1 INTRODUCTION

This is the first time that an SL “Chamonix Workshop” saw an entire session dealing with the PS complex. Under the heading “PS as LHC Pre-Injector”, it was supposed to cover the work (hardware upgrades, MDs, studies) required to convert the PS complex to an LHC proton and heavy ion pre-injector, thus underlining the importance of the PS complex for the LHC project. Five presentations were given during the session, two on protons for LHC, one on ions for LHC, one on PS-SPS matching, and one on PS-SPS supercycle schemes in the LHC era. The project for upgrading the Linac2, PSB, and PS machines to serve as LHC proton pre-injector was launched in the mid-90ies and has entered its final phase by demonstrating the feasibility of a beam with nominal parameters.

The accumulation and cooling of lead ions, the other diet of LHC, was successfully tested in the LEAR ring in 1997, albeit with missing factors in intensity and electron cooling speed of about two. The upgrading of LEAR to LEIR (Low Energy Ion Ring) as well as modifications of the ion Linac3 and the PS machine (under the heading “PS Ions for LHC”, acronym “PIL”) are being evaluated and design reports on LEIR and PIL will be available by end 2001. An overview of both pre-injector chains can be found in [1].

2 THE PS PROTON BEAM FOR LHC

2.1 Parameters of the LHC proton beams

The beam parameters required by the present LHC proton filling scheme at PS ejection are compiled in Table 1, where three intensity levels are considered: (i) the “initial” or “commissioning” beam, enabling LHC physics during the first two years at a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$; (ii) the “nominal” beam for operating the LHC at $10^{34}$ cm$^{-2}$s$^{-1}$; (iii) the “ultimate” beam, which is the foreseeable LHC performance limit at $2.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$. For the nominal and ultimate beams, two limiting effects had to be overcome: (i) the high transverse density leads to excessive space charge at the PSB (50 MeV) and PS (now increased to 1.4 GeV for this reason) injection energies; (ii) longitudinal instabilities of the microwave type, occurring during the debunching-rebunching process foreseen in the initial project. This process was designed to generate the LHC bunch spacing of 25 ns in the PS at 26 GeV/c.

Table 1: LHC proton beams at PS ejection (26 GeV/c)

<table>
<thead>
<tr>
<th></th>
<th>commissioning</th>
<th>nominal</th>
<th>ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons/bunch</td>
<td>$1.8 \times 10^6$</td>
<td>$1.1 \times 10^6$</td>
<td>$1.8 \times 10^6$</td>
</tr>
<tr>
<td>number of bunches</td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\epsilon_r$ rms [µm] not larger than</td>
<td>0.8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>relative transverse brilliance $N_b/\epsilon_r$</td>
<td>0.6</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>$\epsilon_r(2\sigma)$ [eVs]</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>bunch length total [ns]</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

2.2 The PS produces the nominal LHC proton beam

The commissioning of the newly installed hardware started about two years ago and aimed at producing the nominal LHC beam [2]. Already in 1999, a beam with better than nominal transverse properties and 25 ns bunch spacing could be produced; however, its bunch length was about 5 ns, too long to be accommodated by the SPS 200 MHz RF buckets. This was due to a blow-up in momentum spread during debunching, generated by the excessive impedance of the PS.

This bottleneck was overcome by radically changing the scheme [3] to produce the LHC beam, based on the recently invented longitudinal splitting of one bunch into three. In this scheme, 6 PSB bunches are provided to the PS in two PSB batches and stored in six out of seven PS buckets, thus leaving one bucket empty to provide a void for the PS ejection kicker. These 7 buckets are split into 21 by the new process, then accelerated to 26 GeV/c, split into 42 and finally into 84 buckets, out of which 72 are filled. The usual non-adiabatic RF procedure, based on 40 and 80 MHz cavities, shortens the bunches to 4 ns.

Thanks to this new PS scheme, a nominal LHC beam was indeed produced towards the end of 2000:

- $1.1 \times 10^6$ protons/bunch (with bunch-to-bunch intensity variations of ± 20%)
- 25 ns bunch spacing
- $\epsilon_r$ rms ~ 2.5 µm in PSB and PS, both planes, comfortably below the allowed limit of 3 µm
- bunch length ~ 3.8 ns.
2.3 Tasks still to be done

So, is this job now finished? Yes, almost, but there are quite a few tasks still to be done:

- Two 20 MHz cavities are required in the PS for providing \( h=42 \) in the bunch splitting procedure. It is proposed that they are tunable also to 13.3 MHz, which would enable a bunch spacing of 75 ns.
- New transverse dampers in the PS, with a bandwidth of 20 MHz, to correct injection oscillations and tame transverse instabilities.
- The excessive variation of bunch population (up to \( \pm 20\% \)) will have to be reduced to \( \pm 10\% \) which at first sight appears acceptable for LHC.
- Studies on how to produce the initial (commissioning) beam. In fact, this is more urgent than the nominal beam as the LHC will do initial physics with this beam. While its transverse density is smaller than nominal (Table 1), the very tight emittance budget is a big challenge.
- Beam profile monitors are to be upgraded to enable beam size measurements in particular on the tiny initial beam.
- There are doubts whether the ultimate beam is feasible with the new scheme, which compared to the old scheme requires 15% more intensity per bunch in the PSB and at PS injection; fortunately, there is no urgency.

