INJECTION OF THE LEAD ION BEAM FOR LHC INTO THE PS

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Abstract

This paper describes the principles and the layout of the injection of lead ions from the LEIR machine into the PS ring. The kinetic energy of the beam at LEIR extraction is 72.2 MeV/u or 754.57 MeV equivalent proton kinetic energy, corresponding to a 4.8 Tm beam rigidity. This energy requires a new injection septum magnet and an upgrade of the existing injection kicker magnet formerly used for antiproton extraction at 180.3 MeV kinetic energy. Moreover, a local orbit bump at PS ion injection has to be conceived to move the closed orbit near the edge of the septum to reduce the strength of the kicker. A review of the equipment necessary for the injection process is made for the different scenarios studied.

The input beam must be matched to the PS ring. To this end, the optical parameters are calculated at a matching point near the end of the transfer line from LEIR to PS, by tracking back those at the septum. The stray field induced by the upstream magnet unit adjacent to the septum is considered.
1. Introduction

In the perspective of the PS complex conversion (Linac 3, LEIR, PS) into a lead ion injector for the LHC, Pb$^{54}$ ion beams will be injected into the PS ring at 72.2 MeV/u and then accelerated to 4.25 GeV/u, ejected and fully stripped to Pb$^{82}$ ions in the transfer line between PS and SPS. More precisely, two bunches of $4.5 \times 10^8$ ions will be accelerated in LEIR on harmonic $h=2$, ejected in the direction of the PS machine, captured on harmonic $h=16$ every 3.6 s and accelerated to about 1.5 GeV/u. Hence, the harmonic number will be changed from $h=16$ to $h=10$ and the two bunches splitted in four ($h=20$). Finally, harmonic change to $h=17$ will be carried out prior to the acceleration to 4.25 GeV/u for providing a 125 ns bunch separation compatible with the 200 MHz RF system of the SPS. The 72.2 MeV/u LEIR extraction kinetic energy is a compromise between the incoherent tune shift limit at PS injection ($\Delta Q_{inc} < 0.25$), the bunch spacing needed for the ejection kicker rise time, the cycle length and the minimum frequency attainable with the PS RF system [1]. Table 1 summarises the main parameters of lead ion beams at transfer between LEIR and PS. The present note reports possible injection scenarios that fulfil the above requirements.

<table>
<thead>
<tr>
<th>Parameter at PS injection</th>
<th>unit</th>
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<tbody>
<tr>
<td>kinetic energy</td>
<td>MeV/u</td>
<td>72.163</td>
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<tr>
<td>equivalent proton kinetic energy</td>
<td>MeV</td>
<td>779.58</td>
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<tr>
<td>$\gamma$</td>
<td></td>
<td>1.077</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td>0.372</td>
</tr>
<tr>
<td>beam rigidity ($B\rho$)</td>
<td>T·m</td>
<td>4.80</td>
</tr>
<tr>
<td>magnetic field in PS dipoles</td>
<td>Gauss</td>
<td>684.94</td>
</tr>
<tr>
<td>number of injected bunches</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>bunch length ($1\sigma$)</td>
<td>ns</td>
<td>50</td>
</tr>
<tr>
<td>number of Pb$^{54}$ ions per bunch</td>
<td></td>
<td>$4.5 \times 10^8$</td>
</tr>
<tr>
<td>relative momentum spread ($1\sigma$)</td>
<td></td>
<td>0.6·10$^{-3}$</td>
</tr>
<tr>
<td>normalised transverse emittance ($1\sigma$)</td>
<td></td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 1: Summary of lead ion beam characteristics at the transfer from LEIR to the PS.

2. Extraction layout of the former antiproton PS extraction toward LEAR

The past PS antiproton ejection in the direction of the LEAR machine took place in the “long” PS straight-section 26 as shown in Fig. 1 below.

Fig. 1: Layout of the PS straight-section 26 with the antiproton extraction septum.
Antiprotons were fast extracted from the PS ring at 609 MeV/c (180.3 MeV kinetic energy, 2.0 Tm beam rigidity) using kicker and septum magnets located in straight-sections 28 and 26, respectively, yielding a phase difference between these devices near $\pi/4$, not very close to the ideal value $\pi/2$. The betatron functions at kicker and septum are about 12 m. The septum strength used in operation to extract the beam ($B_{dl}=0.105$ Tm, yielding a deflection angle $\delta=51.5$ mrad or $2^\circ57'6''$) did not exceed the maximum attainable value of 0.117 Tm. No local closed orbit distortion was needed since the kicker strength necessary to eject directly from the central orbit ($B_{dl}=192.6$ Gm, yielding a kick $\delta_k=9.5$ mrad) was below the maximum kicker value of 232.4 Gm. Using Eq.1, subsequent beam position and angle at the septum were 80.6 mm and 6.7 mrad. The septum was positioned at 53 mm from the central orbit; its thickness varies between 1.5 mm and 18 mm.

