HEAVY IONS IN 2018

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Abstract

The last month of operation in 2018 will be devoted to lead-lead (Pb-Pb) physics, while no protons will be available from the injectors. In the history of the LHC this is only the 4th Pb-Pb run, but the initial 10 years LHC design goal of 1 nb^{-1} of Pb-Pb luminosity in ALICE, ATLAS and CMS is already in reach.

At this early stage, studies and discussions are still going on and it is not yet possible to decide all details of the run configuration. This contribution presents the current status and possible options as of the end of 2017. The choices of machine configuration and optics, levelling strategies, beam parameters from the injectors and luminosity estimates are discussed, taking into account the requirements of the experiments as presently known.

RUN SCHEDULE

The run is scheduled to start with four days of commissioning just after Technical Stop 3 (TS3) on 4 November. During TS3, ATLAS and CMS need to re-install their Zero Degree Calorimeters (ZDC), which are only used during heavy-ion operation. The commissioning will be followed by about 25 days of physics operation, including an intensity ramp-up to a maximum of 500–600 bunches. As usual, the physics data taking will be interrupted by an ALICE polarity reversal, an ion source refill, van der Meer Scans and machine development (MD) time.

In order to prepare the start of the HL-LHC era (for the heavy-ion programme this will start in Run 3), 1–2 days MD time is planned. The priorities for the experiments during this time have not yet been set. Currently under discussion are experiments on crystal collimation [1] and a quench test using the secondary beams emerging from the interaction point (BFPP quench test) [2]. This is the last chance to make any tests before LS2, so this list is probably not exhaustive.

MACHINE CONFIGURATION

For the most rapid and efficient transition from proton-proton (p-p) to Pb-Pb the two magnetic configurations were, in the earliest runs, kept as close as possible. Thanks to the flexibility and reproducibility of the LHC, and the proven efficiency in setting up new optics, the complexity and diversity of the heavy-ion runs have grown over the years. Recent runs have included several different optics set-ups and energies within the one-month time-frame [3]. For this run the main differences to the p-p configuration are:

- Different beam energy: 6.37 Z TeV instead of 6.5 Z TeV.
- Must squeeze ALICE and LHCb further than in p-p.
- No telescopic squeeze [4] (judgement: simplicity, risk, time, probably not possible for ALICE).

6.37 Z TeV *Beam Energy*

As was already done in 2015, the nominal p-p beam energy of 6.5 Z TeV will be reduced to 6.37 Z TeV. This provides the possibility to compare all collision modes (p-p, p-Pb and Pb-Pb) at the same centre-of-mass energy per colliding nucleon pair. A centre-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV can be produced in collisions of

- p-p at 2.51 TeV (done in 2015 and 2017)
- p-Pb at 4 Z TeV (done in 2013 and 2016)
- Pb-Pb at 6.37 Z TeV (done in 2015 and planned for 2018)

Optics Configuration

Combined Ramp and Squeeze As the dedicated heavy-ion experiment, ALICE collects the majority of its useful luminosity during the heavy-ion runs. Therefore, the most important reason why the optics configuration of the heavy-ion run differs from p-p is that ALICE has to be squeezed to a minimum β^* value similar to that of ATLAS and CMS. Since 2013, LHCb has developed a growing interest in heavy-ion data and also requires to be squeezed further than in p-p.

For these reasons a new Combined Ramp and Squeeze (CRS) will be prepared, which brings (ATLAS, ALICE, CMS, LHCb) from $\beta^* = (11, 10, 11, 10)$ m down to $(1, 1, 1, \sim 1.5)$ m. This will save time in the subsequent squeeze segment at top energy, since ALICE, ATLAS and CMS have to be squeezed only from 1 m to 0.5 m.

Keeping the CRS as commissioned for proton operation, with a goal of $\beta^* = (1, 10, 1, 3)$ m, would mean a significantly longer squeeze at 6.37 Z TeV, because ALICE would have to be squeezed all the way from its injection to final β^* value after the energy ramp. Alternatively, a common CRS, similar to the one described above for the heavy-ion run, could be commissioned during the initial p-p set-up. This option would save the commissioning time of the second CRS. However, it is disfavoured because of several drawbacks: the proton operation would be dependent on the heavy-ion configuration, which is still to be finalised, including the preparation of the necessary optics files for the new squeeze in ALICE. Furthermore, ALICE would have to run at a smaller than usual β^* value during the whole proton run.