2.4 PS-SPS Matching

An optimised matching of the transfer line between the PS and SPS (TT2 and TT10) is imperative to comply with the extremely tight emittance budget. The large amount of earlier work has been continued by systematic and extensive studies [4] of the line in 2000, in close collaboration between the PS and SPS experts. The optics model now fits the measurements which were performed with SEMgrids in TT2, and OTR monitors (allowing visualisation of an x-y image of the beam) in TT10. As a result, there is now

- negligible horizontal and vertical betatron mismatch
- no dispersion mismatch (horizontal, vertical), but
- horizontal-vertical coupling, unmistakably visible on OTR screens.

It looks as if the coupling is generated in the PS. It should be noted that the measurements were performed with a very flat beam \( (\epsilon_h >> \epsilon_v) \) rather than a round LHC-type beam, exacerbating the effect of linear coupling. However, studies in the PS and the line are foreseen to pin down the reason for coupling.

2.5 Alternative bunch trains

The SPS (and to some extent also the PS) is plagued by electron clouds which appear to be generated by the short (4 ns total) LHC bunches in trains with 25 ns spacing. The new way to produce the LHC beam in the PS has a side effect which turns out to be very welcome: the possibility to generate bunch trains [3] different from the nominal ones in order to study these electron cloud effects which very likely will also plague the LHC. Alternative bunch trains featuring

- holes of 12 (24, 36,..) LHC bunches by omitting 1 (2,3,..) PSB rings
- 50 ns bunch spacing, but not yet with nominal intensity
- 75 ns bunch spacing (requiring a 13.3 MHz option for the new 20 MHz RF system in the PS)

and others are feasible or envisaged. Note that trains of up to 48 bunches require only one PSB batch per PS cycle.

3 THE PS AS ION PRE-INJECTOR [5]

3.1 Lead

The ALICE experiment will study Pb-Pb collisions at 2.76 TeV/u and anticipates a luminosity of \( 10^{27}\text{cm}^{-2}\text{s}^{-1} \), with the following beam characteristics:

- \( N_b = 6.8 \times 10^7 \) Pb ions/bunch
- \( \epsilon^{*}_{\text{rms}} = 1.5 \mu\text{m} \) (same physical emittance as protons at collision)
- 608 bunches
- 125 ns bunch spacing.

The transverse beam density \( N_b/\epsilon^{*}_{\text{rms}} \) is ~30 times the one achievable with the present fixed-target operation, therefore it is proposed to transform the old LEAR antiproton ring into a Low Energy Ion Ring (LEIR) where the beam brightness is attainable by accumulating several pulses from Linac3 and by extensive use of electron cooling.

Contrary to the proton beam, ions undergo major losses in the injector chain (change of charge state due to bad vacuum, intrabeam scattering,...), so the overall efficiency between the exit of LEIR and the LHC is estimated at about 0.3. Table 2 compiles a few key parameters of the Pb beam in the LEIR and PS machines.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEIR</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV/u]</td>
<td>~0.03</td>
<td>4.25</td>
</tr>
<tr>
<td>ions/bunch</td>
<td>2 ( \times 10^7 )</td>
<td>10^7</td>
</tr>
<tr>
<td>( \epsilon^{*}_{\text{rms}} ) [\mu m] not larger than</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>number of bunches</td>
<td>4 (possibly less)</td>
<td>4</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>RF harmonic</td>
<td>4 (possibly less)</td>
<td>17</td>
</tr>
<tr>
<td>cycle length [s]</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

The presently selected scheme (others are being contemplated) to produce this beam in the PS complex is sketched below:

- The Electron Cyclotron Resonance Source is upgraded from 100 to 300 \( \mu\text{A} \).
• 4 pulses (~60 µs each) of Linac3 (upgraded to 10 Hz operation), distance 400 ms, are accumulated in LEIR via electron cooling.
• Acceleration to ~30 MeV/u, followed by further electron cooling.
• 4 bunches are transferred from LEIR to the PS into 4 buckets (h=32) and fill 1/8 of the PS circumference.
• After acceleration to an intermediate energy, the RF harmonic is changed in several steps to h=17 (profiting from the partial filling of the ring) which corresponds to the LHC spacing of 125 ns.
• One SPS pulse (52 bunches) is formed of 13 PS bursts.

