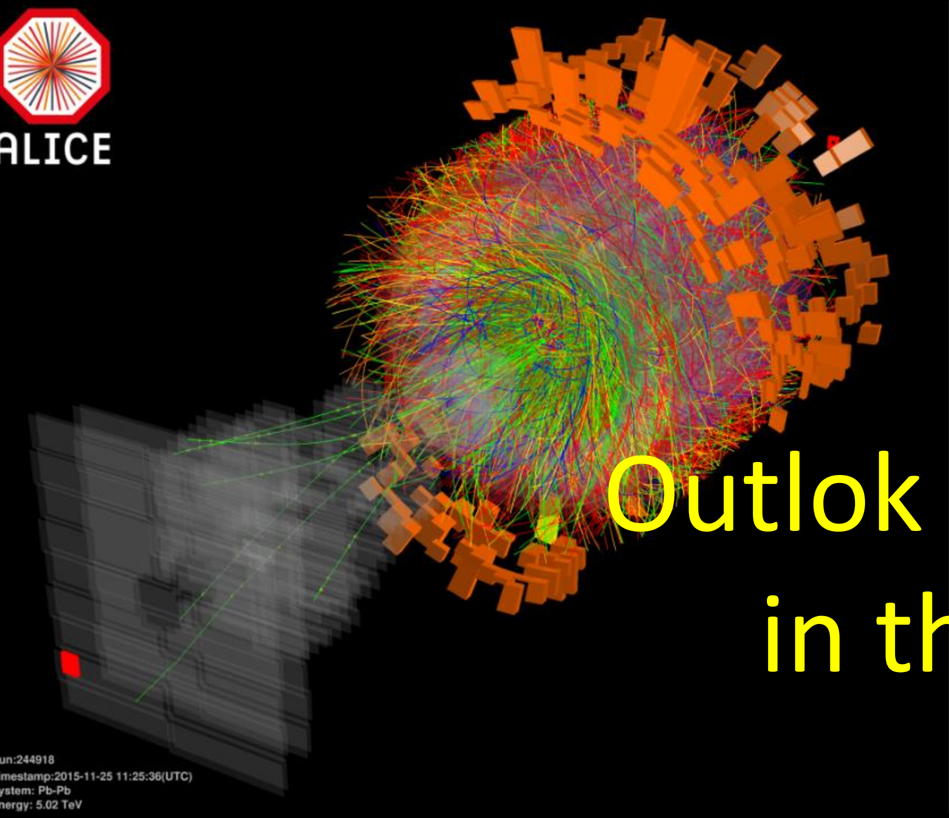
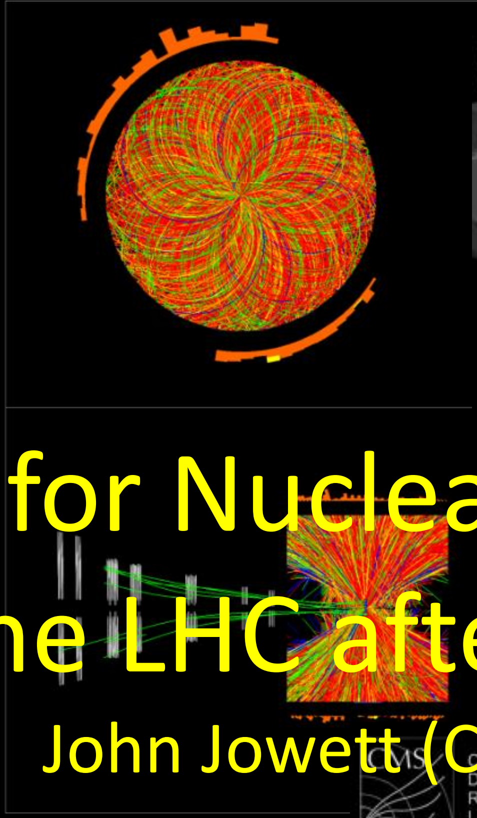
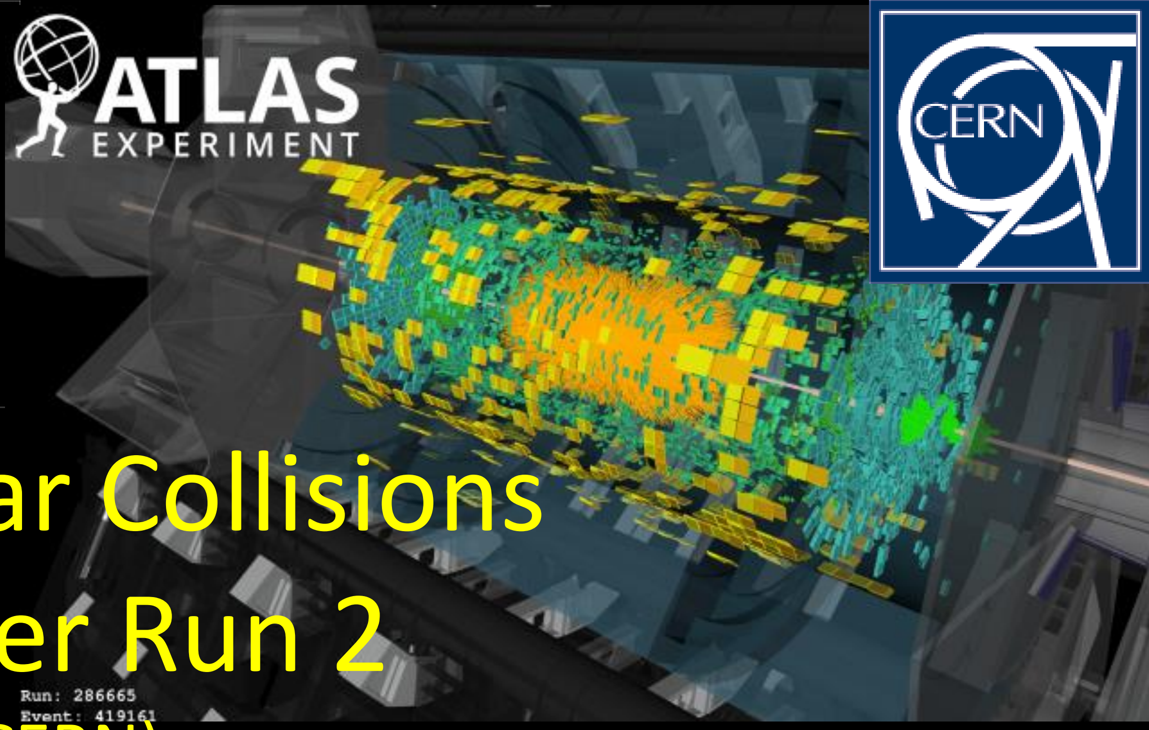
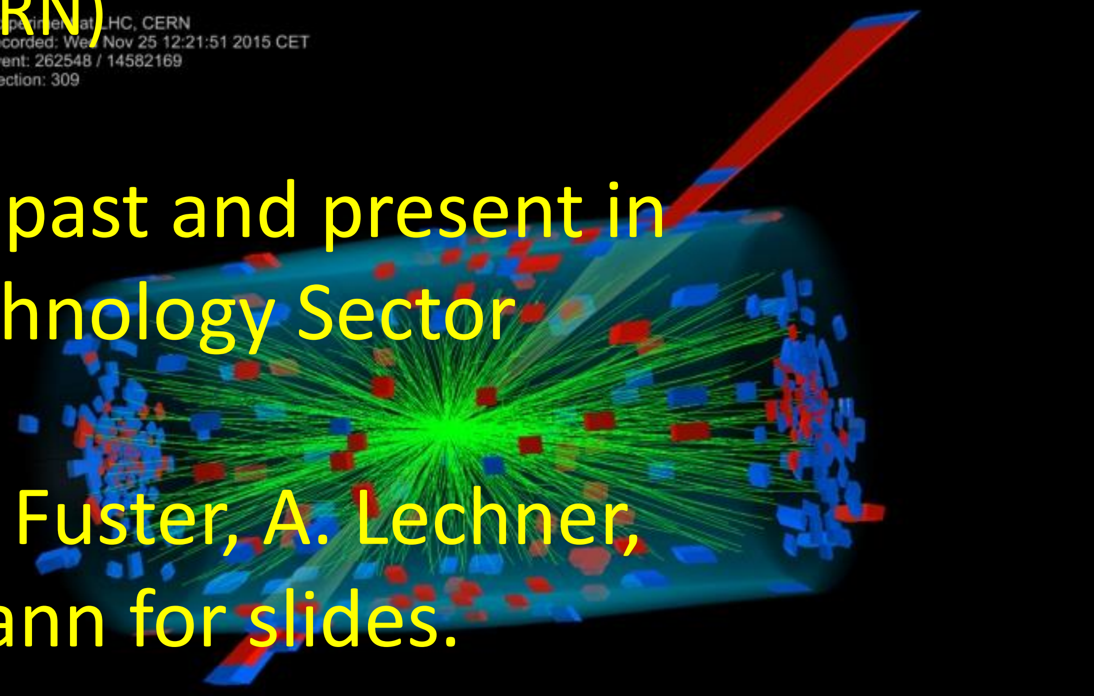






Outlok for Nuclear Collisions in the LHC after Run 2

John Jowett (CERN)



On behalf of many colleagues past and present in CERN Accelerator and Technology Sector

Special thanks to R. Bruce, N. Fuster, A. Lechner, D. Mirarchi, M. Schaumann for slides.

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.

History and Future of Nuclear Beams in the LHC

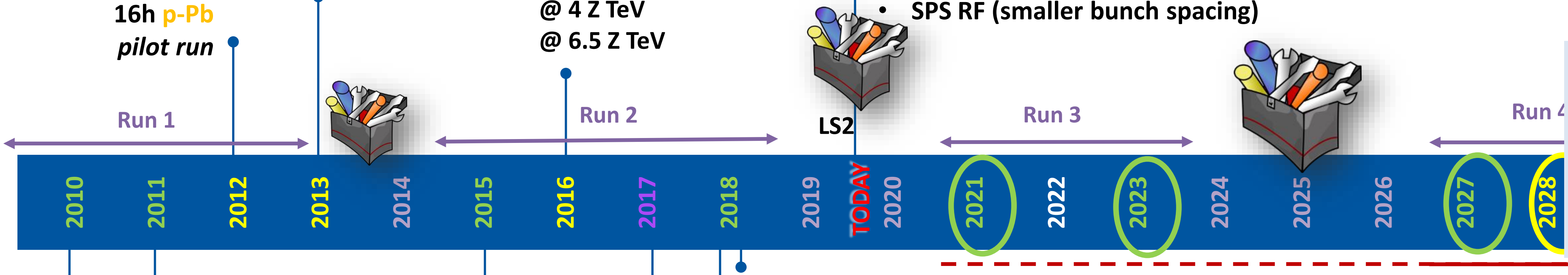
12 one-month heavy-ion runs between 2010 and 2030. **6/12 done**.

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)**



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

HL-LHC

Pb-Pb @ 6.37 Z TeV
3.5 x design luminosity

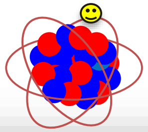
Pb-Pb @ 6.37 Z TeV
6.1 x design luminosity

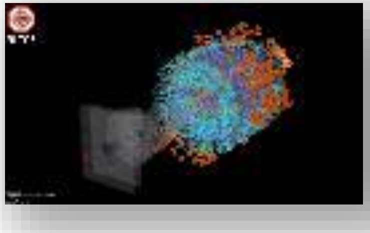
Pb-Pb @ 3.5 Z TeV
0.5 x design luminosity

1st Pb-Pb collisions
@ 3.5 Z TeV

"Upgrade": new species
12h Pb81+ operation

"Upgrade": new species
16h Xe-Xe operation





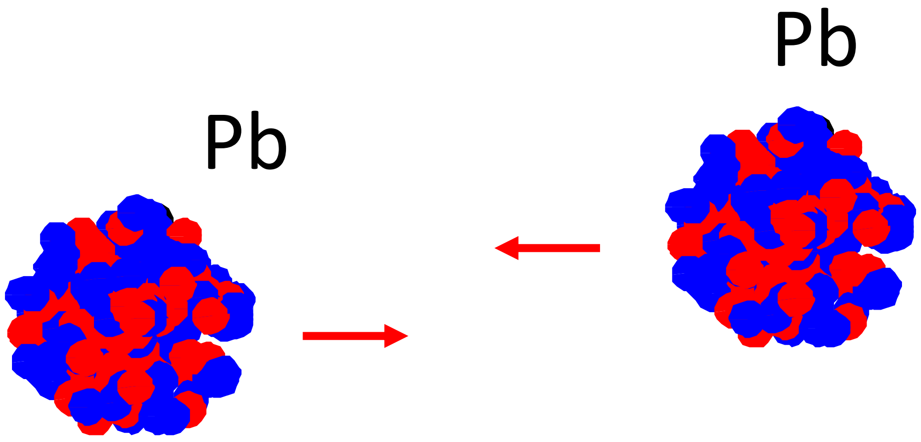
Currently no heavy-ion runs foreseen in Run 5 & 6, but a revised schedule is under discussion.

Runs with lighter nuclei (eg, Ar-Ar, …) proposed for after 2030, see HL-LHC phsyics 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.

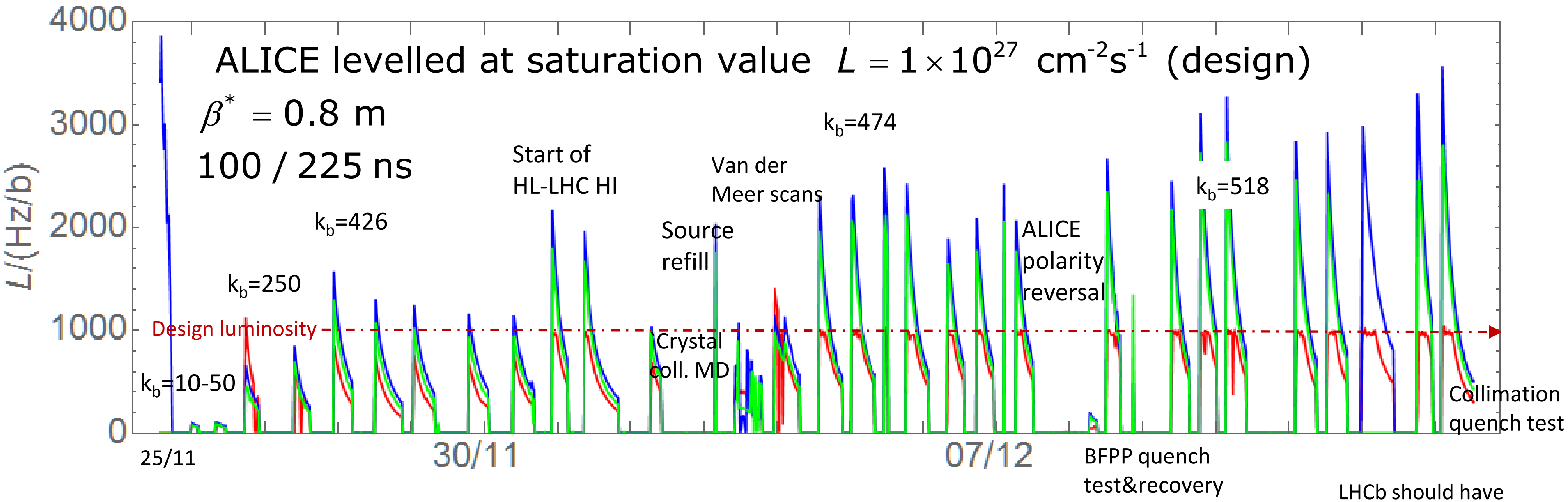


2015

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



LHCb should have about 2% of ATLAS

18 days of Pb-Pb were the first since 2011

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.

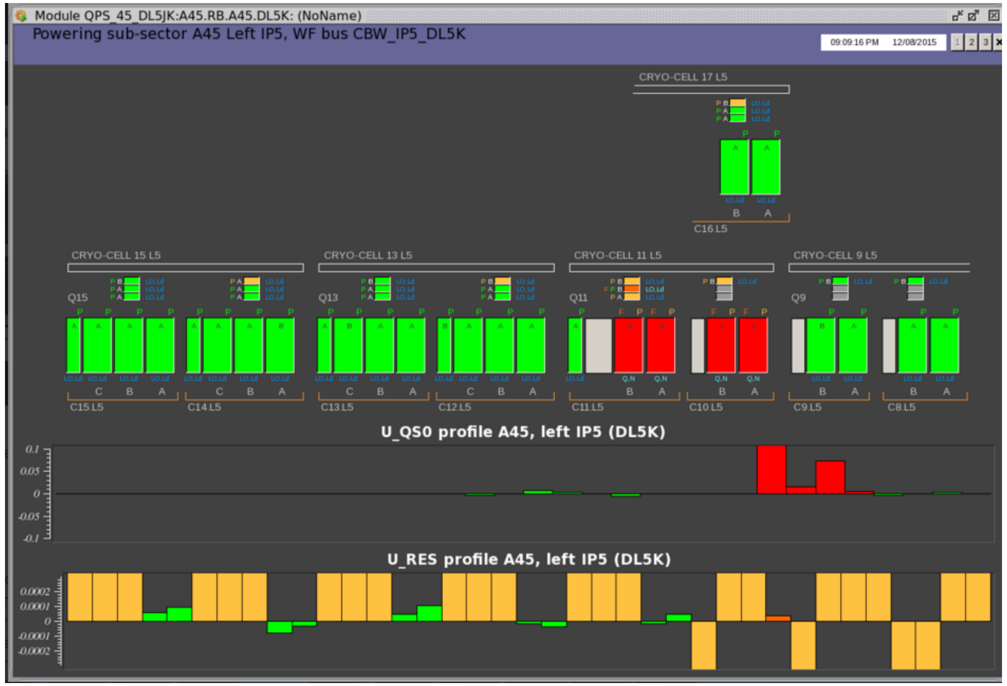
Hadronic cross section is 8 b (so luminosity debris contains much less power).

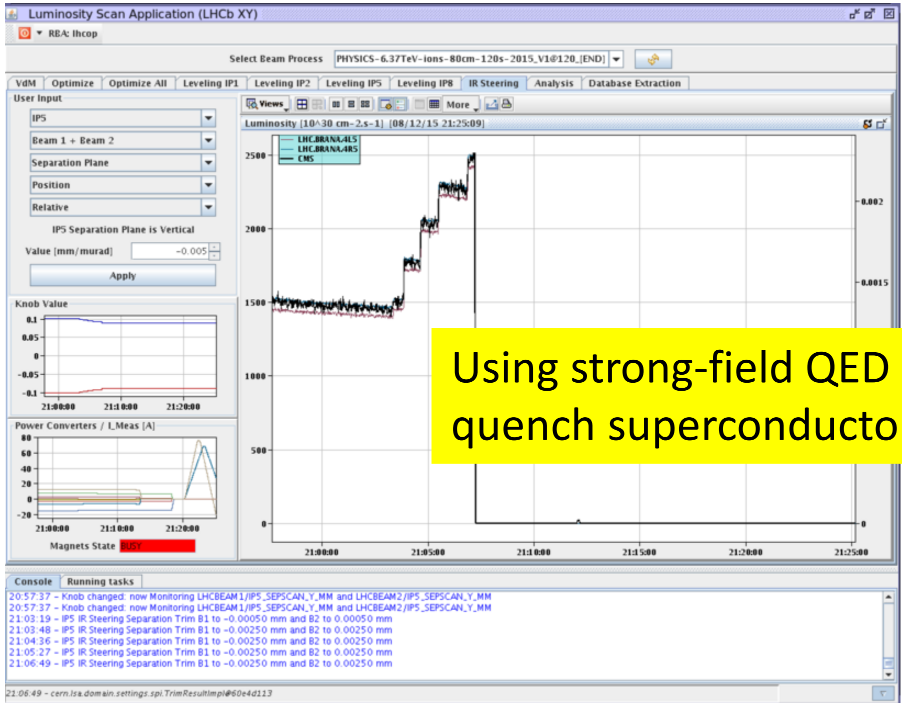
BFPP Quench MD – first luminosity quench in LHC

- 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):

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

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





Select Beam Process: PHYSICS-6.37TeV-ions-80cm-120s-2015_V1@120_[END]

IP5

Beam 1 + Beam 2

Separation Plane

Position

Relative

IP5 Separation Plane is Vertical

Value [mm/murad]: -0.005

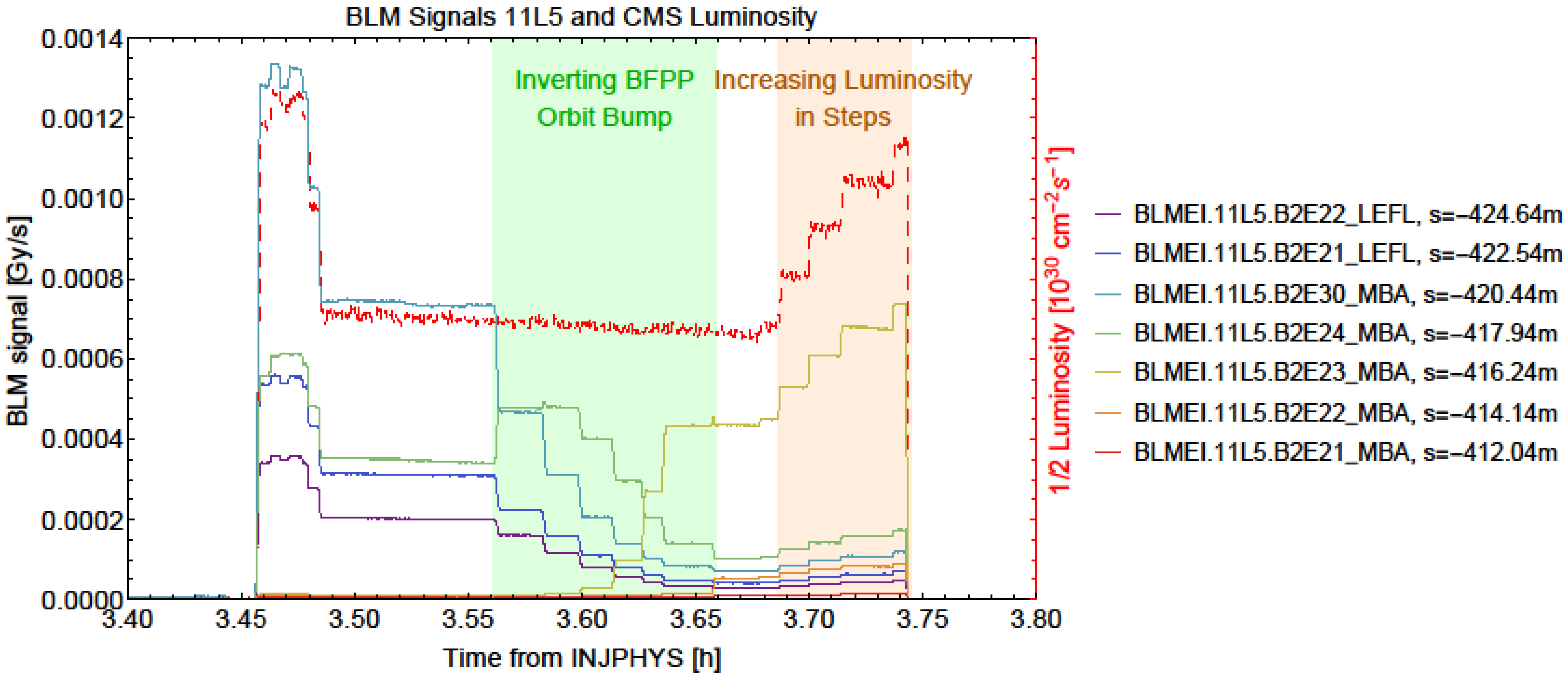
Magnets State: BUSY

```
20:57:37 - Knob changed: now Monitoring LHCBEAM1/IP5_SEPSCAN_Y_MM and LHCBEAM2/IP5_SEPSCAN_Y_MM
20:57:37 - Knob changed: now Monitoring LHCBEAM1/IP5_SEPSCAN_Y_MM and LHCBEAM2/IP5_SEPSCAN_Y_MM
21:03:19 - IP5 IR Steering Separation Trim B1 to -0.00050 mm and B2 to 0.00050 mm
21:03:48 - IP5 IR Steering Separation Trim B1 to -0.00250 mm and B2 to 0.00250 mm
21:04:36 - IP5 IR Steering Separation Trim B1 to -0.00250 mm and B2 to 0.00250 mm
21:05:27 - IP5 IR Steering Separation Trim B1 to -0.00250 mm and B2 to 0.00250 mm
21:06:49 - IP5 IR Steering Separation Trim B1 to -0.00250 mm and B2 to 0.00250 mm
```

```
21:06:49 - cern.lsa.domain.settings.spi.TrimResultImpl@60e4d113
```

Using strong-field QED to quench superconductor!

