1. INTRODUCTION

The chain of LEP injectors[1] provided 4 bunches of positrons at 18 GeV to LEP for the first time during the Octant Test[2] in July 1988. From July 1989 onwards the running-in of the beam transfer channels and of the LEP injection system was conducted at 20 GeV with positrons and with electrons interleaved with the commissioning of LEP[3]. The system became operational in late Summer 1989. Accumulation was soon tried successfully, which is based on betatron stacking in the horizontal plane with subsequent merging of the injected beam with the stored beam by radiation damping.

The injector chain provides LEP with two batches of 4 positron bunches and two batches of 4 electron bunches in the 14.4 s long SPS supercycle. The length of the SPS magnetic cycle for each bunch is 1.2 s and all these four continuous 20 GeV cycles of the SPS are accommodated in the SPS deadtime between 400 GeV proton cycles so that the filing of LEP does not interfere with the injected beam with the stored beam by radiation damping. Since the LEP filling rate has been adequate, performance studies of LEP injection had little priority and only a few measurements could be done. The most relevant results are given under point 4.

2. SPS EJECTION AND BEAM TRANSFER TO LEP

After acceleration in the SPS, the e+ beams are ejected in long straight section LSS6. The e+ beam is ejected in the horizontal plane and follows the existing 430 GeV proton extraction channel, a solution both operationally practicable and cost saving. This channel is also used for injection of e- at 3.5 GeV and of p+ at 26 GeV when the SPS operates in the collider mode. Each bunch is deflected 1.6 mrad from a local orbit bump onto the extraction trajectory, by a full aperture ferrite kicker magnet. Shortly after entering the West Area transfer line TT60 the e+ beam is bent by a vertical switch magnet onto the transfer line to LEP.

The e+ beam requires a dedicated extraction channel in the vertical plane to avoid interference with other SPS equipment. Each e+ bunch is deflected 0.8 mrad by a vertical kicker magnet into the aperture of a current septum magnet, which bends the beam up and over the SPS. In each lepton cycle, the corresponding kicker magnet system produces a burst of pulses, one pulse per bunch. The difference in pulse amplitude within one cycle and also long term is allowed, to reduce tunnel slopes. The sum of horizontal and vertical deflections in both lines is about 100° requiring strong bending magnets. Whenever practical, bending magnets were tilted to combine horizontal and vertical deflections, reducing the total bending power required. They are also made of equal strength to be able to connect them electrically in series, to save in cables and in the number of power supply for the large bends. The lines were required to transmit the SPS design emittance (1σ) of e+ = 0.94 μm and e- = 0.10 μm at 20 GeV and to accommodate an energy spread of σE/E = 0.063%, as well as the energy variation between bunches due to small changes in field between successive extractions and the jitter in beam position due to power supply ripple. The required apertures of the lines are mainly defined by the horizontal and vertical dispersion created by the lumped bends.

At the LEP injection points, a variety of matching conditions are to be provided to adapt the incoming beam to the LEP injection configuration, including:
- betatron matching with variable β* from 20 to 136 m,
- dispersion matching to make the beam either achromatic or matched to the LEP lattice,
- exchange of horizontal and vertical phase planes, so that the smaller vertical SPS (design) emittance is transferred into the horizontal plane, which allows to place the injection beam nearer to the septum, thus reducing the injection oscillation,
- provide the matching conditions for the LEP optics of 60 and 90 degrees phase advance.

The beam focusing of the lines, that copes with the above requirements, is made of FODO structures and such that the main vertical bends are separated by 8 periods, resulting in a period length of 61 m for TI12 and 30 m for TI18. The optical structure of the lines is composed of:
- a few separately powered quadrupoles in the upstream parts, tuned to minimize the beating in the lattices,
- the regular lattices with the F and D series separately powered, the phase plane exchange section consisting of 3 skew quadrupoles, each placed halfway in between regular quadrupoles at a distance of one period, with the regular quadrupoles in between tuned to a phase advance of 90 degrees[5],
- the matching section composed of 8 separately powered by quadrupoles to match the beam at the LEP injection points.

The peak values of the horizontal and vertical dispersion functions which were obtained are little dependant on the actual matching conditions and are for TI12: Dx = 7.8 m and Dy = 5.8 m and
for T118: \(D_x = 7.3\) m and \(D_y = 6.6\) m. The betatron functions are well behaved in the regular parts and in the phase plane exchange sections (less than 150 m in T112 and 100 m in T118) but suffer a blow up in the matching section which grows with increasing squeezing of \(\beta_x\) at injection (up to about 1 km in T112 for \(\beta_x = 20\) m).

For most applications, the optics is fixed up to the phase plane exchange sections. This allowed to install in this region profile monitors (of the secondary emission grid type) at the places where the dispersion functions cross zero (for emittance measurements) and at the places of large dispersion (for energy spread measurements). For beam steering a number of non-interactive beam position monitors of the strip line coupler type were installed which measure horizontal and vertical position of each bunch. Steering is provided only at the bends and the beams are left to drift over the long straights.

The optical performance of the lines was checked by:

a) launching horizontal or vertical betatron oscillations by applying small and known kicks with correction dipoles and measuring the difference amplitude along the line;

b) changing the current settings of the entire line by a small amount of \(\pm 0.1\%\) or less which, since the circulating beam in LSS6 is almost achromatic, induces oscillations in each line proportional to the dispersion functions.

