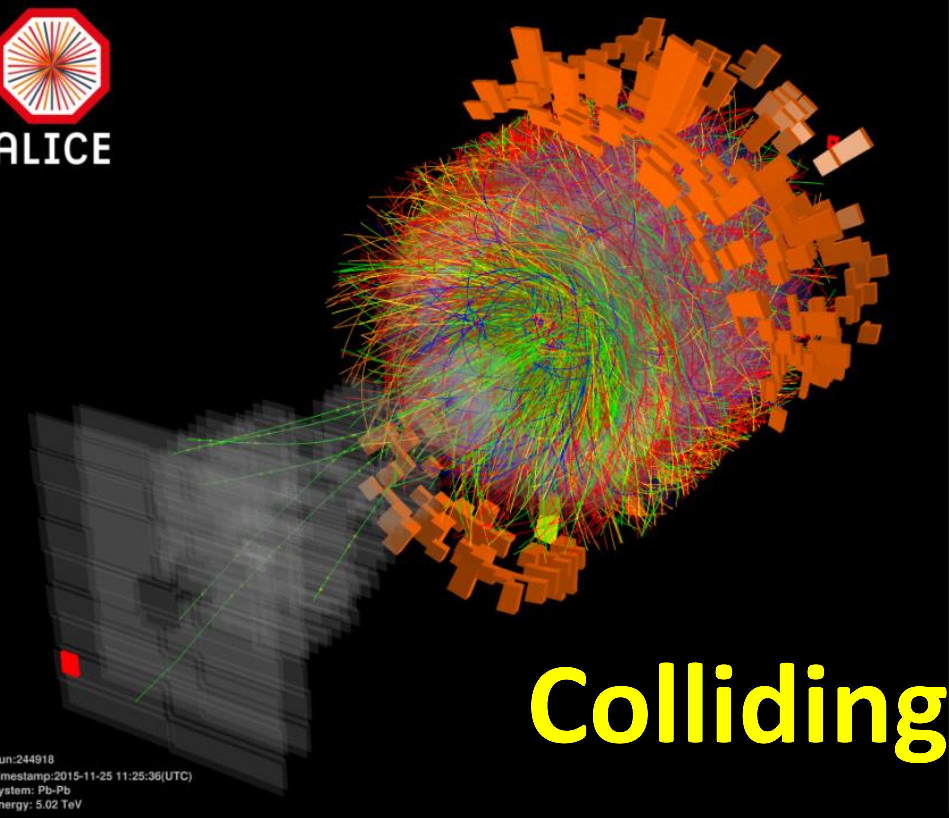
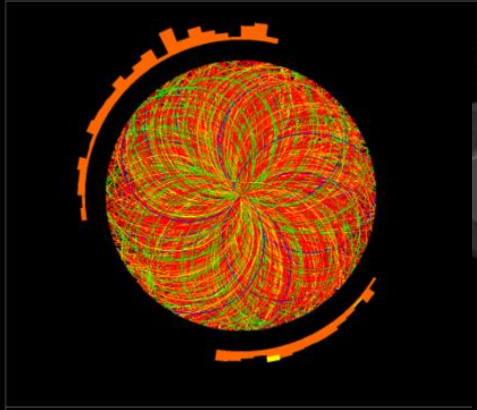
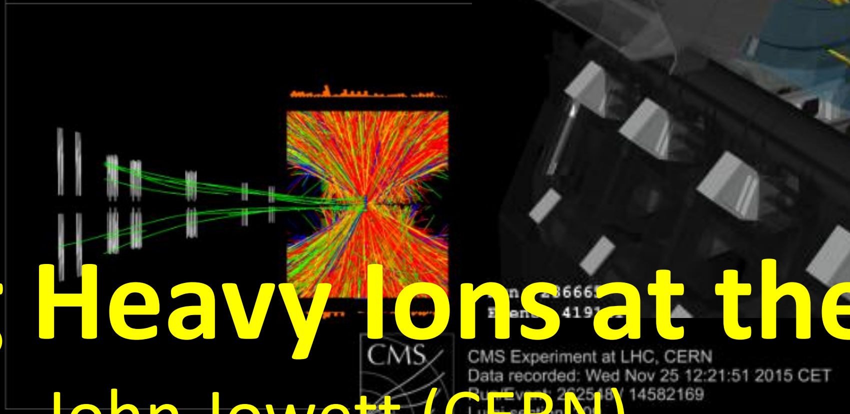
Colliding Heavy Ions at the LHC

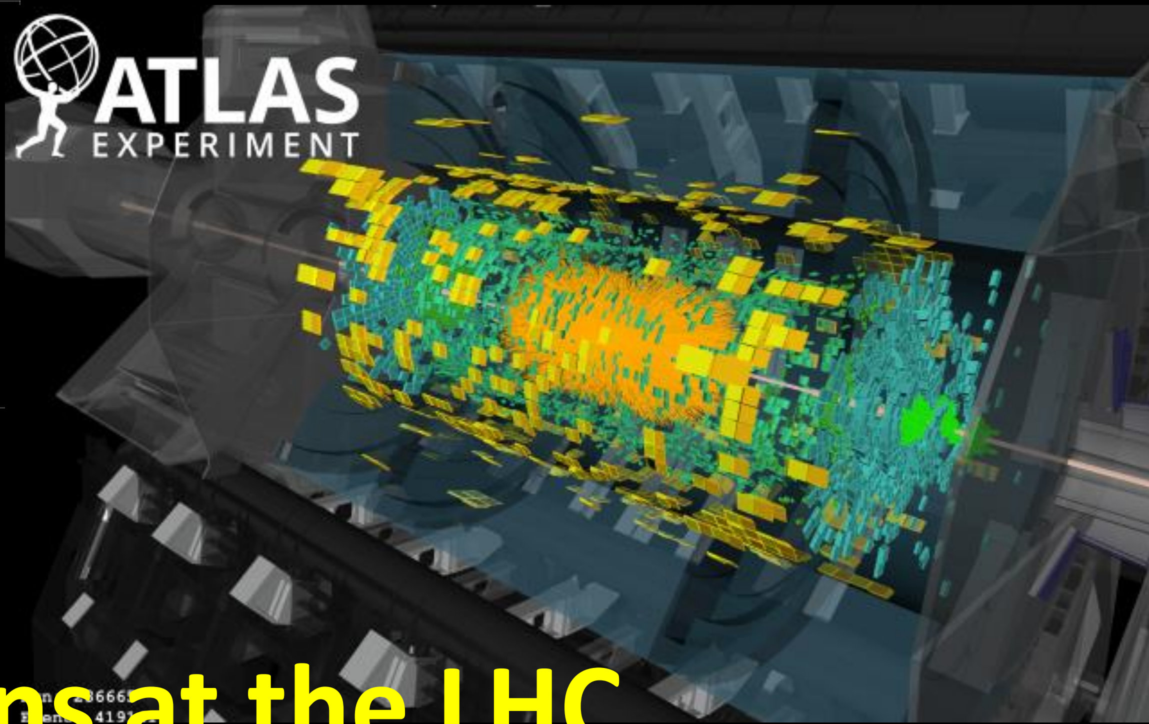
John Jowett (CERN)

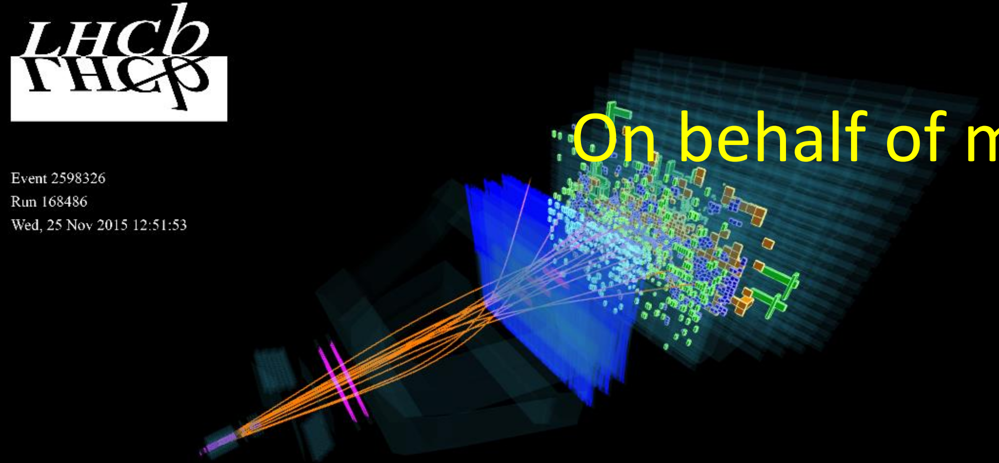
On behalf of many colleagues past and present

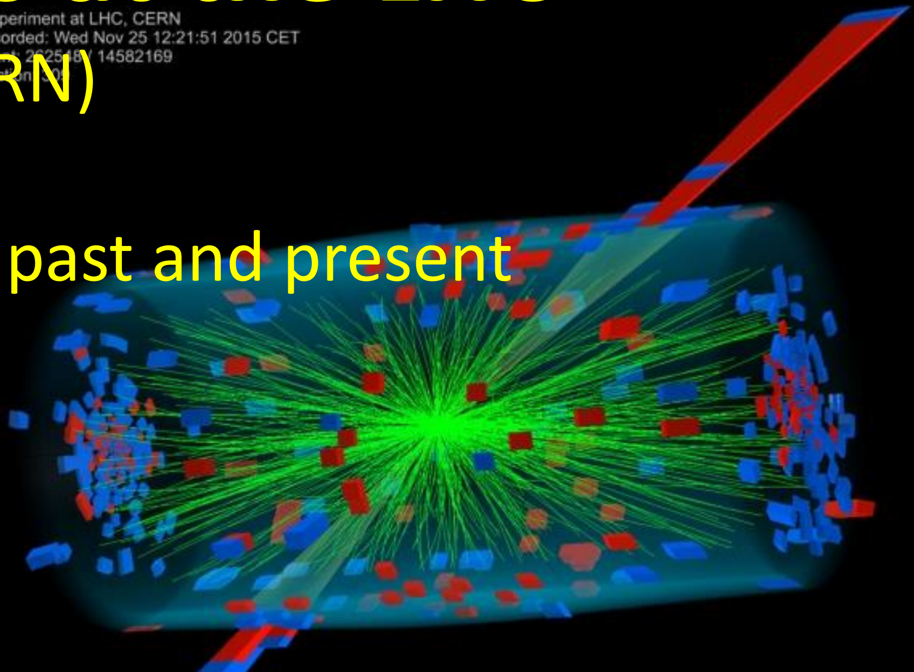












ABSTRACT

- The Large Hadron Collider at CERN not only collides protons but also heavier nuclei. So far Pb+Pb, Xe-Xe and p+Pb collisions, at multiple energies, have been provided for what was initially conceived as a distinct physics program on the collective behavior of QCD matter at extreme energy density and temperature. However unexpected phenomena observed in p+Pb and p+p collisions at equivalent energies have blurred the distinction.
- Intense, low-emittance, ion beams are provided by a dedicated source and injector chain setup.
- When Pb beams collide, new luminosity limits arise from photon-photon and photonuclear interactions but effective mitigations have allowed luminosities over 3 times design.
- Asymmetric p+Pb collisions introduce new features and beam-dynamical phenomena into operation of the LHC but have also achieved luminosity far beyond expectations.
- With experimental requirements for multiple changes in energy and data-taking configurations during very short heavy-ion runs, high operational efficiency and reliability are vital. This invited talk discusses performance, future prospects, and technical challenges for the LHC heavy ion program, including injector performance.

Hadron colliders in the 21st century

- 20th century:
  - Hadron colliders focused on elementary particle physics
  - Used beams of *most elementary* particles available: protons, anti-protons
  - Nothing heavier collided (very brief exception at CERN ISR)
- 2000:
  - RHIC collider at Brookhaven, collides first heavy ions Au+Au (*least elementary* particles to accelerate), then polarized p+p, many other species, Quark-Gluon Plasma (QGP) physics, …
- 2009-10:
  - LHC first p+p and Pb+Pb collisions …
- Now:
  - Both hadron colliders in the world have substantial heavy-ion programmes
  - All hadron collider experiments in the world study heavy-ion collisions
  - Future:
    - Electron-ion collider in USA ?
    - Heavy-ion (and p+p) collisions at HE-LHC, SppC and FCC ?

Where is the new beam physics?

- Optics etc, similar in principle (not in detail) to other beams
- Charge per bunch is usually ~10% of proton bunches
  - Impedance driven collective effects, generally not a problem
  - Traditional beam-beam effects from collective fields also weak.
  - Space charge in lower energy machines is an exception
- However charge per particle is up to two orders of magnitude higher than protons and most of the interesting beam physics of nuclear beams is due to this:
  - IBS, important but well-known
  - Synchrotron radiation damping (twice as fast as protons)
  - New beam-beam effects from ultra-peripheral nuclear collisions – see later
  - More complicated interactions with collimators

Change of operational paradigm

- A major challenge at LHC:
  - Commission new configurations and provide stable physics operation within time frame of one month
  - Experiments require multiple changes of beam conditions (intensity ramp-up, solenoid reversal, beam reversal, low/high/levelled luminosity, special beam energies, Van der Meer scans, …
  - Different from traditional collider operating paradigm of steady, incremental improvement to operating conditions with max energy and luminosity
- This can be achieved with LHC because of (my opinion):
  - Reliability and reproducibility of all systems, especially magnets
  - Thorough understanding of beam physics
  - Efficient, stable, operating procedures and software

Expectations for heavy ions at LHC

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 (
4 P–Pb runs in the 10-year periods before and af
CMS (ALICE being levelled). The smaller lum
part of the run in 2016 are not shown. Emittance
Pb-p runs are generally for Pb. The series of run
Design and record achieved nucleon-pair luminos
factor ≃ 3 from its potential value by levelling.

Quantity	"design"							
Year	(2004)							
Weeks in physics	-							
Fill no.								
Species	Pb–Pb							
Beam energy $E[Z\,\text{TeV}]$	7							
Pb beam energy E [ATeV]	2.76							
Collision energy $\sqrt{s_{\text{NN}}}$ [TeV]	5.52							
Bunch intensity N_b [10^8]	0.7							
No, of bunches k_b	592							
Pb norm. emittance ϵ_N [μm]	1.5							
Pb bunch length σ_z m	0.08							
β^* [m]	0.5							
Pb stored energy MJ/beam	3.8							
Peak lumi. L_{AA} [$10^{27}\text{cm}^{-2}\text{s}^{-1}$]	1							
NN lumi. L_{NN} [$10^{30}\text{cm}^{-2}\text{s}^{-1}$]	43							
Integrated lumi./expt. [μb^{-1}]	1000							
Int. NN lumi./expt. [nb^{-1}]	43000	21000	380	6700	6650	28000	40000	4.3×10^5

The 2004 LHC Design Report foresaw only Pb-Pb collisions in 2 experiments.

Peak luminosity and heavy-ion production in the injectors matched to the capacity of ALICE time-projection chamber (TPC) to provide a complete reconstruction of the very high-multiplicity final states.

Integrated luminosity goal of ~1 nb-1 in first 10 years.

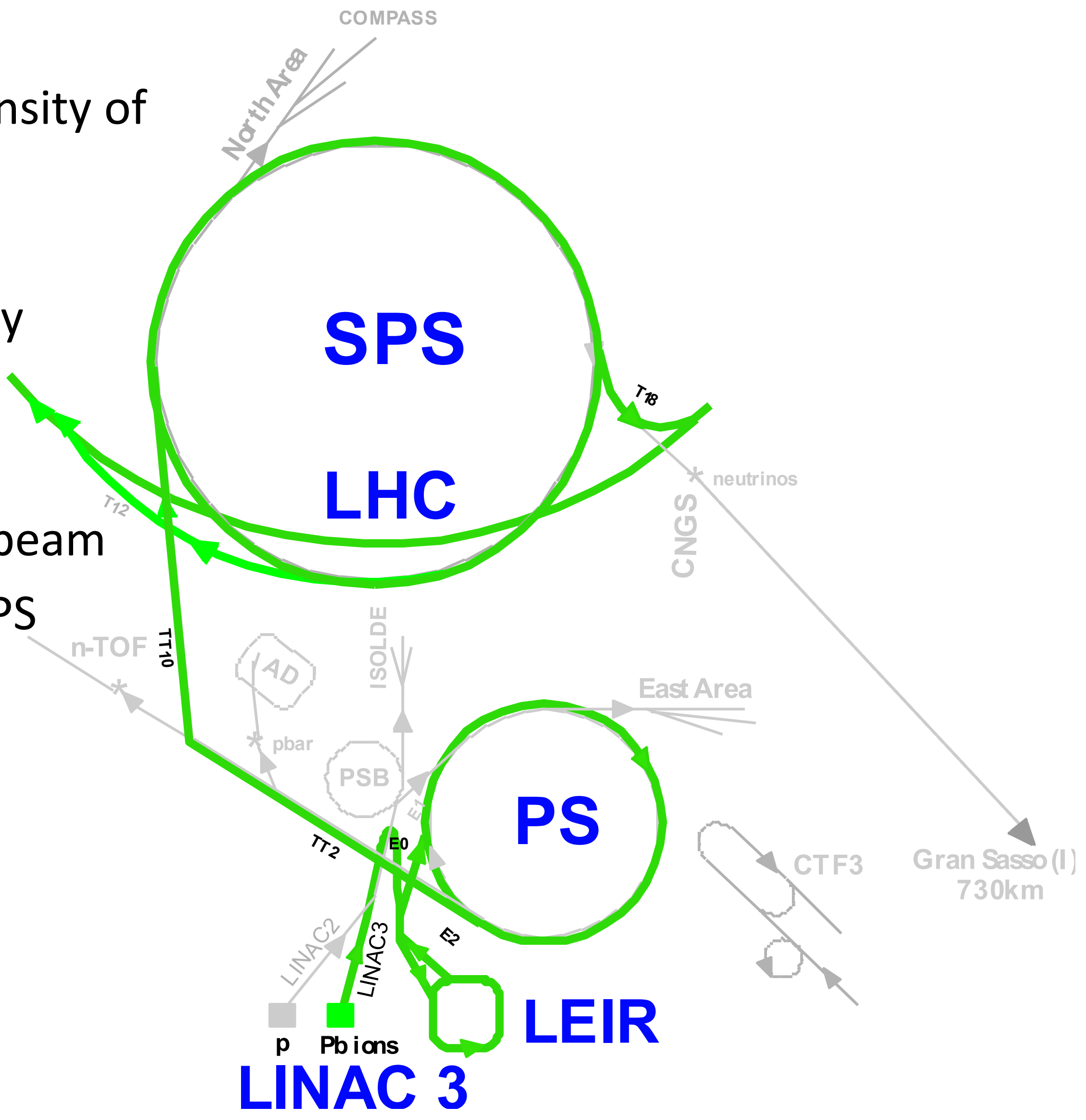
Centre-of-mass energy for nucleon pairs in collisions of ions of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p :

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},$$

HEAVY-ION INJECTORS AT CERN

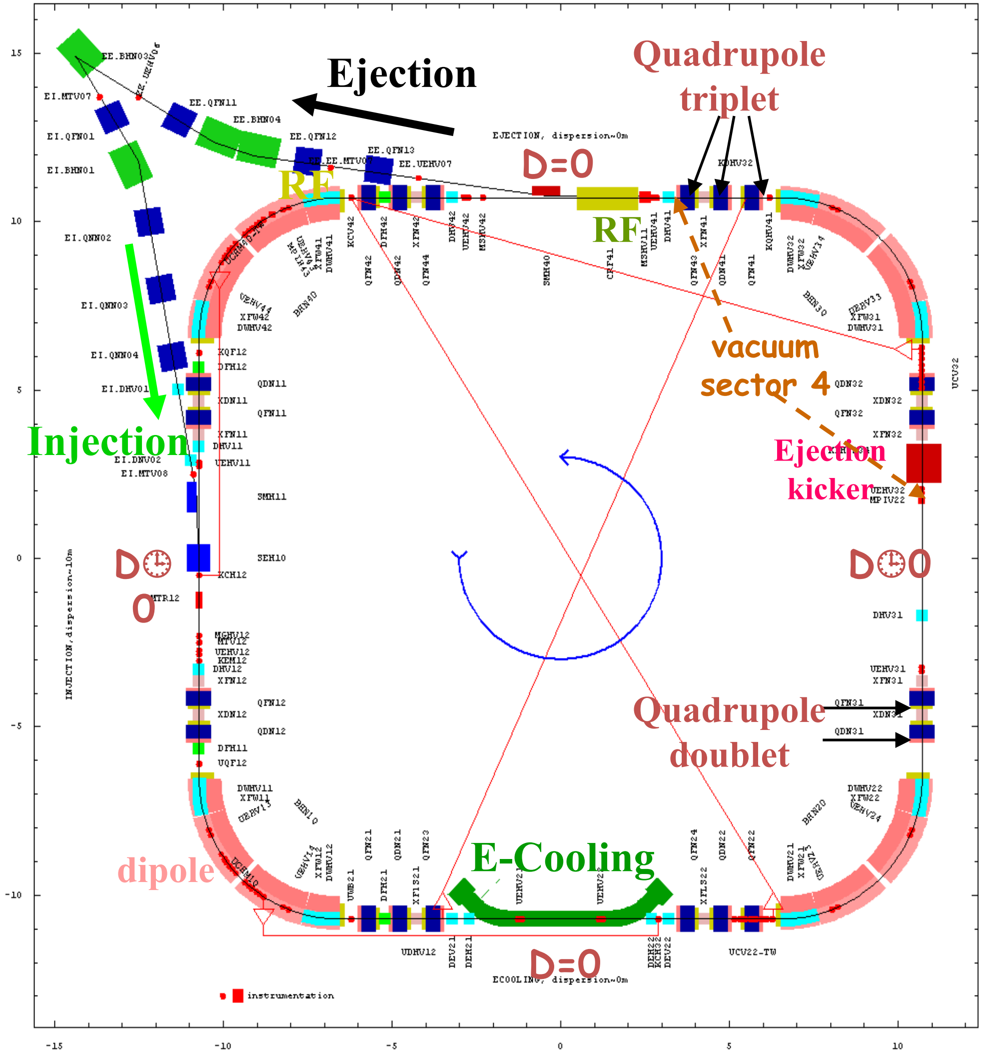
LHC Heavy Ion Injector Chain

- 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



LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- 70 turn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- RF capture
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



