PLANS FOR IONS IN THE INJECTOR COMPLEX

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Abstract

The heavy ion beams required during the HL-LHC era will imply significant modifications to the existing injector chain. We review the various options, highlighting the importance of an early definition of the future needs and keeping in mind the compatibility with the rest of the future CERN physics programme.

DESIGN & CURRENT PERFORMANCE

In the LHC design report [1], a peak luminosity of 10^{27} cm^{-2}s^{-1} was predicted for collisions at 7 ZTeV (p = 2.76 TeV/*c*/u) in the nominal scheme, with 592 bunches per ring, and a spacing of 100ns. Those bunches were produced by splitting the LEIR bunches in two in the PS, on an intermediate flat top. In order to combat expected IBS and space charge effects on the 40-second long SPS injection flat-bottom, complicated RF gymnastics involved further splitting the bunches into bunchlets prior to PS extraction, and recombining them in the SPS just before acceleration, using a 100 MHz RF system to be re-installed (Fig. 1).

To compensate for a somewhat lower current at the output of Linac3, and to meet the high expectations which followed the 2010 run with the "early" beam [2], a different scheme than the "nominal" one was implemented. Inaptly named "intermediate", this new scheme skipped the splitting process in the PS machine, replacing it by a rebucketing from h = 12 to h = 24 (Fig. 2). This yields denser bunches, at the expense of a smaller number of bunches, and a larger bunch spacing – 200 ns instead of 100 ns [3]. The experience with the Pb beam in 2010 had already demonstrated that the IBS and space charge issues on a 40 second long SPS front porch, although quite harmful, were less severe than anticipated, even for denser bunches than originally designed, and did not impose the implementation of the bunchlet scheme.

Another feature of the "intermediate" scheme was a 200 ns batch spacing, made possible by the short SPS kicker rise time at the low magnetic rigidity of the Pb ion beam at injection (equivalent to 17 GeV/*c* protons). Eventually the intermediate beam allowed to reach a peak luminosity of 5×10^{26} cm^{-2}s^{-1} at 3.5 ZTeV/*c* per beam (p = 1.38 TeV/*c*/u). Scaled to the nominal momentum of 7 ZTeV/*c* per beam where the β^* and physical transverse emittances are halved, this corresponds to twice the design goal [4]. Table 1 compares the performance expected with the "nominal beam", and the one achieved in 2011 with the "intermediate beam".

