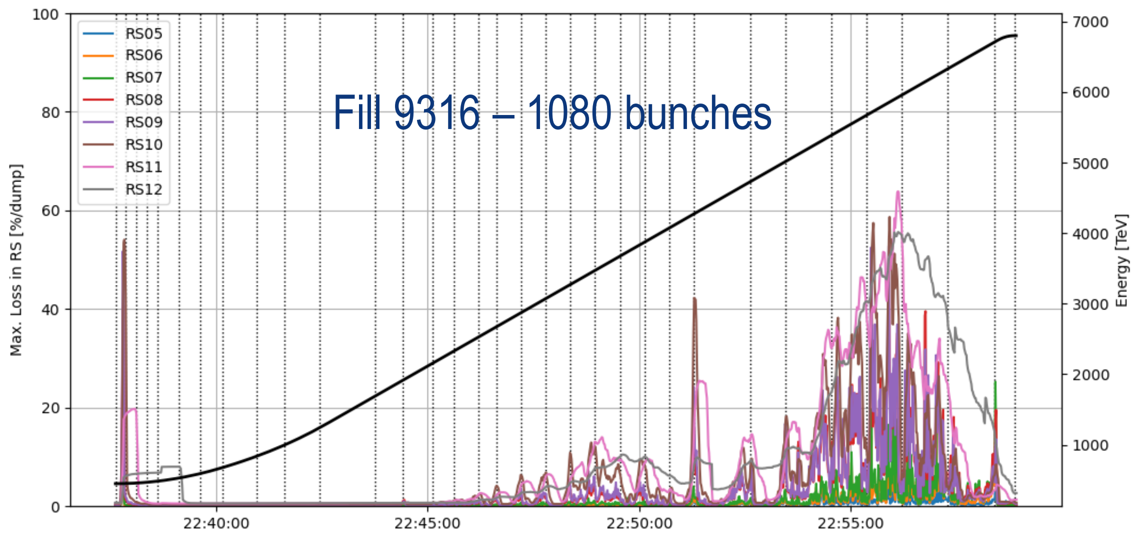


J. Wenninger

Losses in the ramp

- **Important losses observed from the first ramp with trains**
  - Off-momentum losses of un-bunched beam at start of ramp
  - Transverse losses around 6.1-6.7 Z TeV – strongest limitation, mainly in fast running sums
  - Significant slowdown of intensity rampup
  - Losses became more severe on two occasions
- **Loss source not fully understood**
  - Maybe due to the dynamic changes in the squeeze, combined with tightening collimators and 10 Hz activity on the beam
  - Crystal collimators not in perfect channeling orientation
- **Mitigations deployed**
  - Worked on orbit correction in the ramp
  - Minor collimator setting update
  - **BLM thresholds increased in several steps – 13 interventions**
  - Still, reached warnings on the BLMs in almost every ramp, but not strongly limiting at the end



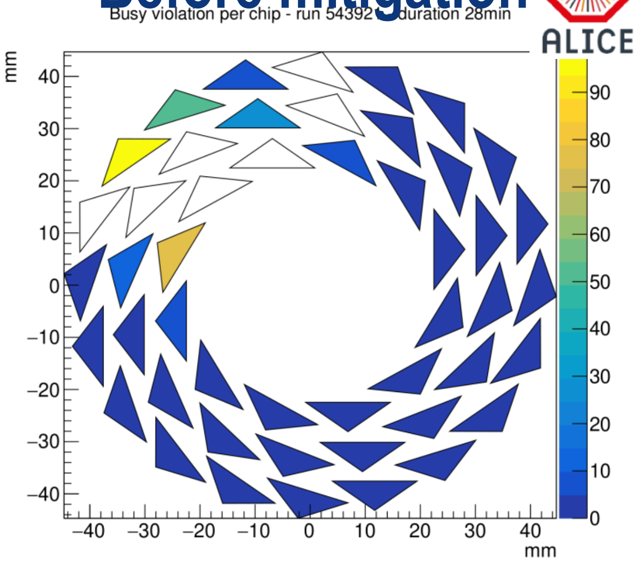


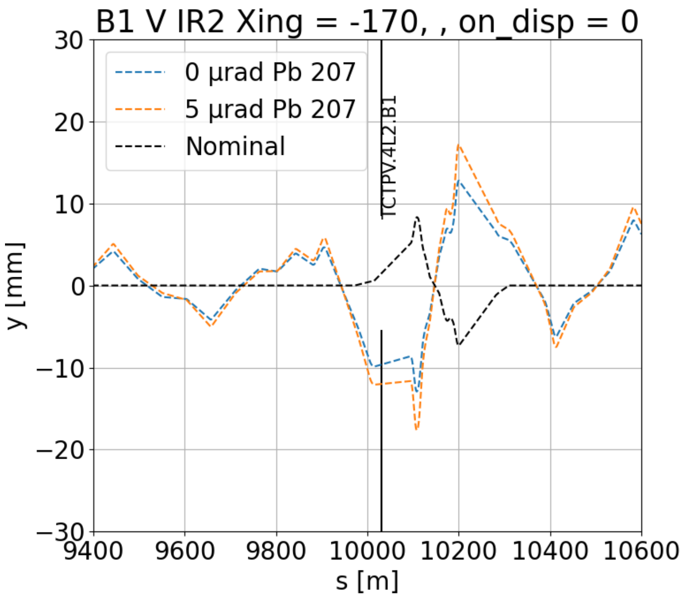
Thanks to M. Hostettler

ALICE background

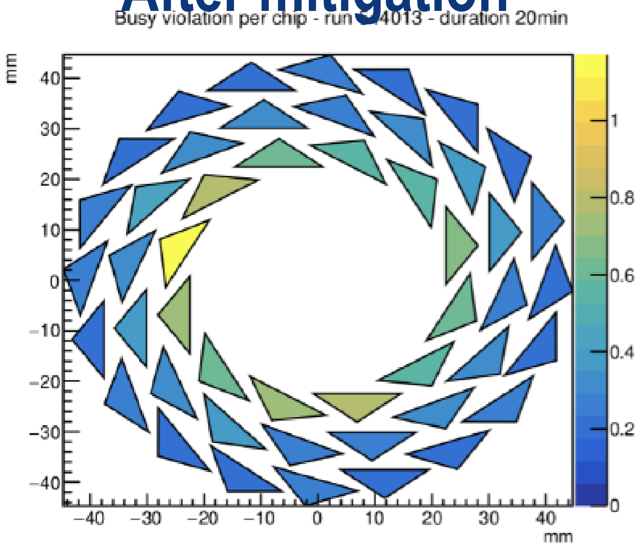
- **Strong background observed in ALICE from the start of the ion run**
  - Some chips of ITS fully saturated, severely affecting acceptance
- **Crash effort launched**
  - 5 fills of machine studies + simulation campaign
- **Main source was identified:**
  - $^{207}Pb^{82+}$ produced in IR7 collimation
  - Hitting bottom jaw of B1 tertiary collimator in IR2
  - Particle shower reaching detector
- **Mitigation found and successfully implemented in operation**
  - Orbit bump implemented that modifies vertical dispersion - “on_disp” knob
  - Makes $^{207}Pb^{82+}$ miss the tertiary collimator

