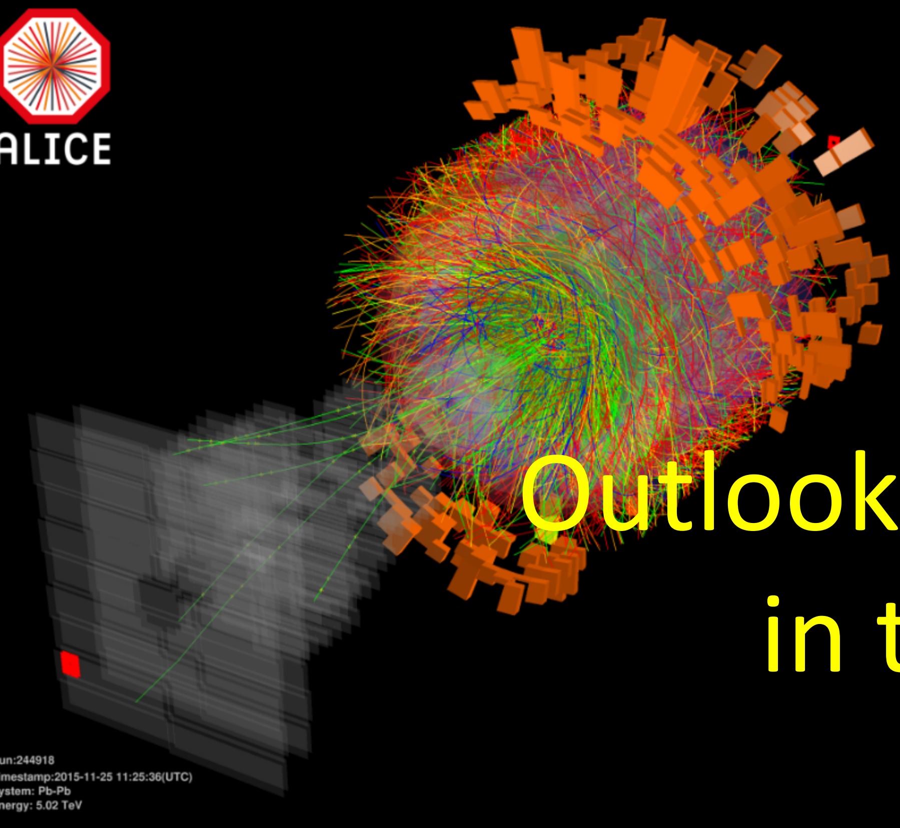
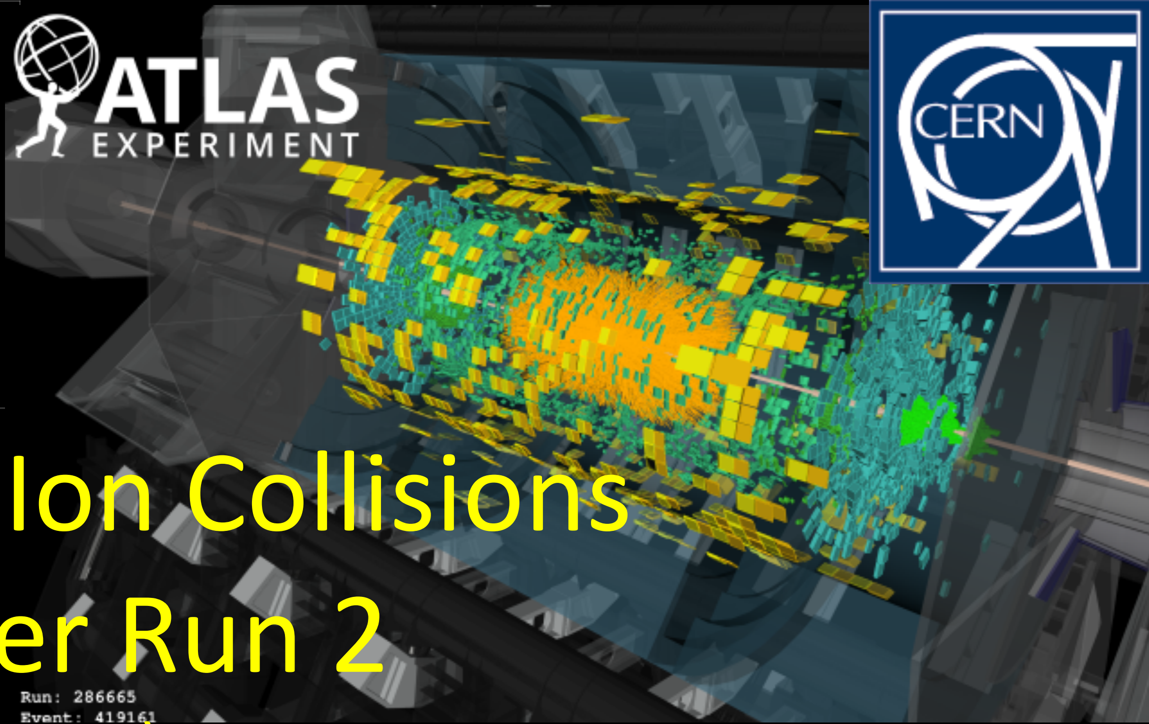
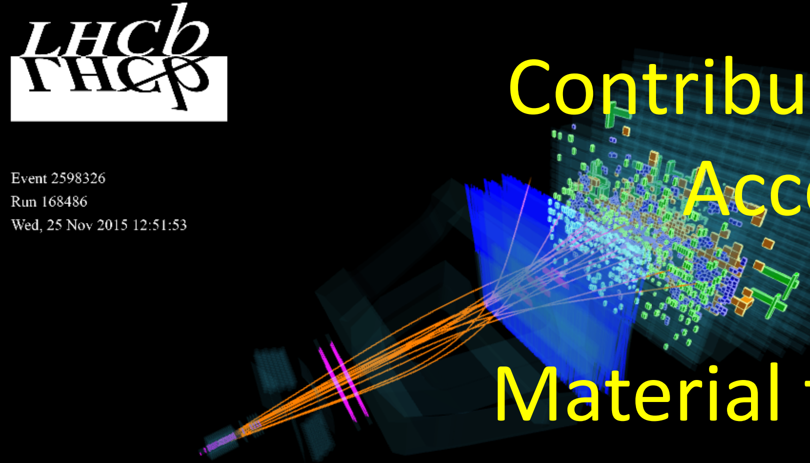
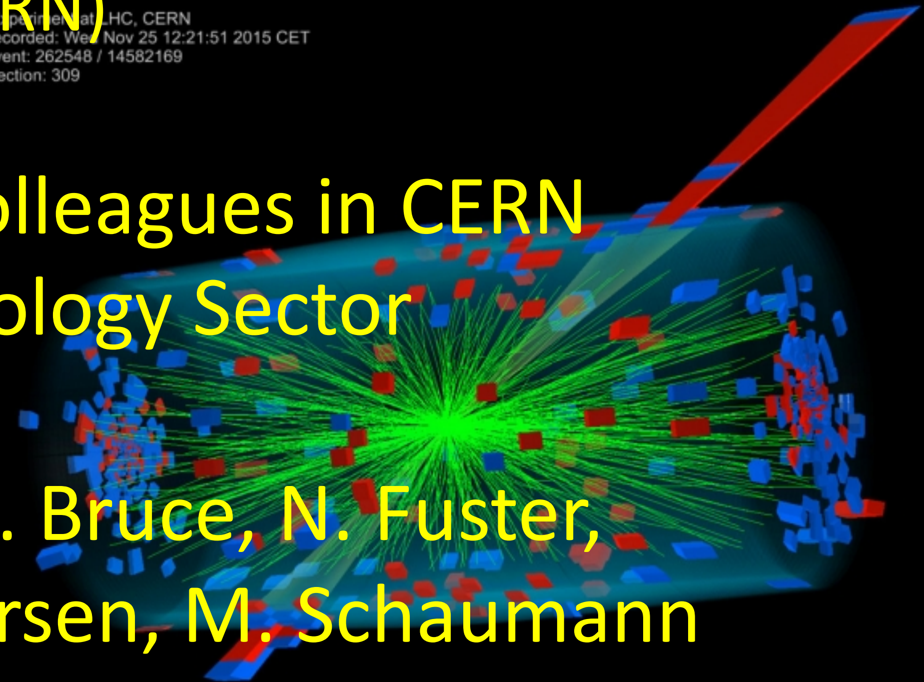
Outlook for Heavy-Ion Collisions in the LHC after Run 2

John Jowett (CERN)









Contributions from many colleagues in CERN Accelerator and Technology Sector

Material from R. Alemany, R. Bruce, N. Fuster, A. Lechner, D. Mirarchi, B. Petersen, M. Schaumann

Abstract

- Last reported at EPS HEP 2011 – after first Pb-Pb run in 2010.
- LHC Run 2 ended with the 2018 Pb-Pb collision run, during which a luminosity 6 times beyond the design was achieved by further exploiting mitigations of the phenomena limiting luminosity that had been established in the 2015 run.
- Similar records were achieved with p-Pb collisions in 2016, a complex run, within a tight time frame, providing data sets at different energies, both in minimum-bias and high-luminosity modes.
- In 2017 a short Xe-Xe collision run demonstrated the collider's flexibility with new species and further extended the physics programme.
- We discuss the prospects for achieving the luminosity goals defined for Runs 3 and 4 and the potential for colliding lighter nuclei.
- Update on plans for O-O and p-O collisions in Run 3.

History and Future of Nuclear Beams in the LHC

12 one-month heavy-ion runs between 2010 and 2030. **6/12 done.**

Upgrade: new collision mode
16h p-Pb *pilot run*

1st p-Pb
high luminosity run
@ 4 Z TeV

p-Pb
@ 4 Z TeV
@ 6.5 Z TeV

LS2 Hardware Upgrades:
- ALICE detector upgrade to 7 x design luminosity
- Dispersion Suppressor collimators for BFPP losses.
- SPS RF (smaller bunch spacing)

Run 1 | Run 2 | LS2 | Run 3 | Run 4

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 TODAY 2020 2021 2022 2023 2024 2025 2026 2027 2028

Short O-O and p-O runs under discussion for 2023

HL-LHC

Pb-Pb @ 6.37 Z TeV
3.5 x design luminosity

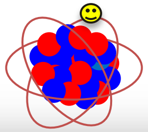
Pb-Pb @ 6.37 Z TeV
6.1 x design luminosity

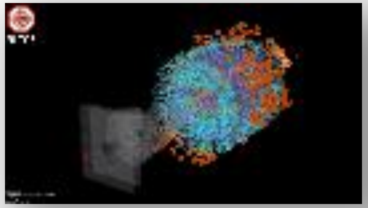
Pb-Pb @ 3.5 Z TeV
0.5 x design luminosity

New species
12h Pb^{81+} operation

1st Pb-Pb collisions
@ 3.5 Z TeV

New species
16h Xe-Xe operation





Run 5 | Run 6

2031 2032 2033 2034 2035 2036 2037

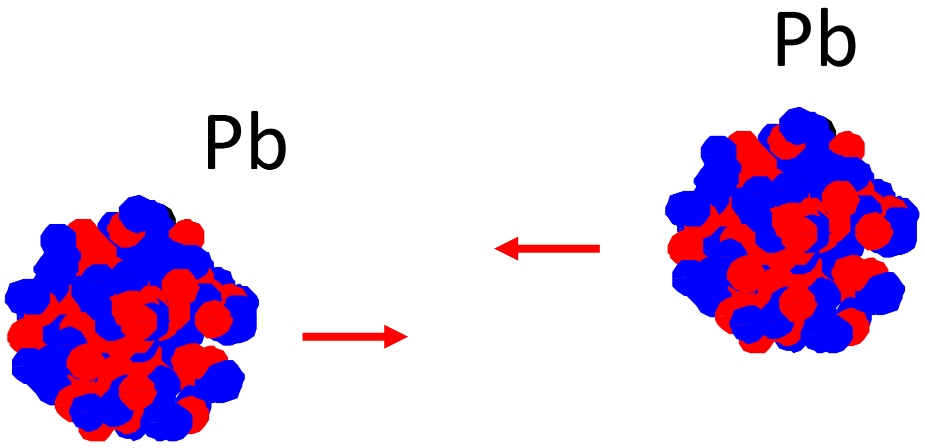
Currently no heavy-ion runs foreseen in Run 5 & 6, but a revised schedule is under discussion.

Runs with lighter nuclei (eg, Ar-Ar, …) proposed for after 2030, see HL-LHC physics report (input to European strategy)

Typical one-month heavy-ion run – highly schematic

- Commissioning new optics with protons
- First injection of ion beams,
- Run through cycle to collisions
- Validation steps through cycle: loss maps, asynchronous dumps to assure rigorous control of losses machine protection
  - Only once the cycle is established, cannot be changed again!
  - Beam-loss monitor dump threshold settings carefully tuned
- Beam intensity ramp-up in physics (constrained by machine protection)
- Luminosity production
- Van der Meer scans with normal physics optics
- Reverse ALICE muon spectrometer polarity
- Re-validate new configuration
- Intensity ramp-up again
- Luminosity production in new configuration
- Small number of essential machine development (MD) studies

Minute and careful planning of every step and beam-time management is crucial. Rapid adaptation and solutions to unforeseen problems.

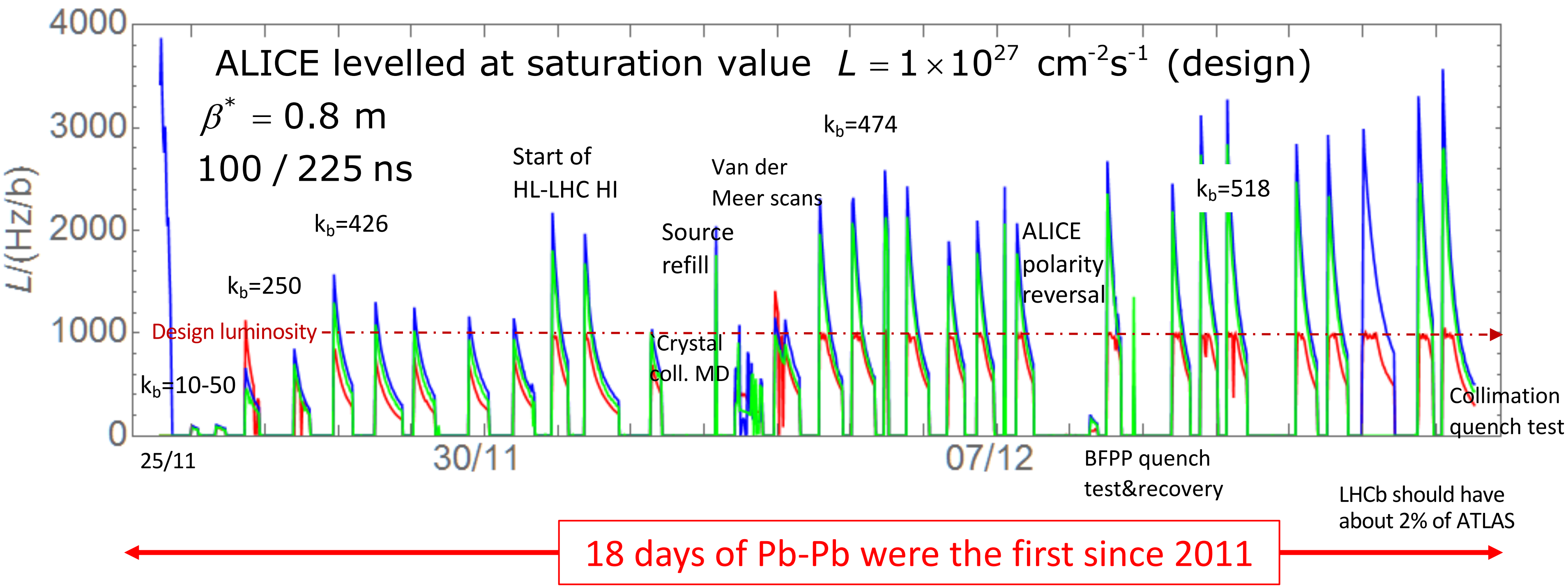


2015

First woman/man-made collisions with total CM energy > 1 PeV

https://home.cern/news/opinion/physics/new-energy-frontier-heavy-ions

Pb-Pb peak luminosity at 3×design in 2015



Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.

Luminosity limit: Ultraperipheral interactions (quasi-real photons)

"Strongest magnetic fields in the universe" (David D'Enterria, FCC Week 2019) of ~10^{15} T cause bound-free pair production and electromagnetic dissociation of nuclei

$$\text{BFPP:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+},$$

$$\sigma = 281\ \mathrm{b},\quad \delta = 0.01235$$

$$\text{EMD1:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n\ ,$$

$$\sigma = 96\ \mathrm{b},\quad \delta = -0.00485$$

Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

$$\delta = \frac{1 + \Delta m / m_{\mathrm{Pb}}}{1 + \Delta Q / Q} - 1$$

Strong luminosity burn-off of beam intensity.

Discussed for LHC since Chamonix 2003 … see several references.

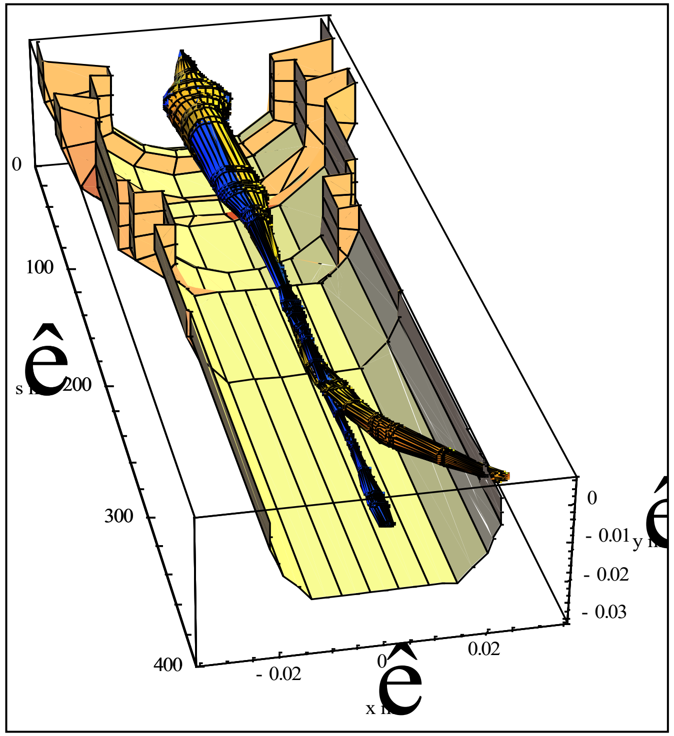
Hadronic cross section is 8 b (so luminosity debris contains much less power).

UPCs create secondary beams from IPs

- Long-standing concern (S. Klein 2001) about losses from bound-free pair production limiting luminosity below design

$$\text{BFPP:}\ {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$

$$\sigma = 281\ \text{b}, \quad \delta = 0.01235$$



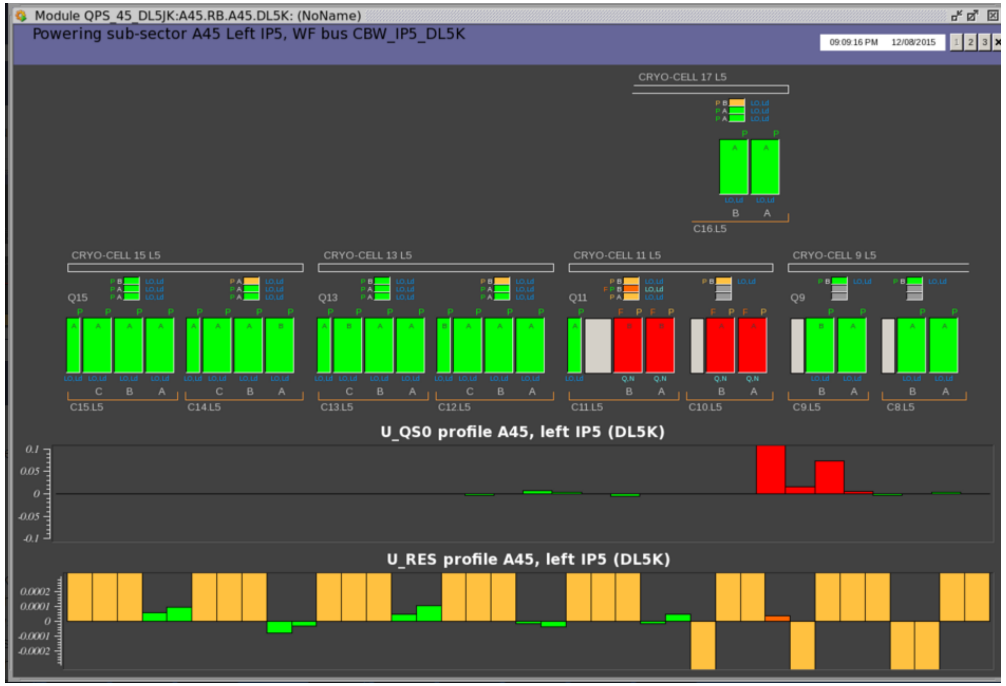
Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen.
Hadronic shower into superconducting coils can quench magnet.