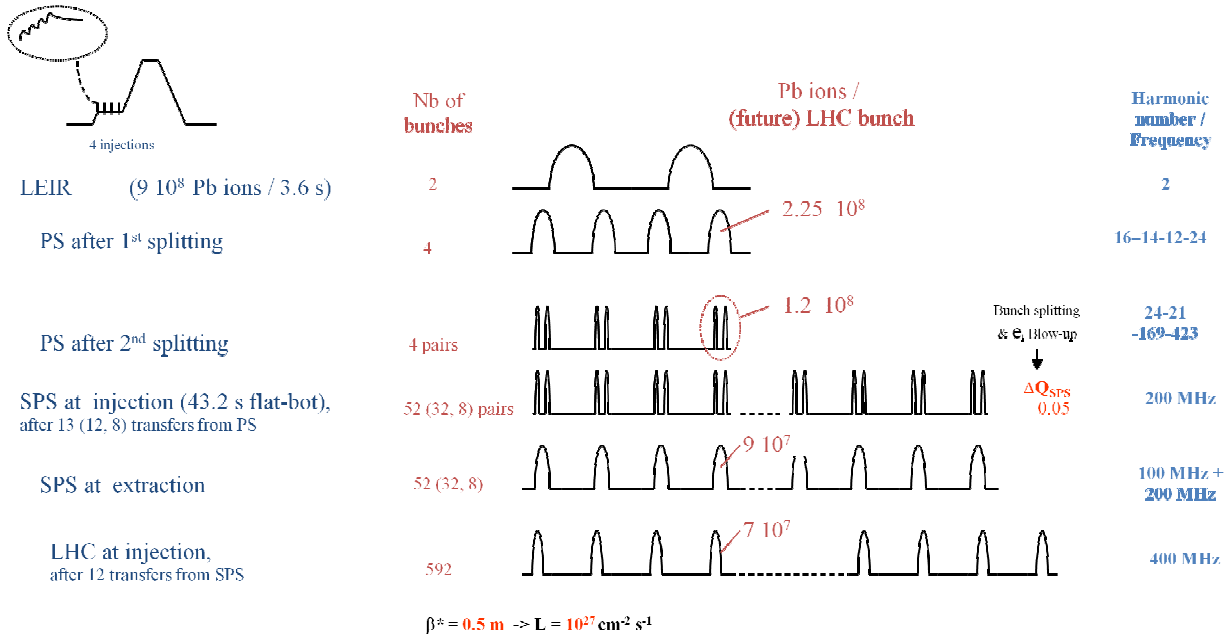

Figure 1: Nominal scheme, as planned in the LHC Design Report.

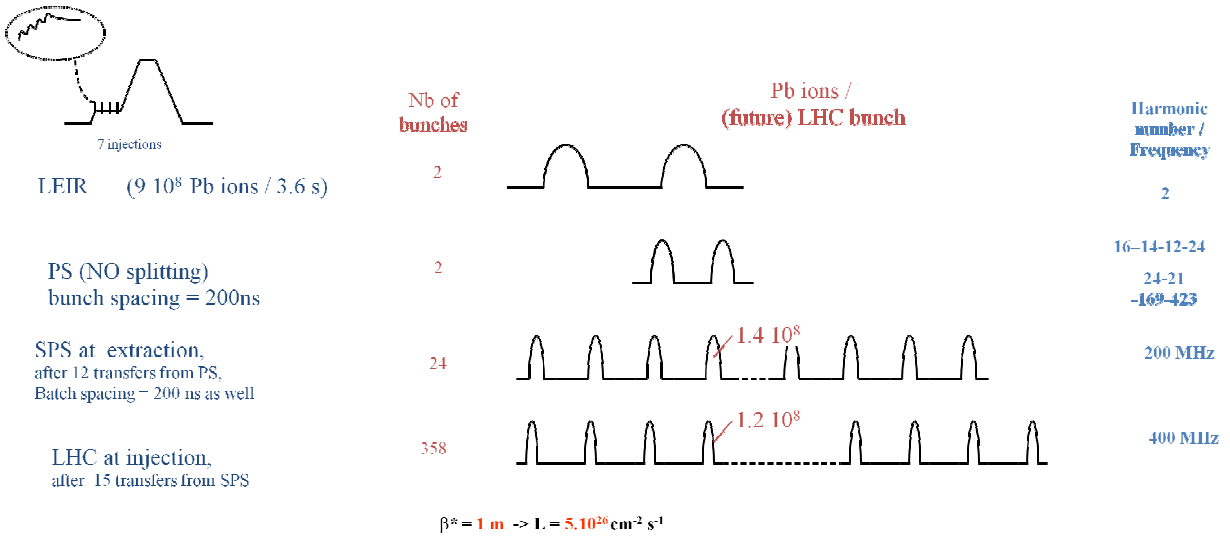

Figure 2: Intermediate scheme, as achieved during the 2011 run.

Table 1: Design and achieved performance.

	Nominal Design	**Intermediate achieved 2011**
	SPS extraction	
Bunches/batch	32, 48 or 52	22 or 24
$\varepsilon^*_{H,V}$ [μm]	1.2	0.9
N_b [ions/bunch]	9×10^7	1.4×10^8
	LHC collisions	
p [TeV/c/u]	2.76	1.38
k_n [bunches]	592	358
β^* [m] at IP2	0.5	1.0
L [Hz/cm^2]	10^{27}	5×10^{26}

Present issues

Several issues hampered the success of the intermediate scheme and will need to be addressed in order to push the luminosity further, when restarting the LHC after LS1:

- The ion current at the exit of Linac3 is about 30% of what is expected. This was mitigated in 2011 by increasing the number of injections into LEIR from 4 to 7, which had implications on the final transverse and longitudinal emittances, given the finite cooling power.
- Some losses occur in LEIR after the RF capture, at the beginning of the acceleration ramp. They are not currently understood although there are many hypotheses.
- Suppression of the splitting, conjugated with the increased number of injections into LEIR mentioned above, led to a larger longitudinal emittance of the bunches in the PS, eventually creating satellites.
- The SPS injection flat bottom lasts over 40 seconds, during which the first injected bunches suffer from losses due to IBS, space charge and RF noise, although the respective share of the different effects still needs to be determined precisely.

