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FIRST XENON-XENON COLLISIONS IN THE LHC

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Abstract

In 2017, the CERN accelerator complex once again demonstrated its flexibility by producing beams of a new ion species, xenon, that were successfully injected into LHC. On 12 October, collisions of fully stripped xenon nuclei were recorded for the first time in the LHC at a centre-of-mass energy per colliding nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$. Physics data taking started 9.5 h after the first injection of xenon beams and lasted a total of 6 h. The integrated luminosity delivered to the four LHC experiments was sufficient that new physics results can be expected soon. We provide a general overview of this Xe-Xe pilot run before focussing on beam data at injection energy and at flat-top.

INTRODUCTION

To date, the LHC heavy-ion programme [1] has been based on collisions of lead ($^{208}\mathrm{Pb}^{82+}$) nuclei, either in Pb–Pb or proton-lead (p–Pb) collisions. The total cross-section for Pb–Pb collisions is dominated by ultraperipheral electromagnetic interactions, which cause the initial beam intensity to decay rapidly. Since the cross-sections for these interactions are proportional to high powers of the nuclear charge, Ze, the beam lifetimes in collisions with lighter nuclei are longer. As a result, more particles are available for hadronic interactions (whose cross-sections vary relatively weakly with the mass number, $A^{2/3}$) and the integrated nucleon-nucleon luminosities are expected to significantly exceed those available with heavier ions. For some physics studies, this can compensate for the smaller volume of Quark-Gluon Plasma created in the most central collisions.

The original design of the LHC did not foresee the operation with species other than protons and Pb ions. Nevertheless it was always kept in mind by the experiments and the possibility of colliding lighter nuclei in the LHC is now been actively considered for high-luminosity operation beyond LHC Run 3.

In 2017, the SPS provided xenon ($^{129}\mathrm{Xe}^{54+}$) beams for its fixed-target programme [2]. Since this was probably the last time, at least for several years, that a species other than Pb would be available from the injector complex, the opportunity was taken to inject them in the LHC and make a short physics run with Xe–Xe collisions. Xe was the third nuclear species brought into collision in the LHC, expanding the spectrum of operational collision species combinations to four (p–p, Pb–Pb, p–Pb, Xe–Xe).

EXECUTION OF THE RUN

A total of about 18 h of LHC time were taken for the Xe collision run. The schedule was designed to include set-up, first injection, validation and physics data taking. A further 12 h were devoted to experiments on crystal collimation, described elsewhere [3]. This tight schedule was only feasible by drastically reducing the complexity of the set-up following the model of the p–Pb pilot run in September 2012 [4, 5] when first injection, validation and physics data-taking were achieved within a single fill. With the same ion species in both rings, the preparation of Xe-Xe collisions was easier than the first set-up of p-Pb, since there was no need to commission a ramp with unequal RF frequencies and the subsequent cogging after RF-frequency locking at collision energy.

Changes to the operational proton cycle were kept to a minimum so that the set-up could be completed within 8 h. The proton-proton configuration was used, all the way from injection to the end of the squeeze to $\beta^* = (0.3, 10, 0.3, 3)\,\mathrm{m}$ in ATLAS, ALICE, CMS and LHCb. The only change to the nominal configuration was the reduction of the external crossing angle in ALICE in order to operate at the usual $\pm 60\,\mu\mathrm{rad}$ at the interaction point (IP), preserving the spectator neutron cone acceptance for the Zero Degree Calorimeters. Compared with the optics for the usual Pb-Pb runs, this was a compromise as it did not provide ALICE with luminosity comparable to ATLAS and CMS. This was compensated to some extent by arranging twice as many colliding bunches in ALICE.

Figure 1 shows the time evolution of the beam intensities and energy and also indicates some important stages of the run: Set-up started with a synchronisation of the RF systems between SPS and LHC, taking into account the revolution frequencies of the new species. After this, injection and circulation of the first Xe bunch was established quickly in both rings. Standard beam measurements of tune, chromaticity, coupling and emittances were performed before collimation loss maps [6] to validate the injection configuration. The machine was then filled with 20 low-intensity bunches per beam. Four non-colliding bunches among them were used for loss maps after the energy ramp to 6.5 Z TeV and in the physics configuration (colliding beams after squeezing to final β^* values). A total beam intensity of 3×10^{11} charges[1] was allowed during the whole operation with Xe beams to respect machine protection constraints (on total intensity) and allow an abbreviated validation of the machine config-

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[1] Roughly that of 2–3 nominal proton bunches.

