ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

COLLIDING HEAVY IONS IN THE LHC

John M. Jowett*, CERN, Geneva, Switzerland

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 programme, including injector performance.

INTRODUCTION

Hadron colliders of the late 20th century were focussed on elementary particle physics so collided mainly protons and anti-protons, the *most elementary* hadronic entities available (CERN's ISR were very briefly an exception [1] to this rule). The 21st century opened with the first colliding beams of gold nuclei—some of the *least elementary* hadronic entities that one can hope to accelerate to high energies—at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory. A decade later, the LHC at CERN continued the programme by colliding lead nuclei at energies over an order-of-magnitude greater for the exploration of hadronic matter at extreme energy density and temperature.

Both hadron colliders currently operating are colliding beams of atomic nuclei (fully stripped heavy-ions) and the active proposals for future hadron colliders, at very high and very low energies, all consider heavy-ion collisions. More remarkably still, although it was not always part of their initial ambitions, *all active experiments* at hadron colliders are now exploiting their complementary capabilities for heavy-ion physics.

Quantum Chromodynamics is the only sector of the Standard Model whose collective and thermodynamical behaviours are amenable to laboratory study (for a recent review, see [2]). RHIC experiments found that their manifestation in the deconfined Quark-Gluon Plasma (QGP) had the unanticipated properties of a strongly-coupled, almost perfect fluid. As foreseen, the higher temperature, longer lifetime and more rapid equilibration of the QGP at the LHC allow studies with a broader spectrum of quarkonia as hard probes. Unexpected phenomena, characteristic of collectivity in small systems were discovered in the first pilot fill of p–Pb collisions in 2012 (see below), and even in rare, high-multiplicity p–p collisions. As at RHIC, thermal production of the heaviest man-made anti-matter and hyper-matter nuclei is observed.

Highly-charged, ultra-relativistic nuclei generate intense electromagnetic fields, equivalent to pulses of quasi-real photons with spectrum extending to hundreds of GeV at the LHC. Ultraperipheral collisions, where the impact parameter is too large for nuclear overlap ($b > 2R_A$), induce photon-photon and photonuclear interactions with cross-sections depending on high powers of the nuclear charge Z. Besides creating a new class of collisional effects limiting collider performance (see below), these access high-energy phenomena beyond those associated with the QGP. A striking example is the first observation of the long-anticipated elastic scattering of light by light [3].

Another difference between the present generation of hadron colliders and their predecessors is the operational paradigm. The previous pp, $p\bar{p}$ and, indeed, also e^+e^- and ep colliders were dedicated, most of the time, to optimised steady luminosity accumulation at the highest energy. Conditions generally changed only slowly as the operators fine-tuned their parameters. Colliding multiple hadronic species, often at specific energies, introduces a third dimension beyond energy and luminosity. In the case of the LHC, the schedule requires recommissioning of a new collision configuration, its validation for the strict requirements of machine protection, an intensity ramp-up and a period of physics data-taking, all within a month. It is hardly possible to identify periods of steady operation in these runs as new ways to improve performance are brought in, almost day-by-day. Recent runs have piled on complexity with multiple variations of the configuration to meet experimental requirements within the same time frame. For example, the LHC is required to make reference p–p, p–Pb and Pb–Pb runs at the same centre-of-mass energy *per colliding nucleon pair* $\sqrt{s_{\rm NN}} = \sqrt{Z_1 Z_2/A_1 A_2}$ (for colliding species $(Z_{1,2}, A_{1,2})$), to elucidate the emergence of collective behaviour in the multi-nucleon systems. Each run also includes interruptions for detector solenoid field reversals, Van der Meer scans, ion-source refills and a strictly minimal set of beam physics studies.

In this talk, I can only outline the main features of the LHC heavy-ion programme to date. Please consult the references for further detail and a proper appreciation of the contributions of many colleagues.

* john.jowett@cern.ch

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

Expectations for the LHC

Early planning of the LHC heavy-ion programme was driven mainly by the requirements of the specialised ALICE experiment. The design Pb–Pb luminosity, $L = 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ [4] at the maximum beam energy, $E_b = 7Z\,\mathrm{TeV} = 2.76A\,\mathrm{TeV} \Rightarrow \sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ for Pb with $Z = 82$, $A = 208$, was matched to the capacity of its 88 m^3 time-projection chamber (TPC) to provide a complete reconstruction of the very high-multiplicity final states. With the assumption that a second experiment would also take data, an integrated luminosity goal of $\simeq 1\,\mathrm{nb}^{-1}$ per experiment over the initial phase of operation was set, assuming annual runs lasting one month. Although the experiments had expressed interest, no collisions of species combinations other than p–p and Pb–Pb were included in [4].