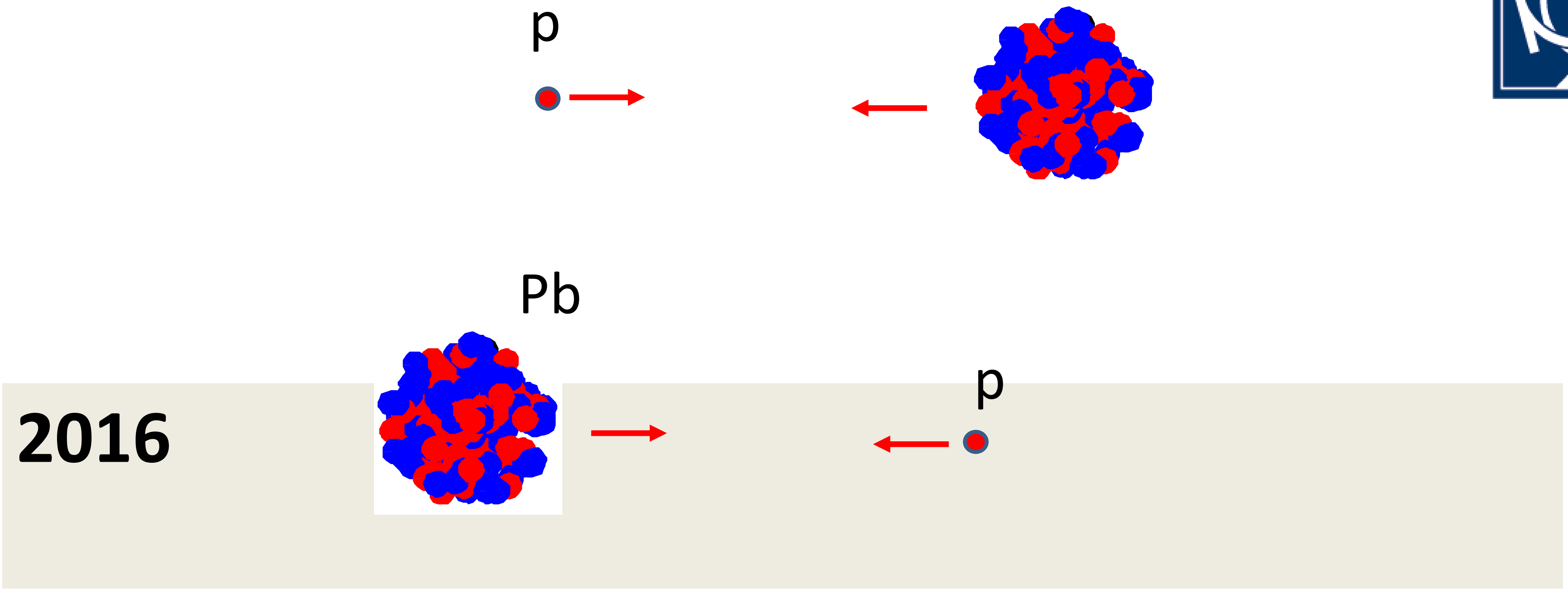
Luminosity and BLM signals during measurement



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



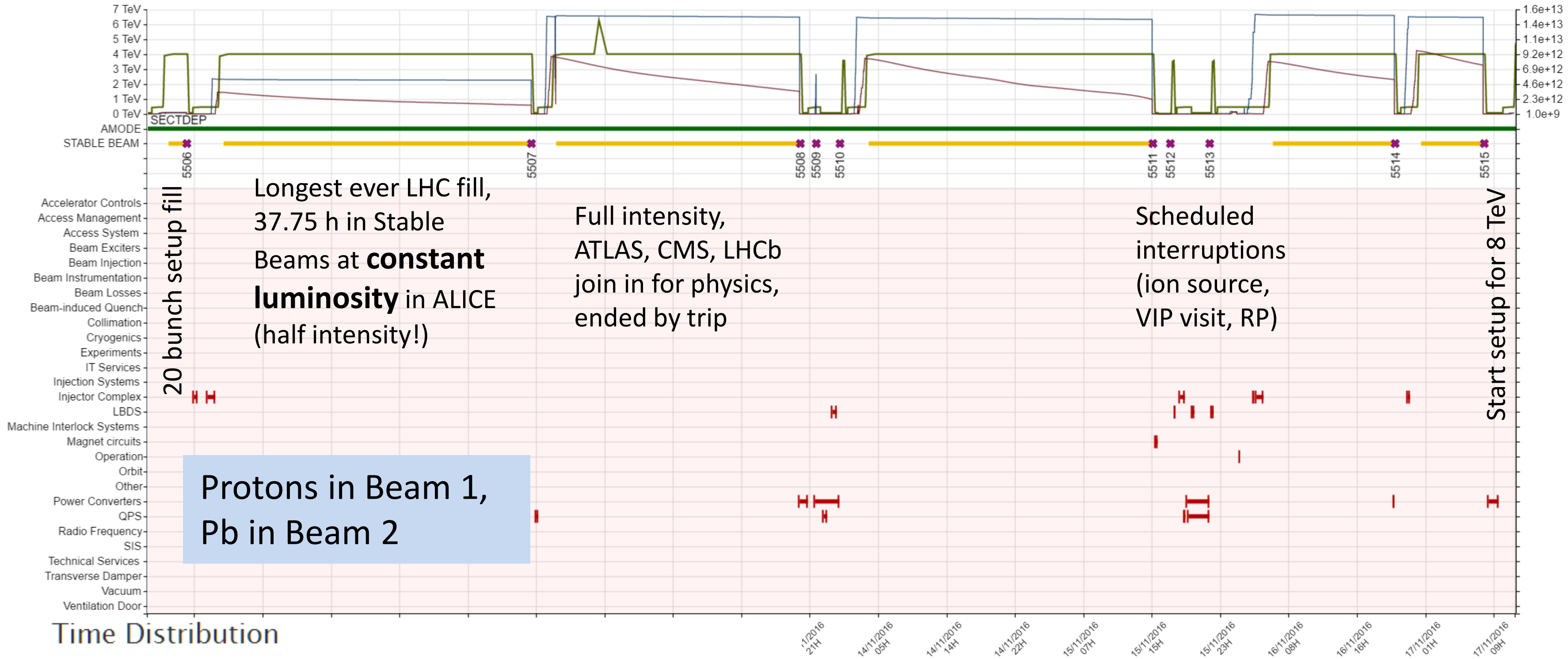
p

Pb

p

2016

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



20 bunch setup fill

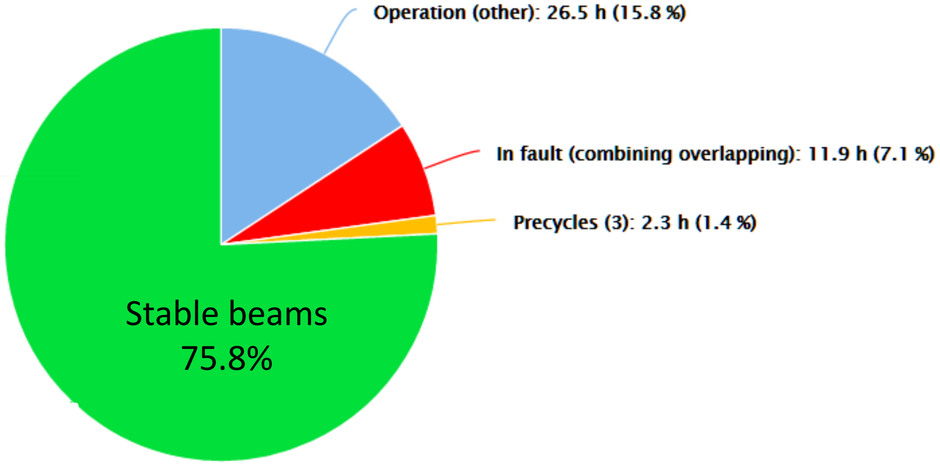
Longest ever LHC fill, 37.75 h in Stable Beams at **constant luminosity** in ALICE (half intensity!)

Full intensity, ATLAS, CMS, LHCb join in for physics, ended by trip

Scheduled interruptions (ion source, VIP visit, RP)

Start setup for 8 TeV

Protons in Beam 1, Pb in Beam 2

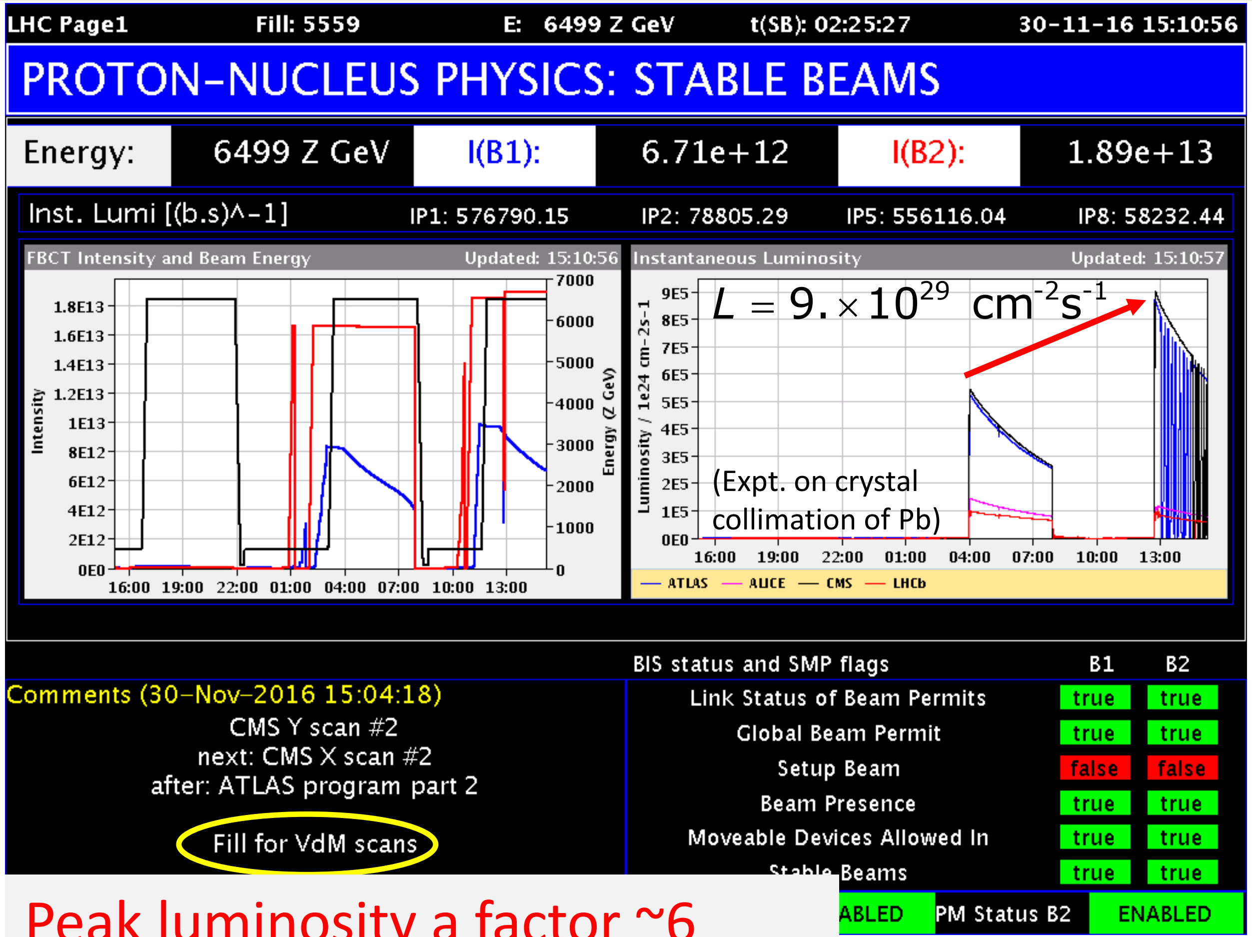


Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!

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



LHC Page1 Fill: 5559 E: 6499 Z GeV t(SB): 02:25:27 30-11-16 15:10:56

PROTON-NUCLEUS PHYSICS: STABLE BEAMS

Energy:	6499 Z GeV	I(B1):	6.71e+12	I(B2):	1.89e+13

Inst. Lumi [(b.s)^-1] IP1: 576790.15 IP2: 78805.29 IP5: 556116.04 IP8: 58232.44

$L = 9.\times 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

(Expt. on crystal collimation of Pb)

Comments (30-Nov-2016 15:04:18)
CMS Y scan #2
next: CMS X scan #2
after: ATLAS program part 2

Fill for VdM scans

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

ABLED PM Status B2 ENABLED

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.

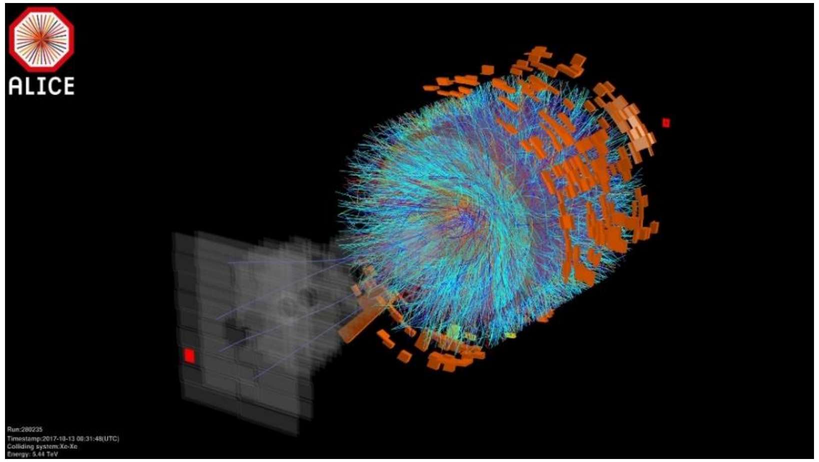
Lessons from the 2016 Pb-Pb run

- 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 β^*=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 …

Reminder: Xe-Xe collisions in LHC, 13 October 2017



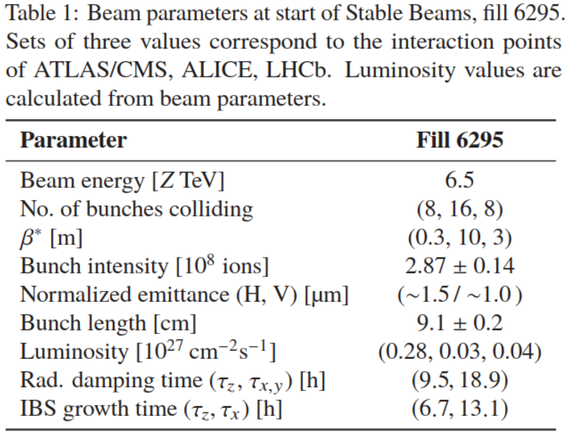


Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

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

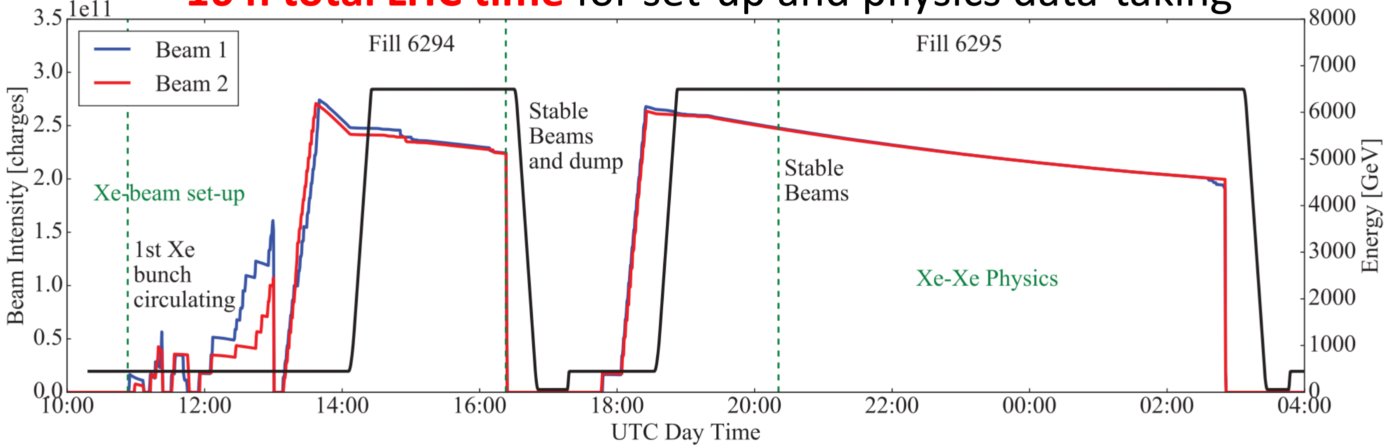


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

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

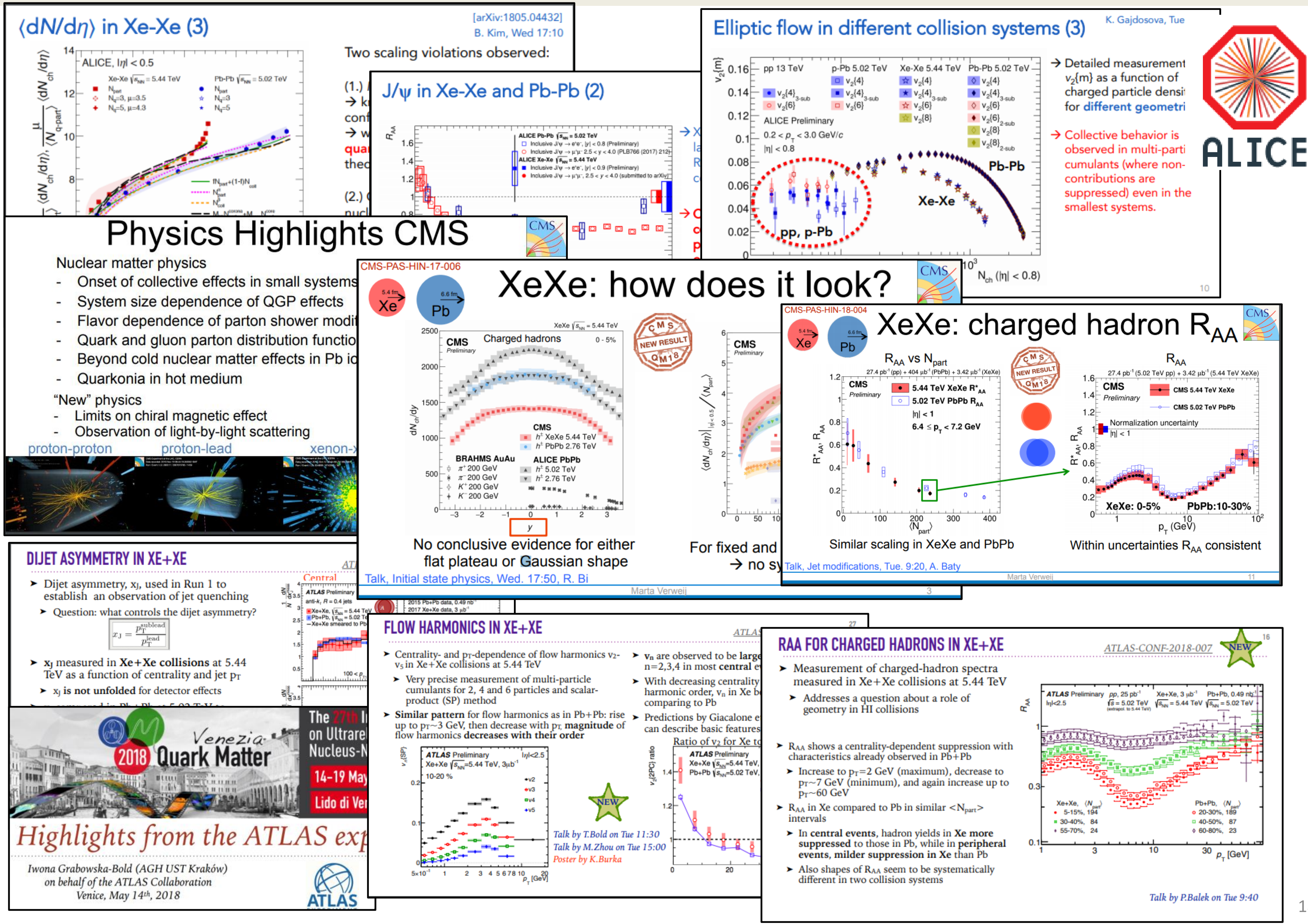
Results from Xe-Xe run of LHC at Quark Matter conference, May 2018

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.



⟨dN/dη⟩ in Xe-Xe (3)

[arXiv:1805.04432]
B. Kim, Wed 17:10

Two scaling violations observed:

J/ψ in Xe-Xe and Pb-Pb (2)

Elliptic flow in different collision systems (3)

K. Gajdosova, Tue

→ Detailed measurement $v_2\{m\}$ as a function of charged particle densi for different geometri

→ Collective behavior is observed in multi-parti cumulants (where non-contributions are suppressed) even in the smallest systems.

Physics Highlights CMS

Nuclear matter physics
- Onset of collective effects in small systems
- System size dependence of QGP effects
- Flavor dependence of parton shower modi
- Quark and gluon parton distribution functio
- Beyond cold nuclear matter effects in Pb io
- Quarkonia in hot medium

“New” physics
- Limits on chiral magnetic effect
- Observation of light-by-light scattering

proton-proton proton-lead xenon-

CMS-PAS-HIN-17-006

XeXe: how does it look?

