# PLANS FOR THE UPGRADE OF CERN'S HEAVY ION COMPLEX

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*Abstract*

To reach a luminosity higher than $6\times10^{27}$ Hz/cm$^2$ for Pb-Pb collisions, as expected by the ALICE experiment after its upgrade during the 2$^{nd}$ Long LHC Shutdown (LS2), several upgrades will have to be performed in the CERN accelerator complex, from the source to the LHC itself. This paper first details the present limitations and then describes the strategy for the different machines in the ion injector chain. Both filling schemes and possible hardware upgrades are discussed.

## MOTIVATION

In the wake of the first two successful Pb-Pb runs in the LHC [1], the ALICE experiment has proposed a detector upgrade for the exploitation period following LS2. A peak luminosity exceeding $6\times10^{27}$ Hz/cm$^2$ for Pb-Pb collisions is expected in order to fulfil the goal of 10 nb$^{-1}$ integrated luminosity by the mid-2020's [2, 3].

Without discussing the limitations on luminosity that will occur in the LHC [4], we propose a realistic baseline strategy for the injectors to achieve this ambitious goal, as well as alternative scenarios, whose feasibility will need to be studied on paper and demonstrated experimentally. A series of measures will have to be taken in the whole ion injector chain: Linac3, the Low Energy Ion Ring (LEIR), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS).

This work is an integral part of the more general LHC Injector Upgrade (LIU) project [5].

## PRESENT LIMITATIONS

The last LHC Pb-Pb run took place in 2011. With up to 358 bunches of $1.2\times10^8$ $Pb^{82+}$ at 3.5 ZTeV per LHC ring, and an average spacing of 200 ns, a peak luminosity of $5\times10^{26}$ Hz/cm$^2$ was obtained. Since then, during the p-Pb run, the average bunch intensity delivered by the injectors has increased, to reach $1.44\times10^8$ in the collider [6]. Assuming the same performance, and scaling with the square of the energy – taking into account the adiabatic emittance shrinkage and the resulting smaller achievable $\beta^*$ –, one can expect a peak luminosity of the order of $3\times10^{27}$ Hz/cm$^2$ at 7 ZTeV, still a factor two below the requested performance.

The intensity per bunch, already twice the design, is a source of space charge detuning and Intra-Beam Scattering (IBS). It is therefore difficult to imagine increasing it even more in the SPS and the LHC due to their long injection flat bottoms, where RF noise also plays a detrimental role. At best one can hope to mitigate these effects [7]. A lower tune optics, "Q20", has been implemented in the SPS, making the beam less sensitive to IBS and decreasing the space charge detuning thanks to larger transverse beam dimensions [8]. Its drawback is a less favourable kick enhancement at injection. The elimination of RF noise has already been the subject of an extensive campaign, still ongoing [9].

The number of bunches, linked to the average bunch spacing, is currently limited by:

- The intensity delivered by LEIR, which presently slightly exceeds the design values [10], but without a further splitting in the PS. This allows to deliver twice the intensity per bunch at the expense of the number of bunches.
- The maximum number of injections into the SPS, currently 15.
- The rise time of the injection kickers of the SPS (200 ns in 2011, but 225 ns with the "Q20" optics) and of the LHC (900 ns), and the length of the LHC abort gap (3.3 µs).

Assuming that the number of injections into the SPS can be increased to 24, which will be the case after this first long shutdown (LS1), and that the rise time of the SPS injection kicker can be decreased, we estimate the peak luminosity in two cases:

- Keeping the current performance of the injectors, but replacing the current batch expansion to 200 ns by a batch compression to 100 ns.
- Doubling the current performance of the injectors, and supplementing the batch expansion to 200 ns by a splitting into 4 bunches spaced by 100 ns.

The results are plotted in Fig. 1, as a function of the SPS injection kicker rise time. The performance of the nominal beam foreseen in the design report [11], and of the 3.5 ZTeV "Intermediate" beam used in 2011 scaled with energy squared, are included for reference.

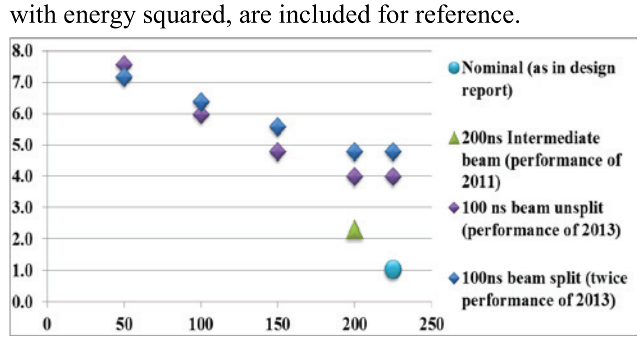


Figure 1: Expected peak luminosity ($10^{27}$ Hz/cm$^2$) at 7 ZTeV, with respect to batch spacing in the SPS (ns).




