The 2018 Heavy-Ion Run of the LHC

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LHC Control Room: One of the last Pb-Pb physics fills before the start of LS2

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- Ion Operation at the LHC
- 2018 Run
  - Configuration
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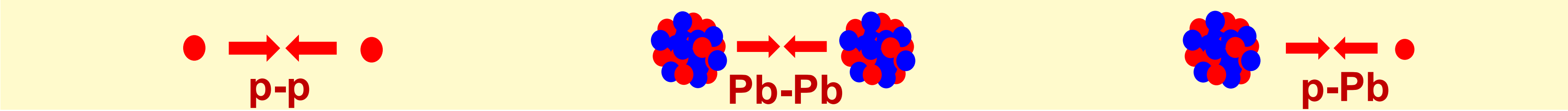
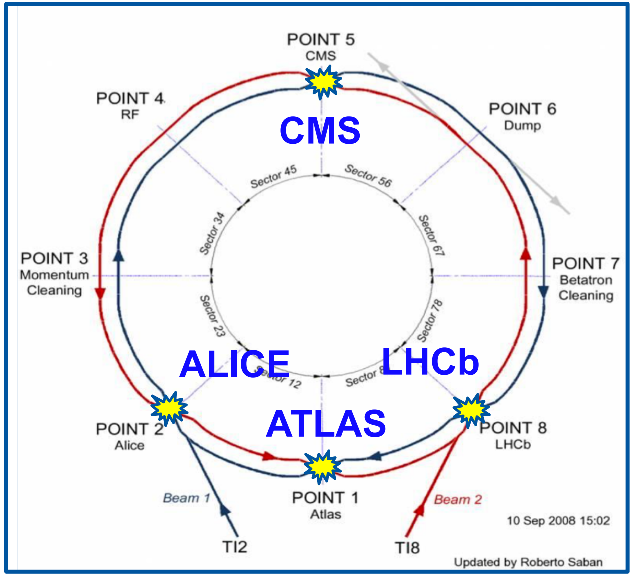
  - Limitations and Luminosity Performance
- Approaching ”HL-LHC” performance

Heavy-Ions in the LHC





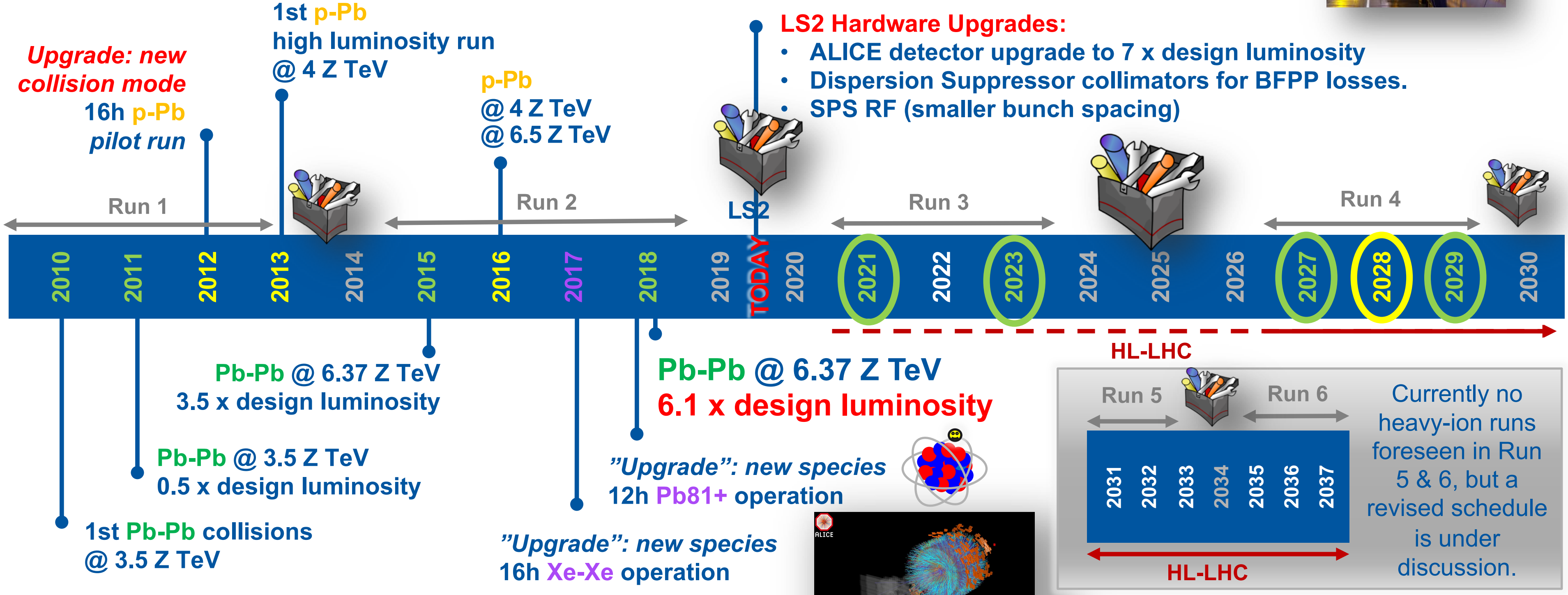
The LHC spends most of its time colliding **proton-proton (p-p)** in its 4 main experiments.