No conclusive evidence for either flat plateau or Gaussian shape

For fixed and → no sy

Talk, Initial state physics, Wed. 17:50, R. Bi

CMS-PAS-HIN-18-004

XeXe: charged hadron R_{AA}

R_{AA} vs N_{part}

Similar scaling in XeXe and PbPb

Within uncertainties R_{AA} consistent

Talk, Jet modifications, Tue. 9:20, A. Baty

DIJET ASYMMETRY IN XE+XE

- Dijet asymmetry, x_J, used in Run 1 to establish an observation of jet quenching
  - Question: what controls the dijet asymmetry?

$$x_J = \frac{p_T^{sublead}}{p_T^{lead}}$$

- x_J measured in Xe+Xe collisions at 5.44 TeV as a function of centrality and jet p_T
  - x_J is not unfolded for detector effects

Quark Matter 2018 Venezia

The 27th I on Ultrarel Nucleus-N

14-19 May

Lido di Ve

Highlights from the ATLAS exp

Iwona Grabowska-Bold (AGH UST Kraków)
on behalf of the ATLAS Collaboration
Venice, May 14th, 2018

FLOW HARMONICS IN XE+XE

- Centrality- and p_T-dependence of flow harmonics v_2-v_5 in Xe+Xe collisions at 5.44 TeV
  - Very precise measurement of multi-particle cumulants for 2, 4 and 6 particles and scalar-product (SP) method
- Similar pattern for flow harmonics as in Pb+Pb: rise up to p_T~3 GeV, then decrease with p_T, magnitude of flow harmonics decreases with their order

- v_n are observed to be large n=2,3,4 in most central e
- With decreasing centrality harmonic order, v_n in Xe b comparing to Pb
- Predictions by Giacalone e can describe basic features

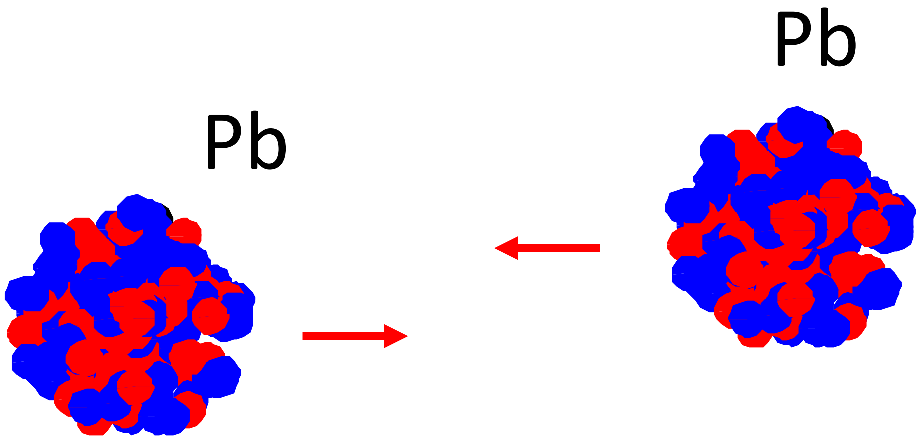
Talk by T.Bold on Tue 11:30
Talk by M.Zhou on Tue 15:00
Poster by K.Burka

RAA FOR CHARGED HADRONS IN XE+XE

ATLAS-CONF-2018-007

- Measurement of charged-hadron spectra measured in Xe+Xe collisions at 5.44 TeV
  - Addresses a question about a role of geometry in HI collisions
- R_{AA} shows a centrality-dependent suppression with characteristics already observed in Pb+Pb
  - Increase to p_T=2 GeV (maximum), decrease to p_T~7 GeV (minimum), and again increase up to p_T~60 GeV
- R_{AA} in Xe compared to Pb in similar <N_{part}> intervals
  - In central events, hadron yields in Xe more suppressed to those in Pb, while in peripheral events, milder suppression in Xe than Pb
  - Also shapes of R_{AA} seem to be systematically different in two collision systems

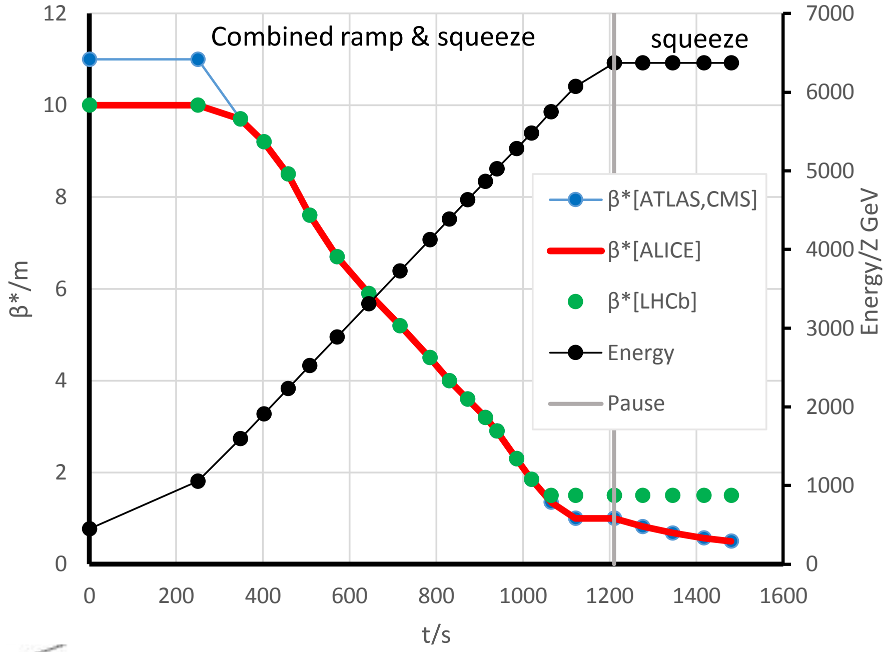
Talk by P.Balek on Tue 9:40

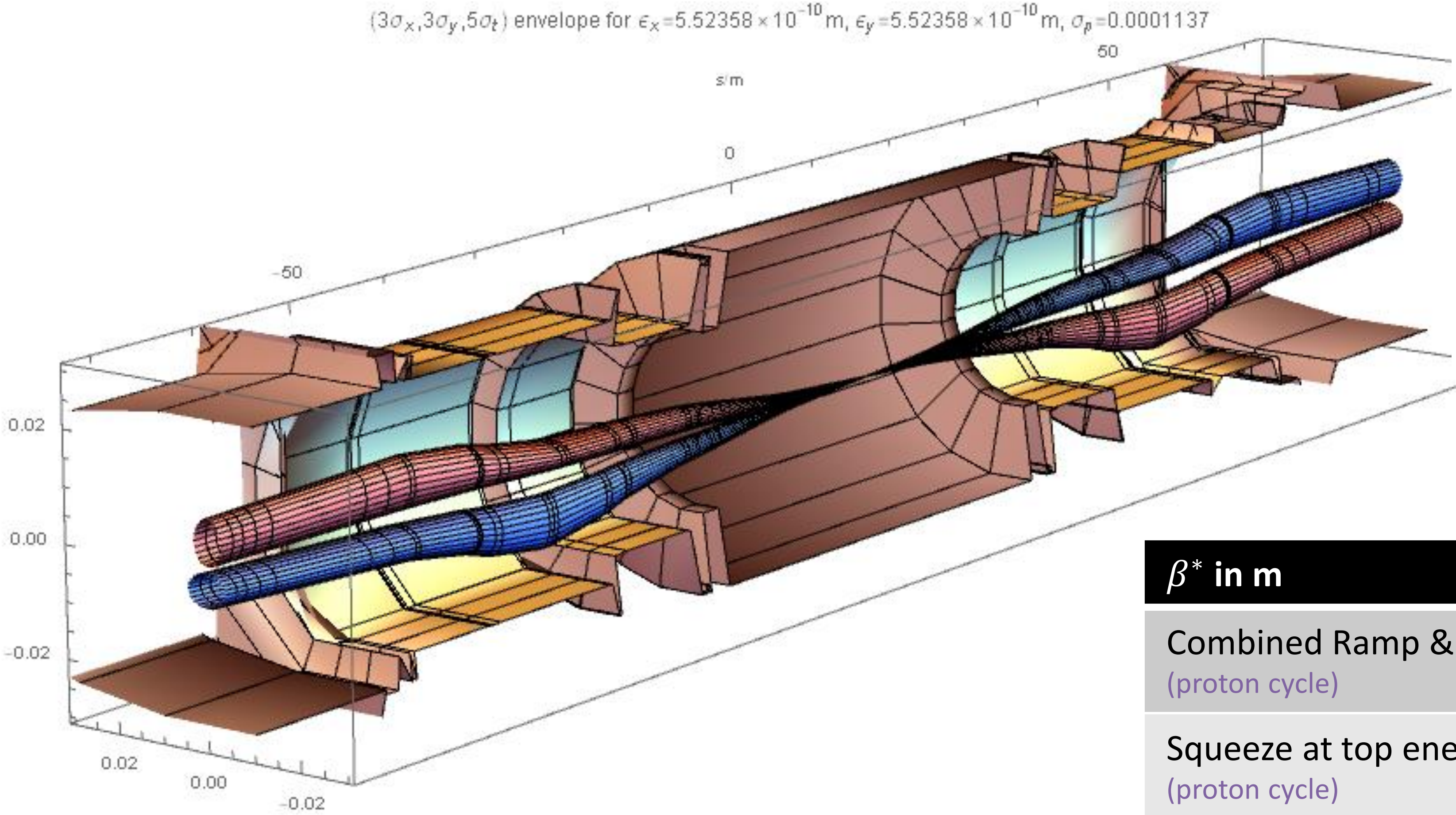


2018

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

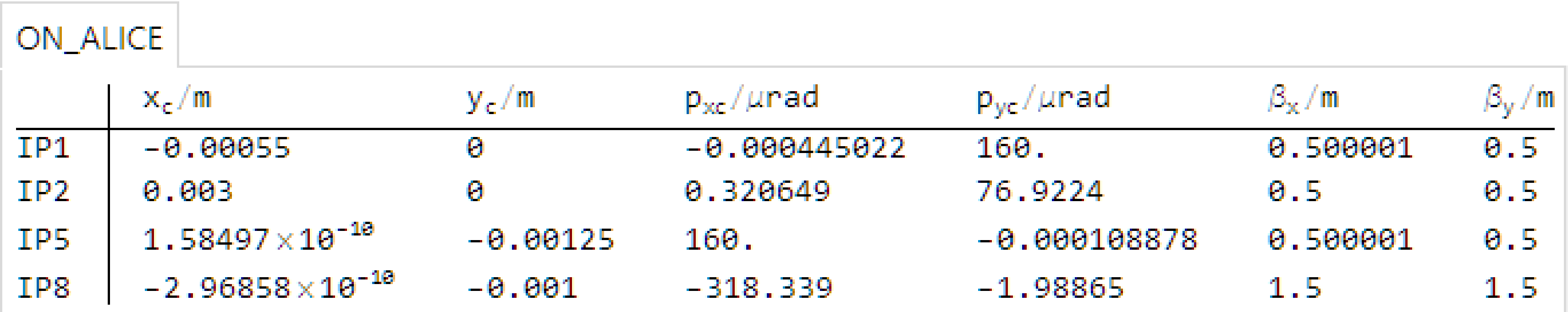
- Optics design by S. Fartoukh, new combined ramp & squeeze
- Gradual divergence from identical to pp optics in 2010 to a completely new cycle in 2018
- Initial problem with beam size in ALICE now understood
- Fixed for reversed-polarity part of run
- Some lessons for optics correction procedure in future





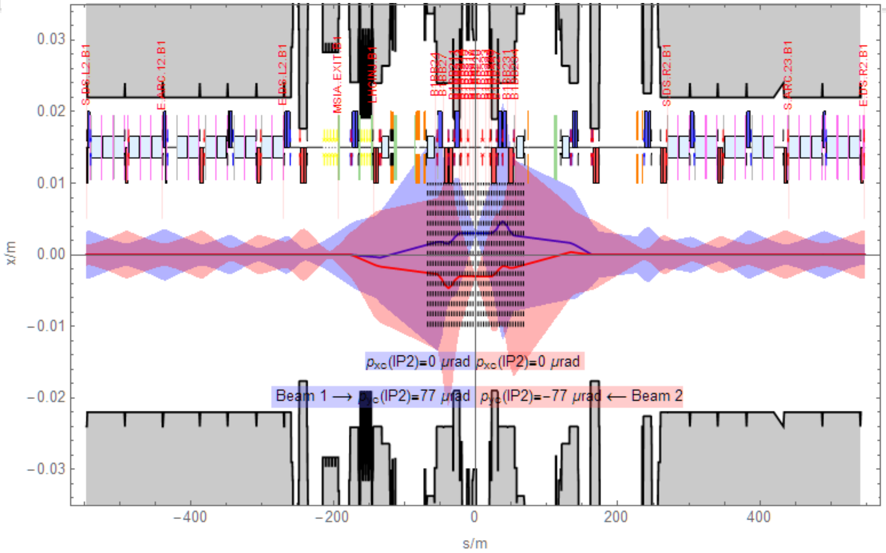
β^* in m	IP1	IP2	IP5	IP8
Combined Ramp & Squeeze (proton cycle)	1 (1)	1 (10)	1 (1)	1.5 (3)
Squeeze at top energy (proton cycle)	0.5 (0.3)	0.5 (10)	0.5 (0.3)	1.5 (3)

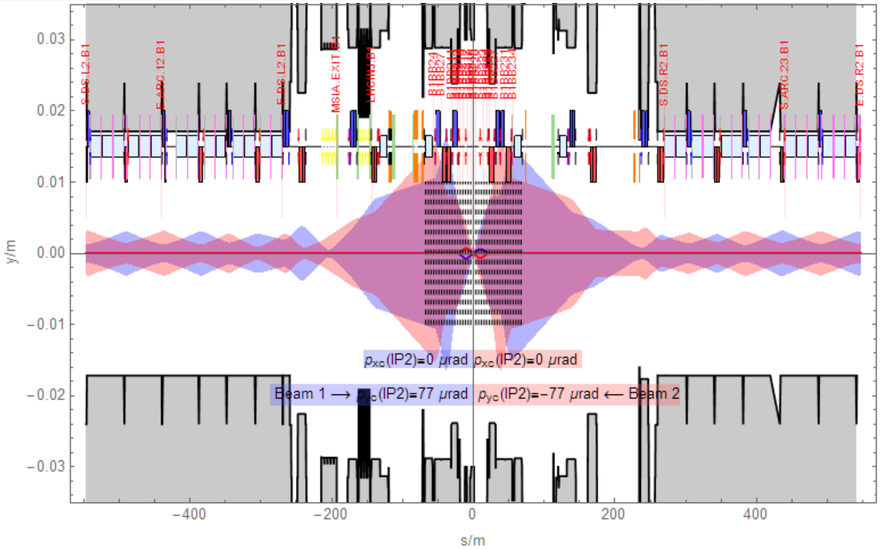
IR2 ALICE +ve: external angle passed through zero in every fill



ON_ALICE

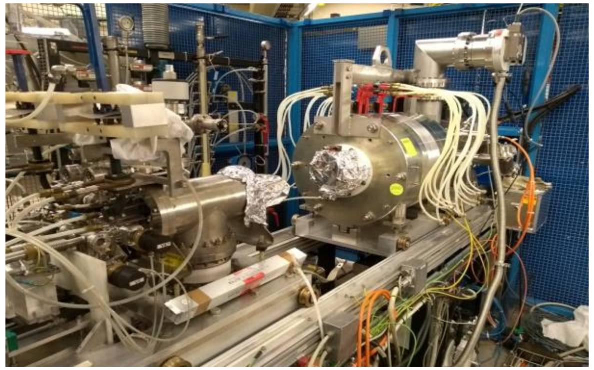
	x_c/m	y_c/m	p_{xc}/µrad	p_{yc}/µrad	β_x/m	β_y/m
IP1	-0.00055	0	-0.000445022	160.	0.500001	0.5
IP2	0.003	0	0.320649	76.9224	0.5	0.5
IP5	1.58497×10^{-18}	-0.00125	160.	-0.000108878	0.500001	0.5
IP8	-2.96858×10^{-18}	-0.001	-318.339	-1.98865	1.5	1.5





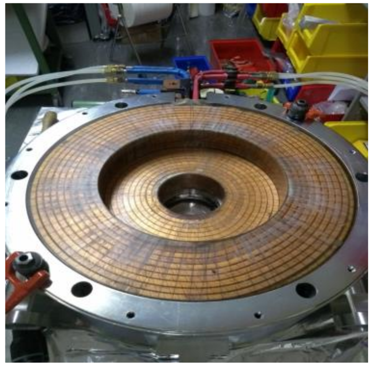
Horizontal parallel separation increased to ±3 mm
IP shift bump still off
Transition through zero external bump to unfavourable polarity with respect to IP (neutrons moving down)
No sign of beam-beam effects.

Major Hurdles …



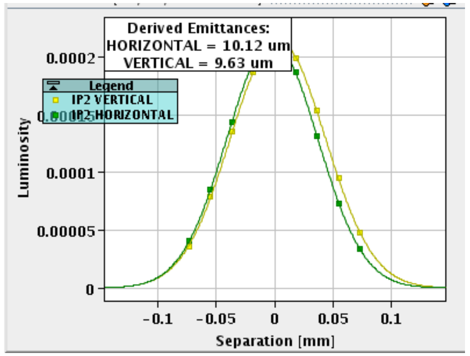
Ion source fault: No ions available after TS3

- 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:

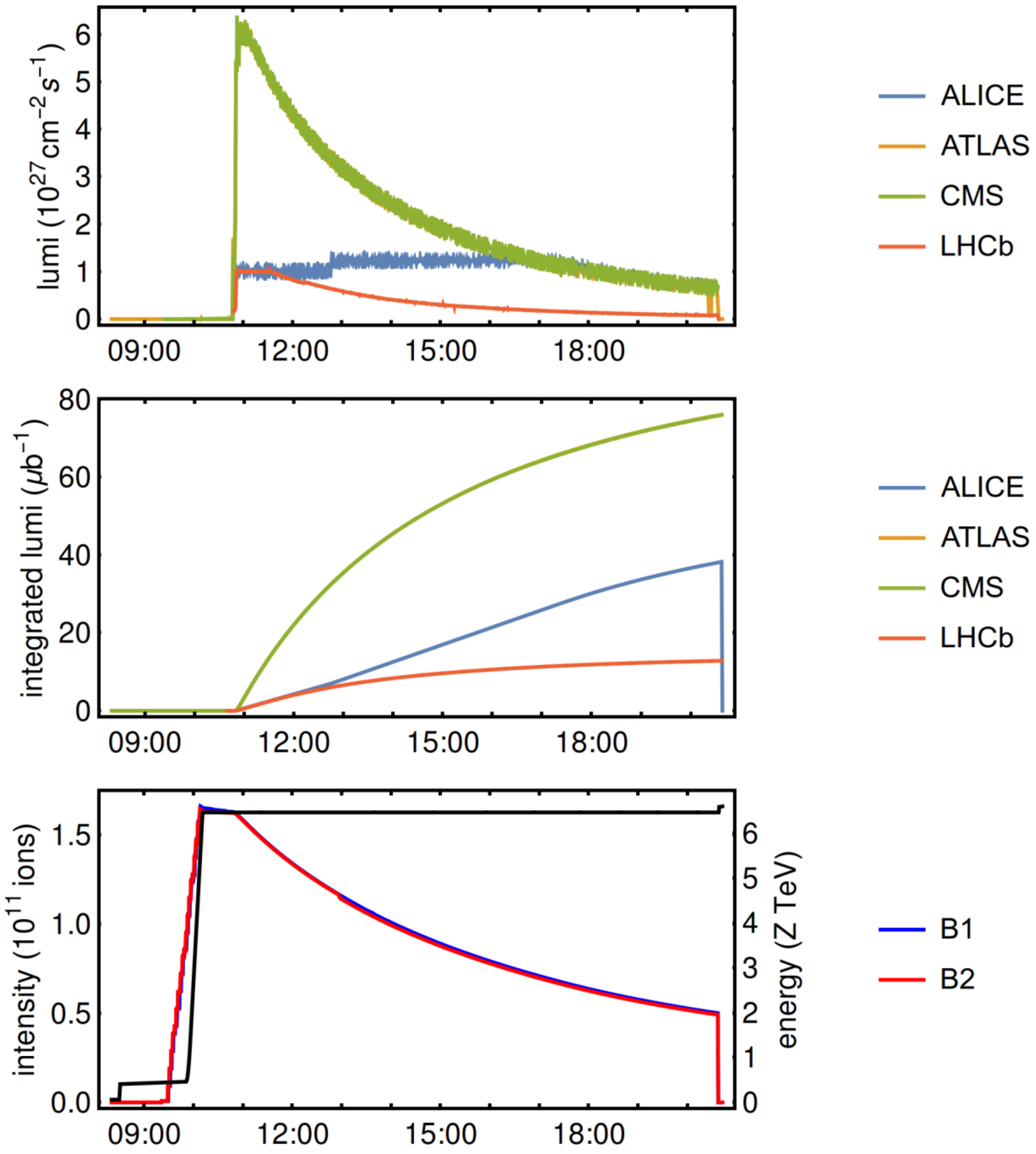
- *Cause:* beam deformation and reduced overlap at IP introduced by strong local betatron coupling in IR2.
- *Solution:* correction with skew-quadrpoles implemented during ALICE polarity reversal.
  - Luminosity sharing strategies used until solution was found.
    - ➢ Filling schemes (number and distribution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


Derived Emittances:
HORIZONTAL = 10.12 um
VERTICAL = 9.63 um

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

- Leveling in ATLAS and CMS gradually increased to 6×10^{27} $cm^{-2}s^{-1}$
- ALICE leveled at design luminosity 1×10^{27} $cm^{-2}s^{-1}$

- After correction of local coupling, ALICE level times increased to ~ 8 h.