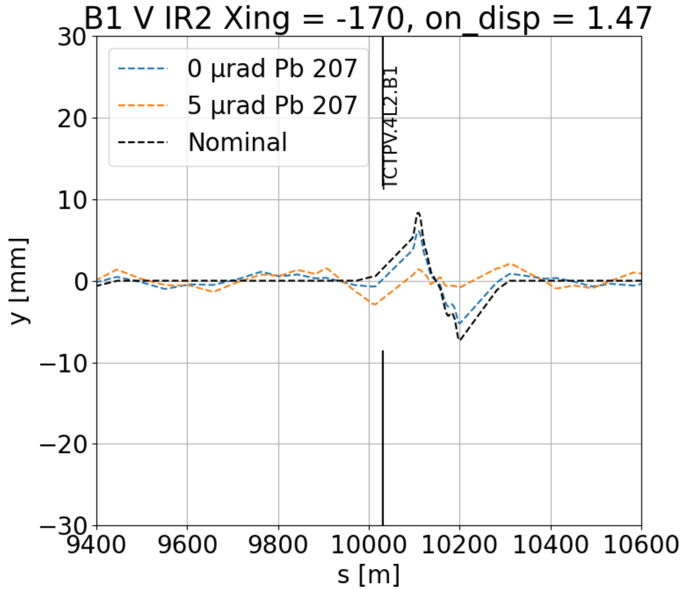
Before mitigation





After mitigation

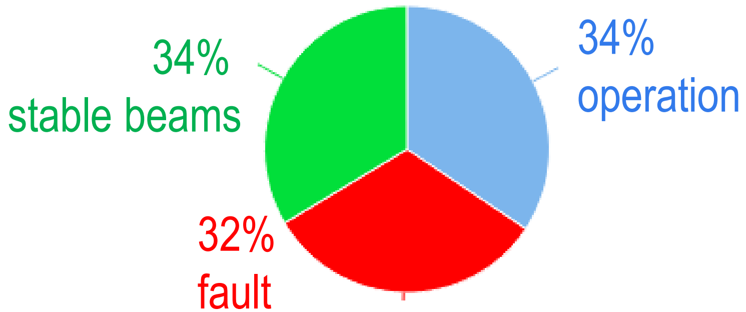




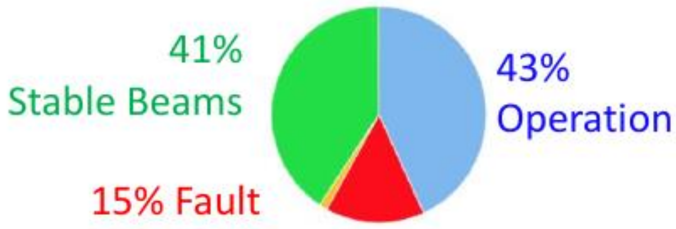
Availability and faults

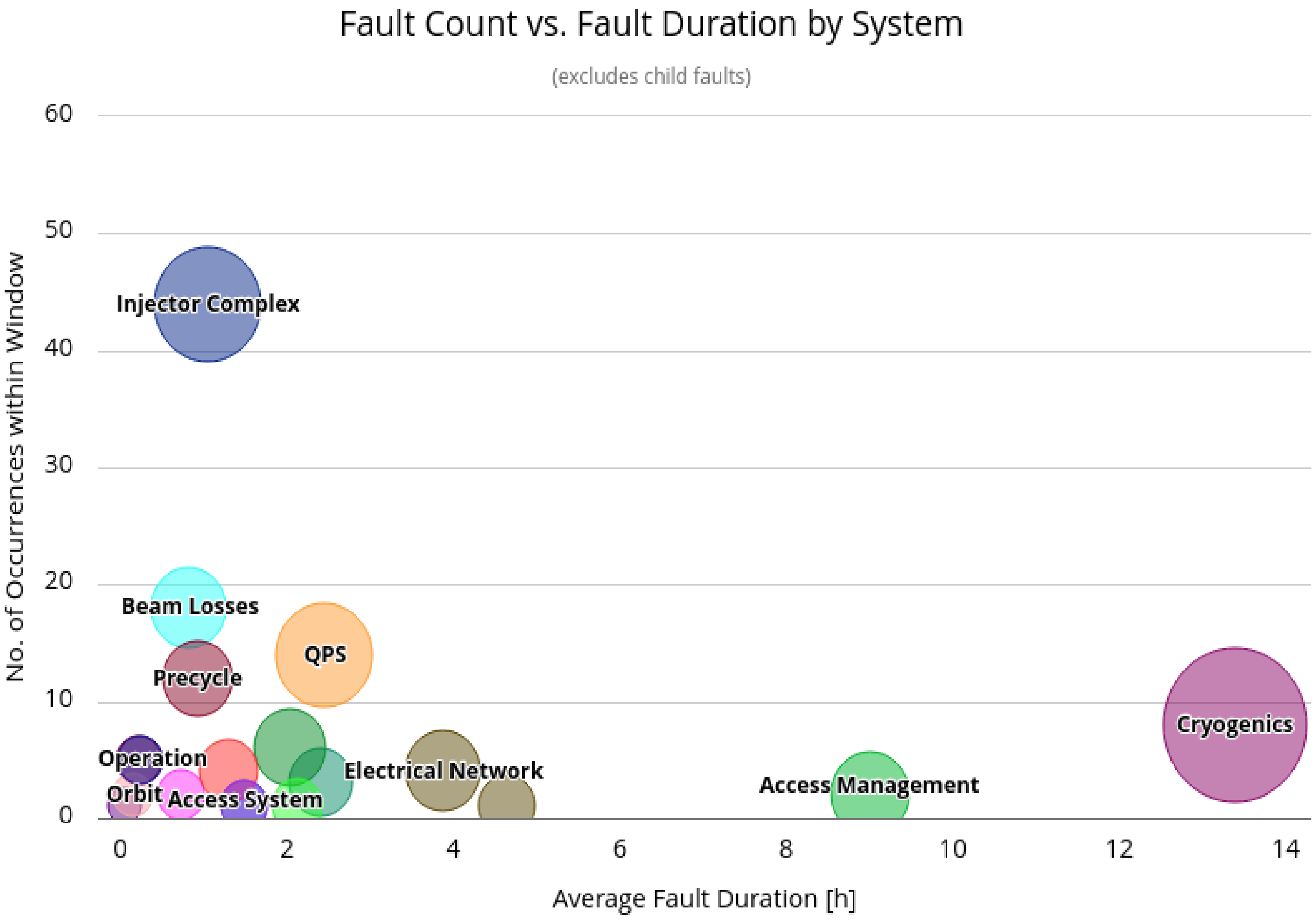
- About **one third of the time in stable beams, fault, and operation respectively**, excluding commissioning and MD

2023 Pb run



2018 Pb run





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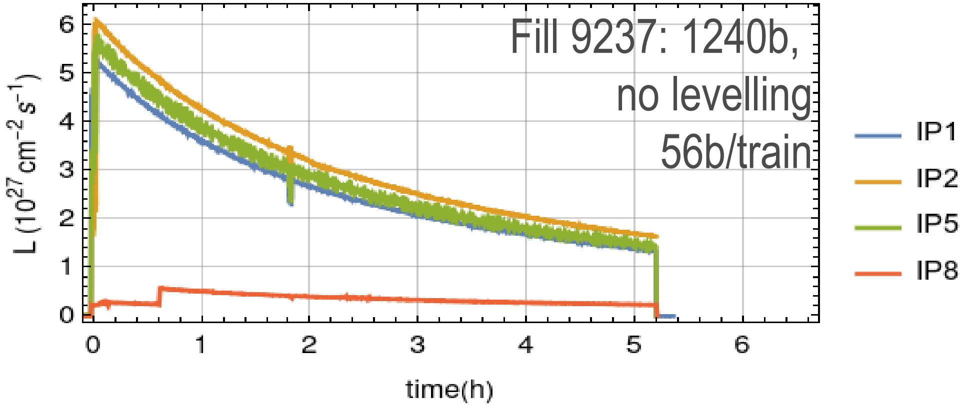
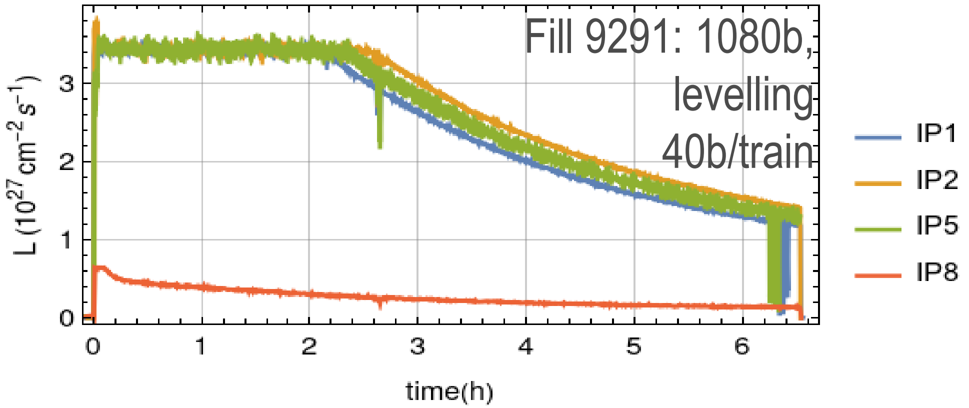
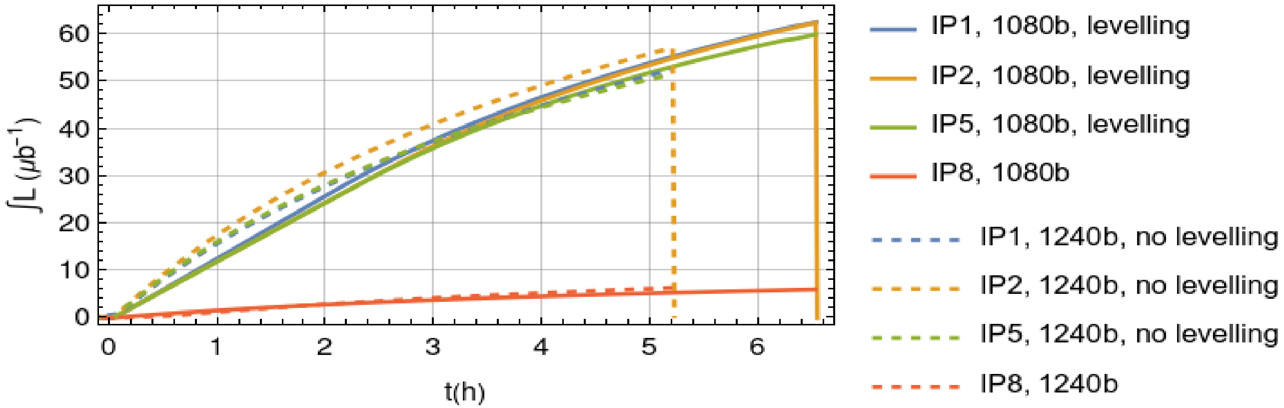
Example fills

