LHC Prospects

2nd LHCb Heavy Ion Workshop, September 4-6, 2019, Chia

Burkhard Schmidt, CERN

Many thanks to John Jowett, who provided most of the material shown here:

https://indico.cern.ch/event/577856/sessions/291389/#20190712

Outline

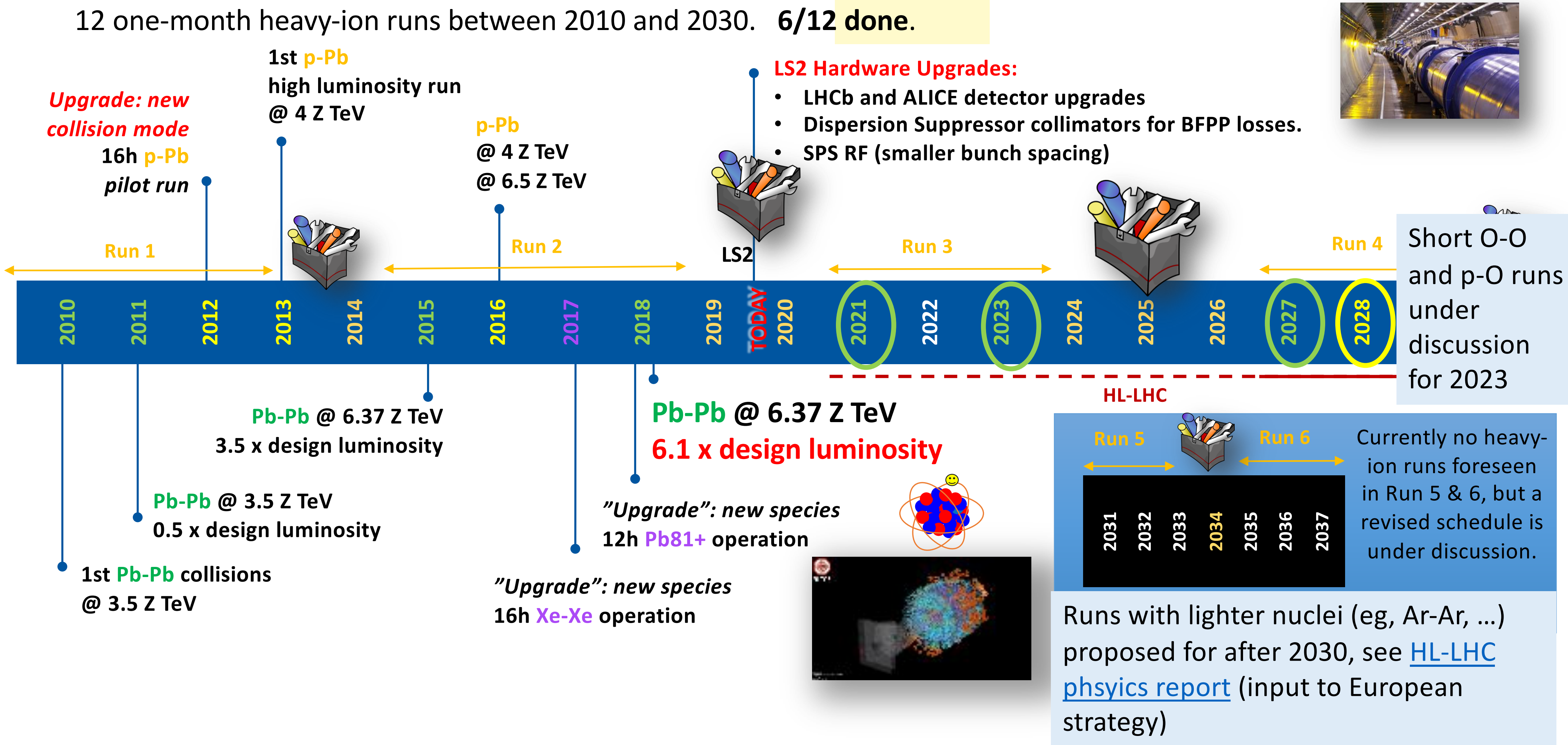
- Introduction
  - History and Future of Nuclear Beams in the LHC
  - LHC Heavy Ion Injector Chain and past improvements

- Achievements so far and lessons learned
  - Pb-Pb collisions in Run II
  - p-Pb collisions in Run II

- Outlook for future Heavy-Ion collisions in Runs III and IV

History and Future of Nuclear Beams in the LHC

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



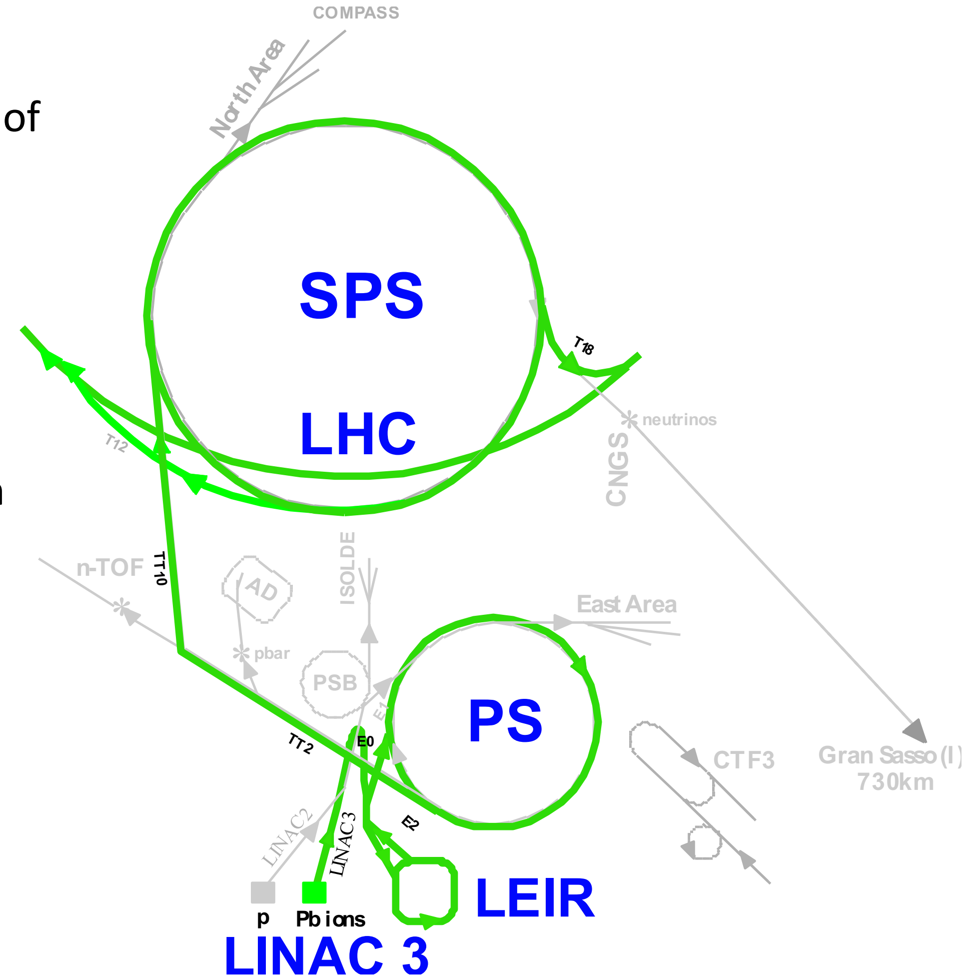
Typical one-month heavy-ion run – highly schematic

- 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 for machine protection
  - Only once the cycle is established, cannot be changed again!
  - Beam-loss monitor dump threshold settings are 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.