Major injector improvements since 2015

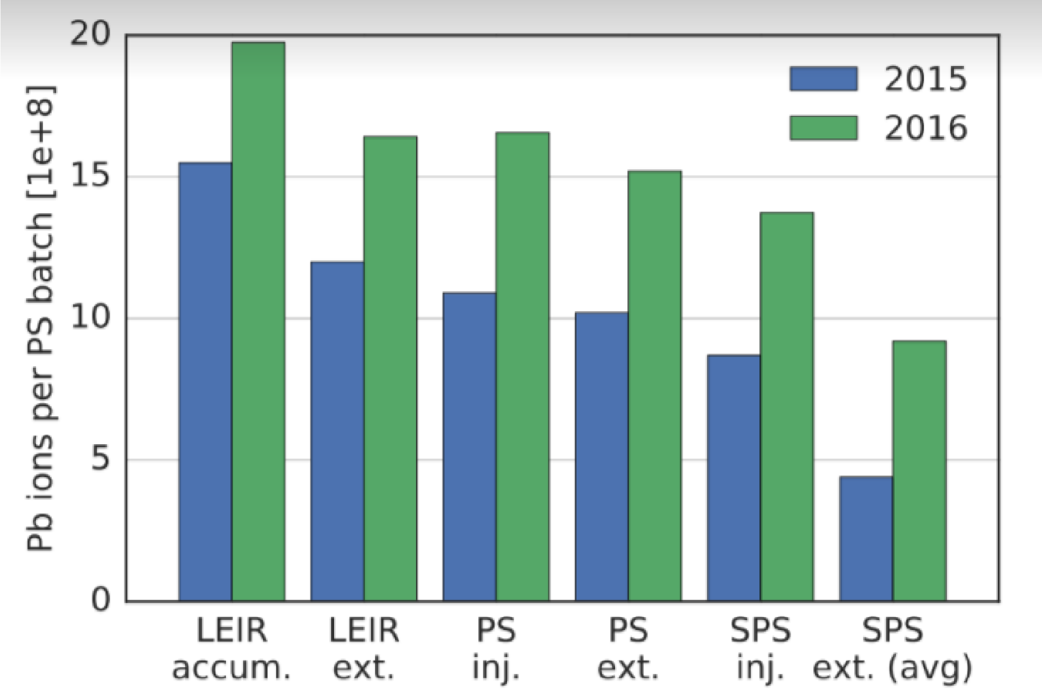


Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

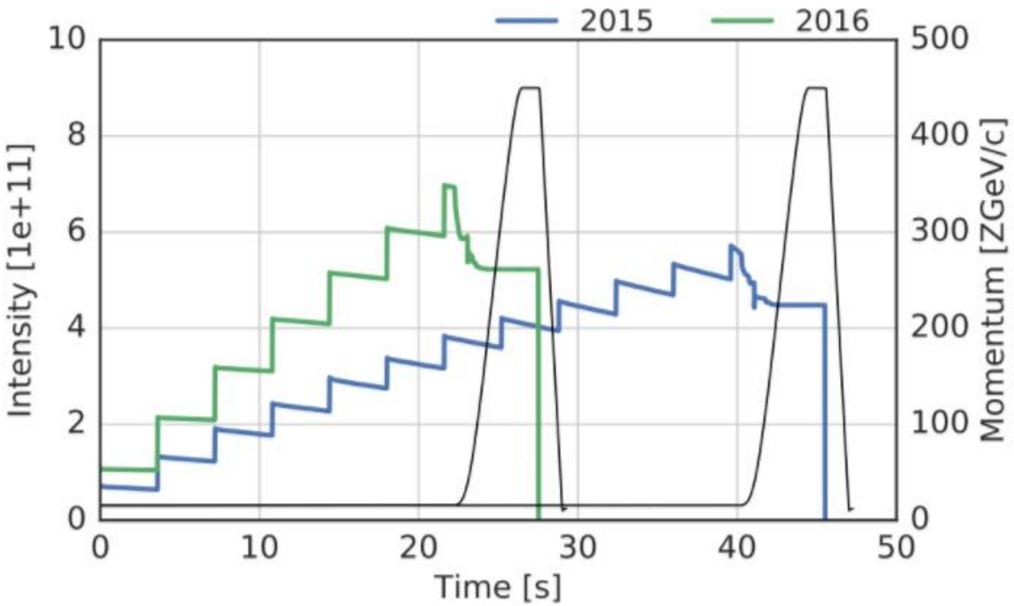
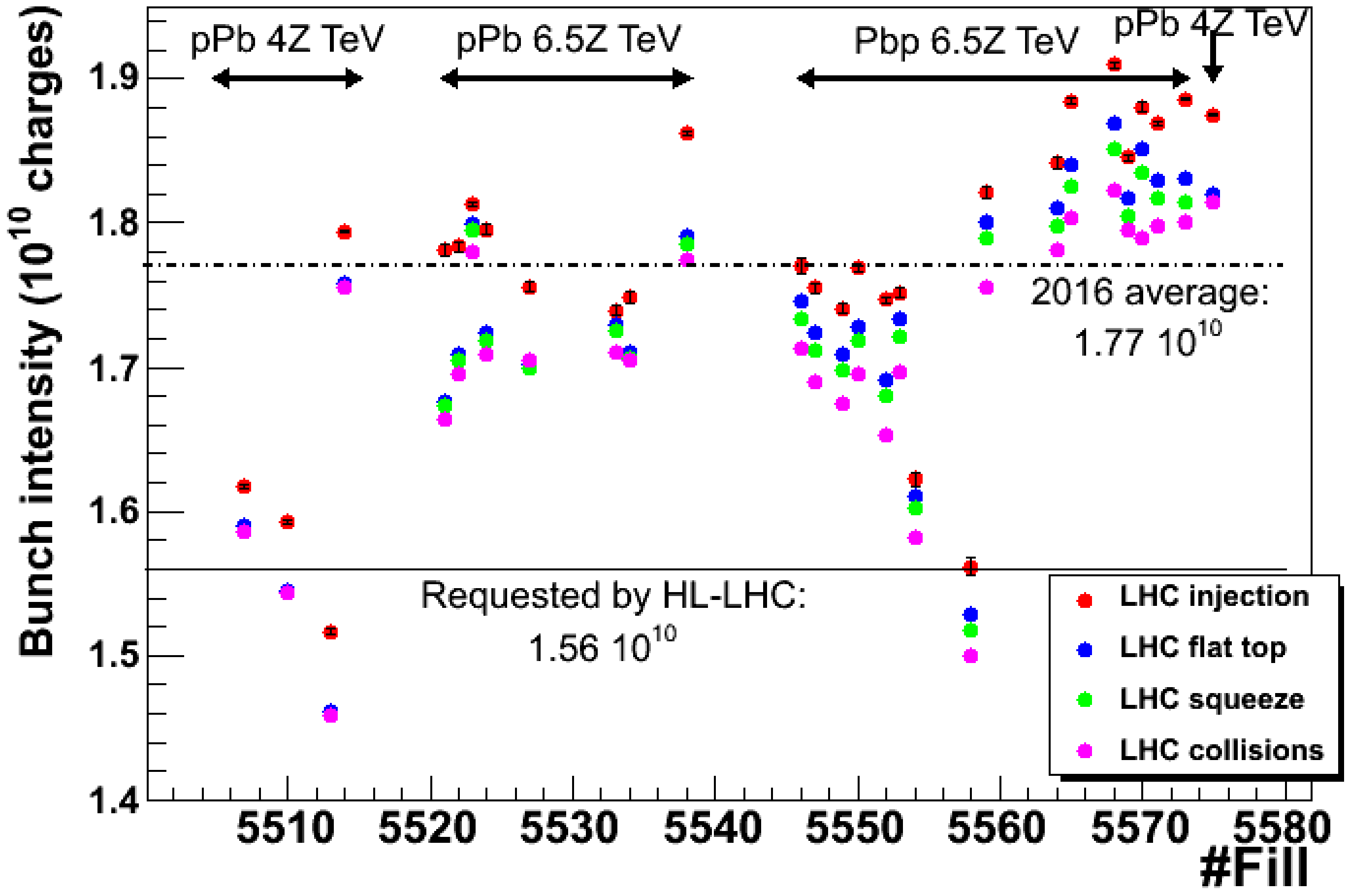


Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

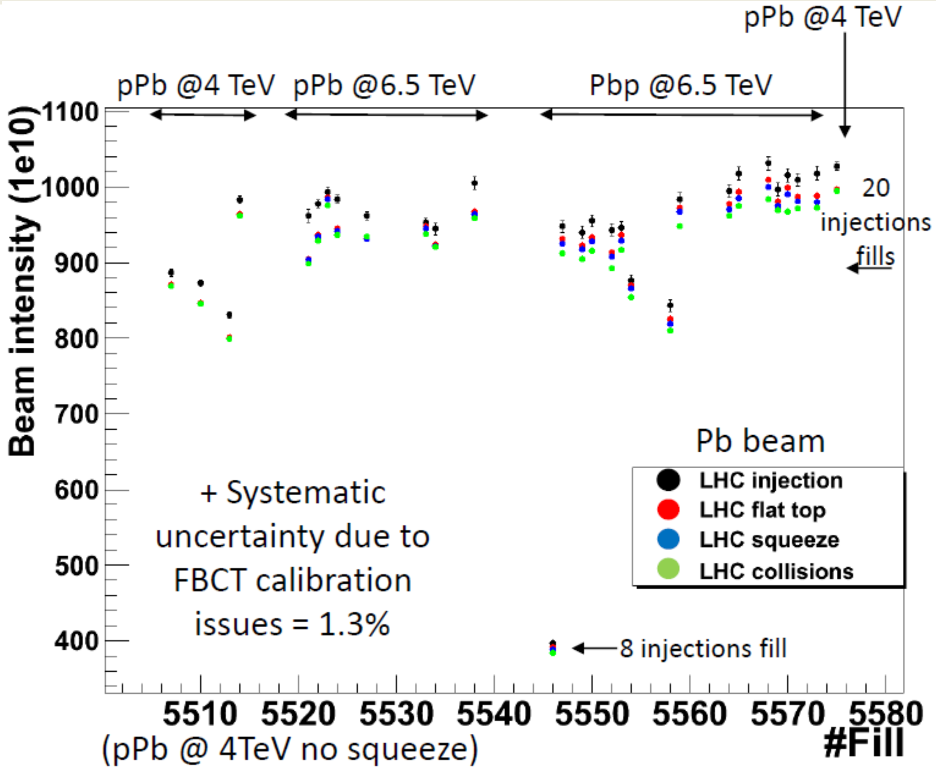
Improvements in upstream injectors allowed re-introduction of bunch-splitting in PS to stay below single-bunch limit in SPS (which remains the main intensity bottleneck).

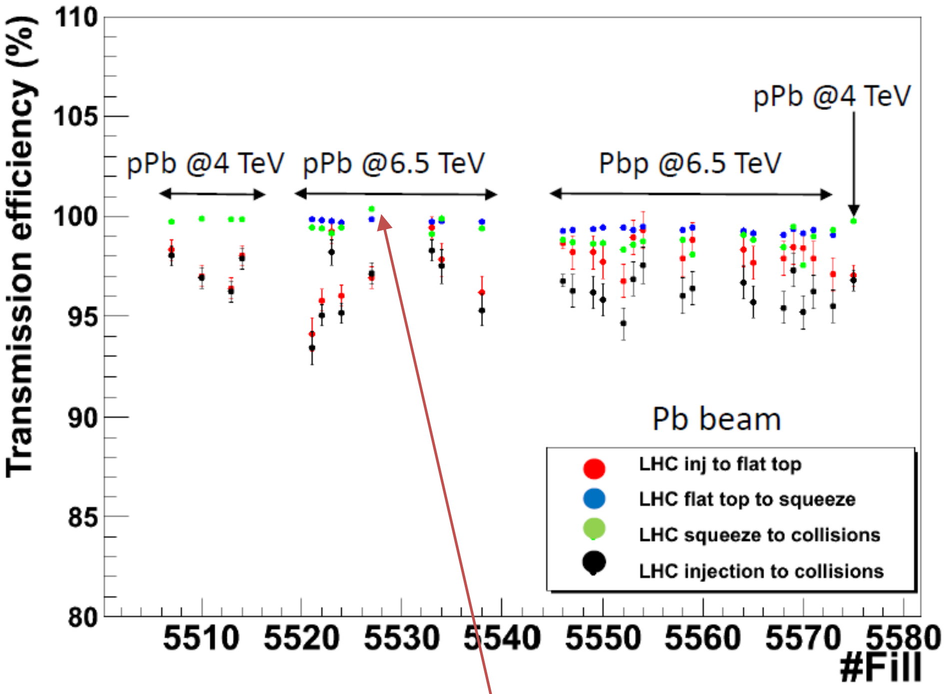
Pb bunch intensity in LHC during 2016 p-Pb run



R. Alemany, M. Schaumann

Intensity transmission: injection to collision, Pb in 2016





Data from 2016 p-Pb run, for Pb beam only.
Expect Pb-Pb to be generally better.

Previous estimates of future Pb-Pb performance assumed 90% transmission from injection to collision.

Data justify using 95% now (previously 90%).

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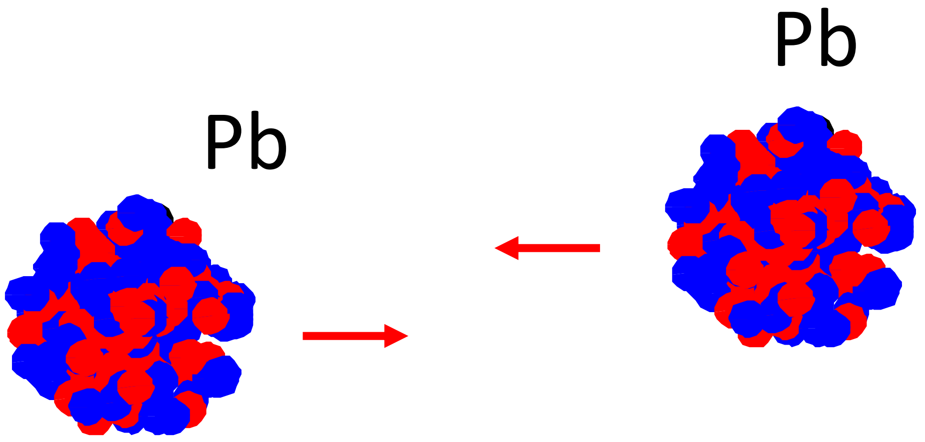
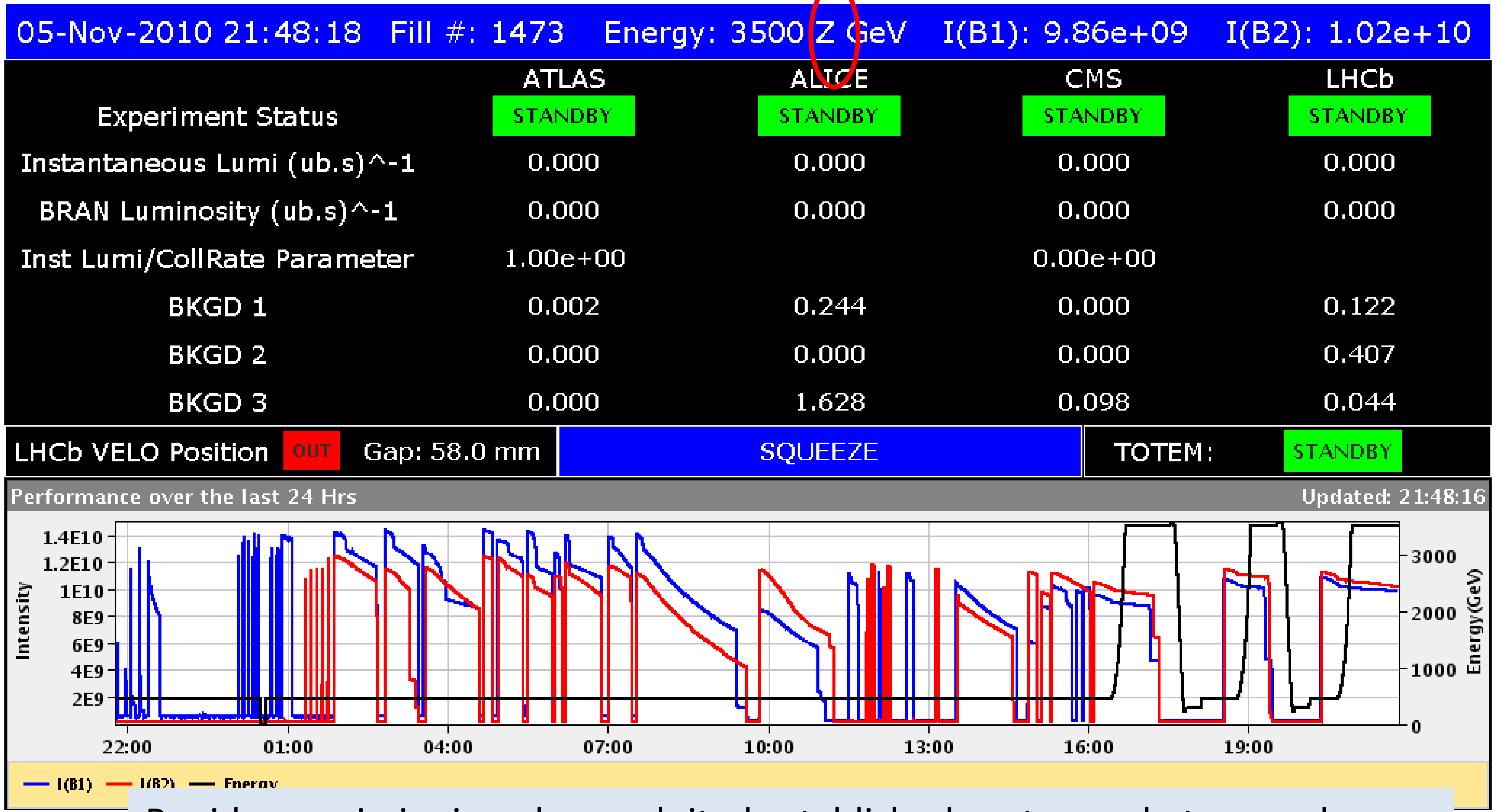
>100% due to FBCT re-calibration



NUCLEUS-NUCLEUS COLLISIONS

First Heavy Ion Run: first 24 h, Thu-Fri 4-5 Nov 2010



Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) . Collision crossing angles and collimation conditions different.

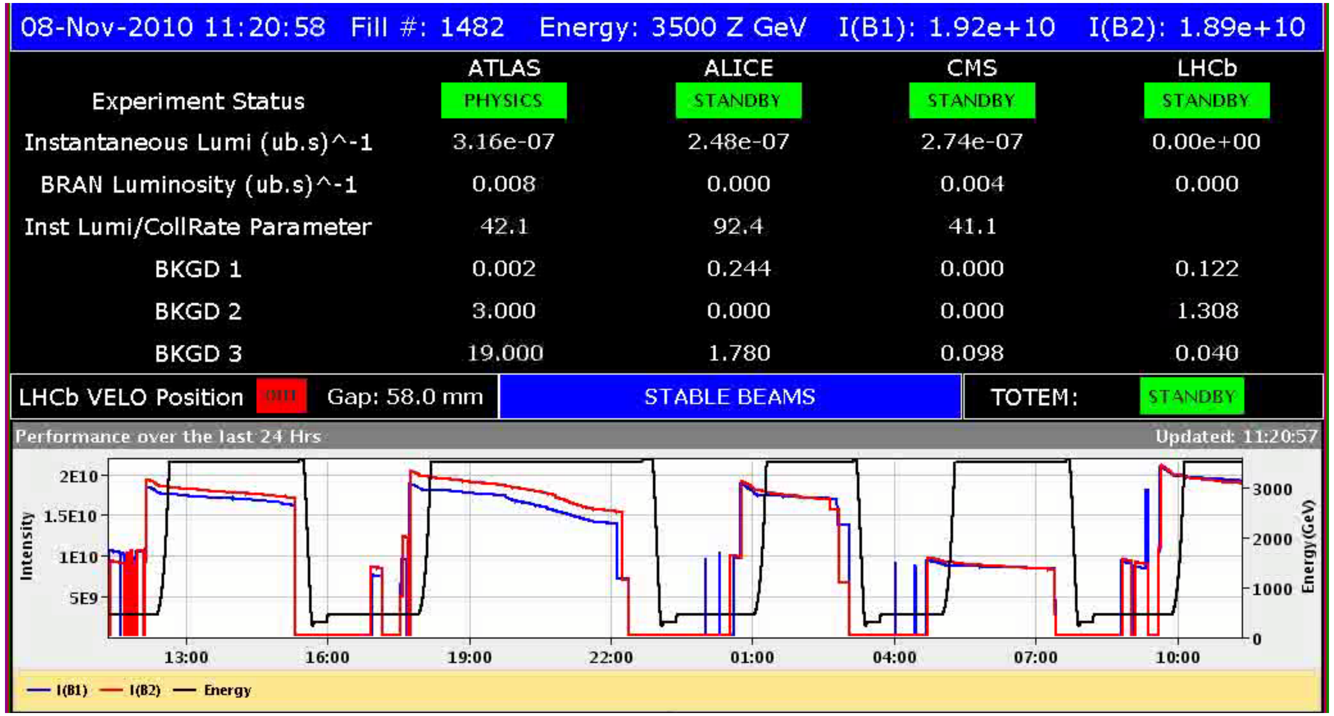
Beam 1
Circ.
& Captu

& Capture

Collimation Checks

Squeeze

Monday morning: First Stable Beams for Pb-Pb



First stable beam with 2 bunches/beam (1 colliding)

Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.