All are also highly capable heavy-ion experiments:
ALICE (IP2) and **ATLAS** (IP1) **/ CMS** (IP5)
LHCb (IP8) since 2012

1 month/year colliding **fully stripped lead** $(^{208}\mathrm{Pb}^{82+})$ or Pb ions with protons.

History and Future …

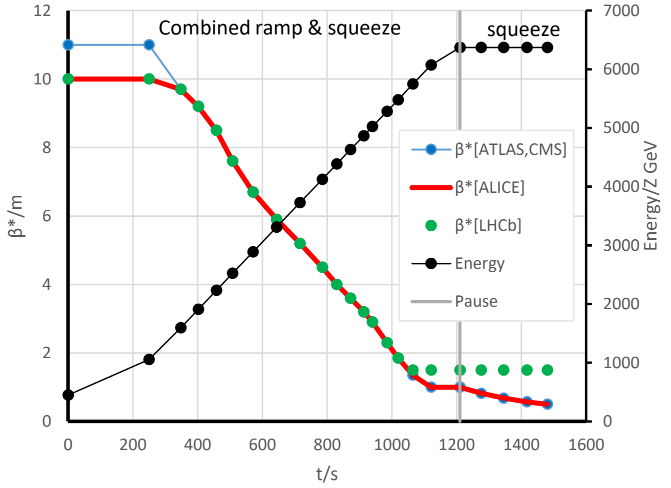
12 one-month heavy-ion runs between 2010 and 2030. **6/12 done**.



New Optics and Magnetic Cycle

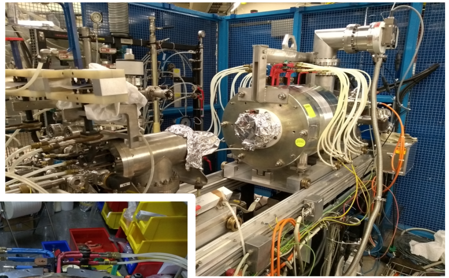
Run 2 Optics commissioning:
R. Tomas et al., **MOPMP033**

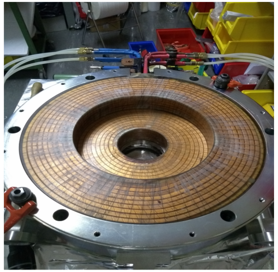
- Same optics as p-p only in 2010.
- Since then **heavy-ion cycles had their own specifications**, incl. lower β^* and crossing angle in ALICE (IP2).
- With implementation of *Achromatic Telescopic Squeeze (ATS) optics* for p-p the decision was taken to **fully decouple proton and ion cycles**, leading to a redesign of the whole heavy-ion cycle in **2018:**
  - ➢ **Redesign of Ramp & Squeeze**
  - ➢ **Smallest β^* ever in ALICE & LHCb**