LHC Heavy Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC



Major injector improvements since 2015

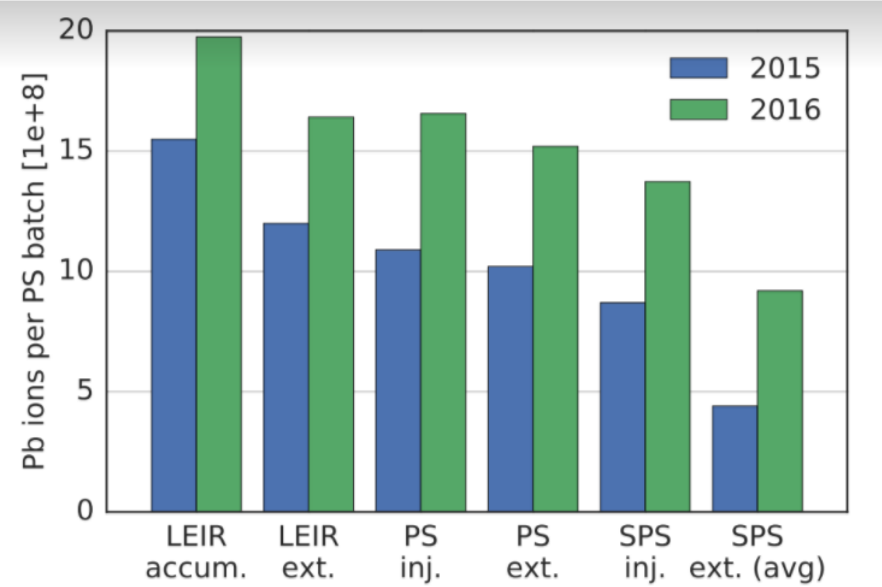


Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

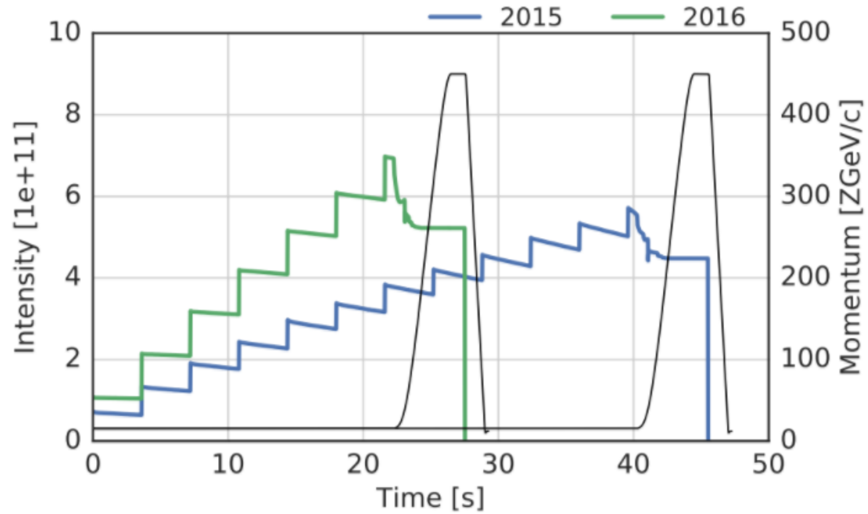
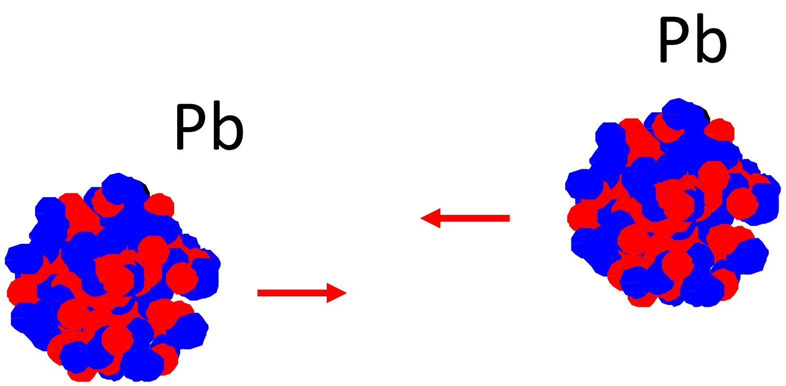


Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

H. Bartosik *et al.*, “The LHC Injectors Upgrade (LIU) Project at CERN: Ion Injector Chain,” *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, paper TUPVA020, pp. 2089–2092.

Improvements in upstream injectors allowed re-introduction of bunch-splitting in the PS to stay below single-bunch limit in the SPS (which remains the main intensity bottleneck).

NB took advantage of these gains in Pb-Pb for the *first time* in 2018.



Pb-Pb in Run II (2015 and 2018)

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 and p–Pb run [12–16]. The original design values for Pb–Pb [4] and p-Pb [17] and future upgrade Pb–Pb goals are also shown (in these columns the integrated luminosity goal is to be attained over the 4 P–Pb runs in the 10-year periods before and after 2020). Peak and integrated 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 p-Pb or Pb-p runs are generally for Pb. The series of runs with $\sqrt{s_{\rm NN}} = 5.02$ TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are $\boxed{\text{boxed}}$ for easy comparison. The upgrade value is reduced by a factor ≃ 3 from its potential value by levelling.

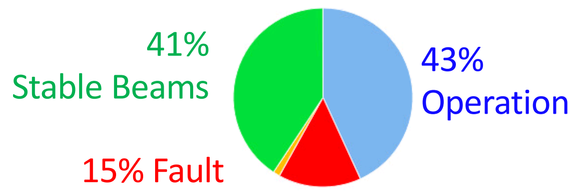
Quantity	"design"		achieved					upgrade
Year	(2004)	(2011)	2010	2011	2012–13	2015	2016	≥2021
Weeks in physics	-	-	4	3.5	3	2.5	1, 2	-
Fill no.			1541	2351	3544	4720	5562	-
Species	Pb–Pb	p–Pb	Pb–Pb	Pb–Pb	p–Pb	Pb–Pb	p–Pb	Pb–Pb
Beam energy E [Z TeV]	7		3.5		4	6.37	4,6.5	7
Pb beam energy E [ATeV]	2.76		1.38		1.58	2.51	1.58,2.56	2.76
Collision energy $\sqrt{s_{\rm NN}}$ [TeV]	5.52		2.51		**5.02**	**5.02**	**5.02**,8.16	5.52
Bunch intensity N_b [10^8]	0.7		~~1.22~~	~~1.07~~	~~1.2~~	~~2.0~~	2.1	1.8
No, of bunches k_b	592		137	338	358	518	540	1232
Pb norm. emittance ϵ_N [μm]	1.5		2.	2.0	2.	2.1	1.6	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	0.8	10, 0.6	0.5
Pb stored energy MJ/beam	3.8	2.3	0.65	1.9	2.77	8.6	9.7	21
Peak lumi. $L_{\rm AA}$ [10^{27}cm^{-2}s^{-1}]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. $L_{\rm NN}$ [10^{30}cm^{-2}s^{-1}]	$\boxed{43}$	$\boxed{31}$	1.3	22.	24	$\boxed{156}$	$\boxed{177}$	$\boxed{260}$
Integrated lumi./expt. [μb^{-1}]	1000	10^5	9	160	32000	650	1.9×10^5	10^4
Int. NN lumi./expt. [nb^{-1}]	43000	21000	380	6700	6650	28000	40000	4.3×10^5

Paper at IPAC2018
https://doi.org/10.18429/JACoW-IPAC2018-TUXGBD2
TUXGBD2
+ its bibliography

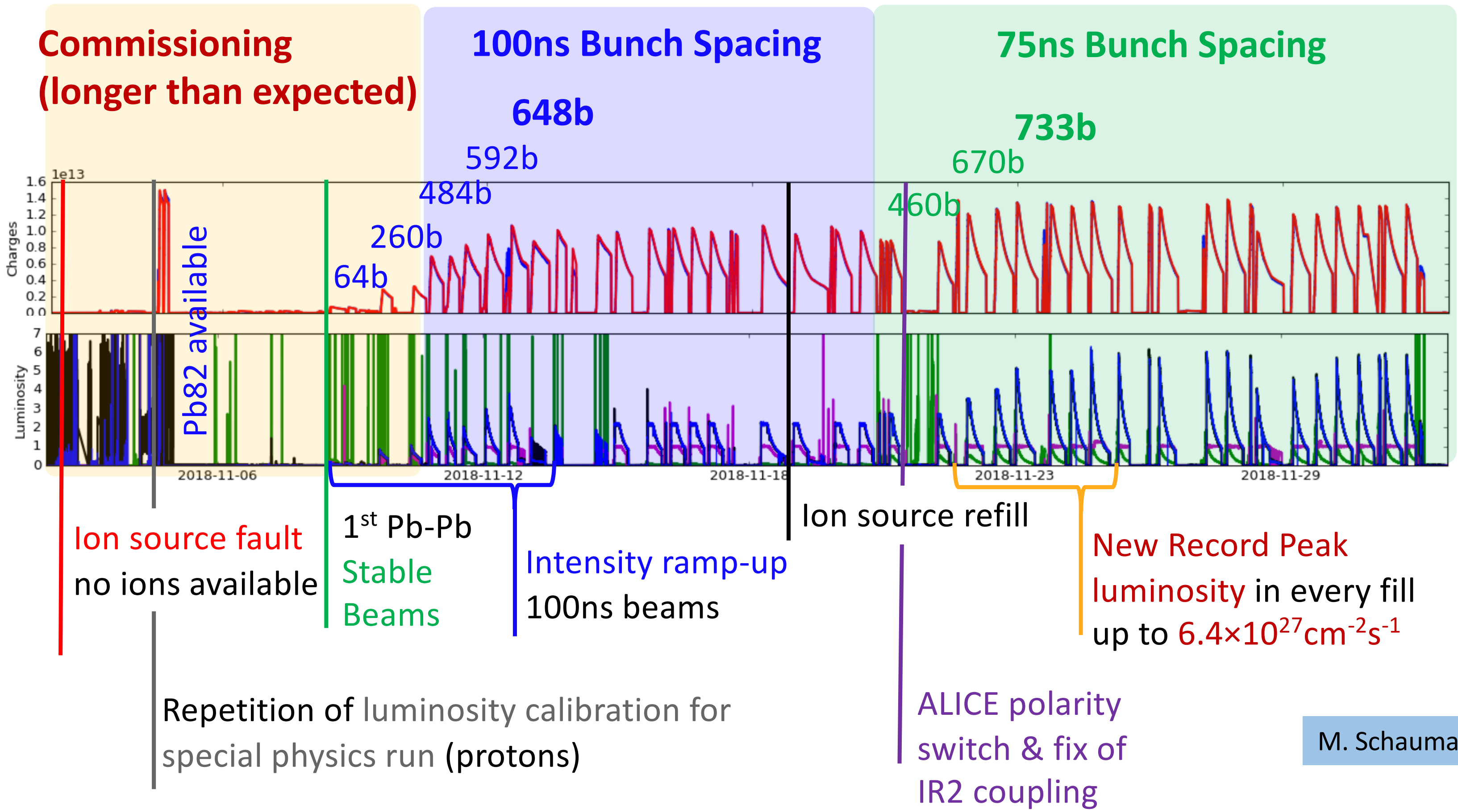
The 2018 Pb-Pb run implemented and exploited most of the features of the configuration for "HL-LHC".