In later Pb-Pb runs, LHC optics commissioning became so efficient that we diverged more and more from the p-p optics.
In 2018, we are preparing a completely new variant of the optics.

Beam instrumentation

- Low charge/bunch was a major concern
  - BPMs intensity threshold, invisibility – no problem in the end
  - Emittance: harder than protons
    - WS: Wire scanner at low energy and intensity – best absolute calibration
    - BSRT: **synchrotron light from nuclei** appeared in first ramp in 2010 (world first!), bunch-by-bunch data can be available – typical large spread in emittance set in at injection

Pb-Pb runs in 2010 and 2011

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 for easy comparison. The upgrade value is reduced by a factor ≃ 3 from its potential value by levelling.

Quantity	"design"							
Year	(2004)		2010	2011				
Weeks in physics	-		4	3.5				
Fill no.			1541	2351				
Species	Pb–Pb		Pb–Pb	Pb–Pb				
Beam energy E[Z TeV]		7	3.5					
Pb beam energy E [ATeV]		2.76	1.38					
Collision energy $\sqrt{s_{\rm NN}}$ [TeV]	5.52		2.51					
Bunch intensity N_b [10^8]		0.7	1.22	1.07				
No, of bunches k_b	592		137	338				
Pb norm. emittance ϵ_N [μm]		1.5	2.	2.0				
Pb bunch length σ_z m		0.08						
β^* [m]		0.5	3.5	1.0				
Pb stored energy MJ/beam	3.8		0.65	1.9				
Peak lumi. $L_{\rm AA}$ [10^{27}cm^{-2}s^{-1}]	1		0.03	0.5				
NN lumi. $L_{\rm NN}$ [10^{30}cm^{-2}s^{-1}]	43		1.3	22.				
Integrated lumi./expt. [μb^{-1}]	1000		9	160				
Int. NN lumi./expt. [nb^{-1}]	43000		380	6700	6650	28000	40000	4.3×10^5

2010 run: optics almost identical to preceding p-p, fast commissioning

2011 run: additional squeeze of β* in ALICE
Spread in bunch intensity and emittance along trains from SPS

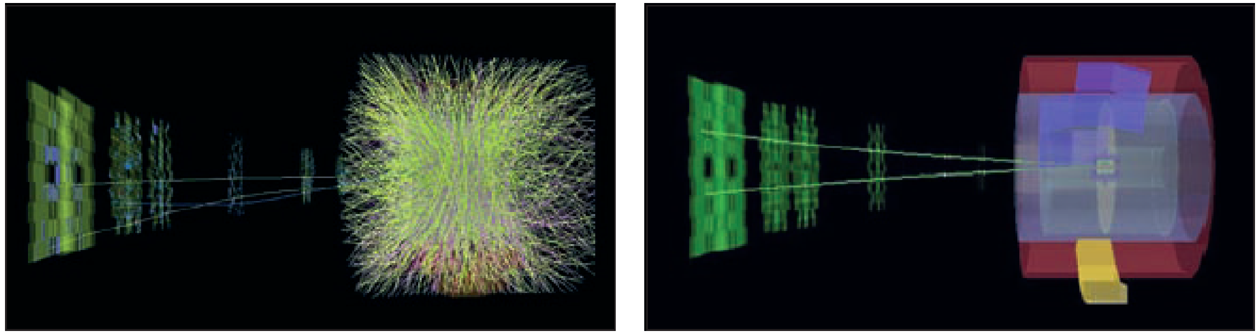
Pb-Pb collisions produce both the messiest (high-multiplicity) and the cleanest events at the LHC.

Using the LHC as a photon collider

ALICE

The protons and nuclei accelerated by the LHC are surrounded by strong electric and magnetic fields. These fields can be treated as an equivalent flux of photons, making the LHC the world's most powerful collider not only for protons and lead ions but also for photon–photon and photon–hadron collisions (*CERN Courier* October 2007). This is particularly so for beams of multiply charged heavy-ions, where the number of photons is enhanced by almost four orders of magnitude compared with the singly charged protons (the photon flux is proportional to the square of the ion charge).

The ALICE collaboration has recently taken advantage of this effect in a study of coherent photoproduction of J/ψ mesons in lead–lead (PbPb) collisions. The J/ψ is detected through its dimuon decay in the muon arm of the ALICE detector, which also provides the trigger for these events. The relevant collisions typically occur at impact



J/ψ candidates in a central PbPb collision (left) and in an ultra-peripheral collision (right).

events (see figure) stands in sharp contrast to central heavy-ion collisions, where thousands of particles are produced.

These interactions carry an interesting message about the partonic substructure of heavy nuclei. Exclusive photoproduction of heavy vector mesons is believed to be a good probe of the nuclear gluon distribution. The cross-section measured in a heavy-ion collision Pb+Pb → Pb+Pb+J/ψ is a convolution of the equivalent photon spectrum with the photonuclear cross-section for γ+Pb → J/ψ+Pb. The latter exchange of two gluons.

At the rapidities (y around 3) studied in ALICE, J/ψ photoproduction is sensitive mainly to the gluon distribution at values of Bjorken-x of about 10^{-2}. Although the experimental error is rather large, the conclusion from ALICE is that the data favour models that include strong modifications to the nuclear gluon distribution, known as nuclear shadowing.

Further reading

B Abelev *et al.* (ALICE collaboration) 2012

Concern about Pb-Pb at LHC

N·H
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 459 (2001) 51–57
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.nl/locate/nima

Localized beampipe heating due to e$^-$ capture and nuclear

Lawrence Be

Received

Abstract

At heavy ion colliders, two
one of the nuclei, and photon
mass ratio by well-defined a
their energy in a localized reg
collider optics. For medium
more than an order of mag
inadequate. The altered-rigid
and used for fixed target exp

PACS: 29.20.-c; 07.89. + b; 25.2

Keywords: Ion colliders; Beam

At RHIC, the local heating due to altered-rigidity beams is within the available cooling capacity. At the LHC, these altered rigidity beams have higher powers, up to 36 W. At the same time, the target regions are shorter than at RHIC, and the cooling capacities are somewhat lower, because the LHC uses supercooled magnets. With niobium beams, the expected heating is 3.2 W/m, 16 times the expected beam heat load of 0.2 W/m. For lead, the 'standard' ion choice, the heating is 2.6 W/m, 13 times the expected load.

These loads are close to the expected quench limit of 8 W/m. When the detailed distribution of energy deposition is considered, electron capture from either lead or niobium beams might deposit enough energy to cause a magnet quench. With GDR, the heat loads are lower, but may be problematic for niobium and calcium beams.

These estimates are based on back-of-the-envelope calculations; the uncertainties are correspond-

Pointed out that UPC processes not only affected beam lifetime (as was already known) but created losses from collisions that could potentially quench superconducting magnets.

Used available estimates of LHC dipole magnet quench limits (via B. Jeanneret) that indicated the heating of the magnet coil would exceed available cooling.

No proper model of beam optics (just a uniform field), angles of incidence, shower calculations, etc.

We added that from 2003 onwards (see references).

Photon-photon processes at the collision point

$$\text{BFPP: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281 \text{ b}, \quad \delta = 0.01235$$

$$\text{EMD1: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n,$$
$$\sigma = 96 \text{ b}, \quad \delta = -0.00485$$

$$\text{EMD2: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n,$$
$$\sigma = 29 \text{ b}, \quad \delta = -0.00970$$

Strong luminosity burn-off of beam intensity.

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

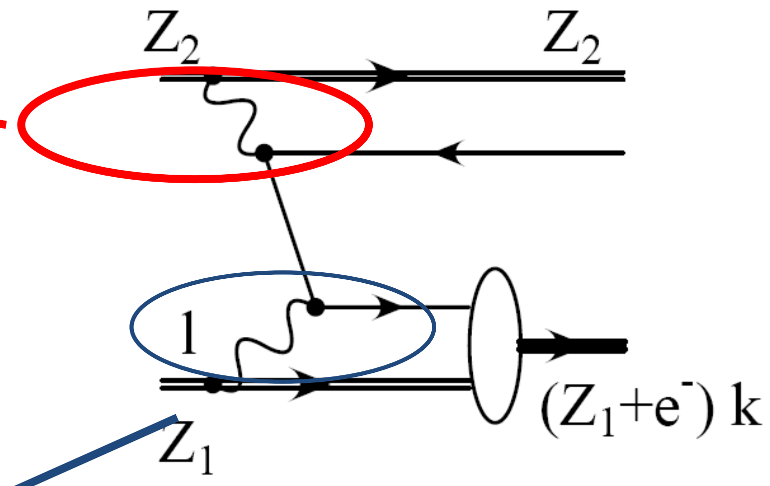
$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Discussed for LHC since Chamonix 2003 … see several references.

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

Pb-Pb BFPP cross-section (heuristic)

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



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

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

$$\Rightarrow \quad \Psi(0) \sim Z_1^{\ 3/2} \quad \Rightarrow \quad |\Psi(0)|^2 \sim Z_1^{\ 3}$$

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

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

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

has very strong dependence on ion charges (and energy)

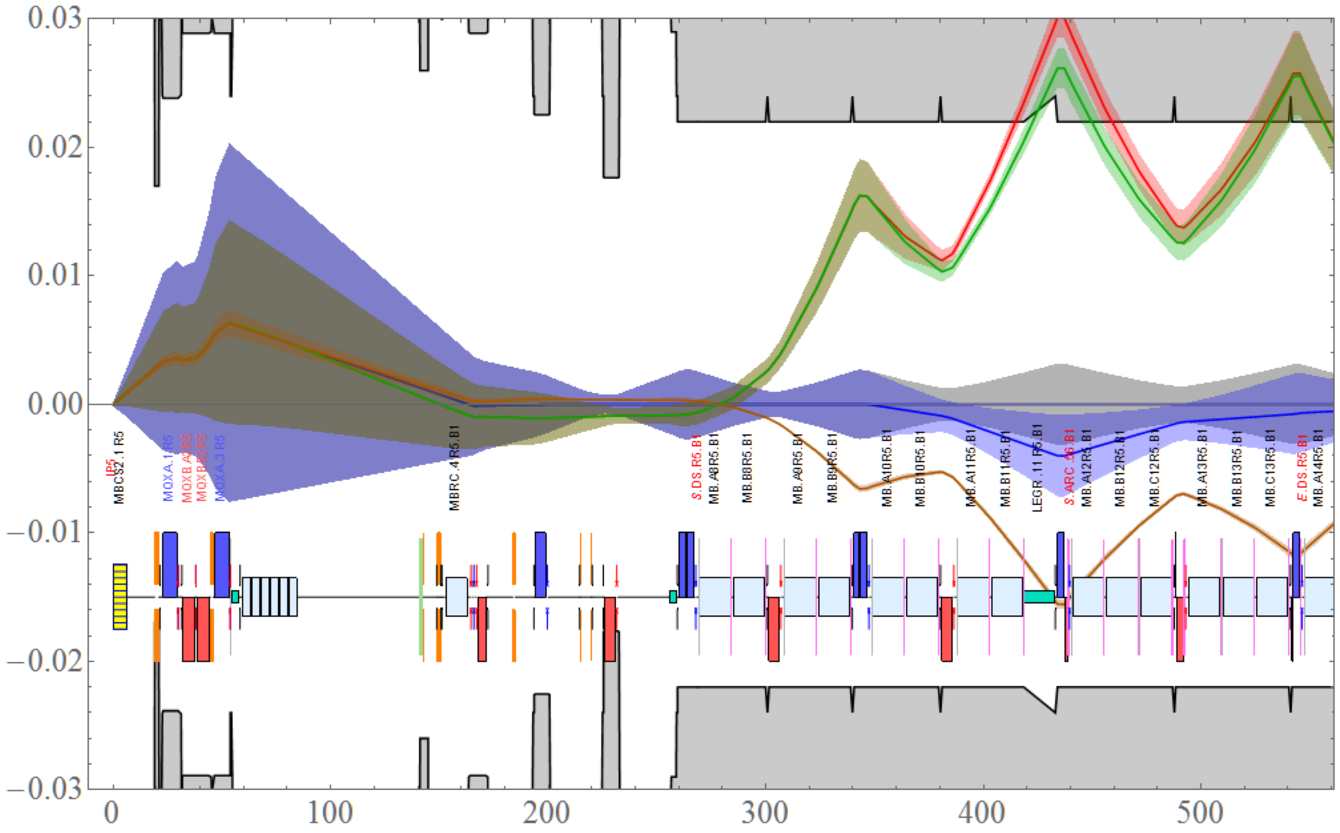
$$\sigma_{PP} \propto Z_1^{\ 5} Z_2^{\ 2} \left[A \log \gamma_{CM} + B\right]$$

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

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

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

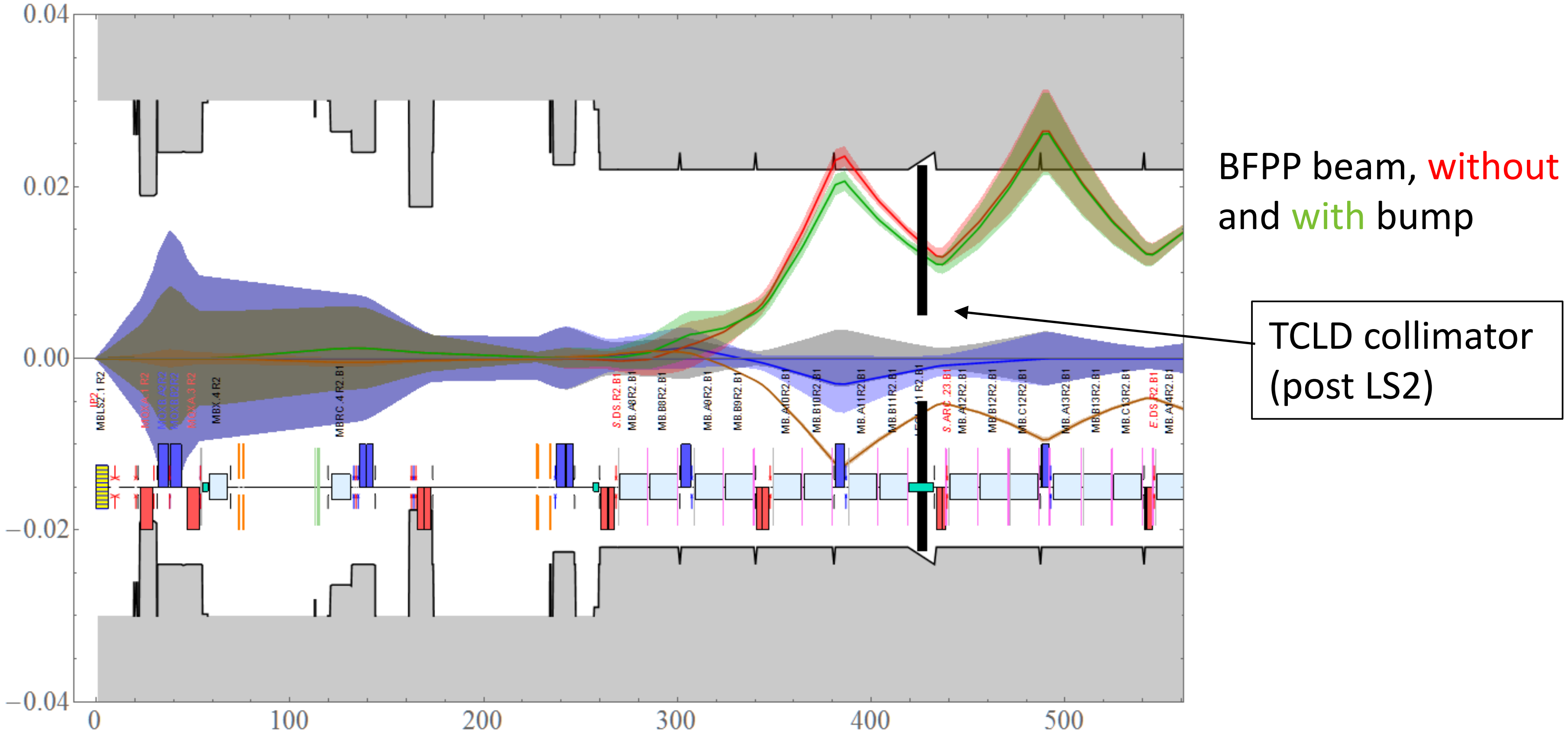
Orbit bumps mitigate BFPP for CMS (or ATLAS)



BFPP beam, without and with bump

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the 2015 run

Orbit bumps alone are not effective for ALICE



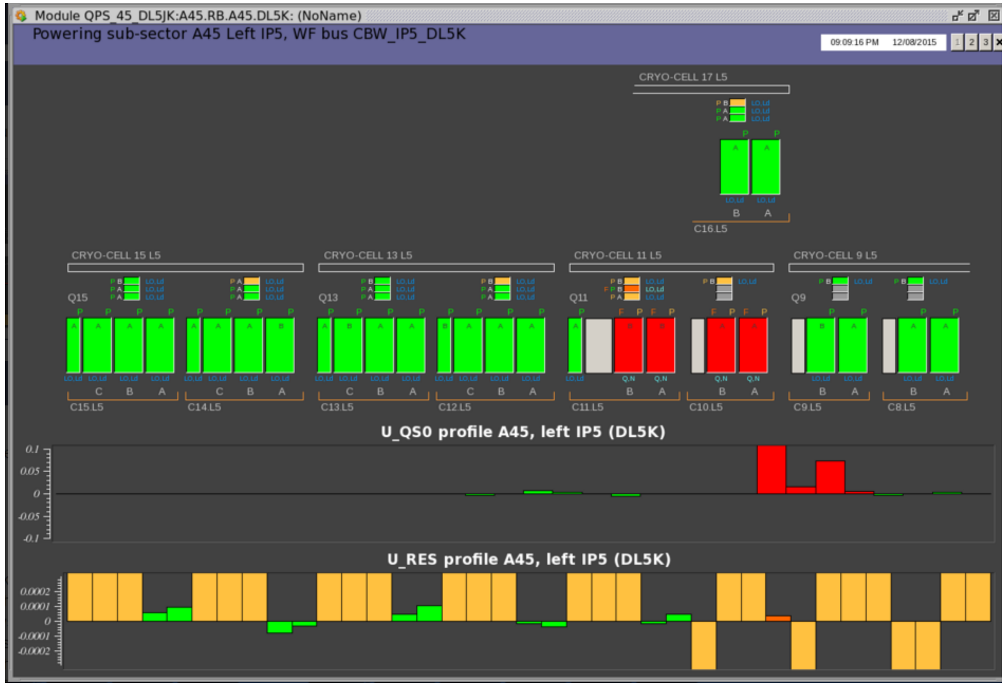
- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – **to be ready for LS2 installation**
- With levelled luminosity in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

