PROCEEDINGS OF SCIENCE

Highlights from the LHC

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In this contribution, highlights of the LHC proton and ion runs are presented, from mid-2023 to mid-2025. Starting from the LHC injector chain, the main achievements and milestones, contributing to the production of HL-LHC proton and ion beams, are covered. Thereafter, the proton luminosity production over the past years is reported, detailing luminosity levelling, optics choices, and cryogenic heat load. Concerning the Pb ion program, the commissioning of slip-stacked HL-LHC ion beams is described along with the luminosity achievements and the special 2025 light-ion run. Finally, an outlook on high-intensity tests and main activities for the upcoming long shutdown is given.

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1. Introduction

The design of the Large Hadron Collider (LHC) [1] foresaw proton operation with a bunch intensity of $1.15{\times}10^{11}$ protons per bunch (p/b) and an optical betatron function at the ATLAS and CMS interaction points of $\beta^* = 55$ cm. In the LHC Run 1 (2010-2012), see Fig. 1, 30 fb^{-1} were accumulated, at a reduced beam energy of 3.5-4 TeV and a β^* down to 60 cm, which is remarkable given the larger-than-design transverse emittances at this lower beam energy. Already in Run 2 (2015-2018), a β^* down to 25 cm was achieved and the design luminosity was surpassed with 160 fb^{-1} accumulated at 6.5 TeV beam energy.

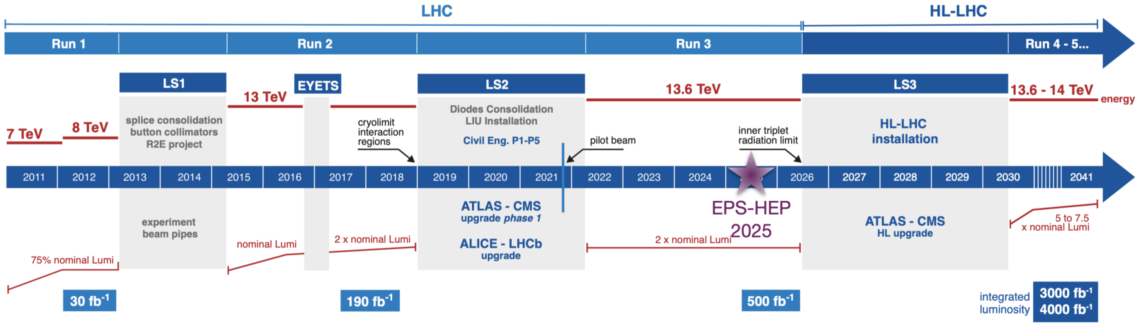

Figure 1: LHC and HL-LHC timeline with center-of-mass energy (dark red) and peak luminosity (light red). The overall accumulated proton luminosity, achieved or aimed at, is shown at the bottom.

In this report, we summarize the LHC performance between July 2023 and July 2025 for proton and ion operation. After a first phase at 30 cm and round optics, in the first half of 2025, a β^* of 60 cm and 18 cm were used in different transverse planes to obtain flat optics. The operational bunch intensity for protons was $1.6{\times}10^{11}$ p/b throughout the entire period. The yearly production reach with these parameters is 110-120 fb^{-1}, as was shown by the excellent results of 2024 operation. Till July 2025, 220 fb^{-1} were accumulated over Run 3 that started in 2022. For the LHC, Run 3 will end on the morning of 29th June 2026. By this date, the aim was to surpass the overall accumulated 500 fb^{-1} since the start of LHC operation; a goal that, at the time of writing, has already been accomplished.

Concerning ion operation, the machine has already entered the High-Luminosity (HL-)LHC era. New equipment and operation techniques have been commissioned in 2023, and challenges have been mitigated over the year-end technical stop (YETS). Thus, in the 2024 ion run, the HL-LHC bunch intensity and luminosity targets have been surpassed. In mid-2025, a successful special ion run took place as well, exceeding luminosity expectations.

For the HL-LHC era [2], the baseline parameters for proton luminosity production are $2.2{\times}10^{11}$ p/b and $\beta^* = 15$ cm, aiming at a yearly production of 300 fb^{-1}. Plans for beam tests in 2025-2026, as well as HL-LHC upgrades, and the restart in 2030 will be outlined at the end of the report.

2. Performance of LHC injectors

The success of the HL-LHC project relies on upgraded beam parameters from the injector complex. The LHC Injector Upgrade (LIU) took place during the Long Shutdown 2. One of