$$x_s = \sqrt{\beta_s \beta_k} \sin(\mu_s - \mu_k) \delta_k$$  $$x'_s = \frac{\sqrt{\beta_k}}{\beta_s} (\cos(\mu_s - \mu_k) - \alpha_s \sin(\mu_s - \mu_k)) \delta_k$$

(1)

Fig.2 shows the Y shape vacuum chamber adjacent to the ejection septum tank used to take the antiproton beam out of the PS ring.

Fig. 2: Y shape vacuum chamber adjacent to the extraction septum 26. The angle between the two pipes is $2^\circ57'6''$ or 51.5 mrad which is the nominal extracted antiproton deflection angle.

3. Proposal for a lead ion injection scenario into the PS

The lead ion beams from LEIR will follow the geometry of the former antiproton transfer line in the reverse direction and will be injected in the PS straight-section 26. The higher 4.8 Tm ion beam rigidity would require a septum strength of 0.247 Tm to handle the 51.5 mrad beam deflection, which is beyond the maximum strength of the present septum (0.117 Tm). Therefore a new septum for ion injection has been proposed with a maximum strength of 0.275 Tm. The new septum magnetic length, gap width, height and thickness will be 0.8 m, 100 mm, 60 mm and 5 mm, respectively [2].

Fig. 3: Layout of the PS straight-section 26 with the future lead ion injection septum.
The axis coordinate of the outer Y shaped injection vacuum pipe with respect to the reference orbit when extended to the longitudinal centre of septum 26 is 84.3 mm. This value will be taken as the reference beam centre position for subsequent calculations of the injection process. All later optics computations have been carried out with BeamOptics [3] using a modelling of the PS lattice taken from [4]. Pushing the beam on the reference orbit from the 83.4 mm beam position at septum would need a kicker strength of 469.8 Gm (δ=9.79 mrad). This threshold is too high even if the present kicker strength could be enhanced by a factor two to 464.8 Gm, with its foreseen upgrading. Thus, a local closed orbit bump over the injection region is needed to push the beam near the septum. The bump position at septum must not exceed the position of the septum with respect to the central orbit minus the half-width of the injected beam and possible orbit distortions. Given the PS optical parameters and the ion beam characteristics the horizontal beam size (at 6σ) around the septum is of the order of 30 mm. Assuming the same 53 mm septum position used for the former antiproton extraction and taking a 13 mm safety margin allowing for other orbit distortions and kicker tuning, the bump position at septum location is found to be 25 mm. It is foreseen to implement a three-magnet bump to create the needed orbit displacement without residual deformation outside the injection region. This bump can be reduced to an almost half-wavelength two-magnet bump if a small residual orbit distortion outside the bump is permitted. Over the ten PS straight-sections centred on straight-section 26, short dipole bumpers may be installed in straight-sections 21, 22, 24, 25, 29 and 30. It is worth mentioning that the vacuum chamber width between PS magnet units 23 and 25 is enlarged towards the inside of the ring (-105 mm, 70 mm) allowing for an inward orbit (between straight-sections 19 and 27) around the slow extraction septum 23. Between magnet units 26 and 29 the vacuum chamber width is enlarged towards the outside of the ring (-70 mm, 105 mm).

3.1. Three-magnet bump (preferred scenario)

Considering the availability of the PS straight-sections in the vicinity of the septum 26, it is proposed to install the three horizontal dipoles with angular deflections δ_{1,2,3} in the straight-sections 21, 25 and 29 to make the required closed orbit bump. The conditions for the closure of the bump may be expressed in terms of the optical parameters as

$$\frac{\delta_1\sqrt{\beta_1}}{\sin(\mu_3 - \mu_2)} = \frac{\delta_2\sqrt{\beta_2}}{\sin(\mu_1 - \mu_3)} = \frac{\delta_3\sqrt{\beta_3}}{\sin(\mu_2 - \mu_4)}$$

(2)

The first kick δ₁ is determined from the knowledge of the bump position x_s at septum using Eq. 1 (with μ_i and δ_i replaced by μ_s and δ_s). Fig. 4 shows a three-magnet bump with a 25 mm amplitude at septum centre location, 31.9 m from the centre of straight-section 21.

