

PERFORMANCE OF THE INJECTORS WITH IONS AFTER LS1

D. Manglunki for the LIU-Ions team

CERN, Geneva, Switzerland

Abstract

We review the performance of the ion injector chain at the light of the improvements which will take place during LS1, and we derive the expected luminosity gain for Pb-Pb and p-Pb collisions in the LHC. We suggest a baseline plan of upgrades that will allow the requirements of the ALICE experiment after LS2 to be reached. An alternative plan is also presented. Finally, we examine the possibility for different ions species for which some of the other experiments have expressed an interest. The main outcomes of the presentation ‘Work effort in the injector complex (including the Linac4 connection)’ will be reminded with emphasis on their consequences on the ion operations.

INTRODUCTION

The Pb^{82+} ion beam brilliance, as delivered from the injectors in February 2013 at the end of the first LHC p-Pb run [1], exceeded the design value [2] by a factor three, as shown in table 1. A Pb-Pb run under those conditions would have delivered about $2.3 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ of peak luminosity at 6.5 ZTeV. Since the peak luminosity requested by the ALICE experiment for the HL-LHC era [3] is of the order of $6\text{--}7 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ at 7 ZTeV, a missing factor of about 3 is still to be found. The retained solution is to increase the number of bunches in the collider, as the bunch brilliance is already a limiting factor on the flat bottom of the SPS, due to space-charge and intra-beam scattering [4]. Increasing the bunch intensity would also decrease the luminosity lifetime due to larger burnoff [5].

Table 1: Pb^{82+} ion beam properties at SPS extraction in 2013, compared to design values.

	Pb^{82+} 2013	Pb^{82+} design	
N_B	22	9	10^7 Ions/bunch
ϵ_H	1.1	1.2	μm (norm. RMS)
ϵ_V	0.9	1.2	μm (norm. RMS)
N_B/ϵ	22.1	7.5	10^7 Ions/ μm

BASELINE SCHEME

The baseline scheme, summarized in Fig. 1 below, assumes up to the LEIR machine, a similar performance as achieved in February 2013, with no significant improvement in the bunch intensity extracted from LEIR. The 2 bunches of $5.5 \times 10^8 \text{ Pb}^{54+}$ ions each, are transferred to the PS in two adjacent buckets of harmonic $h = 16$. A batch compression is performed in the PS on harmonics $h = 16\text{--}18\text{--}21$, yielding a bunch spacing of 100 ns at the end of acceleration. After rebucketing to $h = 169$, the two-bunch batch is transferred to the SPS through the TT2-TT10 line where full stripping to Pb^{82+} takes place. Twelve such transfers are needed to produce a full train. In order to maximize the number of bunches, the batches are injected next to each other, with a batch spacing of 100 ns, thanks to a new ion injection system [6]. The trains supplied by the injector chain to the LHC then consist of 24 bunches, spaced by 100 ns.

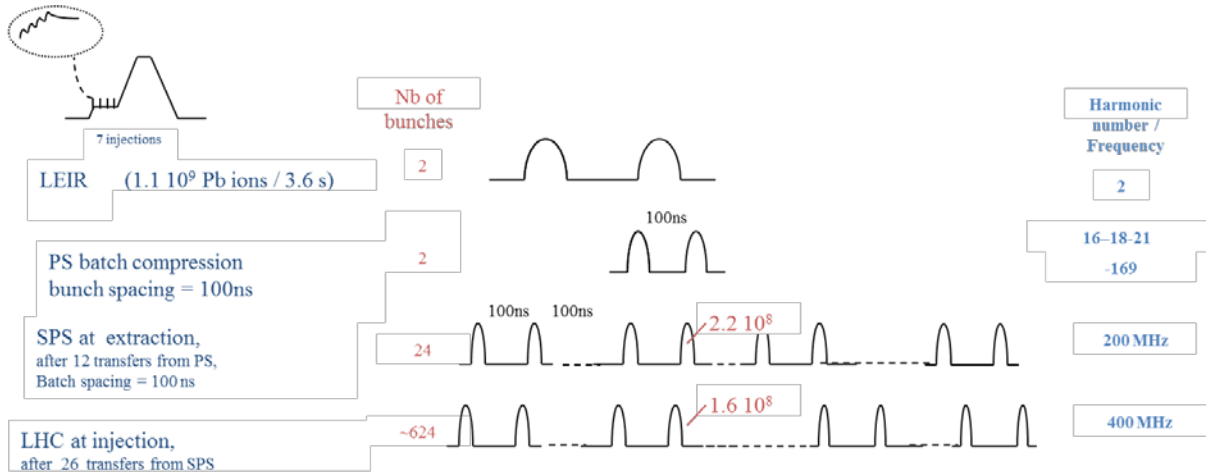


Figure 1: Proposed baseline scheme.