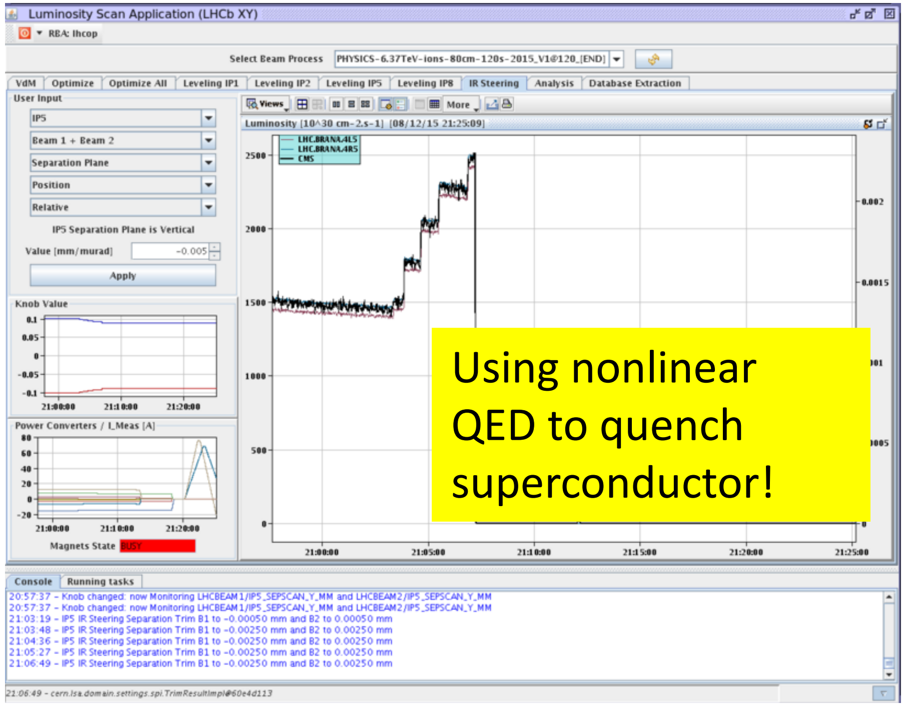
BFPP Quench MD – first luminosity quench in LHC

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

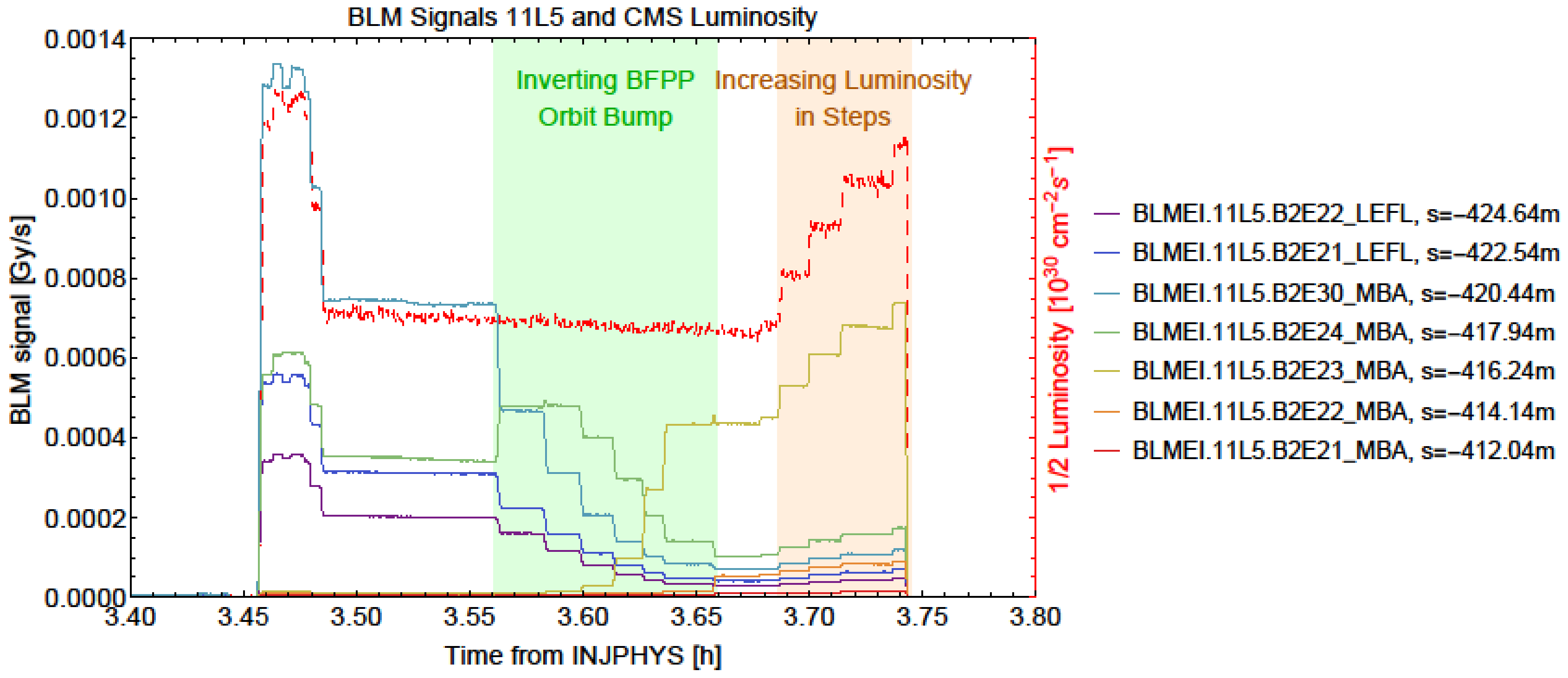
$$L \approx 2.3 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

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



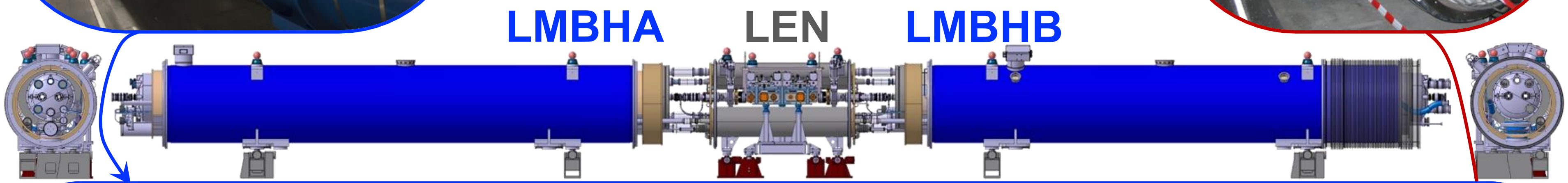


Luminosity and BLM signals during measurement



Resolved decades of uncertainty about steady-state quench level of LHC dipole magnets.
Later a second collimation quench test with Pb was also successful.

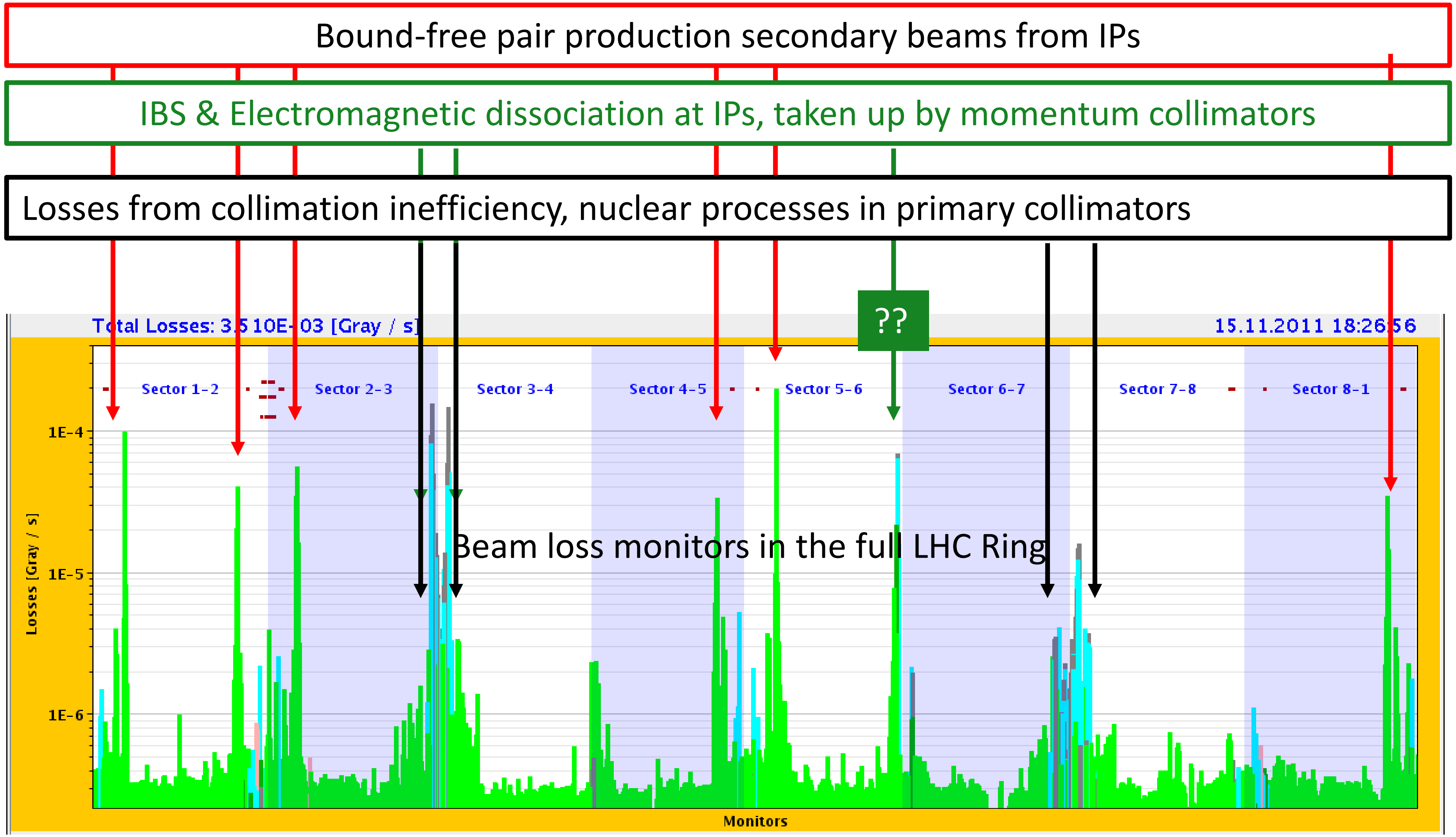
DS collimators



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

F. Savary

Steady-state losses during Pb-Pb Collisions in 2011



No time to fully discuss major topic of heavy-ion collimation in this talk.

Pb-Pb run in 2015

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 $\sqrt{s_{NN}} = 5.02$ TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are boxed for easy comparison. The upg… factor ≃ 3 from its potential value by levelling.

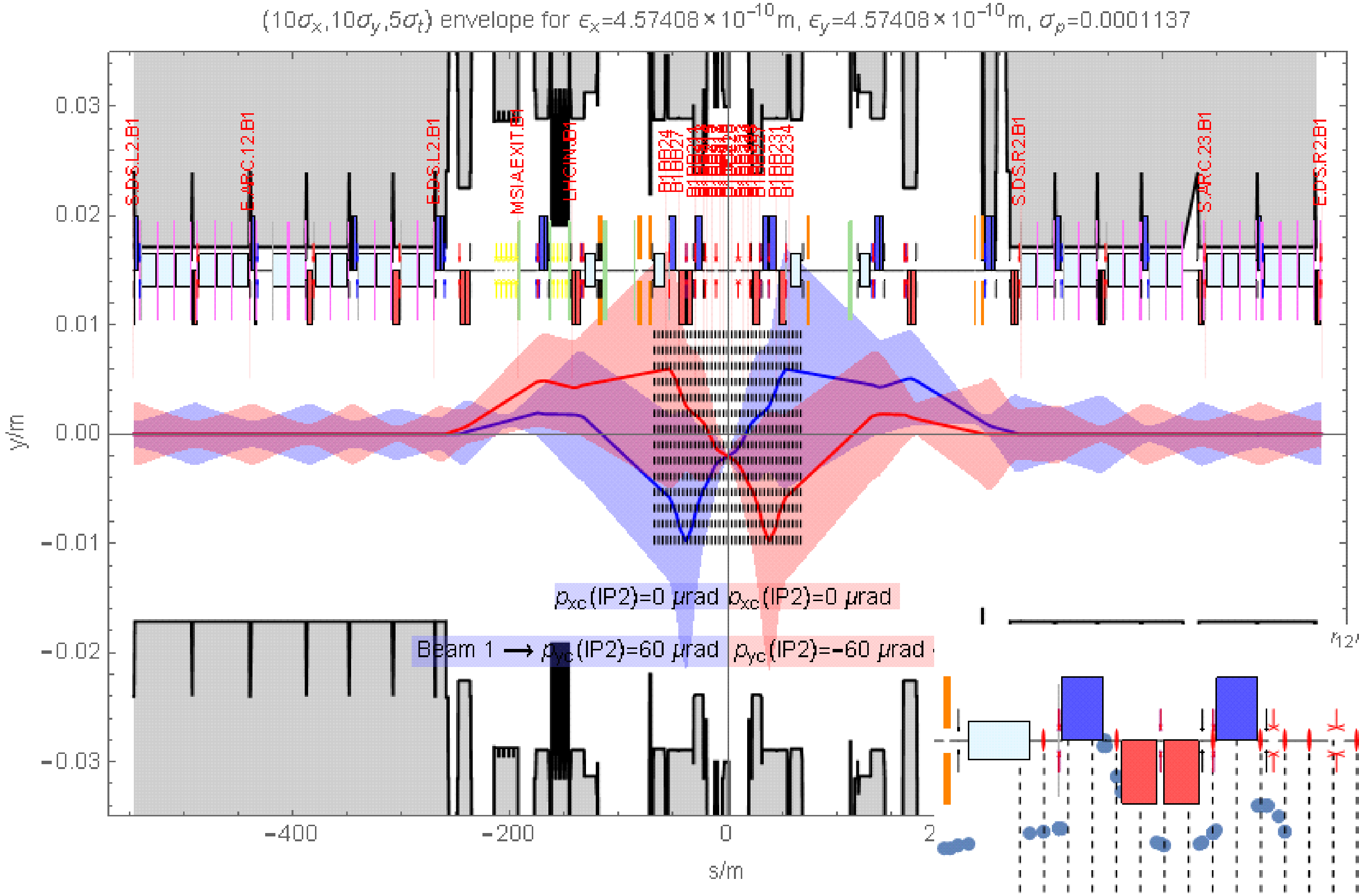
Quantity	"design"		achieved			
Year	(2004)		2010	2011	3	2015
Weeks in physics	-		4	3.5		2.5
Fill no.			1541	2351		4720
Species	Pb–Pb		Pb–Pb	Pb–Pb		Pb–Pb
Beam energy $E[Z\,\mathrm{TeV}]$		7	3.5			6.37
Pb beam energy E [ATeV]		2.7	1.38			2.51
Collision energy $\sqrt{s_{NN}}$ [TeV]	5.52		2.51			**5.02**
Bunch intensity N_b [10^8]		0.7	1.22	1.07		2.0
No, of bunches k_b	592		137	338		518
Pb norm. emittance ϵ_N [μm]		1.5	2.	2.0		2.1
Pb bunch length σ_z m		0.0			0.1	
β^* [m]		0.5	3.5	1.0		0.8
Pb stored energy MJ/beam	3.8		0.65	1.9		8.6
Peak lumi. L_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1		0.03	0.5		3.6
NN lumi. L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	43		1.3	22.		156
Integrated lumi./expt. [$\mu\mathrm{b}^{-1}$]	1000		9	160		650
Int. NN lumi./expt. [nb^{-1}]	43000		380	6700		28000

2015 run: optics substantially different to preceding p-p.

LHCb taking data (complex filling schemes).
Levelling ALICE at design L.

Multiple filling schemes as SPS and LHC injection kicker rise times reduced.

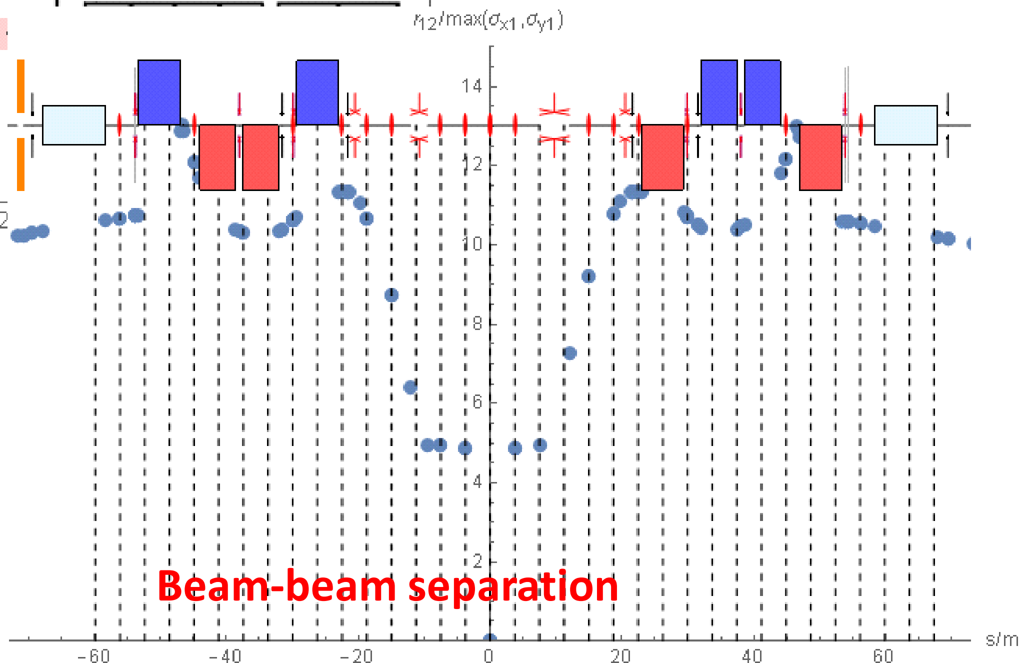
Spectrometer ON_ALICE=-7/6.37 (start of 2015 Pb-Pb run)



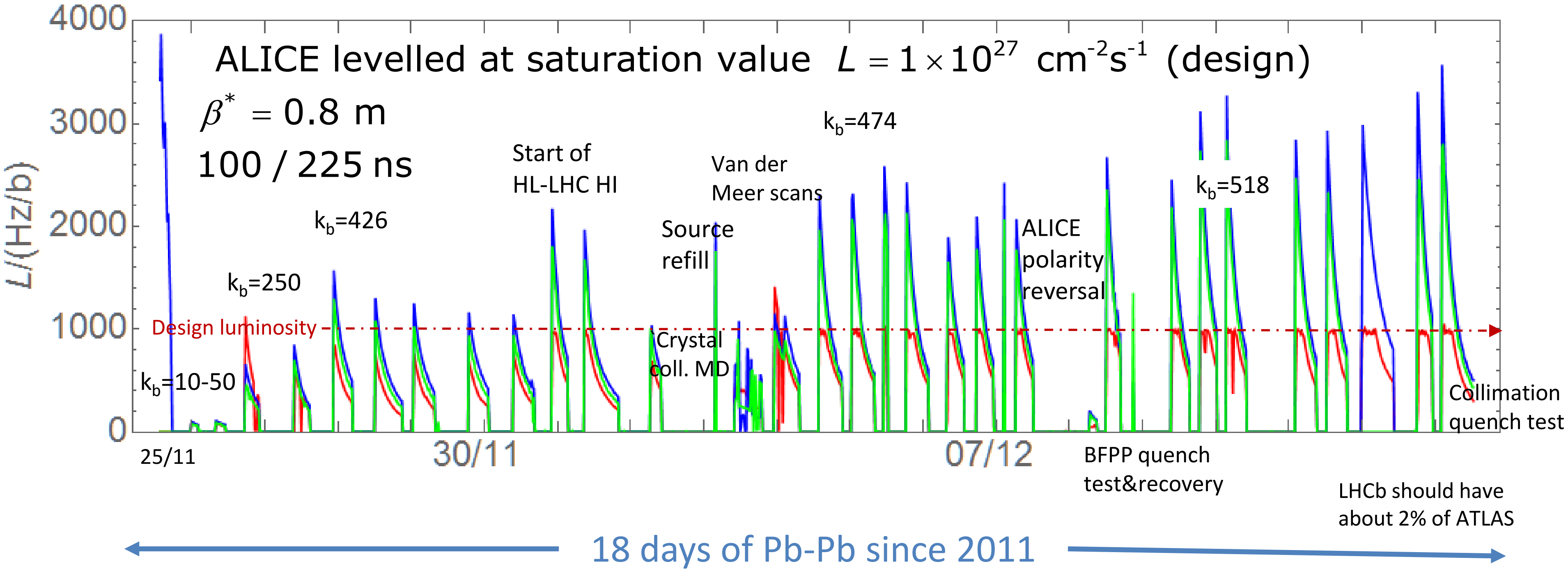
Include downward shift of IP by -2 mm (detector sank).

Constraints on crossing angle to allow spectator neutron cone to reach Zero Degree Calorimeters.

Spectrometer bump angle -77 μrad, external bump +137 μrad for Beam 1.