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)

Major Hurdles of the 2018 run …



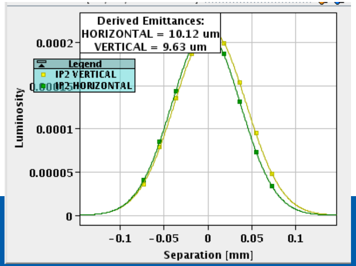


Ion source fault: No ions available for the first few days of the run.

- 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.

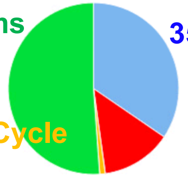
ALICE luminosity lower than expected:

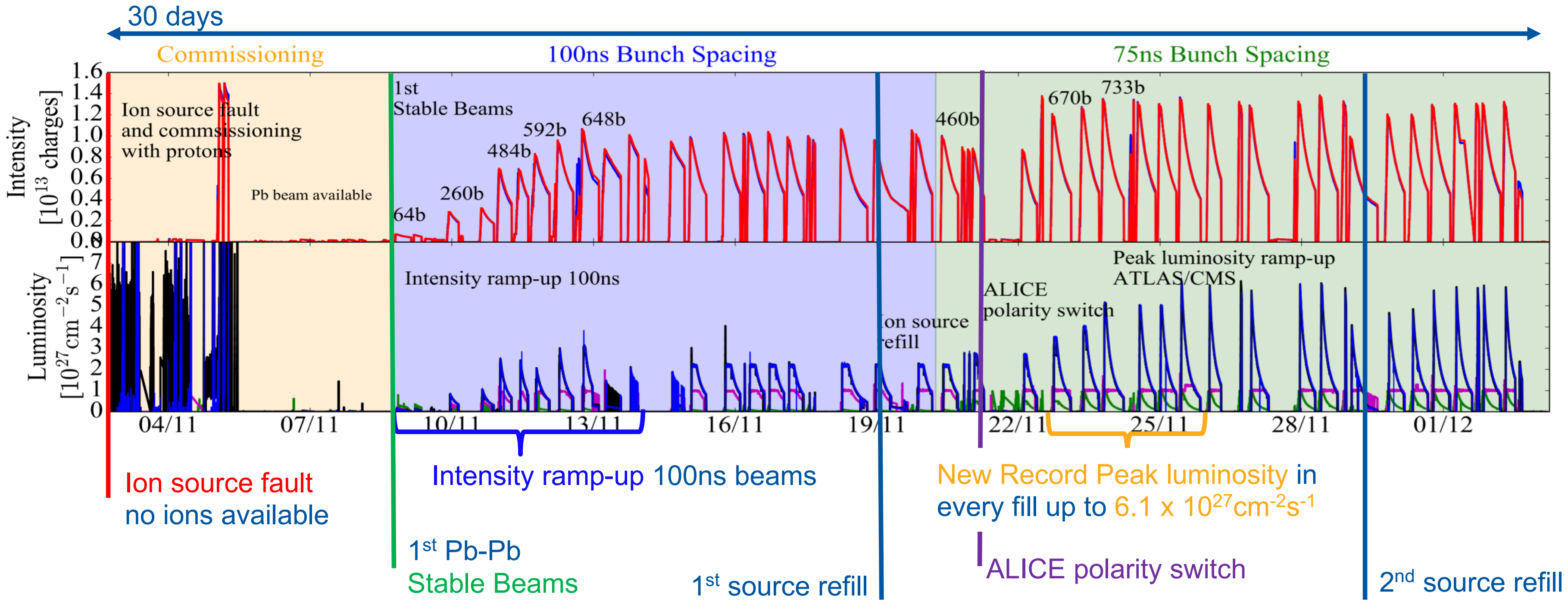
- *Cause:* beam deformation and reduced overlap at IP introduced by strong local betatron coupling in IR2.
- *Solution:* correction with skew-quadrpoles implemented during ALICE polarity reversal.
- Luminosity sharing strategies used until solution was found.
  - ➢ Filling schemes (number and distribution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



