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IONS FOR LHC: TOWARDS COMPLETION OF THE INJECTOR CHAIN

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Abstract

The commissioning of CERN's ion injector complex [1] to allow 1.1 PeV collisions of ions in LHC is well under way. After the Low Energy Ion Ring (LEIR) in 2005 [2] and the Proton Synchrotron (PS) in 2006 [3], the Super Proton Synchrotron (SPS) has now been commissioned with the "Early" ion beam, which should give a luminosity of 5×10^{25} $cm^{-2}s^{-1}$ in the LHC. This paper summarizes the operation in 2007 of all the machines involved in the ion injection chain.

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INTRODUCTION

The commissioning of CERN's ion injector complex [1] to allow 1.1 PeV collisions of ions in LHC is well under way. After the Low Energy Ion Ring (LEIR) in 2005 [2] and the Proton Synchrotron (PS) in 2006 [3], the Super Proton Synchrotron (SPS) has now been commissioned with the "Early" ion beam, which should give a luminosity of 5×10^{25} $cm^{-2}s^{-1}$ in the LHC.

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SOURCE AND LINAC 3

In 2007, the Linac 3 worked with a higher charge state, Pb^{29+} instead of Pb^{27+}. This mode, which had been tested during the previous year, allowed the RF tanks to operate at a lower field, thus reducing the X-ray emission. The intensity delivered after the first stripping foil fluctuated around 20 eμA of Pb^{54+}, reaching up to 30 eμA as peak performance.

At the beginning of 2008, the source RF frequency was upgraded from 14.5 to 18 GHz, which should give an additional margin for maintaining the required intensity in operation. Results of the upgrade commissioning still have to be analysed.

LOW ENERGY ION RING

In 2007 the Low Energy Ion Ring was routinely operated remotely from the CERN Control Centre, thanks to the availability of improved diagnostics [4]. This exercise, meant to identify showstoppers as well as solve resource problems, was done in anticipation of the years ahead when the whole injection chain will be completely in the hands of the operations teams, and the LHC needs to be filled with ions.

During the run, a serious recurrent problem occurred on the transformers for the power supplies of the RF amplifier, causing the destruction of two of them. It was possible to implement a new design in time and this proved to be faultless.

Numerous goals set in the design report [5] were reached during the first half of the run, before LEIR had to deliver beam to the rest of the injection chain:

- After a period of running-in, the beam was eventually accelerated using the synthetic B-train.
- The low level RF digital system [6] was integrated within the controls system.
- A repetition rate of 5 Hz was successfully tested over the whole Linac3-LEIR chain.

As a consequence, LEIR confirmed its ability to routinely produce the Early ion beam for the LHC.

Unfortunately, the Nominal LEIR beam could not yet be completely demonstrated: although sufficient intensity could be accumulated during the low energy plateau, the nominal intensity of 4.5×10^{8} Pb^{54+} ions/bunch was never obtained at high energy, due to losses at the beginning of the ramp; these remain to be understood. However, the transverse emittances were well below the design value of 0.7 μm (normalised RMS) in each plane. The performance achieved for the Early and Nominal beams in LEIR is summarized in Table 1.

Table 1: Performance of Early and Nominal LEIR beams

	Early	Nominal
N [10^{8} Pb^{54+} ions/bunch]	2.2	3.7
I [10^{10} charges/bunch]	1.2	2.0
ε^*_H [μm]	0.5	0.5
ε^*_V [μm]	0.2	0.2
$\varepsilon_{//}$ [meVs/u]	40	50
τ_B [ns]	200	200

PROTON SYNCHROTRON

RF issues

During the shutdown, the sensitivity of the head amplifiers of the radial-loop pickups had been increased by 6 dB to cure the main beam loss that occurred at the start of the accelerating ramp. Another cause of loss was a crosstalk issue, discovered between the synthesizer signal used to pilot the cavities before the arrival of beam and the weak phase pickup signal at injection energy. This was solved by a 30 dB attenuation of the synthesizer signal.

Finally, a stand-alone frequency programme had to be devised for the ion beam control, as the one used for protons together with a charge-to-mass-ratio scaled B-train was too coarse for the ion beam at low energy and shook the beam at each pulse of the B-train.

Following these improvements, the PS eventually delivered the required intensity of 1.2×10^{8} Pb^{82+} ions/bunch for the Early beam.