- **At the start: 1240b, 56b-trains**
  - Baseline scheme foreseen before the run
- **Later: 1080b (or 960b), 40b-trains**
  - Shorter cycle in SPS with 40b-trains → higher bunch intensity in LHC
  - Levelled all fills with 40b-trains to mitigate single-event upsets on QPS
  - Typical levelling time <3h
- **Could produce around 50 μb^{-1} in about 5h**
  - Not a major difference between schemes
  - Detailed analysis pending – need to disentangle effects of levelling from bunch intensity and number of bunches

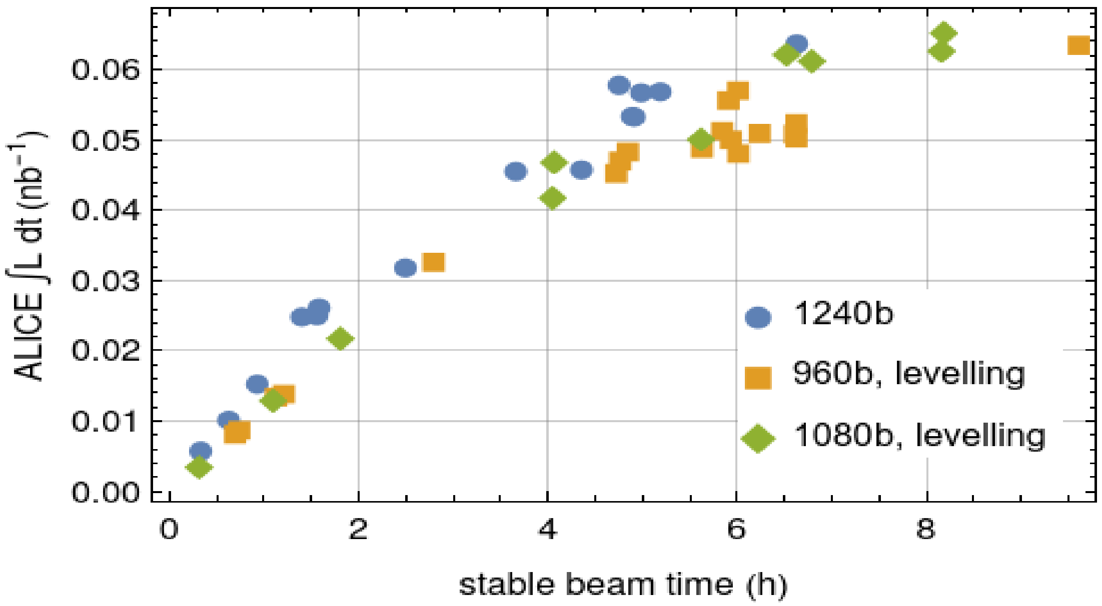


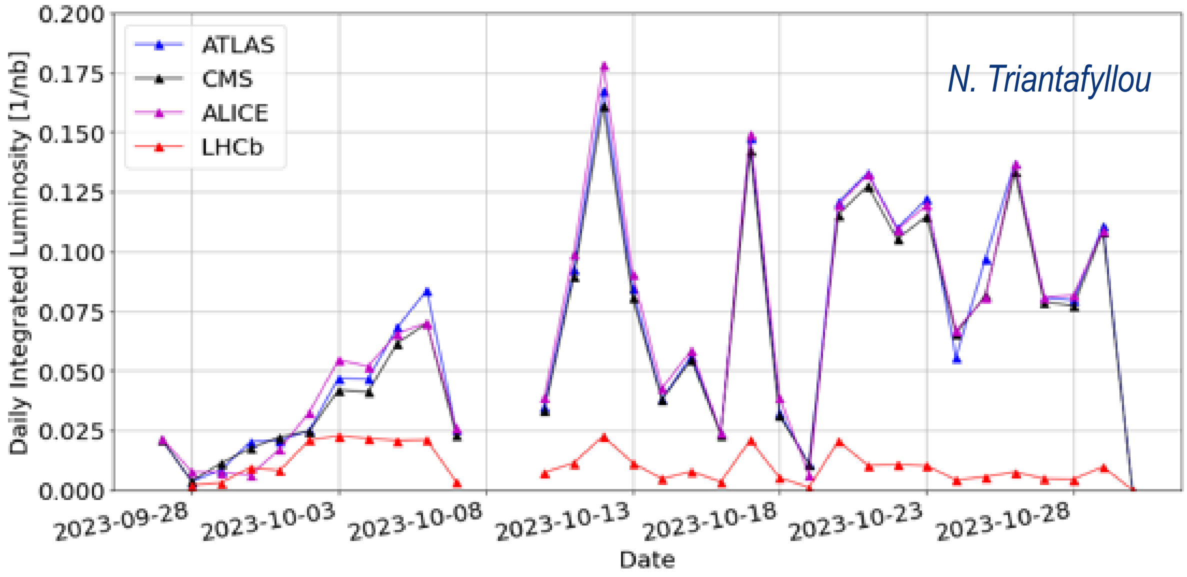




Luminosity production

- **Typically produced 40-60 μb^{-1} per fill** over 4-6 h, if no premature dump occurred
- **Could do up to three fills per day** if no downtime
- **Typical daily production of about 100 μb^{-1}**
  - reached 150 μb^{-1} or above on two occasions