Up to 26 such trains can be sent to each LHC ring, totalling 624 bunches per ring. Assuming LHC operation at 7 ZTeV, a peak luminosity of $4 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ is within reach. The main investment consists in an upgrade of the SPS injection scheme, using a septum recuperated from the PSB extraction line, after its upgrade to 2GeV, and a

faster pulser which had already been foreseen at the time of design [7]. A faster, 50 ns injection system had been considered [8] but had to be discarded due to impedance and resources considerations.

Table 2 summarizes the beam parameters across the injector chain for the baseline scheme.

Table 2: Baseline beam parameters.

Parameter	Unit	Linac 3	LEIR	PS	SPS
Pb charge state (¹)		29+/54+ (¹)	54+	54+/82+ (¹)	82+
Output Energy	[GeV/u]	0.0042	0.0722	5.9	176.4
Output Bp	[T.m]	2.12/1.14 (¹)	4.8	86.7/57.1 (¹)	1500
Injections into the next machine		6	1	12	26x2
Bunches/ring			2	2	24
Extracted intensity/pulse	Ions	4.6×10^8	1.1×10^9	7×10^8	1.9×10^9 (³)
Total extracted charge	Charges	2.5×10^{10}	6.0×10^{10}	3.8×10^{10} / 5.7×10^{10} (¹)	1.6×10^{11} (³)
Ions/bunch at injection	Ions		5.5×10^8 (⁴)	3×10^8	2.2×10^8 (²)
Ions/LHC bunch at extraction	Ions		4×10^8	2.5×10^8	2×10^8 (²) 1.6×10^8 (³)
Bunch spacing at extraction	[ns]	N/A	350	100	100
Normalised transverse rms emittance	[μm]	0.25	0.70	1.0	1.2
Longitudinal emittance	[eVs/u]		0.025	0.045	0.125
4 σ Bunch length	[ns]		200	3.9	1.8
2 σ Momentum spread		0.4×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	3.2×10^{-4}
Repetition time	[s]	0.1	3.6	3.6	49.2
Space charge ΔQ on flat bottom			0.09 (⁴)	0.15	0.18 (²)

(¹) stripper stages between Linac3 & LEIR, then between PS & SPS; parameters before/after stripping

(²) corresponding to the maximum bunch intensity

(³) average intensity taking into account the distribution of bunch intensities along the train

(⁴) at the end of the flat bottom, just before acceleration.

POSSIBLE IMPROVEMENTS

Splitting in the PS

In order to further increase the bunch number in the LHC, one would have to split the beam in the PS, whose RF system cannot accelerate on 20MHz. Hence, splitting down to a 50 ns bunch spacing would have to be done at high energy, close to transition. So, not only new cavities would have to be installed in the PS machine for the RF gymnastics themselves, but also a new gamma-jump scheme, specific to ions, would have to be designed and implemented. For the same reason, a batch compression down to 50 ns bunch spacing at high energy would be impractical. Hence, only splitting to 100 ns bunch spacing in the PS will be considered in the following, using the same bunch structure as already planned for the nominal beam in the design report [9].

Increasing the LEIR bunch population

In order to deliver a similar performance as in table 1 in spite of splitting, the beam intensity out of LEIR should be increased, ideally by a factor 2. However, assuming the splitting allows to double the number of bunches in the LHC, breakeven for the peak luminosity is reached by a factor $2^{1/2}$ only, i.e. an increase of 40%.

Due to a loss that occurs at the beginning of the acceleration ramp (Fig. 2), the intensity extracted out of LEIR is currently limited to about 6×10^{10} charges, corresponding to $5.5 \times 10^8 \text{ Pb}^{54+}$ ions per bunch. A thorough machine development programme has started in order to try and understand, then lift or mitigate this limitation [10]. Provided it is possible, the Linac3 current output needs to be pushed up.