At the end of the lead ion commissioning in the PS, it had already been decided to modify the magnetic cycle.

Originally, in order to avoid vacuum problems at low energy, the intermediate plateau—needed for RF gymnastics of the nominal beam—had been placed at the highest possible momentum compatible with the frequency range of the 10 MHz cavities. Since the vacuum in the PS was better than expected, it was possible to lower the intermediate plateau from 0.31 T to 0.17 T and hence to improve the adiabaticity of the RF gymnastics. Unfortunately, because of other priorities, no further time could be devoted to the Nominal beam, which remains to be demonstrated in the PS.

PS to SPS transfer line re-matching

After the upgrade of power supplies for several quadrupoles in the PS-SPS transfer line TT2, which were still limited in 2006, an accurate re-matching campaign was organised [7], taking into account the effect of multiple Coulomb scattering through the stripping foil on the optical functions. The quality of the matching could be verified by comparing the transverse profiles measured immediately after injection in the SPS and several seconds later, and verifying the absence of filamentation-induced tails (Figure 1).

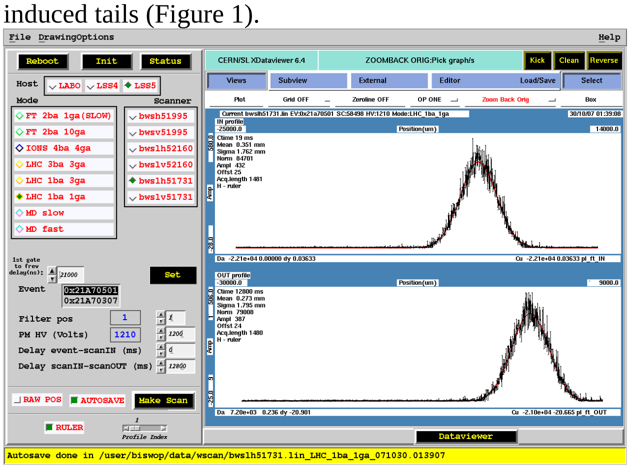

Figure 1: Horizontal wire scanner measurements at injection and 12.8 seconds later.

SUPER PROTON SYNCHROTRON

Three different magnetic cycles were created in order to fulfil the commissioning programme:

- A parallel cycle ramping up to 70 GeV/c/charge to set up beam transfer and energy matching, and to debug acceleration
- A dedicated "Early LHC filling" cycle ramping up to 450 GeV/c/charge (177 GeV/u), coastable at low energy, to also allow studies of beam behaviour on the injection plateau.
- A dedicated cycle, coastable at 270 GeV/c/charge, for collimation studies, not discussed here [8].

Studies at low energy

Apart from the ability of the SPS injectors to produce it, one of the concerns related to the nominal beam is that, in the current scheme, the bunches have to wait up to 40 seconds on the injection plateau, where they are subject to space-charge and intra-beam scattering. Several sessions were devoted to the behaviour of the bunches on the flat bottom. It turned out that, although the space-charge detuning was as high as $\Delta Q_{SC} = 0.092$, practically no transverse blow up was observed over periods of the order of one minute, confirming the expectations induced from experience during the p-pbar period [9].

A more worrying observation was unexpected bunch shortening: although the particles stay in the machine, as indicated by the beam current transformer, the bunch typically lost half of its intensity over a period of about one minute. In principle, IBS can be ruled out as its longitudinal growth rate is negative (-0.5/minute) under the conditions of the measurements. It was only realised after the machine developments that the RF capture voltage of 1.5 MV was only just sufficient for the measured longitudinal emittance of the injected beam (0.035 eVs/u). It is not clear whether this can completely explain the bunch shortening effect, or if RF noise also played a role.

Commissioning of the new low level RF system

As the frequency swing of the fixed tune, wide-band cavities (199.5–200.4 MHz) is not large enough for Pb ions (198.5 MHz at injection), their acceleration in the SPS requires fixed-frequency acceleration [10]. The old ion beam control system used in the past for fixed target experiments [11] was aging and not suited for acceleration of ions for the LHC, which demands a bunch-to-bucket transfer from the PS. A new one, based on digital signal processing was then designed, prototyped, and commissioned [12]. About 180 hours of machine time were used for this commissioning.