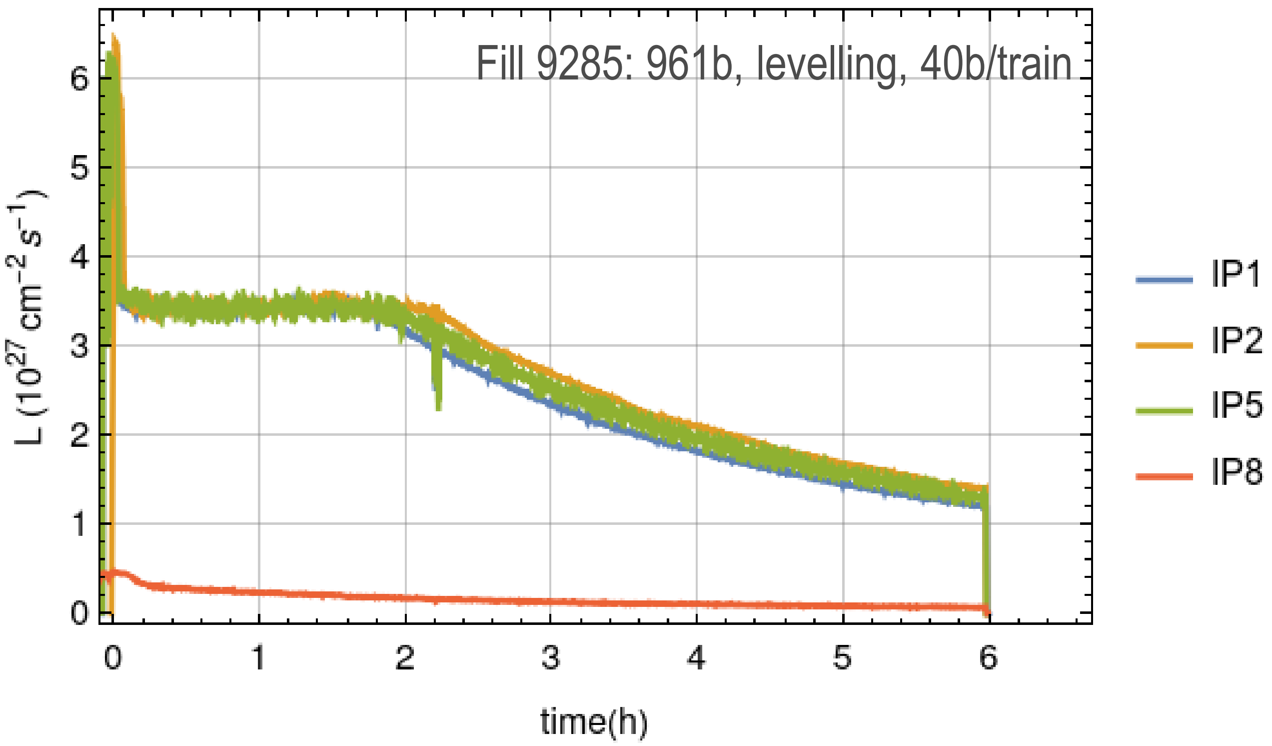




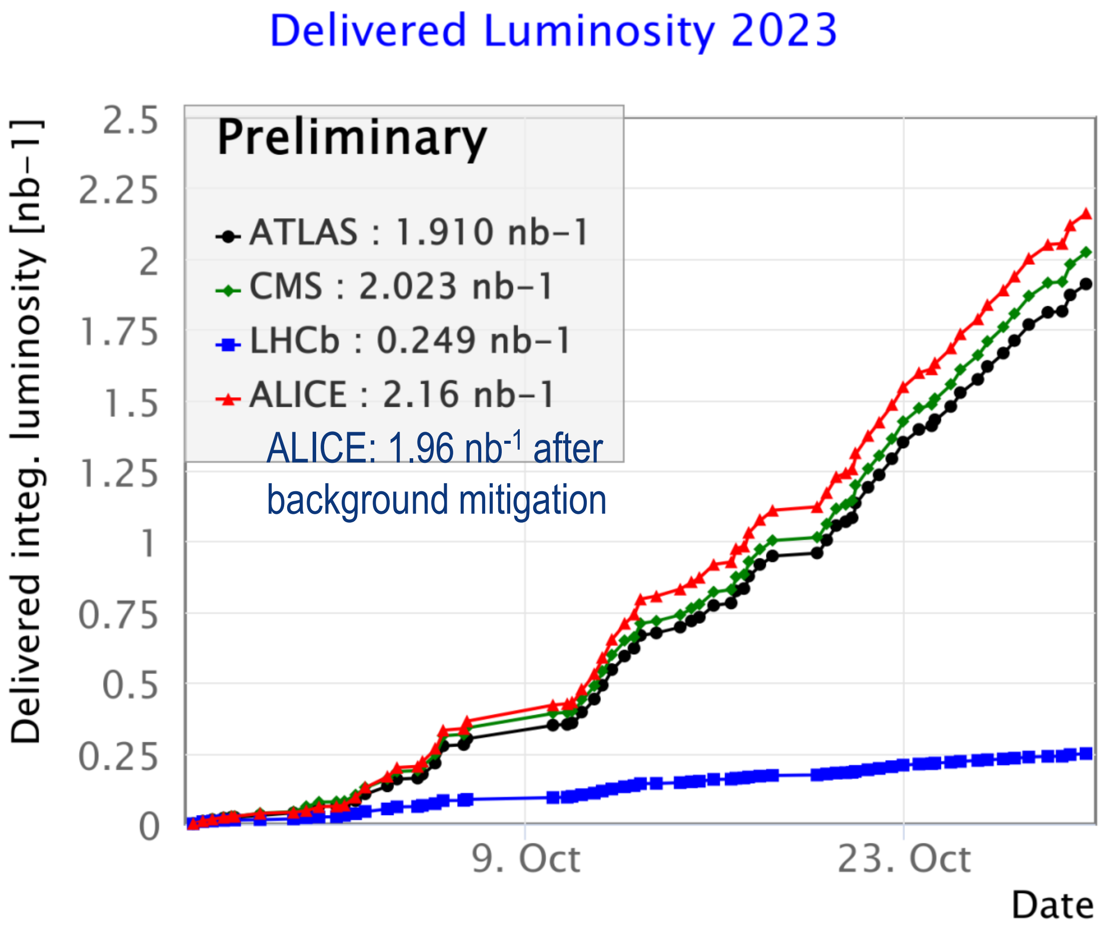
New record luminosity for Pb-Pb

- **Fill 9285 at ALICE: reached 6.4×10^{27} $cm^{-2}s^{-1}$**
  - Fill was levelled, but passed through peak while establishing the levelling
  - In 2018, reached 6.1×10^{27} $cm^{-2}s^{-1}$ at ATLAS/CMS

- **This fill had only 961 bunches**
  - On average **1.82×10^{8} Pb/bunch at start of stable beams**
    - this fill had also the highest bunch current in the run
  - Filling with 40-bunch trains