Levelled,
could be ~15.

Details 2018 Pb-Pb Run



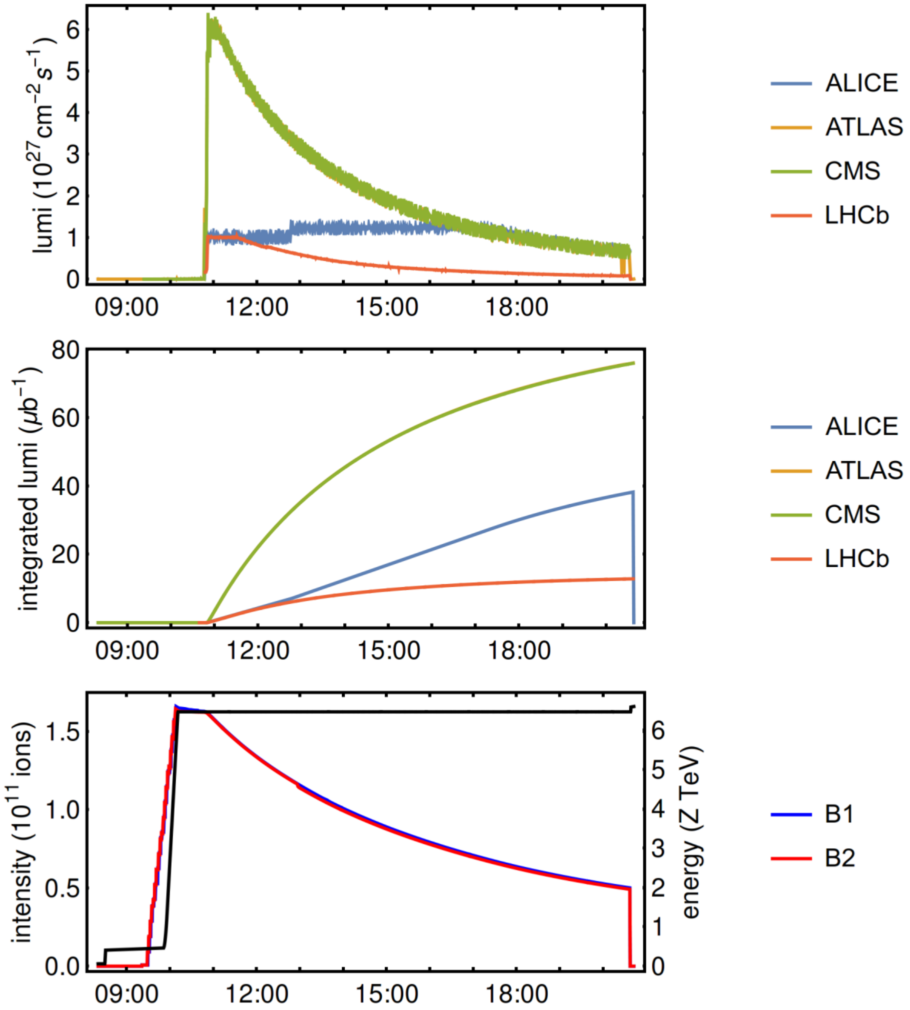
Availability
85%



M. Schaumann

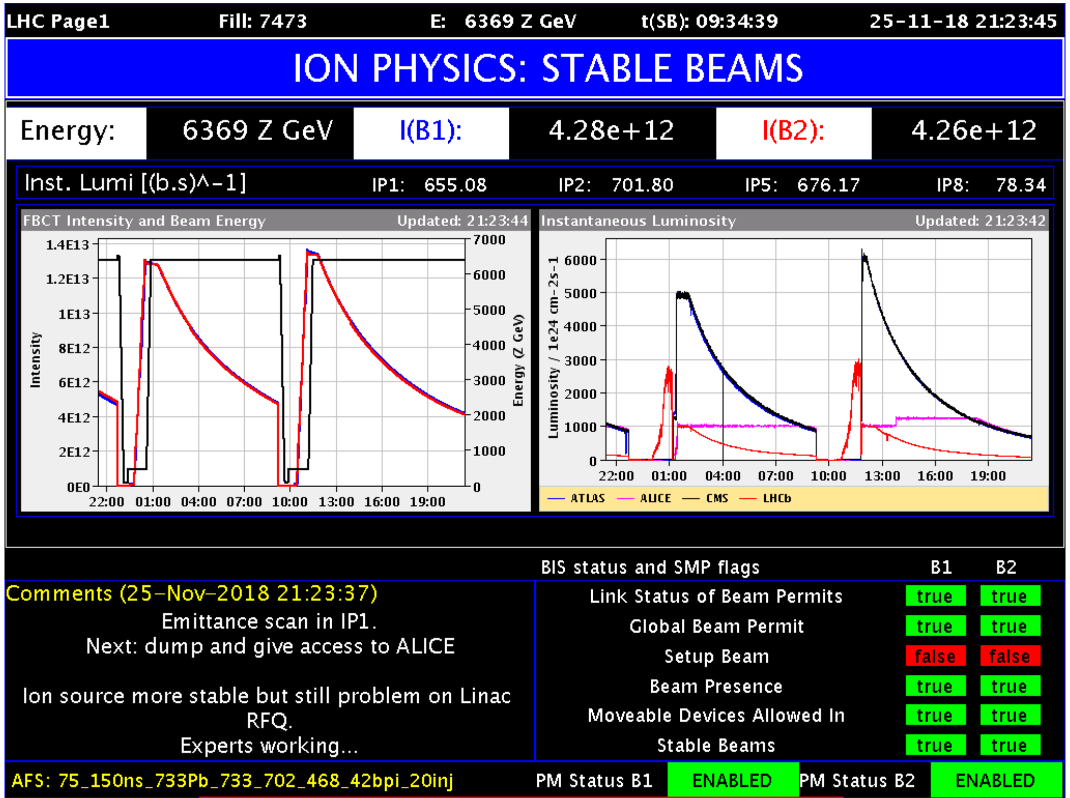
A high peak luminosity Pb-Pb fill in 2018 with 100 ns

- Leveling in ATLAS and CMS gradually increased to 5×10^{27} $cm^{-2}s^{-1}$
- ALICE leveled at design luminosity $1{\times}10^{27}$ $cm^{-2}s^{-1}$
- After correction of local coupling, ALICE level times increased to ~ 8 h.



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

- **Design peak luminosity is exceeded** by factor 5 (to 6) 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.



$$L = 6 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$$
$$= 6 \times \text{design}$$
$$= (47\ \text{kHz hadronic event rate})$$

Nominal HL-LHC levelling value is

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

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.

