IONS: BASELINE, STUDIES PLAN AND STRATEGY FOR PENDING OPTIONS

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Abstract

We will review the performance of the ion injector chain of the LHC during LR1, and the baseline of the upgrades, which are planned in order to reach the performance required after LS2. After overviewing the open issues and a tentative list of planned machine developments, we present the beam characteristics expected during LR2 and beyond.

MOTIVATION

In the light of the first two successful Pb-Pb runs in the LHC [1], the ALICE experiment will be implementing a detector upgrade for the exploitation period following LS2 [2]. As can be seen in Fig. 1, there will only be about 8 Pb-Pb runs between LS2 and 2035 [3], so a peak luminosity exceeding $7x10^{27}$ Hz/cm^2 is expected in order to fulfil the goal of 10 nb^{-1} [4].

Figure 1: LHC schedule beyond LS1, approved in December 2013. Pb-Pb and p-Pb runs have been added in orange.

We propose a realistic baseline strategy for the injectors to achieve this ambitious goal. The feasibility of this baseline strategy is being studied on paper and will be demonstrated experimentally. A series of measures will have to be taken in the whole ion injector chain: Linac3, LEIR, the PS and the SPS.

This work is a part of the LHC Injector Upgrade (LIU) project [5].

BASELINE SCHEME

As the bunch population is already at the limit for the collective effects (space charge and IBS) on the long flat-bottom of the SPS, the scheme is based on an increase by a factor ~3.5 of the number of bunches in the LHC, compared to the latest Pb-Pb, performed in 2011. It is summarized in Fig. 2 below. Just like today, Linac3 will deliver Pb^{29+} ion pulses for the duration of 200 µs at 4.2 MeV/nucleon, stripped to Pb^{54+}. In order to provide the required beam quality, the Linac3 beam intensity should be increased towards the performance described in the design report [6]. The LEIR machine will inject up to 13 Linac3 pulses every 200ms on a long flat bottom. After cooling, the LEIR beam will be bunched on harmonic $h = 2$ and accelerated to 72 MeV/nucleon, before extraction to the PS. In the PS the two bunches will be accelerated to 5.9 GeV/nucleon. On an intermediate flat-top, the batch will be expanded and the bunches split, with a harmonic sequence $h = 16, 14, 12, 24, 21$, as was originally intended and described in the LHC design report [7], the difference being a bunch population twice larger. At high energy, the bunches will be rebucketed to $h = 169$ by one of the three 80 MHz cavities before extraction towards the SPS. As is already the case, the ions will be fully stripped to Pb^{82+} on a 1mm thick aluminium plate located inside a low-beta insertion to minimize the transverse emittance blow-up.

In the SPS, the beam will be injected and captured on a fixed harmonic RF system in order to minimize the RF noise, using the Q20-optics to mitigate the effects of space charge and IBS [8]. Twelve four-bunch batches will be injected with 100 ns batch spacing, apart from a 1 µs gap between the 6th and the 7th batches. In the SPS, after acceleration on fixed frequency to 177 GeV/c/nucleon, momentum slip-stacking will reduce the bunch spacing to 50 ns. The trains supplied to the LHC by the injector chain will then eventually consist of 48 bunches, with a constant bunch spacing of 50 ns. Twenty-six transfers from the SPS will be necessary to fill each LHC ring with up to 1248 bunches. The expected beam parameters can be found in Table 1 below and in [9].