Collision Optics The baseline for the collision optics is the following:

- Crossing angles as in p-p except for ALICE.

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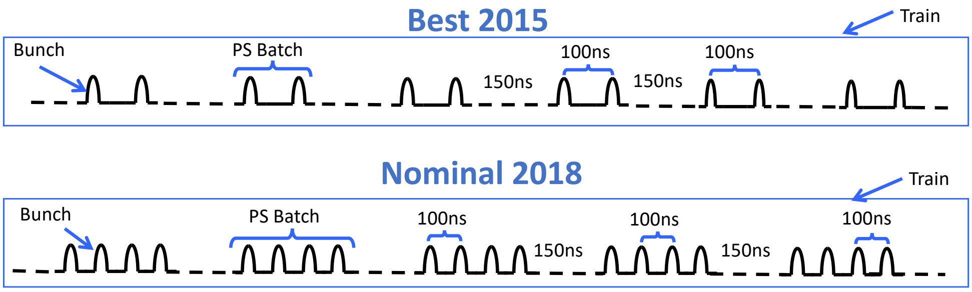

Figure 1: Beam production scheme in the injectors. Comparison between the best scheme used in 2015 and the nominal option for 2018.

  - ALICE crossing angle at 60 µrad for efficiency of the ZDC (this is equivalent to an external crossing angle of 135 µrad).

- ALICE, ATLAS and CMS at the same β^* value.
  - Final choice depends on available aperture.
  - Considered options: $\beta^* = 0.8$ m, 0.6 m or 0.5 m

- LHCb: $\beta^* = 2$–1.5 m (polarity chosen for better aperture, agreed with LHCb)

At the time of this presentation the optics for the ALICE squeeze sequence still have to be prepared. A preliminary optics for $\beta^* = 0.5$ m in ALICE indicate that the IP2 vertical shift and crossing angle aperture should be feasible. Nevertheless, we recommend that the available aperture be confirmed by measurement early in 2018.

EXPECTED BEAMS

Filling Pattern

In the course of the 2015 Pb-Pb run [5] and 2016 p-Pb run [6], the injectors worked hard to provide the best beams to the LHC. These efforts resulted in an improved filling scheme for almost every fill, continually increasing the number of bunches and intensity. The most fundamental improvements made in the injectors and LHC since 2015 are:

- Reduction of the SPS injection kicker gap from 200 ns to, finally, 150 ns [7, 8]. Since this gap defines the spacing between injected PS batches, the SPS trains are shorter for the same number of bunches and more trains fit into the LHC.

- Reduction of the LHC injection kicker gap from 900 ns to 800 ns [8].

- Optimization of the Abort Gap Keeper (AGK) [9]. The AGK defines the last bucket in which the first bunch of the last train is allowed to be injected. Depending on the filling scheme, the flexibility of shifting the AGK by a few buckets can allow one more train to be injected.

- Removal of the intensity limitation in LEIR [10]. This opened the possibility of bunch splitting in the PS, resulting in shorter trains with the same number of bunches and intensity.

All these improvements reduced the various spacings between the bunches in the LHC so that the total number of circulating bunches could be increased, while keeping about the same intensity per bunch.

Figure 1 (bottom) illustrates the nominal injection scheme to be used in 2018: 4-bunch PS-batches internally spaced by 100 ns are accumulated in the SPS with a spacing of 150 ns between them. The optimal number of PS-batches to compose a SPS-train is a trade-off between the intensity decay of circulating bunches on the SPS injection plateau [11] and the reduction of injection gaps to fit more bunches into the LHC. An optimum yields the maximum total beam intensity in the LHC. The expected number lies between 7 and 12 PS-batches per train. For comparison Fig. 1 (top) shows the best scheme used in 2015, which featured 2-bunch PS-batches with the same inter-batch and train spacings. With this scheme a maximum of 518 bunches per beam could be filled into the LHC, out of which 492 bunches collided in ATLAS/CMS, 444 bunches in ALICE and 24 bunches in LHCb. For the upcoming run it is expected to be able to fit a few tens more bunches into the LHC.

As in previous years, different filling schemes can be used through the run, to help optimize luminosity sharing between experiments.