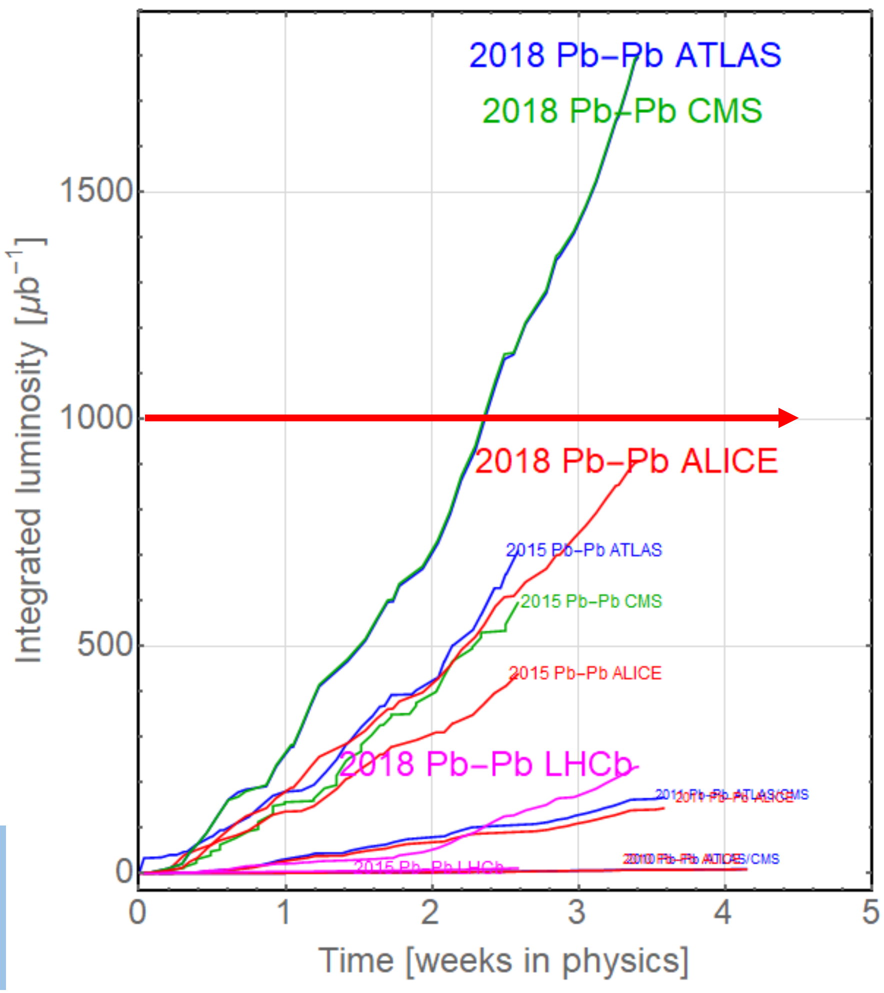
Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

Equivalent energy runs

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

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

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



Luminosity limit: Ultra-Peripheral Interactions

Very strong magnetic fields of ~10^{15} T : cause bound-free pair production and electromagnetic dissociation of nuclei

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

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

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

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

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

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

Strong luminosity burn-off of beam intensity.

Discussed for LHC since Chamonix 2003 … see several references.

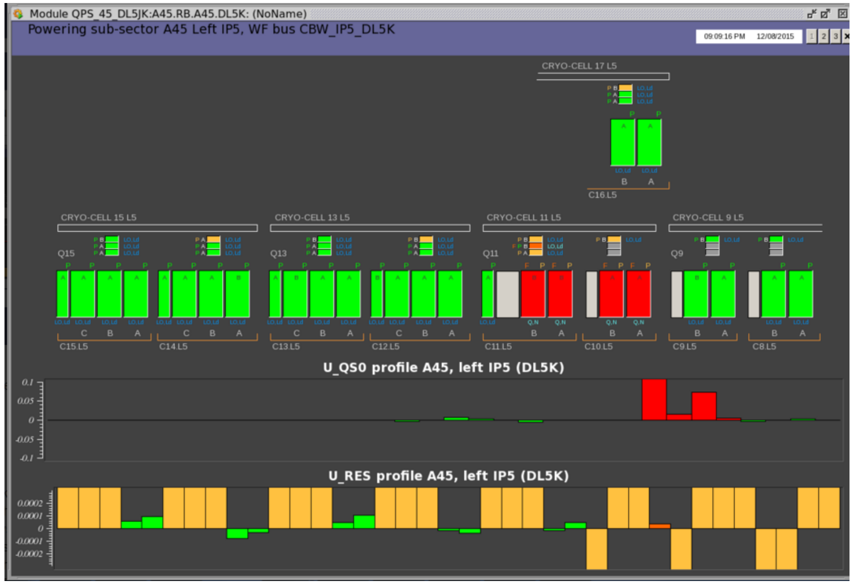
- Hadronic cross section is 8 b (so luminosity debris contains much less power).

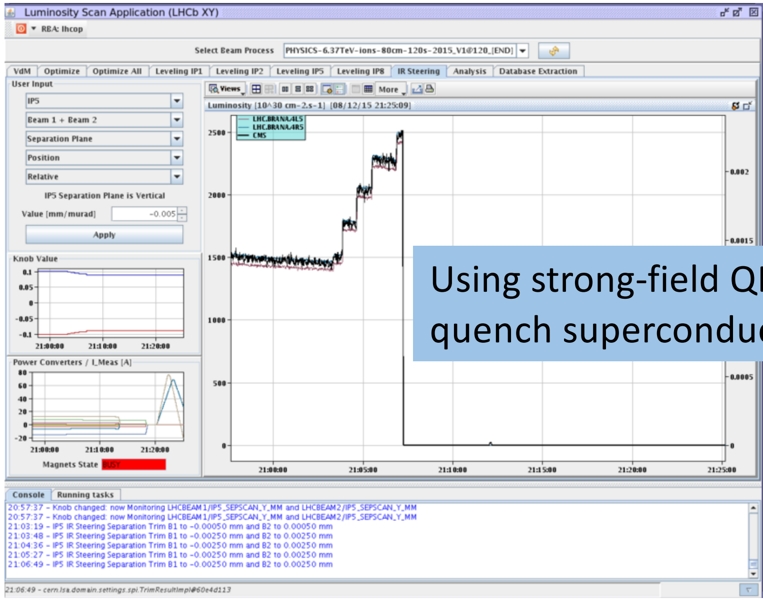
BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for Fill 4707 on 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):

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

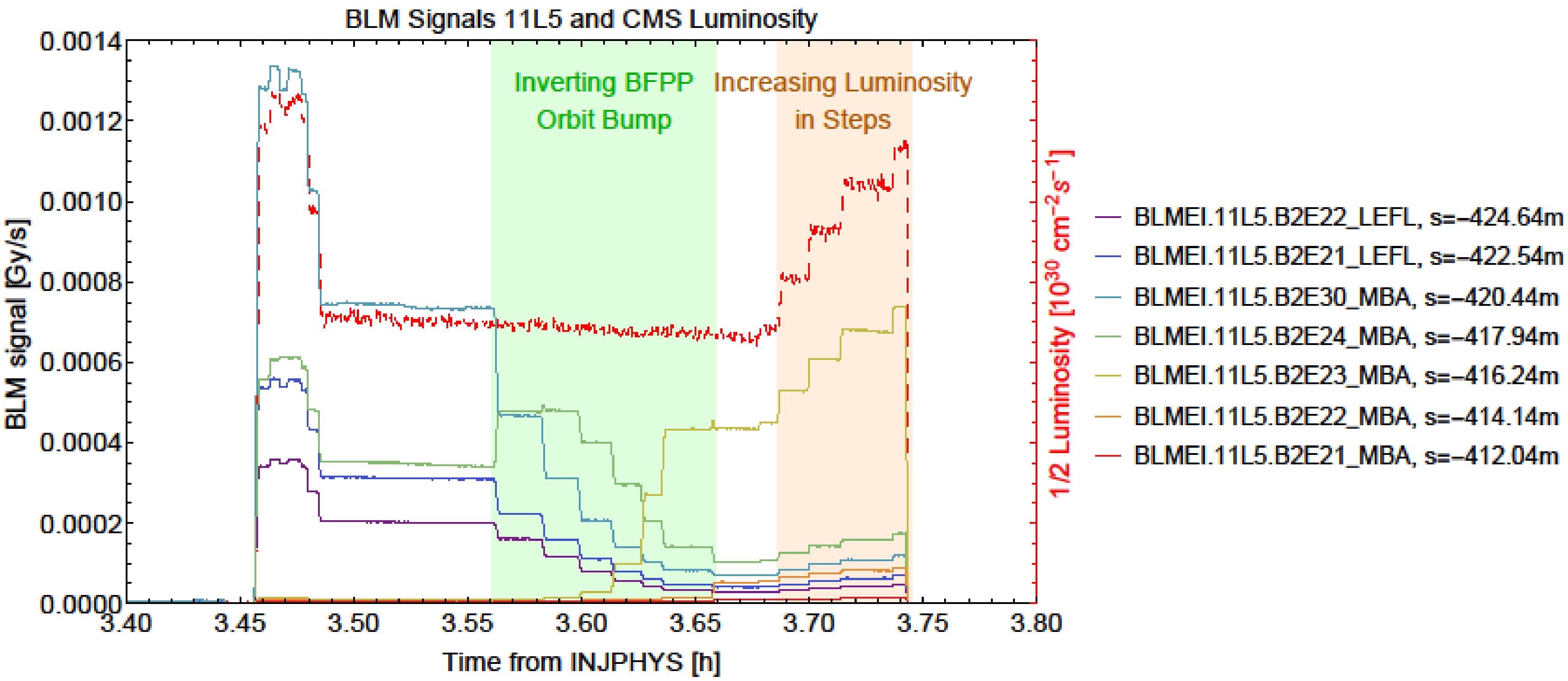
$$\Rightarrow\quad 0.64\ \text{MHz event rate, about 45 W of power in } Pb^{81+} \text{ beam into magnet}$$





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.