2018 Run Overview

Availability
87%



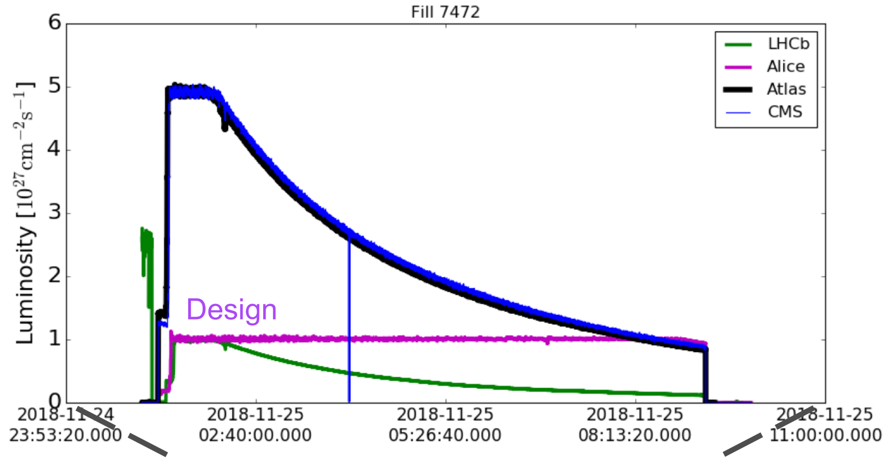


Typical Luminosity Evolution in 2018

ATLAS & **CMS**:
Short levelling period
Record: 6.1 x 10^{27}cm^{-2}s^{-1} peak luminosity

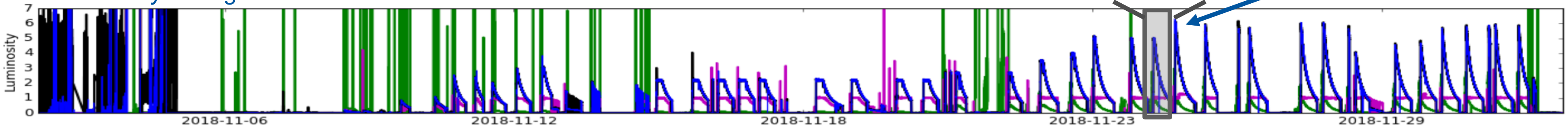
ALICE:
Levelled to design saturation level most of the time in physics.
Upgrade to ~7 x 10^{27}cm^{-2}s^{-1} in LS2.

LHCb:
Also levelled to design value



Record peak luminosity

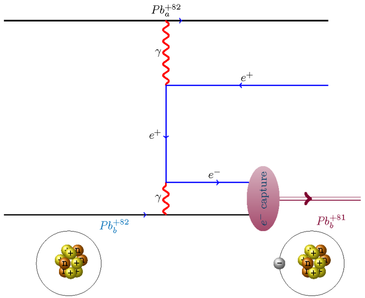
Luminosity through the run



Secondary Beams Created in the Collision

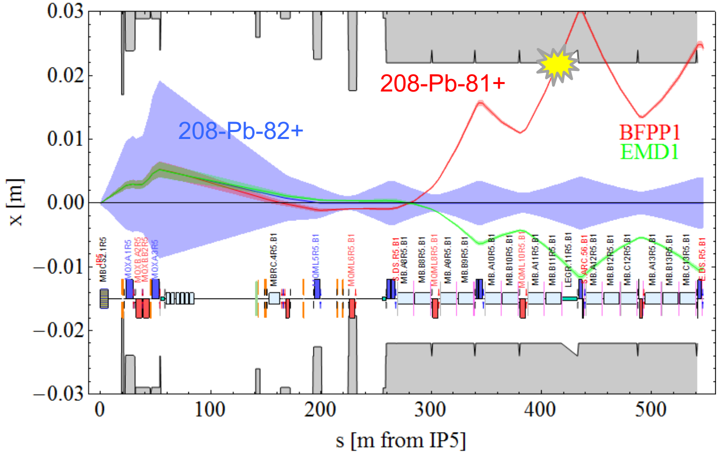
Bound-free pair production (BFPP)

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+}$$



Has large interaction cross-section (~280b) in Pb-Pb collisions and is the main contribution to fast luminosity burn-off.

