IONS FOR LHC: STATUS OF THE INJECTOR CHAIN

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Abstract

The LHC will, in addition to proton runs, be operated with Pb ions and provide collisions at energies of 5.5 TeV per nucleon pair, i.e. more than 1.1 PeV per event, to experiments. The transformation of CERN's ion injector complex (Linac3-LEIR-PS-SPS) to allow collision of ions in LHC in 2008 is well under way. The status of these modifications and the latest results of commissioning will be presented. The remaining challenges are reviewed.

INTRODUCTION

The commissioning of the new ion injection chain for the LHC is advancing in stages, as planned [1]. After the successful first operation of the Low Energy Ion Ring (LEIR) in 2005 [2], the Proton Synchrotron (PS) has now been commissioned with the ion beam.

This paper summarizes the operation in 2006 of all the machines involved in the ion injection chain, except for LEIR which is described in a separate paper [3]. Most of the work presented here was achieved while the machines operated in parallel.

SOURCE AND LINAC 3

In 2006 the Grenoble Test Source for LHC was running most of the time for the commissioning of the LEIR and the PS with lead. During this time the source provided ~100 eμA of Pb^{27+} and Linac 3 gave more than 20 eμA of Pb^{54+}. The beam was stable and the source required very little retuning. Besides beam delivered for LEIR and PS commissioning, studies of the source biased disc were made [4] and the extraction and acceleration of Pb^{29+} was tested. With a similar ion current out of the Linac, Pb^{29+} has the advantage of lower RF fields in the tanks, which reduces the x-ray emission.

PROTON SYNCHROTRON

Beside acceleration, the role of the PS is to adapt the beam from LEIR according to a variety of constraints imposed by the downstream machines. Notably, it is the PS machine that imposes the bunch spacing required by LHC experiments, while the bunch length and repetition frequency at PS ejection must lie within the narrow ranges acceptable by the rf system of the SPS. In the nominal scheme, this requires complex rf gymnastics [5] to be performed at an intermediate energy in the PS cycle. In order to minimize the risk to beam lifetime, the intermediate plateau was chosen close to the highest energy consistent with the frequency range of the cavities performing the gymnastics.

The aim of the commissioning period was to make sure the PS would be able to deliver the "Early beam"; the achieved performance is summarized and compared with the design values, in table 1. However, a lot of time and effort was invested to prepare the "Nominal Beam", in order to identify potential problems and devise solutions [6].

Table 1: Performance of the Early Beam. Transverse emittances are given as normalised RMS values: $\varepsilon^{*}_{H,V} = \sqrt{\gamma^2 - 1}\,\sigma^{2}_{H,V} / \beta_{H,V}$

	Design	Achieved
N [E8 ions/bunch]	1.20	1.1
ε^*_H [μm]	1.00	0.85
ε^*_V [μm]	1.00	0.73
$\varepsilon_{//}$ [eVs/u]	0.05	0.03
τ_B [ns]	3.9	3.0

First injection into PS ring

In order to inject ions from LEIR into the PS, the new septum in its refurbished tank and kicker previously used for antiproton transfer from PS to LEAR, are complemented by a 2-dipole bump in order to cope with the higher magnetic rigidity of the Pb^{54+} beam [5]. The first injections took place on a flat cycle to study the beam behaviour at low energy. The lower limit for the beam lifetime was measured and exceeded 700 ms, confirming the excellent quality of the vacuum in the PS.

LEIR to PS transfer line matching

The transverse matching of the beam delivered has been measured with three secondary emission profile monitors (SEM) installed in the PS. One should note that due to imperfections (one vertical monitor "blind" at the center), the vertical trajectory had to be distorted strongly for the vertical measurement. The dispersion has been determined by measuring the beam position as a function of the momentum offset and the betatron functions and emittances from the beam sizes.

During a first measurement campaign, good betatron matching, but a significant (even though acceptable in terms of induced emittance blow-up) dispersion mismatch has been observed.