The ion accumulation scheme has been tested in LEAR in 1997 and has proven basically feasible but also revealed missing factors of 2 in both accumulated intensity and cooling rates. Following these experiments, a study has been launched to define the upgrade for Linac3, PS, and in particular LEIR, whose major ingredients are:

• Change of the LEIR lattice.
• New electron cooling system, more efficient due to higher electron current and featuring adjustable energy.
• New injection system to enable some 10 turns of a Linac3 pulse to be injected into LEIR.
• Both injected and ejected beams pass through the same line whose magnets have therefore to change strength and sign between injection and ejection (this could be avoided by moving Linac3 which is being considered).

Marked improvement of LEIR vacuum which suffers from excessive desorption by impinging Pb ions (at present, one ion desorbs ~10^5 molecules). Studies on how to treat the vacuum chamber are being pursued.

• Pb^{4+} is stripped to Pb^{2+} in TT2, leading to an excessive transverse emittance blow-up due to Coulomb scattering. A low-β insertion at the location of the stripper foil will reduce this to (still considerable) Δε_{rms} ~ 0.2 µm, but needs new quadrupoles and power converters.

3.2. Lighter Ions

After several years of running with Pb-Pb collisions, ALICE would like to collide lighter ions at much higher luminosities. According to a recent LHC report [6], the ions considered are: In(49), Kr(36), Ar(18), O(8), He(2). The study of how to produce sufficient intensities of each of these ions in the PS complex is very complicated and lengthy. Moreover, the intensities requested appear extremely high as they hit several limitations, in particular the space charge limit in the PS (e.g. the oxygen beam would have the same number of charges per bunch as the nominal proton beam¹). As this may unduly increase the complexity of the project, a more critical study of further possible limitations in the SPS and LHC machines as well as in ALICE is needed. The following ingredients to ease light ion acceleration are considered:

• Move of Linac3 to the South Hall.
• Production of two or even a single bunch in LEIR.
• Light ion acceleration in the PSB.
• Use of a Laser Ion Source which is under development and will be equipped with a 100 J, 1 Hz laser in 2001, potentially yielding short high-intensity pulses for LEIR or the PSB. Conclusive tests results with Pb ions are awaited for end 2001.

3.3. Schedule

Design reports on PIL and LEIR are expected for end 2001, followed by ordering the hardware and installation in the machines (mainly LEIR). According to present ideas, LEIR will be commissioned with Pb ions from mid-2003, the PS from late 2004, and the SPS from September 2005. The LHC could have the first Pb ion beam for testing in October 2006. The schedule for lighter ions, with Ar in 2008, is on even less firm ground. The design report is supposed to include cost estimates for Pb ions alone and the additional cost for light ion production.

4 FUTURE SPS-PS SUPERCYCLES

During the various phases of LHC commissioning and operation, both PS (with PSB) and SPS will have to supply beam to other users (North Hall, CNGS, East Hall, AD, nTOF, ISOLDE,...). These stringent requirements mean that the SPS/PS supercycles will have to undergo many rapid changes per day. This is already daily practice in the PS/PSB complex, but not yet in the SPS. It is therefore proposed [7] to profit from the know-how accumulated on this subject in the PS complex and to extend the PS/PSB cycle manager to SPS needs. To this end, one distinguishes two types of cycles:

• “Coupled” cycles on which the injecting machine is bound to deliver a beam to the higher energy machine (example: PS sends an LHC-type beam to SPS for LHC filling);
• “Uncoupled” cycles which are not needed by the higher energy machine and can therefore be freely dedicated to a user (example: during the time SPS is accelerating the LHC beam, the PS can program cycles e.g. for the East Hall).

Moreover, the system features “spare” cycles whereby “normal” cycles are directed to another “spare” user on very short notice (1-2 s) whenever there are external conditions prohibiting execution of the “normal” cycle.

It is proposed to upgrade the SPS Main Timing Generator along these lines and to foresee 16 different SPS supercycles prepared in advance which can be
rapidly loaded into a future cycle manager. However, one should resist the temptation to design a cycle timing system “doing anything” but difficult to use and, due to its complication, prone to breakdowns.

5 CONCLUSIONS

The highlight of the session “PS as LHC Pre-Injector” was undoubtedly the production of the nominal beam in the PS at 26 GeV/c. The main progress with respect to the 1999 results was the putting into operation of the new production scheme based on the recent invention of triple bunch splitting. The scheme finally produces bunches of ~ 4 ns length which proved not feasible with the old scheme based on a debunching-rebunching process. On top of this, it offers an appreciated fringe benefit: the generation of alternative bunch trains and spacings which prove invaluable to investigate electron cloud effects in the SPS. While progress was very satisfactory also on beam dynamics issues such as matching between the machines, some hardware has still to be done. A proposal to adapt the present PS/PSB supercycle system to the future SPS/PS needs was presented. The Pb accumulation scheme in LEIR, whose basic ingredients were successfully tested with Pb ions, requires an upgrading programme of Linac3, LEIR, PS. This programme depends strongly on the species and quantity of lighter ions the pre-injector should be capable to deliver at a later stage. Design reports will be submitted by end 2001. According to present thinking, Pb ions would become available for LHC in late 2006.

REFERENCES