Bunch parameters

The best average bunch intensity of $N_b = 1.96 \times 10^8$ ions was achieved in 2015 in the last fill of the run (Fill 4720). In 2016 the average bunch intensity again improved by 10%, reaching

$$N_b = 2.14 \times 10^8 \text{ ions,} \tag{1}$$

in Fill 5559, exceeding the design value [12] by a factor 3. The single bunch intensities for these two fills are displayed in Fig. 2 along the LHC circumference.

Emittances around the nominal value are expected:

$$\varepsilon = 1.5\,\mu\text{m}. \tag{2}$$

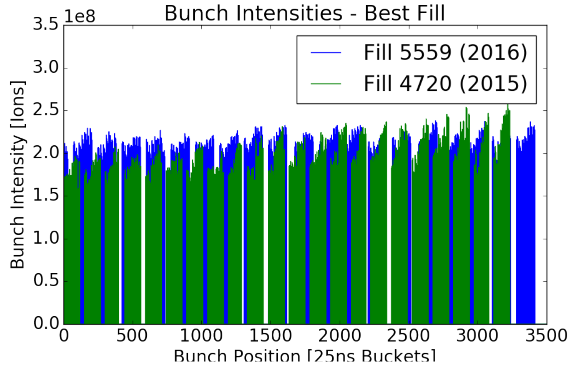

Figure 2: Pb-bunch intensities as a function of the bunch's position in the ring for the best fills from the 2016 p-Pb and 2015 Pb-Pb runs. The maximum average bunch intensity per fill was $N_b = 2.14 \times 10^8$.

The luminosity estimates presented in the following section assume that the injectors can provide the best performance from 2016 directly from the beginning in 2018.

LUMINOSITY PREDICTIONS

ALICE, ATLAS, CMS

As in previous years, ALICE needs to be levelled at $\mathcal{L} = 1.0 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ while ATLAS and CMS do not have an intrinsic luminosity limit. The assumption of the best 2016 bunch parameters (as listed above) and the number of collisions from the best 2015 filling scheme, (IP1/5, 2, 8) = (492, 444, 24), provides a somewhat conservative estimate of the expected luminosity performance. Figure 3 shows the simulated luminosity evolution in ALICE (top) and ATLAS/CMS (bottom) at $\beta^* = 0.5$ m. The peak luminosity in IP1/5 could reach $\mathcal{L} = 5 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$.

For the sake of luminosity sharing and, perhaps, the risk of quenches introduced by secondary beam, ATLAS and CMS will need to be levelled. Figure 3 evaluates four levelling scenarios. ALICE benefits from a lower levelling value in IP1/5, while these experiments lose potential integrated luminosity.

How much either of the experiments gain for a given levelling scenario is quantified in Fig. 4, where the average integrated luminosity per hour is estimated for ATLAS/CMS (dashed lines) and ALICE (solid lines). The calculation assumes a turn-around time of 2.5 h. The colour code is the same as in Fig. 3. The optimal time in collisions for each curve is indicated with a yellow stars. The dashed vertical lines mark the moment when levelling stops in ALICE.

This idealised computation does not include early dumps due to faults or any other source of down time reducing the overall availability of the LHC. From this graph it becomes clear that the ideal run strategy for ATLAS/CMS is very different from that of ALICE. The optimal fill for ALICE would last approximately 8 h. Contrary to that, for ATLAS/CMS the best would be to dump already after only about 4 h.