By the time of the first Pb–Pb run in 2010, both of the general-purpose experiments, ATLAS and CMS, were participating in addition to ALICE. The asymmetric experiment LHCb joined in for the first p–Pb collisions in 2012.

INJECTOR COMPLEX

The original design and parameters of the heavy-ion injectors for the LHC are described in [5]. Meanwhile a series of beam production modes have been implemented [6–8] in a successful quest to achieve performance far beyond the design, the LHC Injectors Upgrade (LIU) project [9].

Upstream of the CERN PS, ion beams have a separate chain of injectors from protons. Heavy ion beams are created in an electron cylotron resonance (ECR) source. In the case of Pb, this starts with the vaporization of a pellet of isotopically pure ^{208}Pb in the source, which is followed by an RFQ and the heavy-ion Linac3, tuned for the acceleration of $^{208}\mathrm{Pb}^{27+}$, and subsequently stripped to $^{208}\mathrm{Pb}^{54+}$, before injection into the Low-Energy Ion Ring (LEIR). Linac3 output intensity increased by 40% between 2015 and 2017 thanks to removal of an aperture restriction at source extraction [8].

Each of several 200 μs pulses from the linac is accumulated by stacking in 6D phase space in a 70-turn injection process with electron cooling followed by RF capture at the injection kinetic energy of 4.2 MeV/u before acceleration. Up to 2015, intensity was limited by losses at the capture phase due to betatron resonances and a large incoherent space-charge tune spread. These were greatly reduced by extensive efforts to optimise settings and modify the RF capture in 2016.

Transfer of the resulting 2 bunches from LEIR to the PS is now almost loss-free and it was possible to reinstate the bunch-splitting foreseen in [5] in 2016 in order to mitigate losses later in the SPS, resulting in a train of 4 bunches spaced by 100 ns instead of 2 bunches at 200 ns, with similar bunch intensity N_b. In the PS itself, losses are minimal, dominated by interactions with residual gas. The final stripping of $^{208}\mathrm{Pb}^{54+}$ to bare nuclei of $^{208}\mathrm{Pb}^{82+}$, occurs in the transfer line to the SPS which remains the largest intensity bottleneck in the whole chain of injectors. Most losses and significant emittance blow-up occur on the long injection plateau needed to accumulate injections from several 3.6 s cycles of the PS and are due to a combination of intra-beam scattering (IBS) and space-charge with a incoherent tune-shift up to $\Delta Q_y \simeq -0.3$. The spacing between PS batches was reduced to 150 ns in 2015 thanks to reductions of the SPS injection kicker rise time. Together with the upstream intensity increases, this allowed the injection plateau to be shortened from 12 to 7 PS injections between 2015 and 2016.

The goals of the LIU project to provide the Pb beams required for the baseline HL-LHC heavy-ion performance after LS2 are thus mostly achieved. The last remaining step will be the implementation of slip-stacking of two bunch trains in the SPS to give a basic spacing of 50 ns in the LHC [9].

An intermediate backup scheme, already tested with Xe beams [10], providing 3 bunches out of LEIR, and a final spacing of 75 ns, may already be used for the 2018 Pb–Pb run.

COLLIDING NUCLEI WITH NUCLEI

Tab. 1 gives a broad, highly simplified, overview of the evolution of the principal beam parameters in the heavy-ion runs to date and compares with the original design and the "HL-LHC" goal [11] for the next decade.

First Commissioning 2010

Commissioning of the first Pb–Pb collisions at the reduced beam energy of 3.5 Z TeV in 2010 [12] followed a cautious approach, exploiting the principle of equal magnetic rigidity to re-establish the orbit and identical optics of the preceding p–p run. The only change was the reduction of the crossing angle to zero in the ALICE experiment, with opening of the tertiary collimators, to allow unimpeded passage of spectator neutrons to the zero-degree calorimeters (ZDCs). Following RF capture with modified frequency and the necessary series of collimation loss-map validations at the main steps of the magnetic cycle, first collisions were established within 4 days and the ramp-up to full performance (Tab. 1, [12]).