Fig. 4: Left: three-dipole bump in PS straight-sections 21, 25, 29. The dipoles are at 0.2 m, 25.1 m, 50.0 m from the centre of straight-section 21. Right: 6σ-beam envelope [mm].
Kicker 28 is at 44.3 m from the centre of straight-section 21. The phase separation between the dipoles 29 and 21 is 0.976\(\pi\). The three kicks producing the bump are 1.8 mrad, -0.1 mrad and 1.7 mrad. The maximum strength of the deflecting dipoles is 86 Gm. It should be noted that kicker 28 is inside the bump extension so that the orbit is displaced by 10 mm in the kicker tank. The 38 mm maximum displacement of the beam is reached in straight-section 25, at about 25 m from the origin of the bump. Upstream straight-section 26 the size of the circulating beam remains within the pipe aperture width (minimum -105 mm, 70 mm), the maximum beam size coordinate on the outside is 58 mm within straight-section 25. In particular, the beam position in straight-section 23, where the electrostatic septum is installed, matches the septum tank aperture well. The beam position and angle at the septum with some relevant parameters for this injection scenario are summarised in Table 2. To achieve this injection the kicker 28 strength has to be enhanced from 232.4 to 330.4 Gm (42% more).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>horizontal tune</td>
<td>6.18</td>
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<tr>
<td>beam position and angle at septum 26</td>
<td>mm/mrad</td>
</tr>
<tr>
<td>orbit bump position and angle at septum 26</td>
<td>mm/mrad</td>
</tr>
<tr>
<td>kicker 28 deflection</td>
<td>mrad</td>
</tr>
<tr>
<td>septum 26 deflection</td>
<td>mrad</td>
</tr>
<tr>
<td>septum 26 position and angle</td>
<td>mm/mrad</td>
</tr>
<tr>
<td>3-dipole bump deflections</td>
<td>mrad</td>
</tr>
</tbody>
</table>

Table 2: Main parameters of the injection scenario.

Fig. 5 shows the horizontal injected beam envelope (at 6\(\sigma\)) from a matching point in the LEIR to PS transfer line located 6.5 m upstream from the septum centre to the kicker 28 location, with that of the subsequent circulating beam over the range of the bump. Calculations of the input beam trajectory include the stray field effect of magnet unit 25 adjacent to straight-section 26. Fig. 6 is a blow-up of Fig. 5 (left) in the vicinity of septum.

![Fig. 5: Left: horizontal injected and circulating 6\(\sigma\)-beam envelopes over the full bump range [mm]. Right: horizontal injected 6\(\sigma\)-beam envelope downstream the septum centre [mm].](image)

Fig. 6: Horizontal injected and circulating 6\(\sigma\)-beam envelopes in straight-section 26 [mm].
3.2. Symmetric three-magnet bump

A more symmetric three-bump with dipoles in straight-sections 22, 25 and 30 could have been envisaged, yielding a lower maximum orbit displacement (32 mm) for the wanted 25 mm bump amplitude at septum 26 as shown in Fig. 7, with the circulating beam envelope. The phase difference between the dipoles 30 and 22 is 0.986π. The kicks producing the bump are 2.1 mrad, -0.1 mrad and 2.1 mrad.

This alternative has been discarded for two reasons. First, it produces an orbit displacement of 18 mm at the kicker location (44.3 m from the centre of straight-section 21), almost twice the value of that of the previous bump, although the magnetic field quality inside the kicker magnet is given at ±1% within ±50 mm from the central orbit. Next, the second 32 mm maximum bump amplitude reached in straight-section 27 adds to the input beam trajectory which is still away from the reference orbit (without bump) so that the beam coordinate on the exterior might move critically towards (it attains 96 mm in straight-section 27) the outer limit of the vacuum pipe aperture width (-70 mm, 105 mm) as shown in Fig. 8.

3.3. Short range three-magnet bump

The following three-bump implementation shown in Fig. 9 requires a shorter extent than the previous scenarios. The bump trajectory is similar to that of the three-magnet bump preferred scenario downstream the septum location. Upstream straight-section 24 the beam trajectory follows the reference orbit. However, the dipole strengths needed to achieve the 25 mm amplitude bump are larger than those of the previous scenarios. The three kicks producing the bump are 7.0 mrad, -5.0 mrad and 1.7 mrad, which yields a maximum deflecting dipoles strength of 329 Gm. The phase difference between the dipoles 29 and 24 is 0.656π.
3.4. Two-magnet bumps

Finally, let consider the option derived from the preferred scenario of an almost half-wavelength two-magnet bump with identical kicks at the two dipoles. The kick producing the bump is 1.7 mrad per dipole. However, the bump does not close due to the 0.976π phase difference between the two dipoles. This non-exact half-wavelength bump yields a residual orbit distortion of ±3.3 mm as shown in Fig. 10. As an alternative, Fig. 11 shows a more symmetric two-magnet bump with dipoles in straight-sections 22 and 30, derived from the aforesaid symmetric three-magnet bump scenario. The phase difference between the dipoles is 0.986π. The kick is 2.1 mrad per dipole yielding a lower residual orbit distortion of ±2.2 mm.

