IONS FOR LHC: PERFORMANCE OF THE INJECTOR CHAIN

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Abstract

The first LHC Pb ion run took place at 1.38 *A* TeV/c per beam in autumn 2010. After a short period of running-in, the injector chain was able to fill the collider with up to 137 bunches per ring, with an intensity of 10^8 Pb^{82+} ions/bunch, about 50% higher than the design value. This yielded a luminosity of 3×10^{25} Hz/cm^2, allowing the experiments to accumulate just under 10 μb^{-1} each during the four week run.

We review the performance of the individual links of the injector chain, and address the main issues limiting the LHC luminosity, in view of reaching 10^{26} Hz/cm^2 in 2011, and substantially beyond when the LHC energy increases after the long shutdown in 2013-14.

INTRODUCTION

In addition to colliding protons, the LHC has also been designed as a heavy ion collider, with a luminosity goal of $L = 10^{27}$ Hz/cm^2 for Pb^{82+} at 2.76 *A* TeV/c per beam. However, the luminosity for the first LHC run was initially supposed to be 20 times lower, at the same energy, using the "Early Scheme" [1, 2].

The commissioning of the ion injector chain, performed in parallel with the routine operation of the whole CERN accelerator complex, started in 2005 with the first beams injected into LEIR [3], followed by the PS in 2006 [4], then by the SPS in 2007 [5]. It was completed on 23 October 2009 when, after the 14 month shutdown of the LHC, a first beam was injected via TI2 through the ALICE experiment. This first beam was a single bunch of about 9×10^7 Pb^{82+} nuclei.

Eventually, the first LHC Pb ion run took place with the "Early Scheme" in autumn 2010, at 1.38 *A* TeV/c per beam, i.e. with the same magnetic rigidity as 3.5 TeV/c protons, ensuring a smooth transition [6].

THE FIRST LHC ION RUN

After a short running-in period during which the injector chain sent single bunches to the LHC for 2×2 then 5×5 collisions, the filling schemes were gradually increased to 17×17, 69×69 then 121×121 using four-bunch batches, while the bunch spacing was decreased from 1.35 μs to 500 ns. For the last 4 days of the run, a new cycle was designed in the SPS to inject eight-bunch trains, eventually allowing 137×137. More aggressive schemes using 12- or 16-bunch trains in the injector chain were designed, but proved impossible to implement because of a limitation in the timing system which has since been lifted [7]. However, this last filling scheme offered the opportunity to test the beam behaviour on a 17 second flat bottom in the SPS – important in view of a future run with the "Nominal" beam.

Table 1 compares the parameters of the Early beam at the end of the injector chain (i.e. out of the SPS) and in collision in the LHC, as expected in the design report, with the ones obtained during the last days of this first physics run. The brightness of the beam is much higher than anticipated, although the vertical emittance suffers some blow-up during acceleration in the SPS.

When comparing the design and achieved luminosities, one should remember that, originally, the collisions were supposed to take place at twice the energy of the 2010 run, where smaller geometric emittances and optical functions at the interaction point would yield higher luminosity.

Table 1: Comparison With Design Parameters

Parameter	Design	2010 run
SPS extraction		
Bunches/batch	4	8
ε^*_H [μm]	1.2	0.6
ε^*_V [μm]	1.2	1.0
N_b [ions/bunch]	9×10^7	1.2×10^8
τ_b (4 RMS) [ns]	1.8	1.3
LHC collisions		
p [TeV/c/u]	2.76	1.38
k_n [bunches]	62	137
N_b [ions/bunch]	7×10^7	10^8
β^* [m] at IP2	1	3.5
L [Hz/cm^2]	5.4×10^{25}	3×10^{25}

The original goal of integrating 3 μb^{-1} per experiment looked ambitious at first. However, thanks to the good performance of all the elements in the chain, including the LHC itself [8,9], ALICE, CMS and ATLAS had accumulated just under 10 μb^{-1} each at the end of the four week run.

PROBLEMS ENCOUNTERED

Since the beginning of the commissioning, and despite the continuous efforts of the experts involved, the linac was never able to deliver the design current of 50eμA for Pb^{54+}. Furthermore, several times during commissioning and twice during the 2011 run, the intermediate electrode suffered a short-circuit which either necessitated a long intervention to repair, or imposed an even lower current out of the Linac. At the end of the run, the LEIR Early cycle was modified to accommodate a double injection (Fig. 1), increasing the LEIR output current by 70%, and restoring the luminosity in the collider.

Figure 1: Double injection into LEIR. The top screen shows the first (white) and second (colour) Linac pulses in the transfer line and accumulated in the ring. The lower screen shows the particle current (yellow/green) and the magnetic cycle (magenta); the flat bottom was lengthened to allow enough time for electron cooling of the particles after the second injection.

Over the course of the run, one of the stripping foils at the exit of the Linac, used to convert Pb^{29+} to Pb^{54+}, started to degrade and had to be changed, although its lifetime expectancy had not even closely been reached. Also, a dependence of the beam energy — either due to the stripping foil or to the RF — on the number of cycles per unit time was observed, imposing a retuning of the Linac-to-LEIR transfer line each time the supercycle was changed.