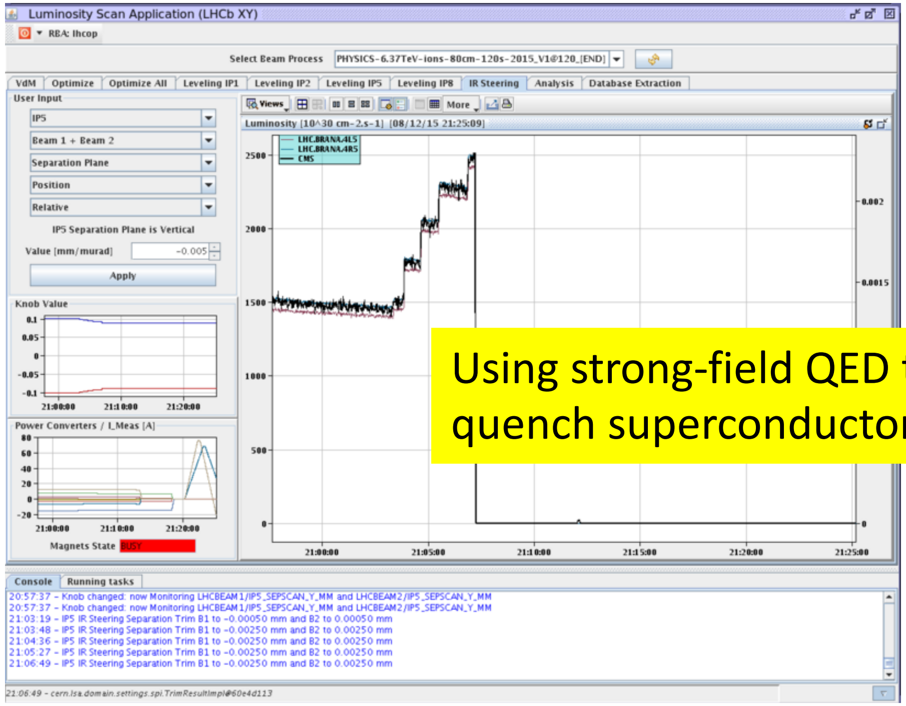
BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

$$L \approx 2.3 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

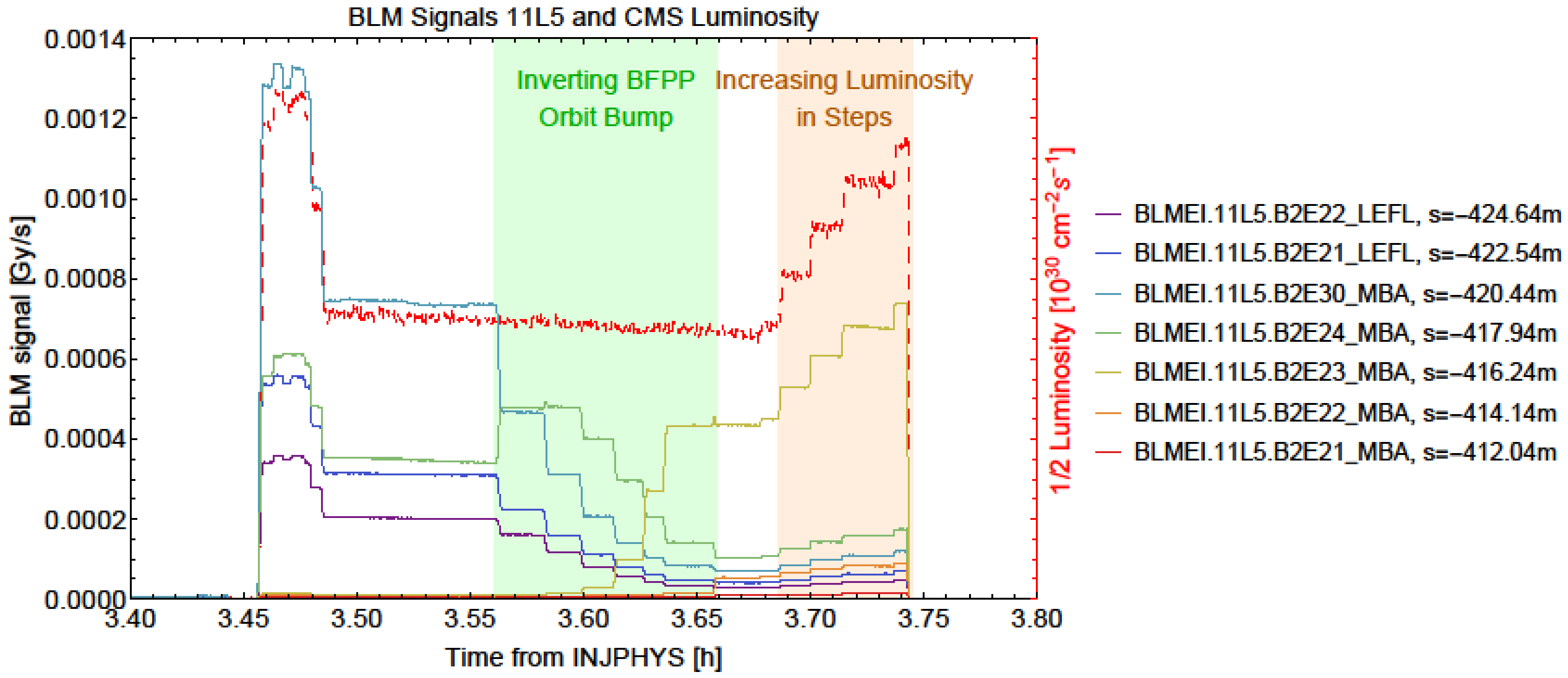
$$\Rightarrow\ \ 0.64\ \text{MHz event rate, about 45 W of power in } \mathrm{Pb}^{81+} \text{ beam into magnet}$$





Using strong-field QED to quench superconductor!

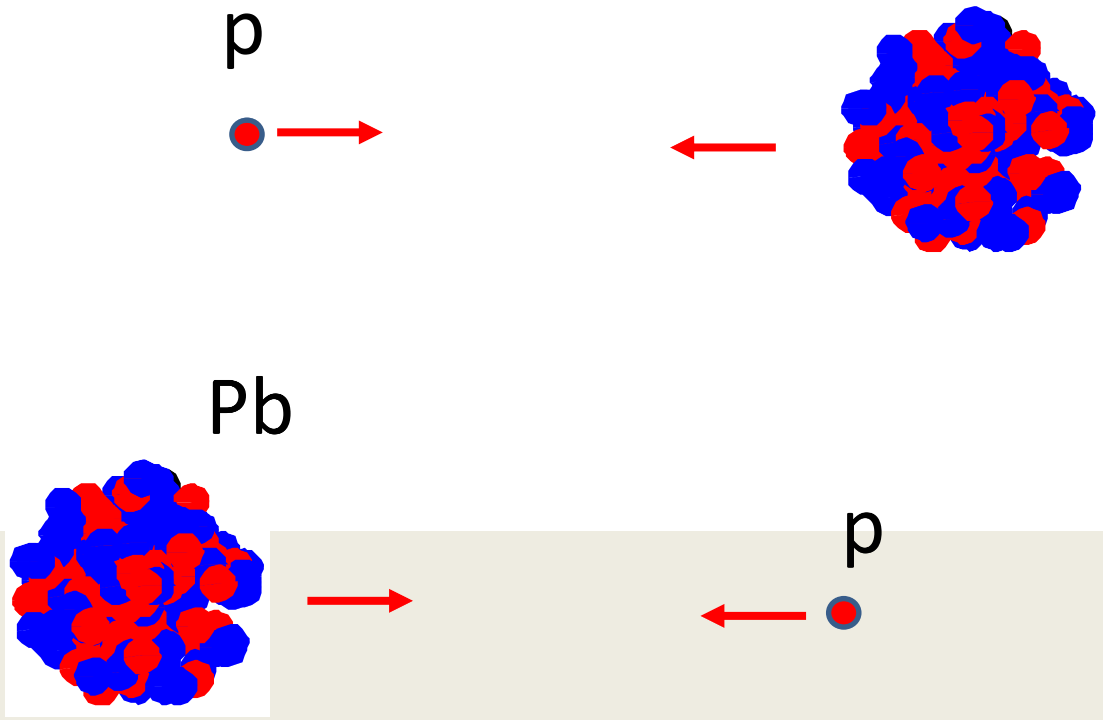
Luminosity and BLM signals during measurement



Intended to resolve decades of uncertainty about steady-state quench level of LHC dipole magnets.
But some uncertainties in interpretation because of chamber misalignment in this particular DS.L5.
Later a second collimation quench test with Pb was also successful.

Lessons from the 2015 Pb-Pb run

- Two new configurations within one month (p-p reference for a week and Pb-Pb) are possible.
- LHCb also takes Pb-Pb collisions at lowest ever $\beta^*=1.5$ m
  - Complicates filling schemes
- BFPP bumps successfully remove the peak luminosity limit for ATLAS, CMS (see later)
- Separation levelling used in ALICE (also in ATLAS, CMS)
- First controlled quench of an LHC dipole using BFPP beam from the collision point
- First successful collimation quench test (with any beam)
- After two Pb-Pb runs in 2010, 2011, the **High Luminosity Pb-Pb** phase started in 2015



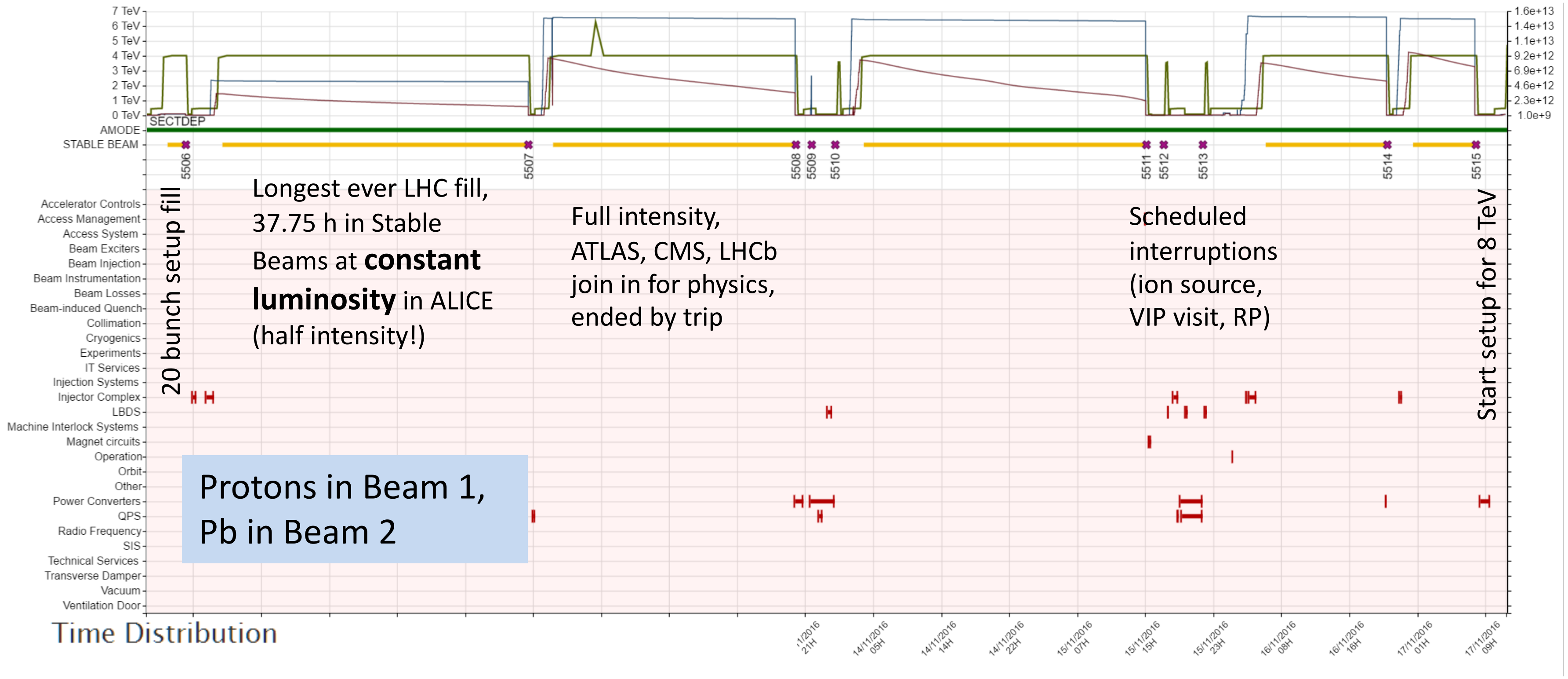
2016

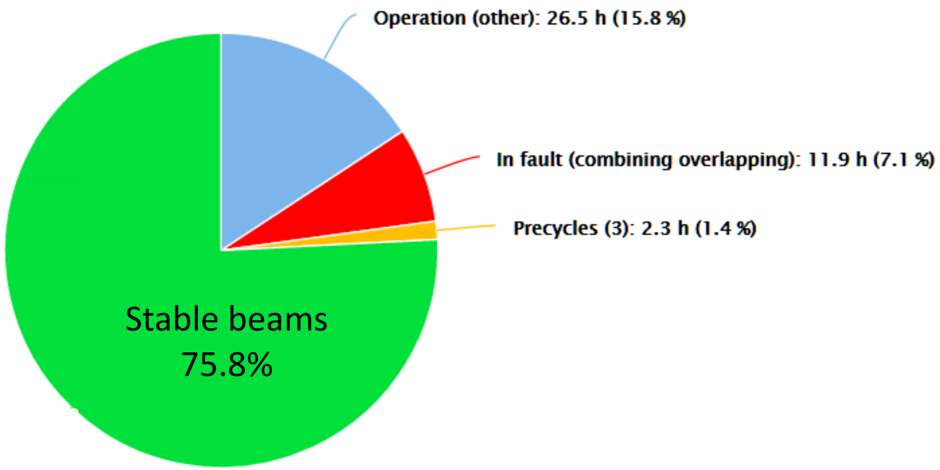
Initially the experiments requested different energies and luminosities and it was not clear how to resolve their differences.

ALICE preferred min-bias running at 5.02 TeV, ATLAS/CMS preferred max energy 8.16 TeV and high luminosity.

Proposed a plan to satisfy all requests within one-month time-frame.

Part 1: 1 week at 5 TeV, levelled luminosity for ALICE



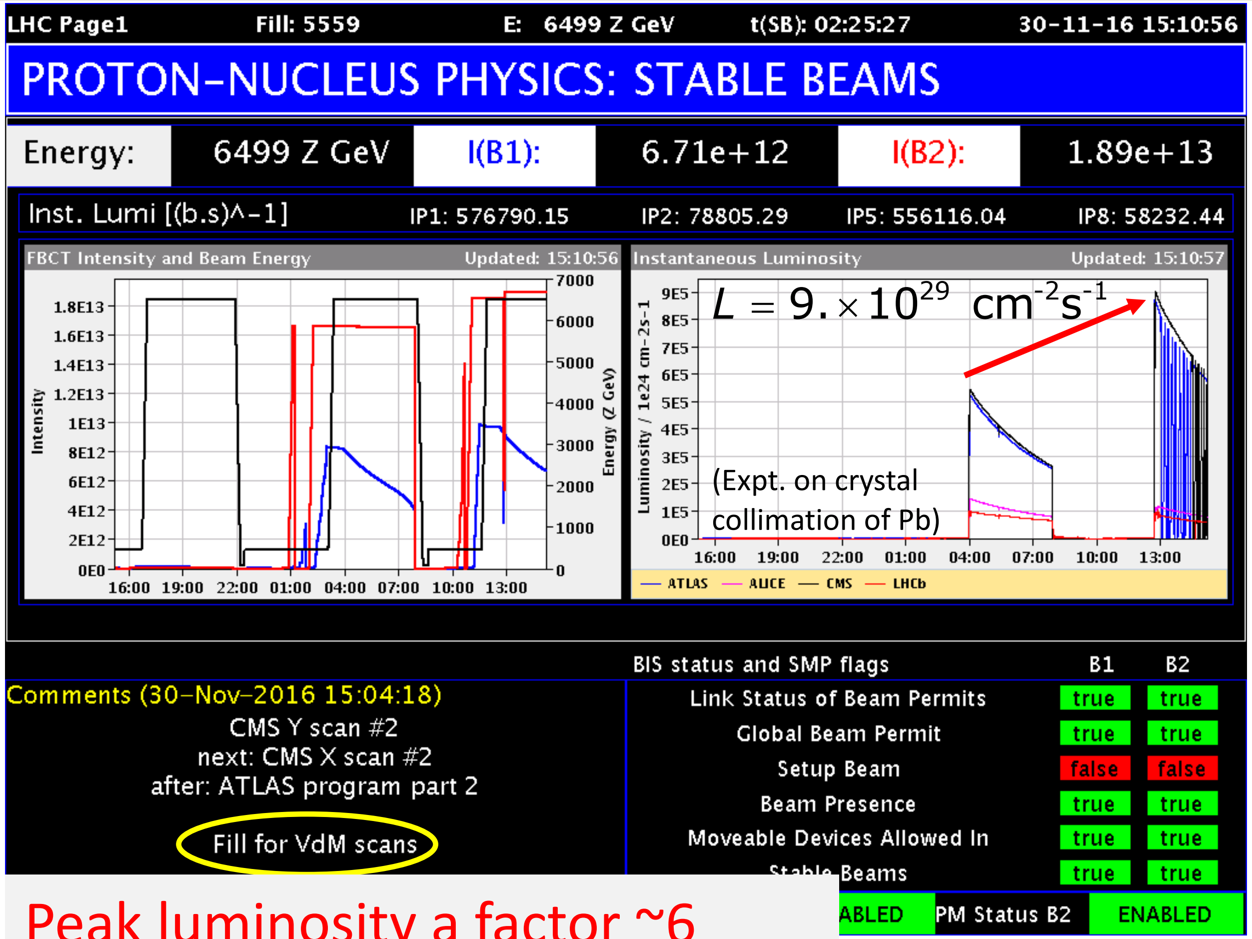


Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!

Part 2: Record Pb-p luminosity in ATLAS/CMS at 8.16 TeV



Peak luminosity a factor ~6 beyond original "design" value

(J. Phys. G 39 (2012) 015010)

Could have gone higher still by further increase of p intensity but limited at present by Pb beam luminosity debris in magnets of Sector 12.

Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

Increase in p intensity to ~3×10^{10}/bunch enabled by new synchronous orbit mode of beam position monitors (R. Alemany, J. Wenninger, beam instrumentation group …)

Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

Goals of p-Pb run surpassed

$\sqrt{s_{NN}}$	Experiments	Primary goal	Achieved	Additional achieved
5 TeV p-Pb (Beam energy 4 Z TeV)	ALICE (priority)	700 M min bias events	**780 M**	
	ATLAS, CMS			>0.4 /nb min bias
	LHCb			SMOG p-He etc
8 TeV p-Pb *or* Pb-p (Beam energy 6.5 Z TeV)	ATLAS, CMS	100 /nb	**194,183 /nb**	
8 TeV p-Pb	ALICE, LHCb	10 /nb	**14,13 /nb**	
	LHCf	9-12 h @ 10^{28} cm^{-2}s^{-1}	**9.5 h** @ 10^{28} cm^{-2}s^{-1}	Min bias ATLAS, CMS, ALICE
8 TeV Pb-p	ALICE, LHCb	10 /nb	**25,19 /nb**	

Note: ALICE and LHCb are asymmetric experiments, with different coverage according to beam direction.

Reminder: first 1 month p-Pb/Pb-p run at 5 TeV in 2013 gave 31/nb to ALICE, ATLAS, CMS and 2/nb to LHCb.