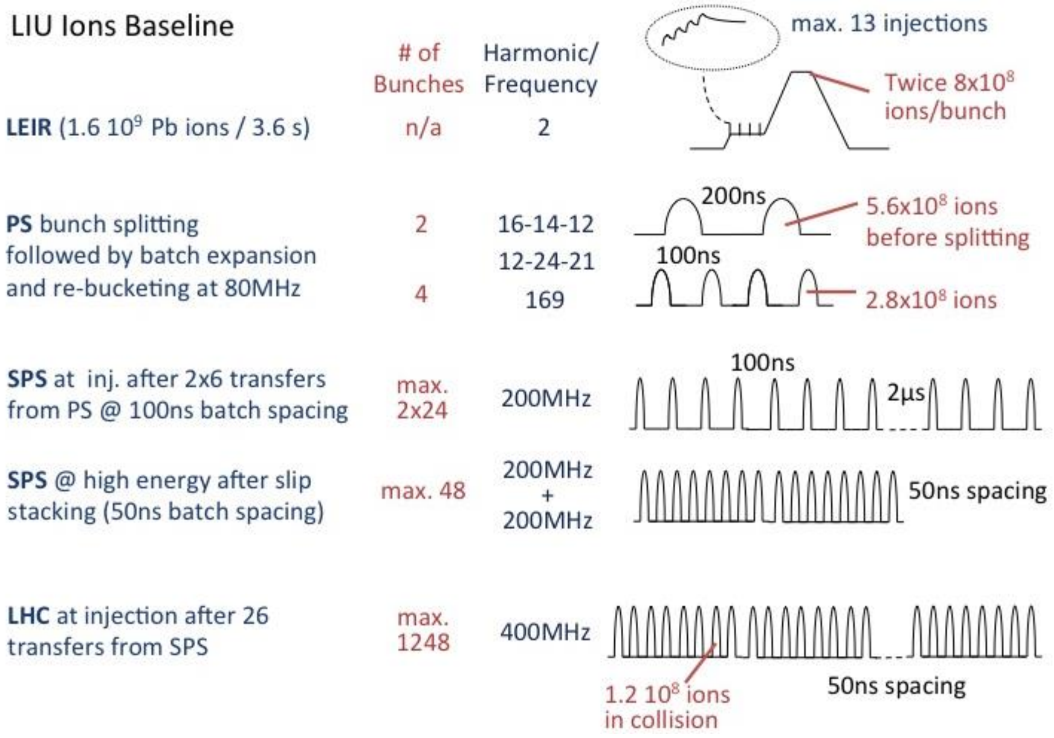

Figure 2: LIU-ION baseline scheme.

Table 1: LHC design parameters, achieved value in 2013 and LIU Ions base line beam parameters by machine in a simplified list. For the full LIU Ions beam parameter table with references, please see [9].

	LEIR before RF-capture (coasting beam)			After RF-capture and per bunch					
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	$\Delta p/p$	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions]	RMS [µm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS[-]	[-]	[-]	[-]
LHC design rep.	1.0E+09	0.67	0.0042	0.040	800	2.0E-03	2	-0.11	-0.11
Achieved 2013	**1.7E+09**	**0.73, 0.33**	**0.0042**	**0.035**	**860**	**1.3E-03**	**2**	**-0.10**	**-0.16**
LIU Ions	2.0E+09	0.67	0.0042	0.035	860	1.3E-03	2	-0.12	-0.19

	PS @ injection (one injection from LEIR)								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	$\Delta p/p$	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [µm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	4.50E+08	0.7	0.0722	0.050	200	6.0E-04	2 -> 4	-0.11	-0.11
Achieved 2013	**5.5E+08**	**0.73, 0.33**	**0.0722**	**0.039**	**177**	**4.4E-04**	**2**	**-0.18**	**-0.27**
LIU Ions	8.0E+08	0.73, 0.47	0.0722	0.039	177	4.4E-04	2 -> 4	-0.24	-0.30

	SPS @ injection (12 injections from PS)								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	$\Delta p/p$	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [µm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	1.2E+08	1	5.9	0.050	3.9	3.3E-04	12x4	-0.03	-0.04
Achieved 2013	**3.8E+08**	**0.5**	**5.9**	**0.042**	**3.9**	**5.4E-04**	**12x2**	**-0.16**	**-0.20**
LIU Ions	2.8E+08	**0.5**	5.9	0.042	3.9	5.4E-04	12x4	-0.12	-0.15

	LHC @ injection								
Variable, convention & units	Beam int.	$\beta\gamma\varepsilon_{H,V}$	Kin. E.	ε_z ($4\pi\sigma_E\sigma_T$)	Bunch len.	$\Delta p/p$	no. of B.	max. $\Delta Qsc_{H,V}$	
	[ions/B]	RMS [µm]	[GeV/n]	[eVs/n]	4 RMS [ns]	RMS [-]	[-]	[-]	[-]
LHC design rep.	7.0E+07	1.4	176.4	0.280	1.8	3.2E-04	592	-1.5E-04	-1.0E-04
Achieved 2013	**1.6E+08**	**1.3**	**176.4**	**0.2…0.52**	**0.9…1.4**	**1.1…1.6E-4**	**358**	**-8.9E-04**	**-9.4E-04**
LIU Ions	1.2E+08	**1.3**	176.4	0.351	1.8	3.5E-04	1248	-2.7E-04	-3.3E-04