This run showed the importance of very carefully crafted commissioning plans, the extraordinary reproducibility and reliability of the LHC hardware and the maturity of operating procedures and controls. Numerous concerns about the feasibility of heavy-ion operation were laid to rest and there was an immediate harvest of significant physics results. A first test of a mitigation scheme for the BFPP loss mechanism (see below) was made.

Luminosity Increase in 2011

In the second Pb-Pb run [13] at 3.5 Z TeV, several improvements were made: longer trains of bunches were injected [18], the optics was modified to provide $\beta^* = 1$ m in ALICE as well as ATLAS and CMS. This resulted in substantial spreads in the intensities and emittances of individual bunches along the trains [19]. The integrated luminosity increased by more than an order of magnitude.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

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

Quantity	"design"		achieved					upgrade
Year	(2004)	(2011)	2010	2011	2012–13	2015	2016	≥2021
Weeks in physics	-	-	4	3.5	3	2.5	1, 2	-
Fill no.			1541	2351	3544	4720	5562	-
Species	Pb–Pb	p–Pb	Pb–Pb	Pb–Pb	p–Pb	Pb–Pb	p–Pb	Pb–Pb
Beam energy $E [Z\,\mathrm{TeV}]$	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 $\sqrt{s_{\mathrm{NN}}}$ [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} $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	150	0.03	0.5	116	3.6	850	6
NN lumi. L_{NN} $[10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\boxed{43}$	$\boxed{31}$	1.3	22.	24	$\boxed{156}$	$\boxed{177}$	$\boxed{260}$
Integrated lumi./expt. [$\mu\mathrm{b}^{-1}$]	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

Beyond Design Luminosity in 2015

The 3rd and latest Pb-Pb run took place after a long shutdown which allowed proton operation at higher energy. However the beam energy was reduced slightly from the 6.5 Z TeV that was used for protons to 6.37 Z TeV in order to match the $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV of the 2013 p–Pb run (see below) and a reference p–p run that occupied the first week of the allotted month [15]. These were the first collisions at a total centre-of-mass energy beyond 1 PeV.

Confidence in the ability to rapidly recommission the LHC had grown to the point where an almost completely new optics and squeeze sequence were implemented. LHCb took Pb-Pb collisions for the first time with $\beta^* = 3$ m. During this run, several improvements were brought in, including a variety of complex filling schemes that allowed the number of bunches to increase from 426 to 518. Although ALICE was levelled at the design saturation value, luminosity went over 3.5 times beyond design in ATLAS and CMS. With the increased energy, synchrotron radiation damping could counter the blow-up of emittances by IBS.

Secondary Beams from the IPs

Among the many processes induced by the intense photon fields in ultraperipheral collisions of Pb nuclei, bound-free pair production (BFPP)

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \rightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^+ \qquad (1)$$

creates a secondary beam of $^{208}\mathrm{Pb}^{81+}$ with a fractional rigidity change $\delta = 0.01235$ that impinges in the dispersion suppressor.

Estimates for the cross section of BFPP have varied since the early realisation that they were in the range of hundreds of barns [20] but various calculations (e.g., [21]) eventually converged to $\sigma \simeq 280$ b and are now considered accurate at the level of a few %.

Concerns that this process could constitute a direct limit on the luminosity of the LHC were raised in [22] which pointed out that the powerful secondary beams of hydrogen-like ions had the potential to quench superconducting magnets downstream of the IP.

First estimates with a realistic optics model [4, 23–25] were subject to long-standing uncertainties in the level of steady-state energy deposition that would quench the magnet coils. In 2003, LHC construction was in full swing, to a strictly constrained schedule, and one could not contemplate the modification of cryogenic sections to inserting special absorbers in the dispersion suppressors.

The question of the quench level was the subject of many studies in the following years with luminosity apparently limited below the design value [26].

The 2015 run demonstrated a technique using orbit bumps to displace the BFPP losses safely into a connection cryostat. The question of the quench limit was finally resolved in the

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

first successful controlled quench test measurement at the LHC [27, 28] which showed that the true level was at about 2.3 times the Pb-Pb design luminosity.