Up to 4 single bunch injections were performed into the SPS. The four bunches were then accelerated up to the 450 GeV/c/charge flat top, as will be required to fill the LHC with the early beam. After optimisation of the tunes (Q_H=26.13, Q_V=26.25) and chromaticities (ξ_H=0.13, ξ_V=-0.53), up to 81% transmission was achieved, see Figure 2.

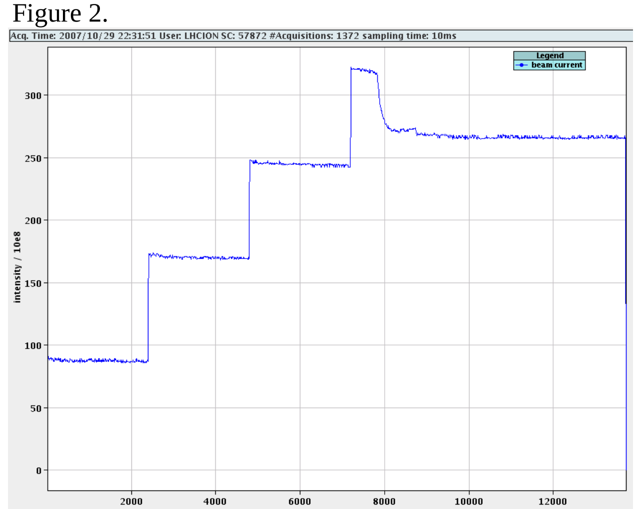

Figure 2: Beam current transformer measurement of injection and start of acceleration of four ion bunches.

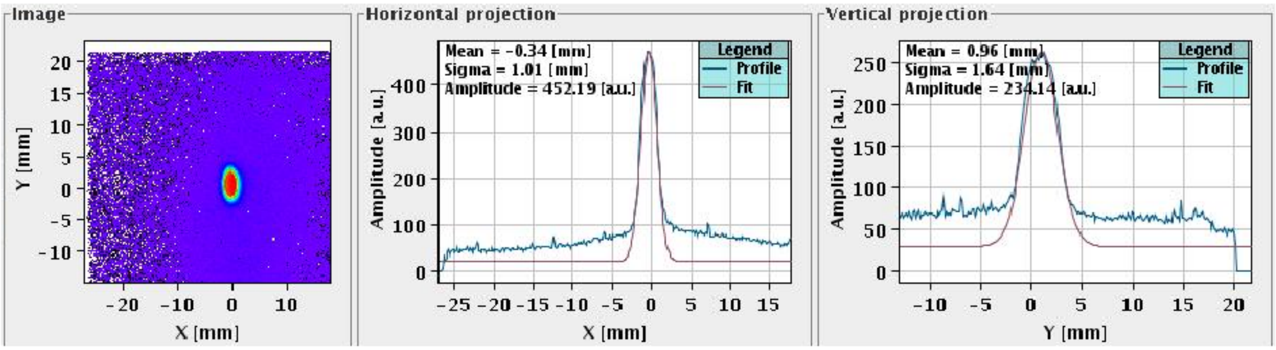

Figure 3: Profile measurements of the extracted Pb^{82+} beam at 177 GeV/n in TT60.

Transfer towards the LHC

Following a week-end of beam transfer lines tests using protons [13], it was possible to organize a short session of machine experiments devoted to the extraction of ions towards the LHC. The ion beam was sent to one of the extraction channels, TT60, where the transverse emittances were measured to be in agreement with the expected values of 1.2 µm (normalised RMS, see Figure 3). Unfortunately, in the meantime a vacuum leak had developed in the PS machine, causing a reduction of the ion beam intensity by a factor 5, so these results need to be reproduced with the required 0.9×10^{8} Pb^{82+} ions/bunch at SPS extraction.

WHAT NEXT?

To optimize the resources for the success of the LHC proton start-up, most of the ion injector chain will be left on standby in 2008. In order to deliver the Early beam to the LHC, the next steps that need to be taken are:

- Reproduction of the results obtained in 2007 with the final versions of the low level RF hardware and software in the SPS.
- Commissioning of the controlled longitudinal blow up with RF noise in the SPS.
- Synchronization of the SPS beam at high energy with the LHC frequency.

  To this end, a period of about 6 weeks will be needed in order to get the SPS ready to fill the LHC with the Early beam.

  For the delivery of the nominal beam in the LHC:
- LEIR and the PS will need more development time in order to understand the limitations.
- New schemes are currently under study to try and shorten the injection plateau of the SPS [14].

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