Secondary beams impact in superconducting magnets downstream the interaction points.

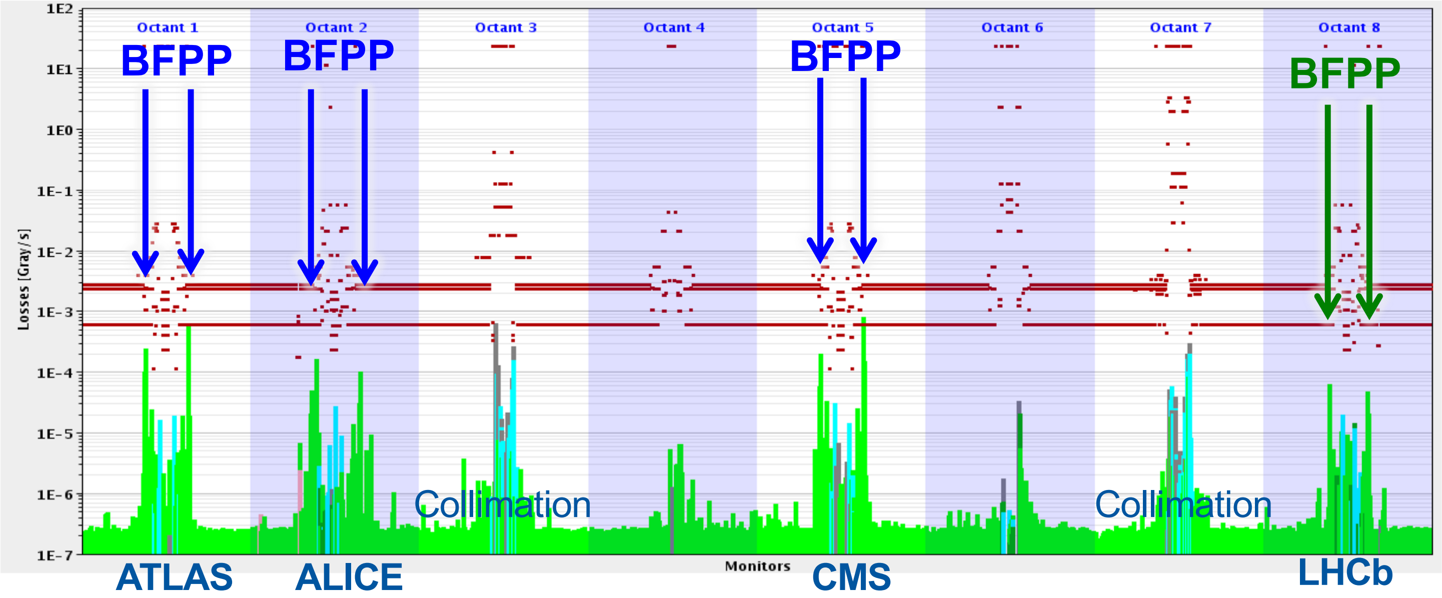


Loss Pattern around the Ring

Loss spikes around all IPs where ions collide …

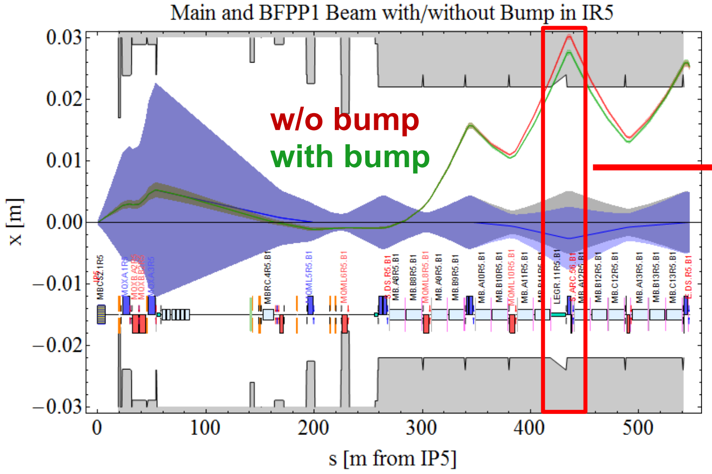
Deposit power >140W → exceeds quench limit of the superconducting magnets.

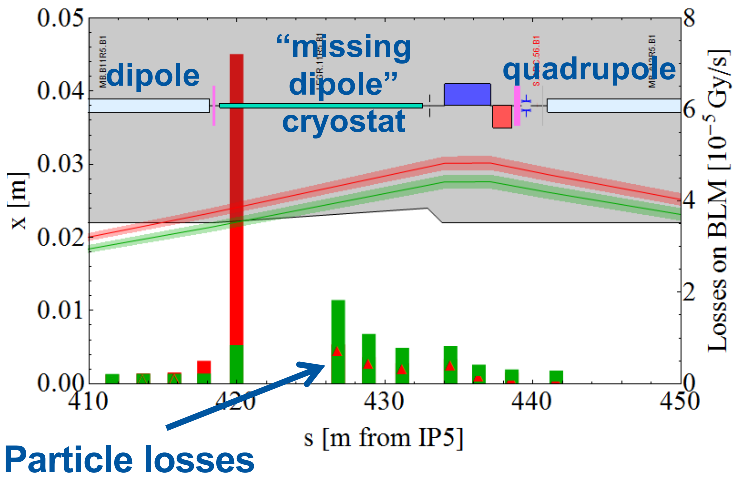
Luminosity limit found at $L \approx 2.3 \times 10^{27} cm^{-2} s^{-1}$ (≅50W into magnet)



Quench Risk Mitigation with Orbit Bumps