Collimation

When nuclear beams interact with the carbon of the primary collimators in the LHC, fragments are produced by a variety of electomagnetic dissociation and hadronic fragmentation reactions [29]. These are lost in numerous locations in the collimation insertions and elsewhere, again potentially quenching superconducting magnets. The physics of nuclear beams interacting with collimators results in significantly higher collimation inefficiency than for protons [30, 31].

Xe-Xe Collisions

Most recently the LHC collided xenon nuclei during a short run on 12 October 2017, described in [32]. Thanks to the injector performance [10] and a rapid commissioning strategy similar to that of the p-Pb pilot run in 2012 it was possible to accumulate a significant luminosity in all four experiments. Since the cross sections for processes like 1 are much smaller, the effective partonic luminosity can be significantly higher than in Pb-Pb. Collimantion of Xe was also studied [33].

Results from all four experiments are anticipated at the forthcoming Quark Matter conference (May 2018).

COLLIDING PROTONS WITH NUCLEI

The two-in-one design of the LHC's main magnets impose equal magnetic rigidities of the beams in the two apertures—if they are to stay on the same central orbits. They will then have unequal revolution frequencies, with Pb beams making 8 fewer turns of the ring per minutes than protons. The displacement of orbits imposed by equalising the beams' RF frequencies is acceptable at collision but not at injection energy. Beam losses and instabilities seen with an analogous mode of operation of RHIC [34] led to scepticism concerning the prospects of p–Pb collisions in the LHC until it was argued that the effects of moving long-range beam-beam encounters were smaller and, to some extent, cancelled in the LHC [35]. A "design luminosity" from [35] was adopted in the physics case document [17], Tab. 1.

First Runs

A feasibility test of unequal frequency injection, ramping ang cogging to equalise frequencies at top energy was finally performed in 2011. This led to a 16 h pilot physics run in 2012 [14, 36] and the unexpected discoveries of long-range correlations indicating collectivity in small systems. In early 2013, the first full p-Pb run took place, gaining 3 orders of magnitude in luminosity in a few days. Operation included separate chromatic correction of the "off-momentum" collision optics, complex filling schemes to illuminate LHCb for the first time, r Van der Meer scans, low-luminosity minimum-bias running, and manipulation of luminosity burn-off to equalise luminosity among the experiments [7, 35]. Reversal of the beam directions half-way through required a partial recommissioning and validation of the optics.

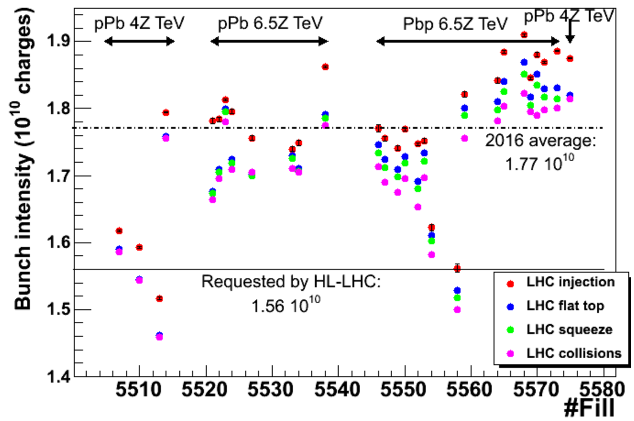

Figure 1: Average bunch intensity (in elementary charges) for each fill during the 2016 p-Pb run, at stages between LHC injection and the start of collisions (from [8]).

Multiple Conditions in 2016

The LHC experiments' requirements for the second p-Pb run in 2016 diverged. ALICE requested low-luminosity minimum-bias operation at the 2013 energy of 4 Z TeV while ATLAS and CMS requested maximum energy (6.5 Z TeV) and luminosity. A complex run scheme, based on the physics of beam lifetime, was proposed with an initial week in the ALICE conditions followed by 2 weeks in the ATLAS/CMS conditions. Further goals for all experiments, including LHCb and LHCf, were worked into the prioritised plan [16]. The low luminosity conditions allowed extremely long fills (up to a record 38 h) and an unprecedented 75% of time spent in Stable Beams. In the high-energy phase, luminosity approached 6 times the "design" value thanks to the implementation of synchronous operation of beam-position monitors allowed the proton bunch charge to be increased beyond that of the Pb beam. In the end all high-priority and most subsidiary physics goals were met.