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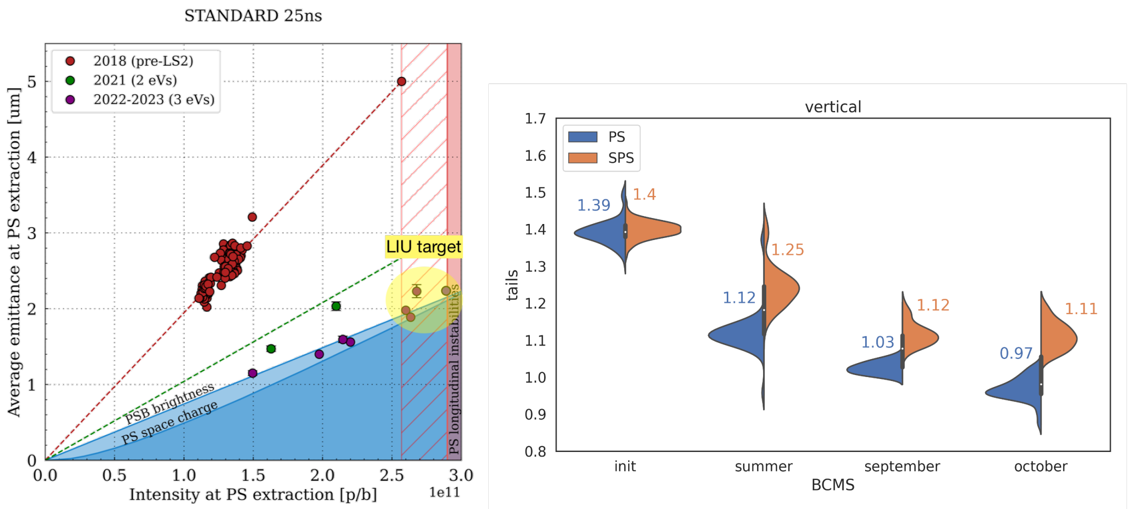
the main goals for Run 3 is to demonstrate reproducible production of HL-LHC beams, both for protons [3] and Pb ions [4]. For protons, an intensity ramp-up of HL-LHC beams took place in 2023. During this period, the Proton Synchrotron Booster (PSB) delivered beams beyond the LIU targets and the Proton Synchrotron (PS) reached LIU targets, see Fig. 2(a). In the Super Proton Synchrotron (SPS), some more scrubbing was needed. LIU parameters were established repeatedly in 2024 both with the ‘standard’ 25 ns spaced beam with 4 trains of 72 bunches (b), which is the HL-LHC baseline beam type, and the high-brightness ‘BCMS’ beam (produced using batch compression, merging and splitting in the PS) with 5 trains of 48 b, which is an alternative for HL-LHC. The BCMS beam was used for its smaller transverse emittance, at a reduced bunch intensity of 1.6×10^{11} p/b in operation. Its transverse tail population has been significantly optimized in the injection chain, see Fig. 2(b), to reduce beam losses in the LHC.



(a) PS reaching LIU target

(b) Improvement of tail population

Figure 2: Injector achievements for proton operation with LIU beams

Concerning the performance of the Pb ion injector chain (Fig. 3(a)), LINAC 3 operated with a beam current above the LIU target and also the Low-Energy Ion Ring (LEIR) achieved the highest operational intensities ever. For the first time in operation, momentum slip-stacked beam [4] was used in 2023. For this, two 100 ns spaced bunch trains are interleaved in the SPS to create a single train with 50 ns spacing, see Fig. 3(b). By 2024, the LIU intensity targets have been exceeded, with ~30 % higher intensity at start of collisions in the LHC compared to the HL-LHC baseline. The improvement of the SPS extracted intensity over the years is depicted in Fig. 3(c). This, along with an improved SPS-to-LHC transmission contributed to the excellent ion performance in the LHC in 2024 [5].

3. LHC proton operation

3.1 Luminosity production

At the time of the last EPS-HEP conference in mid-2023, a damaged bellow in the inner triplet (IT) of Point 8 required a 1.5 months repair. Thereafter, a vacuum leak in the injection absorber in

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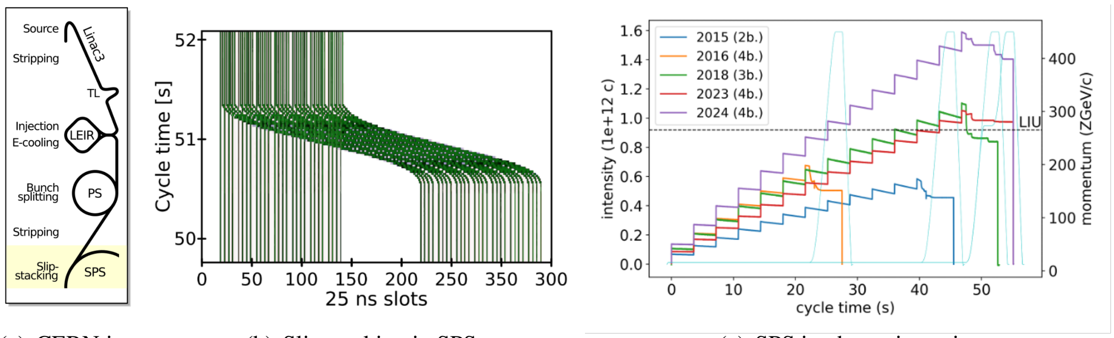

(a) CERN ion injector chain (b) Slip stacking in SPS (c) SPS ion beam intensity

Figure 3: Injector achievements for ion operation with LIU beams

interaction region (IR) 8 appeared, bringing the LHC proton run to a premature end. The integrated proton luminosity in ATLAS and CMS remained at 32 fb^{-1}, roughly half below the expected 75 fb^{-1}. Over the production period, 0.8 fb^{-1}/day were obtained on average, with a β^* levelling from 120 cm to 30 cm. Also, the Run 3 high-beta run was completed. A special 'hybrid' beam with some empty slots has been used in order to overcome heat-load limitations in the cryogenic system.

