Chapter 18

Challenges and Plans for the Ion Injectors

D. Manglunki

CERN, TE Department, Genève 23, CH-1211, Switzerland

We review the performance of the ion injector chain in the light of the improvements which will take place in the near future, and we derive the expected luminosity gain for Pb–Pb collisions in the collider during the HL-LHC era.

1. Introduction

The Pb^{82+} ion beam brightness, as delivered at 177 GeV/nucleon 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 of 3, as shown in Table 1.

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

	Pb⁸²⁺ 2013	Pb⁸²⁺ design	
N_B	22	9	10^7 ions/bunch
n_B	24	52	bunches
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

With this high brightness beam, a Pb–Pb run at 7Z TeV performed with the current filling scheme, described in Section 2.2 below, would deliver a peak luminosity of $2.3 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. Since the peak luminosity requested by the ALICE experiment for the HL-LHC era [3] is of the order of $7 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, a missing factor of 3 is still to be found. The retained solution is to increase the number of bunches in the collider, as the bunch brightness 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 a resulting larger burnoff rate [5].

2. The Current Scheme

2.1. The ion accelerator chain

CERN’s heavy ion production complex (Fig. 1) was first designed in the 1990s for the needs of the SPS fixed target programme [6, 7]. It was rejuvenated at the beginning of the 2000s in order to cope with the LHC’s stringent demands for high brightness ion beams. It currently consists of:

- The Electron Cyclotron Resonance (ECR) ion source,
- The ion Radio Frequency Quadrupole (RFQ),
- The Interdigital H Linear Accelerator (LINAC3),
- The Low Energy Ion Ring (LEIR), an accumulation and cooling storage ring,
- The 25 GeV Proton Synchrotron (PS), and
- The 450 GeV Super Proton Synchrotron (SPS).

Fig. 1. The ion injector part of the CERN accelerator complex (not to scale).

2.2. Production of the bunch trains for the LHC

A sample of isotopically pure ^{208}Pb is inserted in a filament-heated crucible at the rear of the ECR source, whilst oxygen is injected as support gas. With a 10 Hz repetition rate, a 50 ms long pulse of 14.5 GHz microwaves accelerates electrons to form an oxygen plasma, which in turn ionizes the lead vapor at the surface of the crucible. The source operates in the so-called afterglow mode: after the microwave pulse is switched off, the intensity of the high charge state ions from the source increases dramatically. The ions are electrostatically extracted from the source with an energy of 2.5 keV/nucleon.

Out of the different ion species and charge states, a 135° spectrometer situated at the exit of the source selects those lead ions which have been ionized 29 times (Pb^{29+}). The beam is then accelerated to 250 keV/nucleon by the 2.66 m long RFQ which operates at 101.28 MHz. The RFQ is followed by a four-gap RF cavity which adapts the longitudinal bunch parameters to the rest of the linear accelerator: a three-cavity interdigital H (IH) structure, Linac3, which brings the beam energy up to 4.2 MeV/nucleon, requiring about 30 MV of accelerating voltage, for a total acceleration length of 8.13 m. The first cavity operates at the same frequency as the RFQ (101.28 MHz), while the second and third cavities operate at 202.56 MHz. Finally, a 250 kV “ramping cavity”, also operating at 101.28 MHz, distributes the beam momentum over a range of $\pm 1\%$, according to the time along the 200 μs pulse. The linac currently only operates at 5 Hz.

A 0.3 μm thick carbon foil provides the first stripping stage at the exit of the linac, followed by a spectrometer which selects the Pb^{54+} charge state.

A current of about 22 μA of Pb^{54+} is injected over 70 turns in the Low Energy Ion Ring LEIR, whose unique injection system fills the 6-dimension phase space. This is achieved by a regular multi-turn injection with a decreasing horizontal bump, supplemented by an electrostatic septum tilted at 45° , and the time dependence of the momentum distribution coupled with the large value (10 m) of the dispersion function in the injection region. The injection process is repeated up to six times, every 200 ms. The whole process is performed under electron cooling. At the end of the seven injections, the beam is bunched on harmonic 2, accelerated to 72 MeV/nucleon, and fast-extracted towards the PS. At this point the bunch population is of the order of 5×10^8 ions/bunch.

In the PS, the two bunches are injected in two adjacent buckets of harmonic 16 and accelerated by the 3–10 MHz system to 5.9 GeV/nucleon, with an intermediate flat-top for batch expansion. This process consists of a series of harmonic changes: $h = 16, 14, 12, 24, 21$, in order to finally reach a bunch spacing of 200 ns at top energy. Before the single turn extraction, the bunches are finally

rebucketed into $h=169$, using one of the PS's three 80 MHz cavities. This rebucketing only affects the bunch length, not the inter-bunch spacing.

At the exit of the PS, the beam traverses a final stripping stage to Pb^{82+} , through a 1 mm thick Aluminum foil, where the FODO lattice of the transfer line is modified to provide low beta functions in both planes, so as to minimize the transverse emittance blowup. As the stripping foil is located in the same transfer line as the high intensity proton beams for other users (the Antiproton Decelerator, the neutron Time-of-Flight facility, CERN Neutrinos to Gran Sasso, etc.), it needs to move in or out of its position in less than a hundred milliseconds, before or after a series of ion cycles.

The two bunches, now about 3×10^8 ions each, are injected in the SPS, with a bunch-to-bucket transfer into the 200 MHz system. This process can be repeated up to 12 times every 3.6 seconds; the repetition rate is imposed by the duration of the LEIR cycle, while the total number of injections is currently limited by the SPS control hardware.