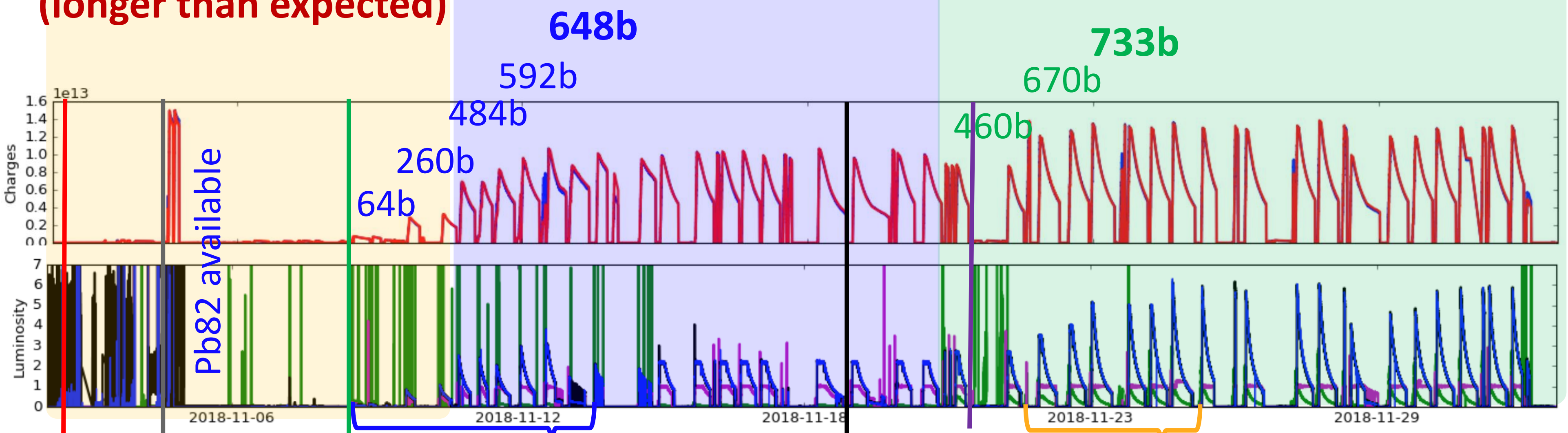


Availability
85%

Commissioning (longer than expected)

100ns Bunch Spacing

75ns Bunch Spacing



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 $6.4\times10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Repetition of luminosity calibration for
special physics run (protons)

ALICE polarity
switch & fix of
IR2 coupling

M. Schaumann

Pb 2018 collimation system cleaning measurements and simulation studies

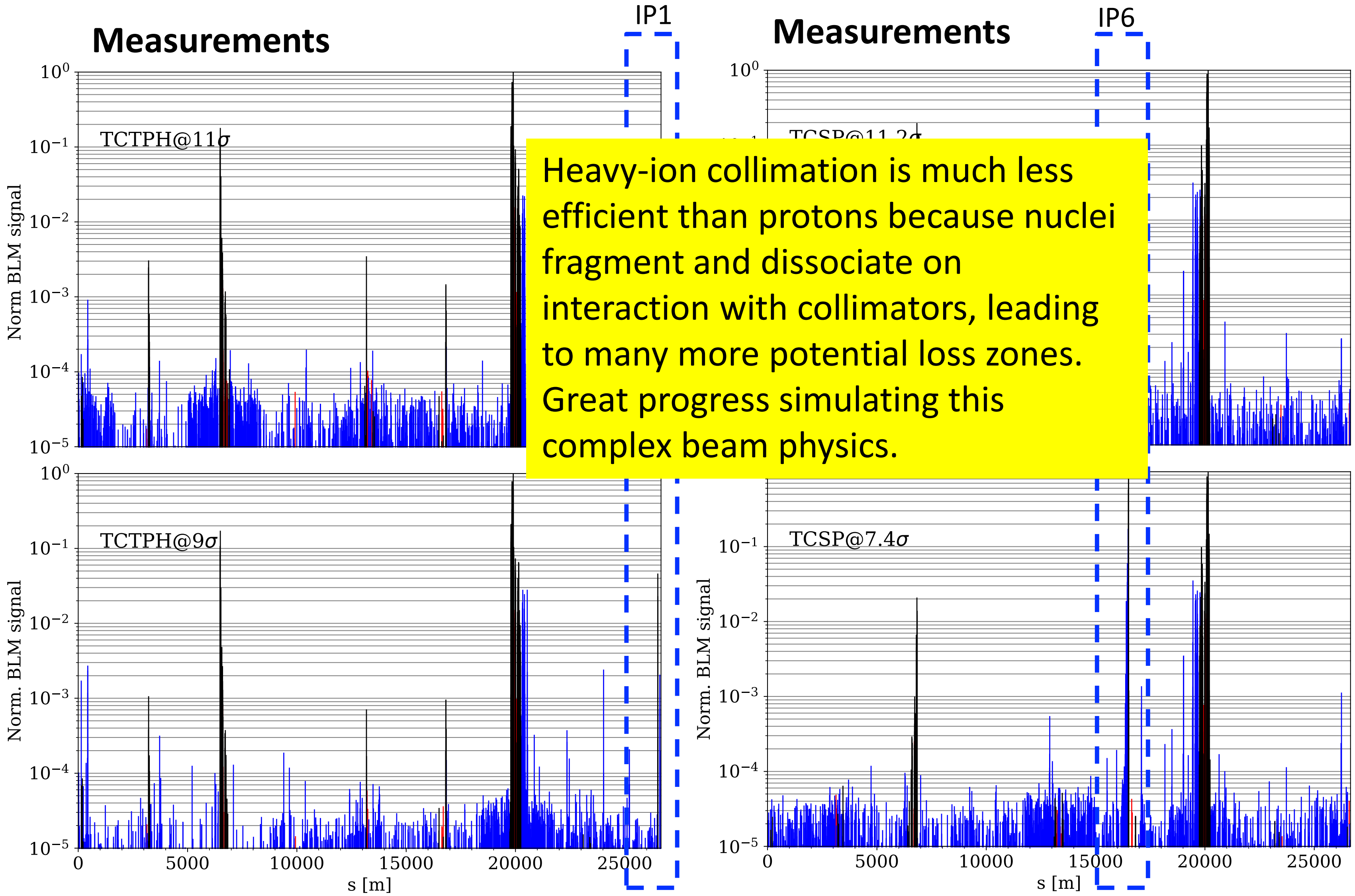
- During the system validation observed higher losses than expected (at EoS/Physics) required to refine the collimator settings.

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

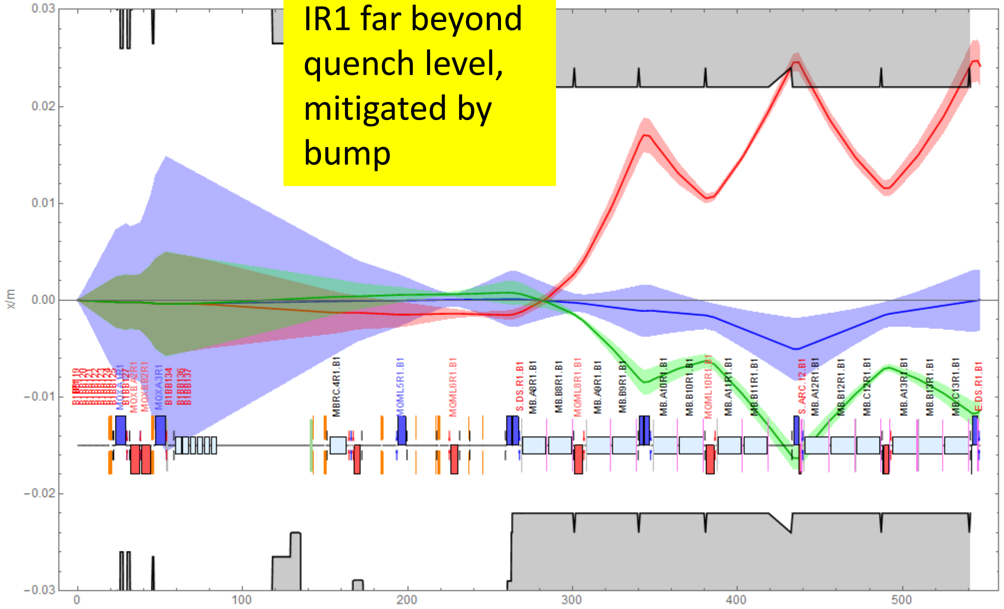
- High losses observed on the TCTPH in IP1 (even higher at EoS).
- Solution adopted: open the TCTPH to 11σ. The losses were reduced by 80%.

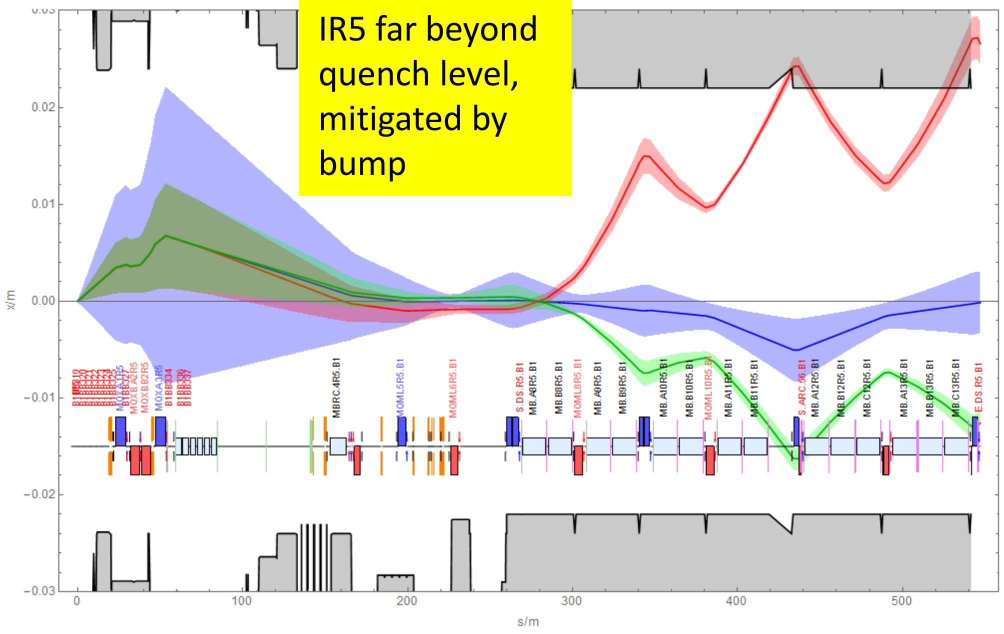


Heavy-ion collimation is much less efficient than protons because nuclei fragment and dissociate on interaction with collimators, leading to many more potential loss zones. Great progress simulating this complex beam physics.

N. Fuster, R. Bruce et al

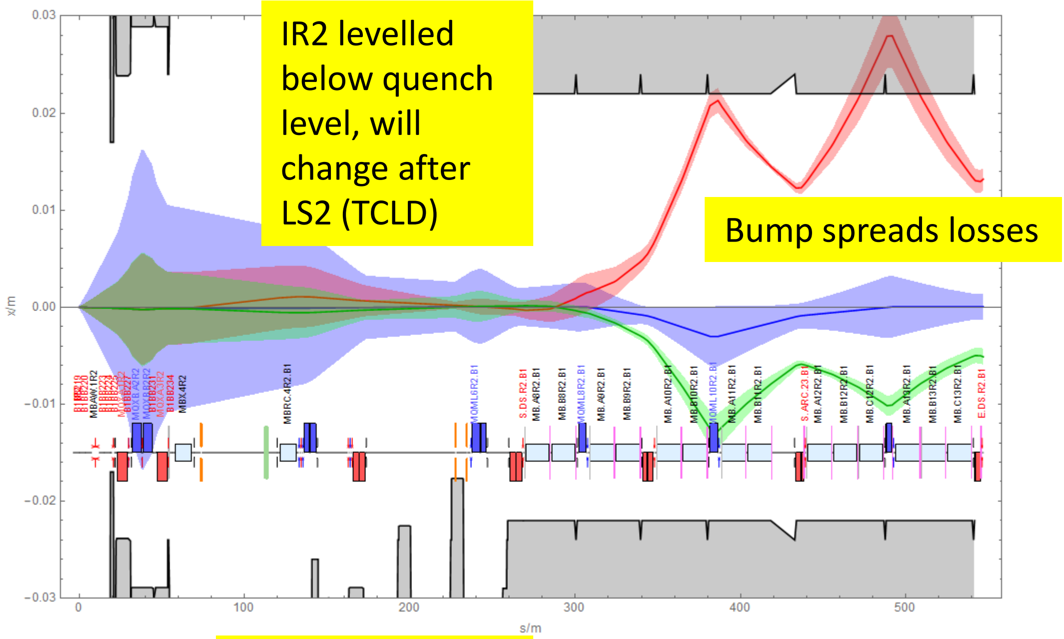
Significant BFPP beams in all IPs (horizontal envelopes)


IR1 far beyond quench level, mitigated by bump

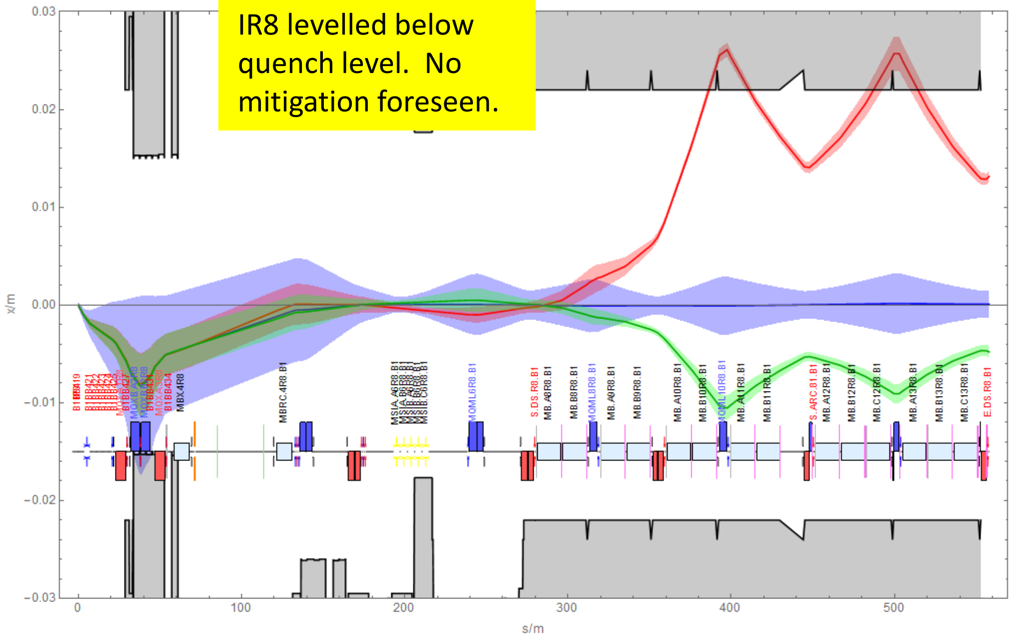

IR5 far beyond quench level, mitigated by bump

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

Chamber misalignment.


IR2 levelled below quench level, will change after LS2 (TCLD)

Bump spreads losses

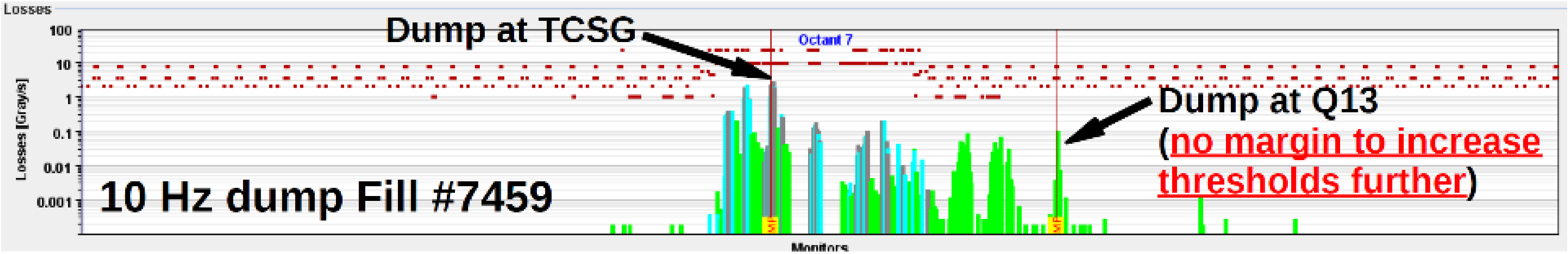

IR8 levelled below quench level. No mitigation foreseen.

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**:



Dump at TCSG

10 Hz dump Fill #7459

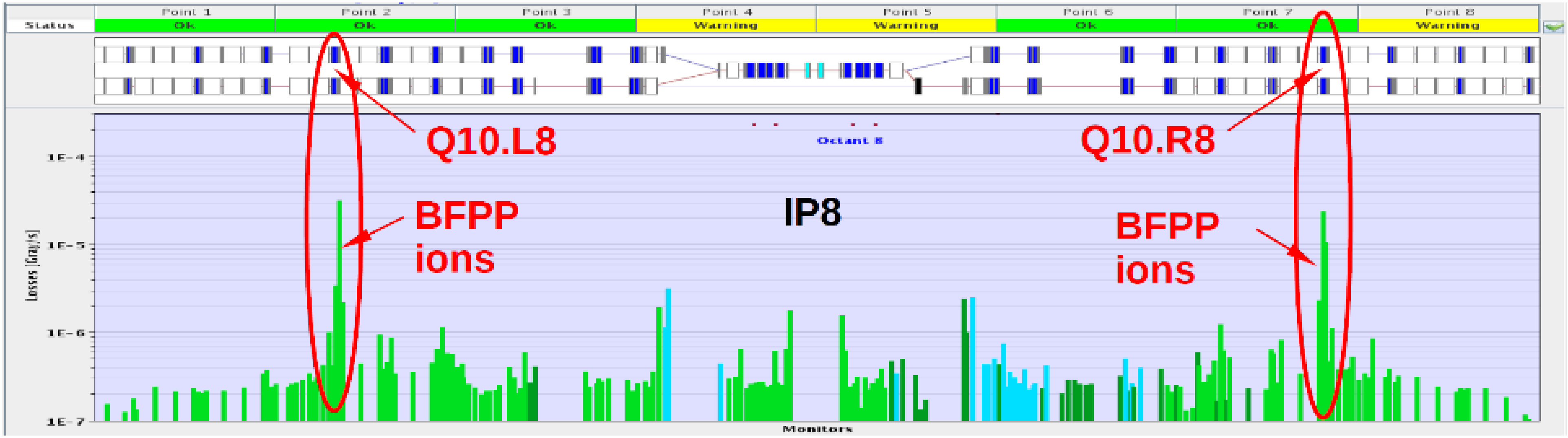
Dump at Q13 (no margin to increase thresholds further)

A. Lechner et al

BLM Threshold changes for BFPP losses

BFPP-related threshold changes essential for luminosity reach:

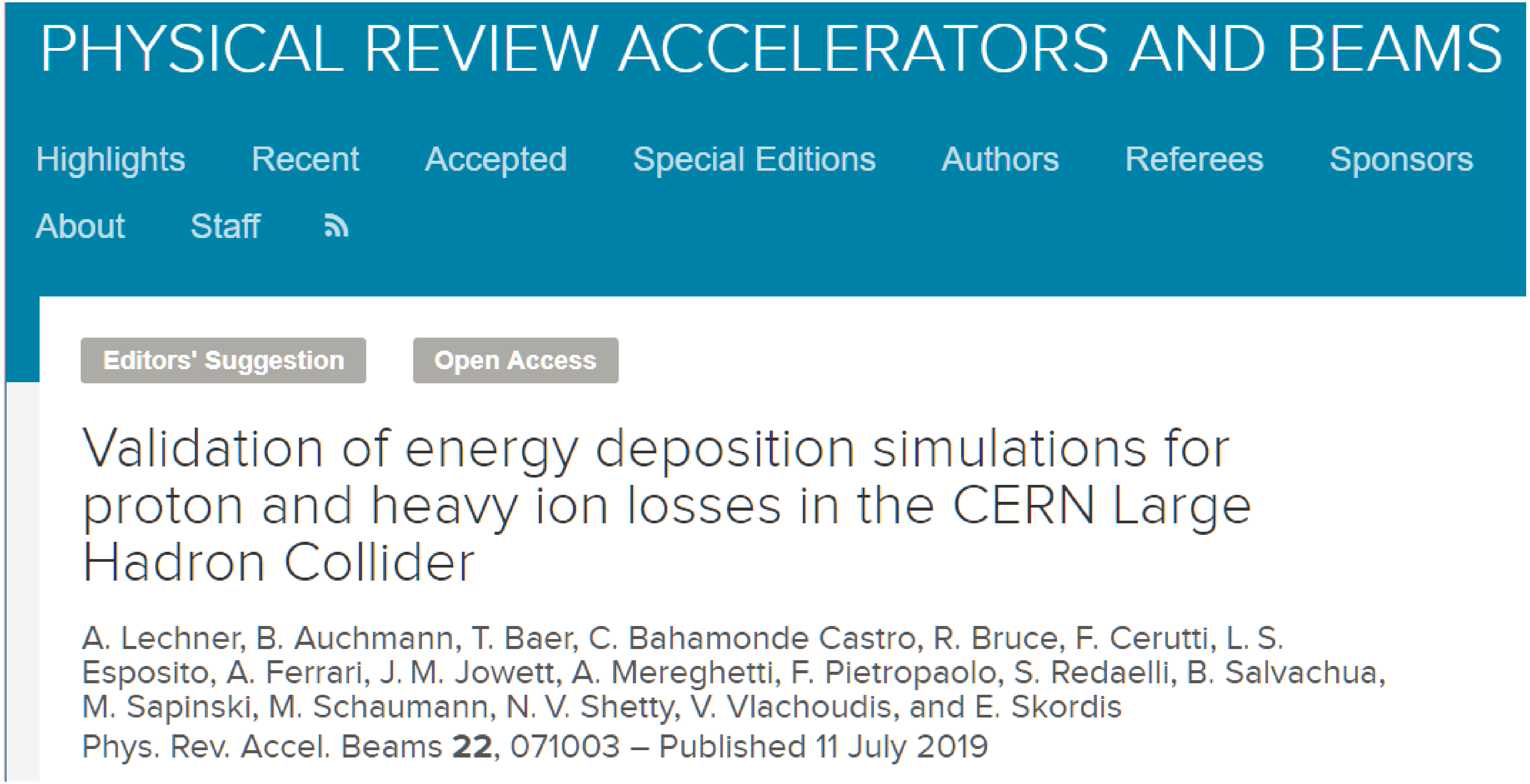
1) **Prevent premature dumps due to BFPP ions in IR1/5**
   - Several threshold and orbit bump optimizations around BFPP loss location (connection cryostats) -> could reach the target luminosity (6-7x10^{27}cm^{-2}s^{-1}) while still protecting against quenches
2) **Prevent premature dumps due to BFPP 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

Energy deposition and beam loss monitors

New paper just published: https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.071003



PHYSICAL REVIEW ACCELERATORS AND BEAMS

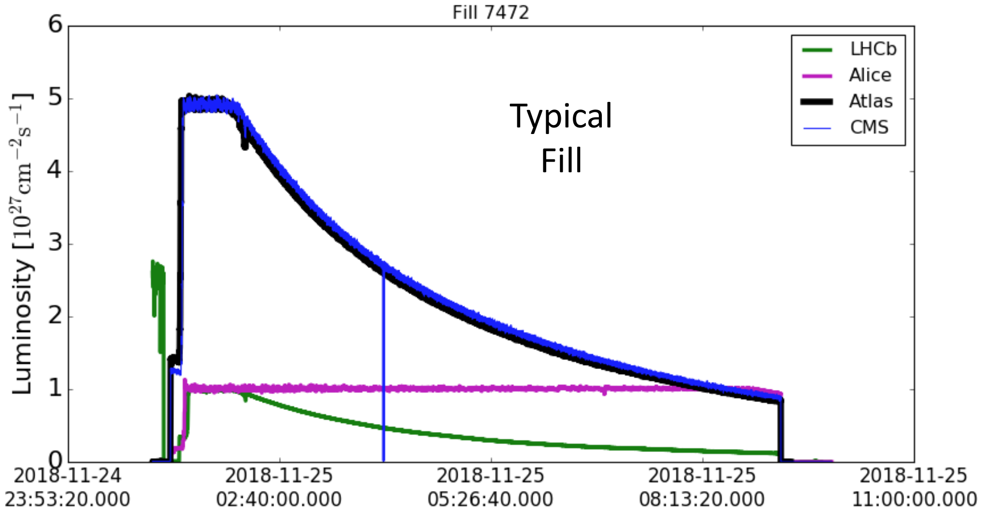
Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider

A. Lechner, B. Auchmann, T. Baer, C. Bahamonde Castro, R. Bruce, F. Cerutti, L. S. Esposito, A. Ferrari, J. M. Jowett, A. Mereghetti, F. Pietropaolo, S. Redaelli, B. Salvachua, M. Sapinski, M. Schaumann, N. V. Shetty, V. Vlachoudis, and E. Skordis