Over the 2023-2024 annual shutdown, the leaky injection absorbers have been replaced with spares. Those exhibit the same non-conformities, but nevertheless do not pose any limitations for operation, because the bellow lifetime was estimated to be > 1 year. A partial consolidation of spring non-conformities in warm vacuum modules took also place. To limit beam-induced heating in the remaining non-conform warm vacuum modules to 2024 operational levels, see Fig 4, several mitigations have been put in place. Since bunch length has a large impact on the normalized power loss, bunch length interlocking has been implemented, and a better control of bunch length during the acceleration ramp has been achieved (Fig. 5). At the same time, it was decided to limit the bunch intensity to $1.6{\times}10^{11}$ p/b, with a potential increase to the Run 3 baseline of $1.8{\times}10^{11}$ p/b foreseen in Autumn 2025.

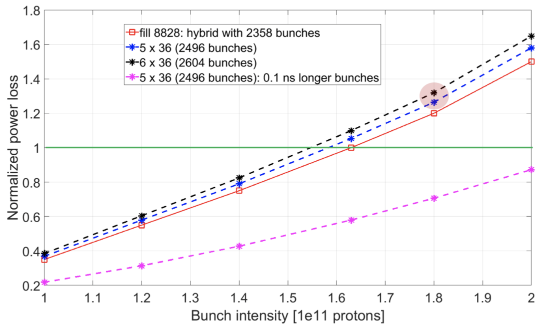

Figure 4: Normalized power loss from beam-induced heating for different beam types; the region below the green line is considered safe for operation

For proton luminosity production, 2024 was the most productive year to date, as depicted in Fig. 6(a). ATLAS and CMS accumulated 124 fb^{-1}, while 11 fb^{-1} and 67.5 pb^{-1} were delivered to LHCb and ALICE, respectively. Also the average production rate of 0.83 fb^{-1} in 24 h and the peak production rate of 1.5 fb^{-1} in 24 h were breaking records.

By mid-2025 (Fig. 6(b)), the luminosity production is on track so far, with 24 fb^{-1} accumulated in ATLAS and CMS, as well as 2.6 fb^{-1} and 14.3 pb^{-1} delivered for LHCb and ALICE, respectively.

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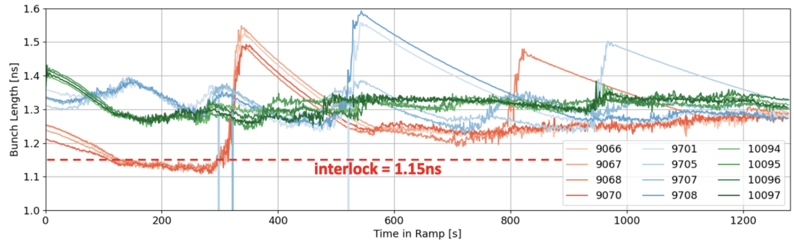
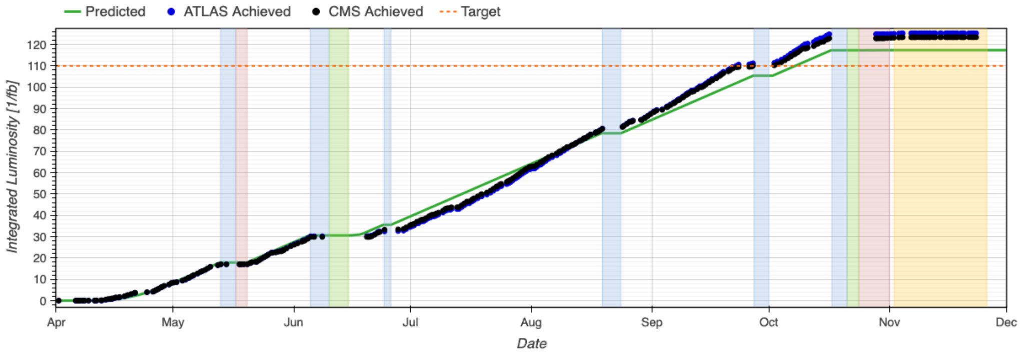
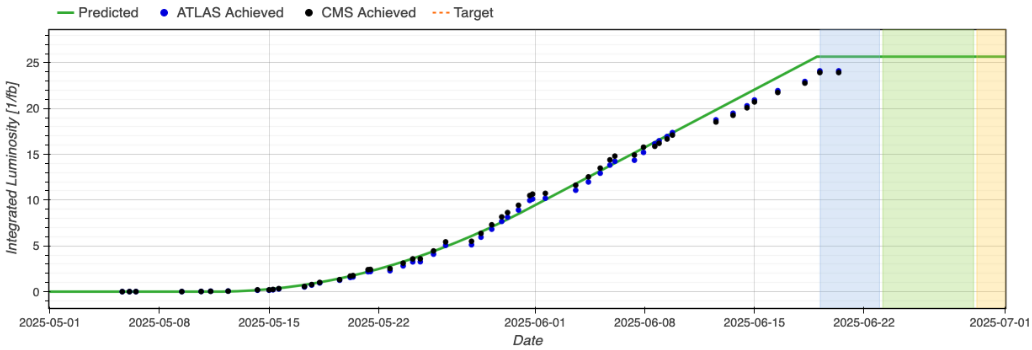


Figure 5: Improved bunch length regulation during the controlled longitudinal emittance blow-up that takes place in the acceleration ramp



(a) Integrated luminosity in 2024



(b) Integrated luminosity till July 2025

Figure 6: LHC proton luminosity production curves as a function of time

The increase in the production rate over the years is illustrated in Fig. 7.