Orbit bumps are used to move the secondary beam losses to a less vulnerable location in order to reduce risk of quench.





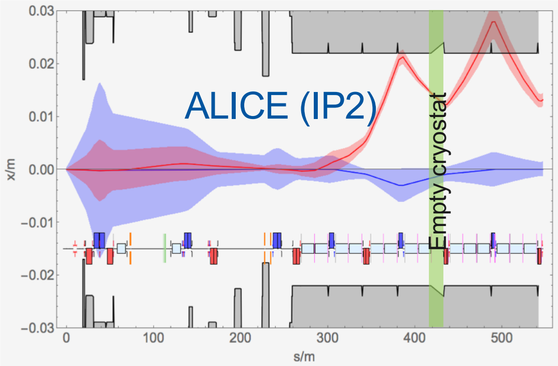
Technique operationally used in ATLAS/CMS since 2015.

BFPP Mitigation around ALICE & LHCb

Due to different optics around **ALICE** and **LHCb, bump technique does not work.**

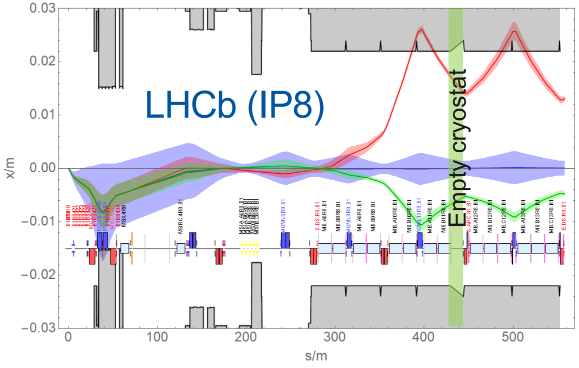
ALICE

- Peak luminosity limited by detector saturation to **1 x 10^{27}cm^{-2}s^{-1}**.
- Bump to distribute losses over two cells.