BLM Threshold changes for BFPP losses

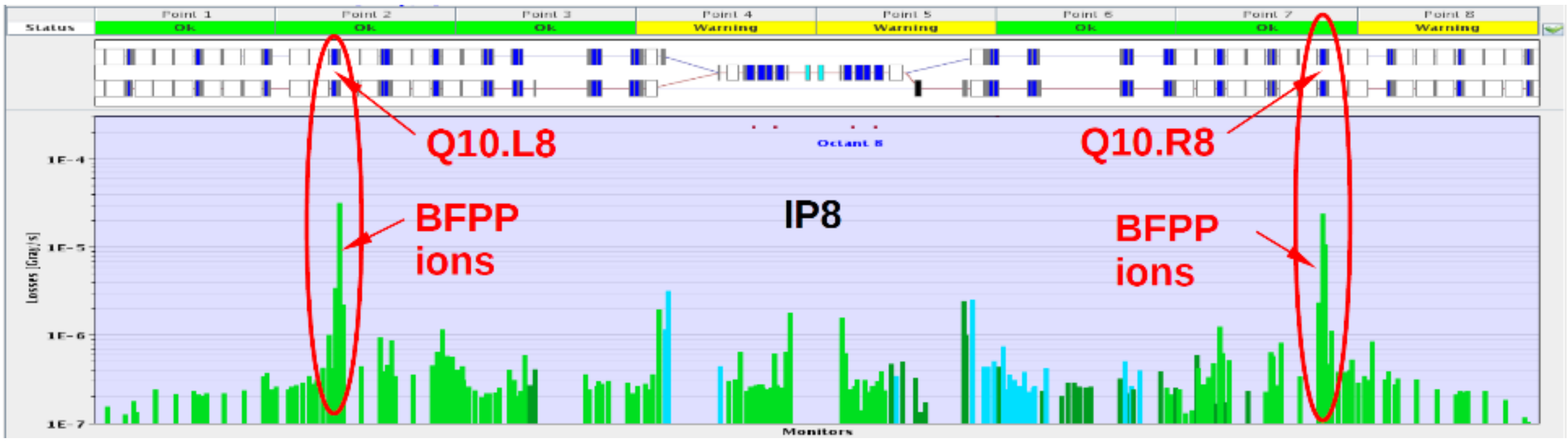
BFPP-related threshold changes essential for luminosity reach:

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 (6-7 x $10^{27}cm^{-2}s^{-1}$) while still protecting against quenches

2) Prevent premature dumps due to BFPP ions in IR8

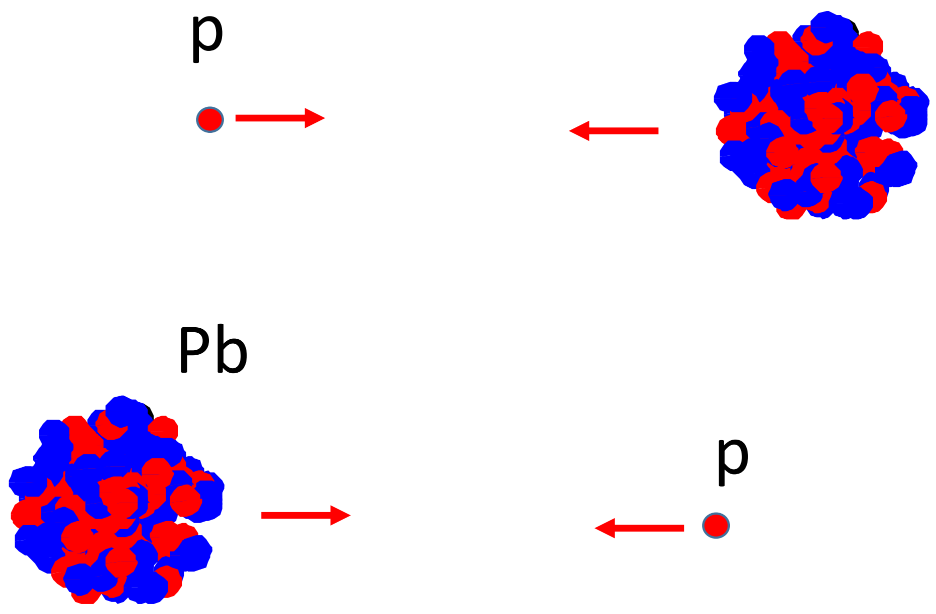
- Luminosity reach in LHCb higher than in previous years ($10^{27}cm^{-2}s^{-1}$) thanks to 75 ns bunch spacing
- BFPP loss location around Q10 -> Q10s had low thresholds to reduce the risk of symmetric quenches
  → would have prevented reaching the target lumi
- Decided to temporarily decrease QPS thresholds, which allowed increasing the Q10 BLM thresholds



A. Lechner et al

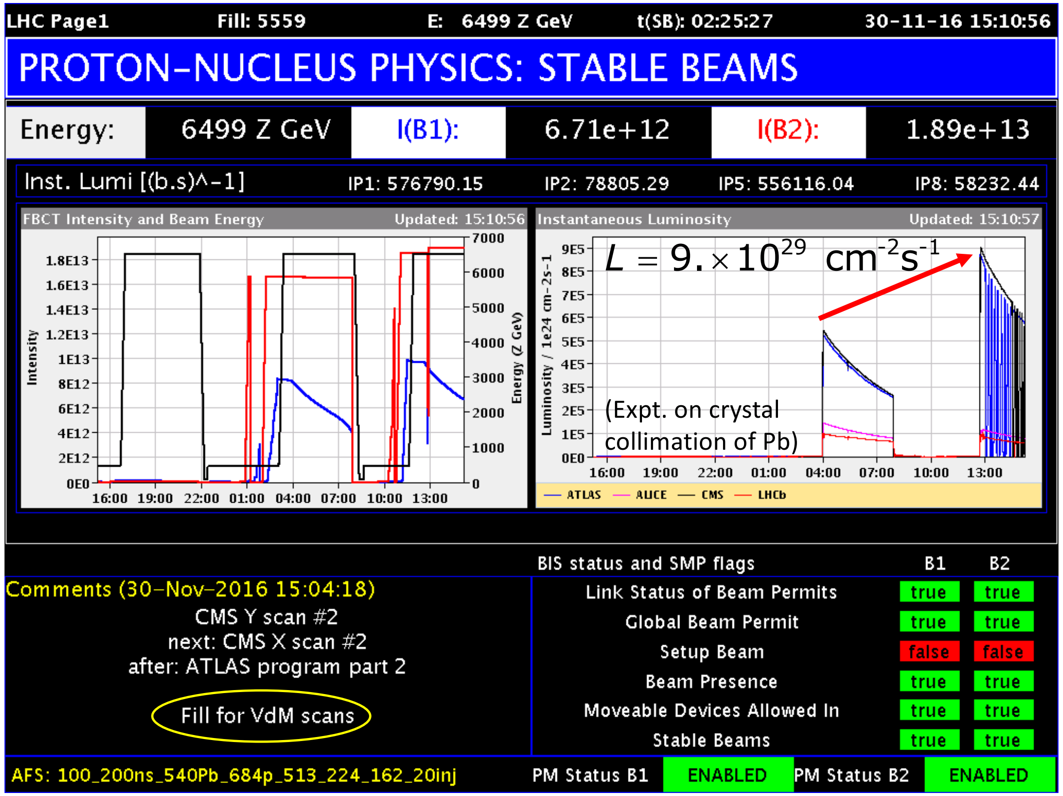
Lessons from the Pb-Pb runs

- After two Pb-Pb runs in 2010, 2011, the **High Luminosity Pb-Pb** phase started in 2015.
- BFPP bump mitigation allows HL-LHC peak luminosity in ATLAS/CMS without quenches (> 6 × design).
- Separation levelling used in ALICE (also in ATLAS, CMS)
- Collimation losses remain critical, avoid premature dumps.
- First controlled quench of an LHC dipole using BFPP beam from the collision point
- 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



p-Pb in Run II (2016)

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.