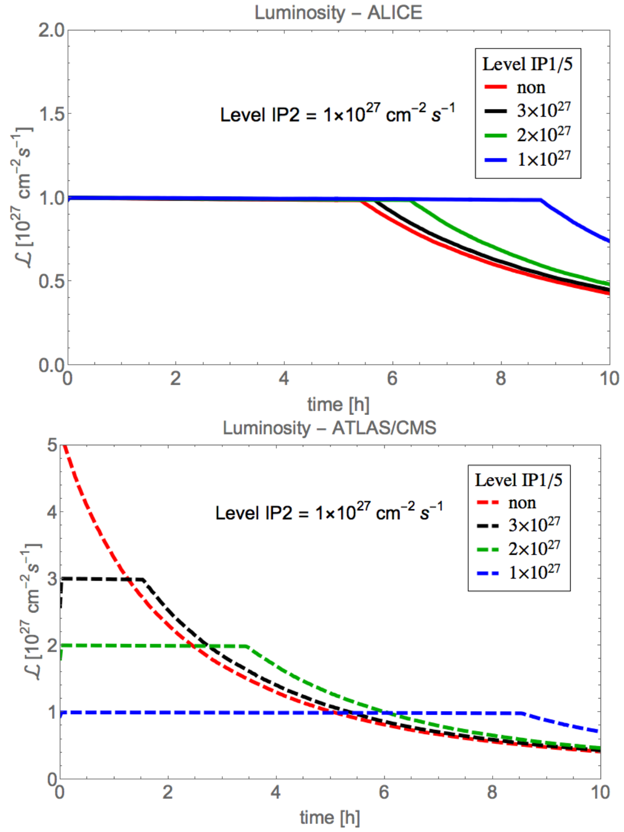

Figure 3: Projection of the luminosity evolution expected for a standard fill. ALICE (top) will be levelled to $\mathcal{L} = 1 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$. For ATLAS and CMS (bottom) four levelling options are presented.

A projection of the integrated luminosity over 21 days of physics operation as a function of the levelling value in IP1/5, including an efficiency factor of 50% to take account of a realistic availability, is displayed in Fig. 5. The highest integrated luminosity for ALICE can be achieved when ATLAS/CMS are levelled to the same value, however that introduces an unreasonable reduction of around 50% to the luminosity potential of these experiments. Table 1 summarises the numerical values[1] of the potential integrated luminosity of the three experiments for IP1/5 levelled to $\mathcal{L} = 3.0 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$.

An increase of the ALICE luminosity target to $\mathcal{L} = 1.3 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$, could improve their total integrated luminosity potential by about 20%, while having only a small impact on the other experiments.

LHCb

The evolution of the instantaneous and integrated luminosity for LHCb at $\beta^* = 1.5$ m with 24 colliding bunches, assumed to be also colliding the other experiments, is illustrated in Fig. 6. If the filling scheme is arranged to give LHCb some private bunches then the luminosity decay may be much slower. Using their first Pb-Pb data set from 2015

[1] Values are taken from the middle point of the black curves in Fig. 5

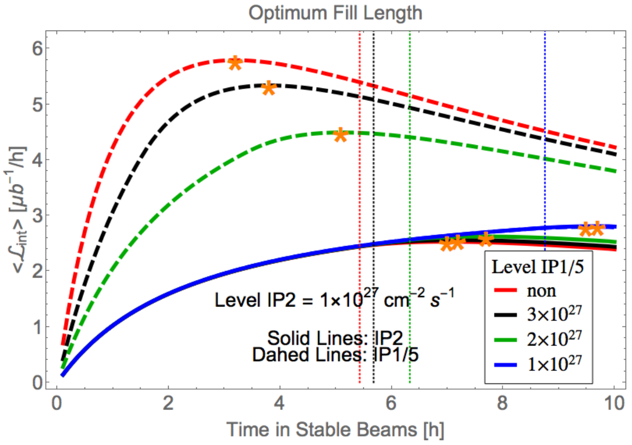

Figure 4: Average integrated luminosity per hour over the duration of one fill and prediction of the optimum fill length for ALICE (solid lines) and ATLAS/CMS (dashed lines) for the levelling options from Fig. 3.

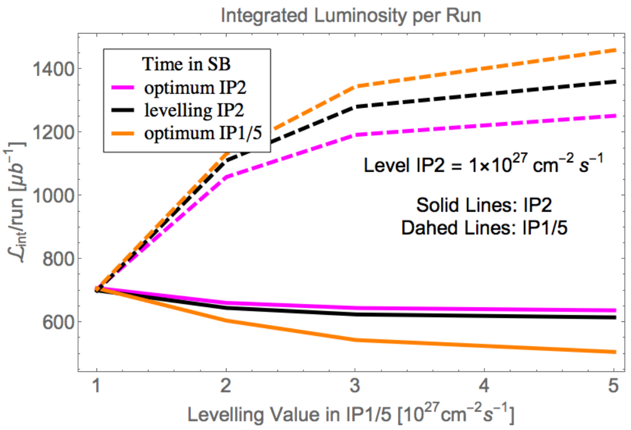

Figure 5: Integrated luminosity projections for the 2018 run comparing levelling the options presented in Fig. 3. ALICE: solid, ATLAS/CMS: dashed lines.