THE LHC'S ION PROGRAMME

The users requirements and the foreseen ion programme which it implies, have already been presented during this workshop [4, 5] so we only remind the main points:

- 2012 will be devoted to p-Pb and Pb-p collisions
- After LS1 in 2013, the LHC will start with protons only in 2014.
- From 2015 to 2017, ALICE expects Pb-Pb collisions at design luminosity, in order to reach around 250 μb^{-1}/year, with a possible p-Pb run once 1 nb^{-1} has been reached.
- After LS2, ALICE expects a higher luminosity than design for Pb-Pb in 2019, then p-Pb in 2020 and finally Ar-Ar in 2021.
- After LS3, in the HL-LHC period, ALICE expects a luminosity higher than 6×10^{27} cm^{-2}.s^{-1} for Pb-Pb collisions at 7 ZTeV/c per beam. Other species, such as U, could be requested. Deuteron-lead collisions, on the other hand, do not seem to be interesting any longer.

It is worth reminding that even without any upgrade, the "intermediate" scheme used in 2011 should already deliver 2×10^{27} cm^{-2}.s^{-1}, i.e. twice the design peak luminosity, once the LHC operates at 7 ZTeV/c per beam.

One should also note that, at the time of writing the design report, one of the concerns was whether the luminosity goal of 10^{27} cm^{-2}.s^{-1} was tolerable for the quench limit [6]. However, measurements performed during the "quench test" at the end of 2011 seem to indicate a current safety margin of the order of ten or even twenty [7], meaning the peak luminosity could be even pushed up to over 10^{28} cm^{-2}.s^{-1}.

ROUTE TO HIGHER LUMINOSITY

The natural way of increasing the luminosity is to increase the number of bunches, while keeping their intensity and transverse emittances at least constant. In the HL-LHC era, all experiments will be ready to accept a bunch spacing of 50 ns, but in order to maximize the number of bunches in the LHC, the spacing of the batches injected in the SPS should be decreased as well, as much as possible. Fig. 3 plots the luminosity, scaled to today's performance, against the batch spacing in the SPS, limited by the rise time of its injection kicker (MKP), in several cases, but keeping the number of PS injections into the SPS to 12, for comparison purposes. The 3.3 μs abort gap and the 0.9 μs rise time of the LHC injection kicker are taken into account. One can see that splitting the bunches in two while keeping the current performance of the injectors does not bring any gain, even with a much shorter MKP rise time. Conversely, bringing the two bunches closer together to say 100ns by batch compression can bring a marginally higher luminosity – 25% with the present MKP, 50% if the batch spacing can be decreased down to 150 ns (Fig. 4). This latter scheme could readily be implemented for the next ion run of the LHC, after LS1. The nominal beam, yielding half the current luminosity, is plotted for reference.