At the end of the run, the lifetime of the LEIR beam started to degrade slightly. Vacuum was suspected but no pressure measurement could confirm it. Scrubbing cycles will be re-implemented in 2011 to test the hypothesis.

The 5 MW recommended maximum power limit, imposed to spare the motor-generator set of the old main power supply, was reached on the PS supercycle for the eight bunch scheme. However, this limit being somewhat arbitrary, it was allowed to ignore it during the LHC fillings.

One of the three 80 MHz cavities installed in the PS has to be tuned to the ion frequency at extraction, for the rebucketing on harmonic $h = 169$; normally it is kept as a spare for the proton beam which needs two. As a proton machine development took place in the middle of the ion run, and one of the 80 MHz cavities broke down during the run, some time was lost in the switchover, as it was not possible to have all cavities tuned to the ion frequency.

The cause of the vertical emittance blow-up during acceleration ramp in the SPS is still unknown.

OUTLOOK FOR 2011 AND BEYOND

Source

The ECR source is presently operated at 14.5 GHz. Since the particle current extracted from an ECR for a given charge state is expected to be proportional to the square of the frequency, operating at 18 GHz should allow an increase of up to 50%, or at least get closer to the design value of 50 eμA of Pb^{54+} out of the Linac. However, as tests at 18 GHz were not able to demonstrate the improvement so far [10], the 18 GHz equipments are being kept as spare, and will eventually be converted for 14.5 GHz operation.

The connection of the intermediate electrode has been completely redesigned in order to prevent the short-circuits which happened several times during the commissioning and the first run. The gas feedback loop has also been redesigned, and the oven filling is now performed with liquid lead. Some experience will be needed to assess the improvement brought by these modifications. A decrease of the oven refill frequency would be particularly welcome to increase the integrated luminosity.

In the longer run, the construction of a second source is being envisaged, in order to shorten the switchover time when the oven needs refilling or in case of a breakdown; it would also allow studies of other species during the LHC ion runs.

Linac

The controls of the ramping cavity have been upgraded in order to provide different sets of command values for different cycles, allowing to independently optimize the beam behaviour of the Early and Nominal machine cycles and their development flavours.

LEIR

More time was devoted in 2010 to study the Nominal beam which had already been demonstrated [11]; in particular the new, digital, Low-Level Radio-Frequency system, needed for dual harmonic acceleration, is now completely operational [12]. A lot of experience with this beam was gained in 2010, in LEIR but also in the PS and SPS, as the Nominal beam is also used to deliver lighter ions by fragmentation to fixed target experiments [13, 14].

PS

Thanks to the new POPS main power supply [15], there will be no more limitations in the power consumption of the PS. This will allow a greater flexibility in the composition of the supercycle.

An intermediate scheme [16] will be tried for the first time in September in the PS. To obtain two very dense bunches spaced by 200 ns at the exit of the PS, a standard, two-bunch Nominal beam is produced in LEIR. It is injected in the PS where the same RF gymnastics as the ones used for the Nominal beam are then applied. The only difference lies in the phase of harmonic 24, which is aligned with harmonic 12, hence performing a rebucketing instead of a splitting. The rest of the gymnastics (batch expansions, rebucketing on $h = 169$), as well as all the transverse settings, are kept unchanged. This should allow rapid and smooth switching between the two schemes, even from one LHC fill to the next.

SPS

In view of the experience with the proton beam in 2011, the SPS injection kicker rise time can be as low as 225 ns with four modules; since the ions are injected in the SPS at a lower magnetic rigidity than the protons, one can imagine not using the fourth module which is the slowest, and further decrease the rise time — and hence, the inter-batch spacing — down to 200 ns. This is of interest for both the Nominal and Intermediate schemes.

New cycles are being designed for the Nominal and Intermediate schemes; they will feature a 40 second long flat bottom to accommodate up to 12 injections of the corresponding beam from the PS. The Nominal scheme should allow injection of about 540 bunches of 7×10^7 ions into the LHC, versus 340 bunches of 12×10^7 ions for the Intermediate which theoretically gives 70% more peak luminosity.

In the longer run, more aggressive filling schemes have been proposed, decreasing the bunch spacing down to 75 ns, but this either requires additional hardware in the PS, or implies an additional complexity of its RF gymnastics [17].

CONCLUSION

The long and careful preparation of the injector chain was vital to the success of the first Pb ion run of the LHC with the "Early Beam". Its performance exceeded expectations, setting the bar quite high for the luminosity goals in 2011: up to 1.4×10^{26} Hz/cm^2, and 30-50 μb^{-1} for the integrated luminosity [8].

Thanks to the needs of fixed target experiments, some operational experience with the Nominal beam was accumulated in the whole injector chain during 2010. It will be used in autumn 2011 during the next Pb ion run of the LHC.

A third, "Intermediate" scheme has been designed as a backup solution to the Nominal beam. It will be tried during the start up phase and kept in reserve in case it proves to allow delivering a higher luminosity in 2011.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Linac, PS and LEIR/SPS operations crews for their help.

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