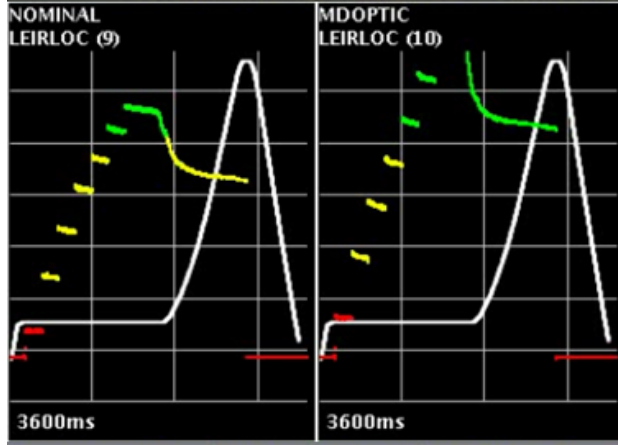


Figure 2: Loss at acceleration on the LEIR nominal and development cycles.

Increasing the LINAC3 current

Compared to the design values, a factor two is missing from the current output of Linac3. A rematching campaign is being performed to try and optimise the beam transmission in the LEBT.

The possibility of accelerating up to three charge states in Linac3 to double the intensity as originally planned at the time of design [11] is now abandoned, as it is likely that the off-central charge states would not be transmitted into the LEIR machine, due to their large momentum error.

Aside from new developments on the ECR source itself, the most promising path consists in doubling the repetition rate from 5 to 10 Hz [12]. The investment will be relatively modest as the source itself is already pulsing at 10 Hz, and the Linac3 has been designed for operating at 10 Hz as well. The LEIR injection system has also been tested at 10 Hz, so only a few magnets and power supplies in the Linac-to-LEIR transfer lines will have to be replaced or upgraded.

Momentum slip-stacking in the SPS

As bunch-splitting or batch compression to reach a bunch spacing of 50 ns both prove difficult to perform in the PS, elegant RF gymnastics in the SPS have been proposed, which will be made possible by the planned upgrade of the SPS radio frequency systems. Momentum slip stacking [13] consists in capturing two trains of bunches with independent beam controls, and by detuning them in momentum, bringing them closer together. Those gymnastics, originally proposed to increase bunch densities [14], can be applied in our case to interleave the bunches (Fig. 3):

- The PS transfers two times 6 batches of four bunches to the SPS, with a batch spacing and a bunch spacing of 100 ns, leaving a gap large enough for two independent RF systems to capture each of them on the same frequency.
- The two trains are detuned in momentum by opposite amounts
- They start slipping towards each other
- Once the bunches are interleaved they are recaptured at average frequency and filament in a large bucket

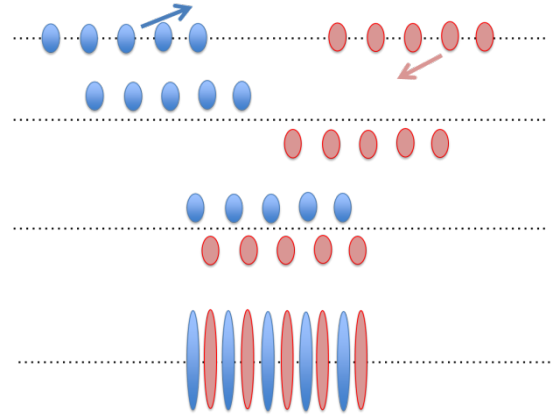


Fig. 3: Schematic for halving the bunch spacing using momentum slip stacking.

One issue is the larger resulting longitudinal emittance, but early simulations indicate the bunch length would still be within the accepted limits of the LHC RF at injection [15]. This issue can be completely dismissed in case of the addition of 200 MHz cavities in the LHC.