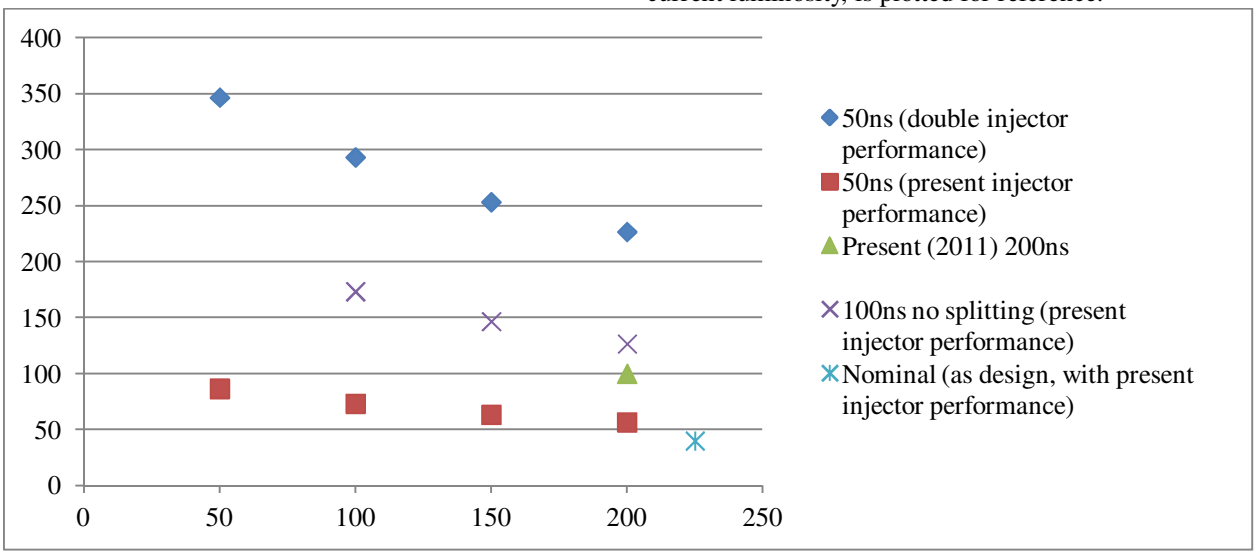

Figure 3: Expected peak luminosity versus SPS injection kicker rise time, scaled according to the various scenarios. 100% corresponds to the 2011 performance of the "intermediate beam", with a 200ns bunch spacing, and an MKP rise time shorter than 200 ns.

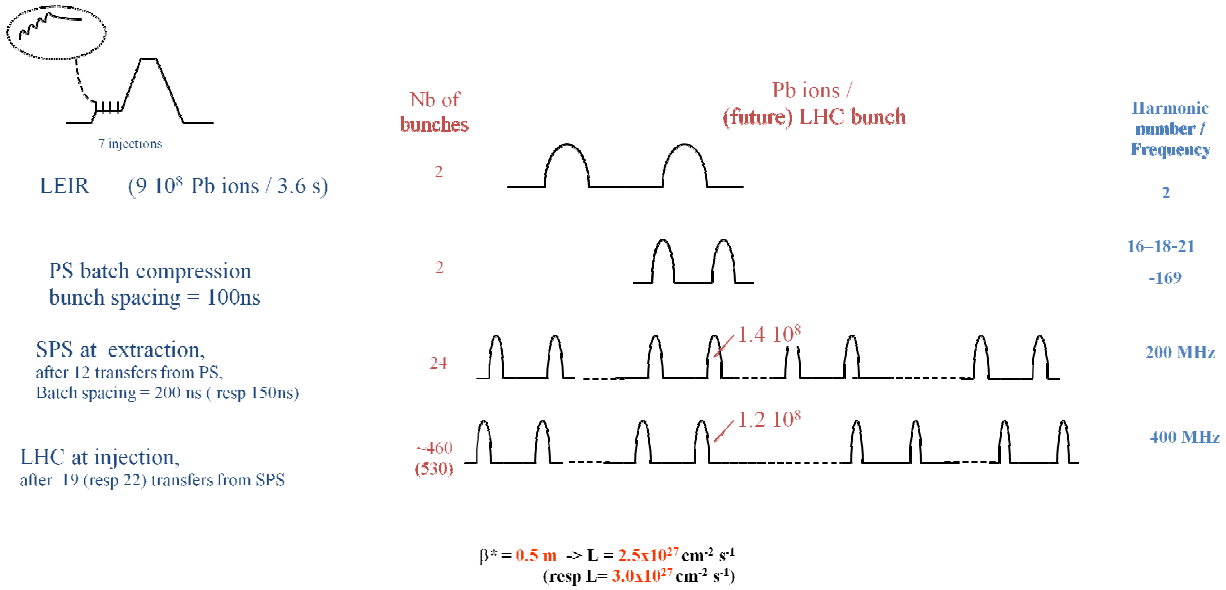

Figure 4: Possible schemes for 2015.