SUMMARY OF UPGRADES

In order to deliver the beam quality described above, the ion injector chain will need to undergo the following series of upgrades:

Linac3

Linac3 will deliver ion beam pulses of 20µA for the duration of 200µs at 4.2MeV/n. These pulses will be spaced by 100ms for the post LS2 injector scheme, versus 200 ms in 2013.

The LEIR machine will accept a maximum of 13 injections from Linac3 during a 3.6 second cycle time. Averaged over a 3.6 second cycle, this results in 3.61 Hz. Linac3 is currently capable of producing continuously pulses at 5 Hz. The air-cooling and ventilation system is running at the limit for operation at 5 Hz, and its renovation to restore the required cooling power is requested to the consolidation project, and should be done in LS2.

The GTS ion source of Linac3 is currently operating at 10 Hz continuous repetition rate. See Fig. 3.

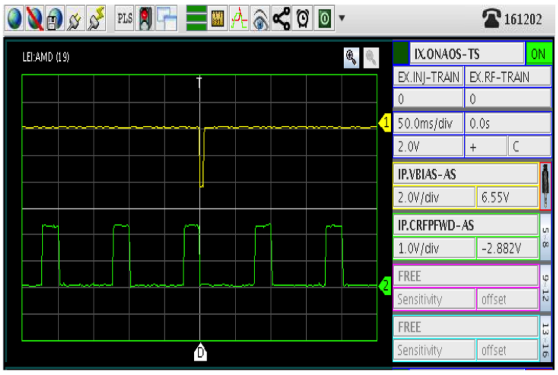

Figure 3: Analog signal of the GTS ion source of Linac3, showing the ion source pulsing with a bunch spacing of 100ms and a bunch duration of 200µs.

The low-energy-beam-transport (LEBT) of Linac3 is under investigation in order to further increase the ion beam intensity delivered to LEIR after LS2 and to get closer to the LHC design report value of the Linac3 current of 50 µA. Numerical simulations suggest that approximately half [10] the ions could be lost from the source extraction system to the RFQ of Linac3 (see Fig. 4). The goal is to reduce the ion beam loss in the LEBT and to increase the overall transmission of Linac3.

Before LS2, a series of machine development sessions are planned to crosscheck measurement and simulation. Before 2015, Linac3 will receive a pepper pot at a location after the LEBT spectrometer bending magnets and before the RFQ. With this it is possible to measure the beam profile and its emittance in the horizontal and the vertical plane. These measurements will serve as input for the numerical simulation of the LEBT and Linac3. It will allow gaining insight into why and where a large fraction of the GTS extracted ion beam is lost.

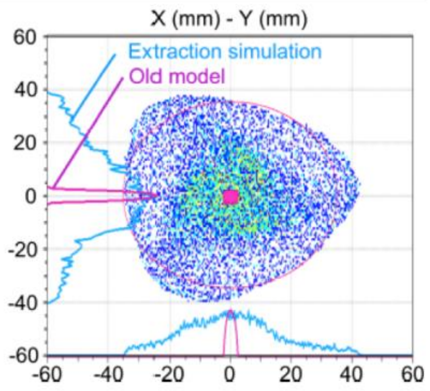

Figure 4: The initial particle distribution as input for the simulation of the LEBT in Linac3. A comparison is shown between the old (blue) input distribution and the new (in red) input distribution leading to a significantly lower beam transmission.

LEIR

To reach the LIU Ions luminosity goal in LHC following the proposed post-LS2 injection scheme, LEIR will need to deliver 8x10^{8} ions per bunch in two bunches to the PS. This ion beam intensity represents an increase of 45% with respect to the ion beam intensity achieved during the 2013 proton-lead run [11].

As explained above, the Linac3 repetition rate will be increased to 10 Hz. This will allow filling LEIR with up to 13 multi-turn injections. Each multi-turn injection will fill LEIR for 72 turns, see Fig. 5.