Pb-Pb peak luminosity at 3×design in 2015



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

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

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

25/11

Nucleus-nucleus programme status

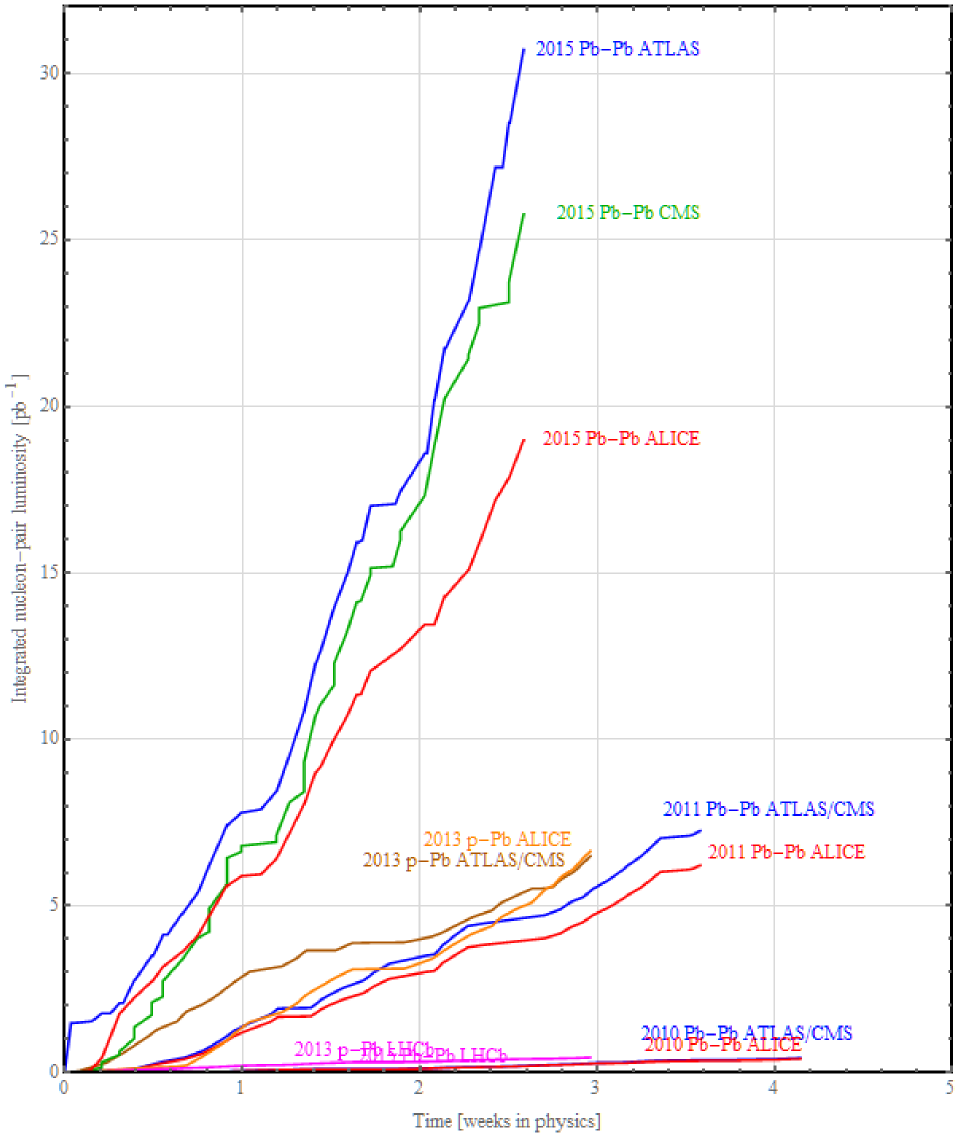
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

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.

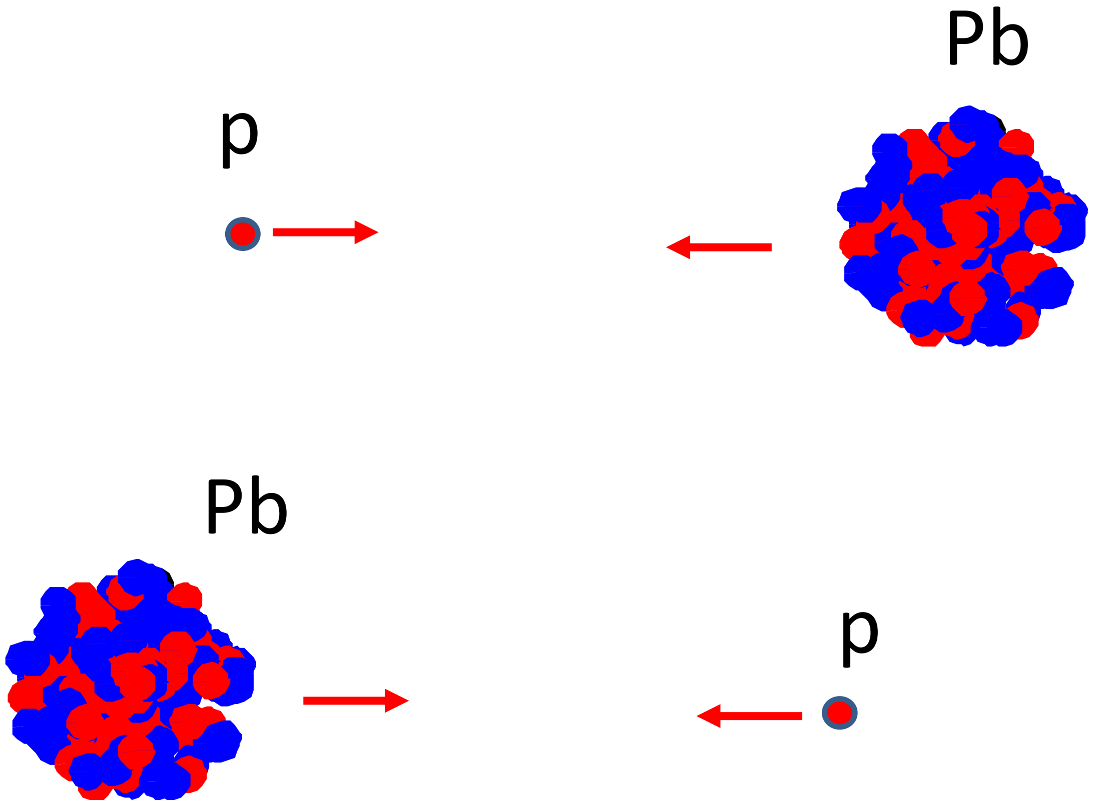
Equivalent energy runs

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

$$\Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4\ Z \text{ TeV} & \text{in p-Pb} \\ 2.51 \text{ TeV} & \text{in p-p} \end{cases}$$

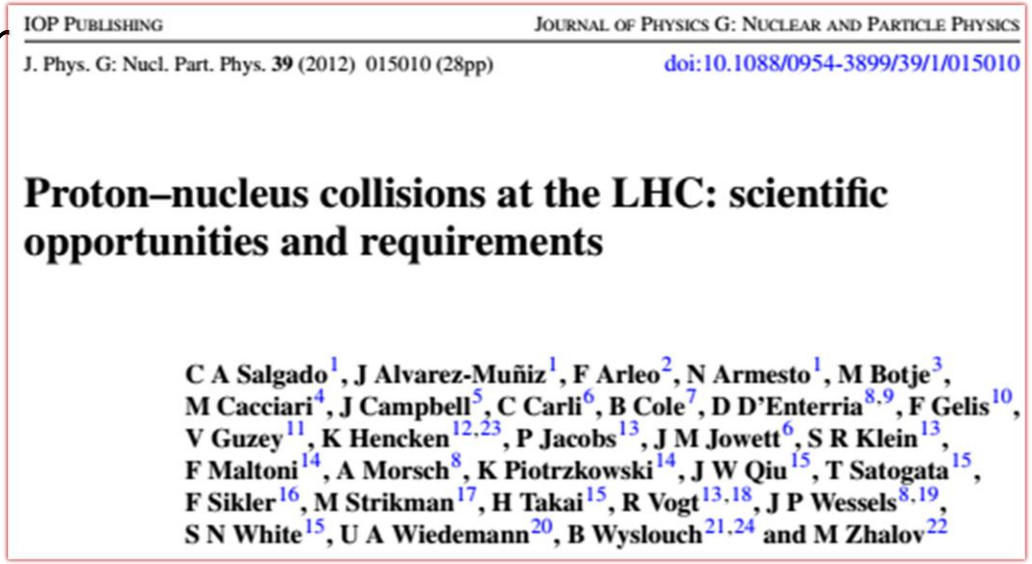


2012 pilot p-Pb run not shown



PROTON-NUCLEUS COLLISIONS

- Long considered desirable by experiments but not included in baseline design of LHC
- 2003: RHIC finds a way to collide deuterons and gold nuclei to overcome problems of unequal revolution frequencies but this way is not open to LHC …
- 2005 CERN workshop on pA in LHC (and EPAC 2006 paper)
  - Predicted that p-Pb in LHC could work (despite RHIC experience …)
  - Physics case written up m



IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015010 (28pp) doi:10.1088/0954-3899/39/1/015010

Proton–nucleus collisions at the LHC: scientific opportunities and requirements

C A Salgado[1], J Alvarez-Muñiz[1], F Arleo[2], N Armesto[1], M Botje[3], M Cacciari[4], J Campbell[5], C Carli[6], B Cole[7], D D'Enterria[8,9], F Gelis[10], V Guzey[11], K Hencken[12,23], P Jacobs[13], J M Jowett[6], S R Klein[13], F Maltoni[14], A Morsch[8], K Piotrzkowski[14], J W Qiu[15], T Satogata[15], F Sikler[16], M Strikman[17], H Takai[15], R Vogt[13,18], J P Wessels[8,19], S N White[15], U A Wiedemann[20], B Wyslouch[21,24] and M Zhalov[22]

- LHC accelerates protons through the momentum range

$$0.45\ \text{TeV (injection from SPS)} \le p_p \le 7\ \text{TeV (collision)}$$

  – p_p is measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC fixes the relation between momenta of beams in the two rings (equal "*magnetic rigidity*")

$$p_{\text{Pb}} = Z p_{\text{p}}$$

where $Z = 82,\ A = 208$ for fully stripped Pb in LHC

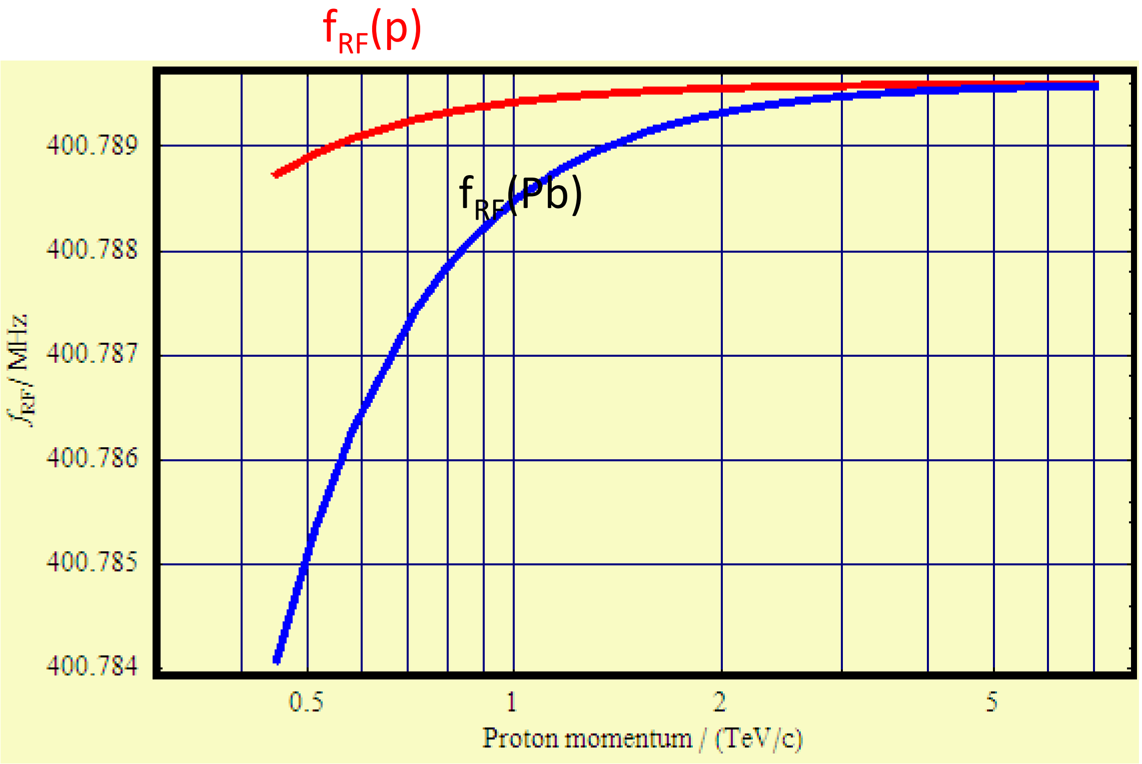
RF Frequency for p and Pb in LHC

Revolution time of a general particle, mass *m*, charge *Q*, is

$$T(p_p, m, Q) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_p}\right)^2} \text{ and RF frequency } \quad f_{RF} = \frac{h_{RF}}{T(p_p, m, Q)}$$

where the harmonic number $h_{RF} = 35640$ in LHC

RF frequencies needed to keep p or Pb on stable *central* orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T\left(p_{\mathrm{p}},m,Q\right) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1+\eta\delta)$$

where $\delta = \dfrac{(p - Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

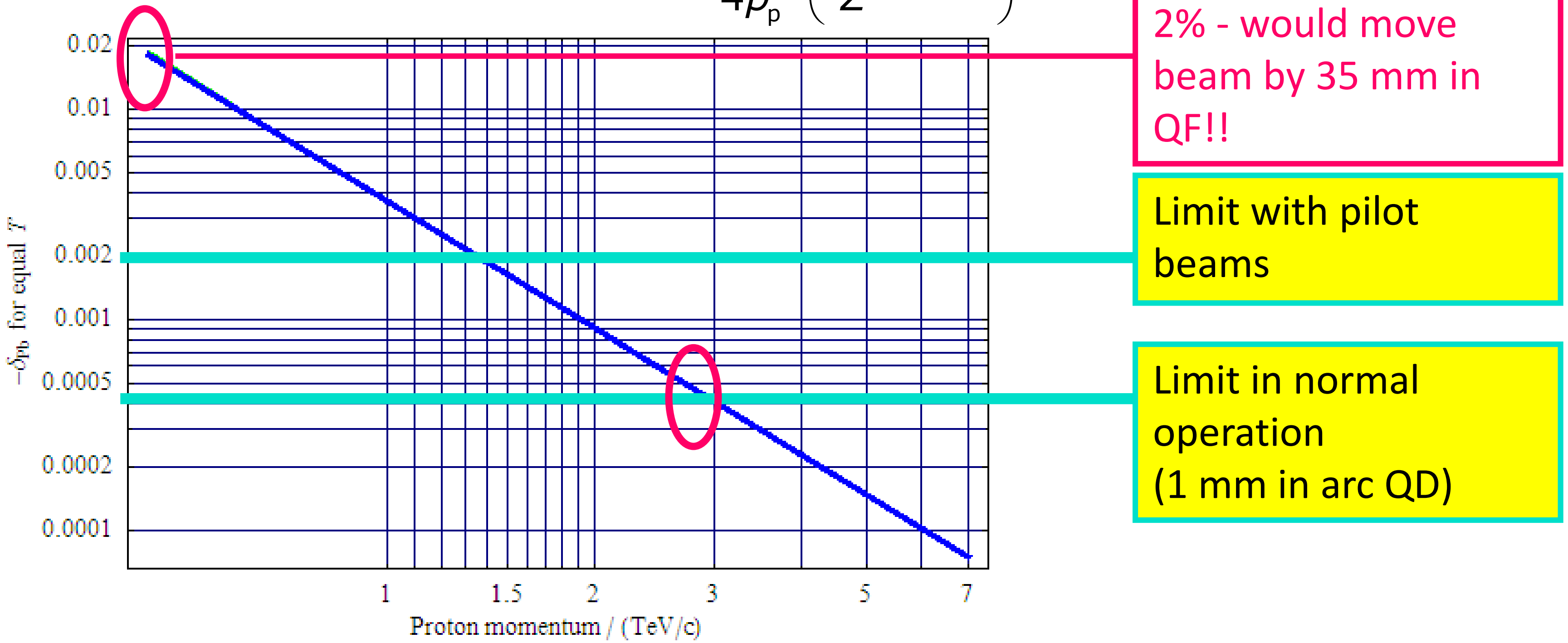
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\quad \gamma = \sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\quad \gamma_T = 55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta > 0$.

Horizontal offset given by dispersion: $\Delta x = D_x\left(s\right)\delta$.

Momentum offset required for equal frequencies through ramp

Minimise aperture needed by $\delta_p = -\delta_{Pb} = \frac{c^2 \gamma_T{}^2}{4 p_p^2} \left(\frac{m_{Pb}^2}{Z^2} - m_p^2 \right).$



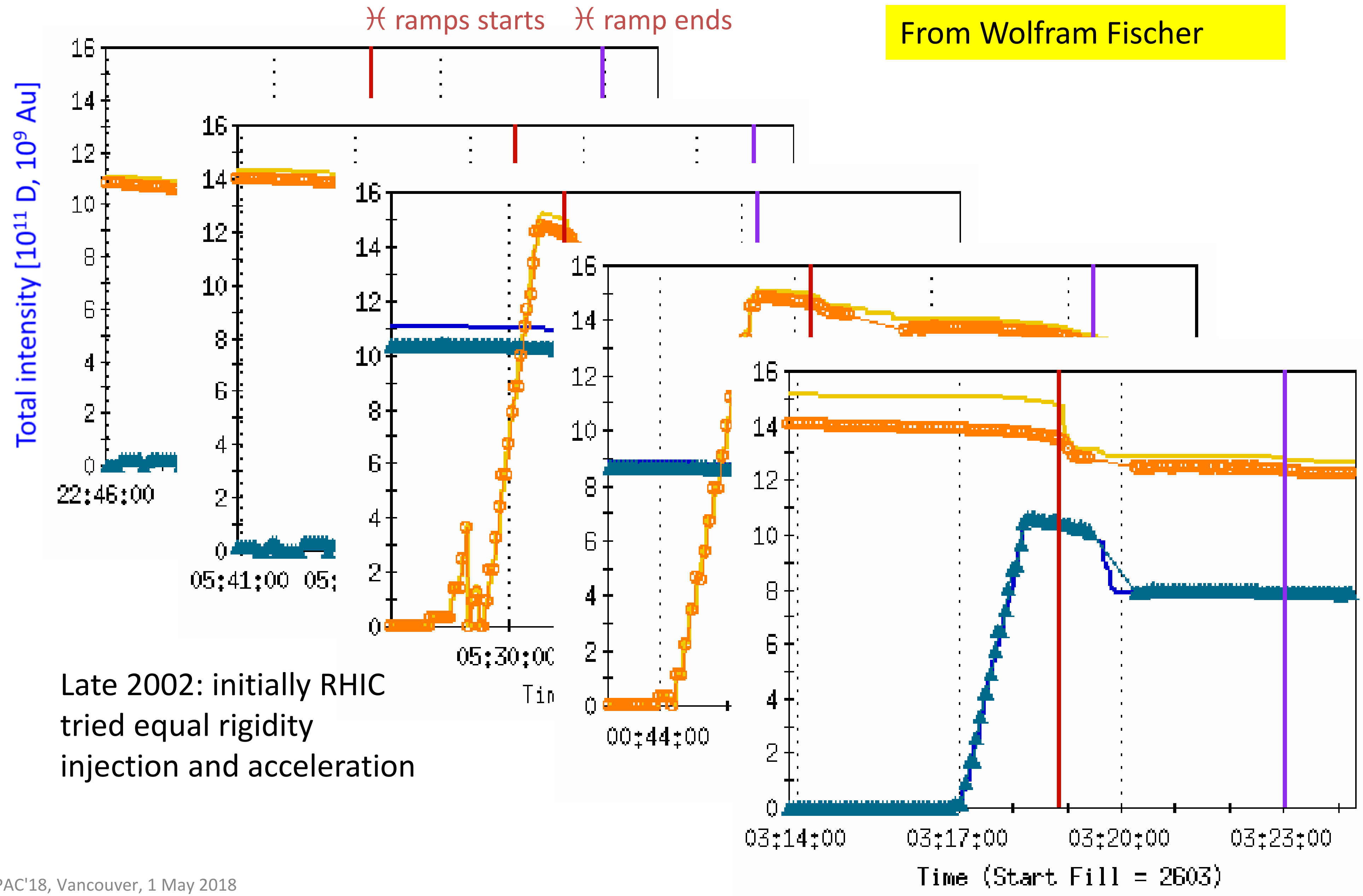
Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, *E*=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

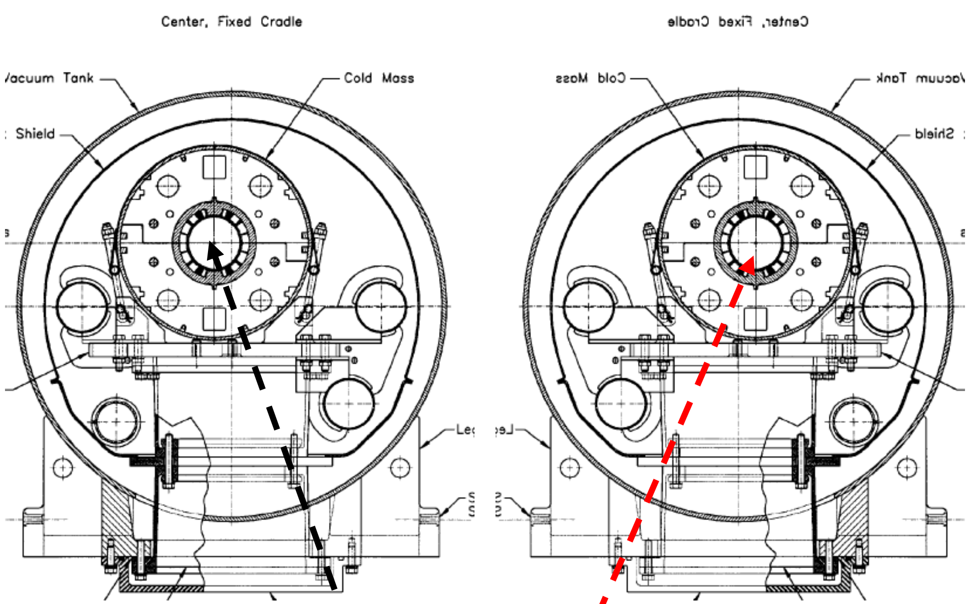
RHIC d-Au injection and ramp $(B\rho)_{\mathrm{d}} = (B\rho)_{\mathrm{Au}}$