LHCb

- **No mitigation implemented.**
- 75ns bunch scheme provides many more collisions in LHCb.
- Peak luminosity levelled **1 x 10^{27}cm^{-2}s^{-1}**



Collimation of Heavy Ions

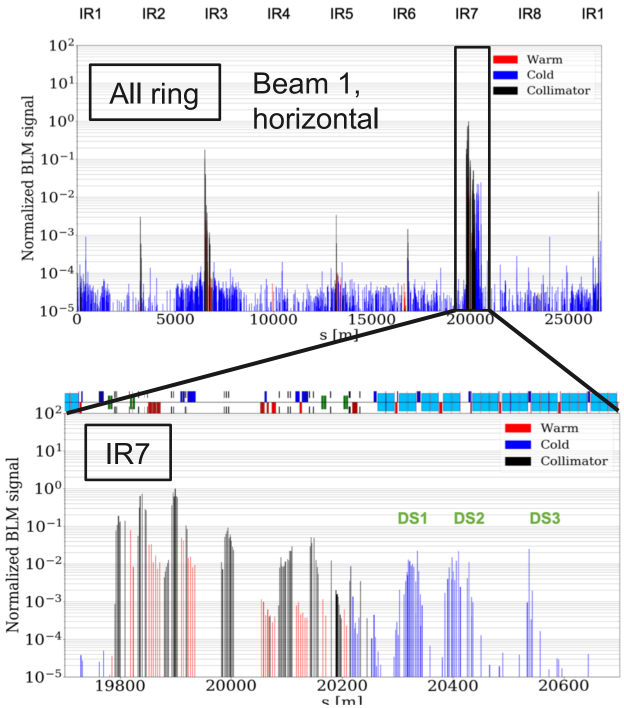
Heavy-ion runs are challenging for collimation:

- Fragmentation within the collimator jaws.
- Cleaning efficiency ~100x worse than for protons.
- More cold losses (blue), especially in the dispersion suppressor (DS) behind collimation insertion (IR7).
- *Risk to limit the intensity.*

2018:

- Mitigation of loss spikes by optimizing collimator settings motivated by simulations.
- 7 out of 48 fills dumped by high losses.

For future runs: replacement of a dipole magnet by two 11T dipoles with a collimator in between.



Plots courtesy of N. Fuster-Martinez

Measurement of collimation efficiency by introducing transverse losses on a safe low-intensity beam.

From: N. Fuster-Martinez et al, **MOPRB050**

Status LHC → HL-LHC

Status and studies of Pb beam in LHC injectors:
M. Meddahi et al, **THXPLM1**
S. Hirlaender et al, **WEPTS040**
A. Saa Hernandez et al, **WEPTS042**
H. Bartosik et al, **MOPGW069**
T. Argyropoulos et al, **WEPTS039** and **MOPGW070**

Most of HL-LHC performance demonstrated!