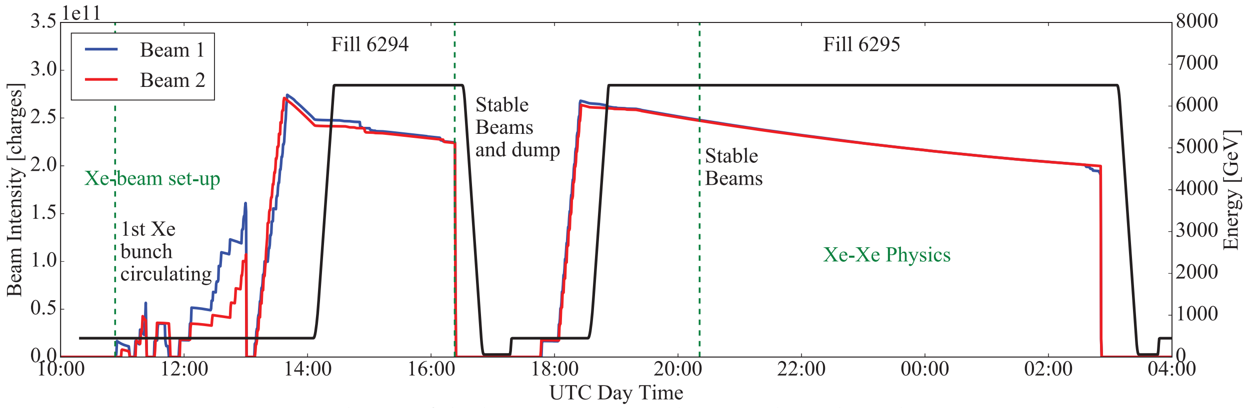

Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

uration [6] in collision conditions. The crossing angle in ALICE was only changed after the beams were brought into collision. The beams were dumped just as "Stable Beams"[2] were declared because an orbit interlock triggered on non-incorporated orbit changes introduced by the crossing angle change.

This mishap was a blessing in disguise because the cycle validation with loss maps was finished and the non-colliding bunches could be omitted for the refill of the collider. This allowed the LHC to accept the full single bunch intensity available from the injectors and led to higher initial luminosity in the second fill and, most likely, higher integrated luminosity in the end. Finally, Stable Beams were declared at 20:21 UTC, and the experiments embarked on 6 h of physics data-taking.

A summary of the beam and collider parameters at the start of data-taking is given in Table 1. Figure 2 shows the luminosity evolution in the four experiments. Since an absolute luminosity calibration is not available at the moment of writing, the plot shows the collision rate published by each experiment normalised to its value at the start of collisions (before crossing angle change in ALICE).

With just 16 Xe bunches per beam, the integrated luminosity delivered to the four large LHC experiments was comparable to that delivered with Pb-Pb collisions in the first one-month run in 2010.

BEAM PARAMETERS AND EVOLUTION

Intensity Lifetime

The beam lifetime is an important parameter giving insight into luminosity burn-off and beam quality. Because of the positioning of the detectors along the circumference of the LHC, some bunches do not collide in certain IPs. This behaviour gives rise to a maximum of 8 different so-called beam-beam equivalence classes defining the collision pattern of each bunch. However, since the bunch number was small, only 5 classes during fill 6294 and 4 classes during fill 6295 were represented. Table 2 displays the 5 different classes in question and their respective collision schedule.

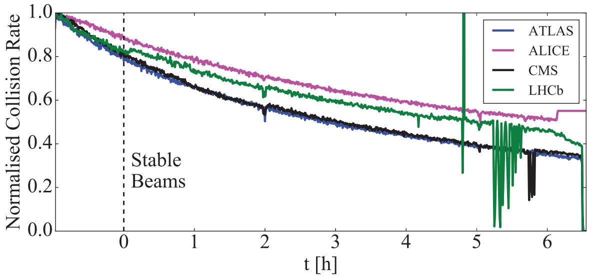

Figure 2: Evolution of the normalised collision rate during fill 6295. Normalisation defined at time of first collisions.

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)

The evolution of the bunch intensities in Beam 1 during Stable Beams of fill 6295 are displayed in Fig. 3. The two classes with low luminosity burn-off (magenta and cyan lines) decay significantly slower than the classes with larger burn-off (black and green lines). In the case of equal colliding species with roughly the same bunch intensities, the intensity decay cannot be expected to be exponential.

Because of the short fill duration (~6 h), exponential fits can reasonably be used to obtain the lifetimes of the individual bunches. The relative loss rates of the bunch intensities,

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[2] Beam mode used to communicate to the experiments that stable collision conditions are established.

Table 2: Beam-beam equivalence classes with their respective colour code used throughout the paper. In addition, the sum of inverse-β^* and the intensity lifetimes during Stable Beams of fill 6295 are displayed. The intensity lifetime of the non-colliding class (class 0) is obtained via linear fit of the loss rates (see Fig. 4).