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## PROPOSED BASELINE STRATEGY

The proposed filling scheme, corresponding to the highest point in Fig. 1, is sketched in Fig. 2:

- LEIR injects 6 pulses (25 µA, 200 µs, 4.2 MeV/u) from Linac3; each pulse is accumulated over 70 turns in LEIR, under continuous electron cooling.
- After acceleration to 72 MeV/u on $h = 2$, LEIR ejects two bunches of $5.5\times10^8$ $Pb^{54+}$ ions each to the PS.
- In the PS, the bunches are injected in two successive $h = 16$ buckets and accelerated to a 370 MeV/u intermediate plateau where the batch is compressed by a series of harmonic changes ($h$ = 16-18-21).
- After acceleration to 5.9 GeV/u on $h = 21$, yielding two bunches of $3.8\times10^8$ ions, spaced by 100 ns, the batch undergoes a final rebucketing to $h = 169$ at 80 MHz.
- The resulting bunch pair, with a spacing of 100 ns, is then extracted towards the SPS. The ions are fully stripped to $Pb^{82+}$ by a 0.8 mm thick Al foil in the transfer line.
- Up to 24 such bunch pairs are injected every 3.6 seconds – imposed by the duration of the LEIR cycle – in the SPS with a 50 ns batch spacing.
- The bunches are injected in the SPS on a fixed harmonic RF at $h = 4653$.
- At the end of its 83 seconds long flat bottom, the SPS low-level RF beam control switches to fixed frequency [12] and accelerates the beam to 177 GeV/u.
- At top energy, the 48 bunches of average intensity $2.2\times10^8$ ions are extracted towards the LHC. This sequence is repeated 19 times to fill the LHC with 912 bunches.

Assuming the same beam performance from the injectors as achieved in 2013 for the p-Pb run [13], a peak luminosity exceeding $7\times10^{27}$ Hz/cm$^2$ can be expected at $E$ = 7 ZTeV.

## ALTERNATE SCENARIOS

As seen in Fig. 1, the principle explained above can already be tested in 2015: with a batch compression to 100 ns in the PS, increasing the number of injections in the SPS should deliver a peak luminosity of $4\times10^{27}$ Hz/cm$^2$ at 7 ZTeV, even with an SPS injection kicker rise time of 225 ns.

If the intensity per bunch can be doubled, re-introducing a splitting stage in the PS can be envisaged, to produce 4 bunches spaced by 100 ns as in the nominal design scheme [10]. Splitting to 50 ns would allow squeezing up to 1400 bunches per LHC ring, but cannot be performed with the current PS RF hardware:

- The 20 MHz cavity cannot accelerate the beam, which forbids splitting before the flat top.
- At 5.9 GeV/u, the beam is too close to transition, making splitting impossible because of a long synchrotron period.