Putting it all together

Assuming (Fig. 4):

- a reasonable increase (~50%) of the bunch density in LEIR,
- splitting the two bunches in the PS in order to send 4-bunch trains into the SPS with 100 ns bunch spacing,
- a new 100 ns rise time injection scheme into the SPS
- momentum slip stacking in the SPS,

one gets a total number of bunches of 1248 bunches in each one of the LHC rings, bringing the peak Pb-Pb luminosity at 7 ZTeV over $\mathcal{L}_{\text{peak}} = 6.0 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. Table 3 summarizes the beam parameters in the injectors for this scheme.

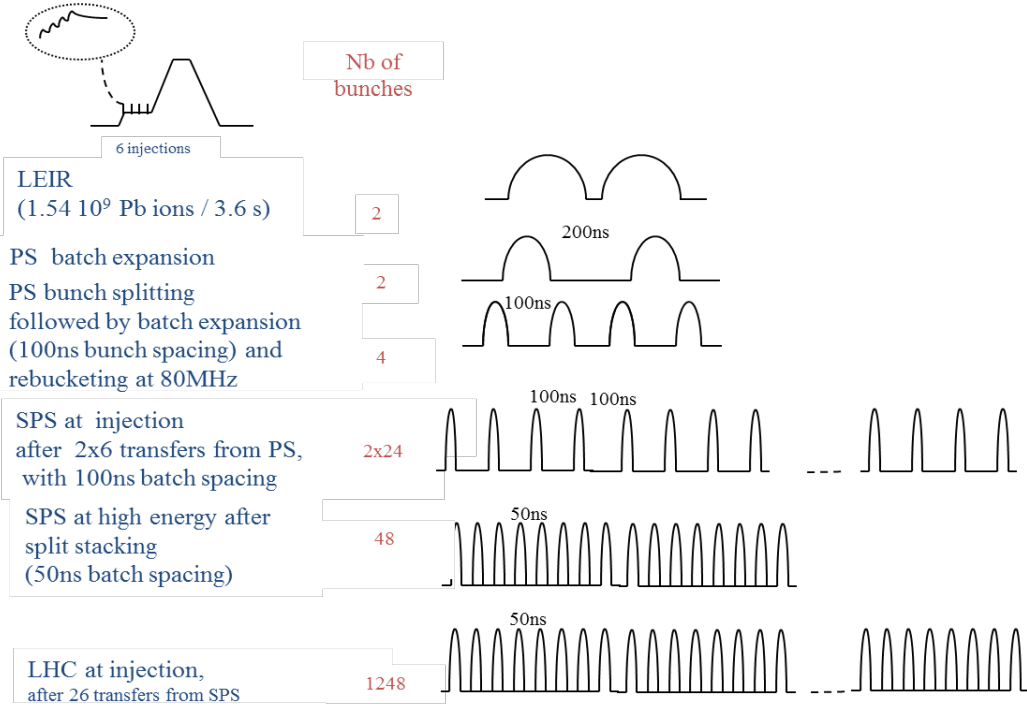


Figure 4: Fully upgraded scheme, with momentum slip stacking in the SPS.

Table 3: Tentative beam parameters for the fully upgraded scheme.

Parameter	Unit	Linac 3	LEIR	PS	SPS
Pb charge state ⁽¹⁾		29+/54+ ⁽¹⁾	54+	54+/82+ ⁽¹⁾	82+
Output Energy	[GeV/u]	0.0042	0.0722	5.9	176.4
Output Bp	[T.m]	2.12/1.14 ⁽¹⁾	4.8	86.7/57.1 ⁽¹⁾	1500
Injections into the next machine		6 (or more)	1	6+6	26
Bunches/ring			2	4	48
Extracted intensity/pulse	Ions	1.3×10^9	1.6×10^9	7.2×10^8	5.2×10^9 ⁽³⁾
Total extracted charge	Charges	7.2×10^{10}	8.6×10^{10}	3.9×10^{10} / 5.9×10^{10} ⁽¹⁾	4.3×10^{11} ⁽³⁾
Ions/bunch at injection	Ions		10^9 ⁽⁴⁾	8×10^8	1.8×10^8 ⁽²⁾
Ions/LHC bunch at extraction	Ions		4×10^8	1.8×10^8	1.5×10^8 ⁽²⁾ / 1.1×10^8 ⁽³⁾
Bunch spacing at extraction	[ns]	N/A	350	100	50
Normalised transverse rms emittance	[μm]	0.25	0.70	1.0	1.2
Longitudinal emittance	[eVs/u]		0.025	0.045	0.24
4 σ Bunch length	[ns]		200	3.9	1.8 ⁽⁵⁾
2 σ Momentum spread		0.4×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	6.4×10^{-4} ⁽⁵⁾
Repetition time	[s]	0.1	3.6	3.6	49.2
Space charge ΔQ on flat bottom			0.13 ⁽⁴⁾	0.23	0.13 ⁽²⁾