Lessons from the 2016 Pb-Pb run

- Remains the most complicated run of LHC so far.
- ≥ 4 new configurations within one month (Min. bias at 5.02 TeV, p-Pb, LHCf and Pb-p at 8.16 TeV) were possible.
- LHCb also takes p-Pb collisions at lowest ever $\beta^*=1.5$ m
  - Complicates filling schemes
- Proton intensity raised by synchronous operation of common BPMs
- First heavy-ion run where *luminosity debris of Pb beam* was significant, so we could not reach peak luminosity limit for ATLAS, CMS
  - Better TCL settings should overcome this in future runs
- Separation levelling used in ALICE (also in ATLAS, CMS)
- After two p-Pb runs in 2012, 2013, the **High Luminosity p-Pb** phase started in 2016

2017 - NO RUN SCHEDULED … AT FIRST

But Xe beams were available in the injectors for fixed target physics …

Xe-Xe collisions in LHC, 13 October 2017

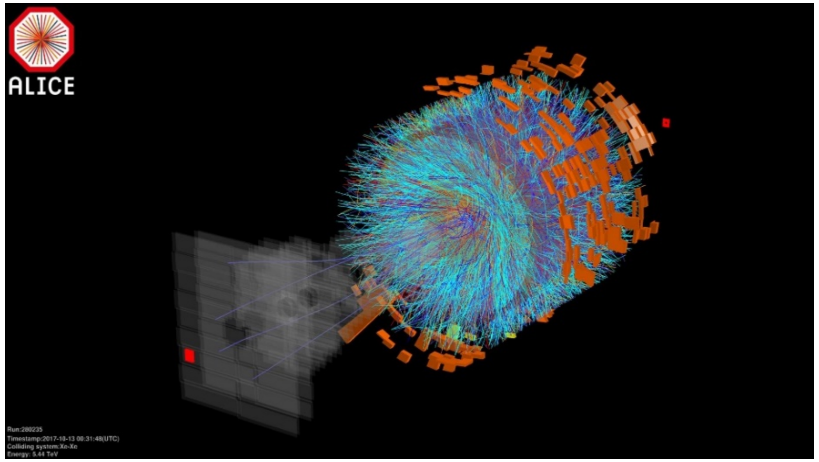


Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

Parameter	Fill 6295
Beam energy [Z TeV]	6.5
No. of bunches colliding	(8, 16, 8)
β^* [m]	(0.3, 10, 3)
Bunch intensity [10^8 ions]	2.87 ± 0.14
Normalized emittance (H, V) [µm]	(~1.5 / ~1.0)
Bunch length [cm]	9.1 ± 0.2
Luminosity [10^{27} cm^{-2}s^{-1}]	(0.28, 0.03, 0.04)
Rad. damping time (τ_z, $\tau_{x,y}$) [h]	(9.5, 18.9)
IBS growth time (τ_z, τ_x) [h]	(6.7, 13.1)

16 h total LHC time for set-up and physics data-taking

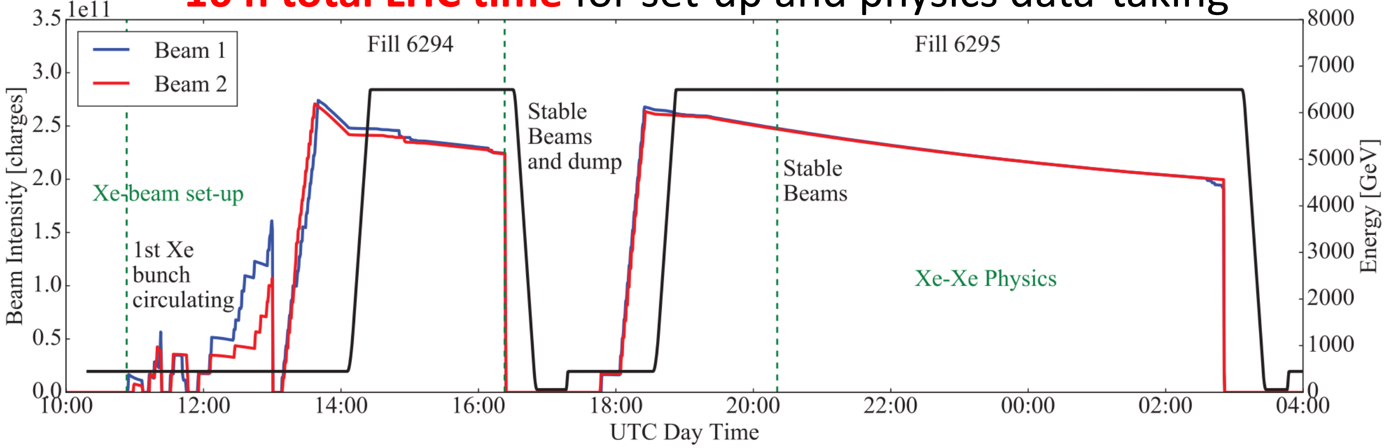


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

This run used p-p optics for fast set-up
⇒ ALICE had β*=10 m so lower luminosity than ATLAS/CMS
Avoid this in future O-O run ⇒ prefer to use a heavy-ion optics.

Papers at IPAC2018
https://accelconf.web.cern.ch/AccelConf/ipac2018/

MOPMF039 First Xenon-Xenon Collisions in the LHC

MOPMF038 Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

TUPAF020 Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon

TUPAF024 Impedance and Instability Studies in LEIR With Xenon

Data on Xe-Xe used in many physics papers at Quark Matter 2018 and later

Results from Xe-Xe run of LHC at Quark Matter conference, May 2018

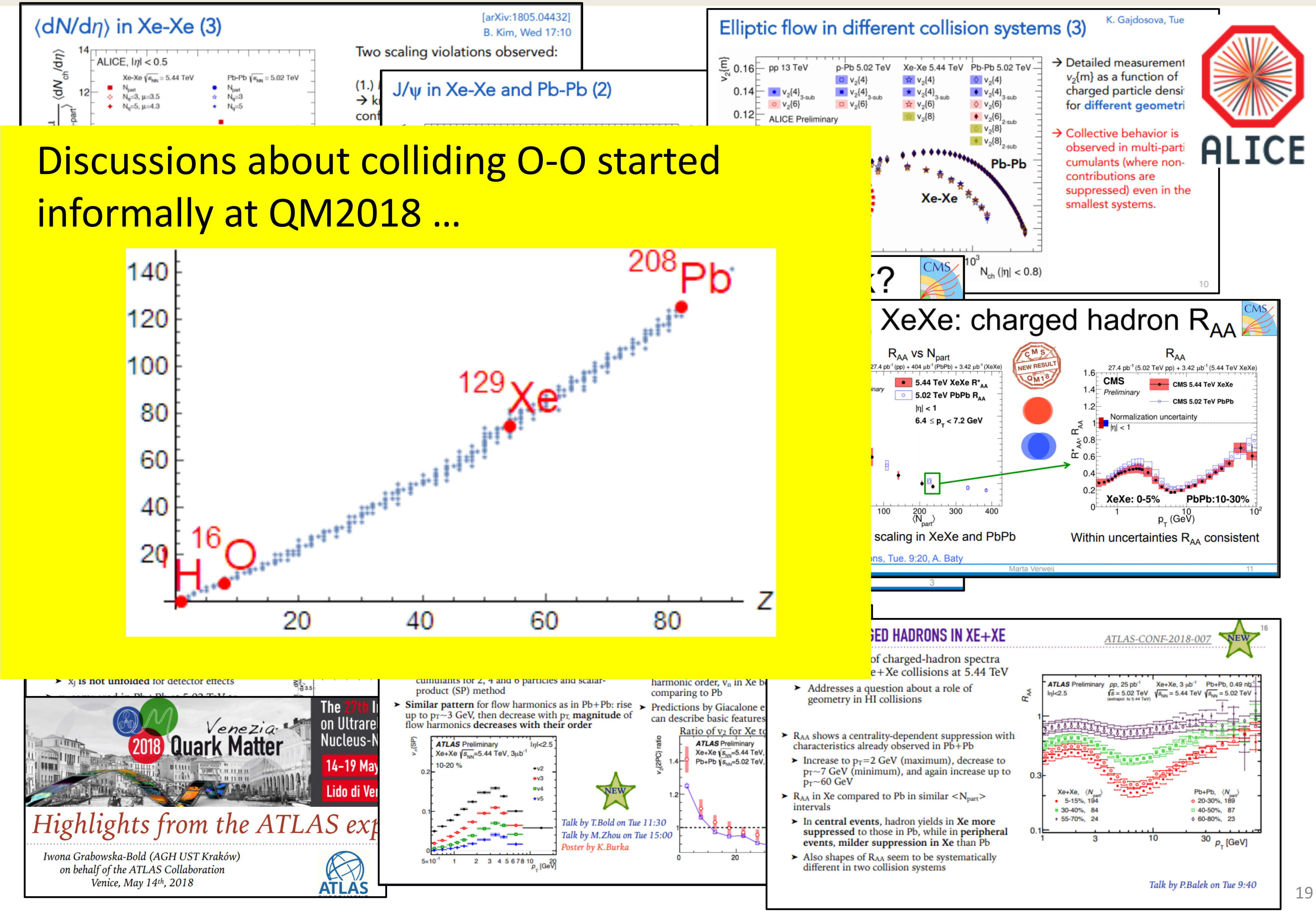
Rich physics harvest from 16 h (6.5 h Stable Beams) Xe-Xe run of LHC on 12/10/2017.

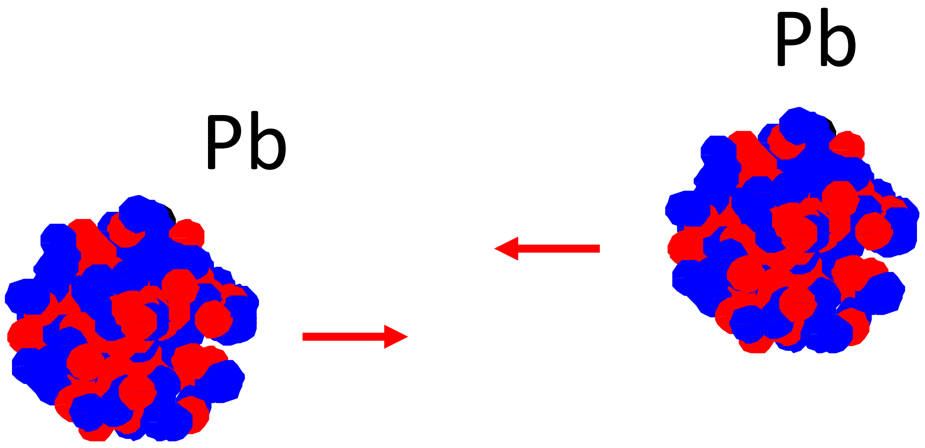
Results reported by all LHC experiments, clarifying the transitions between Pb-Pb, p-Pb and p-p.

Illustrates "beyond-design" potential of LHC.

Input to HL/HE-LHC Physics Workshop case for possible future runs with lighter nuclei.

Discussions about colliding O-O started informally at QM2018 …

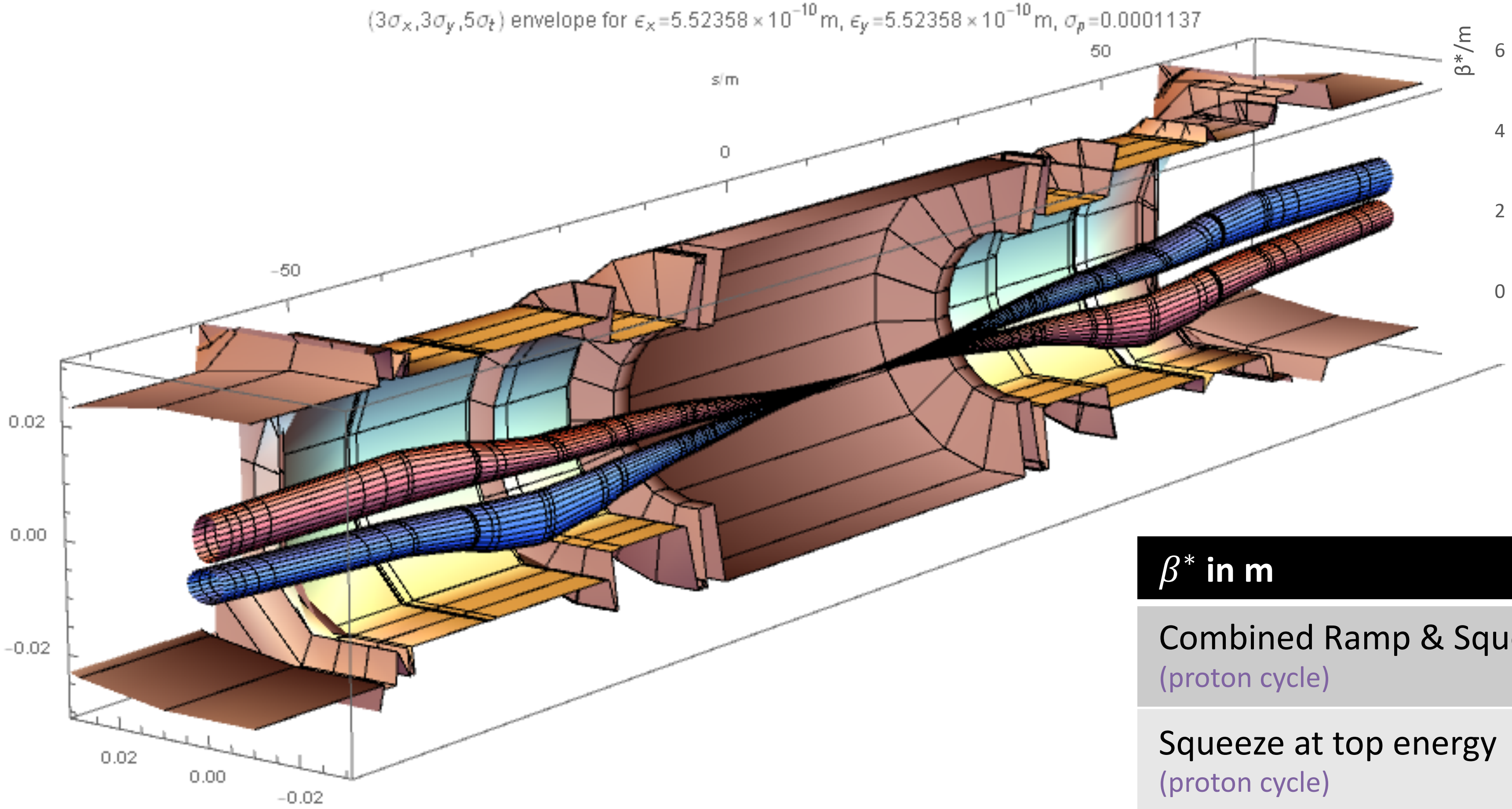


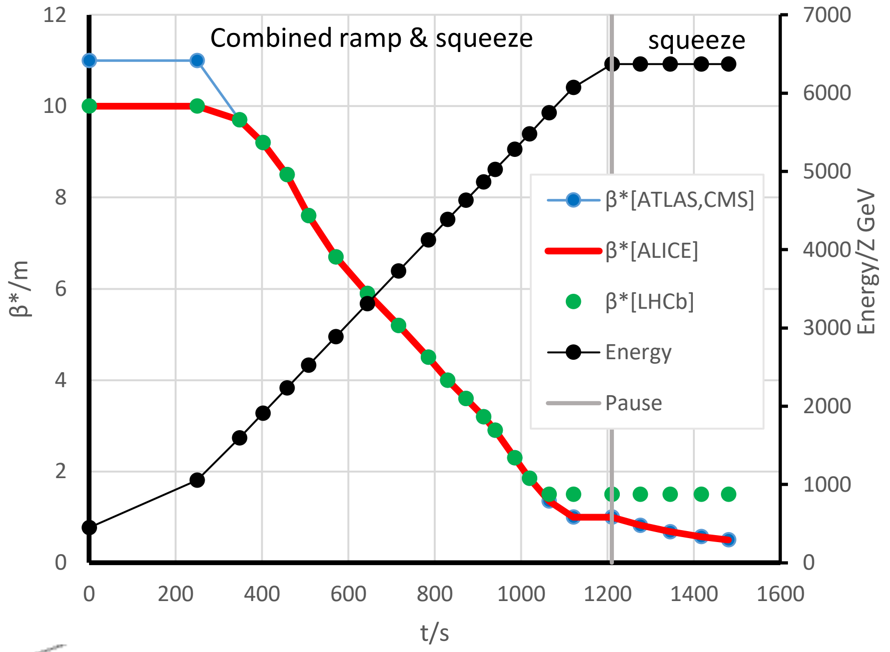


2018

Pb-Pb in 2018: new optics with smallest ever β* in ALICE, LHCb

- Optics design by S. Fartoukh, new combined ramp & squeeze
- Gradual divergence from identical to pp optics in 2010 to a completely new cycle in 2018
- Initial problem with beam size in ALICE now understood
- Fixed for reversed-polarity part of run
- Some lessons for optics correction procedure in future



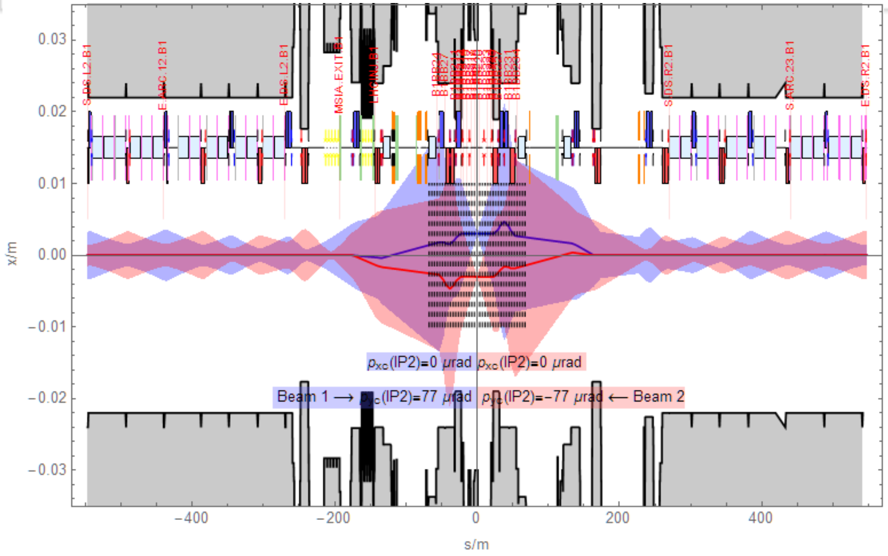


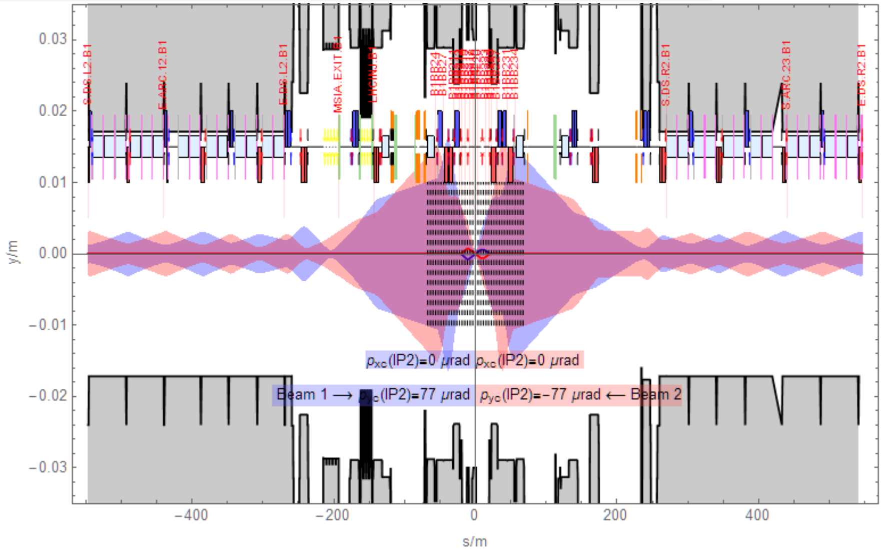
β^* in m	IP1	IP2	IP5	IP8
Combined Ramp & Squeeze (proton cycle)	1 (1)	1 (10)	1 (1)	1.5 (3)
Squeeze at top energy (proton cycle)	0.5 (0.3)	0.5 (10)	0.5 (0.3)	1.5 (3)

IR2 ALICE +ve: external angle passed through zero in every fill

ON_ALICE

	x_c /m	y_c /m	p_{xc} /μrad	p_{yc} /μrad	β_x /m	β_y /m
IP1	-0.00055	0	-0.000445022	160.	0.500001	0.5
IP2	0.003	0	0.320649	76.9224	0.5	0.5
IP5	1.58497×10^{-18}	-0.00125	160.	-0.000108878	0.500001	0.5
IP8	-2.96858×10^{-18}	-0.001	-318.339	-1.98865	1.5	1.5

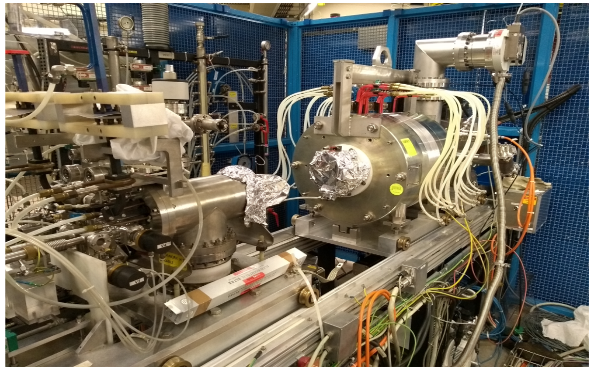


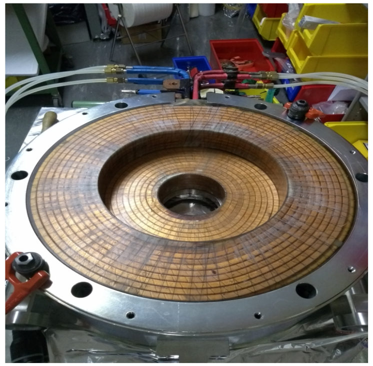


Horizontal parallel separation increased to ±3 mm
IP shift bump still off
Transition through zero external bump to unfavourable polarity with respect to IP (neutrons moving down)
No sign of beam-beam effects.

Crossing angle limited to ~60 μrad to avoid injection elements shadowing ZDC.
Improvements will allow 100 μrad after LS2.

Major Hurdles …



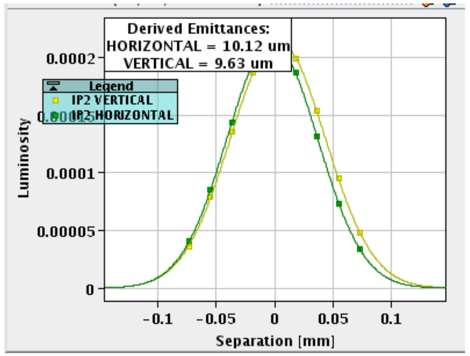


Ion source fault: No ions available after TS3

- Many commissioning tasks were advanced with protons.
- Degraded beam quality during the first week of the run.
  - Resulting in lower beam intensity and longer turn around time.
  - Shorter levelling periods and less time in physics.