Summary of 2023 luminosity production, Pb-Pb

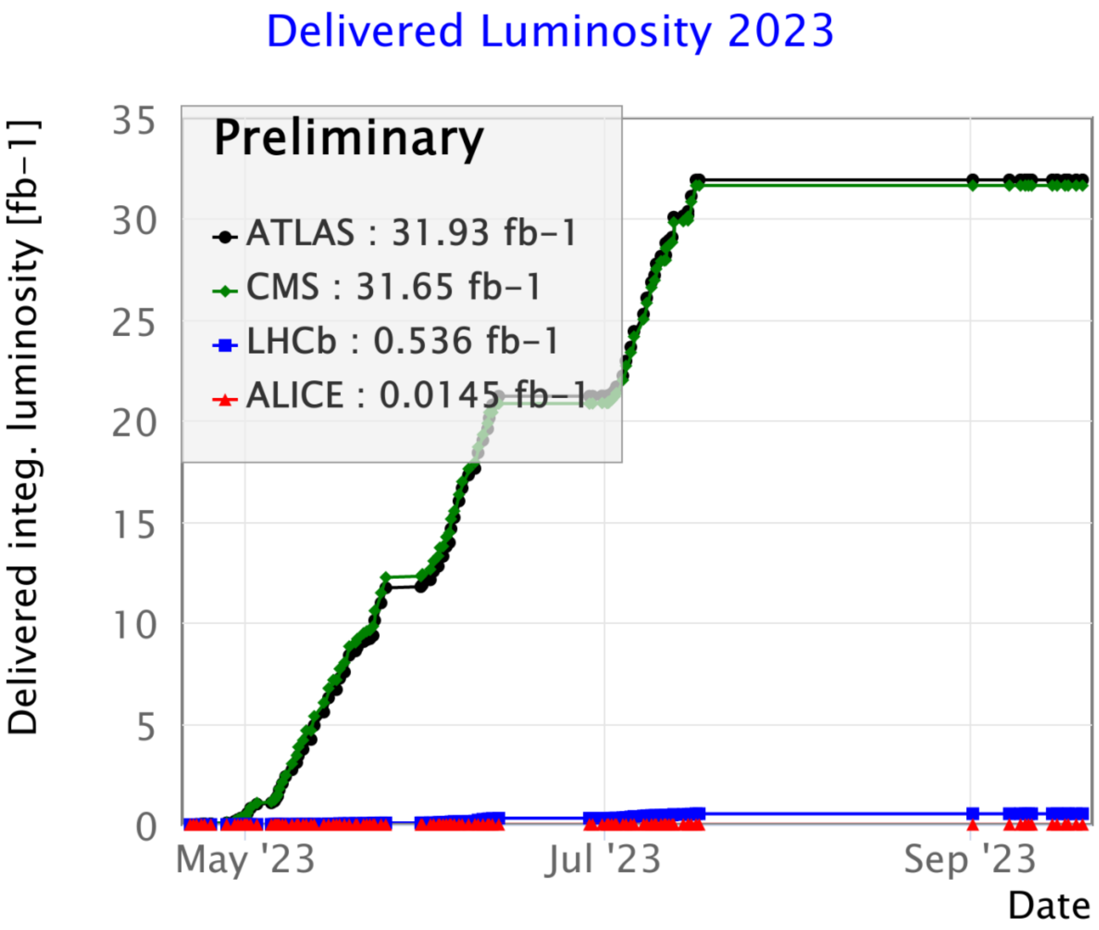


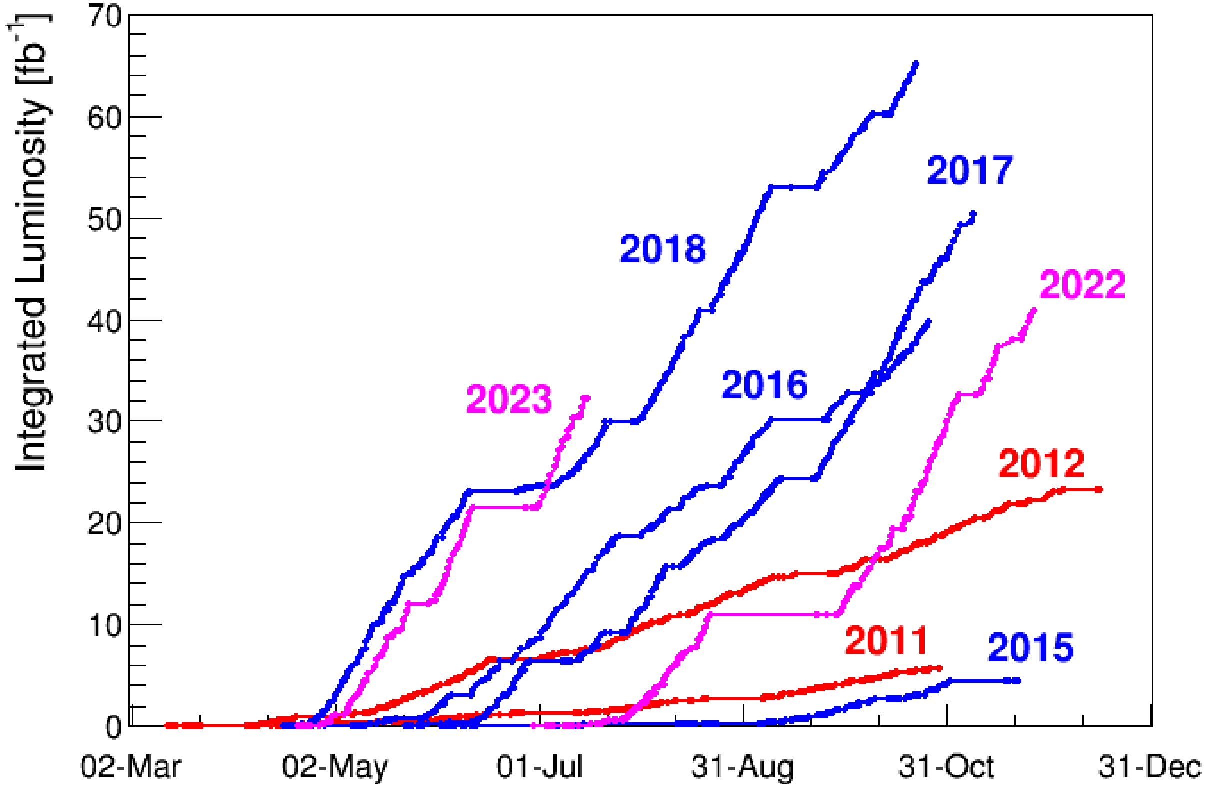
- **Integrated luminosity below initial targets**
  - Suffered from several problems (beam losses, faults), and lower beam brightness than hoped for
- **In spite of problems, pending luminosity calibration, all experiments collected more data than in 2018**
  - ALICE got more data than in Run 1 + Run 2 combined

Comparison 2018:

ATLAS: 1.797 nb^{-1}
CMS: 1.802 nb^{-1}
LHCb: 0.235 nb^{-1}
ALICE: 0.905 nb^{-1}

Summary of 2023 luminosity production, p-p





2023: very good slope until the IR8 triplet incident

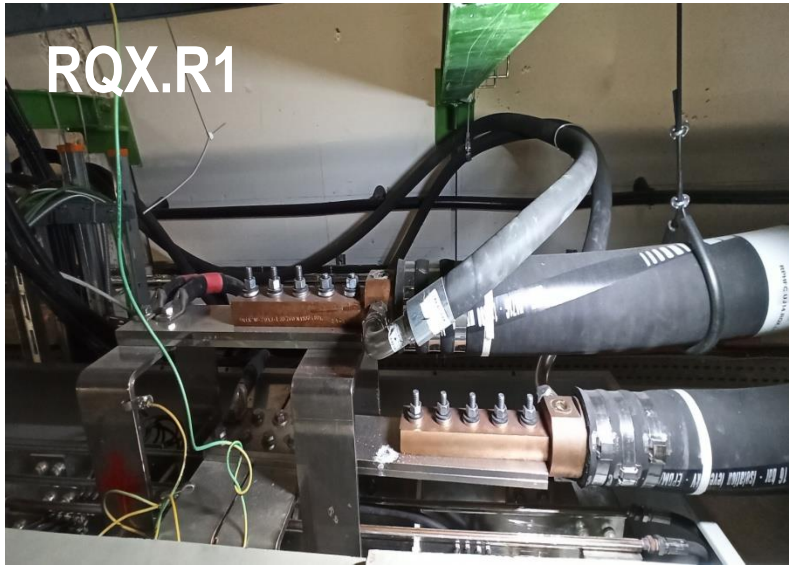
Outline

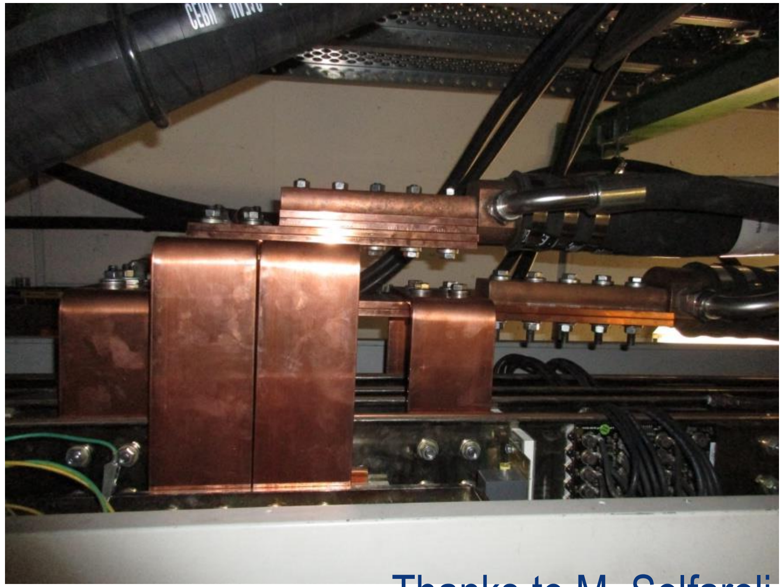
- **Status at last LHCC and main program since then**
- **Summary of high-β run**
- **Constraints on injected intensity and schedule update**
- **Summary of Pb ion run**
  - Beams and machine configuration
  - Problems encountered
  - Luminosity production
- **Reversed polarity powering test and outlook on 2024**
- **Conclusions**

Reversed polarity powering tests

- **Powering tests with reversed triplet polarity carried out in IR1**
  - In view of future LHC operation with reversed polarity → to reduce radiation on triplets and increase triplet lifetime
    - See LMC talk S. Fartoukh

- **IR1 circuits fully validated for operation at nominal current with reversed polarity (IP1 only)**
  - **NO limitations have been identified!**