Class	IPs	$\sum_i \frac{1}{\beta_i^*}$ [m^{-1}]	τ [h]
0	-	0	87.8 ± 5.9
1 ●	2	0.10	79.2 ± 4.6
2 ●	2/8	0.43	72.1 ± 3.8
3 ●	1/2/5	6.77	17.5 ± 0.8
4 ●	1/2/5/8	7.10	16.3 ± 1.1

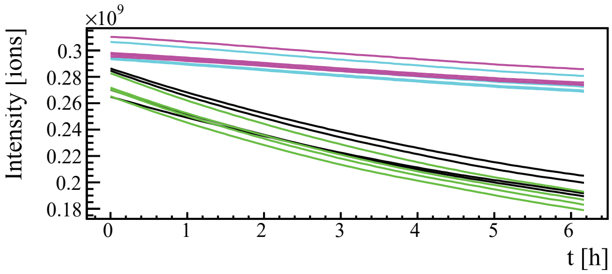

Figure 3: Bunch-intensity evolution of Beam 1 during fill 6295 after declaration of Stable Beams. The colour of each class is listed in Table 2.

i.e., the inverse lifetimes ($1/\tau$), are in good approximation proportional to $\sum_{IP} 1/\beta^*_{IP}$, of the respective equivalence class, as shown in Fig. 4. Both beams exhibit similar loss rates for the corresponding equivalence classes. Since no non-colliding bunch existed in fill 6295, the non-colliding lifetime of about 100 h is obtained via linear extrapolation (dashed lines in Fig. 4). The intensity lifetimes of all equivalence classes are listed in Table 2.

Transverse Emittance

During the two Xe fills, the LHC wire scanners were the only reliable source of absolute emittance values. For different particle species, the synchrotron radiation telescope (BSRT) needs special calibration, which was omitted due to the tight schedule. The normalised emittance at the beginning of Stable Beams was around $\epsilon_{H,n} = 1.5$ µm in horizontal and $\epsilon_{V,n} = 1.0$ µm in vertical. Injected emittances were around 20% smaller.

Bunch Length

At high ion-bunch intensities, the longitudinal growth rate due to intra-beam scattering (IBS) is predominant compared with the effect of radiation damping. Since the luminosity burn-off causes a rapid decay of the intensity and the bunch volume increases over time, a point might be reached at which the effect of radiation damping becomes dominant. Figure 5 shows the evolution of the bunch-length of bunches in Beam 1 during Stable Beams.

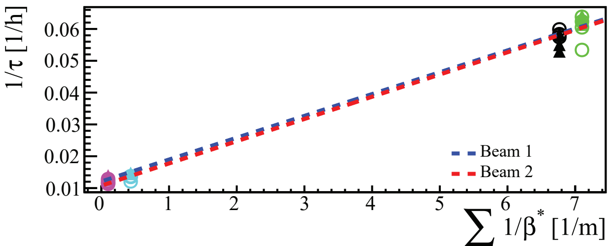

Figure 4: Relative loss rates versus $\sum_{\rm IP} 1/\beta^*_{\rm IP}$ during Stable Beams of fill 6295. Triangles indicate Beam 1 and circles Beam 2. The dashed lines are linear fits to obtain the non-colliding intensity lifetime.

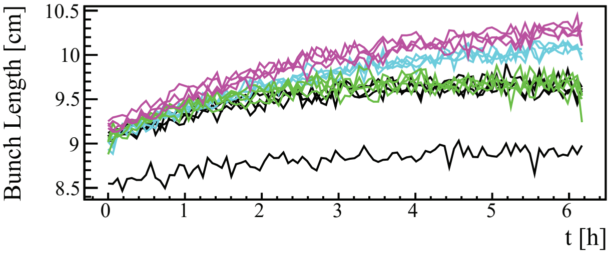

Figure 5: Bunch-length evolution of Beam 1 during Stable Beams of fill 6295.

The bunch length of the two bunch classes with high luminosity burn-off (black and green lines) slows down its growth and might even start to shrink approaching the 5 h mark, while the bunch length of the two classes with low luminosity burn-off (magenta and cyan lines) continues to grow.

CONCLUSION

The CERN heavy-ion injectors and LHC have demonstrated the production and collisions of a medium-mass nuclear species. High-intensity, high-brightness Xe beams were produced in the injector chain and brought into collision at a beam energy of 6.5 Z TeV in the LHC within just a few hours from first injection. During 6 h of stable collisions about 3 µb^{-1} were delivered to ATLAS and CMS. Because of the larger β^* values, fractions of 1 µb^{-1} were delivered to ALICE and LHCb.

This outcome is comparable to the 10 µb^{-1} per experiment delivered in the first one-month heavy-ion run in 2010 with Pb-Pb collisions. Luminosity lifetimes longer than for Pb could be observed and are consistent with the predicted cross-sections for ultraperipheral electromagnetic processes.

This run also provided valuable data on the beam cleaning and collimation efficiency with lighter ions [6]. After the physics data taking finished, experiments on crystal collimation of Xe beams were successfully performed [3] in a further fill.

ACKNOWLEDGEMENT

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