⁽¹⁾ Stripper stages between Linac3 & LEIR, then between PS & SPS; parameters before/after stripping

⁽²⁾ Corresponding to the maximum bunch intensity

⁽³⁾ Average intensity taking into account the distribution of bunch intensities along the train

⁽⁴⁾ At the end of the flat bottom, just before acceleration.

⁽⁵⁾ Assuming 7.5MV RF voltage.

Expectations for 2015

For the first Pb-Pb run, currently planned for November 2015, batch compression RF gymnastics, already tried and tested in 2012, will be implemented in the PS, bringing the spacing between the two bunches down to 100 ns. Up to twelve such two-bunch batches will be accumulated for every cycle of the SPS, with a batch spacing of 225 ns. After 36 injections from the SPS, assuming once again the same performance (intensity per bunch and transverse emittances) as in February 2013, this scheme delivers up to 432 bunches of $1.6 \times 10^8 \text{ Pb}^{82+}$ ions per LHC ring, corresponding to a peak luminosity at 6.5 ZTeV of $\mathcal{L}_{\text{peak}} = 2.8 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

DIFFERENT IONS SPECIES

In the coming years, the ion production complex (Linac3, LEIR, PS, SPS) will need to deliver argon and xenon ions to the North Area for fixed target experiments, mainly NA61/SHINE [16]. The argon beam will be commissioned in the whole injector complex up to the SPS in 2014, with a fixed target run planned for 2015. The experience gained in handling the argon beam will be useful to predict the luminosity of Ar-Ar or p-Ar collisions in the LHC, for which the heavy ion community part of the ATLAS collaboration has already expressed interest [17].

The current planning foresees xenon to be available by 2016 in the SPS for a fixed target run in 2017, but neither Xe-Xe nor p-Xe collisions have been mentioned by any of the LHC experiments so far.

Finally, oxygen is used as a support gas for the production of Pb ions at the level of the source. Switching the source to oxygen production at the beginning or at the end of a Pb-Pb or p-Pb run in the LHC would allow a short O-O or p-O run for forwards physics, as requested by LHC-f [18]. However some commissioning time for the oxygen beam in the injectors would have to be budgeted.

SCHEDULE

Connecting the LINAC4 to the PSB during a 9 month proton stop “LS1.5” in the middle of Run2 could be used for a (maximum) 3.5 month ion run: Pb-Pb collisions in the LHC, primary fixed target Xe ions in the North Area, and machine developments towards high luminosity in the whole injector chain [19]. This would also move xenon out of the way as it would allow a fixed target xenon run during the preceding year, in lieu of the Pb-Pb run in the LHC. However, this solution has been rejected by the heavy ion community in the collider experiments, as their data taking periods have to be regularly spaced, at a rate of one month per year [20].

CONCLUSION

- With the current scheme, the present injector performance would deliver $\mathcal{L}_{\text{peak}} = 2.3 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ at 6.5 ZTeV
- A robust baseline scheme is presented, which ensures bringing the peak Pb-Pb luminosity at 7 ZTeV to $\mathcal{L}_{\text{peak}} = 4.0 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ with feasible upgrades in the injectors, mainly a new ion injection scheme in the SPS.
- Until the SPS injection is upgraded, new RF gymnastics in the PS (demonstrated in 2012) already bring a 22% increase to $\mathcal{L}_{\text{peak}} = 2.8 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ at 6.5 ZTeV for the first LHC run after LS1.
- A promising slip stacking scheme is being investigated, which would bring the performance up to the expectations of the experiments.
- Colliding other ions such as Ar, Xe, or even O, in the LHC can be envisaged but are currently neither scheduled, nor specified.
- The proposal of an extended ion run during the connection of LINAC4 to the PSB in the middle of Run2 has been rejected by the experiments.

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