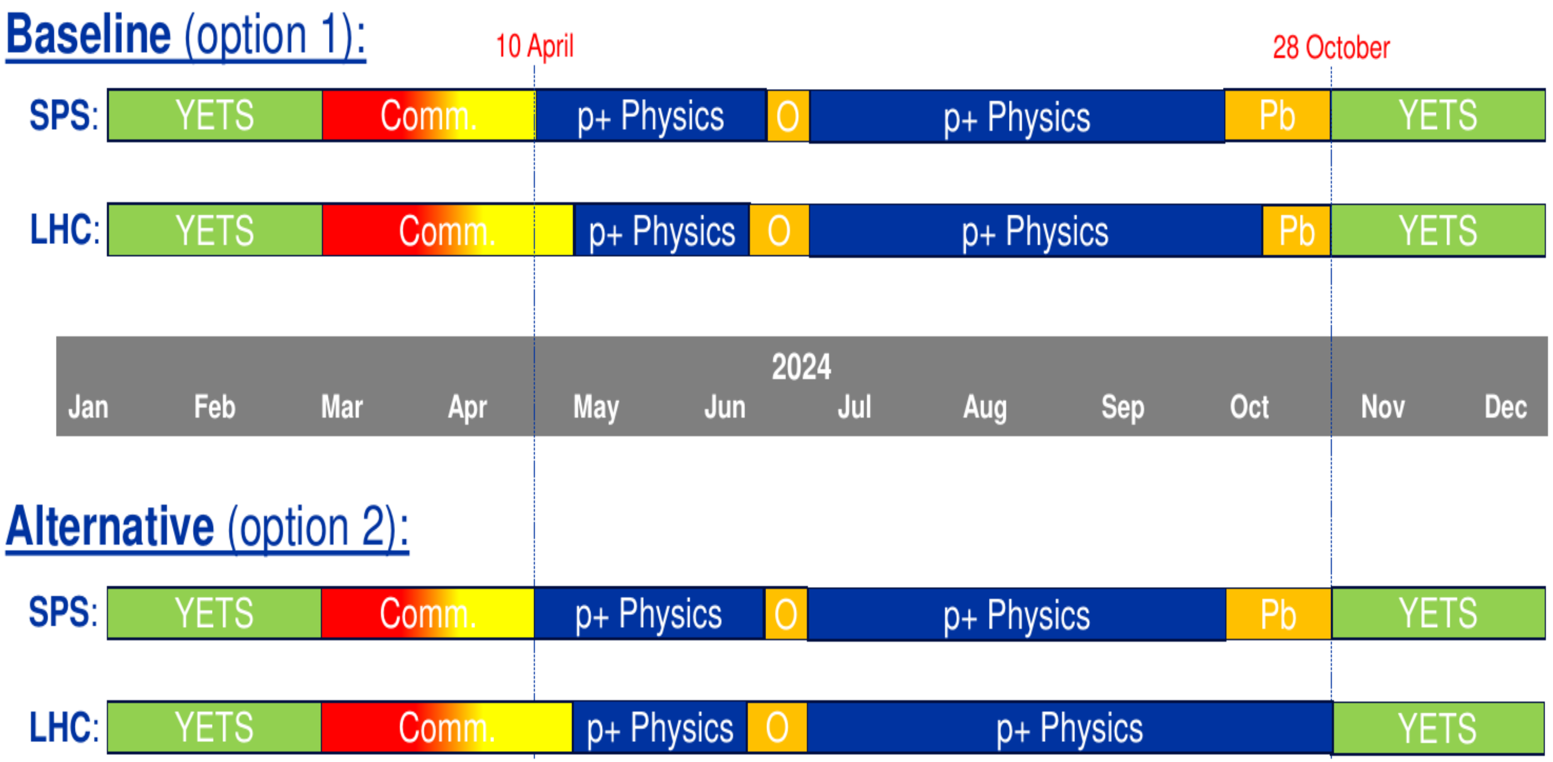


Thanks to M. Solfaroli

Outlook for 2024

- **Different schedule options under discussion**
  - Option 1: ion runs in both 2024 and 2025
  - Option 2: longer ion run in 2025 only

- **Start of 2024 LHC beam commissioning scheduled for March 11**



See LMC talk R. Steerenberg

Outline

- **Status at last LHCC and main program since then**
- **Summary of high-β run**
- **Constraints on injected intensity and schedule update**
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  - Luminosity production
- **Reversed polarity powering test and outlook on 2024**
- **Conclusions**

Conclusions

- **Coming out of an eventful year -** Some rocky periods and very dynamic planning
- **High-β run:** Could accumulate ~300 μb^{-1} in spite of challenging machine configuration
- **Pb-Pb run relied on many new concepts**
  - Slip-stacked 50 ns beams, Crystal collimation, TCLD collimators + BFPP bump in IR2, BFPP bump in IR8, full squeeze in ramp
- **Pb-Pb run faced several problems under time pressure – important lessons learned for the next Pb-Pb run**
  - Ongoing studies to improve understanding and define mitigation measures
- **Major achievements in 2023 Pb-Pb run**
  - Demonstrated slip-stacked beams → 70% more bunches than in 2018
  - Demonstrated factor 6 higher ALICE luminosity thanks to new TCLD collimators and orbit bumps
  - Operational deployment of crystal collimation with demonstrated performance gain
  - In spite of the issues, pending luminosity calibration, delivered more integrated luminosity than in 2018 to all experiments
  - Delivered more integrated luminosity at ALICE than in Run1+Run2
  - Record peak luminosity
- **Schedule for 2024 – 2025 under discussion**

Thanks for the attention!

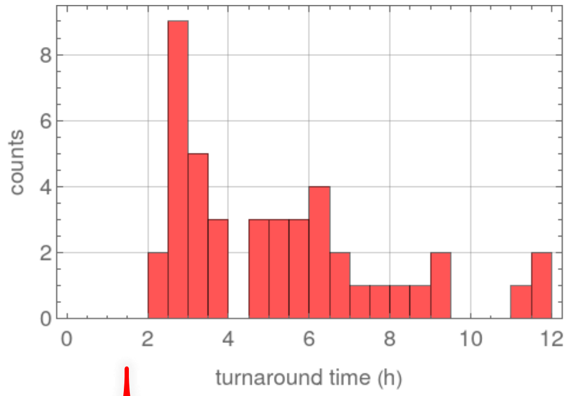
BACKUP

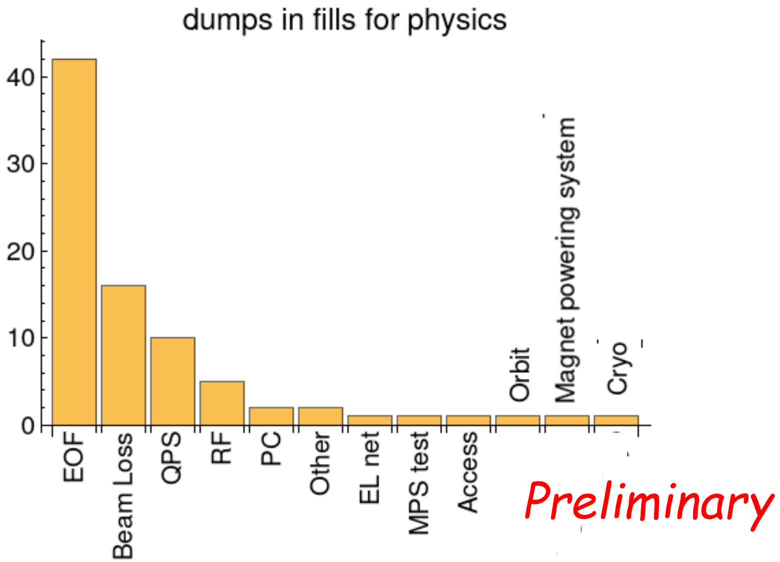
Fill statistics for ion run

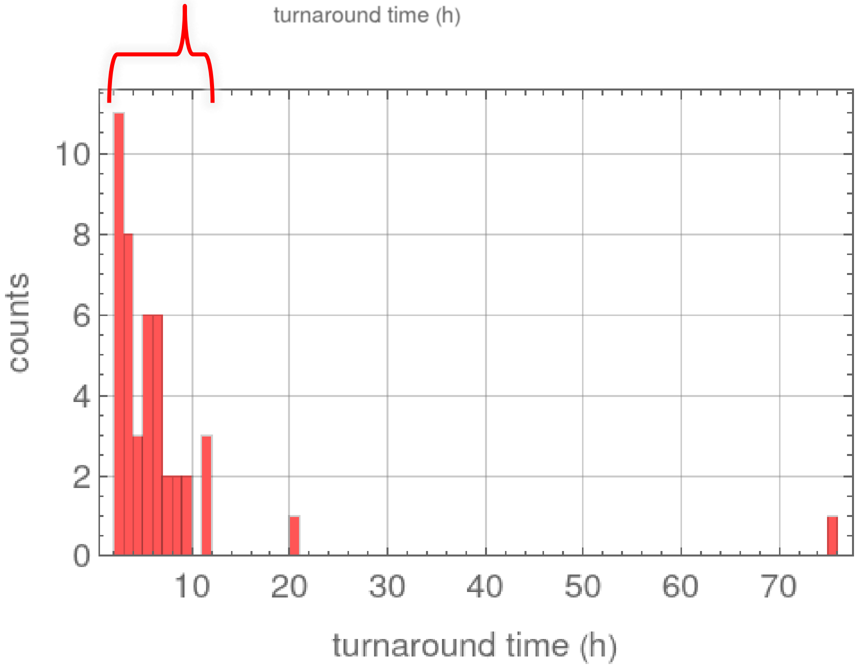
- **Physics fills** (preliminary analysis)
  - 83 fills attempted for physics
  - 67 reached stable beams
  - 42 dumped by operator at end of fill