The scheme which would produce the highest luminosity, a factor 3.5 above the current performance, is summarized in Fig. 5:

- Production of two bunches in LEIR, with twice the current bunch intensity, and the same transverse emittances.
- Batch compression followed by splitting in the PS, yielding four bunches of 3×10^8 ions, spaced by 50 ns.
- 12 transfers of such batches to the SPS, with a batch spacing of 50 ns, giving a train of 48 bunches, equally spaced by 50 ns.
- 26 transfers of the SPS trains to the LHC, giving 1248 bunches per ring.

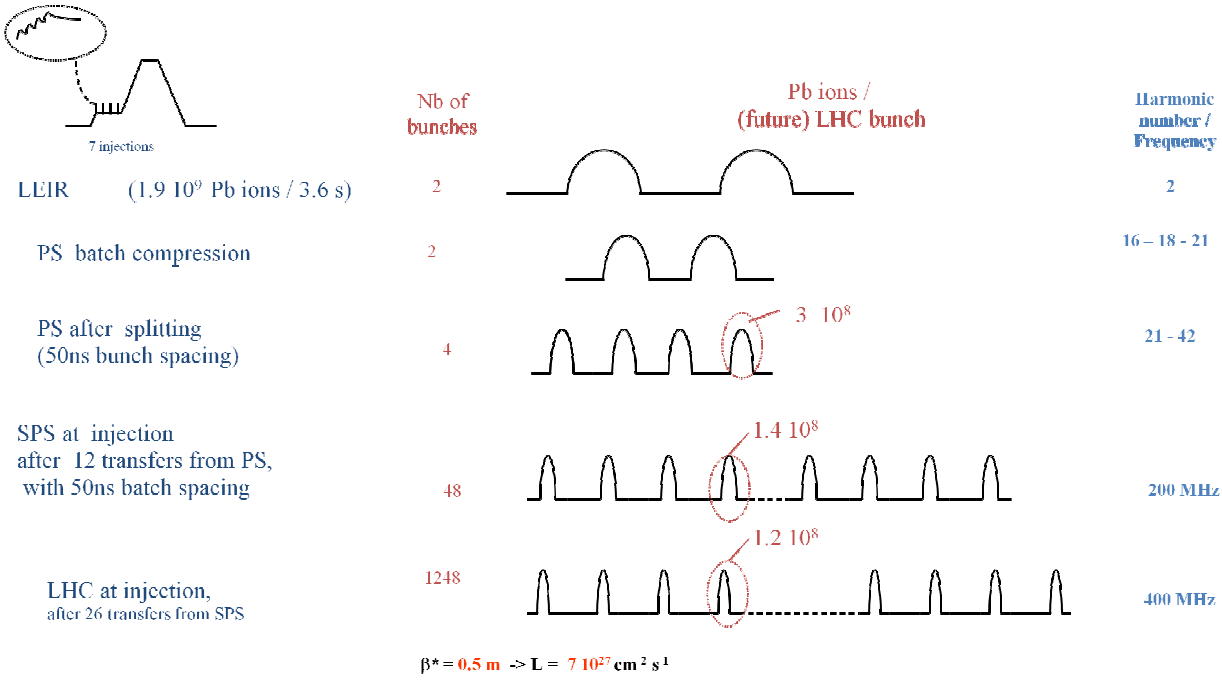

Figure 5: 50 ns spacing scheme for HL-LHC

NECESSARY STUDIES AND UPGRADES

In order to produce the beam describe above, the whole injector complex would need to undergo several upgrades:

Source and Linac3

The output current of the ion linac should be upgraded to deliver the design value of 50μA. Apart from the construction of a completely new facility ("Linac 5"), several possibilities have to be explored in order to reach this goal, such as the improvement of the ECR source, or design and construction of a new one. Another promising development is the simultaneous acceleration of multiple charge states in the IH structure.

In addition, one can think of increasing the repetition rate of the Linac 3, currently 5 Hz. The linac itself had already been design for 10 Hz, but the power supplies of the transfer lines towards LEIR would have to be upgraded.