3.2 Luminosity levelling

In the LHC, luminosity levelling is required, for the time being, by (i) cooling limitations in the IT magnets and (ii) pile-up limitations in the detectors. In a proton production fill, LHCb and ALICE are levelled at all times, while ATLAS and CMS are levelled till sufficient luminosity burn-off is reached. The luminosity control is better than 2.5 %.

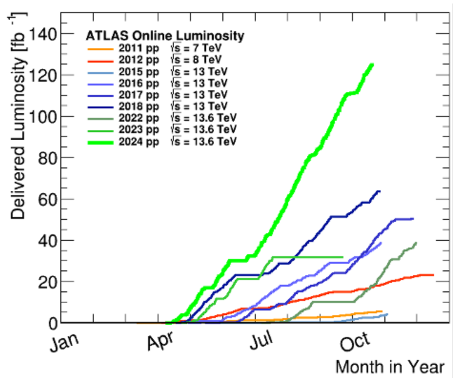


Figure 7: Evolution of the ATLAS proton luminosity production over the years

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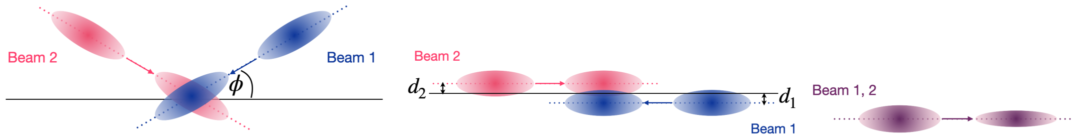
As a levelling technique (Fig. 8), combined β^* (i.e. beam size) and beam-offset levelling is utilized. With the high-brightness BCMS beam used in 2025, the levelling time can be extended by 1-2 h compared to standard beams, resulting in about 6-7 h total levelling time with the operational beam parameters. With increased bunch intensity, also the levelling time is extended.



(a) Crossing angle (b) Beam separation (c) Beam-size squeeze

Figure 8: Schematic representation of beam parameters varied for luminosity levelling in the LHC

As of 2025, quasi-continuous crossing-angle anti-levelling has been introduced in addition to the β^* and offset levelling, see Fig. 9. This extends the levelling time by another ~1.5 h, and increases the integrated luminosity by about 1-2 %. The levelling techniques studies prepare also the ground for the HL-LHC baseline round-optics and alternative flat-optics scenario.

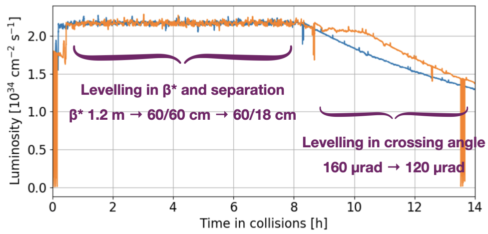


Figure 9: Typical luminosity evolution with (orange) and without (blue) crossing-angle levelling

3.3 Cryogenic heat load

The highest heat-load sectors in the LHC in Run 3 are sectors S78 and S81, see Fig. 10(a). In S78, the maximum operational heat load per half cell (hc) is 170 W/hc, compared to the LHC design of 85 W/hc [1]. The difference is mainly due to electron cloud in the LHC machine. For operational regulation, a margin of 10 W/hc is required.

Over Run 3, a small conditioning effect has been observed, reducing over the years the heat load for the same beam parameters, and allowing to push slightly the operational parameters from year to year. In 2023, the hybrid beam was used to keep the heat load low, < 150 W/hc. Since 2024, the BCMS beam was used, which is preferable for luminosity production. With this beam, the heat load peaked at 177 W/hc with 2352 b in 2024 and 174 W/hc with 2460 b in 2025 (Fig. 10(b)); in both years, the operational bunch intensity being $1.6{\times}10^{11}$ p/b. In all cases, operation occurs close to the limit of the cryogenic capacity.

3.4 Optics configurations

Through the high rate of proton collisions, the equipment in and close to the ITs is irradiated. To better preserve the lifetime of the magnets in this region, the dose can be distributed over different coils using different optics configurations (Fig. 11). The recommended dose limit [6] is 30 MGy in the IT magnets (main quadrupoles and corrector magnets), and 75 MGy in the D1 separation dipole magnets.