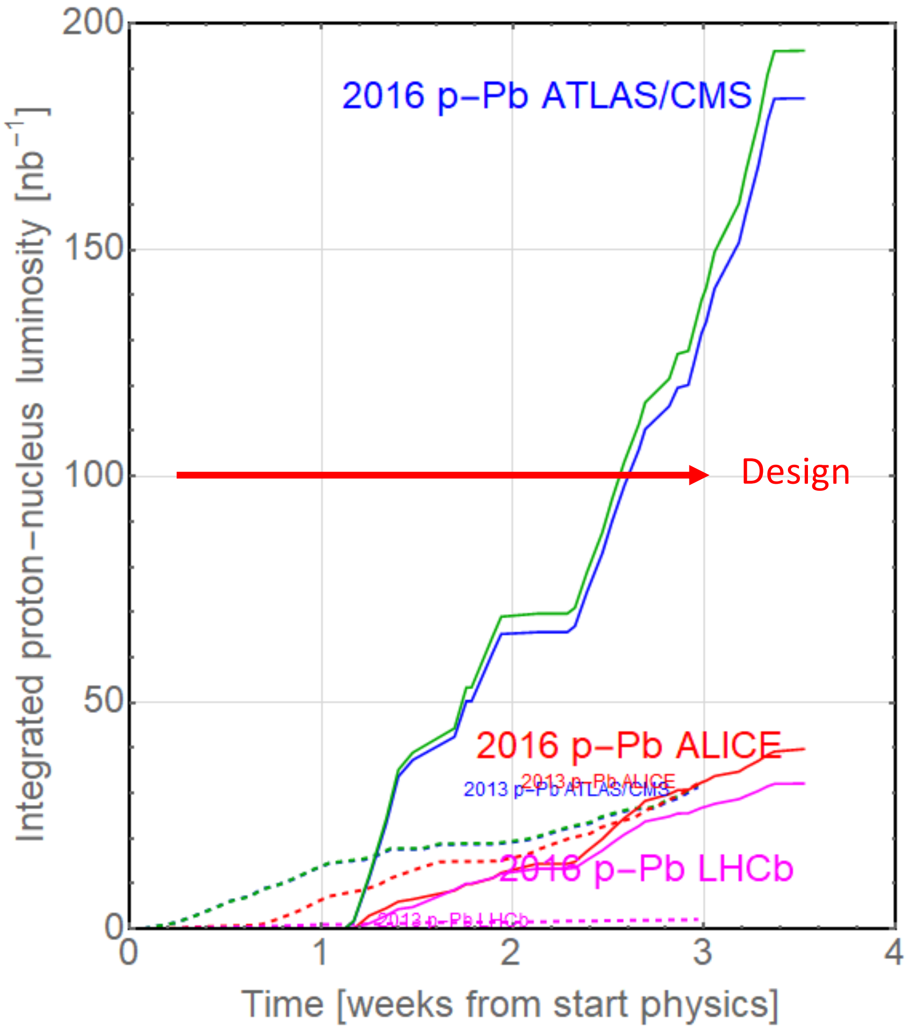
Increase in p intensity to 3×10^{10}/bunch enabled by new synchronous orbit mode of beam position monitors.

Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

Proton-nucleus programme status after 2016

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



Lessons from the 2016 p-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 took p-Pb collisions at lowest ever β^*=1.5 m at IP8
  - 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

Outlook for future heavy-ion runs of LHC

Scenarios for Run III and Run IV

- Taken from the CERN Yellow report (CERN-LPCC-2018-07)

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

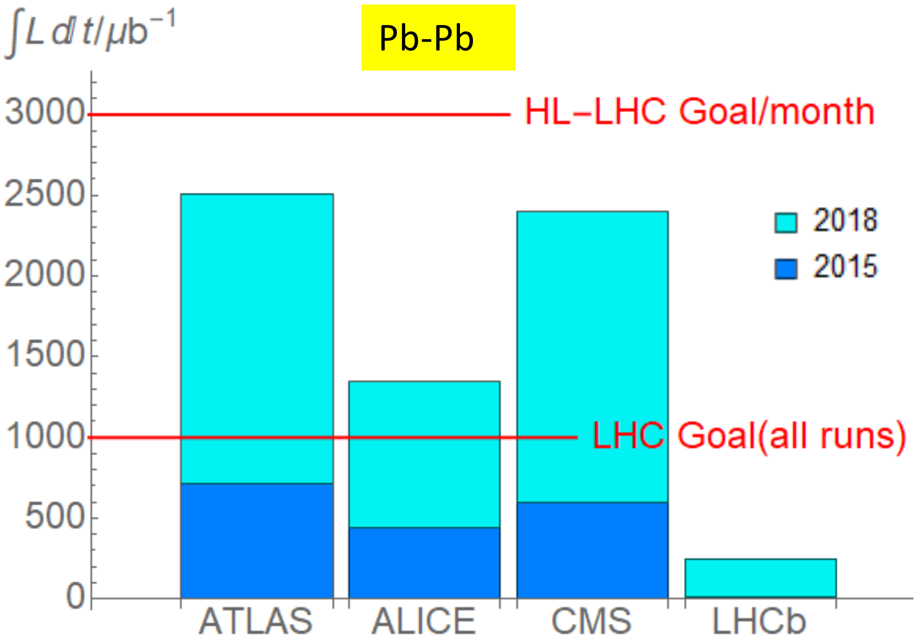
Pb-Pb parameters from Design Report to HL-LHC upgrade

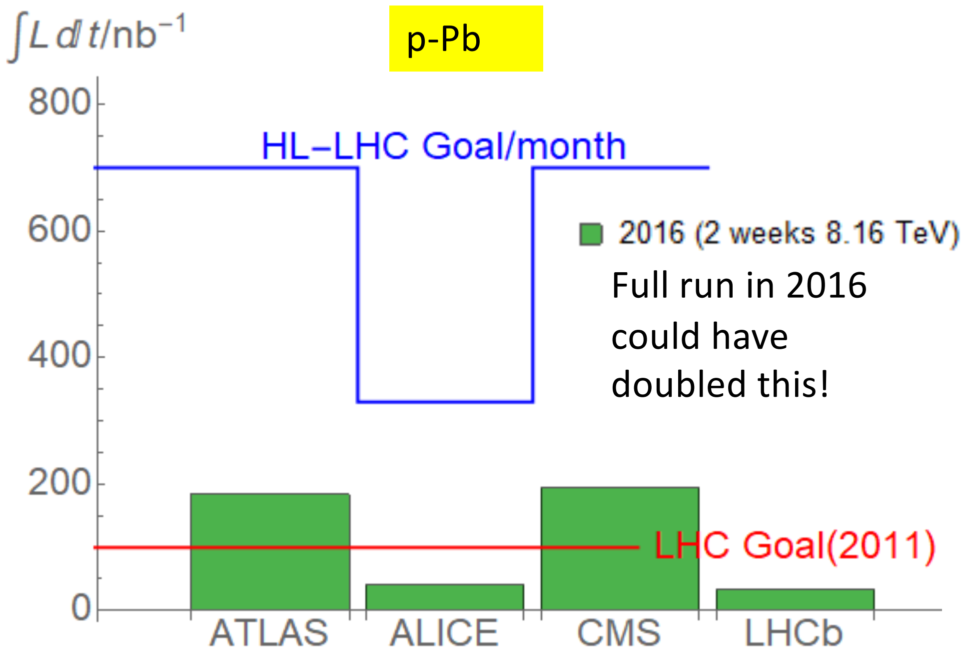
Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb–Pb run (Ref. [2] and references therein). The original design values for Pb–Pb [1] collisions and future upgrade Pb–Pb goals are also shown (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 $\sqrt{s_{\rm NN}} = 5.02\,\rm TeV$ 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 $E[Z\,\rm TeV]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\,\rm TeV]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{\rm NN}}\,[\rm TeV]$	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 $\epsilon_N\,[\mu\rm m]$	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 $L_{\rm AA}\,[10^{27}\rm cm^{-2}s^{-1}]$	1	0.03	0.5	3.6	6.1	7
NN luminosity $L_{\rm NN}\,[10^{30}\rm cm^{-2}s^{-1}]$	$\boxed{43}$	1.3	22.	156	$\boxed{264}$	$\boxed{303}$
Integrated luminosity/experiment $[\mu\rm b^{-1}]$	1000	9	160	433,585	900,1800	10^4
Int. NN lumi./expt. $[\rm pb^{-1}]$	43	0.38	6.7	19,25.3	39,80	4.3×10^5

L_{int} for LHCb not mentioned…

How close are we to the HL-LHC goals ?





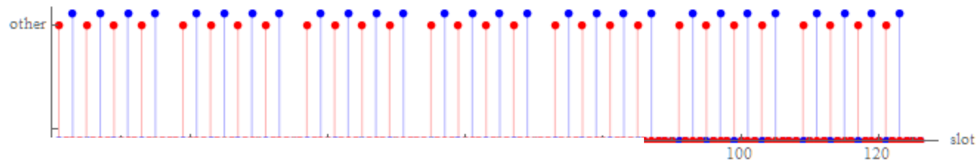
Upgraded ALICE will take similar luminosity to ATLAS/CMS (needs TCLDs in IR2).