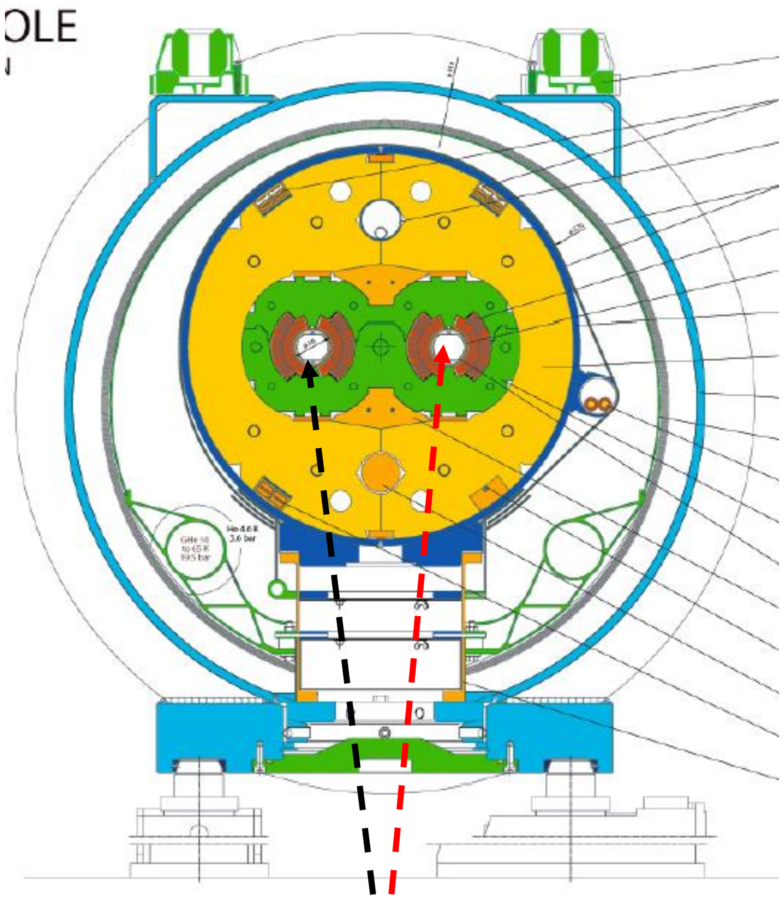
From Wolfram Fischer



Late 2002: initially RHIC tried equal rigidity injection and acceleration

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency d-Au.

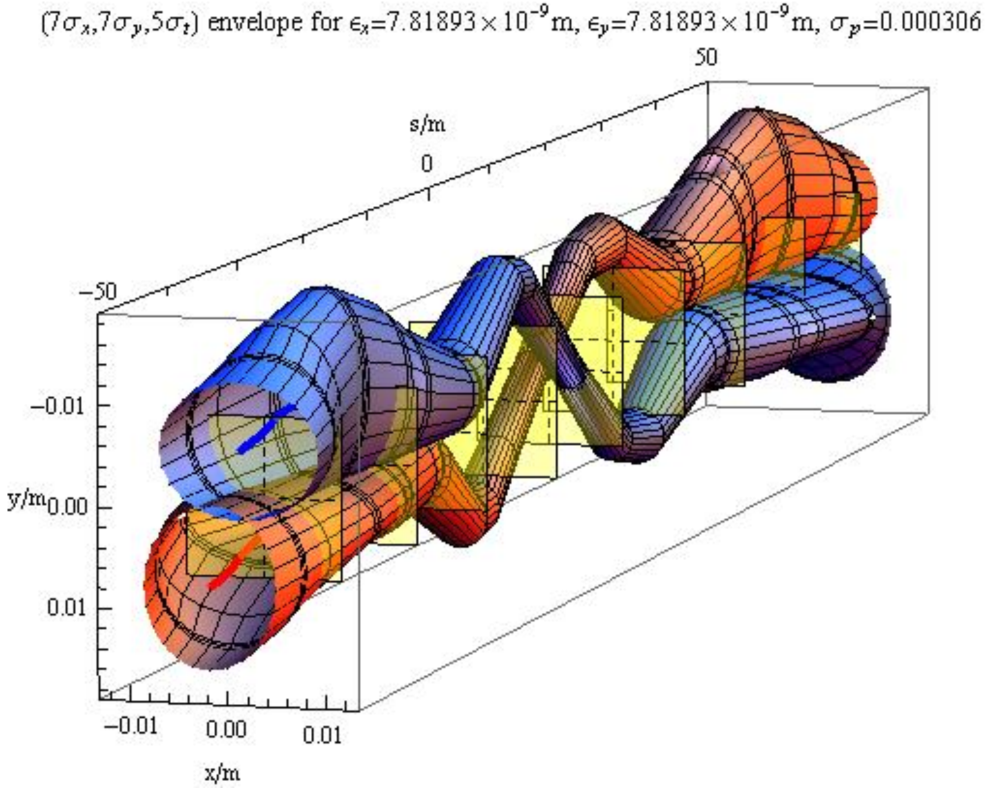
LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

Outline of p-Pb physics cycle (Pb-p similar)

- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF cogging operation to position collision point
- Squeeze optics sequence
- Change ALICE crossing angle to collision configuration
- Collide

At injection the proton beam makes 8 more revolutions per minute than the Pb beam

Beam envelopes around ALICE at injection

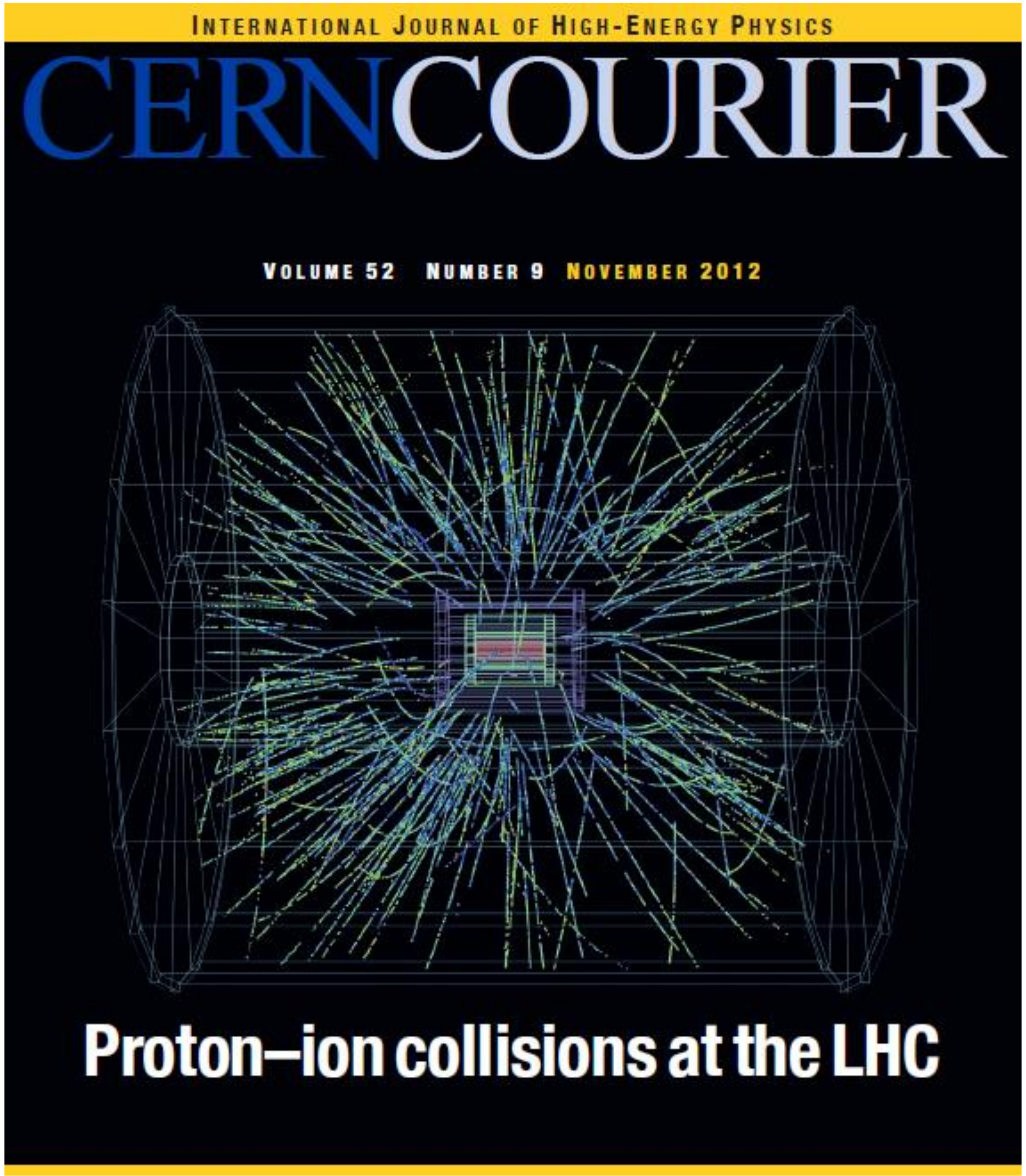


Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.
Other experiments have different separation schemes …

Bunch encounter points move from turn to turn, modulating long-range beam-beam forces.
Pseudo-random kicks, small diffusion.

Cancellations between encounters along experimental insertion.

Simulations of beam dynamics (M. Jebramcik) confirm effects are small at LHC.



Very successful first pilot run (16 h, single fill with 16 bunches) in September 2012.

Full one month run with high luminosity in Jan-Feb 2013, introducing new level of complexity into LHC operation with multiple changes of conditions, including reversal of beams.

P-Pb in 2012, 2013

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 $\sqrt{s_{NN}} = 5.02$ TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are boxed for easy comparison. The up
factor ≃ 3 from its potential value by levelling.

Quantity	"design"		achieved			
Year	(2004)	(2011)	2010	2011	2012–13	2015
Weeks in physics	-	-	4	3.5	3	2.5
Fill no.			1541	2351	3544	4720
Species	Pb–Pb	p–Pb	Pb–Pb	Pb–Pb	p–Pb	Pb–Pb
Beam energy $E[Z\,\mathrm{TeV}]$	7		3.5		4	6.37
Pb beam energy E [ATeV]	2.76		1.38		1.58	2.51
Collision energy $\sqrt{s_{NN}}$ [TeV]	5.52		2.51		**5.02**	**5.02**
Bunch intensity N_b $[10^8]$	0.7		1.22	1.07	1.2	2.0
No, of bunches k_b	592		137	338	358	518
Pb norm. emittance ϵ_N [μm]	1.5		2.	2.0	2.	2.1
Pb bunch length σ_z m	0.08				0.07–0.1	
β^* [m]	0.5		3.5	1.0	0.8	0.8
Pb stored energy MJ/beam	3.8	2.3	0.65	1.9	2.77	8.6
Peak lumi. L_{AA} $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	150	0.03	0.5	116	3.6
NN lumi. L_{NN} $[10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	43	31	1.3	22.	24	156
Integrated lumi./expt. [μb^{-1}]	1000	10^5	9	160	32000	650
Int. NN lumi./expt. [nb^{-1}]	43000	21000	380	6700	6650	28000

2012 run: p-Pb pilot
2013 run: full luminosity p-Pb and Pb-p

LHCb taking data (complex filling schemes).
Levelling ALICE at design L.

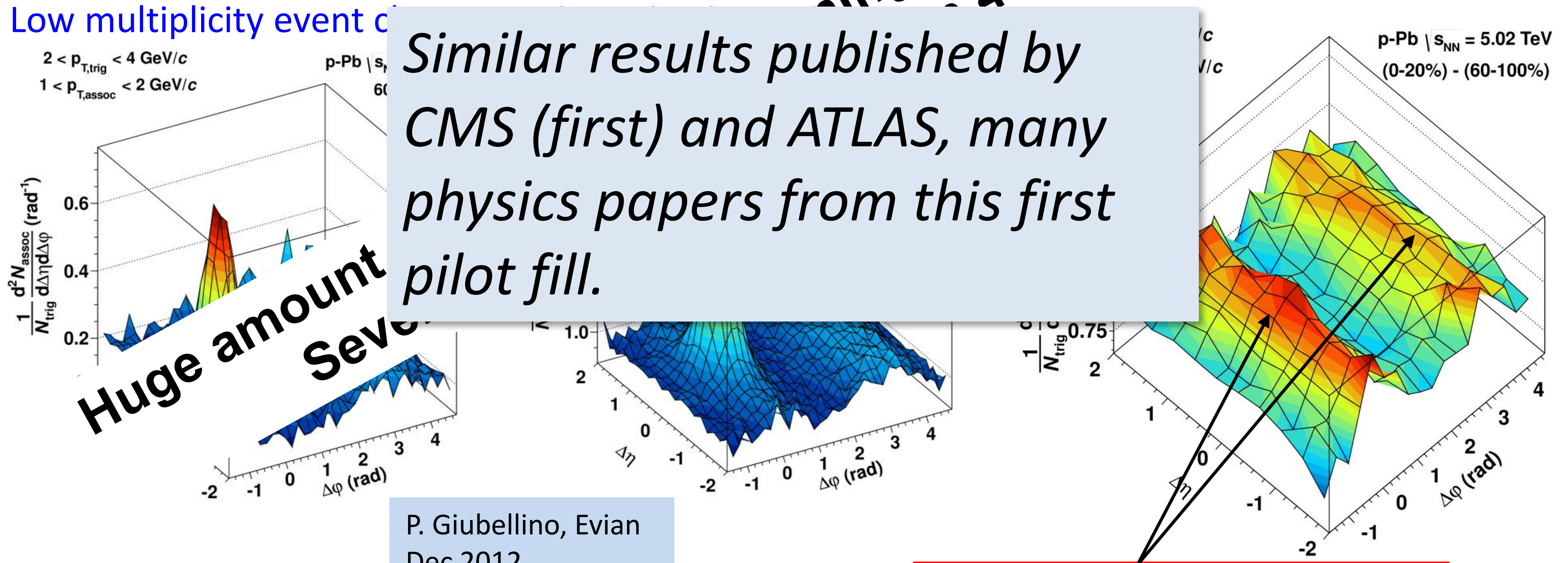
Multiple filling schemes as SPS and LHC injection kicker rise times reduced.

First 4 h of physics: Correlations in p-Pb: the unexpected "ridge"

- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle azimuthal distribution, with $V_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: suggest common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation at similar x-values … considered a sign of saturation effects)
  - In agreement with viscous hydro calculations ?!

…ing a new window in the field
… 4 h of collisions

Low multiplicity event c…



Similar results published by CMS (first) and ATLAS, many physics papers from this first pilot fill.

P. Giubellino, Evian Dec 2012

p-Pb in 2016 at 4 Z TeV and 6.5 Z TeV

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 $\sqrt{s_{NN}}$ = 5.02 TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are boxed for easy comparison. The upgrade value i factor ≃ 3 from its potential value by levelling.

Quantity	"design"		achieved				
Year	(2004)	(2011)	2010	2011	2012–13	2015	2016
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
Beam energy E[Z TeV]	7		3.5		4	6.37	4,6.5
Pb beam energy E [ATeV]	2.76		1.38		1.58	2.51	1.58,2.56
Collision energy $\sqrt{s_{NN}}$ [TeV]	5.52		2.51		**5.02**	**5.02**	**5.02**,8.16
Bunch intensity N_b [10^8]	0.7		1.22	1.07	1.2	2.0	2.1
No, of bunches k_b	592		137	338	358	518	540
Pb norm. emittance ϵ_N [μm]	1.5		2.	2.0	2.	2.1	1.6
Pb bunch length σ_z m	0.08				0.07–0.1		
β^* [m]	0.5		3.5	1.0	0.8	0.8	10, 0.6
Pb stored energy MJ/beam	3.8	2.3	0.65	1.9	2.77	8.6	9.7
Peak lumi. L_{AA} [10^{27}cm^{-2}s^{-1}]	1	150	0.03	0.5	116	3.6	850
NN lumi. L_{NN} [10^{30}cm^{-2}s^{-1}]	43	31	1.3	22.	24	156	177
Integrated lumi./expt. [μb^{-1}]	1000	10^5	9	160	32000	650	1.9×10^5
Int. NN lumi./expt. [nb^{-1}]	43000	21000	380	6700	6650	28000	40000

2016: 1 week minimum bias, very long runs at same energy as 2013, 2015 for ALICE.

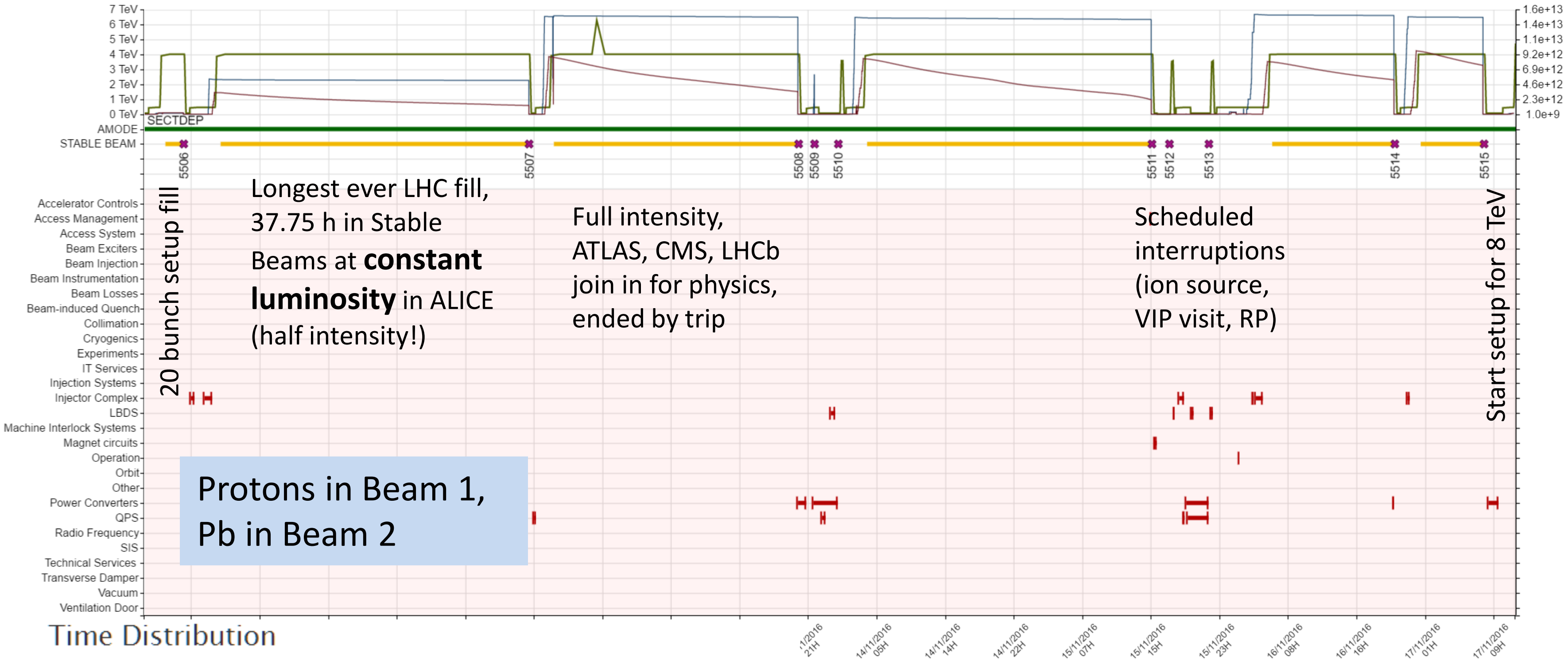
2 weeks max energy and luminosity for ATLAS/CMS

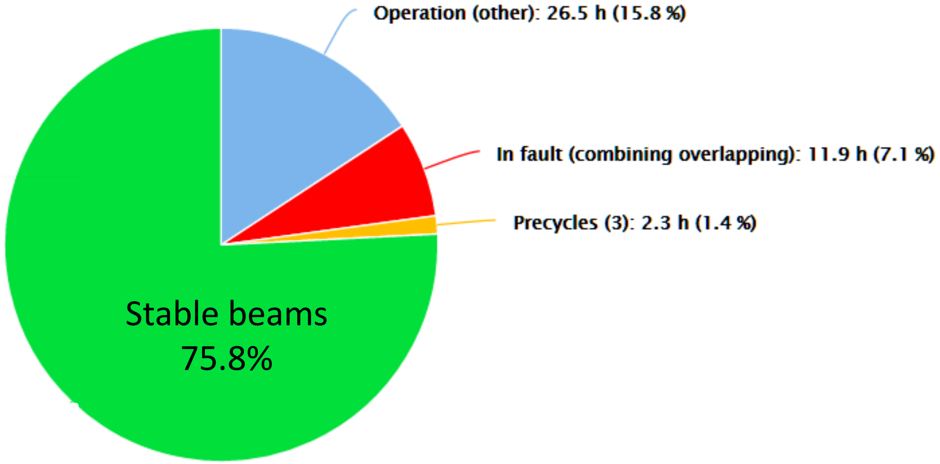
Several subsidiary luminosity goals.