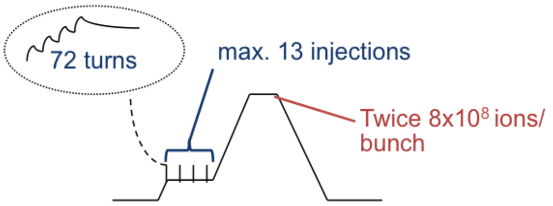

Figure 5: A maximum of 13 multi-turn injections will be accommodated on the low energy plateau in the LEIR machine. Two bunches of 8x10^{8} ions per bunch will be extracted from the LEIR machine and sent to the PS.

LEIR operations in 2013 revealed that effective electron cooling has required the full time span of 200 ms between the individual multi-turn injections. Decreasing the injection spacing to 100 ms will reduce the time available between injections to cool and to shrink the ion beam. Hence, improving the electron-cooling rate is imperative. Extensive machine developments will be conducted before LS2 to investigate quicker electron cooling rates by increasing the electron beam current and by optimizing the LEIR machine optics.

With an injection spacing of 100 ms and the improved electron-cooling rate, LEIR is planned to accumulate up to 2x10^{9} ions on the low energy plateau. From this accumulated beam intensity, LEIR will need to extract two bunches of 8x10^{8} ions each to the. This increase of extracted intensity will require a significant mitigation of the low energy ion beam loss after RF capture in LEIR (see Fig. 6).

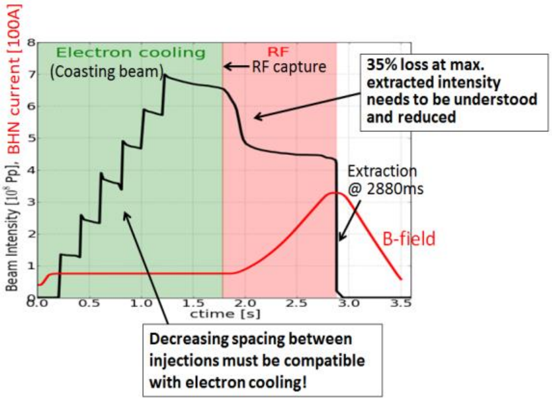

Figure 6: A typical NOMINAL cycle in LEIR with ion beam intensity (black) and main magnet current (red) vs. cycle time. The ion beam loss after RF-capture is currently the performance limiting ion beam loss in LEIR.

We plan to approach this loss mitigation by the following measures:

- More robust and operable beam diagnostics, in particular a fully operational:
  - transverse and longitudinal emittance measurement from Schottky signals.
  - gas ionization profile monitor measurement system.
- Extensive list of machine developments:
  - Re-establish the 2013 beam intensity and low energy loss phenomenon. Check its behaviour to be consistent with the observations from 2013.
  - Compare Ar findings from 2014 and 2015 with re-established Pb beam.
  - Run LEIR with negative chromaticity [12] and design tune with findings from Ar run.
  - Test LEIR Pb-beam with newly found tune from Ar run.
  - Test machine behaviour with higher intensity electron beam of the electron cooler and shortened cooling times.
- In machine modelling and beam dynamics theory, test and refute working hypothesis of:
  - Space charge
  - Faulty transverse damper
  - Impedance
  - Other types of instabilities, not yet considered so far.

PS

In the PS machine, the RF gymnastics originally intended in the design report for the nominal LHC beam will have to be recreated:

- Batch expansion (h = 16 – 14 – 12)
- Bunch splitting (h = 12 – 24)
- Batch expansion (h = 24 – 21)
- Rebucketing at h = 169 (80 MHz)

These gymnastics have been demonstrated during the previous runs, and the needed hardware is currently the same as the one, which has been used until now for the ions, but its maintenance should be included in the consolidation programme.

SPS

The SPS is the machine which will be modified the most for the LIU-ION project, as it will need to implement a new ion injection and the momentum slip-stacking.

Thanks to an improved 100 ns rise time, the new ion injection system will allow stacking the four-bunch batches from the PS with a bunch spacing of 100 ns in the SPS [13]. It will consist in:

- new pulsers for the fast kicker magnets, allowing a rise time of 100 ns. These fast pulsers had already been foreseen at the time of design [14],
- a new injection septum, which will be recuperated from the PS Booster extraction line, after its upgrade to 2 GeV,
- an improved injection damper to mitigate the large oscillations of the bunches situated at the limit of the kick.