Table 1: Estimate of the integrated luminosity to be achieved during the 2018 run, depending on the levelling value of ALICE.

ALICE level	$\mathcal{L}_{\text{int,ALICE}}$	$\mathcal{L}_{\text{int,ATLAS/CMS}}$
$1 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$	$620\,\mu\text{b}^{-1}$	$1280\,\mu\text{b}^{-1}$
$1.3 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$	$740\,\mu\text{b}^{-1}$	$1300\,\mu\text{b}^{-1}$
Gain	+20%	+1%

with a low number of bunches to gain experience, LHCb requests at least 60–70 colliding bunches for this run. To fulfil this request detailed filling schemes have to be studied and luminosity sharing with the other experiments has to be taking into account.

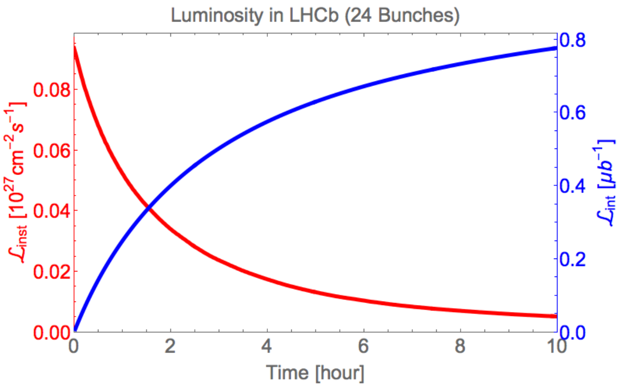

Figure 6: Instantaneous and integrated luminosity prediction for LHCb over one fill with 24 colliding bunches (assumed shared with the other experiments).

POTENTIAL PERFORMANCE LIMITATIONS

BFPP Beams

In Pb-Pb collisions the processes of bound-free pair production (BFPP) and electromagnetic dissociation (EMD) have very large interaction cross-sections ($\sigma_{\text{BFPP}} > 200\,\text{b}$) and are the main contribution to the fast luminosity burn-off. These interactions change the charge-to-mass ratio of ions in the beams and produce secondary beams, which impact in a superconducting magnet downstream the interaction point. The power carried by these beams is proportional to the instantaneous luminosity. At the current Pb-Pb luminosities, the power deposited by the BFPP beams exceeds the quench limit. In 2015, these beams were used to induce a quench under controlled conditions in order to study the quench limit of the superconducting dipole magnets [2, 13]. The targeted magnet quenched at a luminosity of $\mathcal{L} = 2.5 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$, when depositing about 50 W into the magnet. This is well below the expected peak luminosity for 2018.

In order to mitigate the risk of quenches, orbit bumps are used around IP1/5 to move the secondary beam losses into the connection cryostat that replaces a missing dipole in the dispersion suppressor. It does not contain a magnet coil and therefore features a much higher quench limit. This technique was used operationally since 2015, but requires a careful set-up of the bumps at the beginning of the run to achieve the proper loss displacement.

This mitigation strategy does not work in IP2 because the optics in the matching section and dispersion suppressor are different. Here the peak of the trajectory oscillation, at which the particles impact in the magnet, is not close to the connection cryostat, as it is the case in IP1/5. However, because of the lower, levelled, luminosity in ALICE no mitigation technique is required around IP2 before LS2.

Particle losses in IR7

During the 2015 heavy-ion run high loss rates reaching the warning level in the collimation region were observed in different stage of the cycle. Tracking simulations [14] show that the deposit power of fragments emerging from the primary collimator in IR7 can quench superconducting dipoles in the dispersion suppressor around IR7. The power deposition in this case is proportional to the total circulating intensity per beam. No mitigation measures other then the reduction of the intensity (and in turn the *integrated* luminosity) are available in case frequent protection beam dumps or quenches occur in 2018.

A careful evaluation and adjustment of the Beam Loss Monitor (BLM) thresholds around the critical areas is necessary before the run to avoid quenches without compromising availability.

SUMMARY

The planning and studies to prepare the 2018 Pb-Pb run of the LHC are still going on. The projections presented here are preliminary and subject to change.