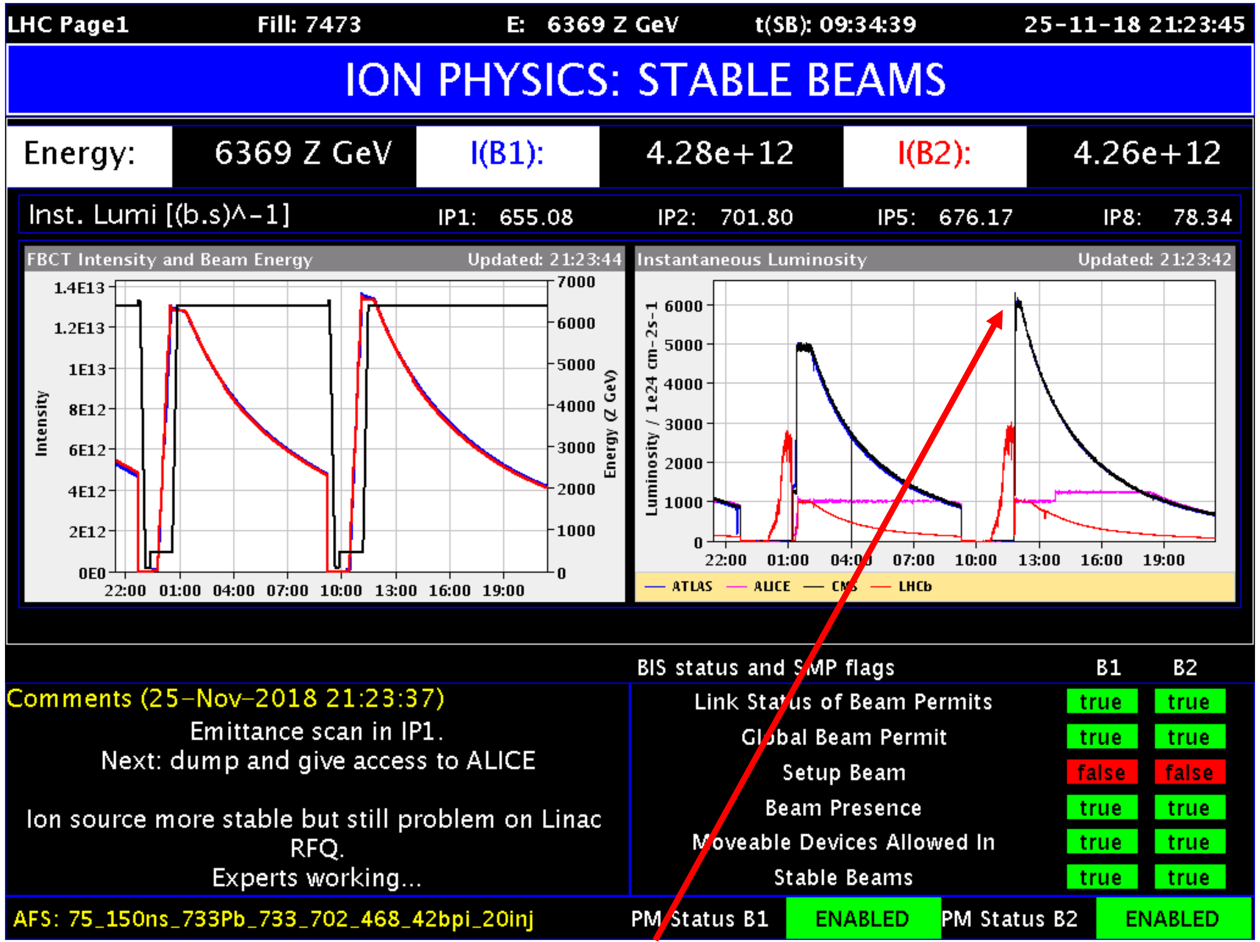
Phys. Rev. Accel. Beams **22**, 071003 – Published 11 July 2019

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



LHC Page1 Fill: 7473 E: 6369 Z GeV t(SB): 09:34:39 25-11-18 21:23:45

ION PHYSICS: STABLE BEAMS

Energy:	6369 Z GeV	I(B1):	4.28e+12	I(B2):	4.26e+12

Inst. Lumi [(b.s)^-1] IP1: 655.08 IP2: 701.80 IP5: 676.17 IP8: 78.34

Comments (25-Nov-2018 21:23:37)
Emittance scan in IP1.
Next: dump and give access to ALICE

Ion source more stable but still problem on Linac RFQ.
Experts working...

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj PM Status B1 ENABLED PM Status B2 ENABLED

$$L = 6\times10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

$$= 6\times\text{design}$$

$$= (47\ \text{kHz hadronic event rate})$$

Nominal HL-LHC levelling value is

$$L = 7\times10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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

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

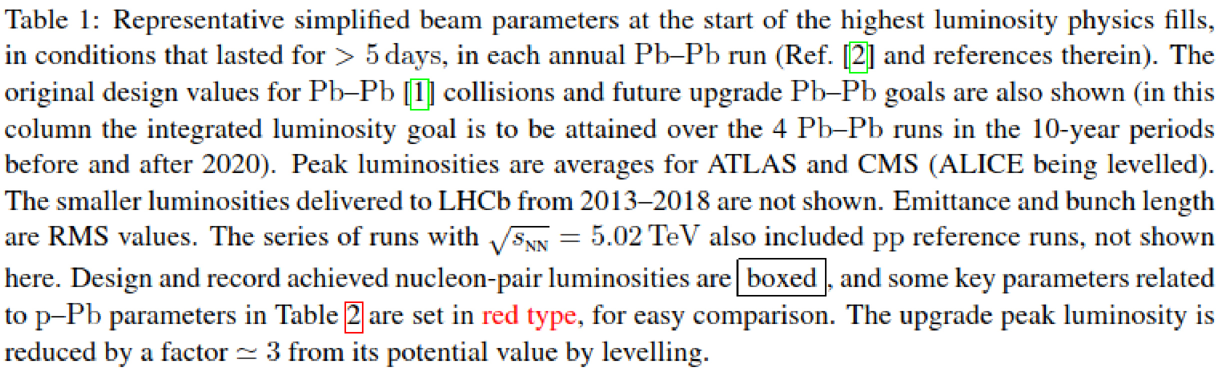
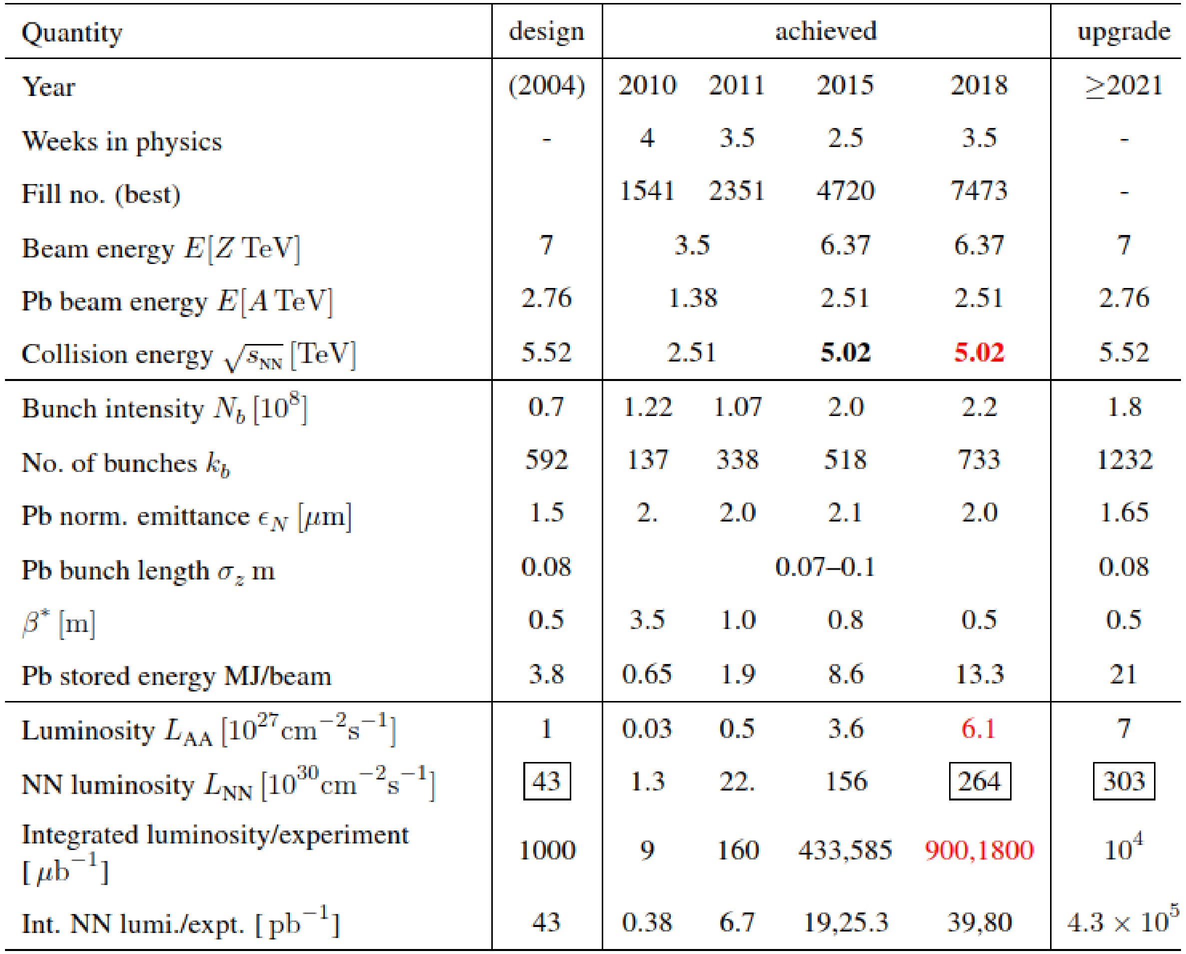


Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb–Pb run (Ref. [2] and references therein). The original design values for Pb–Pb [1] collisions and future upgrade Pb–Pb goals are also shown (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 $\sqrt{s_{\rm NN}} = 5.02\,\mathrm{TeV}$ 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 ≃ 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 $E[Z\ \mathrm{TeV}]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\ \mathrm{TeV}]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{\rm NN}}\,[\mathrm{TeV}]$	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 $L_{\rm AA}\,[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	0.03	0.5	3.6	6.1	7
NN luminosity $L_{\rm NN}\,[10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\boxed{43}$	1.3	22.	156	$\boxed{264}$	$\boxed{303}$
Integrated luminosity/experiment [$\mu\mathrm{b}^{-1}$]	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"

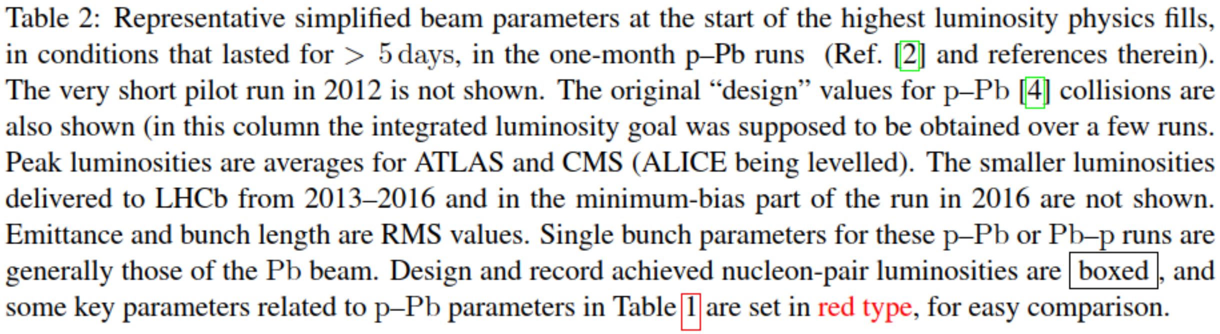
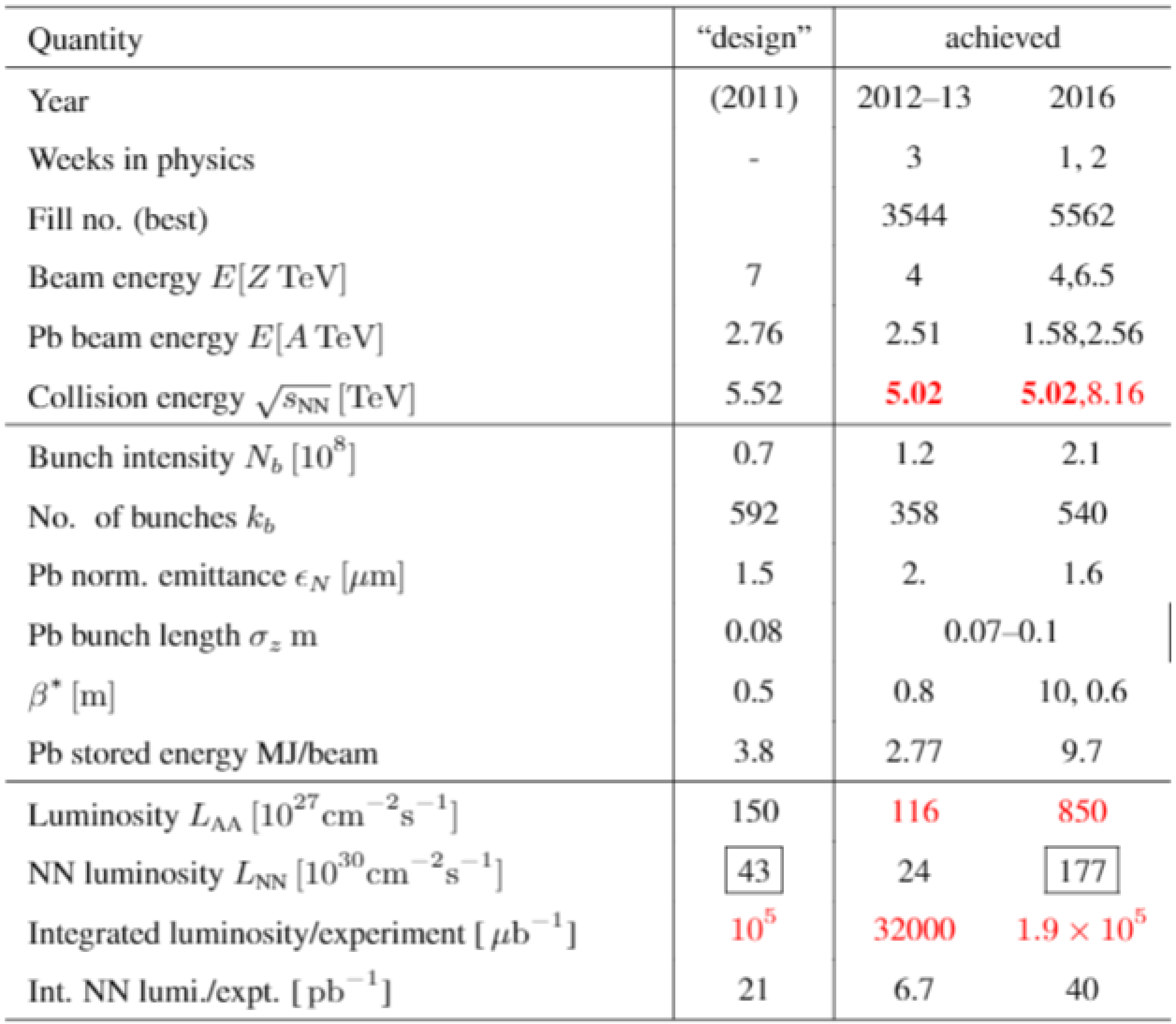


Table 2: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for $> 5\,\mathrm{days}$, in the one-month p–Pb runs (Ref. [2] and references therein). The very short pilot run in 2012 is not shown. The original "design" values for p–Pb [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 $\boxed{\text{boxed}}$, 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.

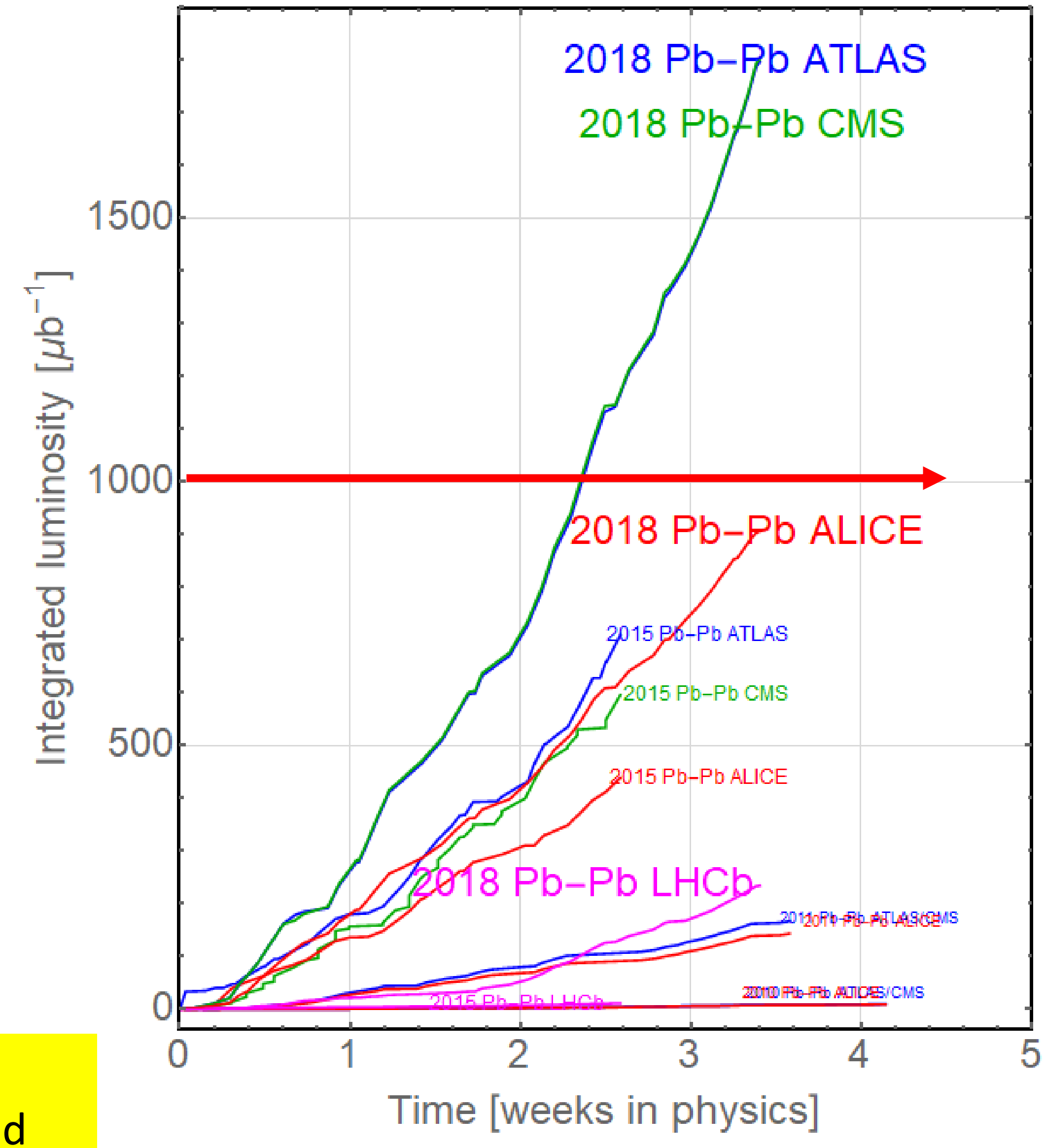
Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

Equivalent energy runs

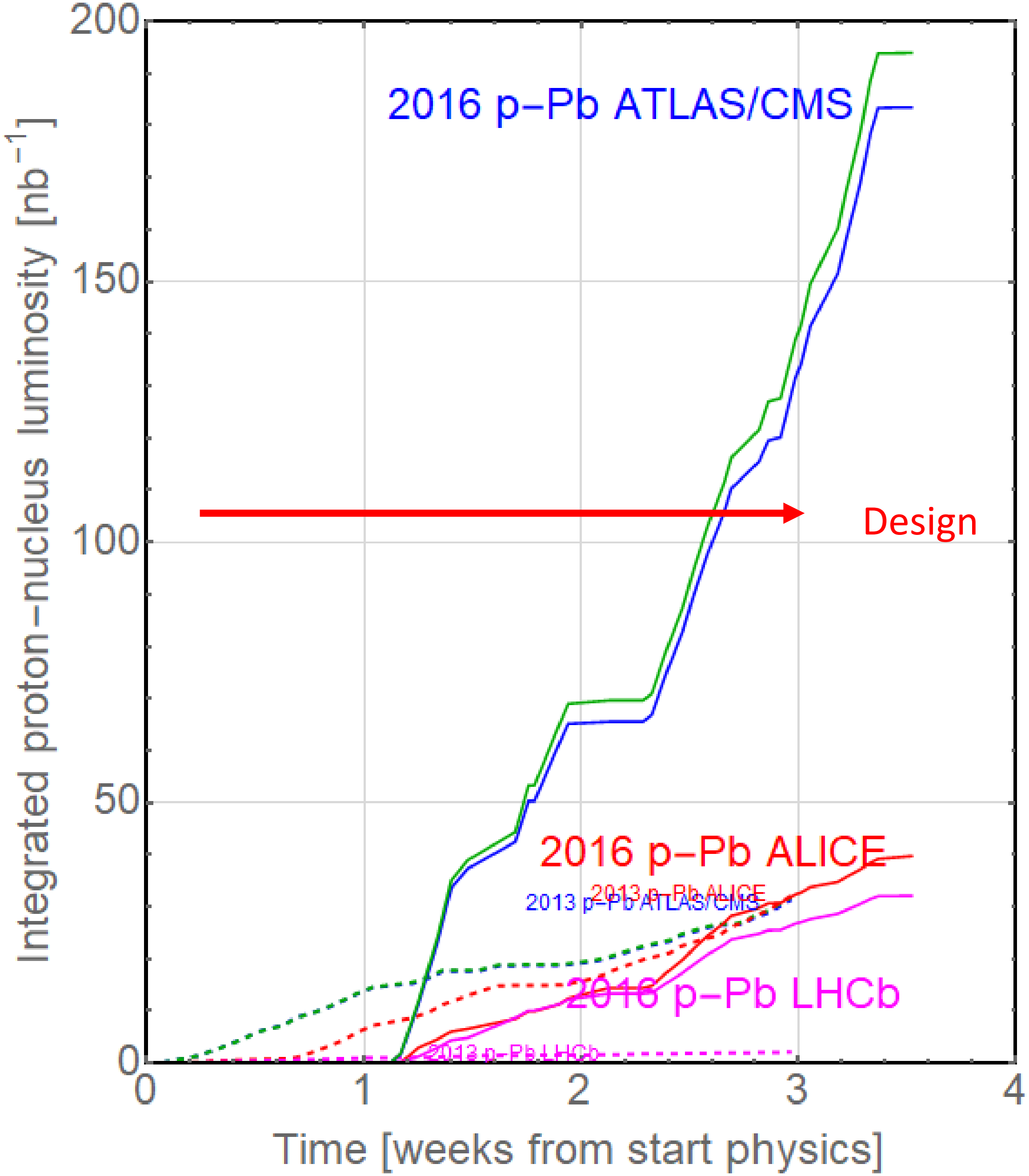
$$\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}\ \ (\sqrt{s}=1.045\ \mathrm{PeV\ in\ Pb\text{-}Pb})$$

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

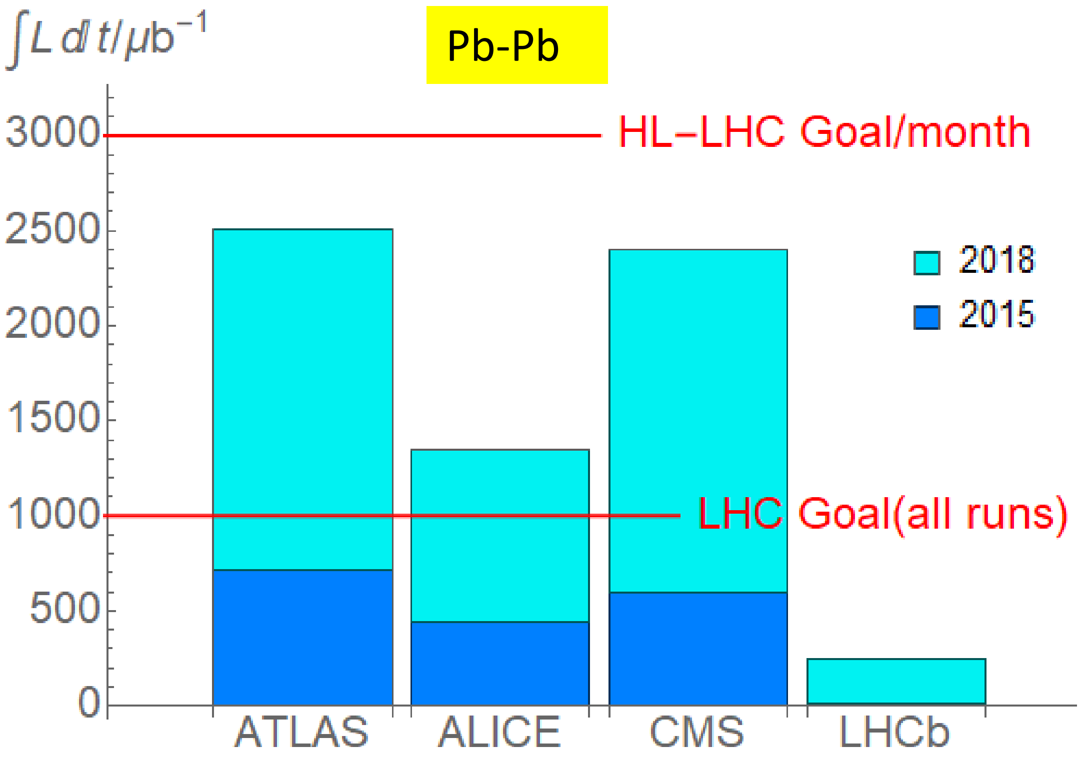
ALICE integrated luminosity in 2018 was equivalent to spending 10.4 days, 100% of the time, at constant levelled saturation luminosity.