The momentum slip-stacking gymnastics [15][16] need two independent RF-cavity controls, which rely on the upgrade of the low level RF. New hardware is needed for this upgrade. The two trains of 24 bunches will be captured independently, and detuned in momentum in opposite directions. The resulting frequency difference will make the two trains slip towards each other. Once the bunches are completely interleaved, they will be recaptured by a common RF, tuned to the average frequency. 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 [17]. A continuation of this simulation study is required to detail and to understand the performance behaviour of the planned SPS momentum slip-stacking for LIU Ions.

Improvements on RF noise (fixed harmonic system on flat bottom) will be achieved by switching to fixed frequency for acceleration of 48 bunches on the low energy plateau. This will improve the emittance growth rate and the consequential energy beam loss.

ADDITIONAL MEASURES

In addition to the above upgrades, the following measures will be implemented to facilitate the required machine studies in order to achieve the LIU Ion goals for intensity in the injector chain and for the peak luminosity in the LHC.

LBS

[18] The LBS line measures the energy and energy spread of the beam from CERN proton Linac2 as well as the ions from Linac3. For Linac3 it is essential to have an energy measurement after the debuncher cavity. The LBS

line essentially consists of a spectrometer magnet, slits and a SEMGrid. The Linac4 project would have renovated this LBS line for 160MeV H- ions, but recently has chosen an alternative energy measurement system, and hence the LBS line will be renovated within LIU-Ions. For this renovation the spectrometer magnet will be replaced with almost identical ones recovered from Linac2, the power convertor will be exchanged for a new one recovered from the Linac4 project, and the controls of the transfer line between Linac3 and the LBS line that is in common with Linac4 will be migrated to FGC3s, and configured in a way to allow simpler sharing of the line between the 160 MeV H- and the 4.2 MeV/nucleon Pb^{54+} ions.

Spare source [option]

As an option, building a second, identical ion source, would allow training new supervisors and machine specialists on real conditions, as well as perform machine experiments on Pb or new species, without jeopardizing the current operations. It could also be used as a hot spare in case of a serious damage of the operation source.

LEIR Dump

At the moment each beam, which is accelerated in LEIR but not requested by the LHC, is either lost on the PS injection septum, or worse, inside the LEIR machine itself. This situation is deemed intolerable for the higher intensity of the LIU Ions beam, which should be disposed of cleanly and safely. A new dump is being designed to this effect between LEIR and the PS. It will be installed at the exit of the switching magnet ETL.BHN10, at the junction between the LEIR transfer line ETL and the PS injection line ETP.

PERFORMANCE BEFORE LS2

[19][20] 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 can deliver up to 432 bunches of 1.6×10^{8} Pb^{82+} ions per LHC ring [21], corresponding to a peak luminosity of $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV.

CONCLUSIONS

- A baseline scheme is presented, which ensures bringing the peak Pb-Pb luminosity at 7 ZTeV to $\mathcal{L}_{peak} = 7.0\times10^{27}$ cm^{-2} s^{-1} .
- It consists of the following upgrades in the whole ion injection chain:
  - New LEBT optics, possibly an Einzel-lens.
  - Doubling the Linac3 repetition rate.
  - Increasing the electron-cooling rate for the new 100ms injection spacing.
  - Mitigating or solving the LEIR intensity limitation.
  - Re-establishing the bunch splitting in the PS, as originally planned at the design stage.
  - A new ion injection system in the SPS, allowing a 100 ns batch spacing.
  - Profiting from the upgrade of the Low-Level RF in the SPS, implement a momentum slip-stacking scheme.
- In addition, the following measures are considered:
  - Renewed spectrometer line to replace the old LBS line (Linac Booster Spectrometer), made obsolete by the connection of Linac4.
  - New dump in the LEIR transfer line, to cleanly dispose of the ion beam when not desired by the PS or the LHC.
  - Optionally, building a spare source for training the specialists and as a spare.
- Until the SPS injection is upgraded, new RF gymnastics in the PS (demonstrated in 2012) already bring a 22% increase to $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV for the first LHC run after LS1.

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