Based on the first measurement, a new setting of the transfer line has been implemented and investigated during a second measurement campaign. Almost perfect matching (betatron functions and dispersion) has been found for the horizontal phase space. A relatively large betatron mismatch has been found in the vertical phase space. The poor result in the vertical phase space may be an artefact induced by the trajectory perturbation (to shift the beam to a working region of the SEM).

RF aspects

In the early scheme, a single bunch is delivered by LEIR, captured on h=16 in the PS and accelerated without gymnastics through transition to top energy, where it is rebucketed on h=169 to reduce the bunch length below 4 ns in order to fit into a 200 MHz bucket in the SPS. Figure 1 shows such a bunch, inside specification, immediately prior to extraction from the PS. The main problems encountered in the PS were a lack of sensitivity of the radial loop at low energy and insufficient accuracy of the raw frequency programme at high energy due to the proximity of transition to the flat-top. The former must await a shutdown for a definitive solution, while the later was cured by the introduction of a frequency trim function.

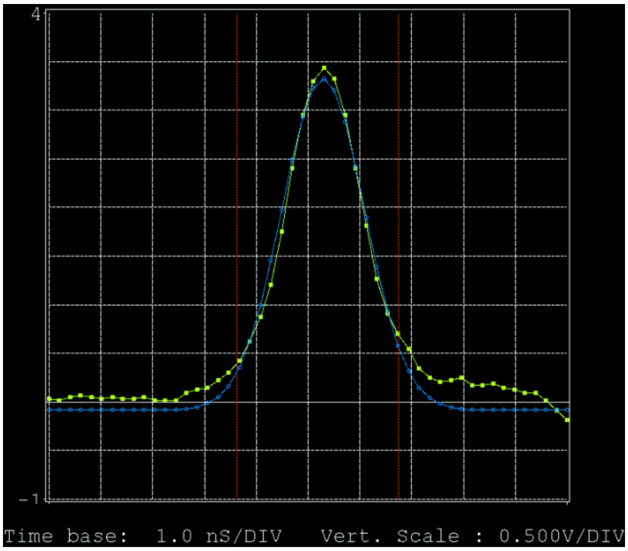

Figure 1: 4ns long Pb54+ bunch from Early Beam, immediately prior to extraction from the PS.

In the nominal scheme, two bunches are delivered by LEIR, are captured on h=16 and, after a series of quasi-adiabatic harmonic changes - including a splitting step - to h=24, four bunches arrive on the flat-top where they are rebucketed on h=169. There was insufficient beam time in 2006 to do much more than debug the rf gymnastics, but four bunches have already been obtained at the end of the intermediate plateau.

Both schemes involve coarse (at h=1) and fine (at h=9) synchronisation steps to lock the PS onto the waiting SPS. This was achieved for the early beam by simulating the SPS reference source.

Transition crossing

The ion beam crosses the transition at a kinetic energy of 4.8 GeV/u (γ_t=6.12). Although neither longitudinal nor transverse microwave instabilities are expected close to the transition at the intensities required for the LHC ion runs, the available gamma-transition jump system will be used for safety, albeit at reduced strength (i.e. identical quadrupole current): due to the 72.2 T.m beam rigidity of lead ions at transition, a maximum transition jump value of only 0.1 can be achieved, instead of the unity transition jump feasible for protons which cross transition at a beam rigidity of 18.9 T.m.

PS to SPS transfer line matching

Pb^{54+} ion bunches have been ejected at 5.88 GeV/u from the PS and stripped to Pb^{82+} in the TT2 transfer line to SPS. A low-β insertion has been implemented to minimise multiple scattering emittance growth through the stripping foil. To this end, four new quadrupoles were added and the first quadrupole of the two TT2 quadrupole strings had to be powered individually to complete the matching [7]. 13 quadrupoles are now available to tune the low-β ion optics instead of 7 used so far to match the proton optics. After the low-β insertion has been put in operation, the emittance blow-up due to multiple Coulomb scattering has been kept within the emittance budget with a comfortable safety margin as shown in the measurement results. In addition, new extraction optics were tried, with one of the kick enhancement quadrupoles off (QKE58). Table 2 shows, for various optics, the expected normalized RMS emittance blow-ups due to multiple Coulomb scattering in a 0.8 mm thick aluminium stripping foil calculated with the formula