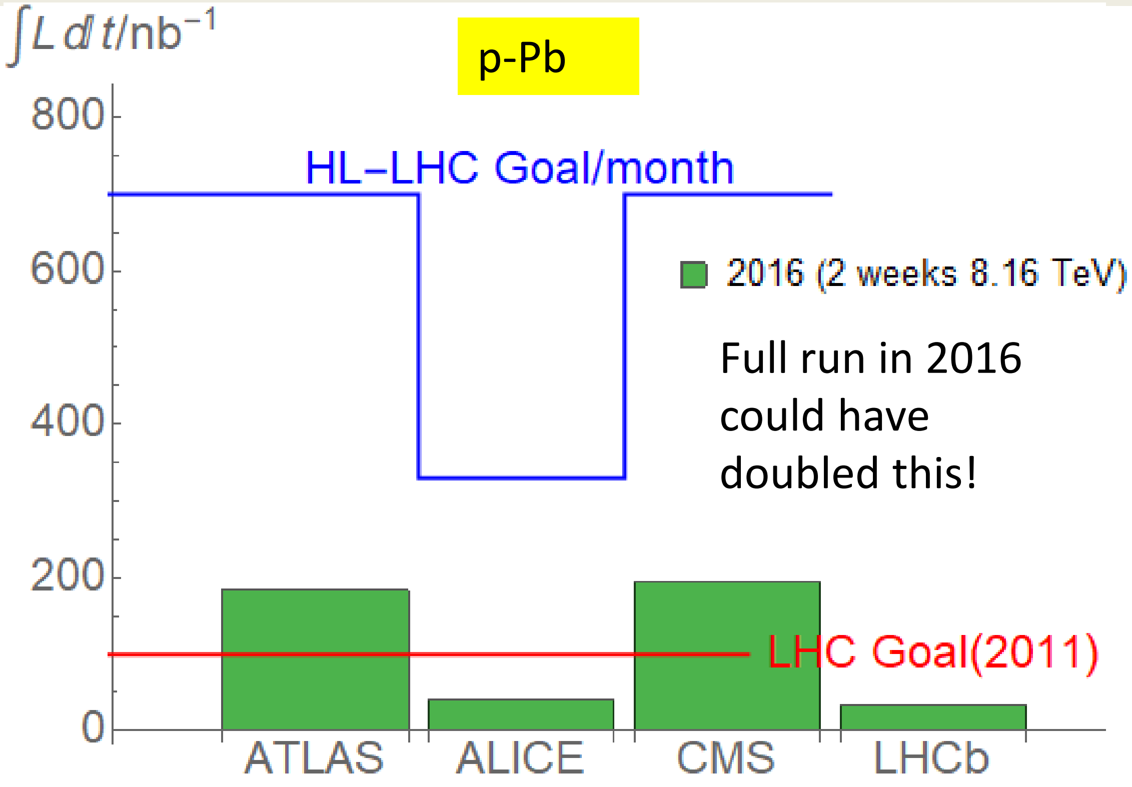


Proton-nucleus programme status after 2016



How close are we to the HL-LHC goals ?





Full run in 2016 could have doubled this!

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)

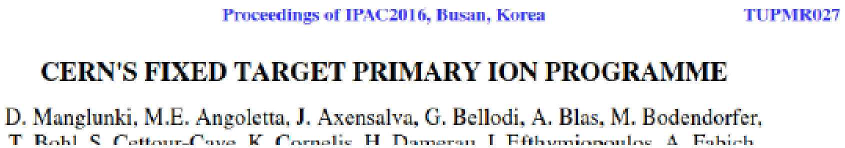
Postulate simple form for bunch intensity dependence on species charge only

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

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

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

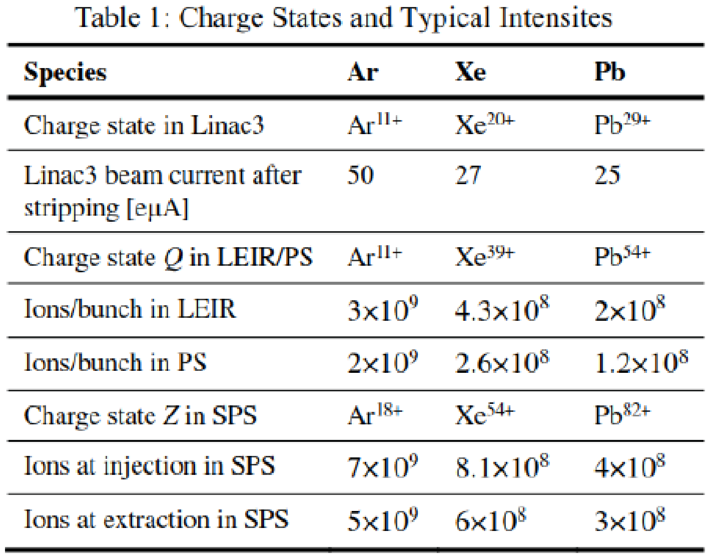


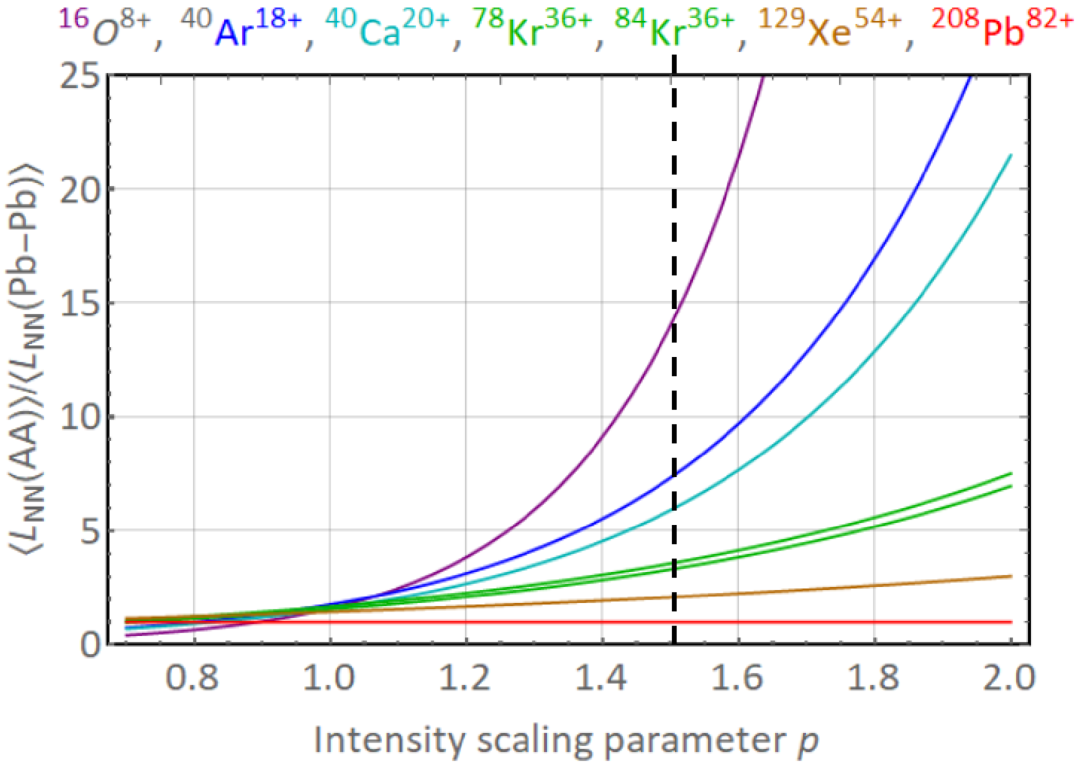
Table 1: Charge States and Typical Intensites

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.

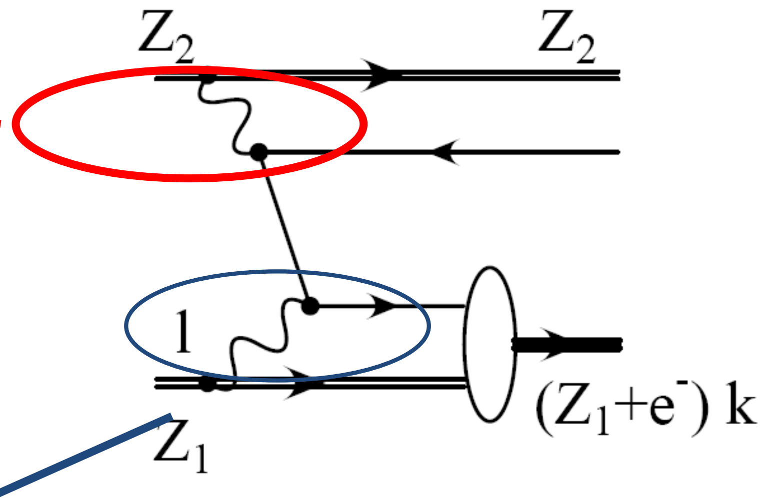
Summary and conclusions

- 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.
  - 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.

BACKUP SLIDES

Pb-Pb BFPP cross-section (heuristic)

Pair production $\propto Z_1^{\,2} Z_2^{\,2}$



G. Baur et al, Phys. Rept. 364 (2002) 359

Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \quad \Psi(0) \square Z_1^{\,3/2} \quad \Rightarrow \quad \left|\Psi(0)\right|^2 \square Z_1^{\,3}$$

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to \left(Z_1 + e^-\right)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

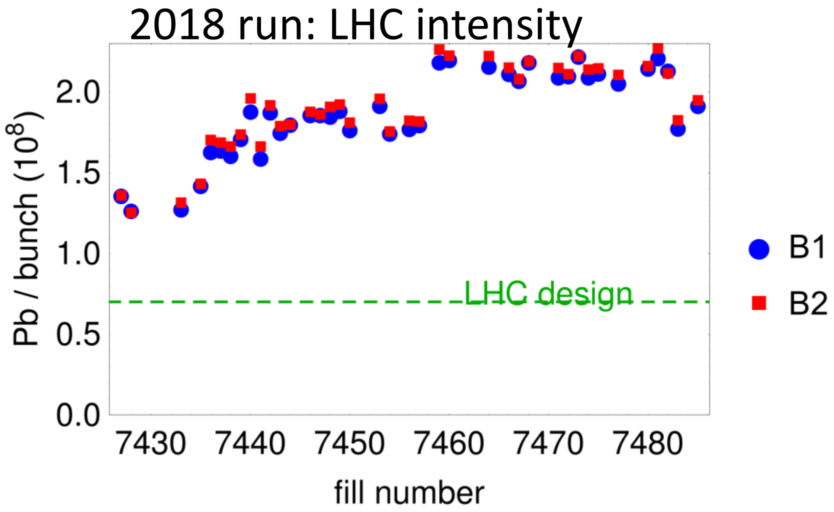
$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2}\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

Total cross-section $\square\ Z_2^{\,2} Z_1^{\,5}$

Bunch intensities in 2018



As usual, integrated luminosity is roughly proportional to total injected intensity.

Major increase with switch from 100 ns to 75 ns scheme during 2018 run.

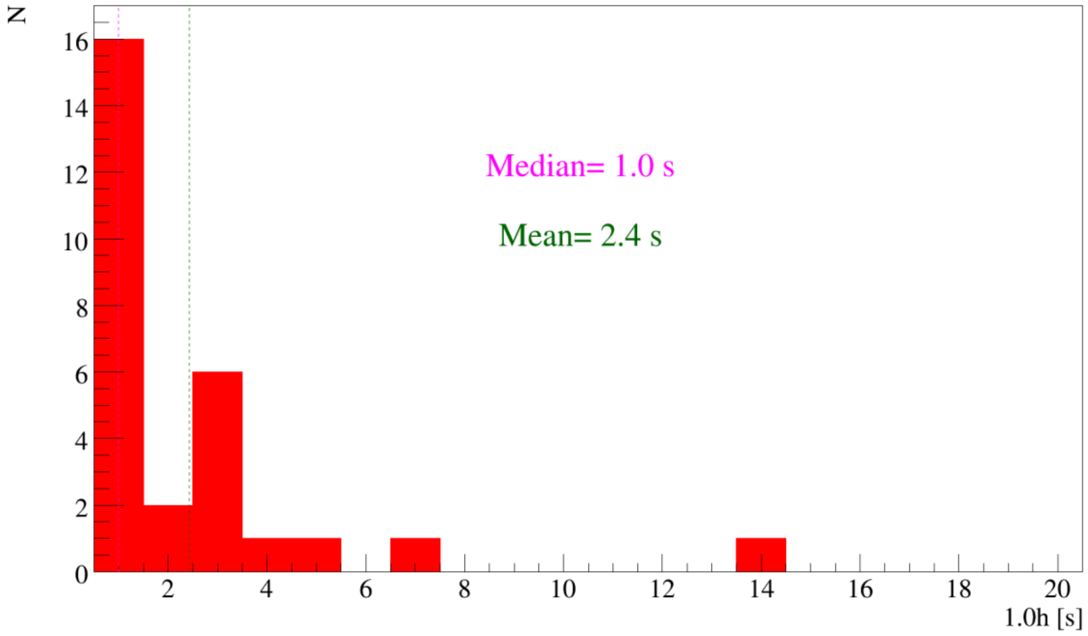
Lifetime dips and dumps

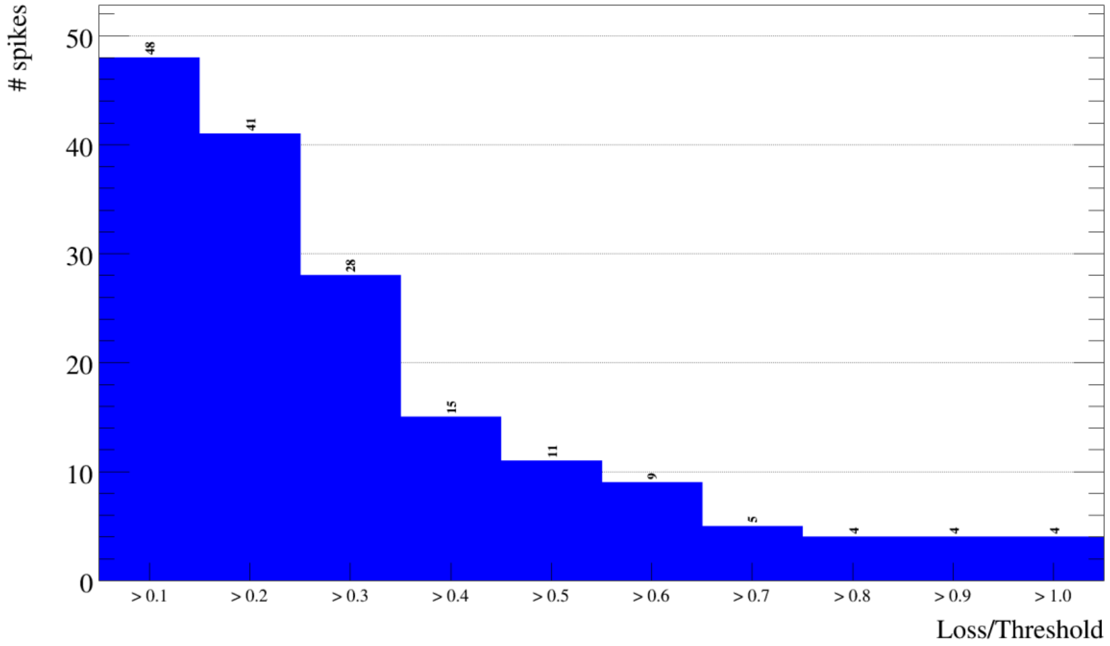
Analysis of lifetime as described in

- CWG 232, spikes: https://indico.cern.ch/event/760786/
- CWG 233, lifetime: https://indico.cern.ch/event/763571/

There are 3 dumps missing in 2018 because the dump wasn't triggered in the RS_09, which was used for the analysis.

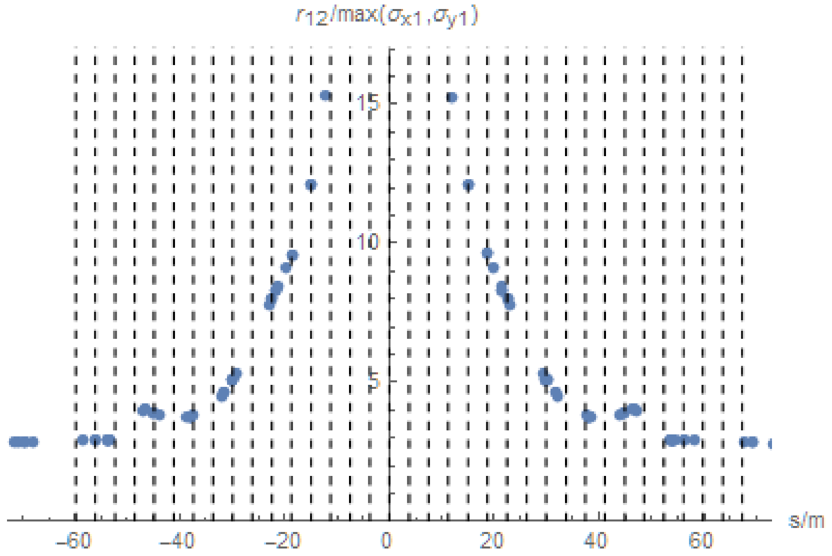
Thus, in total we had 7 dumps in 2018, all due to 10Hz oscillations.





D. Mirarchi

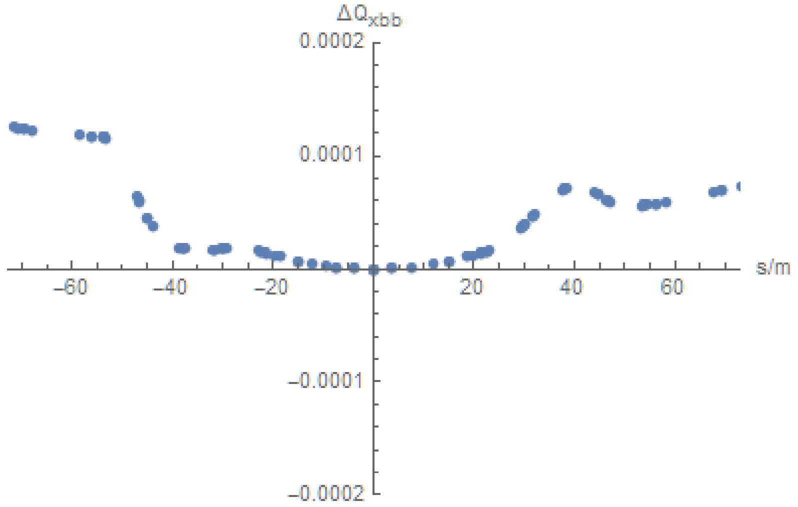
IR2 ALICE +ve, external angle zero, beam-beam Beam 1

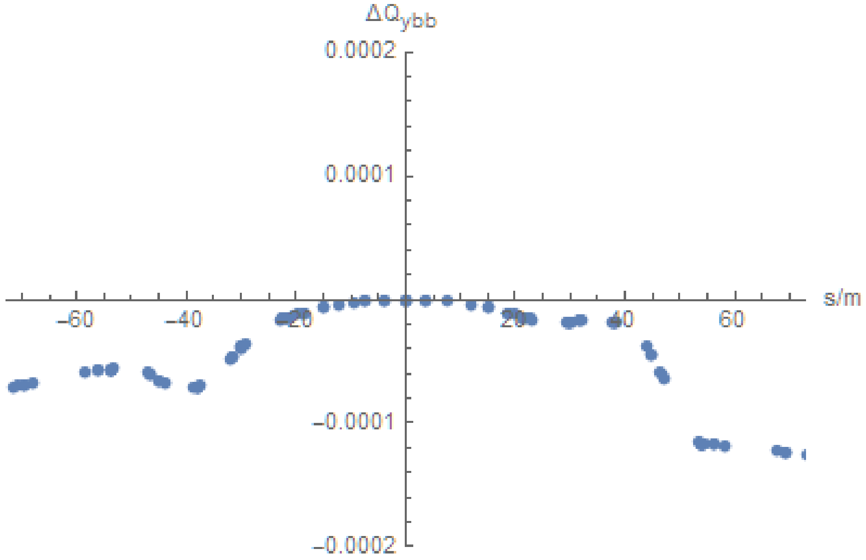


Separations at outermost encounters have been increased by larger horizontal separation.

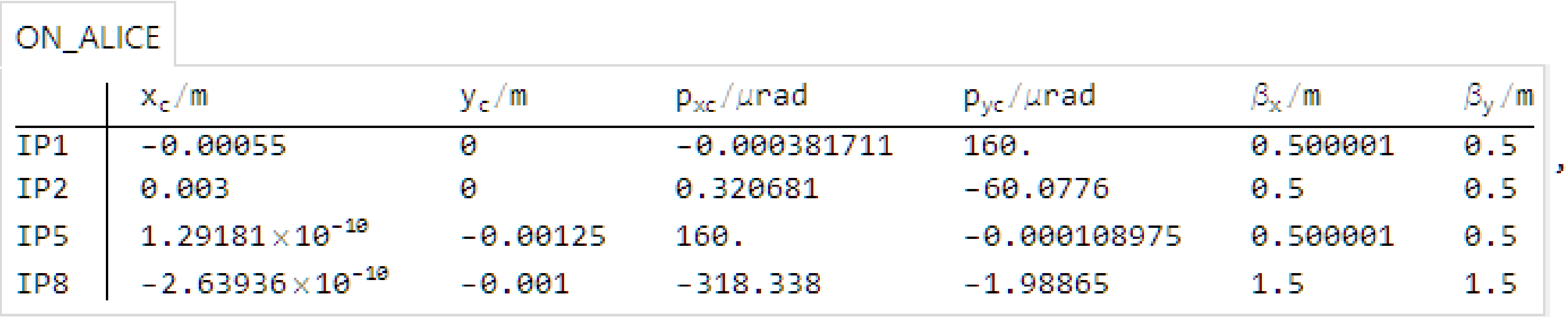
Beam-beam tune-shifts remain small.