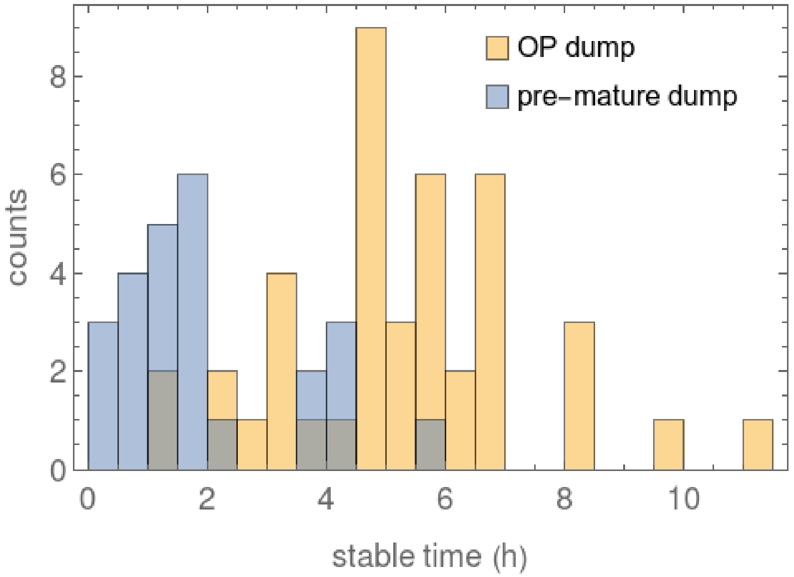
- **Typical stable-beam** time of 4.5-7 h for fills dumped by operator

- **Turnaround time** (for fills with ≥960 bunches)
  - Min 2.3h
  - Mean 7.2h
  - Median 5.2h



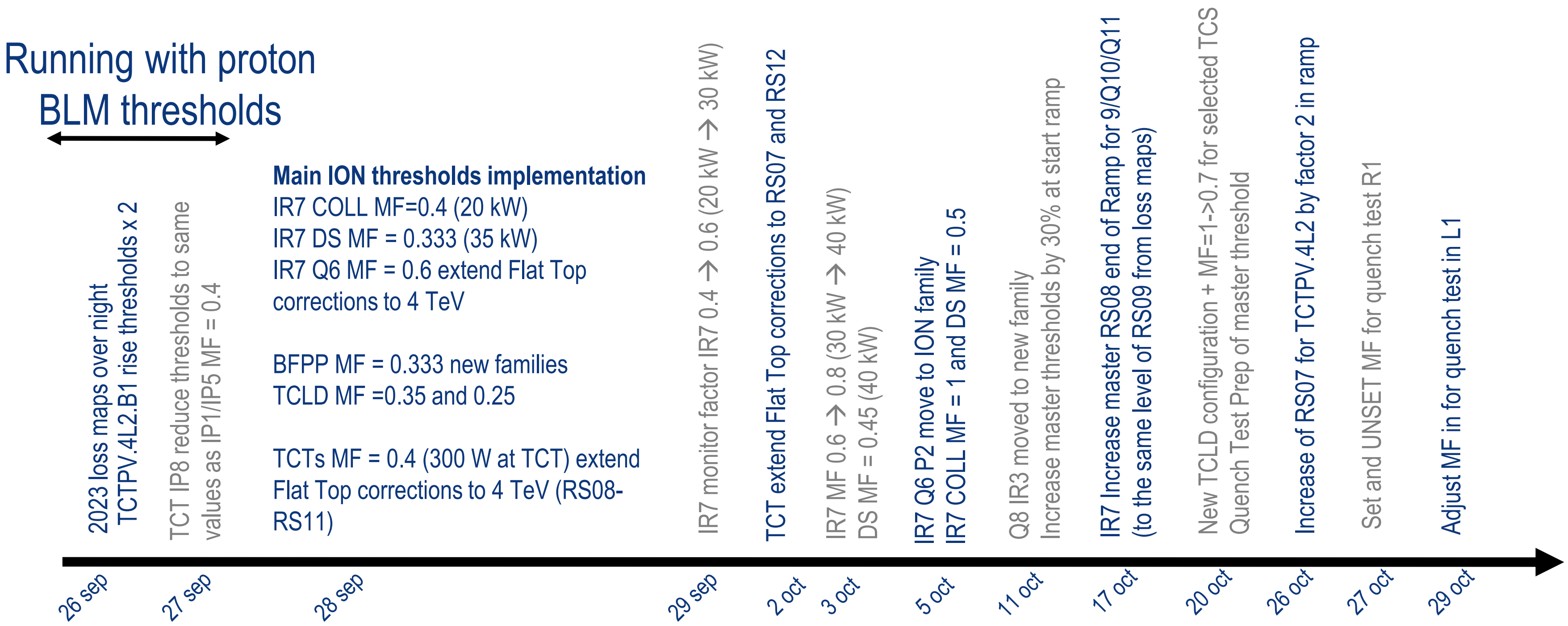






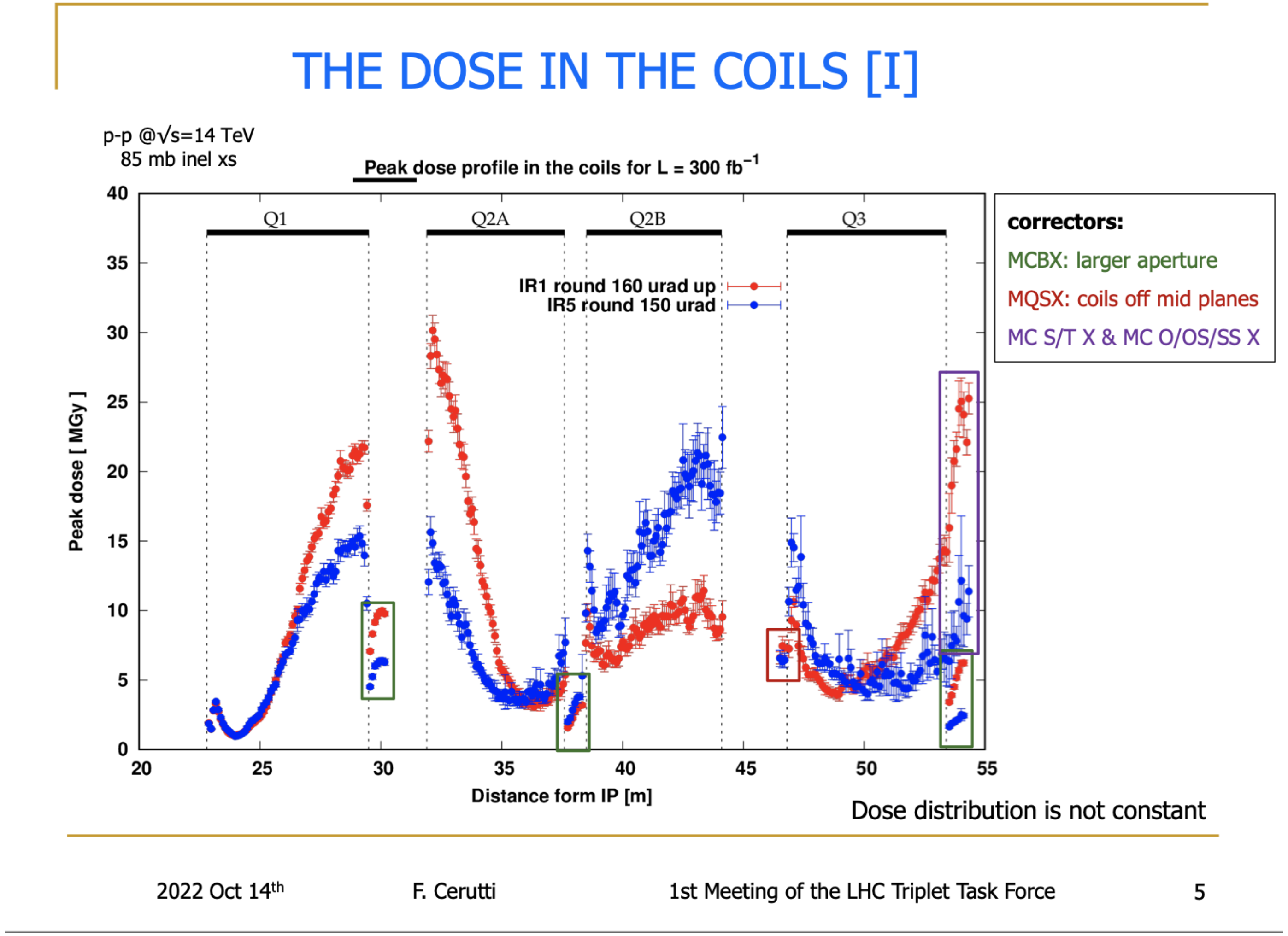
BLM thresholds

- **In total, BLM threshold changes on 13 different days**
  - General strategy agreed before run → see LMC 471
  - All changes discussed with MPP, collimation and other relevant teams beforehand
- **For next ion run, BLM thresholds should be thoroughly reviewed**