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Fig. 9: Left: Short range three-dipole bump in straight-sections 24, 25, 29. The dipoles are at 19.4 m, 25.1 m, 50.0 m from the centre of straight-section 21. Right: 6σ-beam envelope [mm].

Fig. 10: Left: two-dipole bump in PS straight-sections 21 and 29. The dipoles are at 0.2 m and 50.0 m from mid-straight-section 21. Right: residual orbit distortion around the PS ring induced by the bump.

Fig. 11: Left: two-dipole bump in PS straight-sections 22 and 30. The dipoles are at 6.8 m and 56.8 m from mid-straight-section 21. Right: residual orbit distortion around the PS ring induced by the bump.
3.5. No bump

The case of a straightforward injection on the circulating orbit without bump is presented for the sake of completeness, although it cannot be implemented because of the kicker limitation ($\beta d_{l_{\max}} = 464.8 \ Gm$). As for the preferred scenario, the horizontal injected beam envelope and the circulating beam are shown in Fig. 12 and Fig. 13 (nearby the septum).

![Fig. 12](image)

**Fig. 12:** Left: horizontal injected and circulating $6\sigma$-beam envelopes [mm] (469.8 Gm kick strength needed). Right: horizontal injected $6\sigma$-beam envelope downstream the septum centre [mm].

![Fig. 13](image)

**Fig. 13:** Horizontal injected and circulating $6\sigma$-beam envelopes (without bump) in straight-section 26.

4. **Matching conditions between LEIR output and PS input**

Upstream magnet unit 25 adjacent to the septum 26 is made of a closed half-unit (horizontally focusing for positive particles) followed by an open half-unit. The incoming ion beam trajectories pass far off from the central orbit of the closed half-unit (at about 430 mm on average), where the gradient has a reverse polarity, and away of the open half-unit (at about 250 mm on average). The layout of the PS magnet unit 25 is shown in Fig. 14.

![Fig. 14](image)

**Fig. 14:** PS magnet unit 25 with the input ion beam vacuum pipe.
The input beam will then experience the stray field of the magnet. The normalised gradients of the closed and open half-units are plotted in Fig. 15 as a function of the horizontal trajectory offset. The values have been derived from magnetic measurements at 3.5 GeV/c [5]. While the gradient of the open half-unit at 250 mm from the central orbit, and then the deflecting field (integrating the gradient), may be derived from these data by interpolation, they cannot be obtained for the closed half-unit at the far distance of 430 mm. However, the following Eqs. 3-4 have been derived to extrapolate the field and the gradient in the median plane outside the machine aperture [6] ($B_0$ is the reference field level on the central orbit $x=0$, the transverse displacement $x$ is in cm).

$$B_{\text{closed}}(x) = \frac{1.39B_0}{(x-11.52)^2 + 1}$$
$$\left(\frac{dB}{dx}\right)_{\text{closed}}(x) = -0.375B_0 \frac{x-11.52}{7.41} \frac{(x-11.52)^2 + 1}{(x-11.52)^2 + 1}$$

$$B_{\text{open}}(x) = \frac{0.813B_0}{(x+1.94)^2 + 1}$$
$$\left(\frac{dB}{dx}\right)_{\text{open}}(x) = -0.12B_0 \frac{x+1.94}{13.6} \frac{(x+1.94)^2 + 1}{(x+1.94)^2 + 1}$$

![Fig. 15: PS magnet unit 25 normalised gradients [m$^{-2}$] versus the horizontal distance [mm] from the central orbit (magnet unit with yoke oriented inside the centre of the ring).](image)