Fig. 1 shows the substantial improvements [8] in in injector performance and how it evolved during the run.

FUTURE PERFORMANCE

LHC Run 2 will end in early December with a one month Pb-Pb run for which detailed plans are taking shape. Although the Pb–Pb runs have been fewer than anticipated, the luminosity goals of the first phase of operation are in sight. The use of an ATS optics in the preceding p–p operation has required a substantially new opticswith $\beta^* = 0.5$ m in ALICE, ATLAS and CMS and $\beta^* = 1.5$ m, in LHCb. With the bunch intensities already achieved by the injectors in 2016 and a denser filling scheme (possibly reducing the basic spacing from 100 to 75 ns) a substantial improvement over the 2015 performance is expected.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

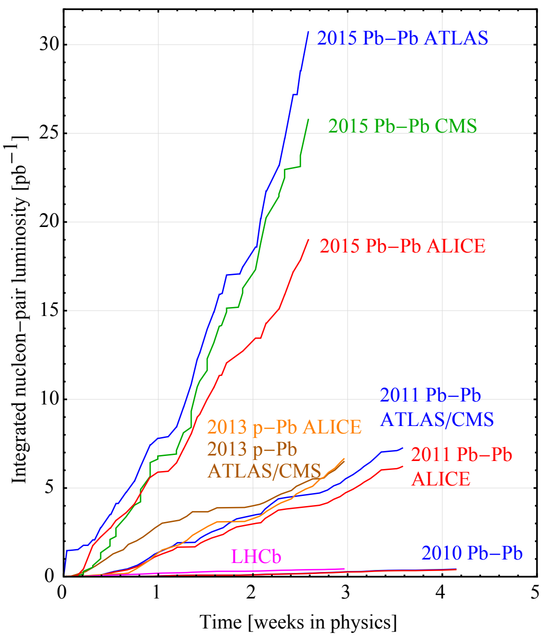

Figure 2: Nucleon-nucleon integrated luminosity in each experiment in all LHC heavy-ion runs to 2015 [12–15], from the first declaration of Stable Beams.

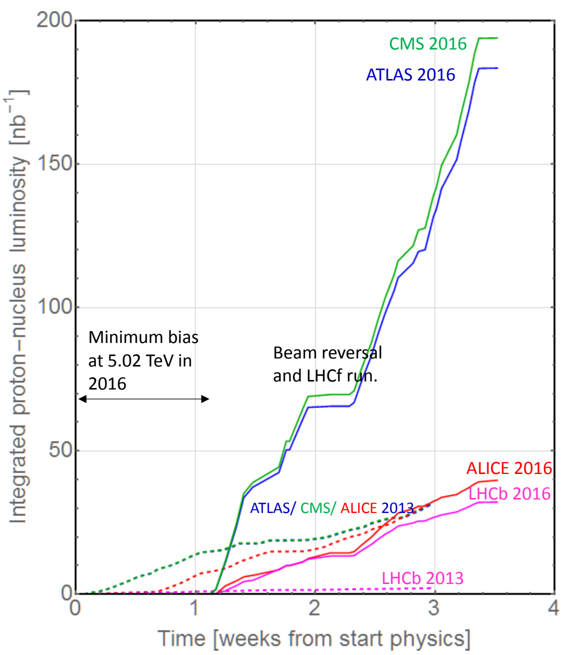

Figure 3: Accumulation of integrated luminosity in each LHC experiment in the p-Pb runs of 2013 and 2016 [14,16], counted from the first declaration of Stable Beams.

A major upgrade of the ALICE detector in the forthcoming LHC shutdown (end of 2018 to 2021) will allow its luminosity to be levelled at $5\times10^{27}\ \mathrm{cm^{-2}s^{-1}}$ similarly to ATLAS and CMS. Although they are currently under review, the present baseline goals for the 2021–29 phase of operation [11,37] include one p–p reference run at $s_{\mathrm{NN}} = 5.5$ TeV, a short p–Pb run and one Pb–Pb run with low magnetic field to study low-mass dileptons. The remaining three one-month runs scheduled before 2029 should accumulate $10\,\mathrm{nb}^{-1}$ of Pb–Pb luminosity in each of the ALICE, ATLAS and CMS experiments. The luminosity goals for LHCb are being finalised but are expected to be of the order of 10% of this.