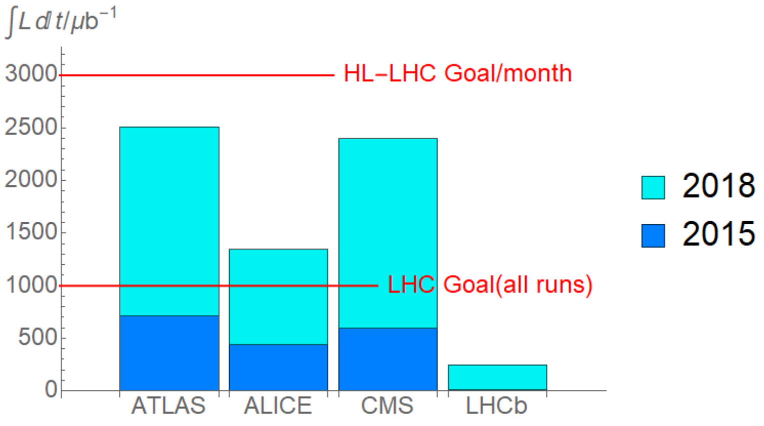
	Pb-Pb (Design)	Pb-Pb (2018 achieved)	"HL-LHC" Pb-Pb (after LS2)	Upgrade Status	
Energy [TeV]	7 Z	**6.37 Z**	7 Z	red	Magnet training
β* at IP (1/2/5,8) [m]	(0.5, -)	**(0.5, 1.5)**	(0.5, 1.5)	green	
Emittance [μm]	1.5	**~2**	1.65	green	
Bunch **Intensity** [10^8 ions]	0.7	**2.2**	1.8	green	
No. Bunches	592	**733**	1232	red	SPS RF Upgrade (slip-stacking)
Bunch Spacing	100ns	**100ns → 75ns**	50ns	red	
Peak **Luminosity** at IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	- / 1 / 1 / -	**6.1 / 1 / 6.1 / 1**	7 / 7 / 7 / ?	yellow	Lumi levelling

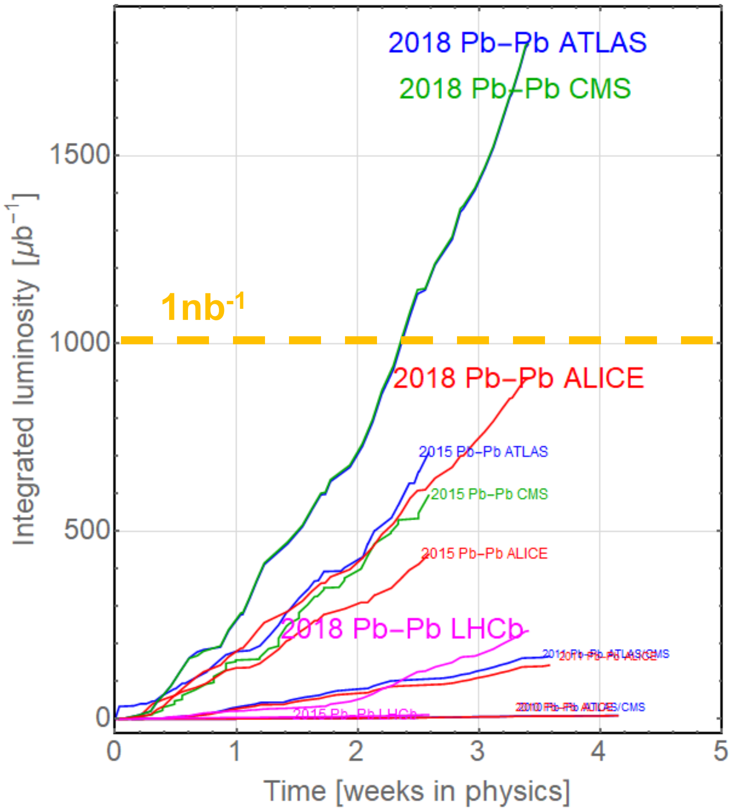
Green values reached & exceeded LHC design

Some collisions in LHCb (not considered in detail yet)

Delivered Luminosity

LHC design goal of 1nb^{-1} in Pb-Pb luminosity already exceeded.





Future performance estimate from 2021:
3 nb^{-1}/run → 12 nb^{-1} in 4 more Pb-Pb runs

Conclusion

extraordinary injector performance

optimizations between & during runs

The LHC Heavy-Ion performance is much higher than originally foreseen.

Control of heavy-ion beam losses, like collimation & BFPP, is critical, complicated and may surprise.

"first 10-year" Pb-Pb luminosity goal of 1nb^{-1} has been exceeded

demonstrated "HL-LHC" peak luminosity performance

Heavy ions will come back to the LHC end of 2021 after the injector and LHC hardware upgrades with the "HL-LHC" configuration.

Thank you for your attention!