The mean gradient and deflection angle seen by the input beam when traversing the stray field of the closed and open half-units are $-0.008$ m$^{-2}$, $2.2$ mrad and $-0.020$ m$^{-2}$, $5.1$ mrad, respectively. These values have to be compared to the nominal $\pm 0.059$ m$^{-2}$ and $31.4$ mrad gradient and angle of the two half-units experienced by circulating beams on the central orbit. The resulting horizontal and vertical transfer matrices in the LEIR to PS transfer line, from the magnet unit 25 stray field entry point, called matching point M, to the centre of septum 26 are

$$M_H = \begin{pmatrix}
1.125 & 6.534 & 0.022 \\
0.0503 & 1.181 & 0.008 \\
0 & 0 & 1
\end{pmatrix} \quad M_V = \begin{pmatrix}
0.878 & 5.683 & 0 \\
-0.049 & 0.825 & 0 \\
0 & 0 & 1
\end{pmatrix}$$

The optical parameters of the PS ring at the lead ion injection point (septum centre) calculated with BeamOptics are given in Table 3 (1$^{st}$ row). Propagating back these values throughout the LEIR to PS transfer line in the reverse direction up to point M located 6.5 m upstream the longitudinal centre of the septum yield the relevant optical parameters at the matching point M. Once transformed to obtain the right sign for the injected particles, the optical parameters at point M, reported in Table 3 (2$^{nd}$ row), are used for afterwards matching with the LEIR extraction point.
5. Conclusion

Scenarios to inject lead ion beam into the PS machine have been studied. They lead to the proposed injection schemes with a three-magnet bump of 25 mm amplitude at septum 26 location to ease the fast kicker 28 to bring the input beam on the reference closed orbit. The three-magnet bumps can be shrunk to almost half-wavelength two-magnet bumps (using one power supply only) provided low residual orbit distortions around the PS ring are allowed. Anyhow, a new injection septum 26 has to be built and the present kicker 28 must be upgraded to handle ion beams with 4.8 Tm beam rigidity. The scenarios that implement such a bump are summarised in Table 4 below, the preferred scenario being the first reported.

<table>
<thead>
<tr>
<th>Dipole location in PS straight-sections</th>
<th>dipole deflection angle</th>
<th>maximum bump amplitude</th>
<th>remarks</th>
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<tr>
<td>3-dipole bump in PS sections 21-25-29¹</td>
<td>1.8, -0.1, 1.7 mrad</td>
<td>38 mm in straight section 25</td>
<td>no residual orbit, require 3 power supplies</td>
</tr>
<tr>
<td>3-dipole bump in PS sections 22-25-30²</td>
<td>2.1, -0.1, 2.1 mrad</td>
<td>32 mm in straight sections 25 and 27</td>
<td>higher orbit displacements downstream the septum</td>
</tr>
<tr>
<td>3-dipole bump in PS sections 24-25-29³</td>
<td>7.0, -5.0, 1.7 mrad</td>
<td>38 mm in straight section 25</td>
<td>short bump extension but require higher dipole kicks</td>
</tr>
<tr>
<td>2-dipole bump in PS sections 21-29⁴</td>
<td>1.7, 1.7 mrad</td>
<td>38 mm in straight section 25</td>
<td>≈3 mm residual closed orbit, require only 1 power supply</td>
</tr>
<tr>
<td>2-dipole bump in PS sections 22-30⁵</td>
<td>2.1, 2.1 mrad</td>
<td>32 mm in straight sections 25 and 27</td>
<td>≈2 mm residual closed orbit, require only 1 power supply</td>
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</table>

¹ preferred 3-magnet bump scenario, ² symmetric 3-magnet bump, ³ short-range 3-magnet bump, ⁴ derived from the preferred scenario, ⁵ derived from the symmetric three-magnet bump scenario.

Table 4: Summary of some possible dipole bump implementations yielding a 25 mm amplitude bump at septum 26 location.

Table 5 lists the injection septum and kicker integrated field strengths required to realise these scenarios. The case of an injection scheme without bump is also given.

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>integrated magnetic field for 4.8 Tm lead ion injection</th>
<th>foreseen maximum integrated magnetic field</th>
</tr>
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<tbody>
<tr>
<td>septum 26</td>
<td>0.247 Tm (51.5 mrad)</td>
<td>0.275 Tm</td>
</tr>
<tr>
<td>kicker 28 with a 25 mm bump</td>
<td>330.4 Gm (6.9 mrad)</td>
<td>464.8 Gm¹</td>
</tr>
<tr>
<td>kicker 28 without bump</td>
<td>469.8 Gm (9.8 mrad)</td>
<td>464.8 Gm¹</td>
</tr>
</tbody>
</table>

¹ assuming twice the present 232.4 Gm maximum kicker strength.

Table 5: Injection septum and kicker integrated magnetic fields.
Acknowledgements

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References