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

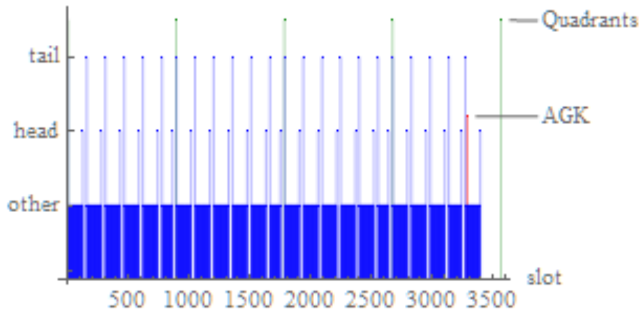
More bunches from slip-stacking in future.

"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.

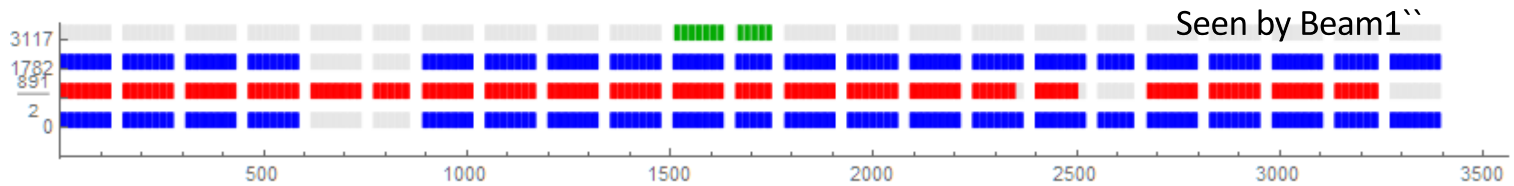
Filling scheme example for HL-LHC

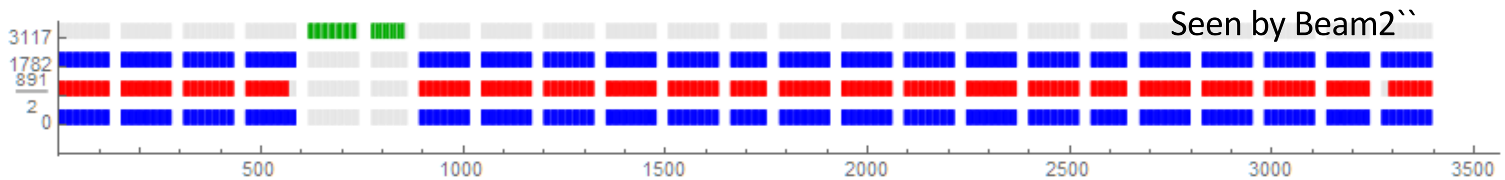


56 bunch SPS train
after slip-stacking



Displace two trains in Beam 2 to make collisions in LHCb





23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

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!
For Pb-Pb they are a bit more optimistic than HL-LHC baseline.

Proceedings of IPAC2016, Busan, Korea TUPMR027

CERN'S FIXED TARGET PRIMARY ION PROGRAMME

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Table 1: Charge States and Typical Intensites

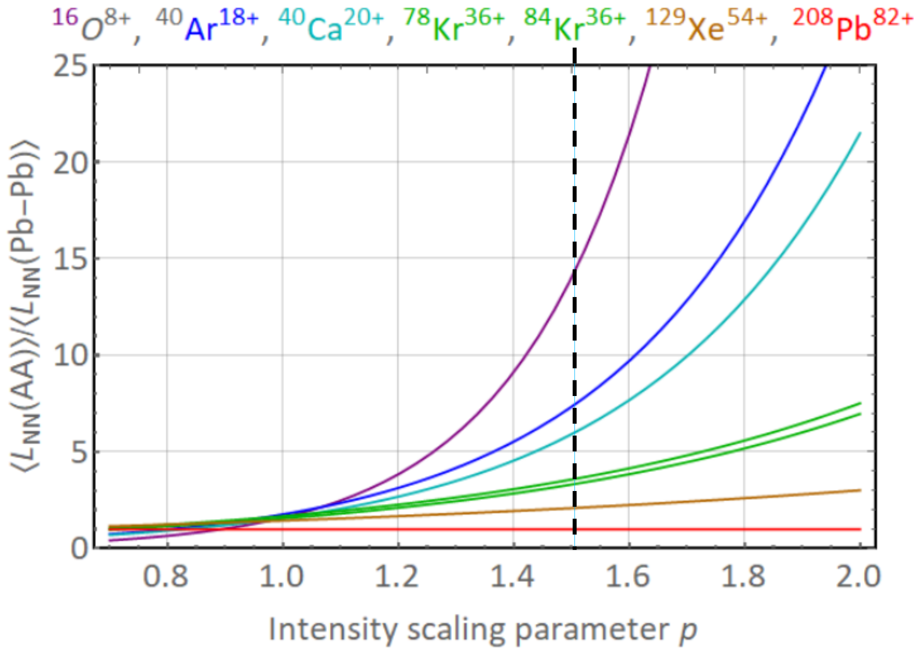
Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state Z in SPS	Ar^{18+}	Xe^{54+}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

Don't go too low in Z with this!
Not everything in the periodic table will work well in the ion source.

Considered only for Run 5 !

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 2022 / 2023.

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)
- **First short runs with new species** can have significant physics output.
- 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.
- **BLM settings** also require careful analysis and tuning.

➢Have come **close to the full “HL-LHC” performance** in Pb-Pb and p-Pb.

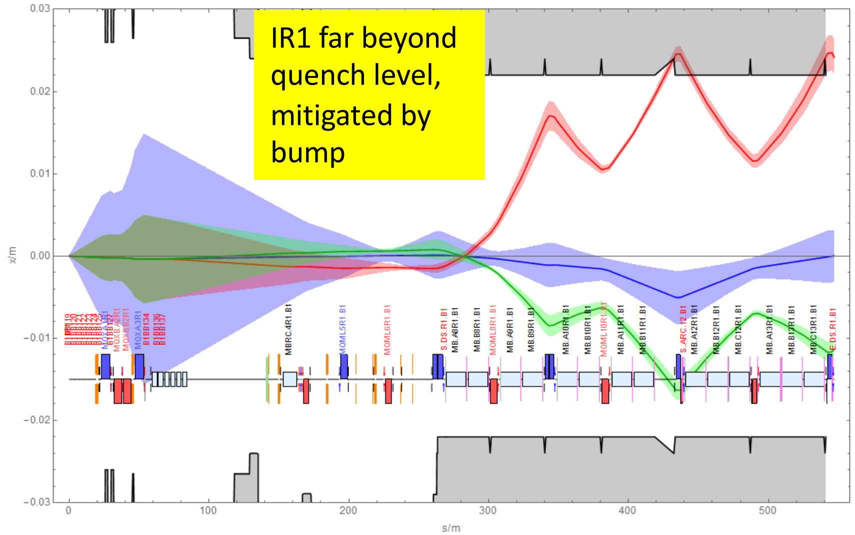
Specific case for LHCb

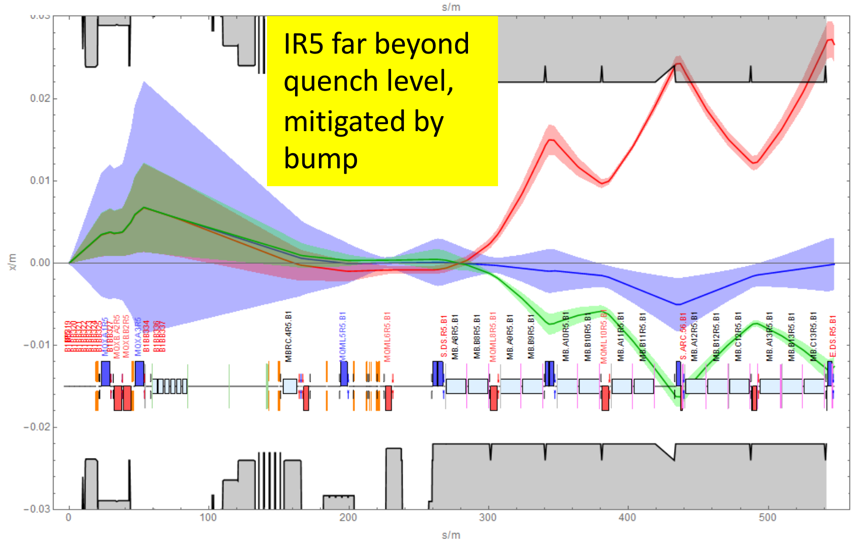
- Without **special mitigation measures** (e.g. a TCLD collimator as in ALICE) our luminosity during Pb-Pb operation will be limited to $10^{27}/cm^2/s$.
- LHCb should officially request the installation of such a collimator in LS3 for Run 4, also in view of long term plans of LHCb in HI-physics.

- The **displaced interaction point of LHCb by 11.25m** leads to no collisions in point 8 with 50ns bunch spacing, unless trains are displaced.
- Therefore, the proposed slip-stacking with 50ns bunch spacing after LS2, which provides excellent luminosities to ALICE, ATLAS and CMS, is very dis-favorable for LHCb. Only the displacement of some trains gives some Pb-Pb luminosity, but **much less than we had in 2018**.
- The only way out seem to be **mixed filling schemes** with 50ns and 75ns bunch-spacing, similar to what was done in 2018 with 100ns and 75ns.