No adverse effects observed in any fill.





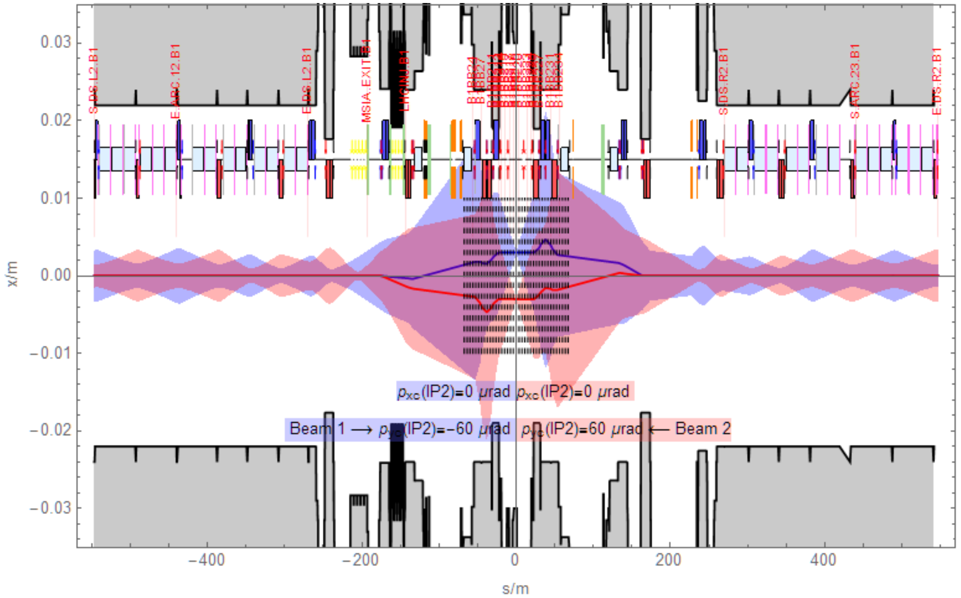
IR2 ALICE +ve, external angle reversed

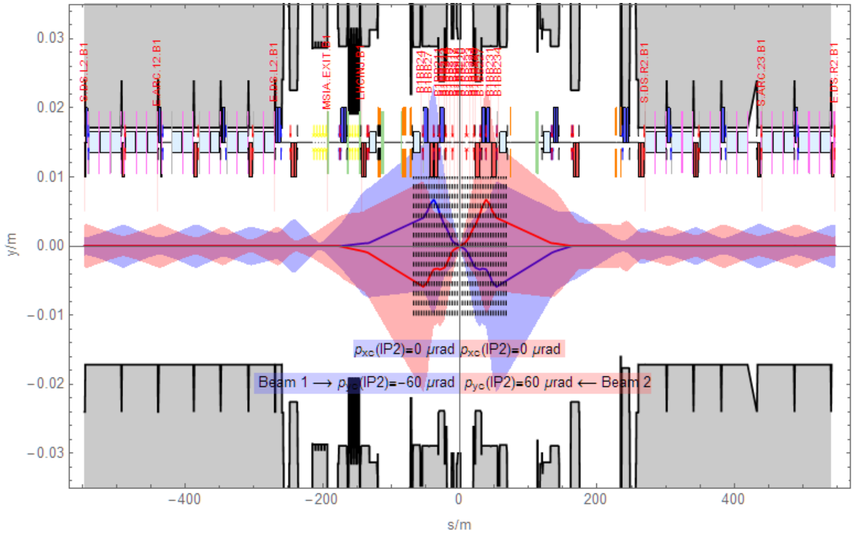


ON_ALICE

	x_c/m	y_c/m	p_{xc}/µrad	p_{yc}/µrad	β_x/m	β_y/m
IP1	-0.00055	0	-0.000381711	160.	0.500001	0.5
IP2	0.003	0	0.320681	-60.0776	0.5	0.5
IP5	1.29181×10^{-10}	-0.00125	160.	-0.000108975	0.500001	0.5
IP8	-2.63936×10^{-10}	-0.001	-318.338	-1.98865	1.5	1.5

,



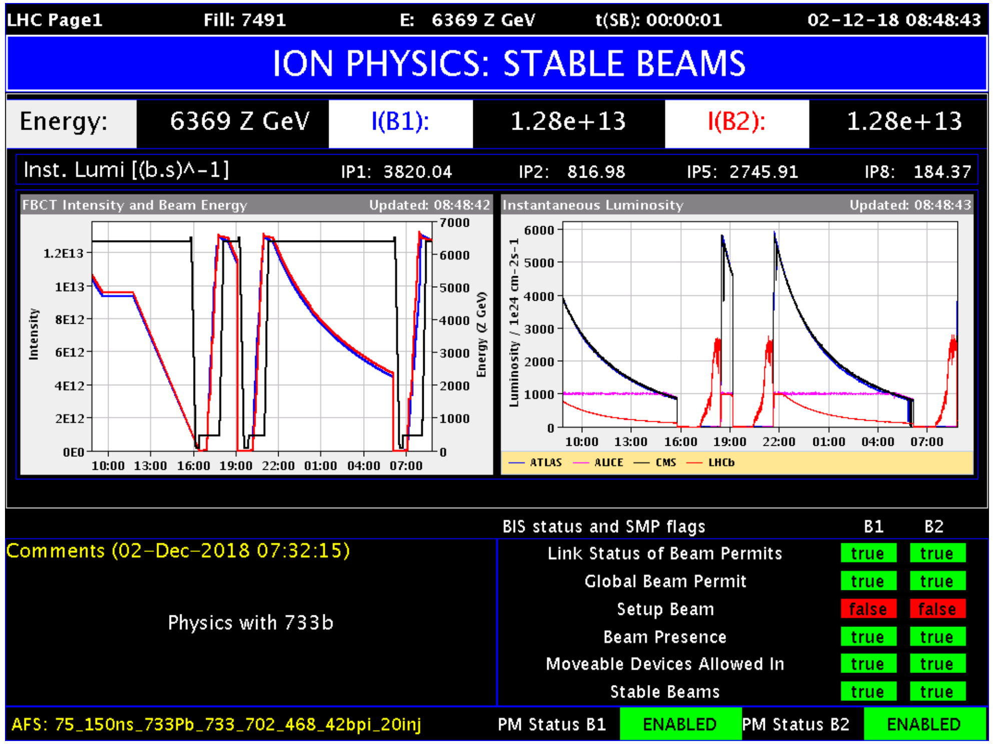


Horizontal parallel separation still at ±3 mm, could have started to bring it down before this point

IP shift bump still off

Reversed external bump to unfavourable polarity with respect to IP (neutrons moving down)

Production fills with long ALICE levelling



LHC Page1 Fill: 7491 E: 6369 Z GeV t(SB): 00:00:01 02-12-18 08:48:43

ION PHYSICS: STABLE BEAMS

Energy:	6369 Z GeV	I(B1):	1.28e+13	I(B2):	1.28e+13

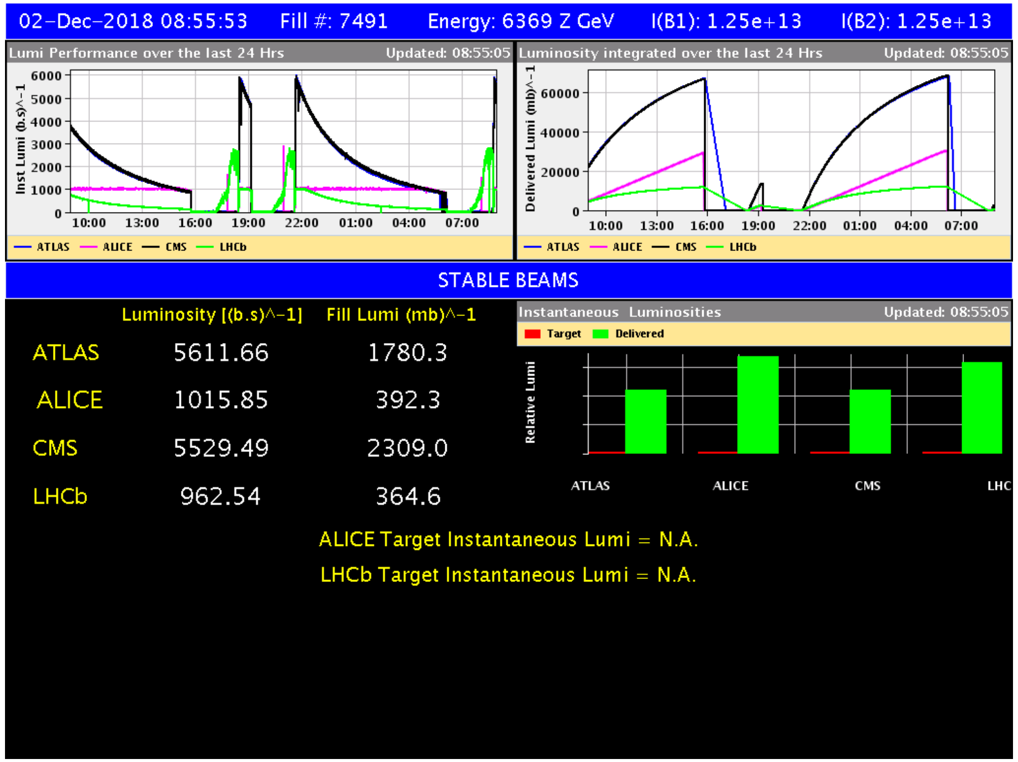
Inst. Lumi [(b.s)^-1] IP1: 3820.04 IP2: 816.98 IP5: 2745.91 IP8: 184.37

Comments (02−Dec−2018 07:32:15)

Physics with 733b

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj PM Status B1 ENABLED PM Status B2 ENABLED



02−Dec−2018 08:55:53 Fill #: 7491 Energy: 6369 Z GeV I(B1): 1.25e+13 I(B2): 1.25e+13

STABLE BEAMS

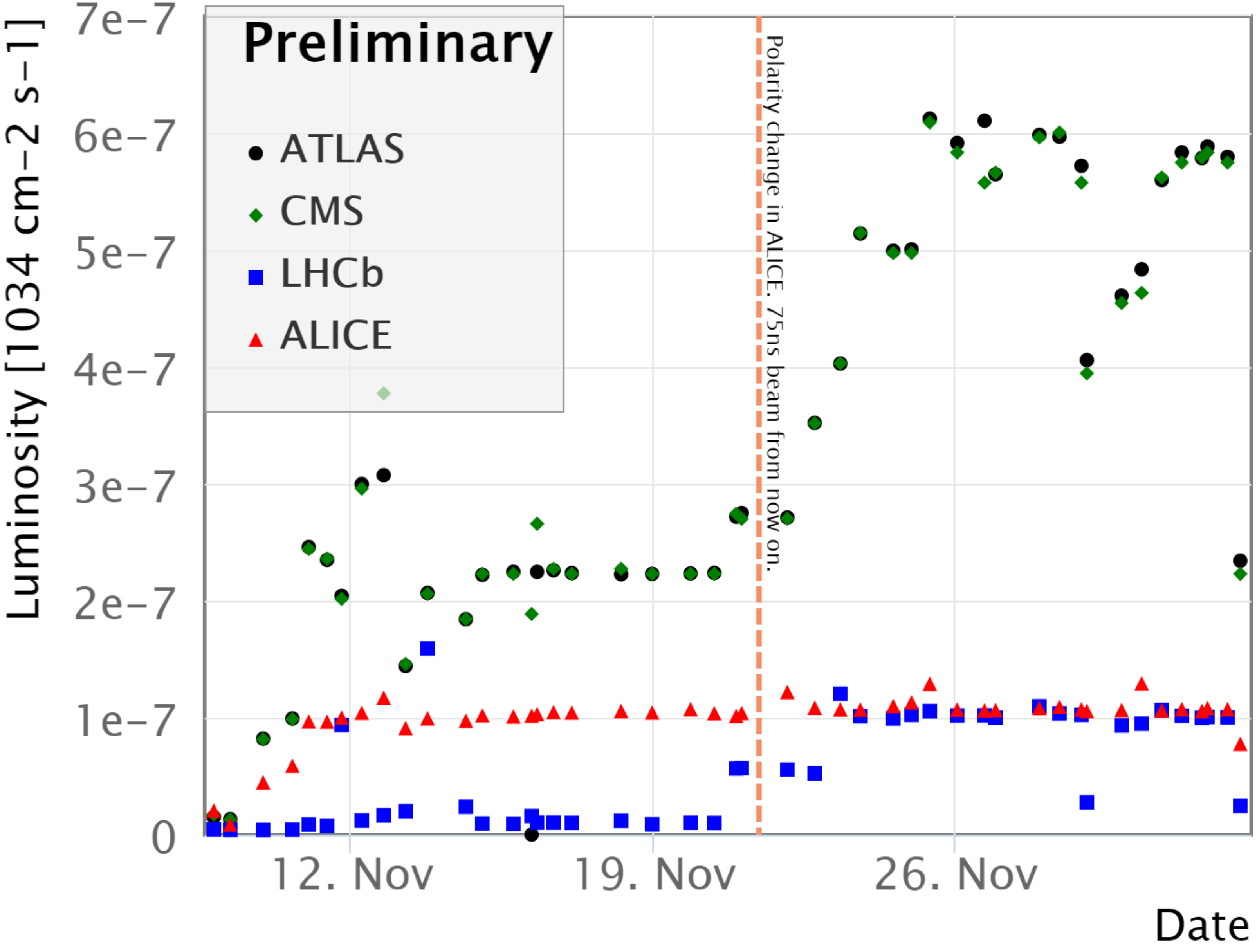
	Luminosity [(b.s)^−1]	Fill Lumi (mb)^−1
ATLAS	5611.66	1780.3
ALICE	1015.85	392.3
CMS	5529.49	2309.0
LHCb	962.54	364.6

ALICE Target Instantaneous Lumi = N.A.

LHCb Target Instantaneous Lumi = N.A.

Peak Luminosity in 'Stable Beams'

2018



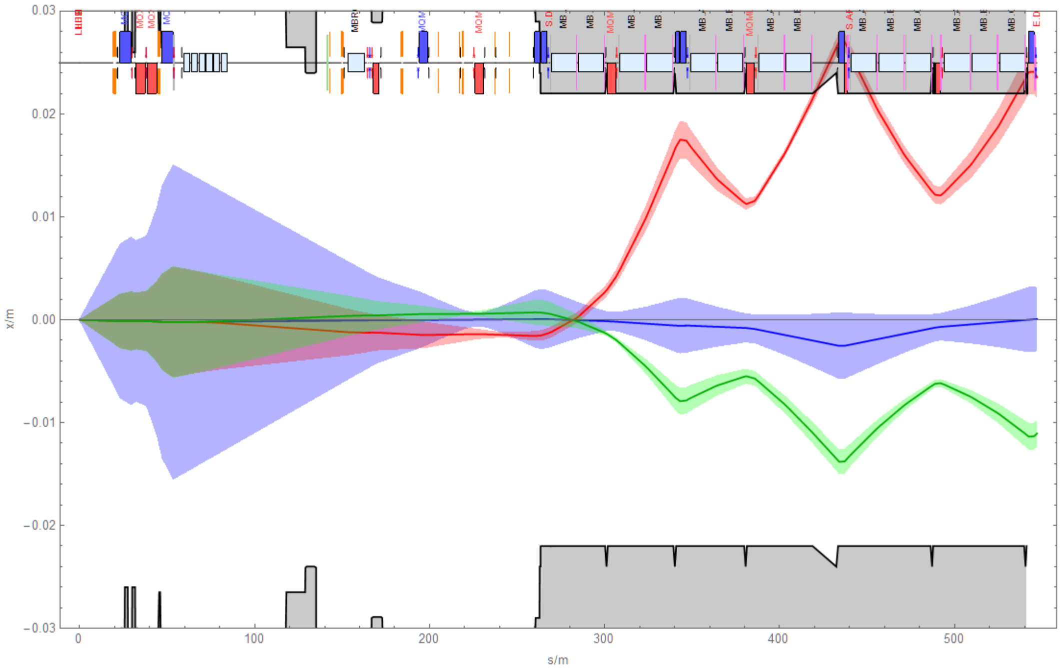
Achieved and HL-LHC/LIU baseline (2017) Parameters

	Pb-Pb (2018 achieved)	**HL-LHC request**		
Energy [TeV]	**6.37 Z**	7 Z	🔴	LS2 magnet training
Particle Charge Z	**82**	82	🟢	
β^* at IP 1/2/5/8 [m]	**0.5 / 0.5 / 0.5 / 1.5**	0.5 / 0.5 / 0.5 / ?	🟢	
Emittance [μm]	**~2.0**	1.65	🟡	
Bunch **Intensity** [10^8 ions]	**~2.3**	1.8	🟢	
No. Bunches	**733**	1232	🔴	Slip stacking
Bunch Spacing	**100ns → 75ns**	50ns	🔴	Slip stacking
Peak **Luminosity** IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	**6.4 / 1 / 6.4 / 1**	7 / 7 / 7 / ?	🟡	Luminosity levelling?

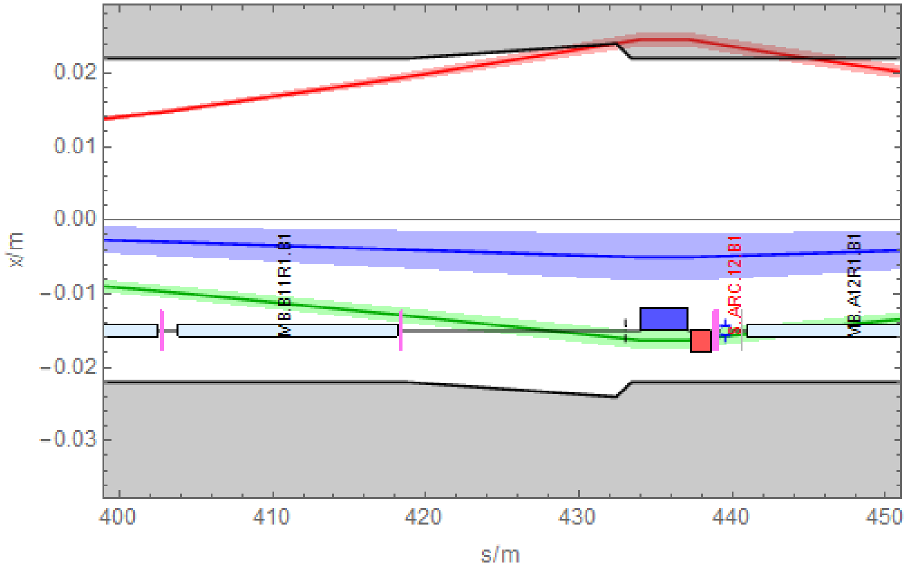
Green values are above LHC design

Some collisions in LHCb
(not considered in detail yet)

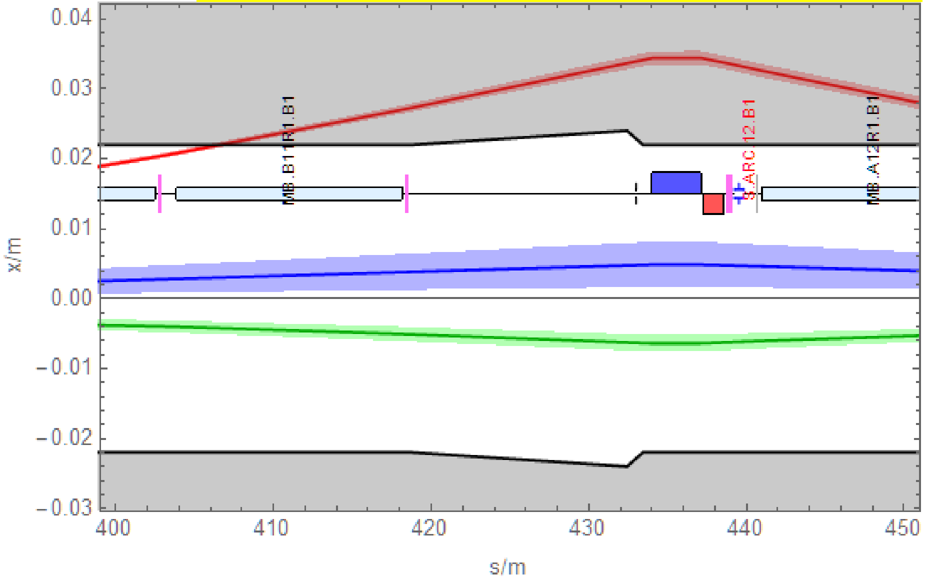
BFPP quench experiment right of ATLAS



Physics configuration with negative orbit bump moves BFPP impact point into connection cryostat – no magnet to quench.

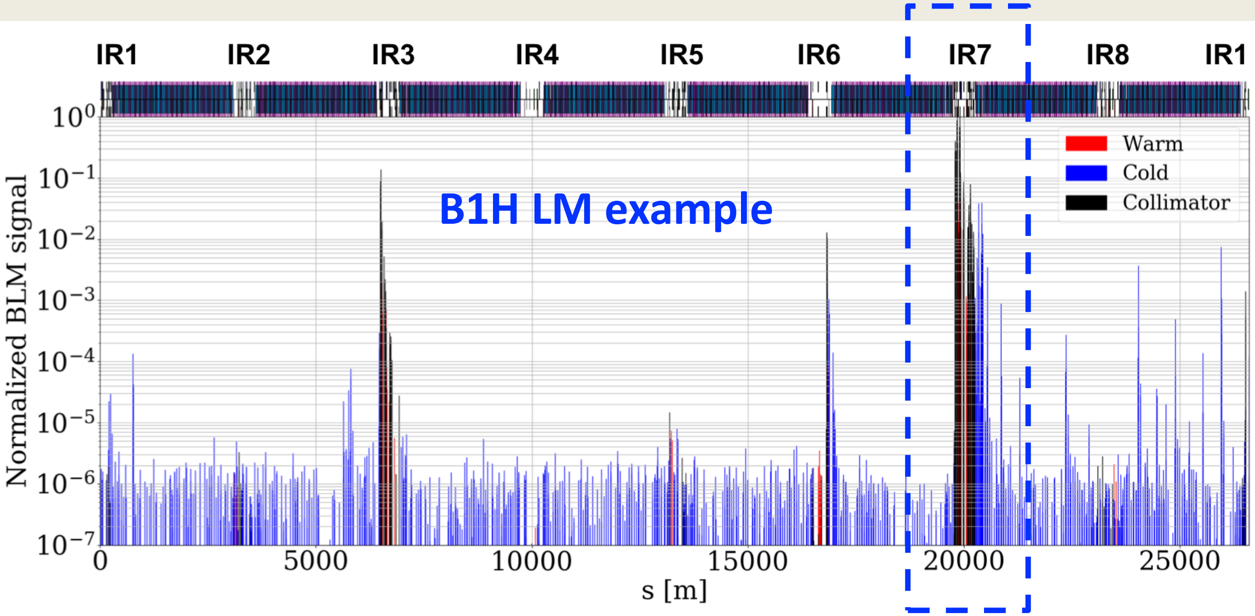


Reversing bump moves loss point into the centre of a magnet. Increase luminosity at IP until quench.