The target luminosity of 300 fb^{-1} in Run 3 can only be achieved by pushed beam parameters and crossing angle, and the dose projections for the nominal focusing-defocusing-focusing (FDF)

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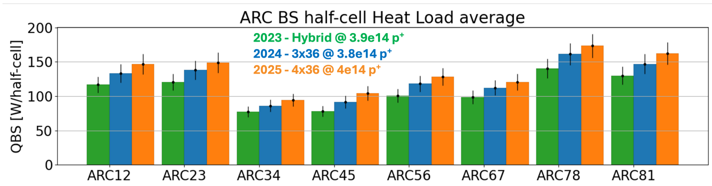
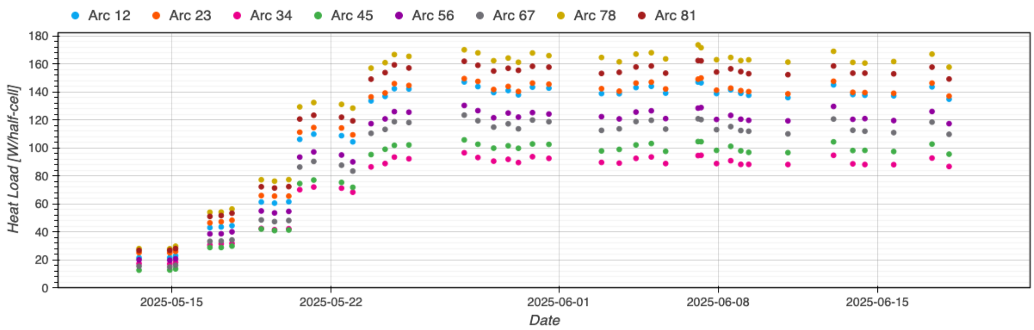
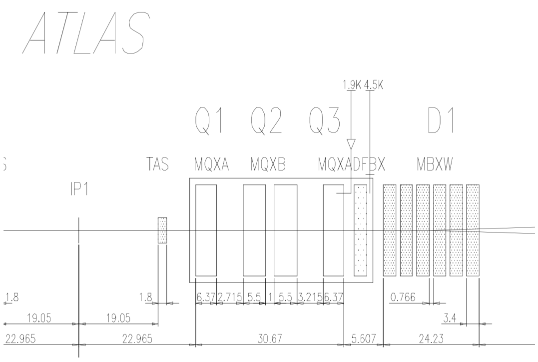


(a) Heat load in different sectors

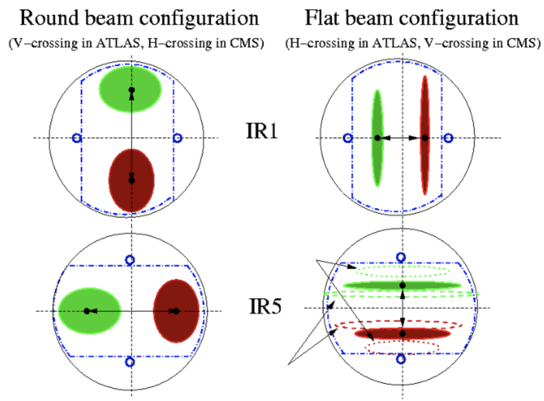


(b) Heat load evolution in 2025

Figure 10: Cryogenic heat load in the LHC



(a) Schematic layout of the right side of IR 1



(b) Round (left) and flat (right) beams

Figure 11: The layout of the interaction region and the beam configurations used

optics exceed the recommended limit. To spread the dose more evenly over the different magnets, and to reduce the overall dose, a reverse-polarity (DFD) optics and crossing angle [7] have been used in IR 1 during the 2024 run. The drawback of this solution was an increased background at the FASER and SND experiments. For this reason, in 2025, nominal polarity in IR 1 has been restored and reverse polarity in IR 5 has been implemented, requiring operation with flat optics in the non-circular beam screens, see Fig. 11(b). Thanks to flat optics, the crossing planes could also be inverted to achieve the best performance.

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3.5 Automation and availability

To achieve high integrated luminosity, availability and turnaround are key factors. In the LHC, an immense effort is continuously being invested in ensuring that failures do not repeat or, if possible, are even prevented from happening. Yearly luminosity targets are set with a fraction of more than 50 % time spent in stable beams, and in 2024, 53.7 % of the beam operation time was spent in stable beams.

Another key factor is automation, which limits human errors and optimizes the time spent on operational tasks. A large fraction of the LHC operational processes is automated, and the effort to automate more tasks in the future is continued. Just to mention a few, the levelling logic is automatic for the operators, and at the same time, controllable by the experiments through their requests. Throughout the ramp and in stable beams, the bunch length and the orbit is controlled through feedback algorithms. For HL-LHC, new tools, e.g. to minimize the RF power at injection, are being put in place.

4. LHC ion operation

4.1 The HL-LHC ion upgrade

For the ion operation, the HL-LHC era has already started, as improvements were implemented in the Long Shutdown 2. The slip stacking in the SPS [4] allows to inject ~70 % more bunches into the LHC. Newly-installed crystal collimators [8, 9], see Fig. 12, allow to handle higher beam losses. Orbit bumps and new collimators around ALICE enable sustaining about a factor six higher collisional losses [10]. Last but not least, the upgraded ALICE detector can handle higher event rates to digest the higher luminosity. The richness of the LHC ion program and the preliminary plans for the long-term future are shown in Fig. 13. In Run 3, another two Pb ion runs lie ahead.