LHCb taking data (complex filling schemes).
Levelling ALICE at design L.

Multiple filling schemes, optics.

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



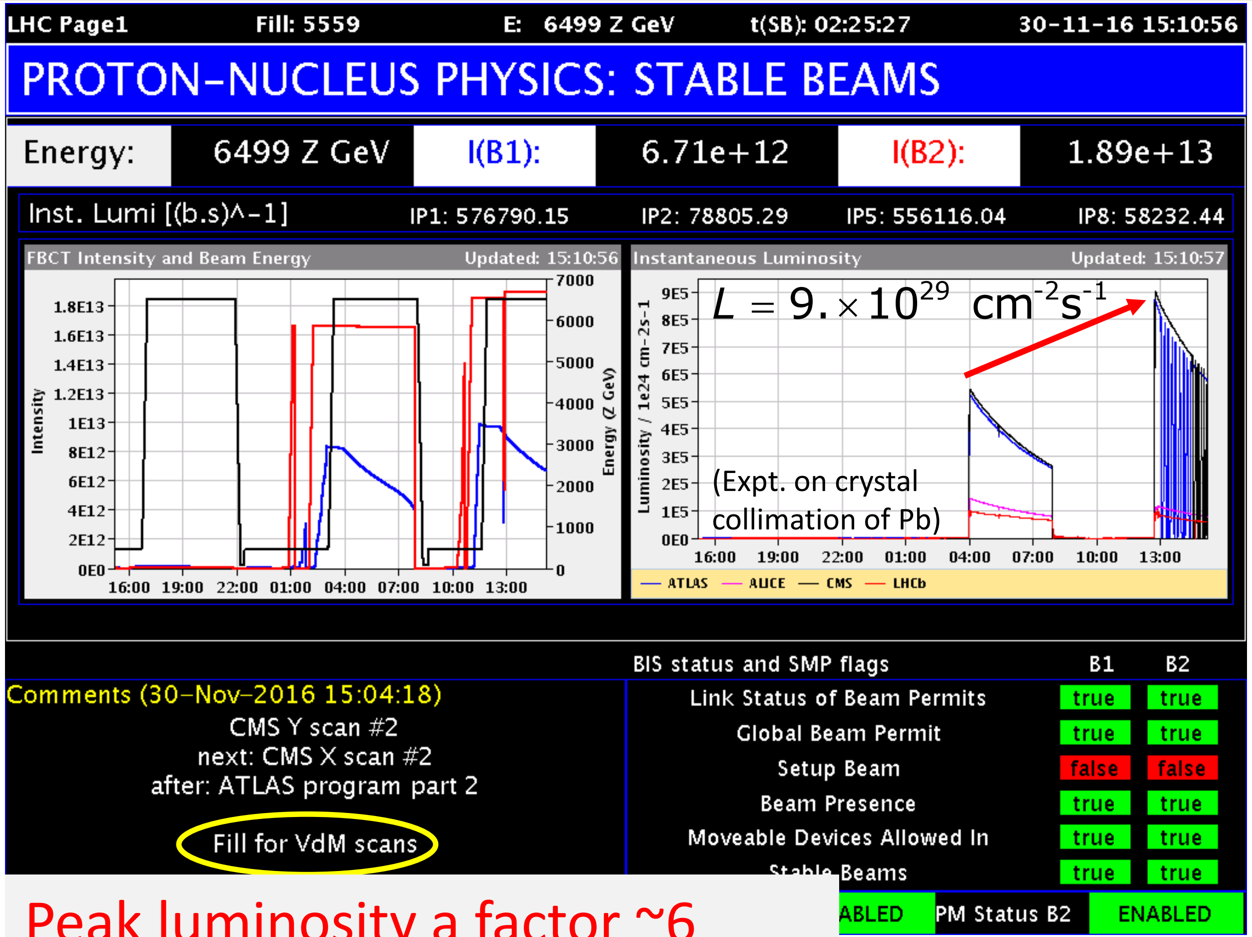


Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!

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



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

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

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

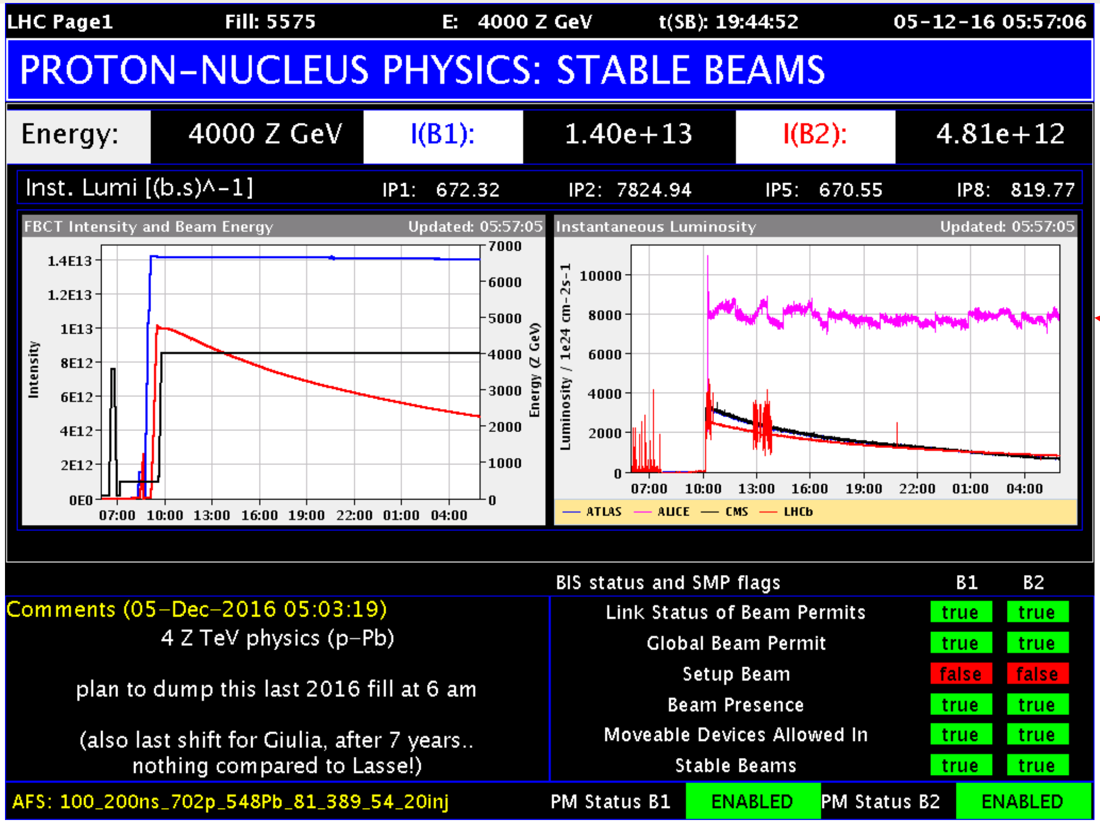
Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

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

Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

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

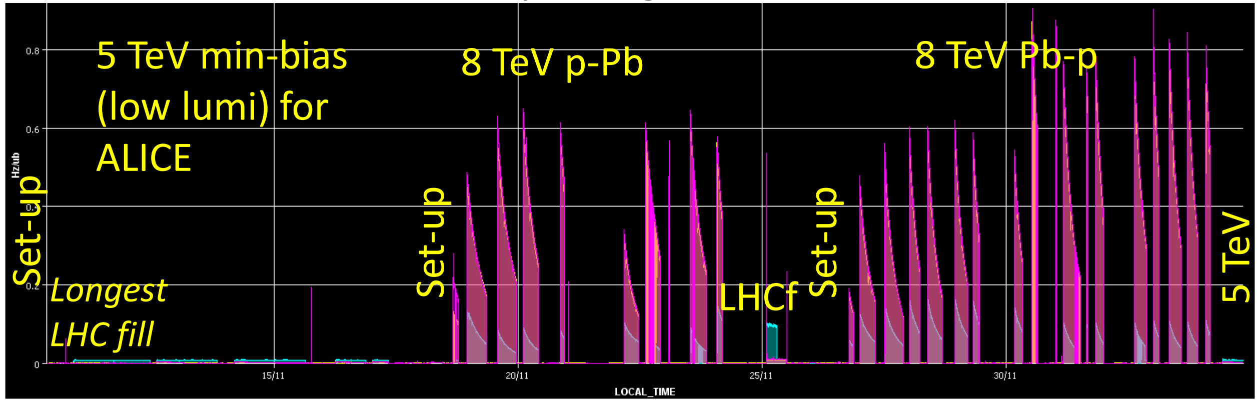


Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

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



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.

Proton-nucleus programme status

Feasibility and first p-Pb run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

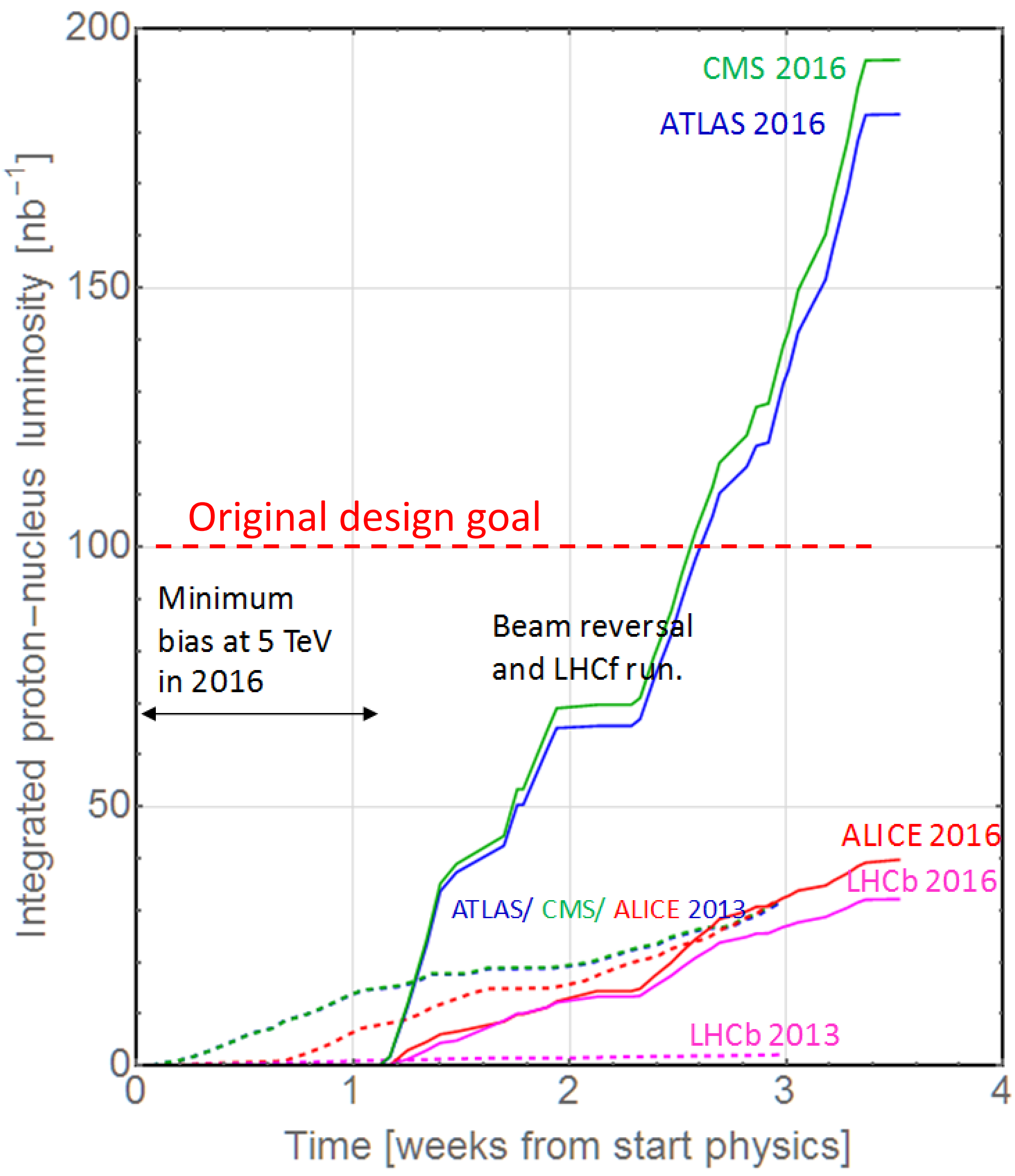
Minimum bias run at 4 Z TeV mainly for ALICE

High luminosity run for all experiments (+LHCf) at 6.5 Z TeV, with beam reversal p-Pb and Pb-p.

Ie, 2 new optics and 3 setups with full qualifications in 1 month.

Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.



FUTURE PERFORMANCE (HL-LHC)

Future upgrade parameters

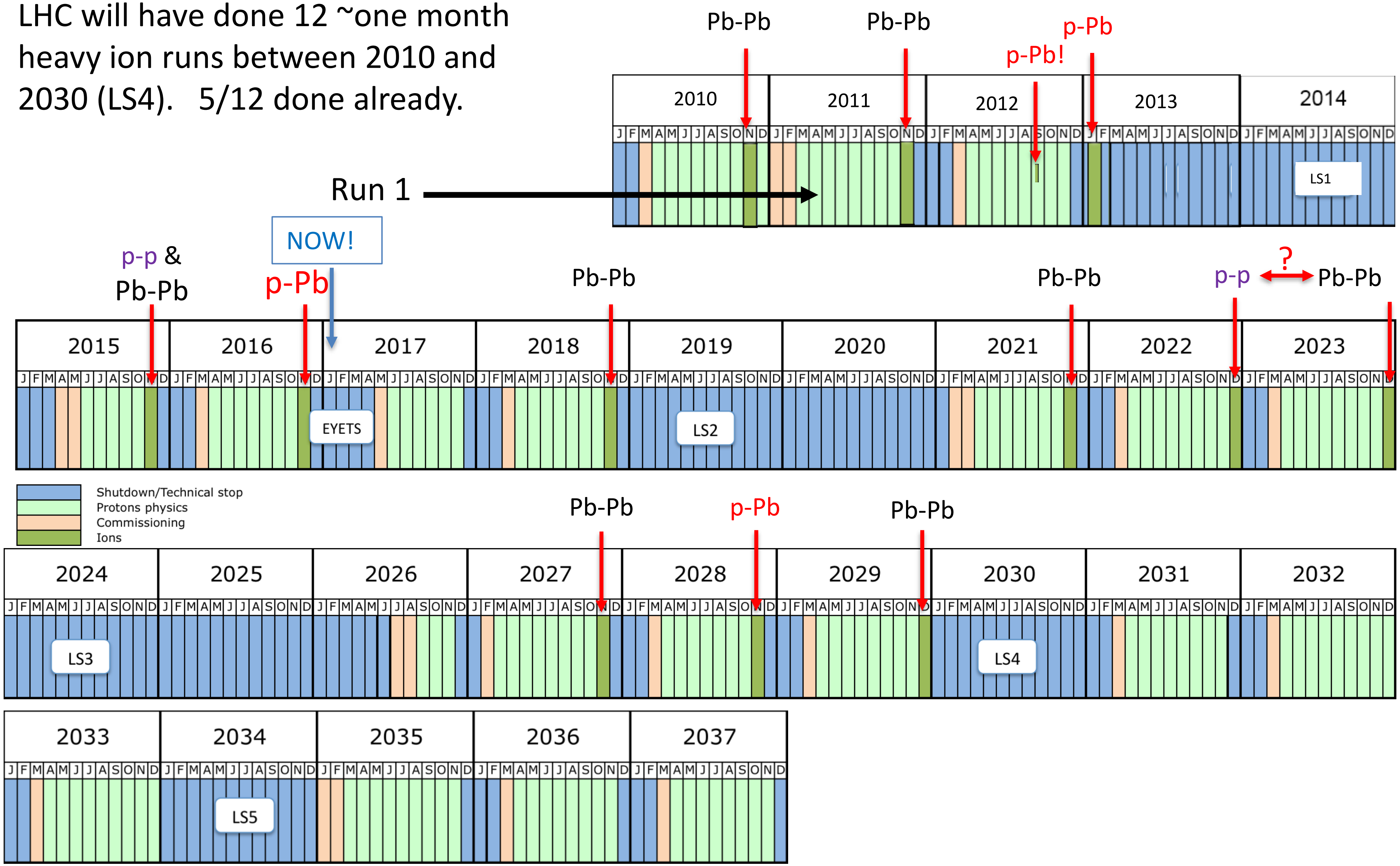
Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for > 5 days, in each annual Pb-Pb and p–Pb run [12–16]. The original design values for Pb–Pb [4] and p-Pb [17] and future upgrade Pb–Pb goals are also shown (in these columns 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 $\sqrt{s_{NN}}$ = 5.02 TeV also included p–p reference runs, not shown here. Design and record achieved nucleon-pair luminosities are 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 $\sqrt{s_{NN}}$ [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_{AA} [10^{27}cm^{-2}s^{-1}]	1	150	0.03	0.5	116	3.6	850	6
NN lumi. L_{NN} [10^{30}cm^{-2}s^{-1}]	43	31	1.3	22.	24	156	177	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

Levelled, could be ~15.

LHC heavy-ion runs, past & baseline future
+ species choices according to ALICE 2012 LoI (under review in HL-LHC workshop) `

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.



LIU baseline (Jan 2017) parameters at start of collisions

- Simplified scenario -
  - See injectors upgrad paper H. Bartosik et al, IPAC 2017
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)

$$\langle N_b \rangle = 1.8\times10^8 \;\; = 95\% \;\times\; 1.9\times10^8 \text{ injected } \; (\text{c.f. design } 0.7\times10^8)$$

  - Initial emittance (start of stable beams)

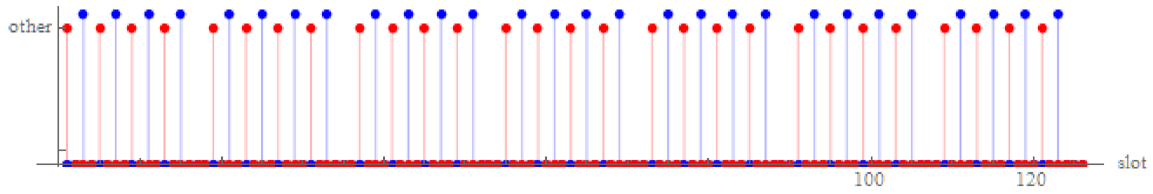
$$\varepsilon_{xn} = 1.65\times10^{-6}\text{m} \quad (> \text{design, some blow up from injected } 1.5\times10^{-6}\text{m })$$

  - Crossing angles 170, 100, 170 μrad, operation at 7*Z* TeV
  - Other bunch parameters as Design Report nominal
  - Three luminosity-sharing scenarios, to illustrate possibilities (equal β* scenario is nominal!):

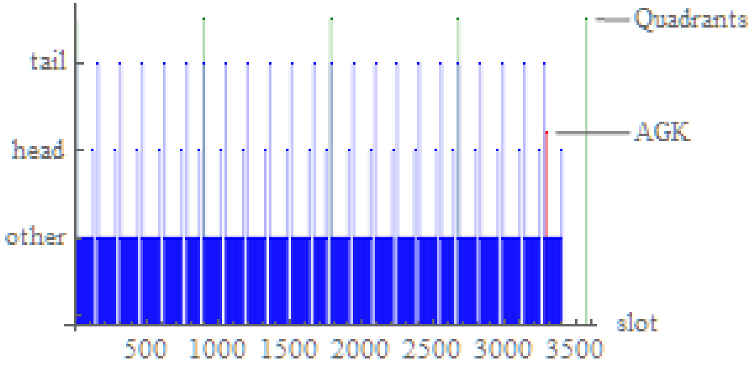
$$\beta^* = \begin{cases} (\infty, 0.5, \infty) \;\; \text{m} \;\; \text{(only ALICE colliding)} \\ (1.0, 0.5, 1.0) \;\; \text{m} \;\; \text{(ATLAS/CMS at half ALICE)} \\ (0.5, 0.5, 0.5) \;\; \text{m} \;\; \text{(equal)} \end{cases}$$

  - Some collisions in LHCb (not shown in detail)