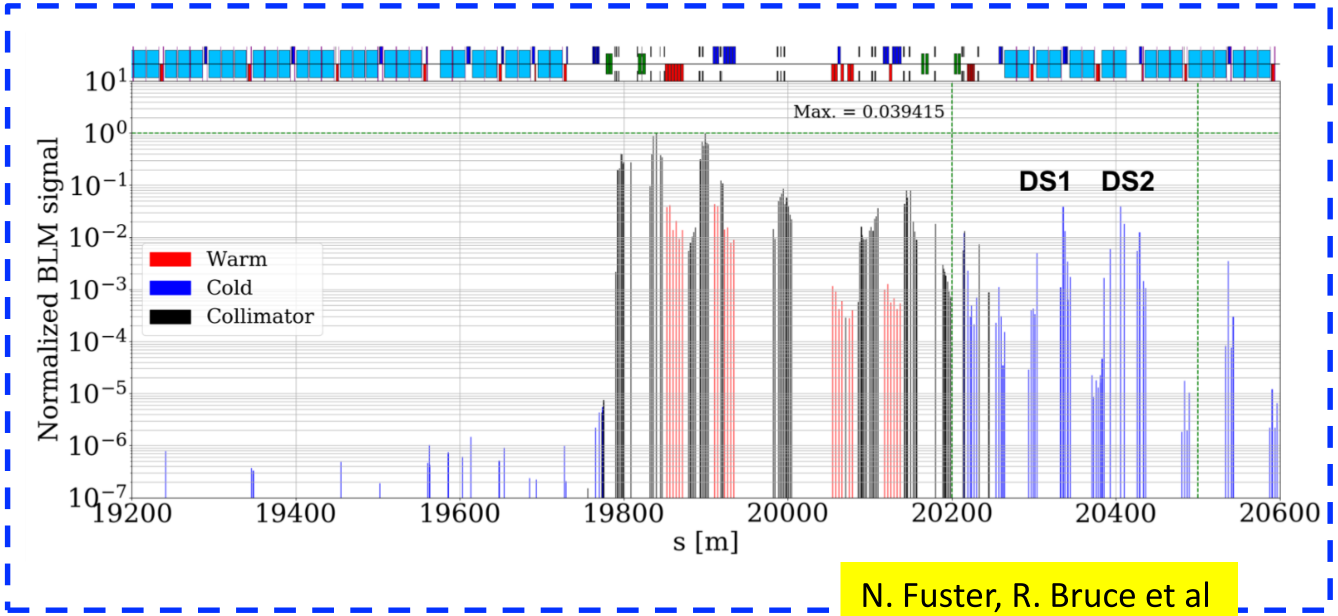
Xe 2017 collimation system cleaning measurements and simulation studies

- ☐ Betatron **cleaning measured for the two beams and planes.**
- ☐ **Observed a degradation** by more than two orders of magnitude with respect to protons on the inefficiency in the DS after the betatron cleaning insertion as well as additional loss spikes in the arcs.



Collimator settings

Collimator	Half gap [σ]	B2H [σ]
TCP/TCSP/TCLA	7	5/6.5/10
TCP/TCSP/TCLA	3	15/18/20
TCTP	1/2/5/8	9/37/9/15
TCL	1/5	out
TCSP/TCDQ	6	7.3/7.3

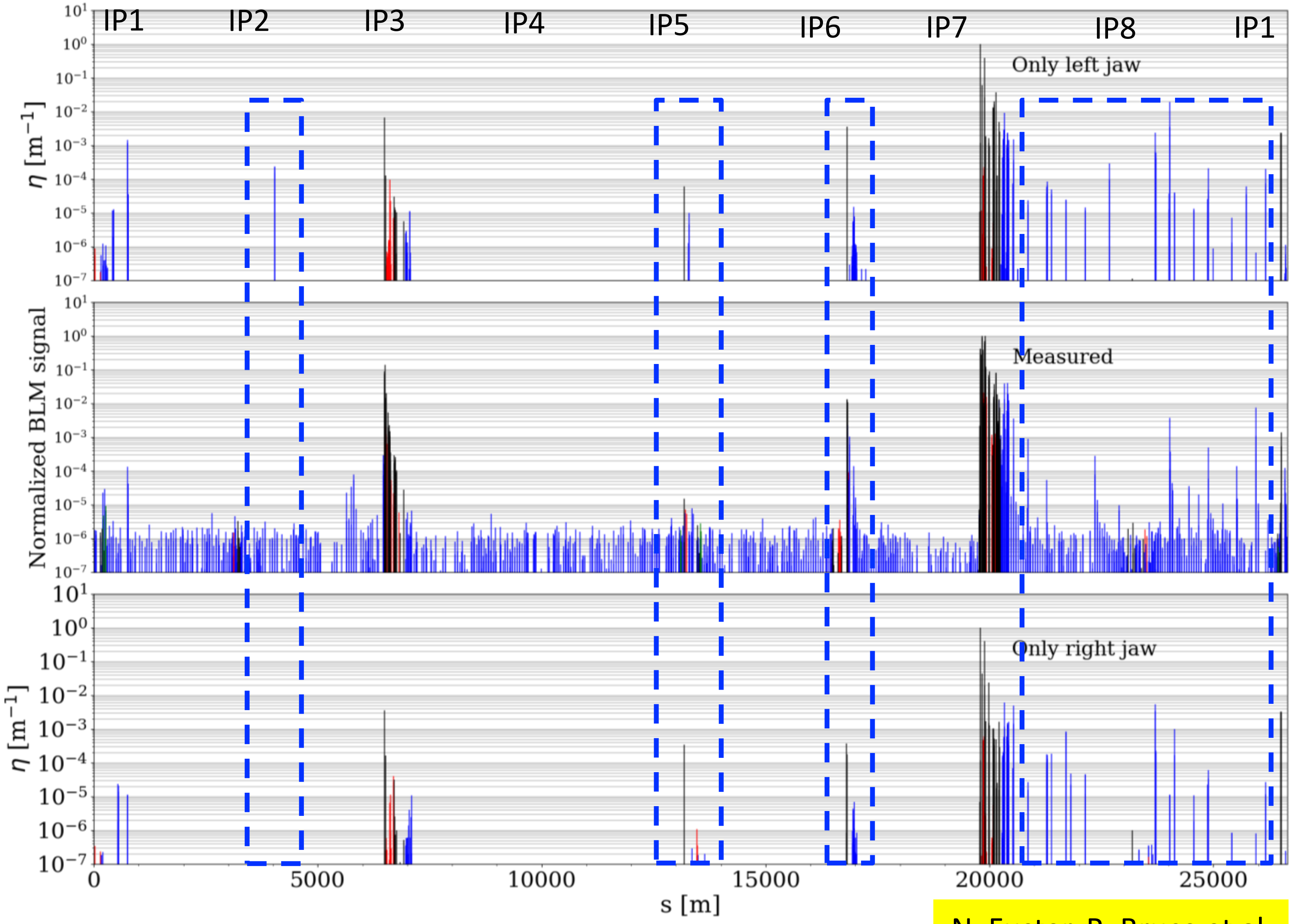


N. Fuster, R. Bruce et al

Xe 2017 collimation system cleaning measurements and simulation studies

- ☐ Simulations performed with hiSixtrack-FLUKA coupling (Thanks to FLUKA team and P. Hermes)
- ☐ Fragmentation processes at the collimators considered and secondary beam tracked all along the beamline.

- ☐ A good understanding of the agreement between simulations and measurements is crucial for determining possible future operational limitations.
- ☐ A **first comparison shows a good overall agreement** of losses along the ring, although some discrepancies are present.
- ☐ Asymmetric TCP simulations also performed.
- ☐ Simulations very sensitive to the impacting beam parameters at the TCP, CO and aperture misalignments. **Detailed studies are on going.**



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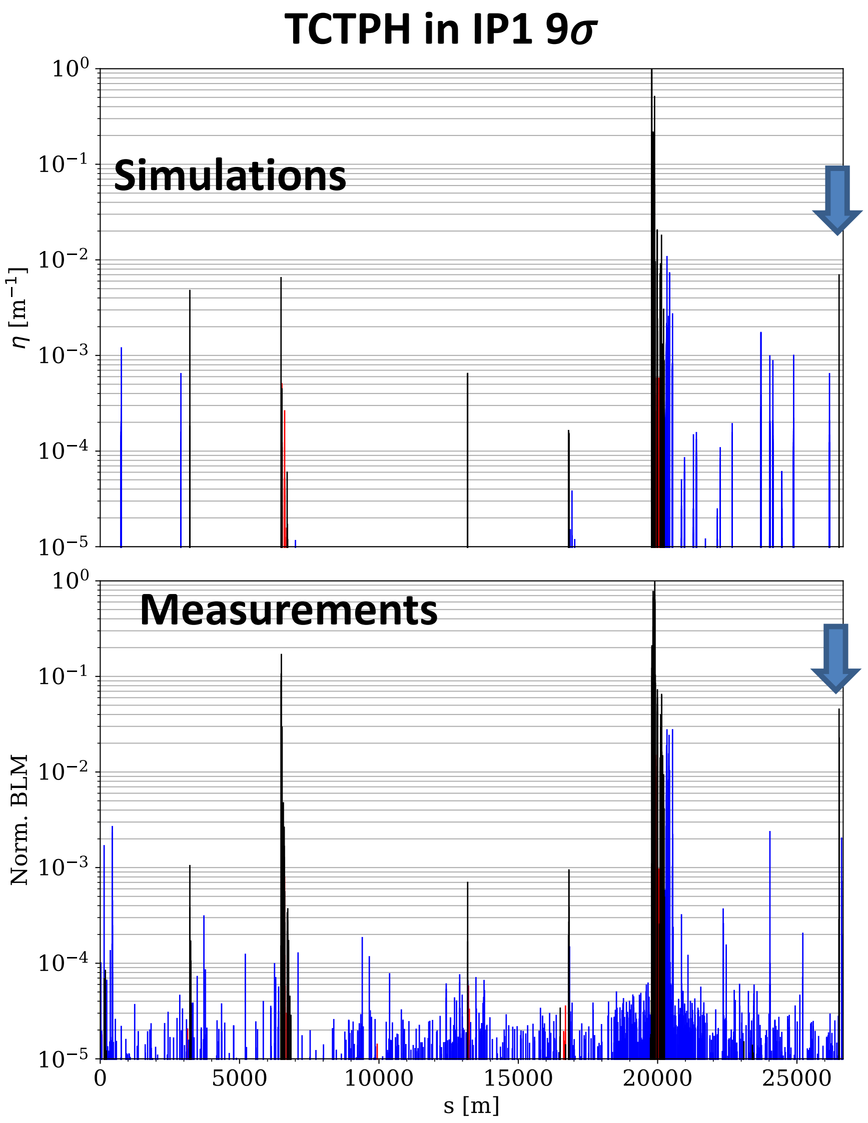
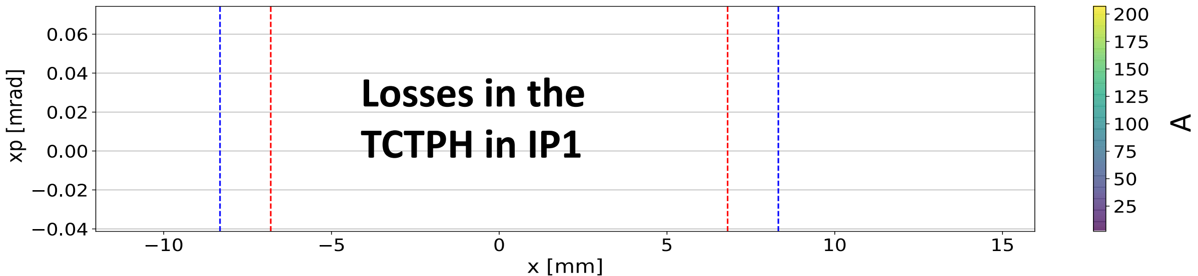
Pb 2018 collimation system cleaning measurements and simulation studies

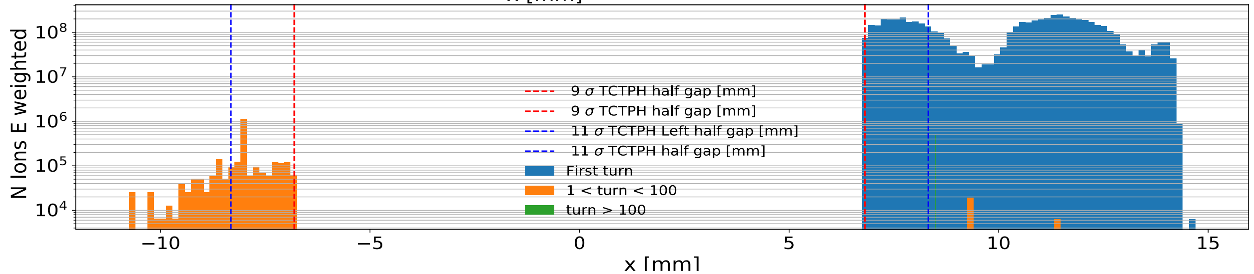
TCTPH IP6 losses study



Simulations:

- ☐ 87% of losses in the TCTPH come from the LEFT TCP jaw.
- ☐ Energy lost in the TCTPH dominated by first turn heavy-ion fragments.
- ☐ By opening the TCTPH to 11 σ the energy lost on the TCTPH in IP1 is reduced by ~30%.





Measurements:

- ☐ 50-90% reduction of BLM signal of TCTPH in IP1 with both adopted changes on the settings:
  - ☐ Asymmetric TCP settings (left TCP opened by 0.5 σ).
  - ☐ TCTPH opened to 11 σ.

Quite good understanding of where the secondary beam is deposited in the beam line but not in absolute values.

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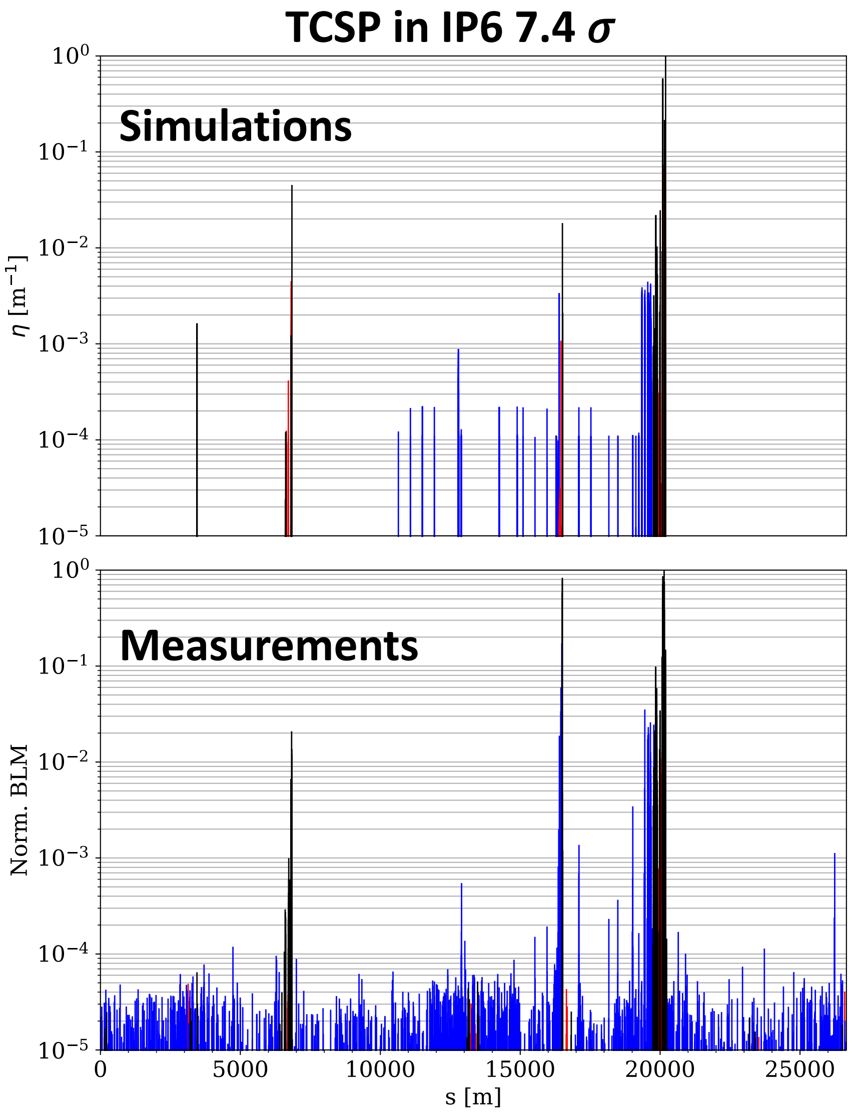
Pb 2018 collimation system cleaning measurements and simulation studies

TCSP IP6 losses study



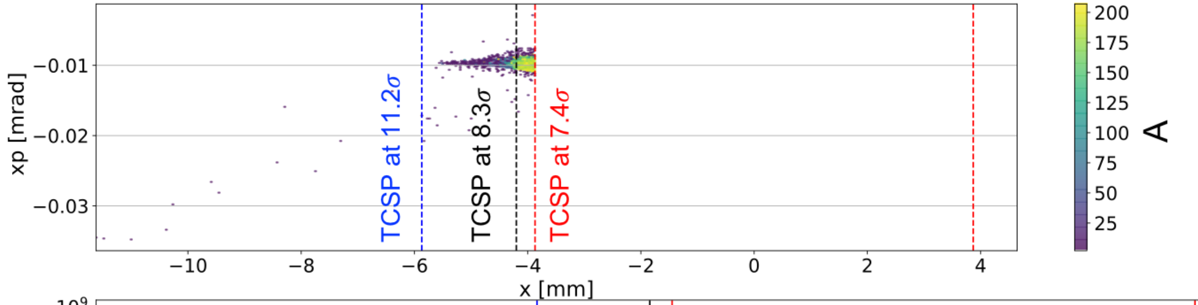
Simulations:

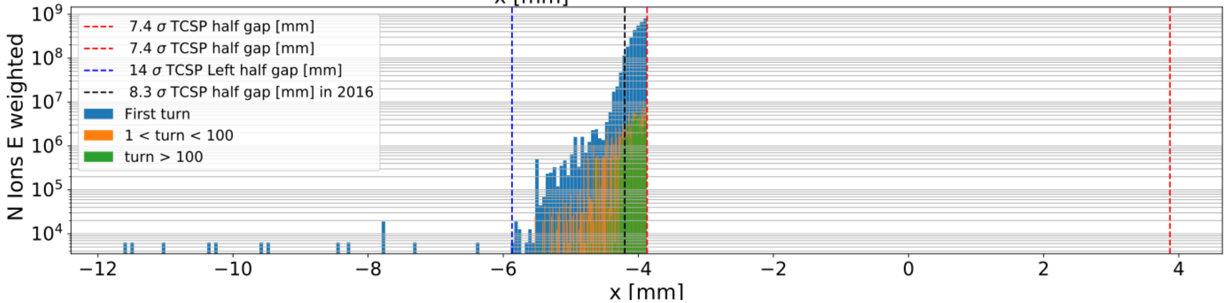
❑ Losses only observed on the right ® TCSP jaw (L jaws in the shadow of TCDQ).

❑ Dominated by first turn effect.

❑ With 2016 settings (8.3σ) we observed one order of magnitude less energy of first impacts on the R TCSP jaw.

❑ By opening the R TCSP jaw by 2 mm losses are reduced by 99.%





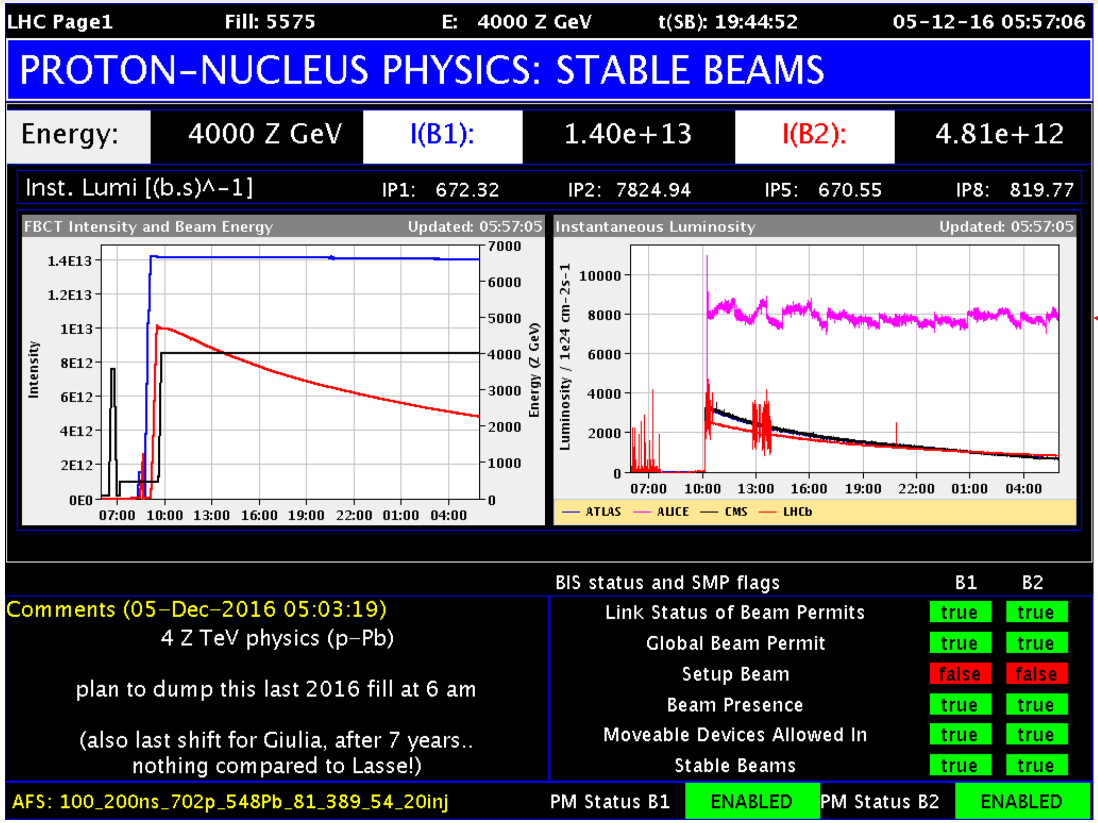
Measurements:

❑ With 2 mm (11.2 σ) opening of the R TCSP jaw the losses reduced by 98%.

Quite good understanding of where the second beam is deposited in the beam line but not in absolute values.

N. Fuster, R. Bruce et al

Last LHC fill of 2016 - back to p-Pb at 5 TeV



LHC Page1 Fill: 5575 E: 4000 Z GeV t(SB): 19:44:52 05-12-16 05:57:06

PROTON-NUCLEUS PHYSICS: STABLE BEAMS

Energy:	4000 Z GeV	I(B1):	1.40e+13	I(B2):	4.81e+12

Inst. Lumi [(b.s)^-1] IP1: 672.32 IP2: 7824.94 IP5: 670.55 IP8: 819.77

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

Comments (05-Dec-2016 05:03:19)

4 Z TeV physics (p-Pb)

plan to dump this last 2016 fill at 6 am

(also last shift for Giulia, after 7 years..
nothing compared to Lasse!)

AFS: 100_200ns_702p_548Pb_81_389_54_20inj

PM Status B1 ENABLED PM Status B2 ENABLED

Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

Levelled 19h50 in Stable Beams, dumped at 06:02 Monday 5 Dec.

Complex run made possible by extraordinary quality of LHC construction and operation, excellent performance of ALL the injectors together.

Luminosity during the whole run