At a fixed harmonic, the heavy mass of the ions would yield too large a frequency swing (198.51–200.39 MHz) for the range of the travelling wave cavities of the SPS (199.5–200.4 MHz). Hence, instead of using a fixed harmonic, the ions are accelerated using the “fixed frequency” method in the SPS: a non-integer harmonic number is used, by turning the RF on at the cavity center frequency during the beam passage and switching it off during its absence, to correct the RF phase and be ready for its next passage in the cavities. The phase is adjusted by an appropriate modulation of the frequency. Aside from its complexity, one drawback of the method is that the beam has to be constrained in a relatively short portion ($\sim 40\%$) of the circumference of the machine.

The SPS ion beam, now consisting of 24 bunches, is then accelerated to 177 GeV/nucleon before its single turn extraction towards the LHC via one of the transfer lines TI2 or TI8. This operation is repeated 30 times, fillings each ring of the LHC with 360 bunches.

3. Planned Upgrades

3.1. Doubling the repetition rate of Linac3

The possibility of accelerating up to three charge states in Linac3 to double the intensity as originally planned at the time of design [8] 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.

Hence, aside from new developments on the ECR source, the most promising path consists in doubling the repetition rate from 5 to 10 Hz [9]. 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.

3.2. Overcoming the intensity limitation in LEIR

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} proton charges, corresponding to $5.5 \times 10^8 \text{ Pb}^{54+}$ ions per bunch. A thorough machine development program has started in order to try and understand, then overcome or mitigate this limitation [10].

Fig. 2. Loss at acceleration on the LEIR nominal and development cycles. The white curve represents the magnetic field, while the coloured one represents the number of ions circulating in the machine. One can see the 7 injections on the flat bottom, followed by the acceleration ramp, at the beginning of which the loss occurs. The bunch population is presently limited to $5.5 \times 10^8 \text{ Pb}^{54+}$ ions per bunch.

3.3. Bunch splitting in the PS

In order to further increase the bunch number in the LHC, one would have to split the bunches in the PS, whose RF system cannot accelerate on 20 MHz. 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 is considered, using the same bunch structure as already planned for the nominal beam in the design report [11]: the RF gymnastics are similar to the ones currently used, and described in Section 2.2 above ($h = 16, 14, 12, 24, 21$). The only difference is the phase of harmonic 24 which is shifted by 180° , resulting in bunch splitting. The final spacing between bunches at the PS flat top is 100 ns. These gymnastics have been tried and tested during machine development sessions in parallel to the early LHC runs.

3.4. *New injection scheme into the SPS*

In order to maximize the number of bunches, the 4-bunch batches from the SPS will be injected next to each other, with a batch spacing of 100 ns, thanks to a new ion injection system [12]. A faster, 50 ns injection system had been considered [13] but had to be discarded due to impedance and resources considerations. The new system consists of:

- 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 kickers rise time.

3.5. *Momentum slip-stacking in the SPS*

As bunch-splitting or batch compression to reach a bunch spacing of 50 ns both prove difficult, if not impossible, 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 [15] consists of 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 [16], can be applied in our case to interleave the bunches, as sketched in Fig. 3:

- The PS transfers two times six batches of four bunches to the SPS, with a batch spacing and a bunch spacing of 100 ns. In between the two trains of 24 bunches, is a $1\ \mu\text{s}$ 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.

- Due to the frequency difference, the two trains start slipping towards each other.
- Once the bunches are interleaved, they are recaptured at average frequency and filament in a large bucket.

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]. This issue would be completely dismissed in case of the addition of 200 MHz cavities in the LHC.

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

Fig. 4. Upgraded filling scheme.

4. The Upgraded Filling Scheme

The upgraded filling scheme assumes all upgrades listed above have been implemented, namely:

- Doubling the Linac3 repetition rate to 10 Hz.
- A reasonable increase ($\sim 50\%$) of the bunch density in LEIR.
- RF gymnastics 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.

The new proposed filling scheme, sketched in Fig. 4, should deliver up to 1248 bunches in each one the LHC rings, bringing the peak Pb–Pb luminosity at 7Z TeV to $\mathcal{L}_{\text{peak}} > 7.0 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. Table 2 summarizes the projected beam parameters in the injectors.

Table 2. Projected beam parameters in the circular machines

	LEIR	PS	SPS
Charge state ⁽¹⁾	54+	54+/82+ ⁽¹⁾	82+
Output Energy [GeV/u]	0.0722	5.9	176.4
Output Bρ [T.m]	4.8	86.7/57.1 ⁽¹⁾	1500
Injections into the next machine	1	6+6	26
Bunches/ring	2	4	48
Number of ions/pulse	1.6×10^9	7.2×10^8	5.2×10^9 ⁽³⁾
Total extracted charge	8.6×10^{10}	3.9×10^{10} / 5.9×10^{10} ⁽¹⁾	4.3×10^{11} ⁽³⁾
Ions/bunch at injection	10^9 ⁽⁴⁾	8×10^8	1.8×10^8 ⁽²⁾
Ions/LHC bunch at extraction	4×10^8	1.8×10^8	1.5×10^8 ⁽²⁾ 1.1×10^8 ⁽³⁾
Bunch spacing at extraction [ns]	350	100	50
Normalized transverse rms emittance [μm]	0.70	1.0	1.2
Longitudinal emittance [eVs/u]	0.025	0.045	0.24
4σ Bunch length [ns]	200	3.9	1.8 ⁽⁵⁾
2σ Momentum spread	1.2×10^{-3}	1.1×10^{-3}	6.4×10^{-4} ⁽⁵⁾
Repetition time [s]	3.6	3.6	49.2
Space charge ΔQ on flat bottom	0.13 ⁽⁴⁾	0.23	0.13 ⁽²⁾

⁽¹⁾ Stripper stage 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.

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