The current strategy foresees to operate at a beam energy of $E_b = 6.37\,Z$ TeV and a minimum β^*(IP1, IP2, IP5, IP8) = (0.5, 0.5, 0.5, 1.5) m. This will be reached with a combined ramp and squeeze to $\beta^* \approx (1, 1, 1, 1.5\text{–}2)$ m and a short subsequent squeeze process at top energy to reach the final value.

All four main experiments will participate in the data-taking. A strong intensity burn-off is to be expected from the high luminosity experiments, while ALICE is limited to a maximum of $\mathcal{L} = 1 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$. Moreover, LHCb has requested more colliding bunches than in previous runs. Luminosity sharing strategies have to be specified.

A good calibration of the BSRT to obtain reliable emittance values will be crucial for the performance analysis during and after the run in view of HL-LHC

The peak luminosity could approach five times the design value, mainly thanks to the high bunch intensity from the injectors. Nevertheless, the performance might potentially be limited by high losses in the BFPP locations and IR7. In preparation of the run, collimation simulations of the expected losses in IR7 for quench protection and spike identification are required. The BLM thresholds should be adjusted accordingly.

Potential protection dumps due to collimation losses remain the most significant performance risk in 2018. They would require the beam intensity to be reduced.

POSTSCRIPT

Since this presentation was given, the prospect of using a filling scheme with a basic 75 ns bunch spacing has been under consideration. This could lead to a significantly higher integrated luminosity.

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REFERENCES

[1] R. Rossi et al., *Status of Crystal Collimation Studies at the LHC*, Proceedings of IPAC2017, Copenhagen, Denmark, 2017, paper MOPAB007.

[2] M. Schaumann et al., *Bound-Free Pair Production in LHC Operation at 6.37 Z TeV per Beam*, Proceedings of IPAC2016, Busan, Korea, 2016, paper TUPMW028.

[3] J.M. Jowett, *Colliding Heavy Ions in the LHC*, Proceedings of IPAC2018, Vancouver, BC, Canada, 2018, paper TUXGBD2.

[4] S. Fartoukh, *Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade*, Phys. Rev. ST Accel. Beams 16, 111002, Published 19 November 2013.

[5] J.M. Jowett, M. Schaumann et al., *The 2015 Heavy-Ion Run of the LHC*, Proceedings of IPAC2016, Busan, Korea, 2016, paper TUPMW027.

[6] J.M. Jowett et al., *The 2016 Proton-Nucleus run of the LHC*, Proceedings of IPAC2017, Copenhagen, Denmark, 2017, paper TUPVA014.

[7] B. Goddard et al., *SPS Injection and Beam Quality for LHC Heavy Ions with 150 ns Kicker Rise Time*, Proceedings of IPAC2016, Busan, Korea, 2016, paper TUPMR048.

[8] W. Bartmann et al., *Impact of LHC and SPS injection kicker rise times on LHC filling schemes and luminosity reach*, Proceedings of IPAC2017, Copenhagen, Denmark, 2017, paper TUPVA007.

[9] C. Wiesner et al., *AGK and Abort Gap Protection*, 8th LHC Operations Evian Workshop, 2017, this conference.

[10] A. Huschauer et al., *Progress in the Understanding of the Performance Limitations in the CERN Low Energy Ion Ring*, Proceedings of IPAC2017, Copenhagen, Denmark, 2017, paper THPAB049.

[11] M. Schaumann, *Semi-Empirical Model for Optimising Future Heavy-Ion Luminosity of the LHC*, Proceedings of IPAC2014, Dresden, Germany, 2014, paper TUPRO014.

[12] O.S.Brüning et al. (Eds.) ,*LHC design report v.1: The LHC main ring*, CERN-2004-003-V1 (2004).

[13] C. Bahamonde Castro et al., *Power Deposition in LHC magnets due to Bound-Free Pair Production in the Experimental Insertions*, Proceedings of IPAC2016, Busan, Korea, 2016, paper TUPMW006.

[14] P. Hermes, *Heavy-Ion Collimation at the Large Hadron Collider : Simulations and Measurements*, PhD Thesis, University of Münster, Germany, Munster U.: 2016-09-22, CERN-THESIS-2016-230.