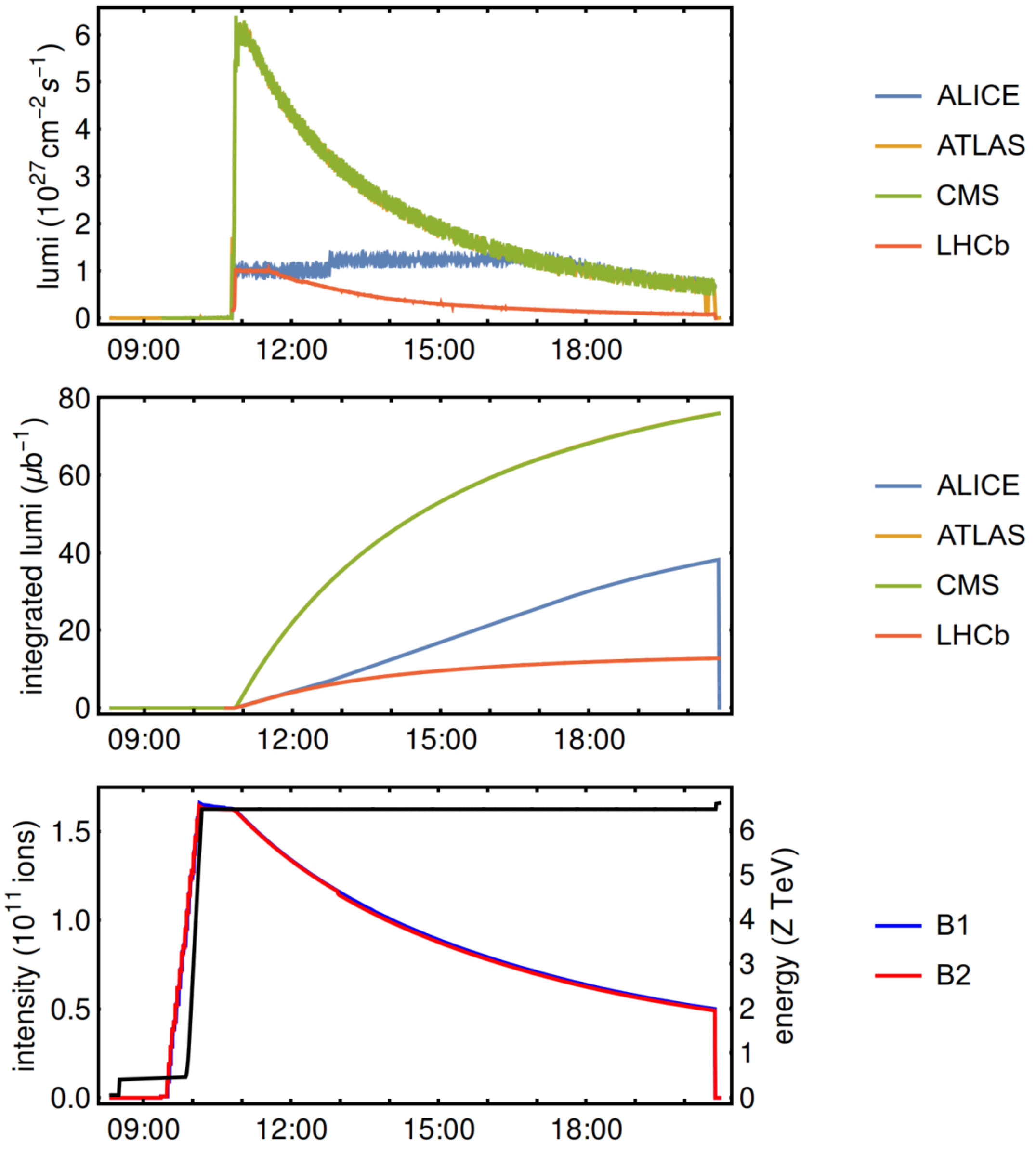
ALICE luminosity lower than expected:

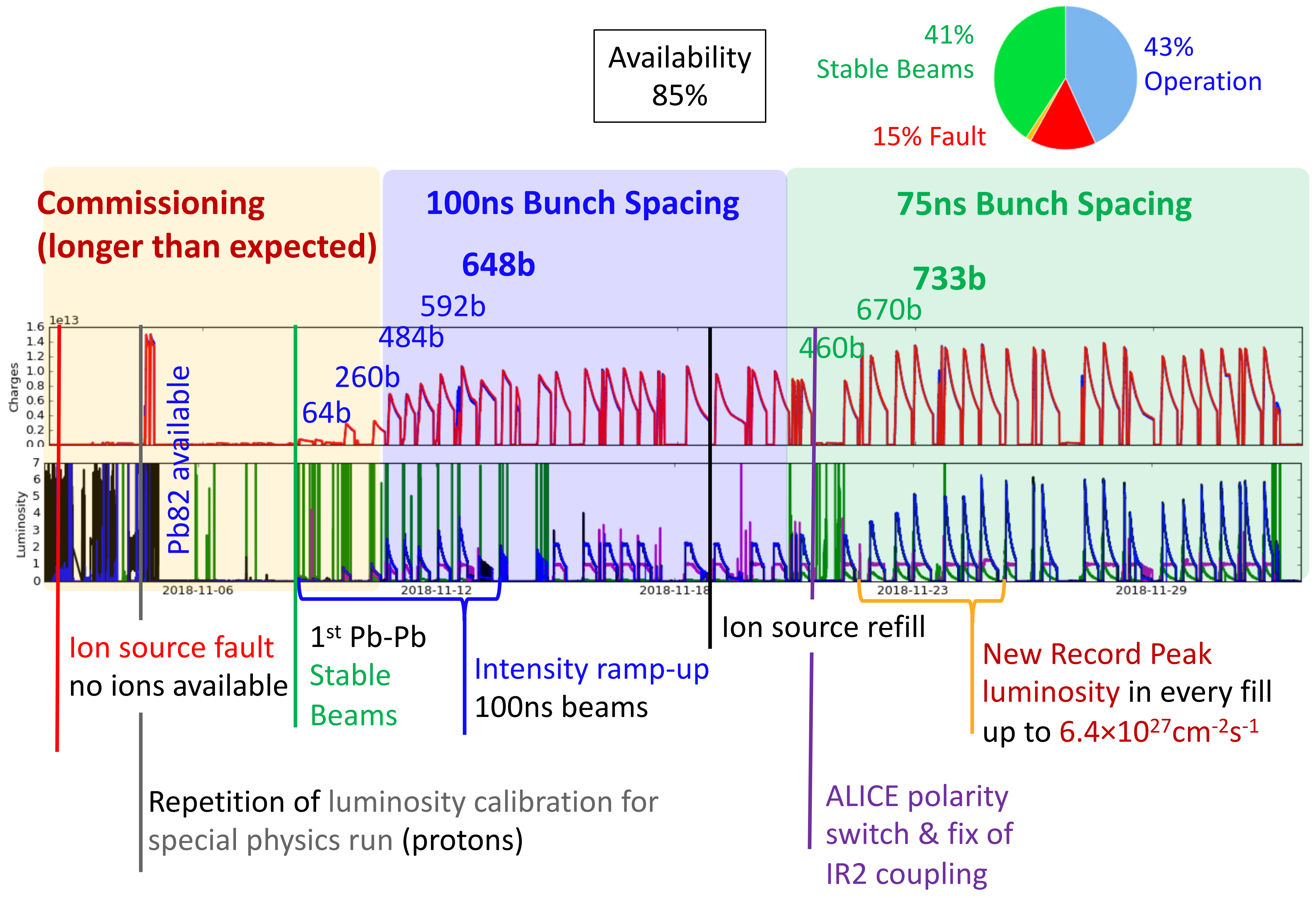
- *Cause:* beam deformation and reduced overlap at IP introduced by strong local betatron coupling in IR2.
- *Solution:* correction with skew-quadrpoles implemented during ALICE polarity reversal.
  - Luminosity sharing strategies used until solution was found.
    - Filling schemes (number and distribution of bunches).
    - Luminosity levelling target of ATLAS/CMS.



A high peak luminosity Pb-Pb fill in 2018 with 100 ns

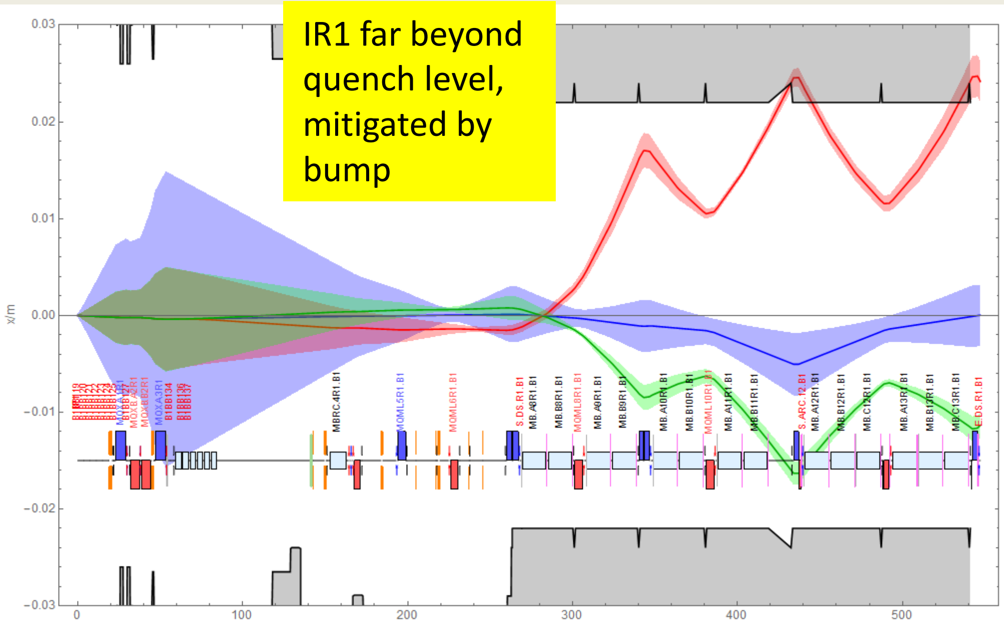
- Levelling in ATLAS and CMS gradually increased to 6×10^{27} cm^{-2}s^{-1}
- ALICE levelled at design luminosity 1×10^{27} cm^{-2}s^{-1}
- After correction of local coupling, ALICE levelling times increased to ~ 8 h.

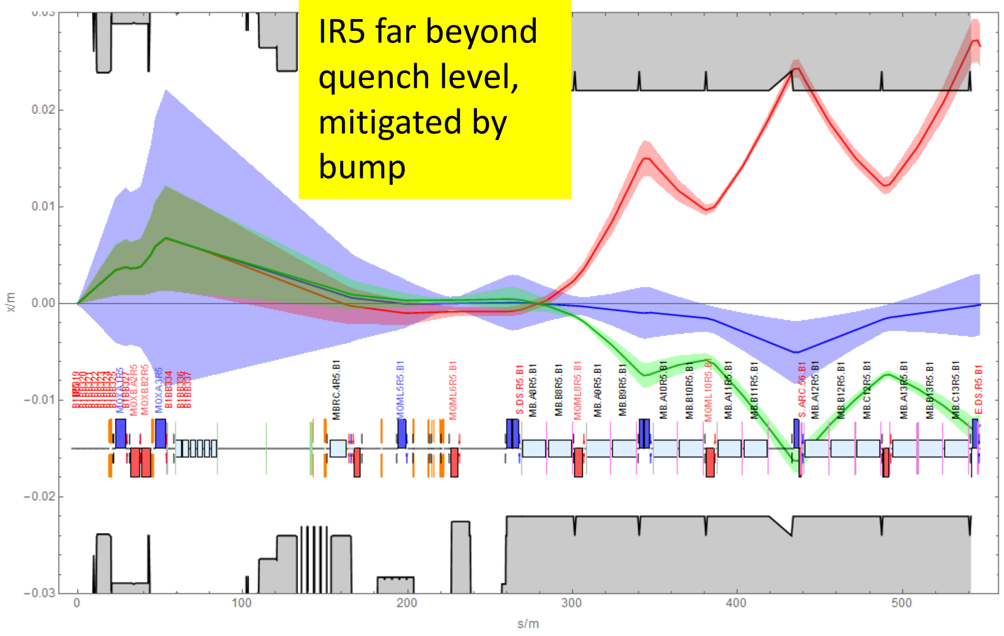



Availability 85%
41% Stable Beams
43% Operation
15% Fault
Commissioning (longer than expected)
100ns Bunch Spacing
75ns Bunch Spacing
648b
592b
484b
260b
64b
733b
670b
460b
1e13
Charges
Luminosity
Pb82 available
2018-11-06
2018-11-12
2018-11-18
2018-11-23
2018-11-29
Ion source fault
no ions available
1st Pb-Pb Stable Beams
Intensity ramp-up 100ns beams
Ion source refill
New Record Peak luminosity in every fill up to 6.4×10^27 cm^-2 s^-1
Repetition of luminosity calibration for special physics run (protons)
ALICE polarity switch & fix of IR2 coupling

M. Schaumann

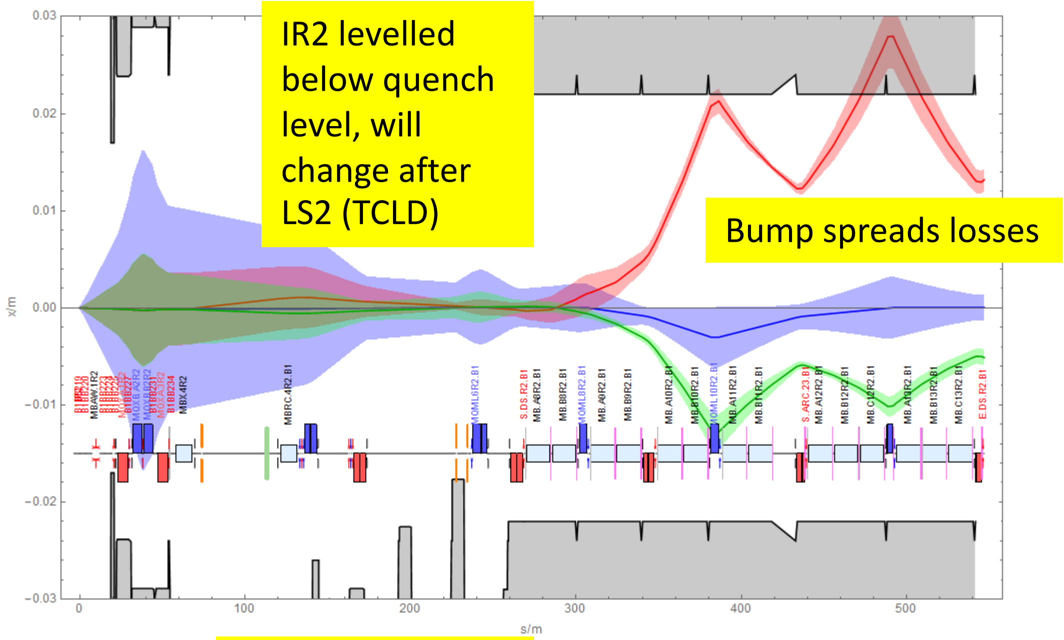
Significant BFPP beams in all IPs (horizontal envelopes)

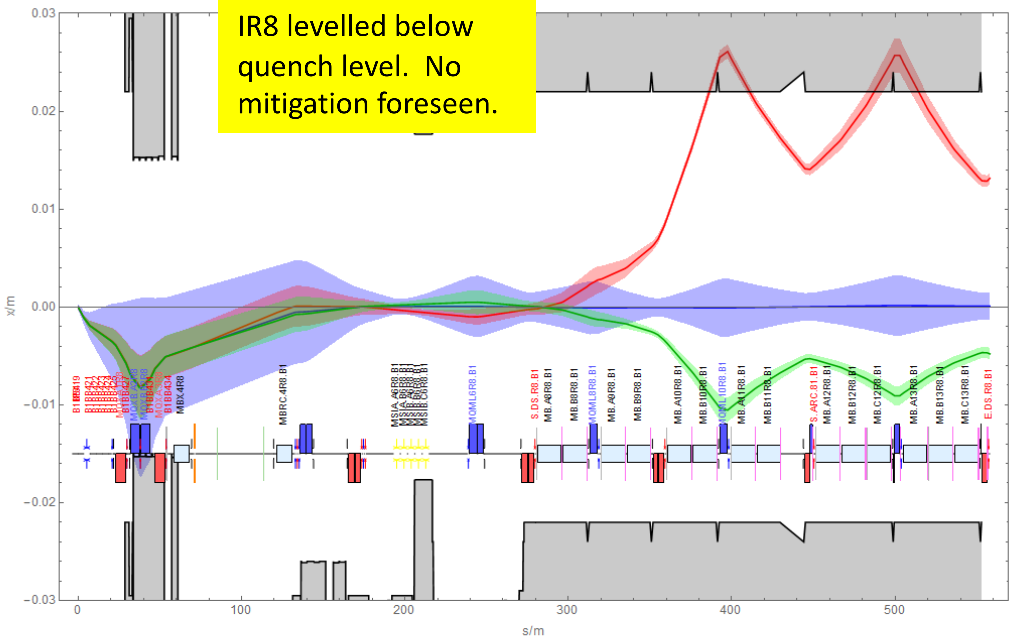




Bumps were adjusted empirically, good agreement with calculation, except left of IP5, location of 2015 BFPP quench test.

Chamber misalignment.





Pb 2018 collimation system cleaning measurements and simulation studies

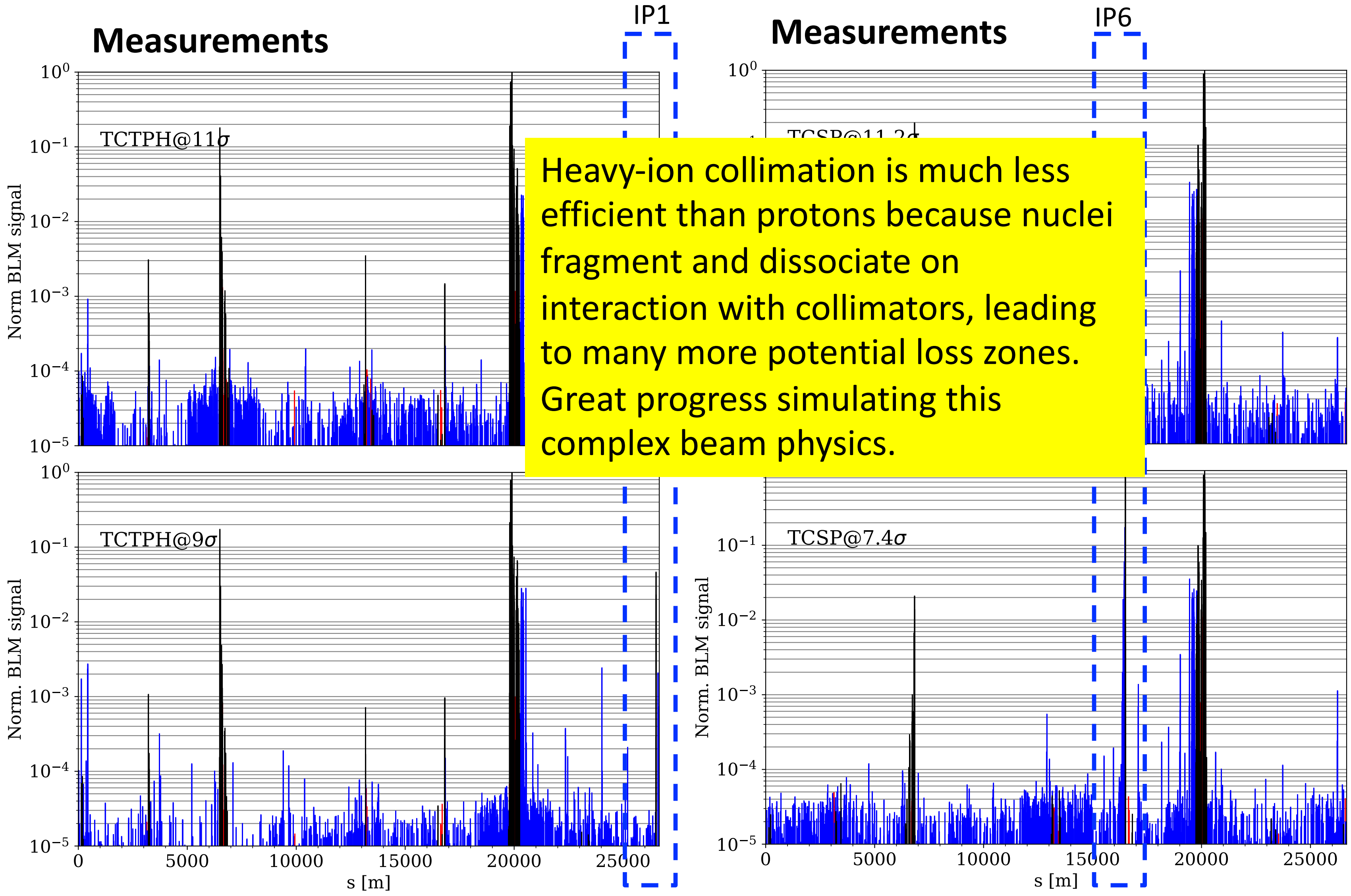
- ❑ During the system validation observed higher losses than expected (at EoS/Physics) required to refine the collimator settings.