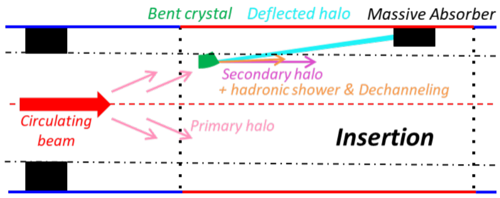

Figure 12: Crystal collimation for ions: bent crystals deflect the beam halo towards massive absorber collimators

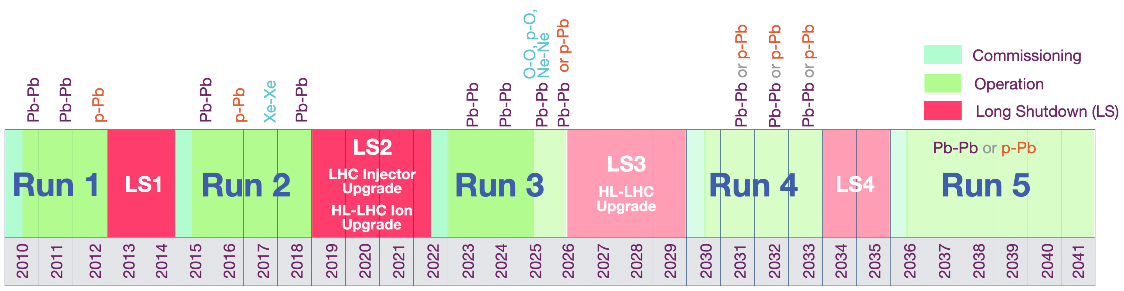

Figure 13: Long-term schedule of the LHC ion program showing the variety of species explored and the potential long-term future in the HL-LHC era

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4.2 Luminosity production

During the first ion run in 2023, the new equipment and operational techniques had to be commissioned. In this first year, many challenges were encountered, such as frequent, radiation-induced beam dumps in the quench protection system, recurrent beam dumps due to 10 Hz horizontal orbit oscillations and transverse losses in the ramp, a high background in the ALICE experiment [11], and issues with the crystal goniometer stability. Through dedicated effort and studies, all of these issues could be mitigated for the 2024 ion run.

In addition, the bunch parameters of slip-stacked beam in 2023 were below the expected values, with bunch intensities below the HL-LHC target of $1.8{\times}10^{8}$ Pb/b and large transverse emittances of > 2 µm. Taking all these factors into account, the integrated luminosity still reached ~2/3 of the initial goal and surpassed the 2018 production, with an average daily production of 80 µb^{-1} [12]. The peak luminosity broke records in ALICE with $6.4{\times}10^{27}$ cm^{-2}s^{-1}.

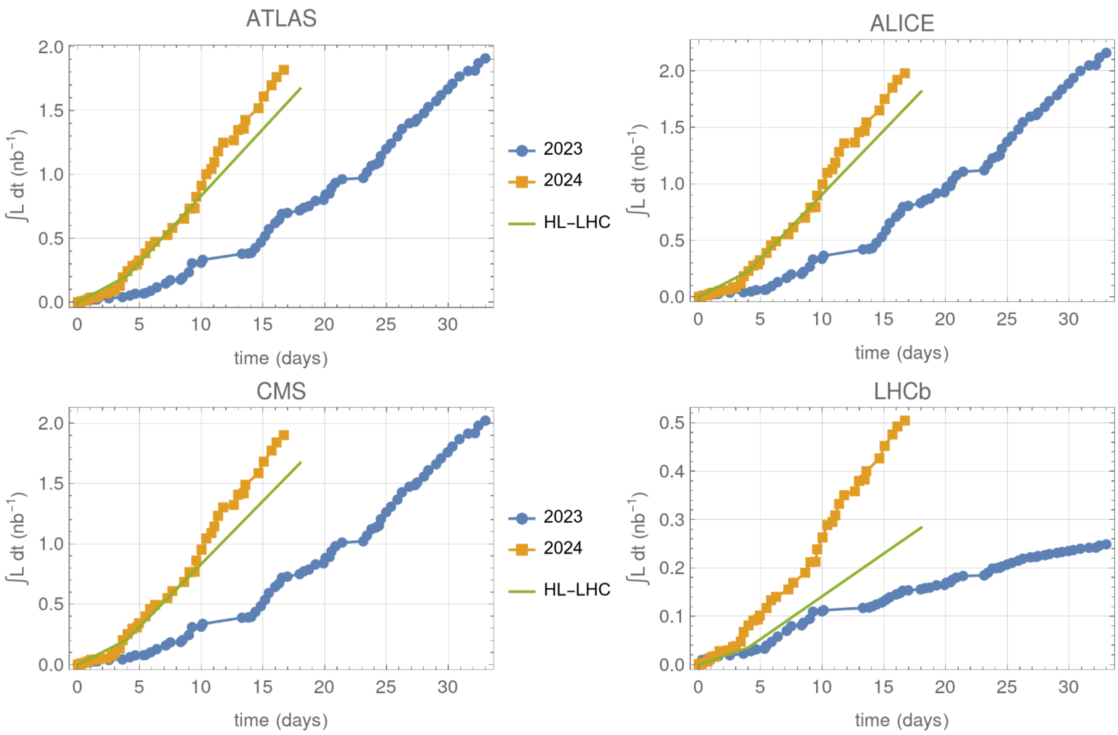

Figure 14: Luminosity production during the 2023 (blue) and 2024 (orange) ion runs in the four LHC experiments