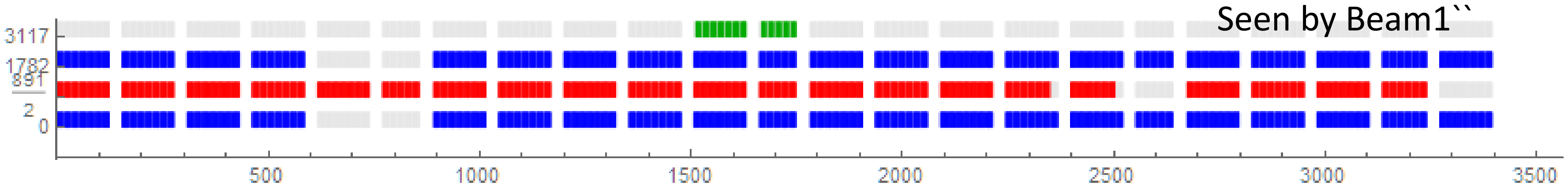
Filling scheme with some collisions in LHCb

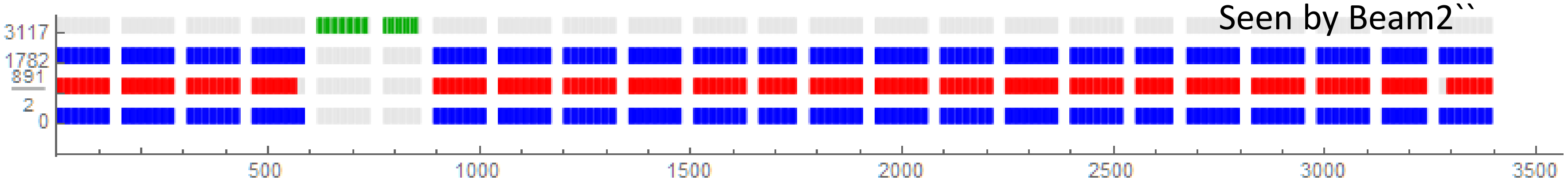


56 bunch SPS train after slip-stacking



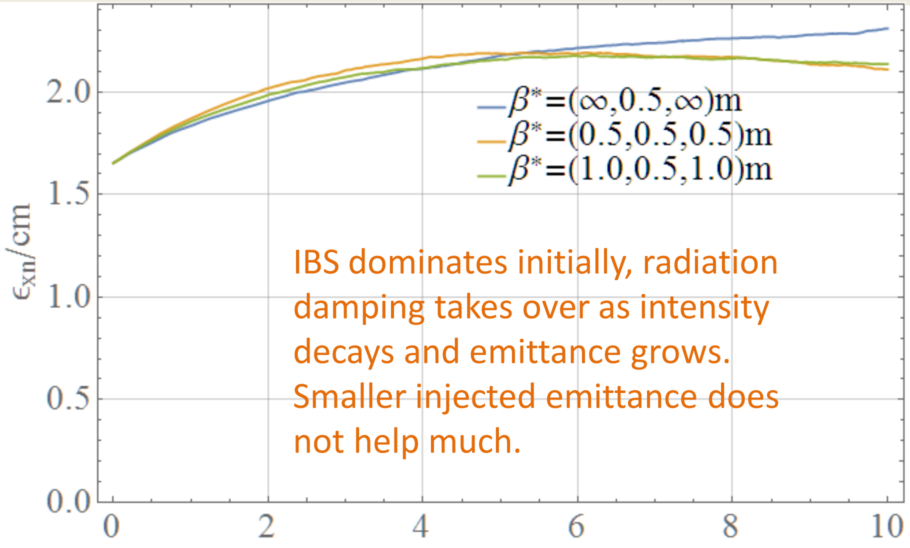
Displace two trains in Beam 2 to make collisions in LHCb (assumption while waiting for specification).

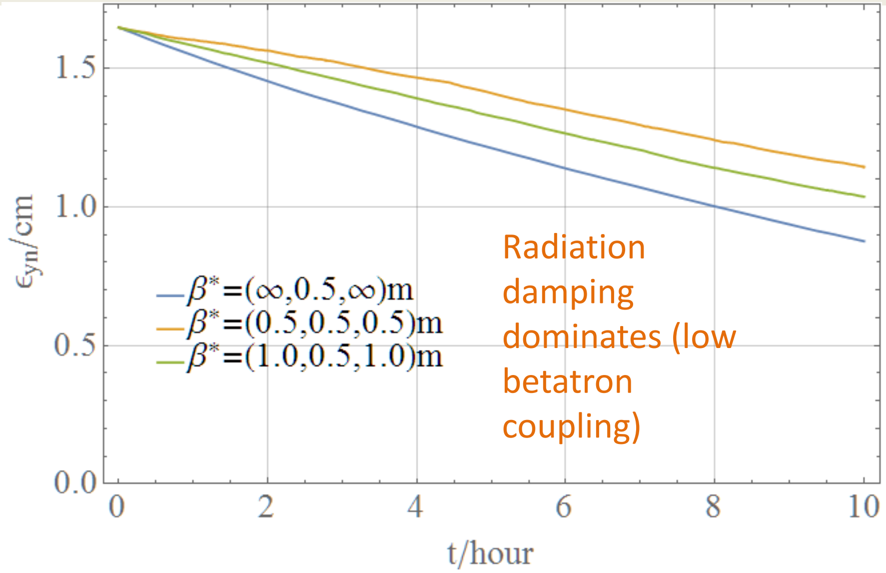


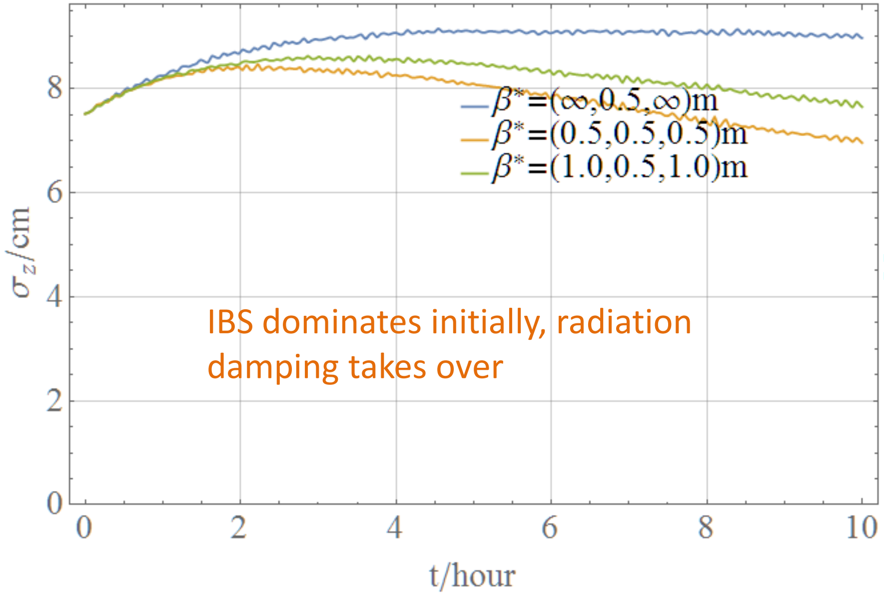


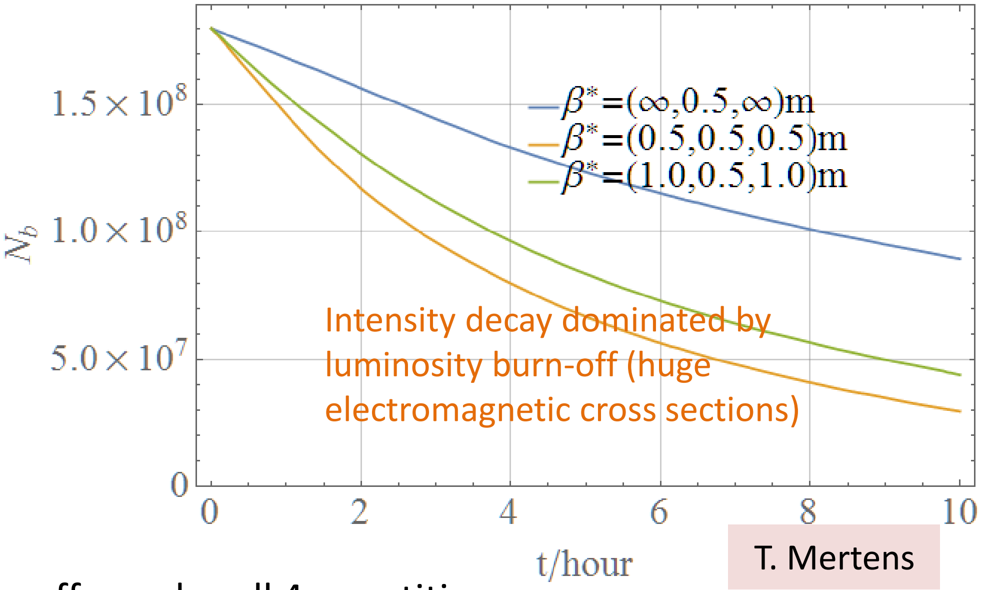
23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

CTE Simulation of (most typical) colliding bunch pair





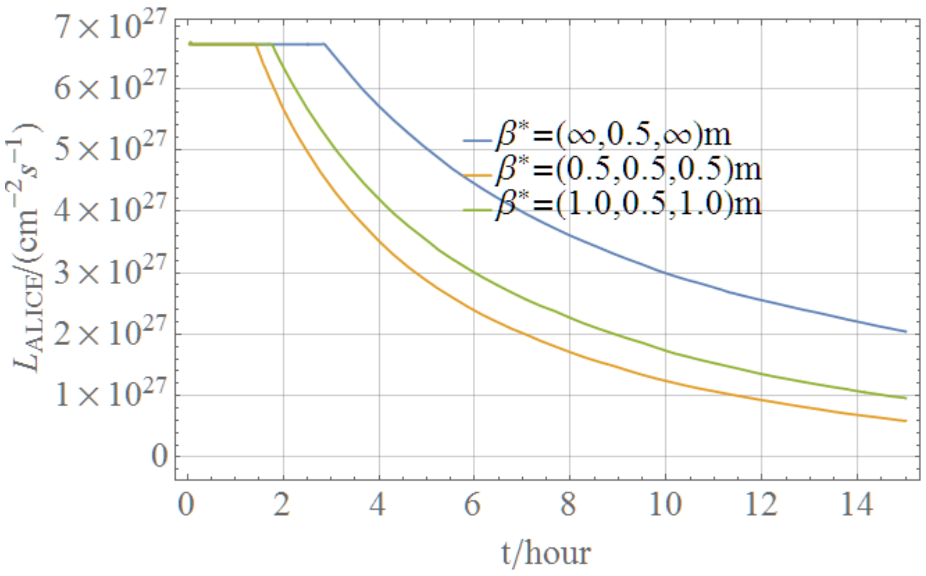




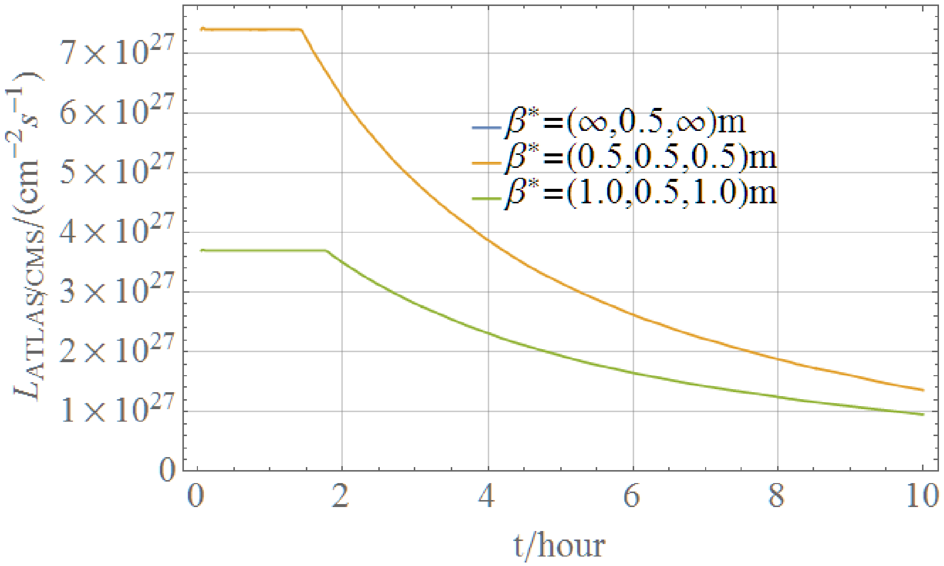
T. Mertens

Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.
Different evolution according to luminosity-sharing scenario.
(Does not include additional emittance growth usually seen in operation.)

Experiments' luminosities in an ideal (prolonged) fill

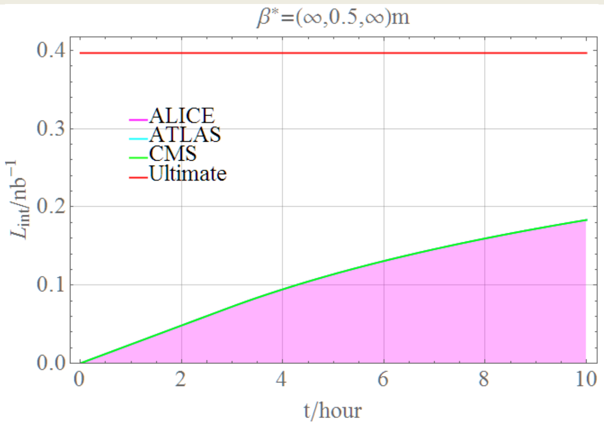


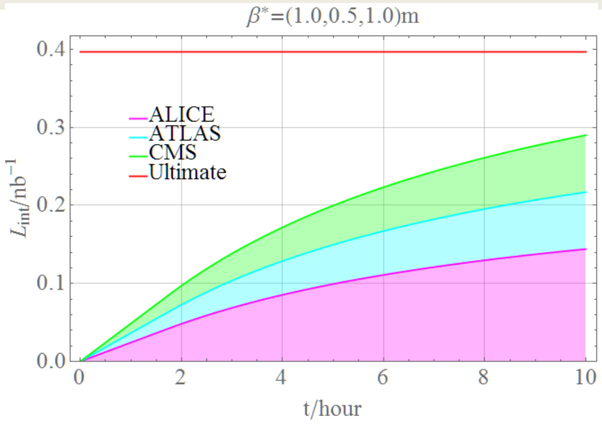
ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

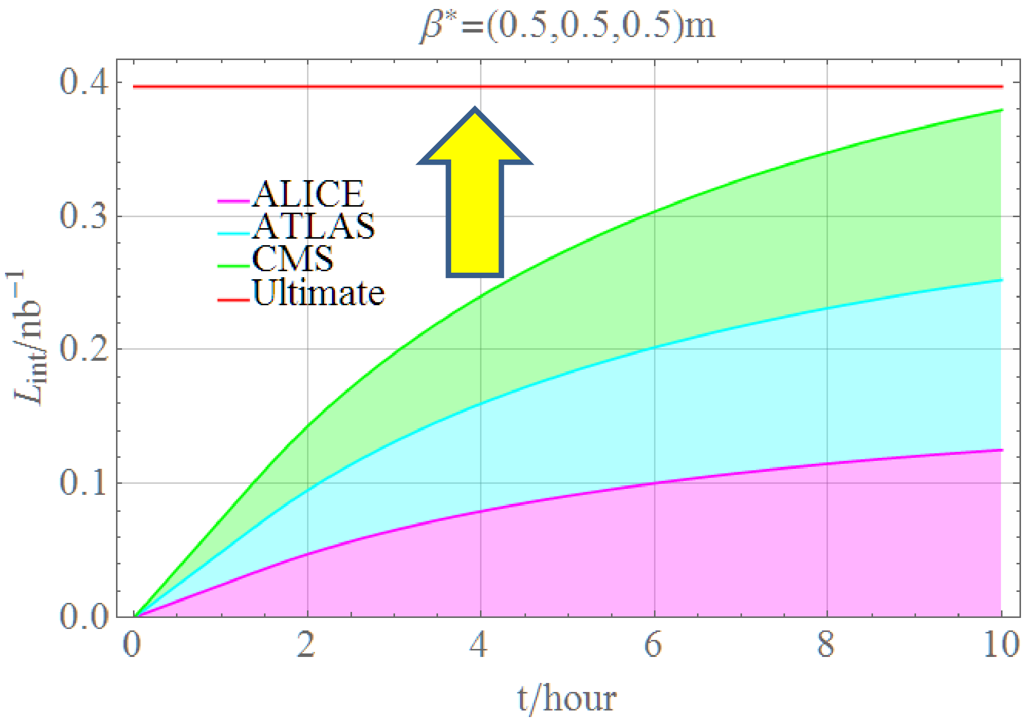


ATLAS or CMS, *assumed* levelling at slightly higher levels than ALICE

Integrated luminosity in prolonged fills





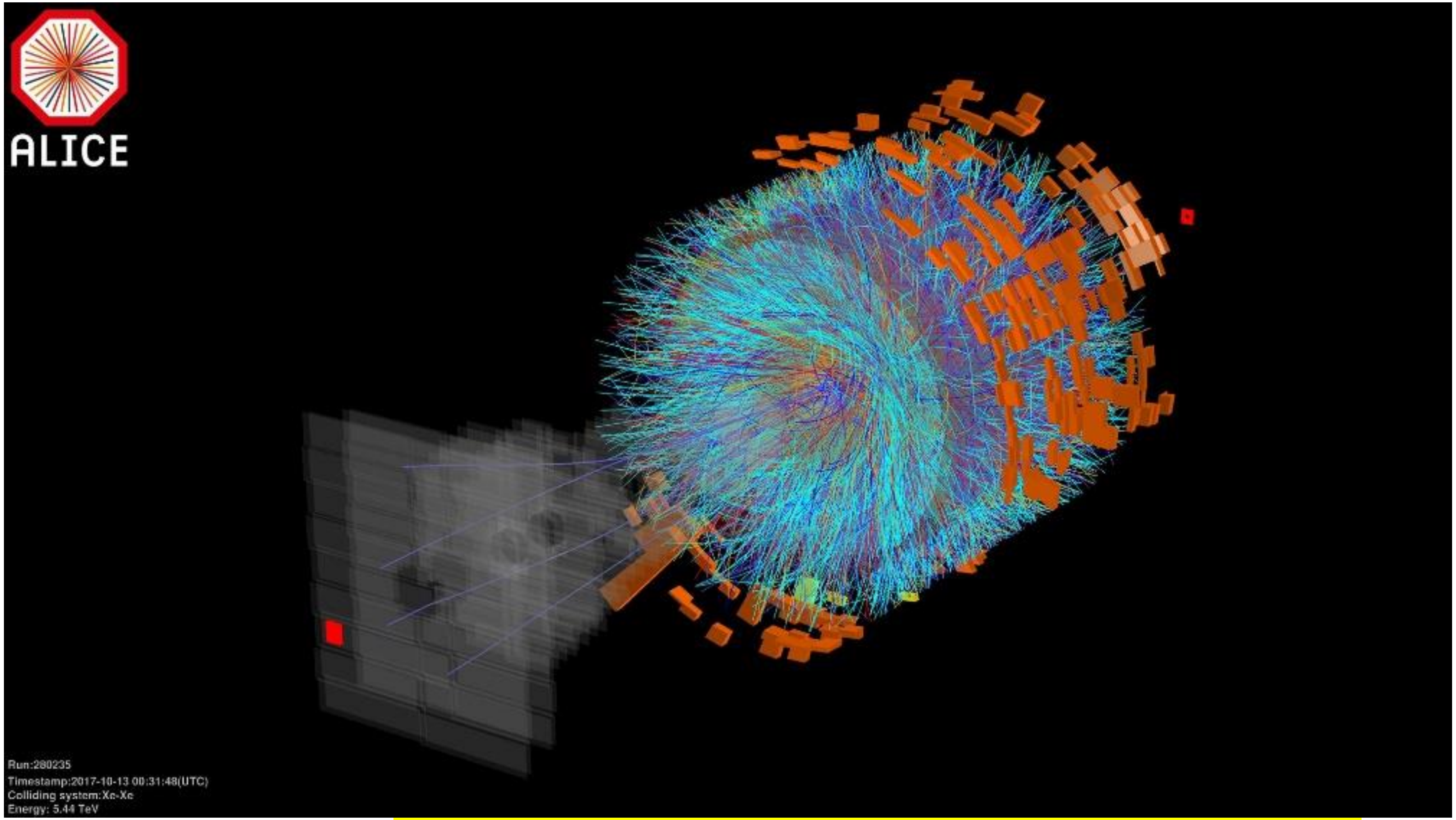


Ultimate luminosity to share

$$L_{int,max} = \frac{k_c N_b}{\sigma_c}$$

Fraction obtained is the luminous efficiency.

Xe-Xe collision in LHC, 13 October 2017



Future interest in lighter species? more partonic luminosity

Papers:

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

Conclusions and outlook

- Heavy-ion operation of LHC has surpassed initial expectations both
  - quantitatively (3.5 times design luminosity after about 10 weeks of Pb-Pb operation since 2010)
  - qualitatively (asymmetric p-Pb collisions, unforeseen in the design, have yielded almost 6 times their nominal luminosity and a rich harvest of unexpected physics results).
- It has been possible to rapidly recommission the LHC in multiple new configurations very efficiently.
- The foundations are almost laid for another order of magnitude in integrated Pb-Pb luminosity in the coming years.
- The largest remaining uncertainties are related to the high collimation inefficiency of nuclear beams and the implementation of slip-stacking injection in the SPS.
- First Xe–Xe collisions have demonstrated the potential of lighter species as a path to higher hadronic luminosity.