Backup

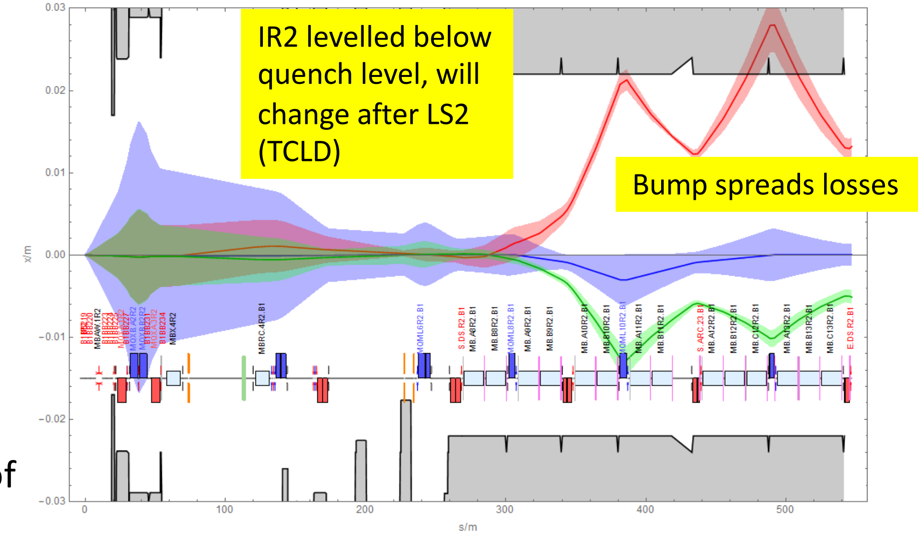
Significant BFPP beams in all IPs (horizontal envelopes)

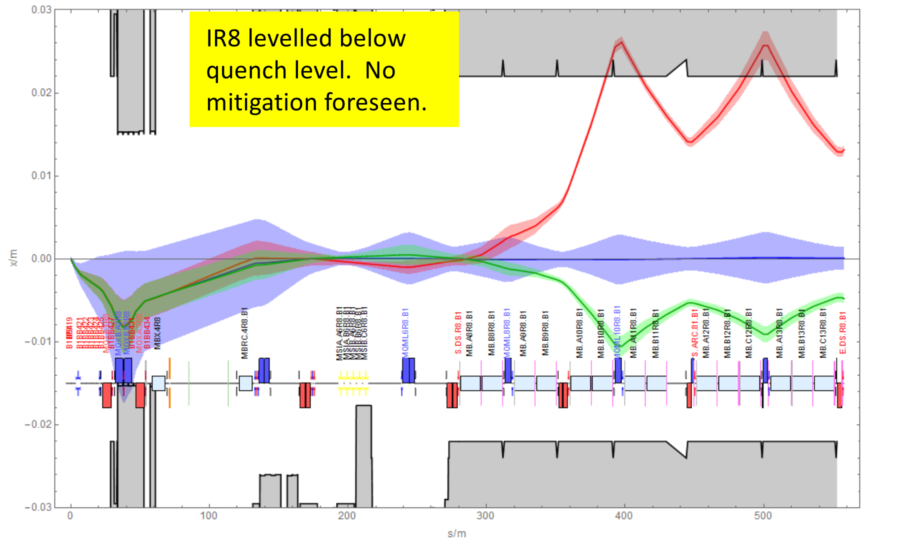




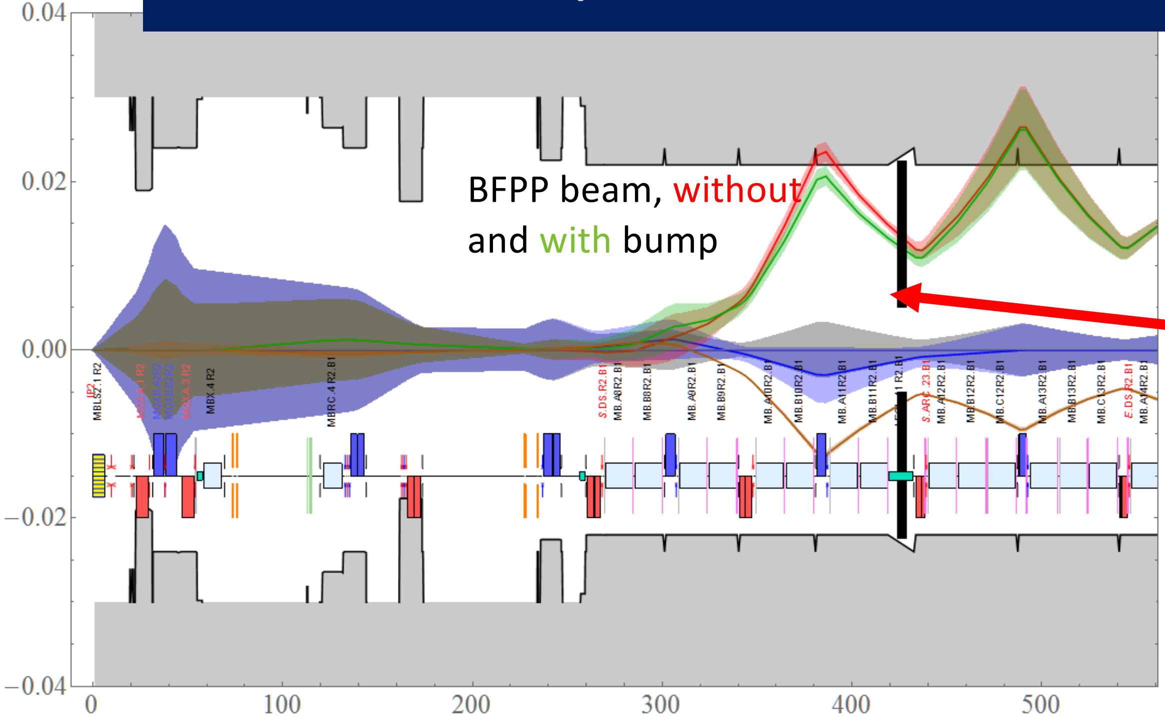
Bumps were adjusted empirically, good agreement with calculation, except left of IP5, location of 2015 BFPP quench test.

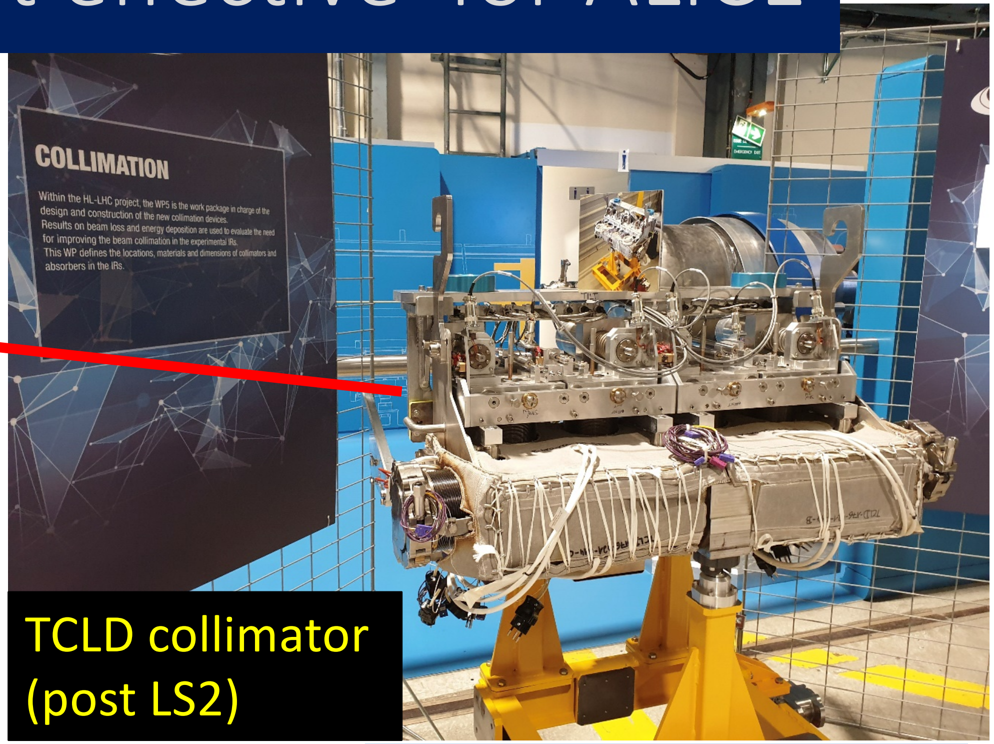
Chamber misalignment.





Orbit bumps alone are not effective for ALICE





- 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).