TCSP in IP6

- ❑ High losses at the level of the TCP observed on the right TCSP jaw.
- ❑ Solution adopted: opening the right jaw by 2 mm. The losses were reduced by 99%.

TCTPH in IP1

- ❑ High losses observed on the TCTPH in IP1 (even higher at EoS).
- ❑ Solution adopted: open the TCTPH to 11σ. The losses were reduced by 80%.



Heavy-ion collimation is much less efficient than protons because nuclei fragment and dissociate on interaction with collimators, leading to many more potential loss zones. Great progress simulating this complex beam physics.

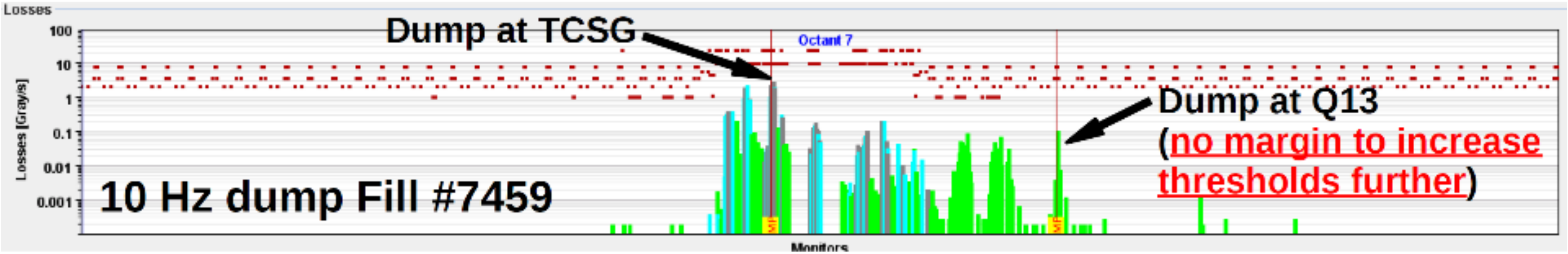
N. Fuster, R. Bruce et al

BLM Threshold changes for collimation-driven losses

Collimation-related threshold changes essential for Pb halo losses:

1) **Adjusted the dumping hierarchy for Pb losses in IR7**
   - With proton thresholds, would dump first at cold magnets in DS (cleaning inefficiency about a factor of 100 worse for Pb than for protons)
   - Decreased master thresholds at two skew secondary collimators to dump first at these collimators
2) **Aligned corrections for collimation losses to the energy of the Pb run**
   - In proton operation FT corrections only active above 6.39 TeV (Pb run: 6.37 TeV)
   - Extended all collimation-related FT corrections to 6.37 TeV
3) **Removed bottlenecks due to leakage of ion fragments from IR7**
   - Increased the master thresholds at DS magnets according to 2015 Pb quench test to avoid premature dumps

Despite all optimizations in DS, **10 Hz dumps in IR7 were unavoidable**:

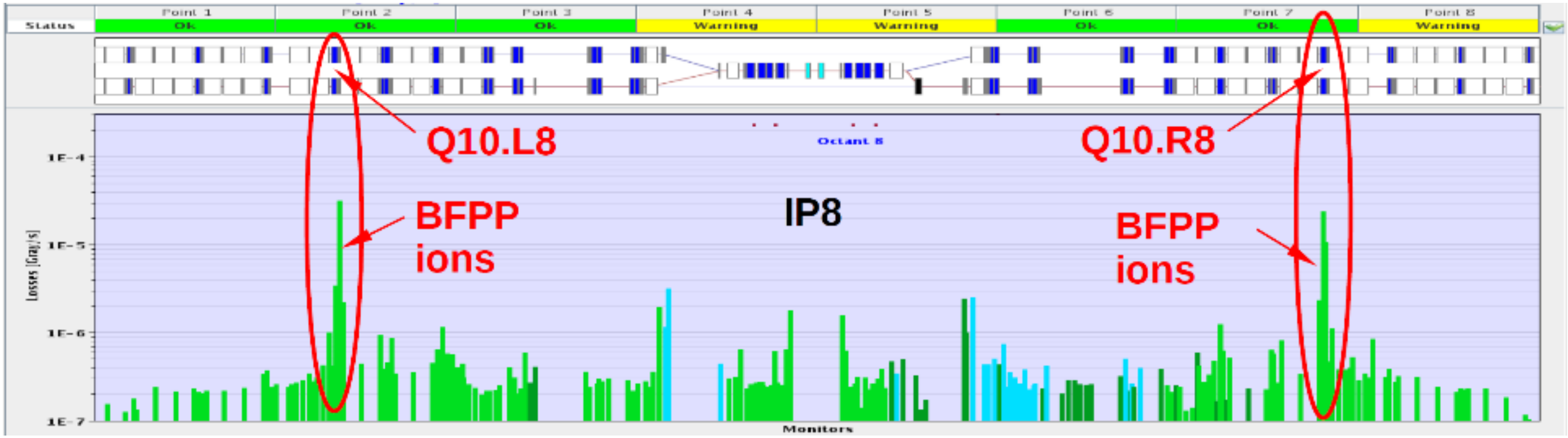


A. Lechner et al

BLM Threshold changes for BFPP losses

BFPP-related threshold changes essential for luminosity reach:

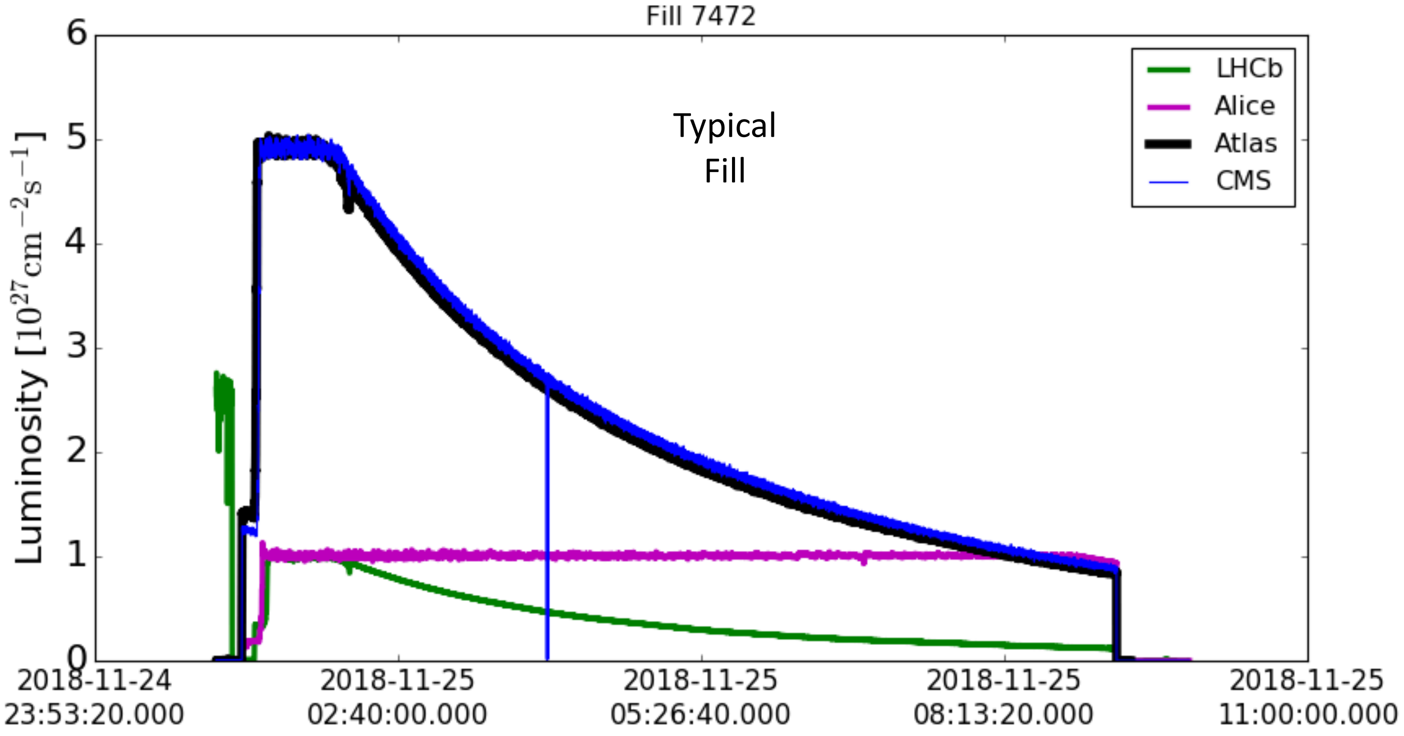
1) **Prevent premature dumps due to BFPP ions in IR1/5**
   - Several threshold and orbit bump optimizations around BFPP loss location (connection cryostats) -> could reach the target luminosity (6-7x10^{27}cm^{-2}s^{-1}) while still protecting against quenches
2) **Prevent premature dumps due to BFPP ions in IR8**
   - Luminosity reach in LHCb higher than in previous years (10^{27}cm^{-2}s^{-1}) thanks to 75 nsec bunch spacing
   - BFPP loss location around Q10 -> Q10s had low thresholds to reduce the risk of symmetric quenches -> would have prevented reaching the target lumi
   - Decided to temporarily decrease QPS thresholds, which allowed increasing the Q10 BLM thresholds



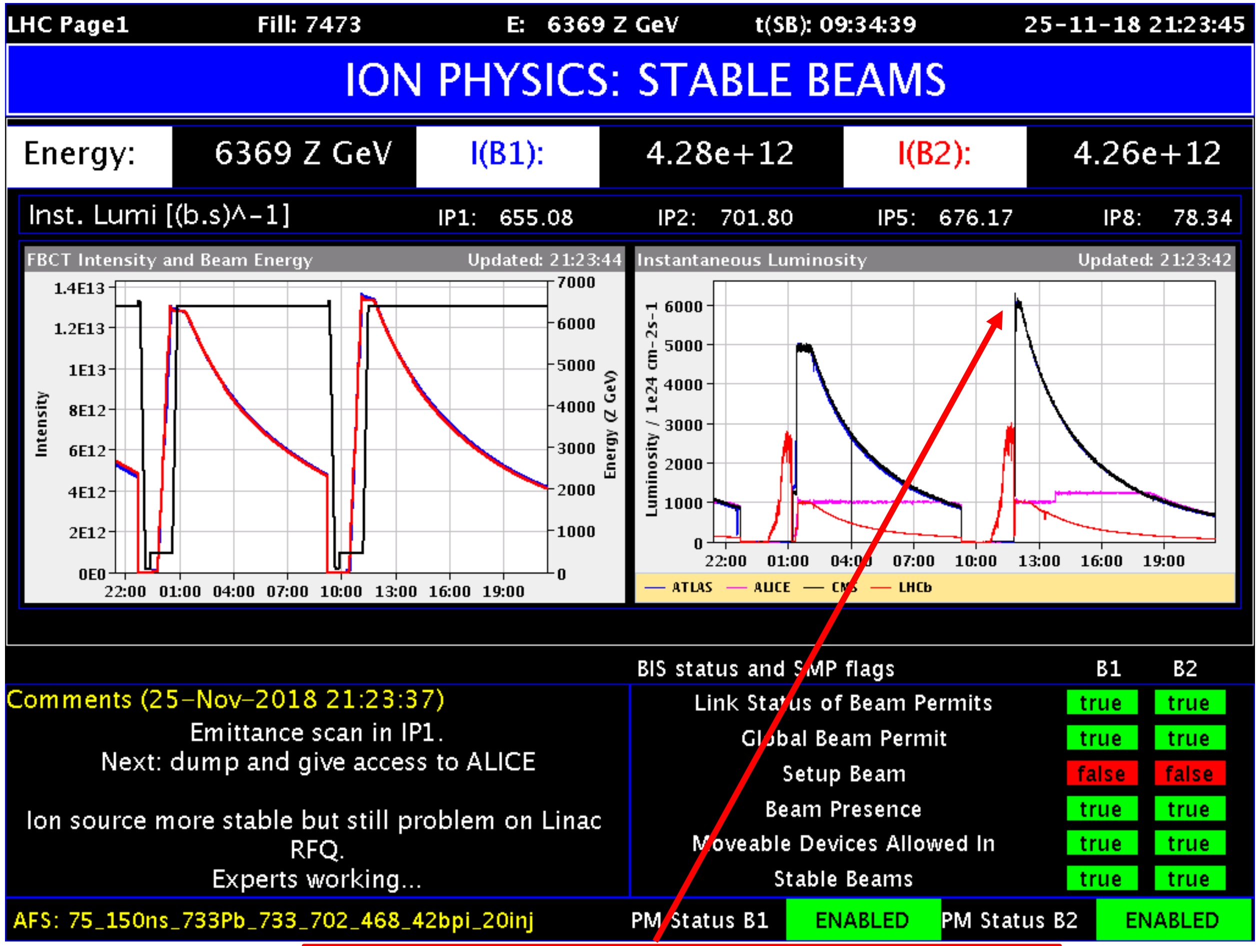
A. Lechner et al

A high peak luminosity Pb-Pb fill in 2018 with 75 ns

- **Design peak luminosity is exceeded** by factor 5 in ATLAS/CMS.
  - → **Almost reaching nominal HL-LHC target luminosity**
  - → Demonstrated feasibility in ATLAS/CMS
- **ALICE levelled** to design saturation value **most of the time in Stable Beams**.
- **Factor 100** increase in **LHCb fill luminosity** over 2015.



Peak Pb-Pb luminosity record, 25 November 2018



$L = 6 \times 10^{27}$ cm^{-2}s^{-1}

$= 6 \times$ design

= (47 kHz hadronic event rate)

Nominal HL-LHC levelling value is

$L = 7 \times 10^{27}$ cm^{-2}s^{-1}

Comparison of BFPP losses with dump thresholds (specially set in BFPP loss zones) shows that we can go considerably further.

Unfinished business … the second BFPP Quench Experiment

Thanks to everyone concerned for 3 years of analysis and elaborate preparation following the first successful beam-induced quench with BFPP from Pb-Pb in 2015.

Scheduled from 00:00 to 06:00, 3 Dec, the last few hours of Run 2.
Intended to resolve ambiguities from misaligned chamber in 2015 BFPP quench experiment.

Thanks to PS, LEIR and Linac3 teams who all scrambled in the middle of the night to repair a series of faults and intervene.

- PS main magnet fault
- LEIR performance degraded, cannot fix?
- HI source instability and unexpected deterioration of stripper foil after Linac3

We hope to measure the steady-state quench level of the LHC dipole in **Nov 2021** …

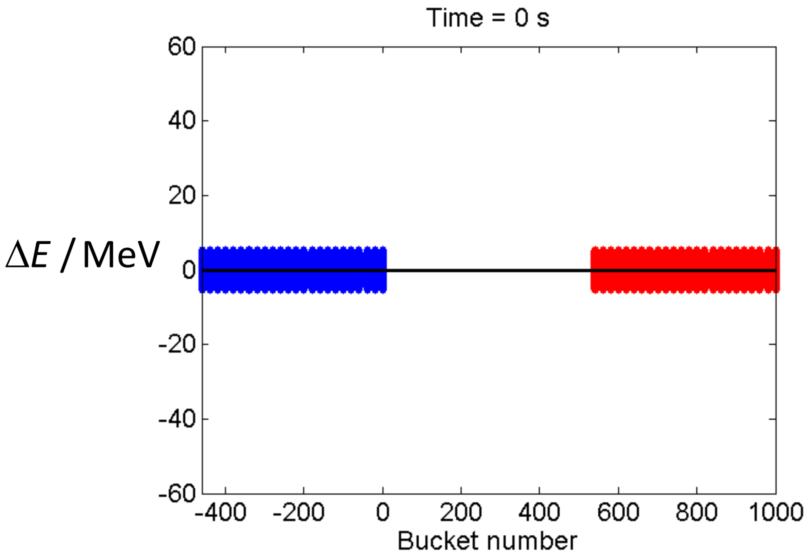
Lessons from the 2018 Pb-Pb run

- BFPP bump mitigation allows HL-LHC peak luminosity in ATLAS/CMS without quenches (> 6 × design).
- Collimation losses remain critical, avoid premature dumps.
- 75 ns filling scheme works very well, bunches at limit of stability in SPS
  - Provides many more collisions for LHCb, who can take them!
  - Peak luminosity up to 10^{27} $cm^{-2}s^{-1}$ does not quench LHCb
- "Invisible"local coupling at IR2 reduced ALICE luminosity in first half of run
  - Solved by skew-quad knob that reversed error in settings
  - Avoid same problem in future with specific checks
  - More generally, one should plan set-up phases with *just-in-time validation*
    - We had planned to validate reversed polarity earlier, before finding the solution. This would have been lost time. *So leave validation until just before luminosity operation.*

OUTLOOK FOR FUTURE HEAVY-ION RUNS OF LHC

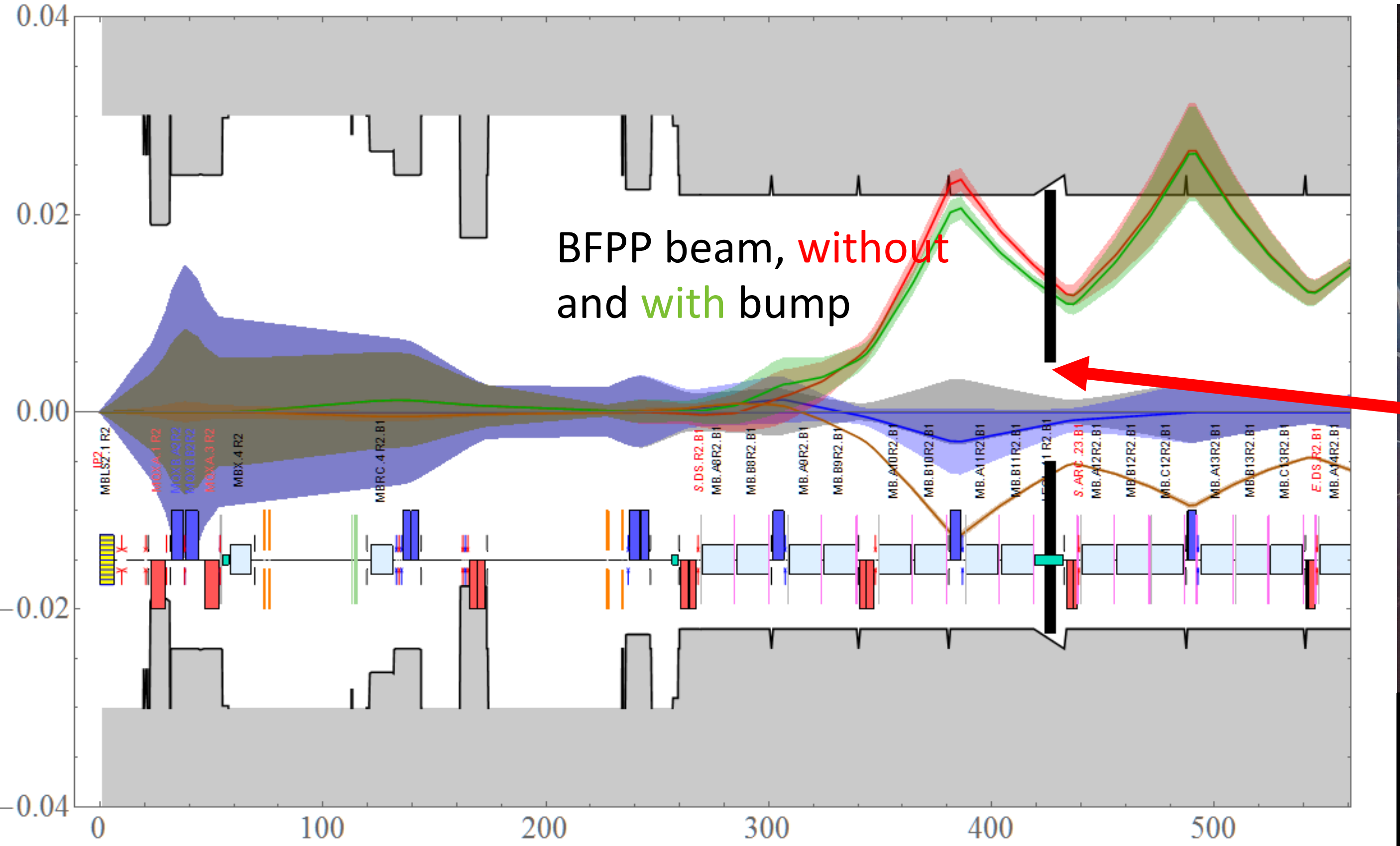
SPS momentum slip stacking for 50 ns bunch spacing