Single bunch intensities have already exceeded these requirements and the only major step left to achieve the required intensity in the LHC [11] is the implementation of slip-stacking injection in the SPS, which will provide close to a factor 2 in total intensity.

In the LHC itself, the only significant hardware upgrade being made for future heavy-ion operation is the installation of dispersion suppressor collimators (TCLDs) in IR2, to mitigate the BFPP loasses and in the betatron collimation insertion IR7, to improve the cleaning efficiency for both protons and heavy ions [38].

CONCLUSIONS AND OUTLOOK

Heavy-ion operation of the LHC has surpassed initial expectations both quantitatively (3.5 times design luminosity after about 10 weeks of Pb-Pb operation since 2010, Fig. 2) and qualitatively (asymmetric p-Pb collisions, unforeseen in the design, have yielded almost 6 times their nominal luminosity, Fig. 3, 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.

ACKNOWLEDGEMENTS

The success of LHC heavy-ion operation depends, not only on the small team who specialise in it, but also on the work of numerous colleagues who contributed to the design, construction, understanding and operation of the LHC and its injectors since the early 1980s.

REFERENCES

[1] W. Fischer and J. M. Jowett, "Ion Colliders," *Rev. Accel. Sci. Tech.*, vol. 07, pp. 49–76, 2014.

[2] J. Schukraft, "QM2017: Status and Key open Questions in Ultra-Relativistic Heavy-Ion Physics," *Nucl. Phys.*, vol. A967, pp. 1–10, 2017.

[3] M. Aaboud *et al.*, "Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC," *Nature Phys.*, vol. 13, no. 9, pp. 852–858, 2017.

[4] O. S. Brüning *et al.*, "LHC Design Report, Vol. 1. The LHC Main Ring," 2004.

[5] M. Benedikt *et al.*, "LHC Design Report. Vol. 3. The LHC injector chain," 2004.

[6] M. Angoletta *et al.*, "Ions for LHC: Performance of the Injector Chain," *Proc. 2nd Int. Particle Accelerator Conference*, San Sebastian, Spain, May 2011, pp. 2529–2531, 2011.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUXGBD2

[7] D. Manglunki *et al.*, "The First LHC p-Pb Run: Performance of the Heavy Ion Production Complex," *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13),* Shanghai, China, May 2013, paper WEPEA061, pp. 2648–2650.

[8] R. Alemany-Fernández *et al.*, "Performance of the CERN Injector Complex and Transmission Studies into the LHC during the Second Proton-Lead Run," *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17),* Copenhagen, Denmark, paper TUPVA128, pp. 2395–2398, 2017.

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

[10] R. Alemany-Fernandez *et al.*, "Performance of the cern low energy ion ring (leir) with xenon beams," *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, paper TUPAF020, this conference.

[11] J. M. Jowett *et al.*, "HL-LHC beam parameters for ions," *LHC Performance Workshop (Chamonix 2017)*, vol. https://indico.cern.ch/event/580313/, 2017.

[12] J. Jowett, G. Arduini, R. Assmann, P. Baudrenghien, C. Carli, , *et al.*, "First Run of the LHC as a Heavy-ion Collider," *Proc. 2nd Int. Particle Accelerator Conference,* San Sebastian, Spain, May 2011, pp. 1837–1839, 2011.

[13] J. M. Jowett *et al.*, "Heavy Ions in 2012 and the Programme up to 2022," *Proc. Chamonix 2012 Workshop on LHC Performance, CERN-2012-006*, 2012.

[14] J. M. Jowett, R. Alemany-Fernandez, *et al.*, "Proton-Nucleus Collisions in the LHC," *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13),* Shanghai, China, May 2013, paper MOODB201, pp. 49–51.

[15] J. M. Jowett *et al.*, "The 2015 Heavy-Ion Run of the LHC," *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, p. 1493, 2016.

[16] J. Jowett, R. Alemany-Fernández, *et al.*, "The 2016 Proton-Nucleus Run of the LHC," *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, paper TUPVA014, pp. 2071–4, 2017.

[17] C. Salgado, J. Alvarez-Muniz, F. Arleo, N. Armesto, M. Botje, *et al.*, "Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements," *J.Phys.*, vol. G39, p. 015010, 2012.

[18] D. Manglunki *et al.*, "Performance of the CERN Heavy Ion Production Complex," *Proc. 3rd Int. Particle Accelerator Conference,* New Orleans, USA, May 2012, vol. C1205201, pp. 3752–3754, 2012.