In the 2024 ion run, operation beyond the HL-LHC target was achieved, with bunch intensities of $2.3{\times}10^{8}$ Pb/b and a maximum stored beam energy of 26.9 MJ [5], compared to the target of 20.5 MJ. The proton-proton reference run was successfully completed in 7 days. In ALICE, ATLAS, and CMS, the target integrated luminosity of 1.9 nb^{-1} was reached (Fig. 14), in half the time compared to 2023. In the production fills, 2 h levelling at $6.4{\times}10^{27}$ cm^{-2}s^{-1} was achieved. The mean daily production amounted to 142 µb^{-1}, well exceeding the expected 118 µb^{-1} for HL-LHC [13]. The LHCb experiment collected double the luminosity in 2024 than in 2023 (Fig. 14). The mean daily production was 37 µb^{-1}, almost double the HL-LHC projection of 20 µb^{-1}.

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4.3 Special ion run 2025

In an eight-day special ion run in July 2025, beam commissioning and data production for three different configurations, p-O, O-O, and Ne-Ne, was executed on a tight schedule. The excellent machine availability, together with a meticulous preparation, were the main contributors that allowed reaching integrated luminosities beyond expectations and showcase the flexibility of the LHC machine. The produced luminosity is summarized in Table 1.

Table 1: Integrated luminosity targets and achievements for different runs and experiments.

Run	Metric	LHCf	ATLAS	ALICE	CMS	LHCb
p–O	Target	1.5 nb^{-1}	—	5 nb^{-1}	3 nb^{-1}	2 nb^{-1}
	Achieved	1.8 nb^{-1}	6.9 nb^{-1}	7.85 nb^{-1}	48.4 nb^{-1}	33.1 nb^{-1}
O–O	Target	—	0.8 nb^{-1}	0.5 nb^{-1}	0.8 nb^{-1}	0.5 nb^{-1}
	Achieved	—	8.2 nb^{-1}	5.15 nb^{-1}	9.4 nb^{-1}	5.75 nb^{-1}
Ne–Ne	Target	—	0.1 nb^{-1}	0.1 nb^{-1}	0.1 nb^{-1}	0.1 nb^{-1}
	Achieved	—	1.0 nb^{-1}	0.91 nb^{-1}	0.91 nb^{-1}	0.61 nb^{-1}

5. Towards HL-LHC

The HL-LHC project [2] comprises the implementation of various new technologies during Long Shutdown 3 [14] in the LHC machine, including twelve more powerful focusing magnets and sixteen superconducting crab cavities around ATLAS and CMS. These require also civil engineering of new tunnels and shafts and superconducting links to deliver high DC currents to the magnets. Apart from crystal collimators (for ion operation), additional collimators will also be installed to decrease impedance and reinforce machine protection.

5.1 Beam tests planned in 2025-2026

During the 2025-2026 runs, and interleaved with the production periods, dedicated beam dynamics measurements are taking place to prepare the machine for the HL-LHC era. Bunch trains of 2.3×10^{11} p/b have already been injected and accelerated, while ensuring that the beam-induced heating power does not exceed the operational level through limiting the total number of bunches.

For the last two weeks of the LHC Run 3, in the end of June 2026, a 'preparatory run' with HL-LHC beam is presently being discussed. Such a special run could help to pinpoint challenges at an early stage and gain some experience with operation at HL-LHC intensities, thus being a critical investment for the success of HL-LHC.

5.2 Production of HL-LHC equipment

Most of the HL-LHC equipment has also passed the prototyping stage and is going into production. For the crab cavities, prototype cryomodules both with the double-quarter-wave and RF-dipole cavities have been tested in the SPS machine and crabbing has been successfully demonstrated. The series production of ten cavities of each type and 20 power amplifiers has started.

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For the new IT magnets, a 'string' assembly has been put in place in a surface building, with the aim to study and validate on the surface the collective behaviour of the different magnets. The main equipment for this string assembly has already been installed and first powering tests are expected in early 2026.

Concerning the HL-LHC magnets for IR 1 and 5, manufacturing, cryo-stating, and testing is at full production speed. A large variety of magnets is being produced, with NbTi and Nb_3Sn technologies.

5.3 Mitigations during Long Shutdown 3

To reduce the electron-cloud-induced heat load towards the cryogenic system, it is foreseen to reduce the secondary electron yield by treating about 13 km of the beam screens, spread over all the LHC sectors and amounting to significant portion of the total length, for each beam. This is planned to be achieved with an in-situ coating, depositing an amorphous carbon coating layer. Significant advancements in prototyping and on a full-scale model have been achieved. In addition, for IR 1 and 5, new cryoplants will also be installed to increase the cryogenics capacity for Run 4.

To overcome power limitations for the main RF system at injection, the existing klystrons will be replaced with high-efficiency klystrons. This will allow to increase the power output from 300 kW to 350 kW towards each RF cavity, and thus overcome start-of-ramp beam losses that could otherwise prevent from accelerating the full HL-LHC beam.