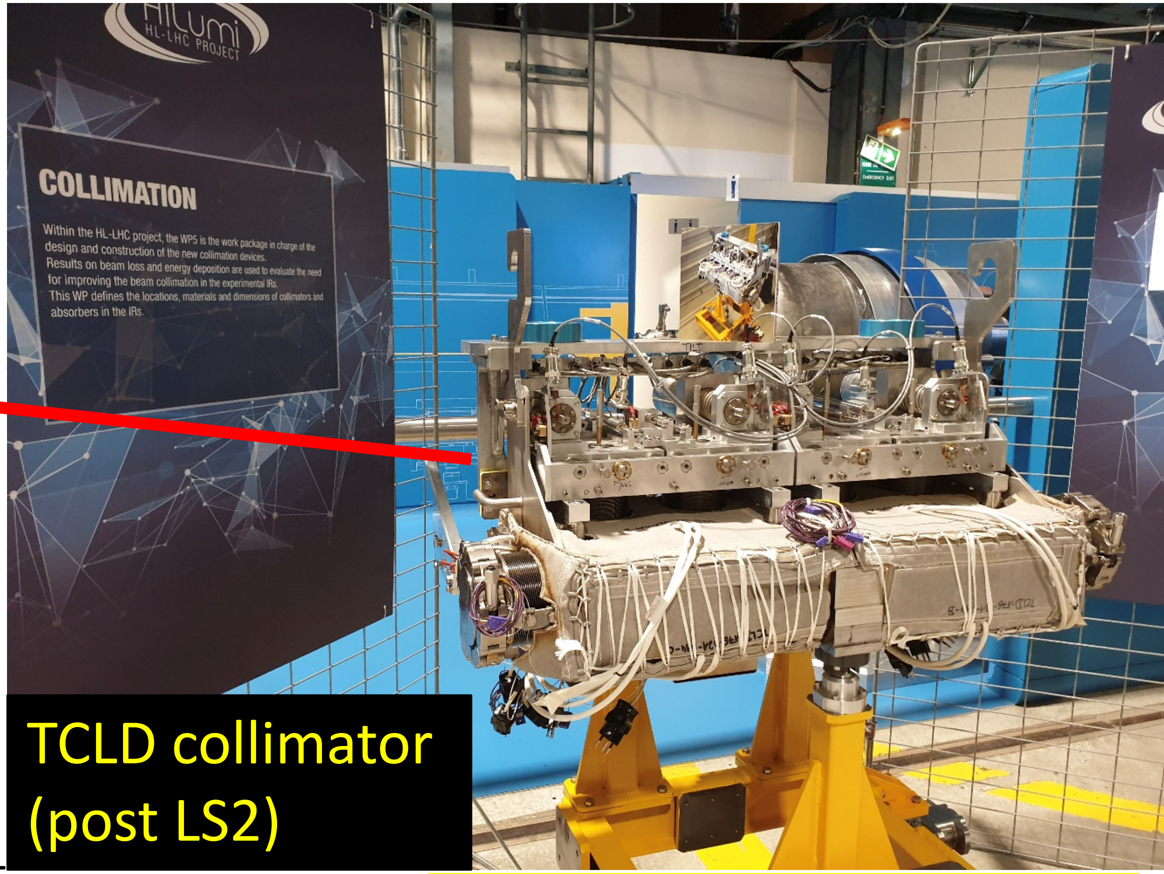
- Feasibility relies on
  - Large bandwidth of SPS 200 MHz travelling wave cavities
  - Low ion intensity (no need for feed-back, feed-forward, …)
  - Independent cavity control (SPS LLRF upgrade in LS2)
- Macroparticle simulations show
  - Proof of principle (without intensity effects)
  - Longitudinal emittance blow-up (factor 2.5) at re-capture due to filamentation in large bucket
  - Bunch rotation at extraction becomes necessary for injection into LHC
  - Optimization of re-capture is crucial to keep losses <5%



H. Bartosik, Chamonix 2017

BFPP: Orbit bumps alone are not effective for ALICE - upgrade

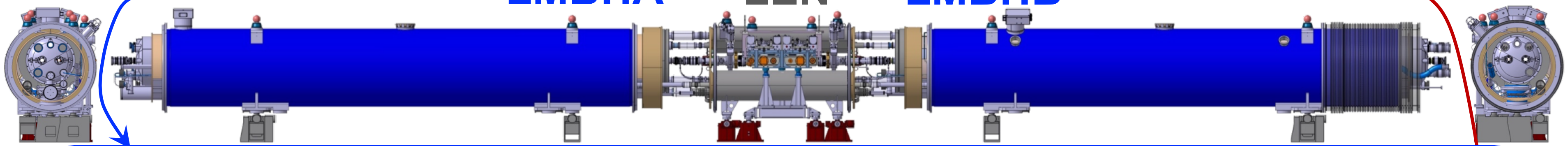




- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – **to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in 2015
- **TCLDs should allow luminosity increase for upgraded ALICE to run at at 50 kHz**

Also during LS2, further TCLD collimators will be installed between 11 T magnets in IR7 to improve Pb collimation (first application of Nb_3Sn superconductors in an operating accelerator).

DS collimators



- **IP7**, for both proton and heavy-ion collimation losses
  - Design, fabricate, test, and install during **LS2**, around **IP7**, **two 11 T Dipole Full Assemblies** (replace the MBs MBA-B8L7 and MBB-B8R7)
  - Fabricate and test **one spare 11 T Dipole**
  - Plan **includes 14 magnet models**, and ~~2~~1
)
- **IP2**, for heavy-ion secondary beams
  - Design, fabricate, and install during **LS2**,
    Cryostat Full Assemblies, i.e. no 11 T Dip
  - Fabricate **one spare Connection Cryostat**
  - A Connection Cryostat Full Assembly con
    cryostats, **LEP**, and one
    by-pass cryostat, **LEN**

Because of some delays in building 11 T magnets, at most one beam will be equipped with these by end of LS2.
Hence potential total intensity limit until second set can be installed (end-of year Technical Stop?).

F. Savary

Pb-Pb parameters from Design Report to HL-LHC upgrade

Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb–Pb run (Ref. [2] and references therein). The original design values for Pb–Pb [1] collisions and future upgrade Pb–Pb goals are also shown (in this column the integrated luminosity goal is to be attained over the 4 Pb–Pb runs in the 10-year periods before and after 2020). Peak luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2018 are not shown. Emittance and bunch length are RMS values. The series of runs with $\sqrt{s_{\rm NN}} = 5.02$ TeV also included pp reference runs, not shown here. Design and record achieved nucleon-pair luminosities are $\boxed{\text{boxed}}$, and some key parameters related to p–Pb parameters in Table 2 are set in red type, for easy comparison. The upgrade peak luminosity is reduced by a factor $\simeq 3$ from its potential value by levelling.

Quantity	design	achieved				upgrade
Year	(2004)	2010	2011	2015	2018	≥2021
Weeks in physics	-	4	3.5	2.5	3.5	-
Fill no. (best)		1541	2351	4720	7473	-
Beam energy $E[Z\,\text{TeV}]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\,\text{TeV}]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{\rm NN}}$ [TeV]	5.52	2.51		**5.02**	**5.02**	5.52
Bunch intensity $N_b\,[10^8]$	0.7	1.22	1.07	2.0	2.2	1.8
No. of bunches k_b	592	137	338	518	733	1232
Pb norm. emittance ϵ_N [μm]	1.5	2.	2.0	2.1	2.0	1.65
Pb bunch length σ_z m	0.08	0.07–0.1				0.08
β^* [m]	0.5	3.5	1.0	0.8	0.5	0.5
Pb stored energy MJ/beam	3.8	0.65	1.9	8.6	13.3	21
Luminosity $L_{\rm AA}$ $[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	1	0.03	0.5	3.6	6.1	7
NN luminosity $L_{\rm NN}$ $[10^{30}\text{cm}^{-2}\text{s}^{-1}]$	$\boxed{43}$	1.3	22.	156	$\boxed{264}$	$\boxed{303}$
Integrated luminosity/experiment [μb^{-1}]	1000	9	160	433,585	900,1800	10^4
Int. NN lumi./expt. [pb^{-1}]	43	0.38	6.7	19,25.3	39,80	4.3×10^5

p-Pb runs to date vs "design"

Table 2: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in the one-month p–Pb runs (Ref. [2] and references therein). The very short pilot run in 2012 is not shown. The original "design" values for p–Pb [4] collisions are also shown (in this column the integrated luminosity goal was supposed to be obtained over a few runs. Peak luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2016 and in the minimum-bias part of the run in 2016 are not shown. Emittance and bunch length are RMS values. Single bunch parameters for these p–Pb or Pb–p runs are generally those of the Pb beam. Design and record achieved nucleon-pair luminosities are boxed, and some key parameters related to p–Pb parameters in Table 1 are set in red type, for easy comparison.

Quantity	"design"	achieved	
Year	(2011)	2012–13	2016
Weeks in physics	-	3	1, 2
Fill no. (best)		3544	5562
Beam energy $E[Z\,\mathrm{TeV}]$	7	4	4,6.5
Pb beam energy $E[A\,\mathrm{TeV}]$	2.76	2.51	1.58,2.56
Collision energy $\sqrt{s_{\mathrm{NN}}}$ [TeV]	5.52	5.02	5.02,8.16
Bunch intensity N_b [10^8]	0.7	1.2	2.1
No. of bunches k_b	592	358	540
Pb norm. emittance ϵ_N [μm]	1.5	2.	1.6
Pb bunch length σ_z m	0.08	0.07–0.1	
β^* [m]	0.5	0.8	10, 0.6
Pb stored energy MJ/beam	3.8	2.77	9.7
Luminosity L_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	150	116	850
NN luminosity L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$\boxed{43}$	24	$\boxed{177}$
Integrated luminosity/experiment [$\mu\mathrm{b}^{-1}$]	10^5	32000	1.9×10^5
Int. NN lumi./expt. [pb^{-1}]	21	6.7	40

Nucleus-nucleus programme status after 2018

LHC "first 10-year" baseline Pb-Pb luminosity goal was 1 nb^{-1} of Pb-Pb luminosity (only) in Runs 1+2.

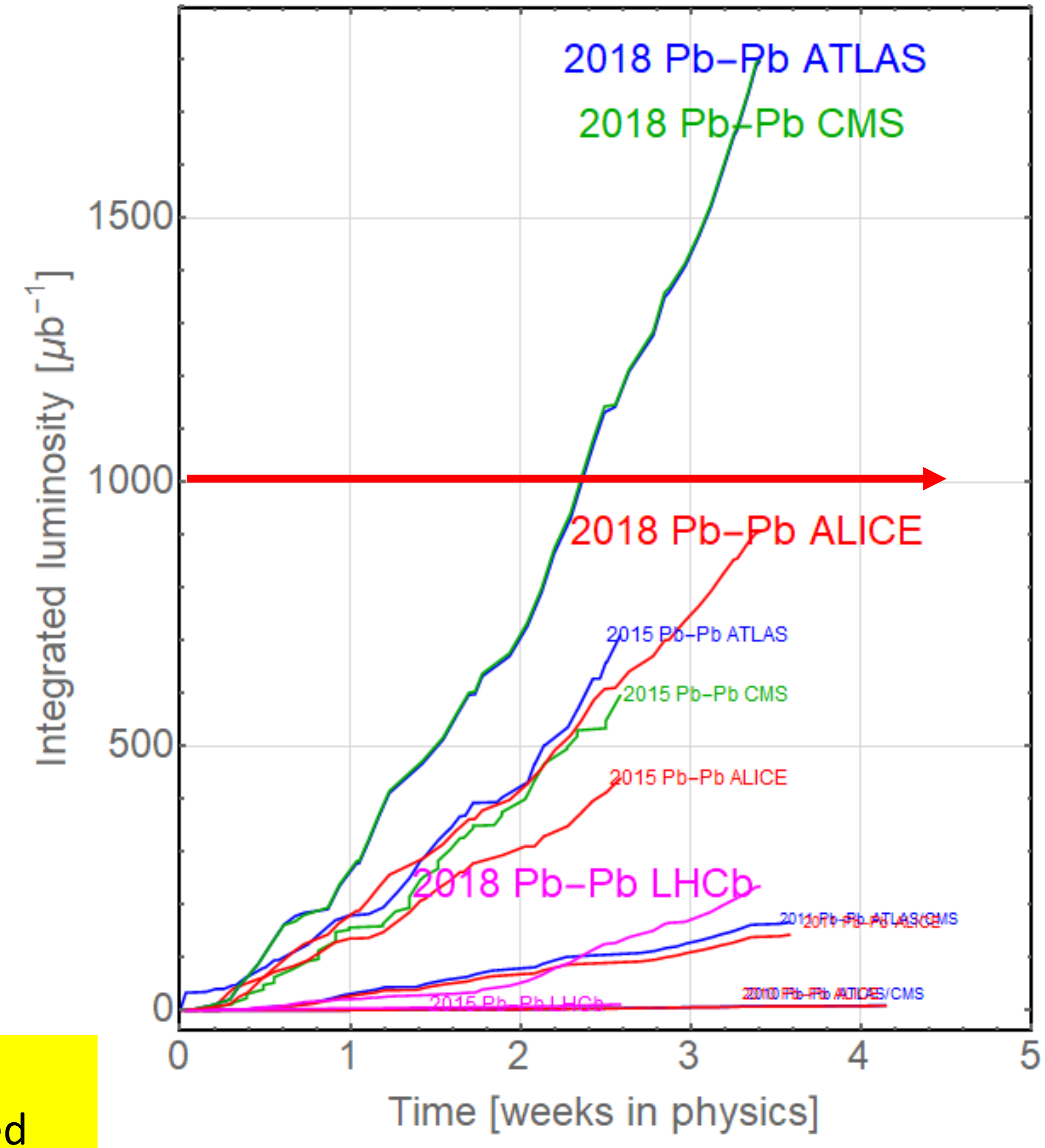
Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

Equivalent energy runs

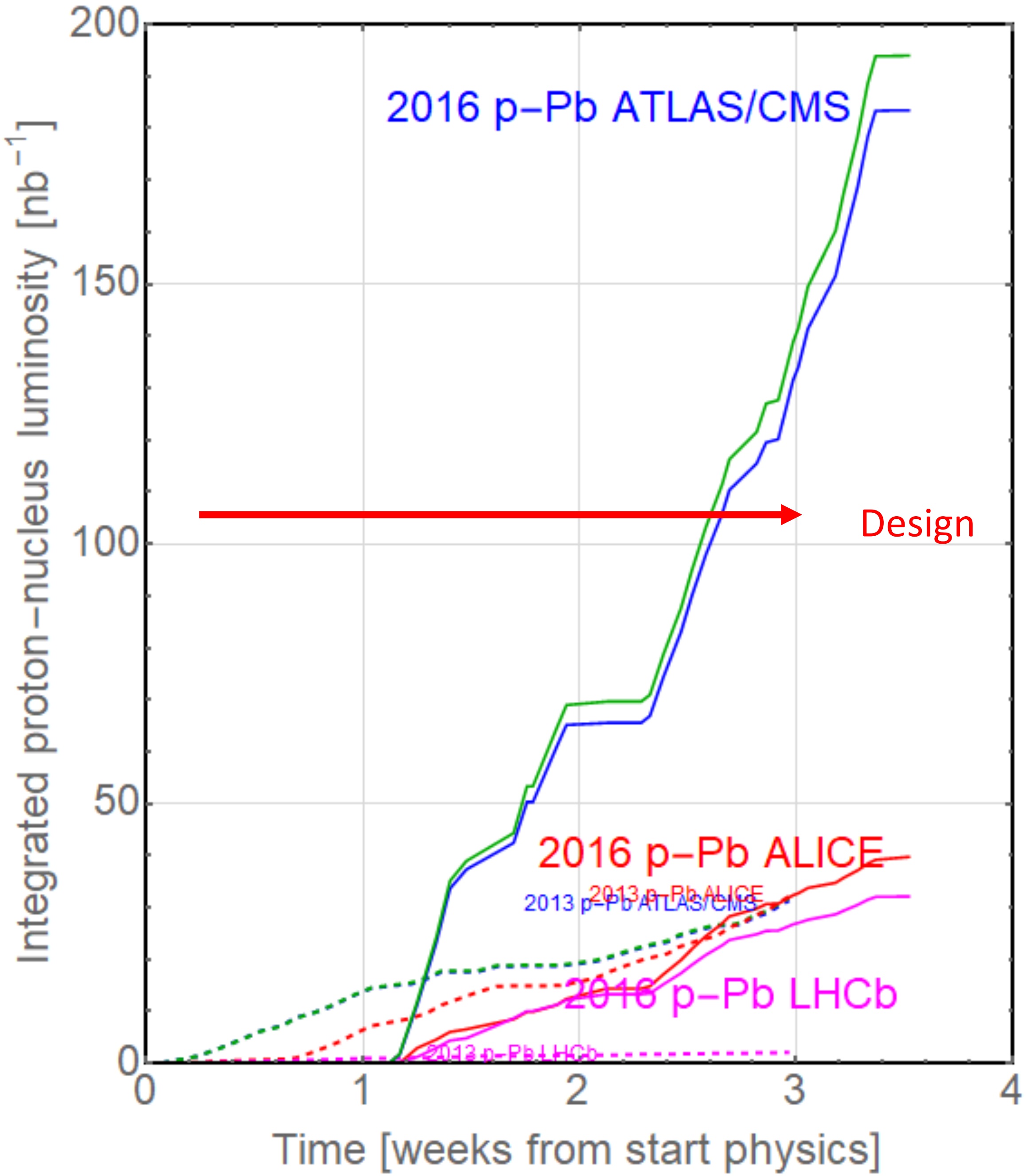
$$\sqrt{s_{NN}} = 5.02\ \text{TeV}\ \ (\sqrt{s}=1.045\ \text{PeV in Pb-Pb})$$

$$\Rightarrow E_b = \begin{cases} 6.37Z\ \text{TeV} & \text{in Pb-Pb (2015,2018)} \\ 4\ Z\ \text{TeV} & \text{in p-Pb (2013,part 2016)} \\ 2.51\ \text{TeV} & \text{in p-p (2015)} \end{cases}$$

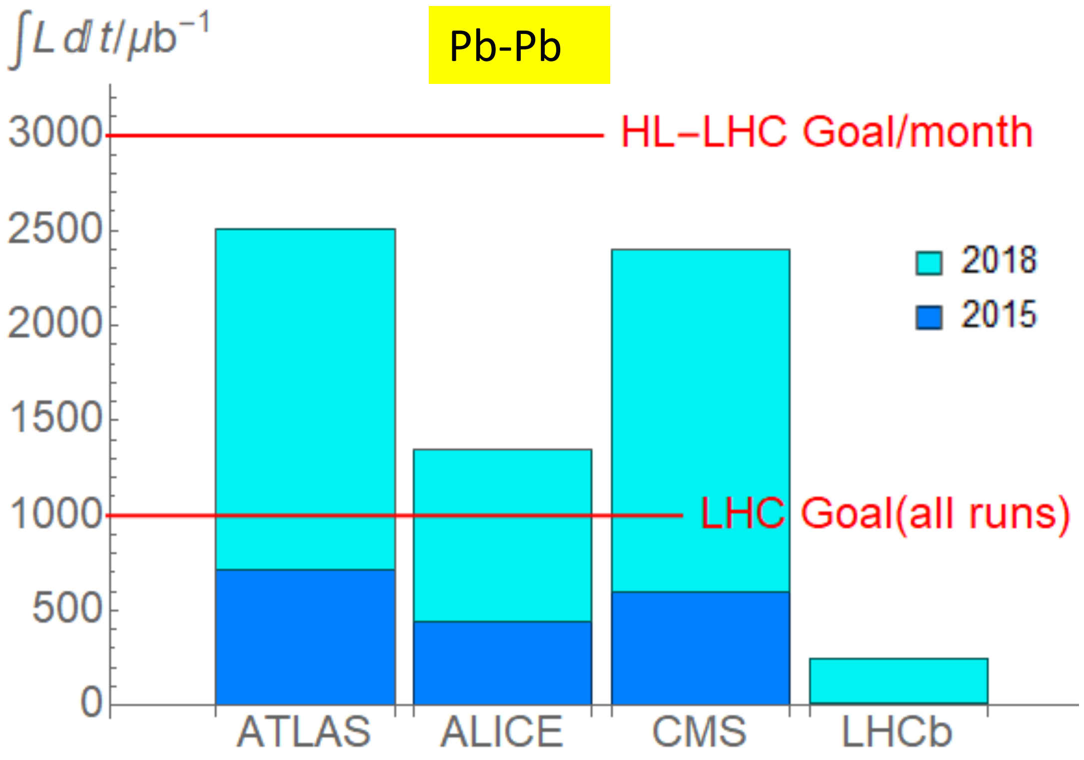
ALICE integrated luminosity in 2018 was equivalent to spending 10.4 days, 100% of the time, at constant levelled saturation luminosity.