[19] M. Schaumann and J. M. Jowett, "Bunch-by-Bunch Analysis of the LHC Heavy-Ion Luminosity," *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13),* Shanghai, China, May 2013, pp. 1391–1393, May 2013.

[20] H. Gould, "Atomic physics aspects of a nuclear collider," *Lawrence Berkeley Laboratory Report No. LBL-18593*, 1984.

[21] H. Meier *et al.*, "Bound free electron positron pair production in relativistic heavy ion collisions," *Phys.Rev.*, vol. A63, p. 032713, 2001.

[22] S. R. Klein, "Localized beam pipe heating due to e-capture and nuclear excitation in heavy ion colliders," *Nucl.Instrum.Meth.*, vol. A459, pp. 51–57, 2001.

[23] J. M. Jowett, "Ions in the LHC ring," *Proceedings of the Chamonix 2003 Workshop on LHC Performance*, vol. CERN-AB-2003-008-ADM, 2003.

[24] J. M. Jowett, J. B. Jeanneret, and K. Schindl, "Heavy Ion Beams in the LHC," *Proc. of the Particle Accelerator Conf. 2003, Portland*, p. 1682, 2003.

[25] J. M. Jowett, H. H. Braun, *et al.*, "Limits to the performance of the LHC with ion beams," *Proceedings of the 2004 European Particle Accelerator Conference,* Lucerne, Switzerland*, May, 2004*, pp. 578–580, 2004.

[26] R. Bruce, S. Gilardoni, J. Jowett, and D. Bocian, "Beam losses from ultra-peripheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation," *Phys.Rev.ST Accel.Beams*, vol. 12, p. 071002, 2009.

[27] B. Auchmann *et al.*, "Bound-Free Pair Production in LHC Pb-Pb Operation at 6.37 Z TeV per Beam," *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, paper TUPMW028, pp. 1497–1500.

[28] C. Bahamonde Castro *et al.*, "Power Deposition in LHC Magnets Due to Bound-Free Pair Production in the Experimental Insertions," *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, paper TUPMW006, pp. 1418–1421, 2016.

[29] H. Braun, H. A. Fassò, A. Ferrari, M. Jowett, J. R. Sala, P. and I. Smirnov, G. "Hadronic and electromagnetic fragmentation of ultrarelativistic heavy ions at lhc," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 021006, Feb 2014.

[30] H. H. Braun *et al.*, "Collimation of heavy ion beams in LHC," *Proceedings of the 2004 European Particle Accelerator Conference,* Lucerne, Switzerland*, May, 2004*, paper MOPLT010, p. 551, 2004.

[31] P. Hermes *et al.*, "Simulation of Heavy-Ion Beam Losses with the SixTrack-FLUKA Active Coupling," *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, paper WEPMW029, pp. 2490–93, 2016.

[32] M. Schaumann *et al.*, "First xenon-xenon collisions in the LHC," *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, paper TUPVA014, p. paper MOPMF039.

[33] N. Fuster-Martinez *et al.*, "Cleaning performance of the collimation system with xe beams at the large hadron collider," *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, paper MOPMF038, this conference.

[34] T. Satogata *et al.*, "Commissioning of RHIC deuteron-gold collisions," *Proceedings of the 2003 Particle Accelerator Conference, Portland, Oregon*, pp. 1706–1708, 2003.

[35] J. M. Jowett and C. Carli, "The LHC as a proton-nucleus collider," *Proc. European Particle Accelerator Conf.,* Edinburgh, UK, May 2006, pp. 550–552, 2006.

[36] R. Alemany *et al.*, "First proton-nucleus collisions in the LHC: the p-Pb pilot physics," CERN-ATS-Note-2012-094 MD, Nov 2012.

[37] B. Abelev *et al.*, "Upgrade of the ALICE Experiment: Letter of Intent," Tech. Rep. CERN-LHCC-2012-012. LHCC-I-022. ALICE-UG-002, CERN, Geneva, Aug 2012.

[38] P. Hermes, R. Bruce, J. Jowett, *et al.*, "Betatron Cleaning for Heavy Ion Beams with IR7 Dispersion Suppressor Collimators," *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15),* Richmond,USA, May, 2015, paper TUPTY025, 2015.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.