LEIR

The most urgent issue in LEIR is to try and understand the reason for the beam loss at the beginning of the accelerating ramp. No hypotheses are currently ruled out, including:

- Limitations due to direct space charge
- Limit with irregular lattice lower than expected
- Too small transverse emittances after cooling
- Impact of Bdot (too fast or too slow)
- Instabilities

PS

For the implementation of the suggested scheme, the PS is the machine which would need the least modifications. The RF gymnastics have to be designed and implemented, but the hardware already exists, and the know-how is well established.

SPS

In the LHC design report [1], the MKP was supposed to be upgraded in order to allow a batch spacing as low as 125 ns for injection at $\gamma = 5.45$. Injection at $\gamma = 7.31$ currently imposes a lower limit of about 200 ns. In order to reach a factor 3.5 in peak luminosity, a rise time shorter than 50 ns is needed. This would imply a complete revision of the injection scheme, including the construction of 30 new, short kicker magnets. A lot of

R&D is necessary for such a drastic improvement – which would also benefit the proton physics.

For the problem of the bunches degradation on the long injection flat bottom, several remedies are being studied.

- The RF noise can be decreased by staying on a fixed harmonic system during injection, and only switching to the fixed frequency beam control for acceleration.
- The space charge and IBS effects can be somehow mitigated by the use of Q20 optics [8] which result in larger transverse beam dimensions.
- The bunchlet scheme originally proposed in the design report could be revived. However, the impedance of the additional 100 MHz cavities could be detrimental to the stability of the proton beam, so independently of its cost, this solution is not favoured.

Finally, provided the issues mentioned above are solved, one can think of an even longer injection flat bottom of the SPS, with 15 injections or more. This number is limited to 12 by the current hardware.

OTHER SPECIES

Argon and Xenon

Fixed target Ar and Xe runs are foreseen to take place respectively in 2014 and 2015 in the North Area at the SPS. To that effect, the ECR source, RFQ, and Linac3 will exceptionally be running with these two species for 13 weeks each during the first long shutdown (LS1), in 2013. The Ar beam will be commissioned in the rest of the injector complex (LEIR, PS, SPS) in 2014. As was the case for the Pb beams, the beam structure will be identical in the SPS as the one needed to fill the LHC for the Ar-Ar collisions. This will allow a gain of experience with the LHC beam while fulfilling the needs of the fixed target experiments. Although not yet approved, and not requested before 2021, Ar beams could be available for collisiopns in the LHC as early as 2015.

Deuterons

At present, deuterons cannot be accelerated in Linac3 as it is, and four solutions have been proposed [9] in order to provide them:

1. Build a new source, a new low energy beam transport (LEBT), a new RFQ, and re-use the current Linac3 IH structure to accelerate to the LEIR injection energy.
2. Build a new source, a new LEBT and a new RFQ, which accelerates to the final energy to inject into LEIR.
3. Build a completely new linac dedicated to creation and acceleration of deuterons, with an acceleration structure optimized for the different beam velocities.
4. Build a new compact cyclotron with an internal deuteron source, delivering intermediate intensities at an energy optimized for the injection into LEIR.

Each of these options have their drawbacks and advantages, which will have to be weighted and evaluated with the available budget, should deuterons be required by the users. In any case, the earliest date for deuterons availability cannot be before LS3.

Uranium

No formal requests exist at present for collisions of U beams in the LHC. In addition to the usual accelerator physics issues, due to its toxicity - both chemical and radiological - uranium poses severe handling and safety problems which would need to be studied and solved.

CONCLUSIONS

- With the present injector complex, increasing the number of bunches seems to be the only route for a marginally higher luminosity, and at the expense of a longer LHC filling time.
- A solution exists to produce up to 3.5 times the current peak luminosity, i.e. about 7×10^{27} $cm^{-2}.s^{-1}$ at 7 ZTeV/*c* per beam, but it necessitates an upgrade of the beam production stage (ECR source and/or Linac3) and of the SPS injection kicker.
- If we are to implement the suggested improvements in order to reach the required Pb-Pb luminosity (provided the LHC can digest it), it is more than time to start the RnD on all parts of the injector chain.
- Ar and Xe will be available after LS1 (parameter list still to be defined and optimised) but other species, if desired, would come in addition, and require more studies, in particular a new source & pre-accelerator for deuterons, or safety and handling issues for Uranium.

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