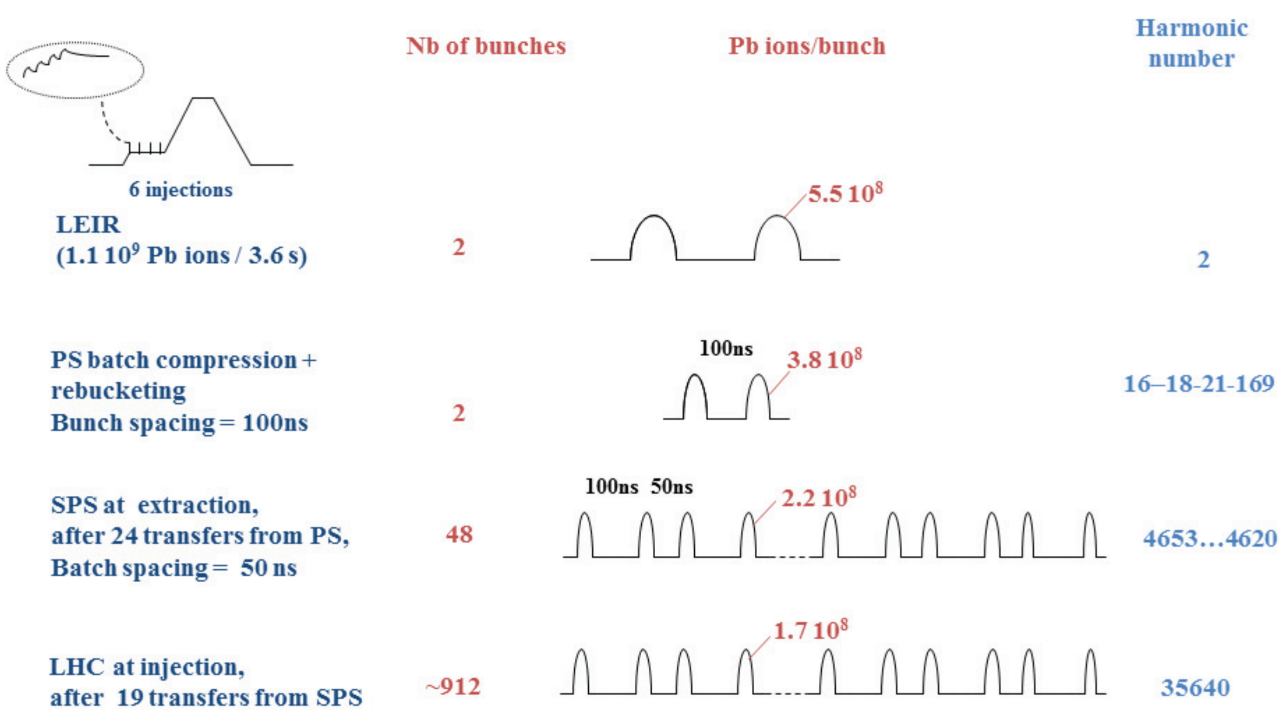


Figure 2: Alternating 100/50 ns spacing scheme, with 24 PS injections into the SPS. The beam intensities correspond to the ones achieved for the p-Pb run in 2013.

## UPGRADES AND STUDIES NEEDED

For each of the machines of the injector chain, a list of topics to be studied has been identified:

### *Linac3*

In order to diagnose the present performance of Linac3, currently half of design, and possibly increase the number of ions accelerated per pulse:

- Implement an emittance measurement device in the Low Energy Beam Transport (LEBT).
- Correct the matching in the LEBT.
- Increase the Linac3 repetition rate from 5 to 10 Hz.
- Modify Linac3 for multiple charge acceleration [14].

### *LEIR*

In spite of a low injected current from Linac3, and a loss – still to be understood – at the beginning of acceleration, LEIR delivers a higher beam density than nominal [7, 10]. However, a factor two would be necessary if one wants to re-implement a splitting in the PS, in order to double the number of bunches without sacrificing their intensity. To this effect, we need to:

- Implement more robust diagnostics, in particular emittance measurements from Schottky signals and Gas Ionisation Beam Profile Monitor.
- Identify the cause for the loss, and if possible cure or at least mitigate it.
- Add a proper beam dump in the extraction transfer line to cope with the increased beam current.

### *PS*

As the ion batch compression on $h = 16\text{-}18\text{-}21$ to 100 ns bunch spacing has already been demonstrated during machine development sessions in 2013, the PS machine is practically ready for the implementation of the proposed baseline scenario. However, we propose to:

- Operationally implement the batch compression low –level hardware.
- Study ways of achieving a splitting into 4 bunches spaced by 50ns, either using fast $\gamma_t$-jump optics, or acceleration hardware on 20 MHz.

### *SPS*

To implement the proposed scheme, the SPS will have to undergo resource-hungry upgrades:

- Preliminary studies have started for a new 50 ns rise-time ion injection system in the SPS, but the feasibility needs to be demonstrated and resources allocated [15].
- Working at fixed harmonic ($h = 4653$) minimizes the RF noise on the 83 seconds long flat bottom, but a method to switch from fixed harmonic to fixed frequency before acceleration still needs to be implemented. Other sources of RF noise can probably be identified.

## CONCLUSION

In light of the performance achieved during the 2013 p-Pb run, scaling with the energy squared, a peak luminosity of $4\times10^{27}$ Hz/cm$^2$ at 7 ZTeV is well within reach. However, to ensure $6\times10^{27}$ Hz/cm$^2$ or more as requested by the experiments after LS2, several upgrades will need to be implemented in the injector chain, expensive both in terms of money and manpower.

The proposed baseline filling scheme consists of an alternating 100 ns and 50 ns bunch spacing, yielding up to 912 bunches of $1.5\times10^8$ $Pb^{82+}$ ions per LHC ring in collision. The main ingredients will be batch compression in the PS, and a new 50 ns rise-time injection system in the SPS. Alternate schemes are under study, which would need doubling the bunch intensity in LEIR, and an additional bunch splitting in the PS.

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