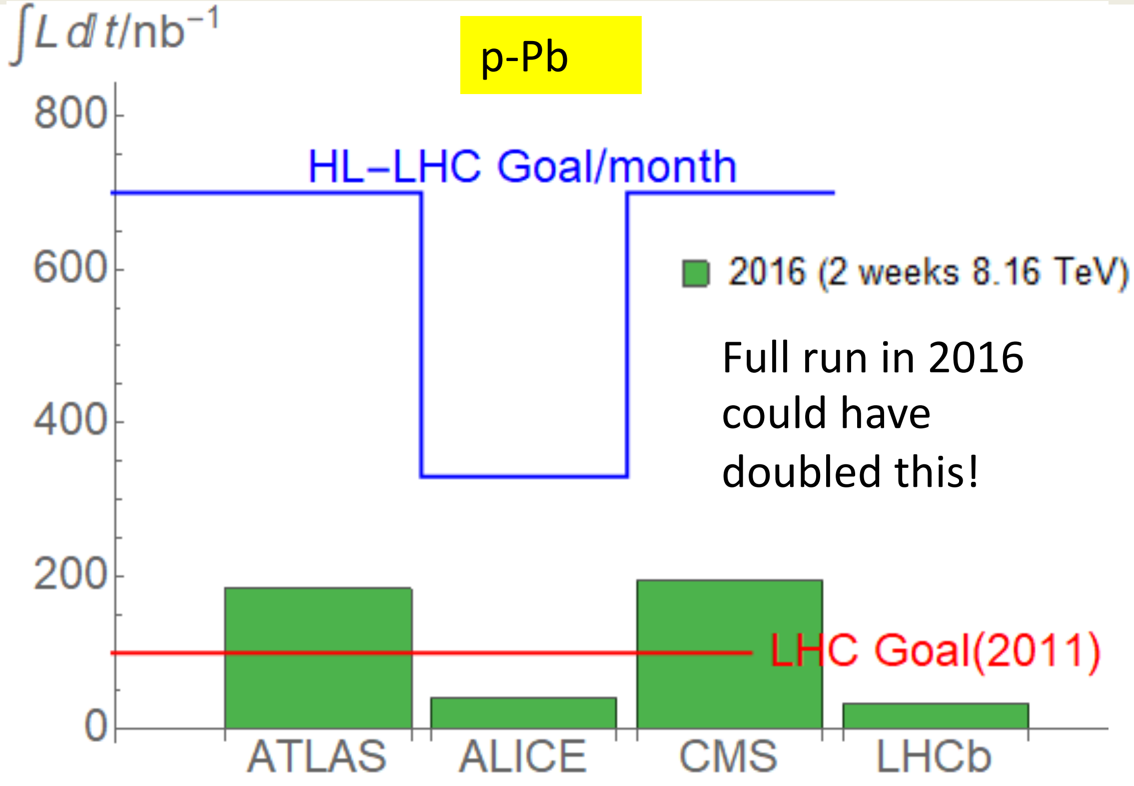


Proton-nucleus programme status after 2016



How close are we to the HL-LHC goals ?





Upgraded ALICE will take similar luminosity to ATLAS/CMS (needs TCLDs in IR2).

With 75 ns for full run, 2018 could have produced more.

More bunches from slip-stacking in future.

"Goal" = estimates by M. Jebramcik, assuming same 50 ns Pb beam, with slip-stacking, as for Pb-Pb and matching proton beam.
Even upgraded ALICE will be levelled.
Assuming ATLAS, CMS are not, for now.
HL-HE-LHC Physics Workshop is now requesting more runs with p-Pb than in former plan.

Beam parameters for potential runs with lighter ions

- Experience with other species in LHC injectors for fixed target
  - Less stringent requirements on beam quality (emittance)

Postulate simple form for bunch intensity dependence on species charge only

$$N_b(Z,A) = N_b(82,208)\left(\frac{Z}{82}\right)^{-p}$$

$$\text{where } p=\begin{cases} 1.9 & \text{fixed target experience} \\ 0.75 & \text{Xe run vs best Pb} \end{cases}$$

Use this highly simplified scaling to project future luminosity performance as a function of *p*.
Assume that other quantities (like geometric beam size), filling scheme, other loss rates, etc, are equal.

Treat results only as tentative and indicative only!

Proceedings of IPAC2016, Busan, Korea TUPMR027

CERN'S FIXED TARGET PRIMARY ION PROGRAMME

D. Manglunki, M.E. Angoletta, J. Axensalva, G. Bellodi, A. Blas, M. Bodendorfer,
T. Bohl, S. Cettour-Cave, K. Cornelis, H. Damerau, J. Efthymiopoulos, A. Fabich

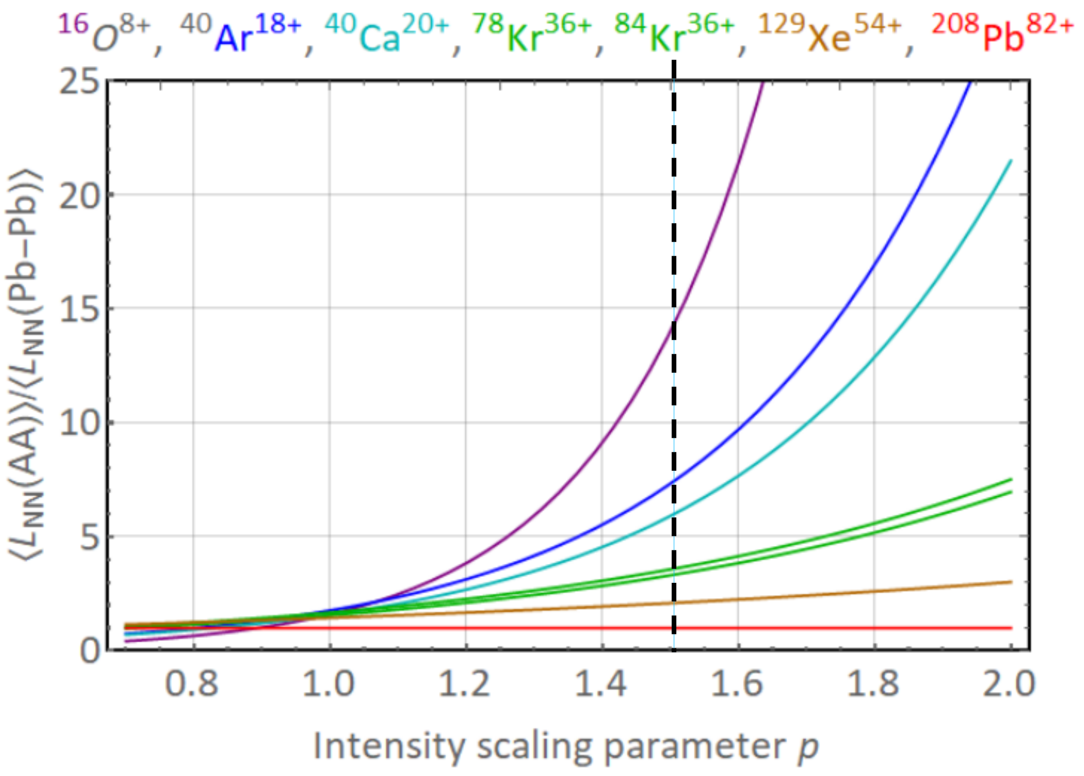
Table 1: Charge States and Typical Intensites

Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state Z in SPS	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^9	8.1×10^8	4×10^8
Ions at extraction in SPS	5×10^9	6×10^8	3×10^8

Study range of p-values
p=1.5 seems reasonable

Time-averaged nucleon-nucleon luminosity ratio vs Pb

- Show ratio of time-averaged luminosity to Pb-Pb
- Analytical calculation with burn-off only
- Lower cross sections for ultraperipheral collisions so more beam particles converted to hadronic luminosity
- Assuming 2.5 h turnaround time, 3 experiments with full luminosity
- Nucleon-nucleon luminosity in 1-month run: gains ranging up to a factor ~13 for lightest considered ion (O) at p=1.5
- The dramatic improvements in transmitted Pb intensity in 2015-16 were the result of many detailed studies and improvements
- Projections have large uncertainties!



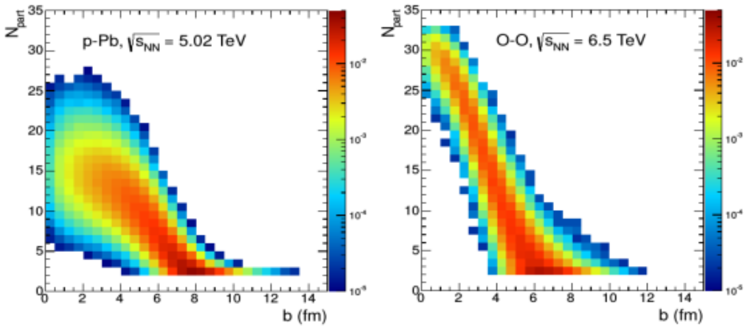
Detailed plans now in preparation for short O-O (QGP system size, etc) and p-O (cosmic rays) runs in 2023.

OXYGEN IN RUN 3 (?)

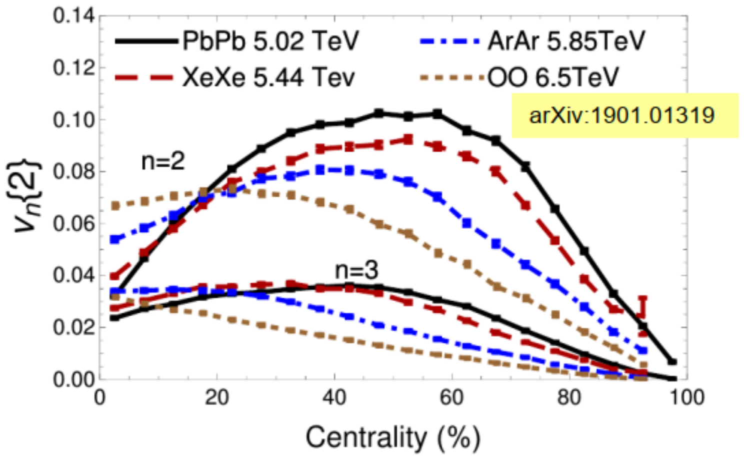
Motivation for Oxygen-Oxygen Run

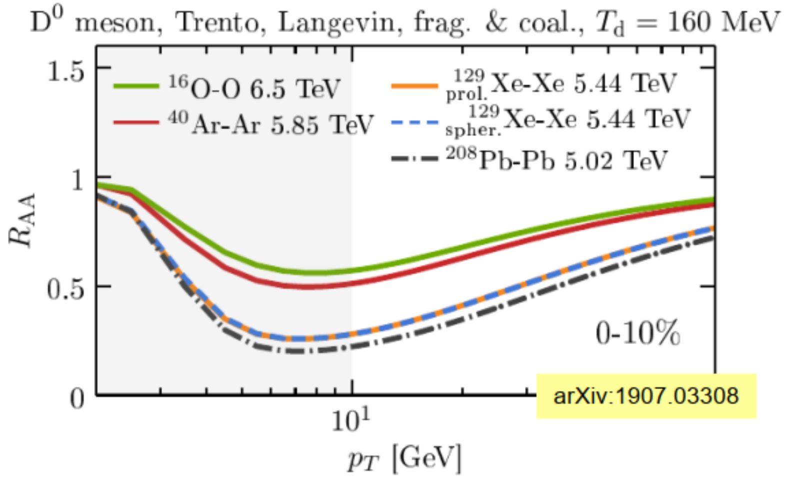
3

- Oxygen-Oxygen collisions can be used to study emergence of collective effect in small systems
  - Open questions for emergence of QGP-like effects in high-multiplicity pPb and pp collisions
  - O-O has similar multiplicity to pPb, but geometry is better defined



- Study bulk-particle production, such as flow harmonics and charged-particle energy loss
- With enough luminosity, could search for suppression of hard probes





B. Petersen, LMC

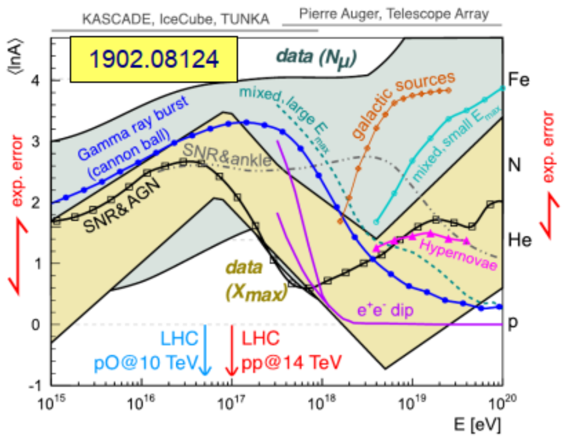
Luminosity Requests for O-O Run

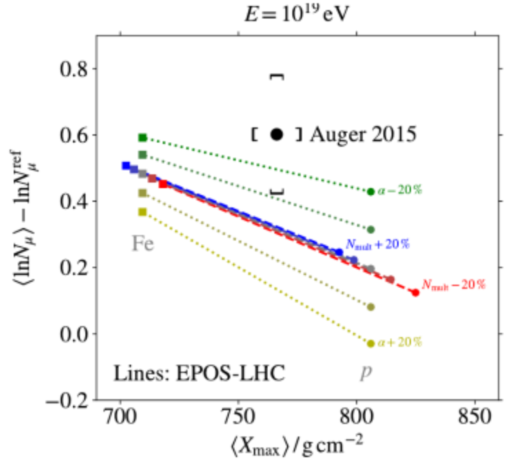
- No real luminosity requests yet
- Some luminosity reference points:
  - ~10/μb – Equivalent luminosity to Xe-Xe run
    This would already provide interesting physics
  - ~0.5/nb – Sufficient for comprehensive soft physics program
  - ~2/nb – Equivalent to 2010 PbPb run for hard-probes
  - ~30/nb – Equivalent to 2011 PbPb run for hard-probes
- Main interest is from ALICE, CMS and ATLAS
  - Provided small impact on PbPb/p-p running
  - LHCf also interested if there is no p-O run

B. Petersen, LMC

Motivation for Proton-Oxygen Run

- Strong interest in cosmic ray community in p-O measurements at LHC energy to improve modeling of high energy air-showers
  - Air-shower models critical in extracting mass of cosmic ray (lnA), which helps identify the source
- Currently modeling errors larger than experimental uncertainty (10%)
  - LHC pp measurements have already improved modeling
- Furthermore have discrepancy between mass extracted from muon density and shower maximum observations
  - Too low muon density predicted
- Wish list for p-O measurements:
  - Double-differential production x-sections for charged pions, kaons, and protons
  - Production x-section for neutral pions and neutrons
  - Energy flow over pseudo-rapidity, separated for hadrons and gammas





See also Tanguy Pierog's Granada t B. Petersen, LMC

Luminosity requests for p-O Run

- Request is to aim for 5% precision in shower modeling to match experimental precision
  - Requires measurements across full rapidity range, i.e from all experiments
  - Minimum sample ~10^8 minimum bias events

- Main interest is from LHCb and LHCf
  - LHCb would like >2/nb (~10^4 J/ψ)
  - LHCf would like ~1.5/nb (~4×10^5 π^0)
- Special requirements from LHCf
  - Low pile-up (μ~0.01) and >2μs bunch spacing
    - Would take O(40) hours with 36 colliding bunches, so adjustments likely needed to keep time to minimum
  - Need to install detector in TAN during TS
    - Removal after special run takes 2-3 hours
    - Might also want to install ZDCs for other experiments

B. Petersen, LMC

Physics Case Summary

- Good physics case for short Oxygen run in the LHC
  - O-O collisions to study small system behavior
  - p-O measurements to significantly improve modeling of high-energy cosmic ray interactions in the atmosphere
- All experiments have expressed interest in either short O-O or p-O run at different priority levels
  - Some concern as to whether it counts in p-p or Pb-Pb “budget”
    - In LPC opinion should count as “special run”, but will ultimately reduce time available for regular p-p running
    - Should be limited to less than one week duration
- Brief physics case has been presented to the LHCC:

The **LHCC fully supports** the physics case for a short run with Oxygen-Oxygen and proton-Oxygen collisions in the LHC and **encourages** the CERN accelerator management to initiate a full study and cost evaluation of possibly injecting Oxygen into the LHC during Run 3.

B. Petersen, LMC

First estimation of bunch intensities @LHC injection

First estimation (next slide) of bunch intensities for LHC (for O4+ and O8+) have been calculated such:

1. **Radiation Protection** could perform **initial simulations and RP assessment** in the accelerator complex
2. **LHC experiments** could **assess** the **physics interest** of such a run based on luminosities

3. Since no data for oxygen exists, the transmission efficiencies used are averages measured in 2016 for Pb [Ref. 6]

4. The bunch intensity values have (at least) the following **uncertainties**:
   - transmission efficiencies for oxygen (no experimental values exist yet)
   - the stripping efficiency of O4+ to O8+ in TT2
   - the LEIR IBS contribution (only the space charge contribution has been considered)
   - the PS & SPS space charge and IBS for oxygen

R. Alemany, LMC

Bunch intensities across the injector chain up to LHC injection

R. Alemany, LMC

- Two charge states (intensities out of Linac3):
  - **O4+** ➔ **70 eµA** measured at the end of Linac3 [Ref. 5,7]
  - **O8+** ➔ ITL.MFC02 ~200 eµA of **O2+** [Ref. 7], in ITH.TRA41 **~180 eµA** (values at the end of the linac calculated, assuming same transmission as O4+ and 100% stripping from O2+ to O8+)

- Two operational cycles: **EARLY = 1** injection, **NOMINAL = 7** injections
- Being a low energy machine ➔ **LEIR space charge is an issue! (See slide 27)**

Q	#inj	**#Ions accumulated at LEIR injection (1e10 ions)**	**LEIR Space charge limit (1e10 ions)**
O4+	1	1.1	2.25
O8+		1.4	0.6
O4+	7	7.7	~~2.25~~
O8+		9.8	~~0.6~~

7 injections is not worth

O4+ ➔ O8+

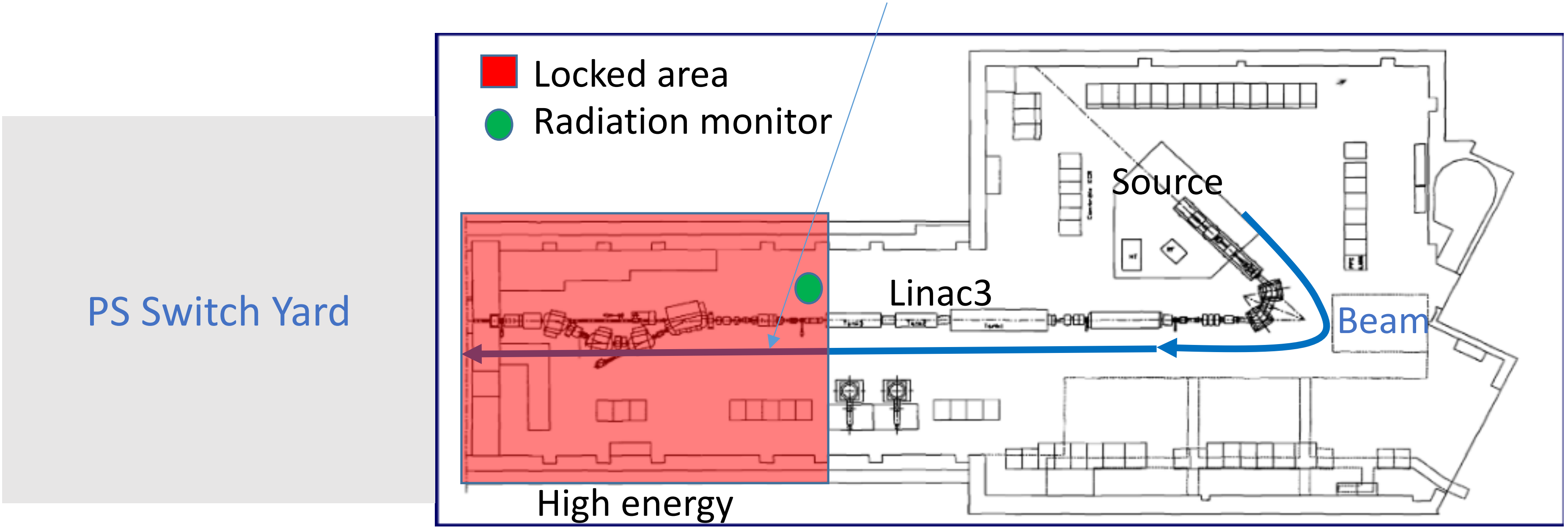
No stripping

Intensity/bunch injected into LHC (1e10 elementary charges)
3.97
2.42

From intensities point of view ➔ **O4+** / **EARLY** best candidate
Gives highest bunch intensity at LHC injection
And fulfils LHC luminosity requirements

Radiological impact in Linac3

Mitigation action: Creation of a Linac3 high energy beam zone, with appropriate barriers and accessibility control. however, some equipment still locked inside.
→ Exact fencing solution to be determined after measurements in 2021