5.4 Restart after Long Shutdown 3

The Long Shutdown 3 will start in the LHC on the morning of the 29th June 2026, and preparation is being carried out intensively [15]. With its duration of 47 months, it is a unique opportunity for extensive consolidation, maintenance, and enhancements not only in the LHC, but across the entire CERN accelerator complex. It is therefore important to put the LHC consolidation and HL-LHC installations into the context of the CERN-wide activities during the shutdown.

As for the restart in the HL-LHC era, the LHC Run 4 will start in 2030 with a 'commissioning' year. The main goal of this first year will be to re-establish the 2026 performance. As of 2031, an intensity ramp-up to HL-LHC intensities is foreseen.

6. Conclusions

The LHC has to date already surpassed the goal for the total integrated proton luminosity of 500 fb^{-1} by the end of Run 3. Both for proton and ion operation, 2024 has been an extremely successful year. For protons, 124 fb^{-1} were accumulated, with record-breaking peak luminosity production per day. Also the 2025 proton production is promising so far. The lead ion program has entered in 2023 the HL-LHC era, and has already in 2024 surpassed all expectations both in terms of beam parameters and luminosity production. The special ion run with oxygen and neon in 2025 has been concluded with equally excellent results. Finally, the LHC machine is being prepared, via beam tests and via construction of new equipment, for a more luminous proton program after the upcoming Long Shutdown 3.

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References

[1] Brüning, O. S. and Collier, P. and Lebrun, P. and Myers, S. and Ostojic, R. and Poole, J. and Proudlock, P., *LHC Design Report*, CERN, Geneva (2004).

[2] O. Aberle, I. Béjar Alonso, O. Brüning, P. Fessia, L. Rossi, L. Tavian et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN Yellow Reports: Monographs, CERN, Geneva (2020), 10.23731/CYRM-2020-0010.

[3] H. Damerau, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, K. Hanke et al., *LHC Injectors Upgrade, Technical Design Report*, vol. Volume 1, protons, CERN, Geneva (2014), 10.17181/CERN.7NHR.6HGC.

[4] J. Coupard, H. Damerau, A. Funken, R. Garoby, S. Gilardoni, B. Goddard et al., *LHC Injectors Upgrade, Technical Design Report*, vol. Volume 1, ions, CERN, Geneva (2016), 10.17181/CERN.L6VM.UOMS.

[5] R. Bruce, A. Lechner, B. Salvachua, B. Lindstrom, C. Young, D. Mirarchi et al., *Exceeding high-luminosity LHC performance targets during the 2024 Pb-Pb ion run*, *Proceedings of the 16th International Particle Accelerator Conference (IPAC2025): Taipei, Taiwan, 2024* (2025) 899.

[6] F. Cerutti, *Triplet luminosity lifetime*, in *the 10th LHC Operations Workshop, Evian, France* (2021), https://indico.cern.ch/event/1077835/contributions/4533356/.

[7] S. Fartoukh, *RP optics options for 2024 and beyond*, in *the Joint Accelerator Performance Workshop 2023, Montreux Switzerland* (2023), https://indico.cern.ch/event/1337597/contributions/5634840/.

[8] M. D'Andrea, O. Aberle, R. Bruce, M. Butcher, M. Di Castro, R. Cai et al., *Operational performance of crystal collimation with 6.37 z tev pb ion beams at the LHC*, *Phys. Rev. Accel. Beams* **27** (2024) 011002.

[9] S. Redaelli, O. Aberle, A. Abramov, R. Bruce, R. Cai, M. Calviani et al., *Crystal collimation of heavy-ion beams at the Large Hadron Collider*, *Phys. Rev. Accel. Beams* **28** (2025) 051001.

[10] M. Schaumann, J.M. Jowett, C. Bahamonde Castro, R. Bruce, A. Lechner and T. Mertens, *Bound-free pair production from nuclear collisions and the steady-state quench limit of the main dipole magnets of the CERN Large Hadron Collider*, *Phys. Rev. Accel. Beams* **23** (2020) 121003.

[11] H. Guerin, R. Bruce, R. Cai, F. Cerutti, M. Danisch, L. Esposito et al., *Simulation of machine-induced background to ALICE in the 2023 LHC ion run*, *Proceedings of the 16th International Particle Accelerator Conference (IPAC2025): Taipei, Taiwan, 2024* (2025) 825.

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[12] N. Triantafyllou, R. Bruce and S. Redaelli, *Analysis of the performance in the 2023 LHC Pb-Pb run*, *Proceedings of the 15th International Particle Accelerator Conference (IPAC2024): Nashville, TN, USA, May 19-24, 2024* (2024) 955.

[13] R. Bruce, M. Jebramcik, J. Jowett, T. Mertens and M. Schaumann, *Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider*, *Eur. Phys. J. Plus* **136** (2021) 745.

[14] J. Tock and others., *The third long shutdown (LS3) of the CERN accelerator complex*, in *Proc. 16th International Particle Accelerator Conference*, IPAC'25 - 16th International Particle Accelerator Conference, pp. 891–894, JACoW Publishing, Geneva, Switzerland, 06, 2025, DOI.

[15] J. Tock, *The Long Shutdown 3*, in *the CERN ATS Newsletter* (2025), https://ats-news.web.cern.ch/the-long-shutdown-3/.

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