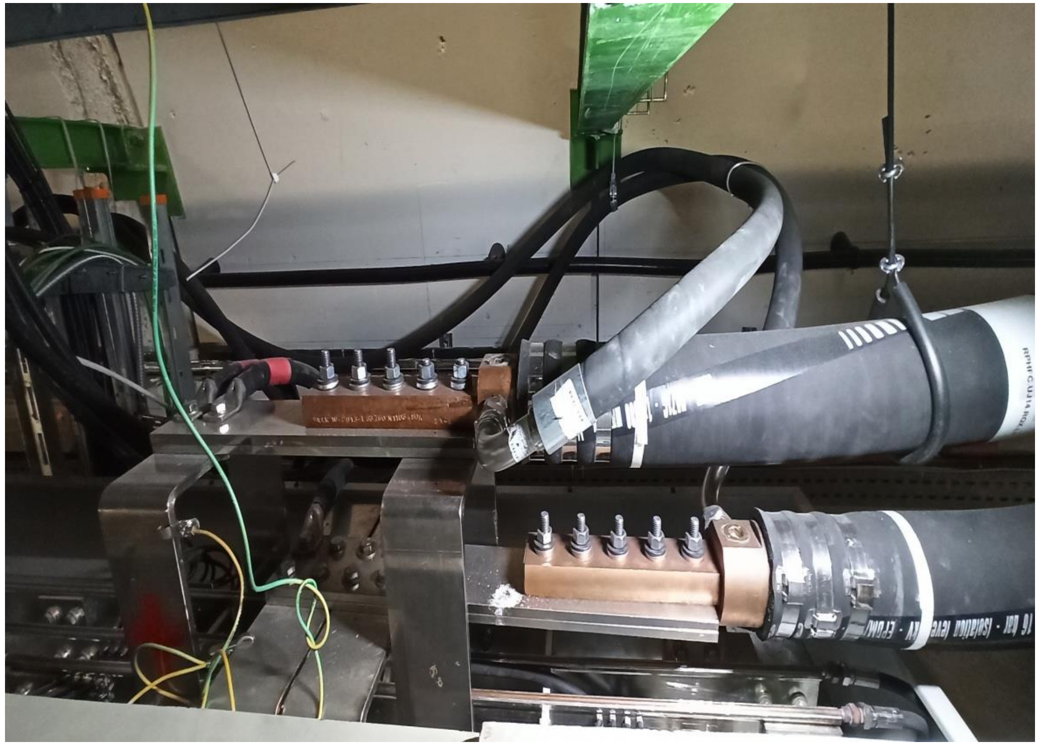
Many thanks to A. Lechner, S. Morales Vigo, B. Salvachua for continuous follow-up

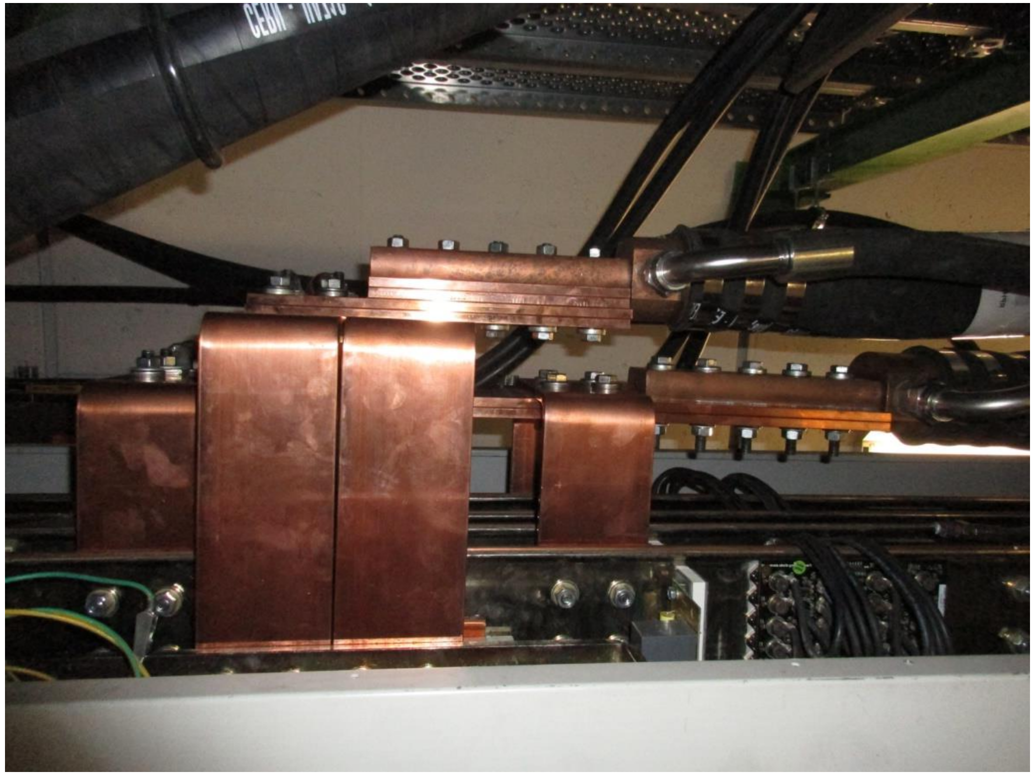
Radiation on IT - distribution



The **IT taskforce** is mandated to carry out a full analysis of the **impact of radiation on the lifetime** of equipment in the LHC **inner triplet regions** and to propose possible mitigation measures

Example of RQX.R1





Status

Some activities (disconnection of the cables from DFBX+pressurization) skipped, due to **non- significant movement** of the cables:

- Not obvious, although hoped for
- Faster inversion
- No long access needed to DFBX

	RQX.R1	RQX.L1
Polarity reversal	COMPLETED	COMPLETED
Circuit unlock	COMPLETED	COMPLETED
Interlock tests	COMPLETED	COMPLETED
Current tests	COMPLETED	COMPLETED

The identified activity breakdown is:

- RP survey (HSE-RP) – 2 hours
- Lock-off (consignation) the power converters (SY-EPC/EN-ACE) – 2 hours
- Switch-off the Quench Heater power supply (TE-MPE) – 30 minutes
- Installation of a scaffolding around the power converters (SY-EPC) – ½ day
- ~~Disconnection of the DC cables from the DFB (TE-MPE) – 2 hours~~
- ~~Depressurization of the DC cables (EN-CV) – 1 hour~~
- Disconnection of the DC cables from the power converter (SY-EPC + EN-EL to support in case repositioning is needed) – 1 hour
- Installation of the new metal pieces on the power converter and reconfiguration of the FWD (Free Wheeling Diode), the FWT (Free Wheeling Thyristor) and the RTQX1 power converter (SY-EPC) – ½ day
- Re-connection of the DC cables to the power converter (SY-EPC/EN-EL) – 1 hour
- ~~Pressurization of the DC cables (EN-CV) – 1 hour~~
- ~~Re-connection of the DC cables to the DFB (TE-MPE) – 2 hours~~
- Removal of a scaffolding around the power converters (SY-EPC) – 3 hours
- Unlock (de-consignation) the power converters (SY-EPC/EN-ACE) – 2 hours
- Switch-on the Quench Heater power supply (TE-MPE) – 30 minutes

The circuits have been fully validated for operation at nominal current with reversed polarity (IP1 only).

NO limitations has been identified!

Thanks to M. Solfaroli