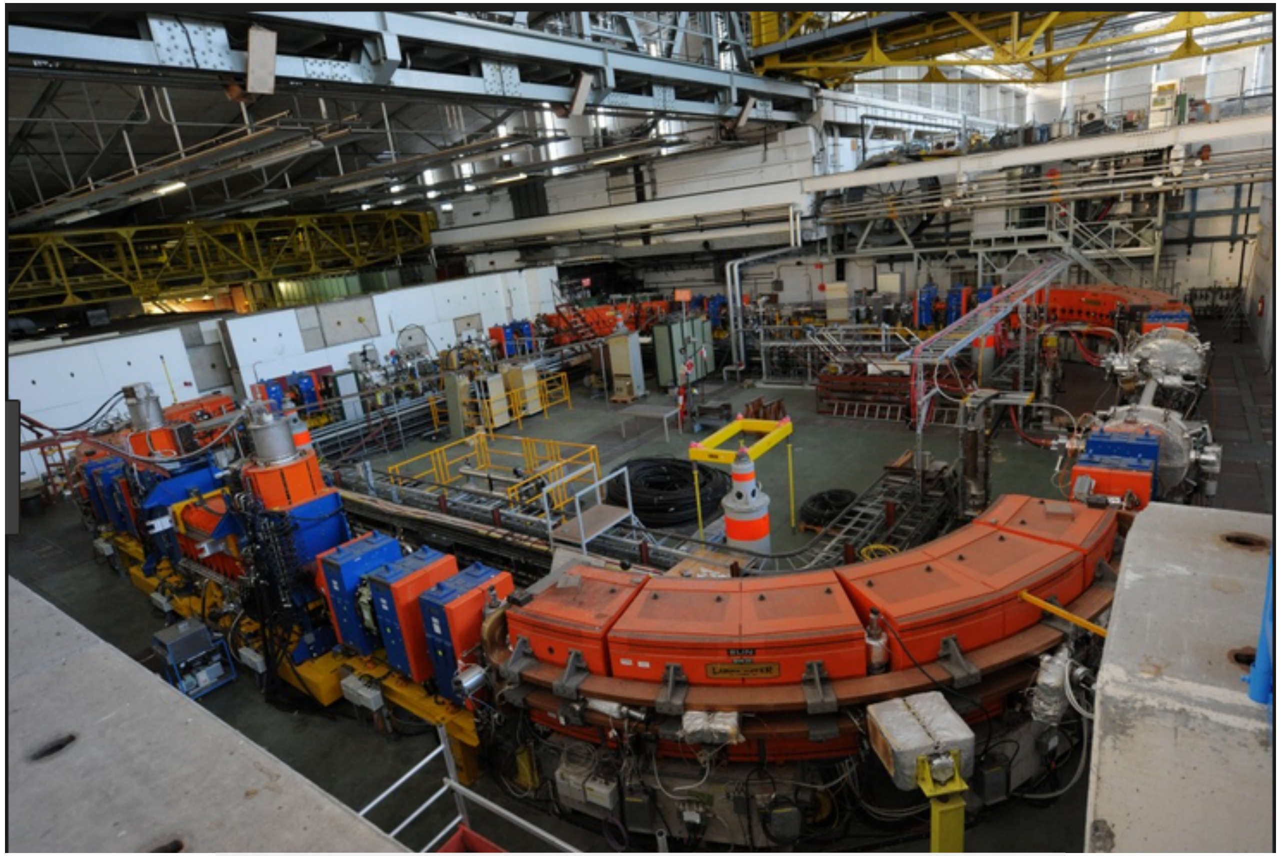


PS Switchyard must be made inaccessible during oxygen operation
➔ PS switchyard Access system to be interlocked with Linac 3 beam stoppers for oxygen operation

R. Alemany, LMC

Radiological impact in LEIR

	Loss scenario at maximum energy
Linac3	Sustained beam loss inside Linac3 Hall at I_{max}
LEIR	Accidental but sustained beam loss at I_{max} 1
	Continuous losses at 10% of I_{max} 2
PS	Accidental but sustained beam loss at I_{max}
	Continuous losses at 10% of I_{max}
	Continuous localised beam loss at stripping



Building 150
Open roof
Picture taken from the visitor platform

Constraints:

1. Open roof (potential 'easy access') (Scenario 1) 2
2. Stray radiation inside B.150 (Radiation Area) (Scenario 2
3. Stray radiation on-site and off-site (Non-designated area, close to the Meyrin site fence) (Scenario) 2

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Radiological impact of light ions in the injectors: conclusions

- Preliminary study to determine main implications of planned Oxygen ion operation done
- Linac3 Oxygen measures to be done in 2021

- **Linac3**: regardless the charge state
  - fencing of high energy part mandatory (Limited Stay Radiation Area)
  - additional active and interlocked RP monitoring
  - losses must be effectively limited
- **LEIR**:
  - O8+ (245 MeV/u) for given intensities:
    - roof shielding to be considered
    - visitor platform to be removed
  - O4+ (67 MeV/u) for given intensities:
    - roof shielding not required
    - no access to visitor platform
- **PS Switchyard and PS Booster**:
  - no access during oxygen ion operation
  - access interlock

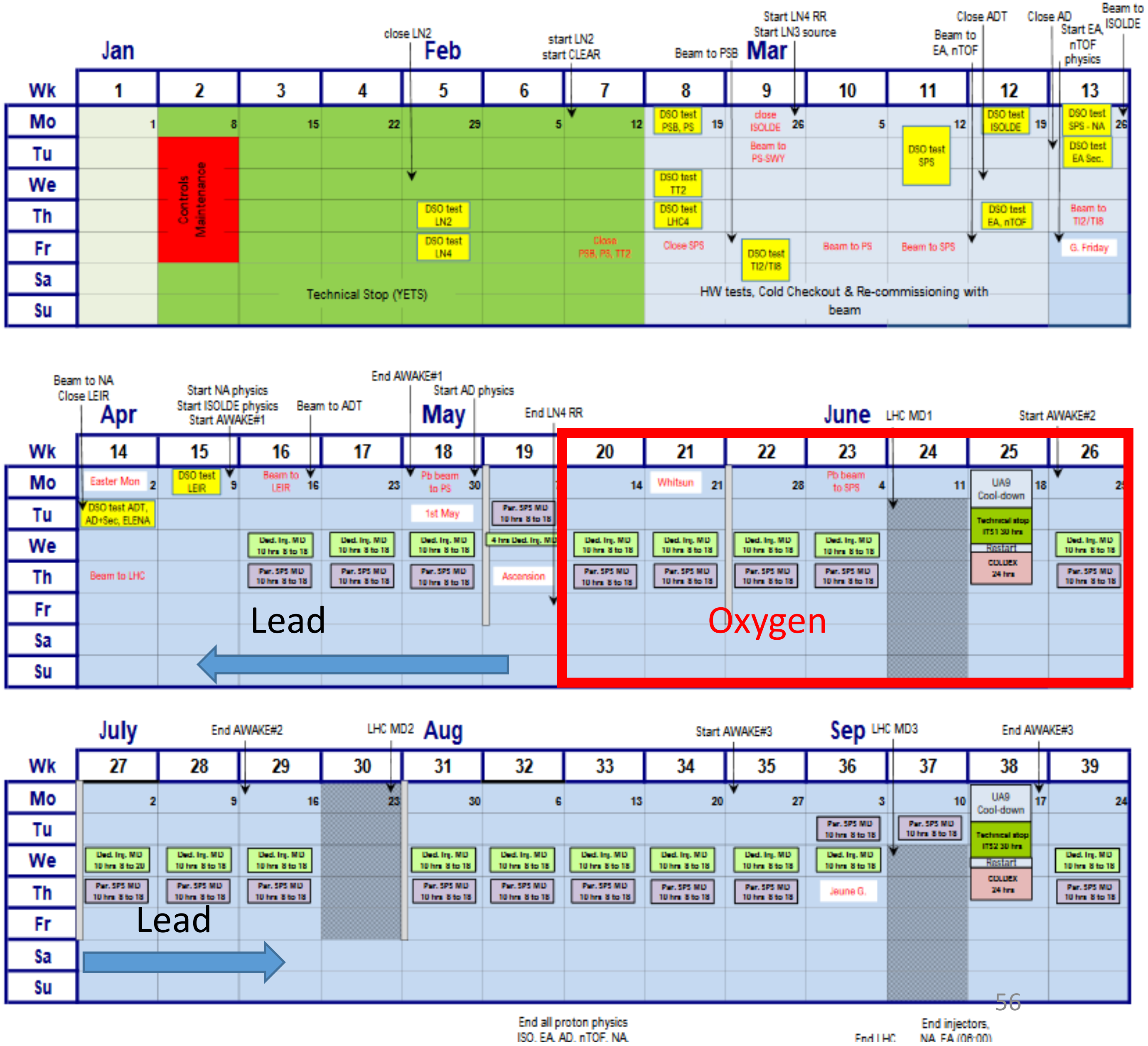
From RP point of view → **O4+** best candidate; requires less shielding measures to be put in place

R. Alemany, LMC

Schedule proposal

R. Alemany, LMC

- ➢ We propose to carry out the run in 2023
    - ➢ pPb potentially in the schedule
    - ➢ 50 ns proton bunches
- ➢ Start-up ion complex with Pb up to PS
- ➢ **If EARLY Oxygen beam:**
    - **Week 20 switch to Oxygen**
    - Week 22 beam to LEIR
    - Week 23 beam to PS
    - Week 24 beam to SPS
    - Week 26 beam to LHC
    - **Week 27 Pb back to the complex**



LHC commissioning considerations

- O-O for a few fills within set-up beam limits
  - Shortens validation process, fewer loss maps, etc.
  - “Early” beam sufficient from injectors
  - “Nominal” (trains) only worthwhile for full set-up, longer run
- ALICE should have similar luminosity to ATLAS/CMS
  - Re-use optics set-up for Pb-Pb in previous year
  - Identical $\beta^*=(0.5,0.5,0.5,1.5)$ to 2018
  - Could use identical or similar combined ramp and squeeze to 2018
- p-O run for cosmic ray physics
  - Similar O beam
  - Matching p beam, also constrained by set-up beam intensity
  - Similar injection, cogging, etc as p-Pb
  - *Maximum* luminosity estimate for p-O easily fulfils requirements $\Rightarrow$ need to level to keep pileup below 0.01 in LHCf (see Brian’s talk)
- Planning
  - Earlier in year than main Pb-Pb or p-Pb run (see Reyes’ talk)
  - After technical stop to allow LHCf detector installation in TAN (see Brian’s talk)

Needed commissioning – first estimates

- **O-O commissioning**
  - Recheck entire cycle: orbit, tune, Q’, coupling collisions, optics @ low beta – 3 shifts.
    - Time estimate based on the fact that optics reproducible
    - Could do it with protons
  - Clean-up the cycle with new settings (assume optics is stable !) – 1 shift.
  - Setup of injection and capture – 1 shift
  - Validation
    - 1 shift for TCT setup (if needed), and loss maps + asynch dump test
    - Low-intensity setup beam with bunch spacing > abort gap: do asynch dump test only at injection and collision (TBC with MP and ABT)
  - Total time 6 shifts → ~2-3 days

- **p-O commissioning**
  - Setup of injection frequencies, p-beam, cogging – 1 shift
  - Validation - 0.5 shift. Use cogging fill?
  - Sufficient with p-O (O-p not requested)
  - Total time ~2 shifts → ~0.5-1 day

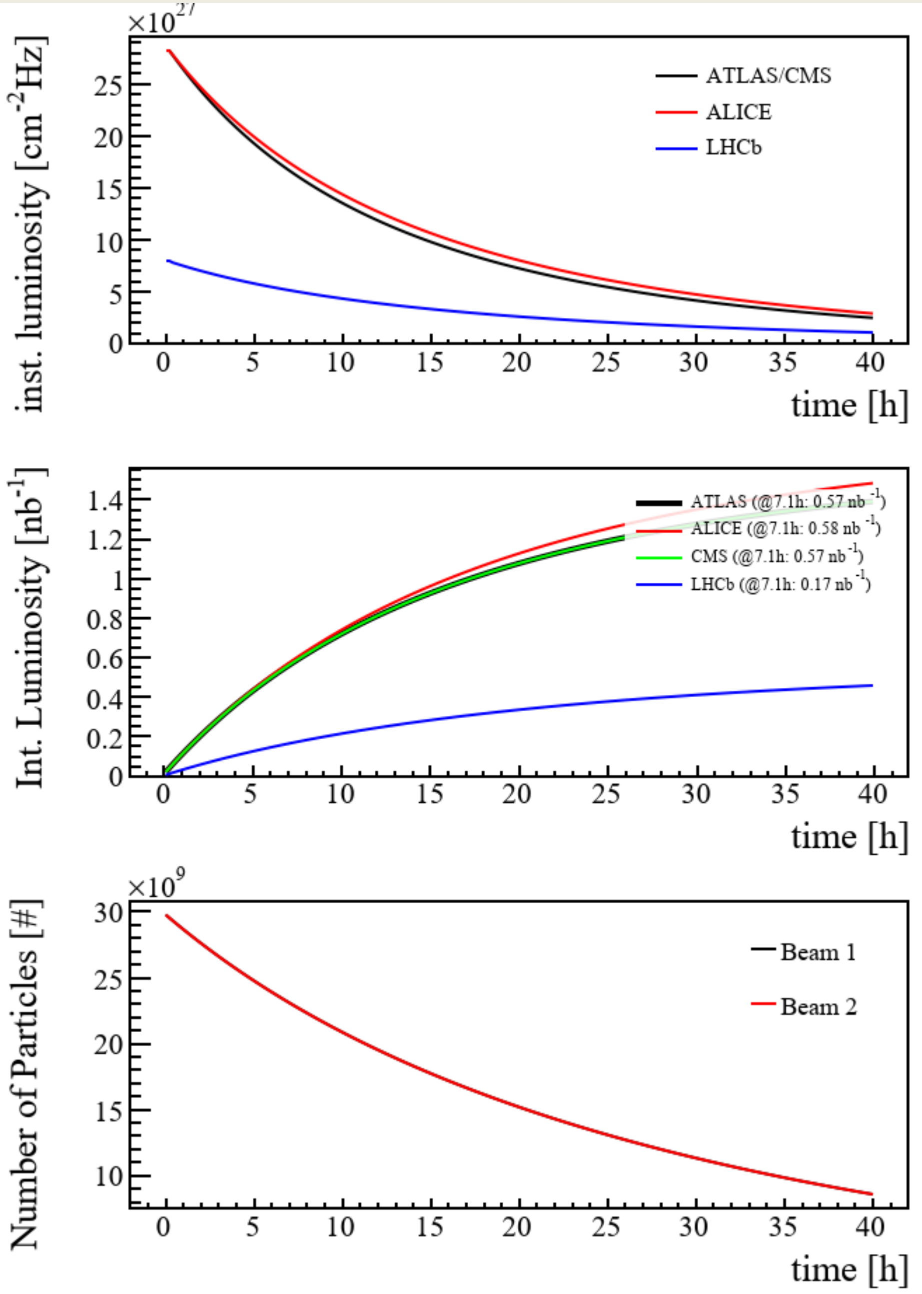
Example luminosity evolution, assumptions:

- Stay below set-up beam limit: 3×10^{11} charges per beam
- For O-O, assume 3.97×10^{10} charges/bunch (4.96×10^{9} O^{8+})
  - See talk R. Alemany
  - Assume 6 bunches, 4 colliding per IP (filling pattern to be optimized)
- For p-O, use lower bunch intensity and more bunches
  - Assume 36 bunches, 24 colliding per IP (filling pattern to be optimized)
  - level at 10^{28} $cm^{-2}s^{-1}$ for LHCf pileup

	IP1/5	IP2	IP8
β^* [m]	0.5	0.5	1.5
$\theta/2$ [μrad]	100	100	170

- Normalized emittance at flat-top as for Pb: ε_n=2.09 μm
- Luminosity evolution from coupled ODE model
  - (Burn-off, IBS, radiation damping, empirical non-luminous losses … for each bunch class)
  - N.B. radiation damping rates are 4 times slower than Pb

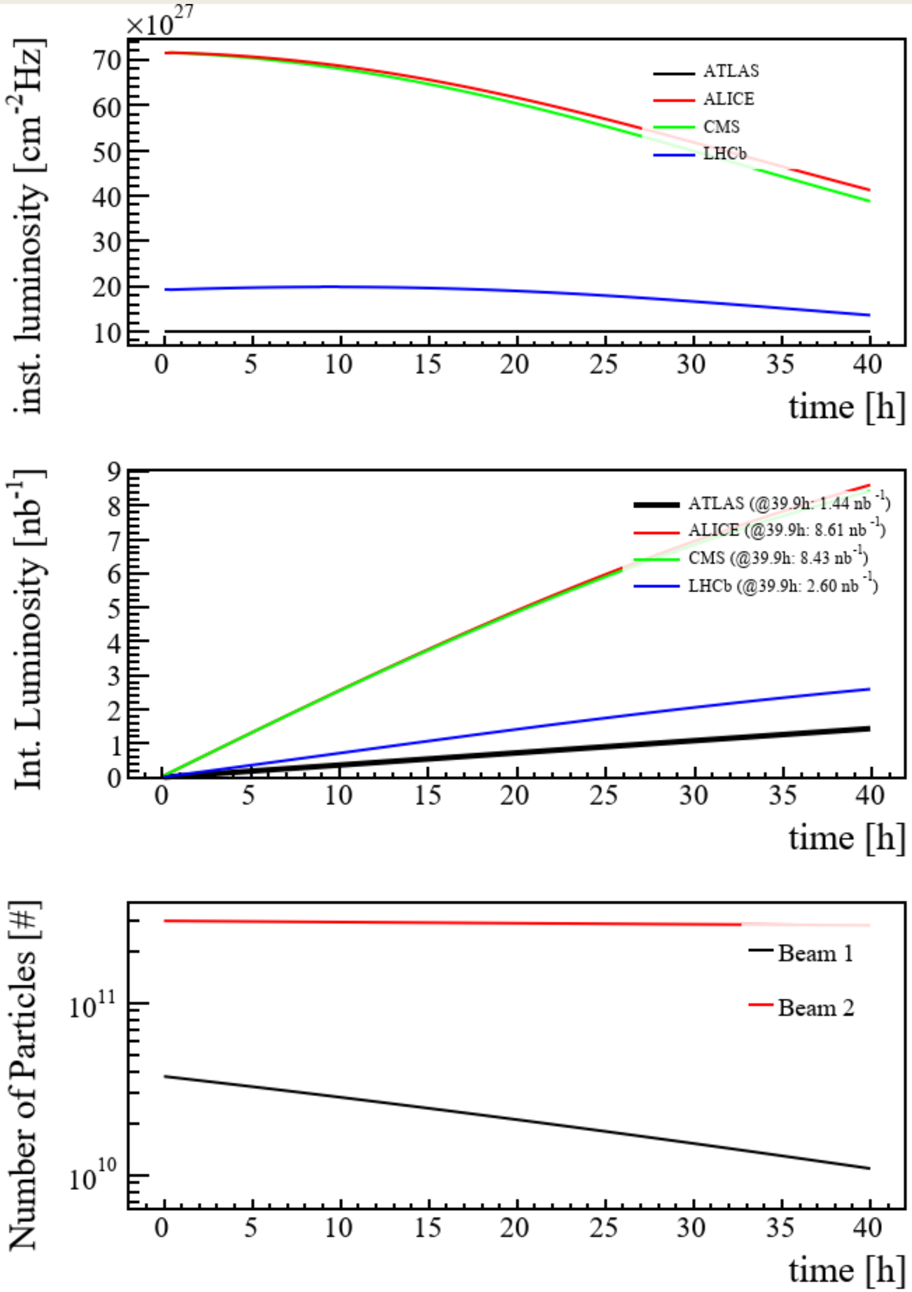
Oxygen-oxygen fill - conservative



- Assumed no levelling
- Around 8h in stable beams are enough to reach 500 μb^{-1} for soft physics program
  - (less for LHCb)
- In 1 day with 2-3 fills, we could get significantly above 1 nb^{-1}

N_b=4.96×10^9 O^{8+} (3.97×10^{10} charges)
Filling pattern "6b_4_4_4"

Proton-oxygen pilot fill – conservative



- Assume IP1 is levelled at 10^{28} $cm^{-2}s^{-1}$ for LHCf
- In levelling, need about 42h to reach target (1.5 nb^{-1}) for LHCf
  - LHCb above 2nb^{-1}
  - Probably need 2-3 fills, could take 2-2.5 days
- For non-levelled experiments, expect significantly more

$N_{b,O}$=1.04×10^9 O^{8+} (8.33×10^9 charges)
$N_{b,p}$= 8.33×10^9 p
Filling pattern "36b_24_24_24"

Possible preliminary timeline of run

- O-O commissioning: 2-3 days
- O-O physics run: 1 day
  - Hope for >1 nb^{-1} in ALICE, ATLAS, CMS.
  - Allows for soft physics program and some hard-probe measurements
- p-O commissioning: 0.5 – 1 day
- p-O physics run: 2-2.5 days
  - Aim for 1.5 nb^{-1} in LHCf and 2 nb^{-1} in LHCb
- Total: ~6-7 days
  - Less physics time would still be useful

Assumes that O beam has been commissioned in the injectors (in parallel with p-p operation) first.

Summary and conclusions

- The LHC can collide more types of beam, with much higher performance, than originally foreseen.
  - Including asymmetric beams (p-Pb) despite the two-in-one magnet design
  - LHC ion injector chain working far beyond design parameters
  - Rich physics output (see heavy-ion parallel and plenary talks)
- Planning the set-up of 1-month runs is critical, especially as one cannot backtrack after validations.
- Control of heavy-ion beam losses, like collimation, BFPP, is critical, complicated and may surprise. But simulations are increasingly reliable guide to details of mechanisms.
  - Crystal collimation (very successful tests in MD, not described here) holds promise!
- BLM settings also require careful analysis and tuning.
- We have come close to the full “HL-LHC” performance in Pb-Pb and p-Pb.
- First short runs with new species can have significant physics output – good prospects for O-O and p-O run in 2023.