$$\Delta\varepsilon_{H,V} = \frac{\sqrt{\gamma^2 - 1}}{2}\beta_{H,V}\left\langle\theta^2\right\rangle$$

where $<\theta^2>$ is the RMS multiple scattering angle. At the time of the commissioning, one matching quadrupole (labelled QFO205) out of the 13 was equipped with a power converter delivering a maximum current (400 A) below the value required for the nominal low-β optics. A temporary, constrained, low-β optics had to be implemented.

The emittance and optics were measured both with this constrained low-β optics and with the regular optics, with the stripping foil positions both “In” and “Out”. The measured normalized RMS emittances are shown in Table 3 from which the normalized RMS emittance blow-ups due to the stripping process are derived.

Tables 2 and 3 show quite a good agreement between the calculated and measured emittance growth for the constrained low-β optics. However the measured emittance growth for the regular optics is about 36% higher than the calculated one.

Table 2: Values of envelope function β and normalised RMS emittance growth due to mismatch, calculated with various TT2 optics; PS ejection optics with kick enhancement quadrupole (QKE58) on/off

Optics	β_H m	β_V m	$\Delta\varepsilon^*_H$ µm	$\Delta\varepsilon^*_V$ µm
Nominal low-β (QFO205=437 A, QKE on)	5.0	4.4	0.07	0.06
Restricted low-β (QFO205=400 A, QKE on)	8.1	5.6	0.11	0.08
Restricted low-β (QFO205=330 A, QKE on)	8.9	8.1	0.13	0.11
Restricted low-β (QFO205=330 A, QKE off)	10.2	6.9	0.14	0.10
Regular β (QFO205=156 A, QKE on)	23.6	22.1	0.33	0.31

Table 3: Blow-up of normalised RMS transverse emittances due to stripper, respectively measured with low-β and regular TT2 optics; PS extraction optics with QKE58 on.

	Stripper position	ε^*_H µm	ε^*_V µm	$\Delta\varepsilon^*_H$ µm	$\Delta\varepsilon^*_V$ µm
Low-β optics	Out	0.34	0.34	0.12	0.09
	In	0.46	0.43		
Regular optics	Out	0.40	0.33	0.45	0.43
	In	0.85	0.76		

Transfer to the SPS front porch

This part of the programme had never been planned beforehand but as a few hours of dedicated machine development time were still available, it was decided to try and bring the beam down the whole PS-to-SPS transfer line. Currents were set up according to the nominal optics used for the LHC proton beam, scaled to the lower magnetic rigidity of the lead ion beam. Although no instrumentation was available in the middle of the line, without any further adjustment, beam was immediately observed on the last screen, just upstream from the SPS injection septum! This has been made possible by the new LHC Software Architecture (LSA) in function at the SPS [8], and the fact that the operations teams for all the accelerators now work in a single control room, the CERN Control Centre (CCC), allowing for a much more efficient collaboration between them [9].

WHAT NEXT?

The next steps we hope to achieve in 2007 are:

- Installation of new power supplies in the PS-SPS transfer line, allowing the implementation of the full low-beta scheme.
- Injection of the Early Beam in the SPS, followed by acceleration and extraction.
- Production of the Nominal Beam in LEIR and PS
- Study of the behaviour of the ion bunches on the SPS injection flat bottom (intra-beam scattering and Laslett tune shift), in order to test the expectation that no further complicated RF manipulations will be necessary for the Nominal Beam in the SPS [10,11]

CONCLUSION

- The source, LINAC 3, LEIR and PS are practically ready to supply the Early Beam, and the LHC ion injection chain is on schedule.
- Although some power supplies still need upgrading, the low-β scheme at the stripper was validated with lower currents.
- Last minute transfer of the lead ion beam to the SPS front porch proved to be a successful test for the LHC Software Architecture and the CCC.
- Fine tuning of the RF manipulations needed for the Nominal Beam will need more machine development time in 2007.

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