Measurements with beam confirmed that the lines, including phase plane exchange, performed as calculated. Short term stability measured with the couplers is better than 1 mm. Results of some measurements are compared with design values in Table 1.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Dispersion at coupler or SEM (m)</td>
<td>7.1 / 7.9</td>
<td>7.3 / 7.4</td>
</tr>
<tr>
<td>Hor.: 3.9 / 3.3</td>
<td>6.4 / 6.5</td>
<td></td>
</tr>
<tr>
<td>Vert.: 0.3 / 0.4</td>
<td>0.9 / 0.9</td>
<td></td>
</tr>
<tr>
<td>Emissatce 1 (\sigma) ((\mu)m)</td>
<td>0.09 / 0.06</td>
<td>0.09 / 0.06</td>
</tr>
<tr>
<td>Hor.: 0.02 / 0.07</td>
<td>0.02 / 0.06</td>
<td></td>
</tr>
<tr>
<td>Vert.: 0.02 / 0.07</td>
<td>0.02 / 0.06</td>
<td></td>
</tr>
<tr>
<td>Energy spread ((\sigma) E/(\beta))</td>
<td>0.06% / 0.06%</td>
<td>0.04% / 0.05%</td>
</tr>
<tr>
<td>Momentum passband of horizontal momentum</td>
<td>7% / 7%</td>
<td>5% / 5%</td>
</tr>
<tr>
<td>Id of actual beam</td>
<td>(\pm 0.2% / \pm 0.2%)</td>
<td></td>
</tr>
</tbody>
</table>

Beam dumps are installed at both ends of the lines for radiation safety and machine interlock reasons but also for commissioning and setting up of beams. They consist of a movable, remotely controlled, cylinder 0.8 m long, made of CuCr1 alloy and housed in special vacuum tanks. In front of each of them is placed a luminescent screen type monitor.

Nearly 90% of the magnets in the lines are elements recuperated from the ISR transfer lines. Only the compact dipoles installed on top of the SPS and LEP machines and the injection septum magnets are specially designed and built. The dipoles are of the \(H\) type and can produce a field in the gap of 1.7 T while maintaining the good field region thanks to a hole placed in the pole, a concept developed already for the dipoles for the \(p^+\) transfer lines.

The steel septum magnets provide the last vertical deflection of the injection beam and deposit it in the median plane of LEP close and almost parallel to the machine axis. They are designed to produce a field of 0.9 T in the gap. For reasons of accessibility and installation of the LEP vacuum chamber placed in the septum groove and which must also be baked and magnetically shielded, no magnetic bridge crosses over the septum groove, which is shown in Fig. 2.

3. LEP INJECTION SYSTEM

The injection system consists of 3 full aperture kicker magnets and one thin copper septum magnet in each of the 2 injection zones\(^6\). It is installed in the regular LEP arcs in positions which would normally be occupied by main dipoles. The necessary space has been created by replacing the 24 standard dipoles of 2 lattice periods by 12 special ones, operating at twice the field\(^8\).

The kickers are placed adjacent to successive F-quadrupoles and create a fast \(\pi\) orbit bump in the horizontal plane. The horizontally deflecting copper septum magnet is placed immediately downstream of the central kicker (Fig. 3).

![Fig. 3 - Layout of the LEP injection system](image)

Kickers as well as the copper septum magnets are powered by pulses of about half sine shape. Rise and fall times are about 3 \(\mu\)s and 7 \(\mu\)s. The flat top time, measured between 99% amplitudes, is 5 \(\mu\)s. The short pulse duration assures that only that stored bunch is kicked, to which the injected bunch shall be added. Counter rotating bunches and other forward rotating bunches are not deflected.

The pulse generators of the kickers are capable of producing bursts of up to 8 pulses per second with a minimum pulse to pulse repetition time of 65 \(\mu\)s. The actually chosen repetition time in the 4 bunches injection scheme is 467 \(\mu\)s.

All these fast pulsed magnet systems operate reliably and according to their design specifications.

4. RESULTS OF MEASUREMENTS WITH BEAM

Injection has been performed with \(D_x = 0\) and \(D_y = 2.2\) m in the injection channel at the exit of the septum; the latter value equals the \(D_x\) in LEP at this azimuth. With \(D_x = 0\) all injected particles can be put as close as possible to the septum independent of their momentum. Hence, the average value of the betatron amplitude of the injected beam in LEP is reduced. This improves significantly injection and, therefore, is used in operation. Since the emittance ratio of the SPS is still close to 1, see Table 1 and Ref. [4], exchange of horizontal and vertical emittance in the beam transfer channel has not yet been used.

The injection process is quite sensitive to the position of the bumped stored beam relative to the septum and the injected beam, which enters LEP on the other side of the septum from the inside of the LEP ring. The former distance is relevant for the scraping of the stored beam on the septum, the latter distance determines the amplitude of the damped coherent betatron oscillation the injected beam performs around the stored beam in LEP.

As an example, Fig. 4 shows the maximum current \(I_{\text{max}}\) which could be stored in this experiment, and the stacking efficiency \(\eta\), defined as the ratio of stacking rate, plotted against the distance \(\Delta x_1\) between the bumped orbit and the close-by edge of the septum where \(\beta_x = 122\) m. The second scale \(\Delta x_2\) gives the betatron amplitude of the centroid of the injected beam in LEP at \(\beta_{x,\text{max}} = 136\) m. Only one electron batch consisting of 4 bunches was injected every
14.4 s at 20 GeV. Wigglers were off but separators were on; no positron beam stored.

It can be seen from Fig. 4 that $I_{\text{max}}$ is vanishing when $\Delta x_1$ gets too small because the stored beam is scraping on the septum. With increasing $\Delta x_1$, $I_{\text{max}}$ rises to a plateau with a slope consistent with the expected bunch widening by longitudinal turbulence\[9\]. The plateau is probably due to synchro-betatron oscillations\[10\].

Fig. 4 also shows that $\eta$ is the monotonically decreasing with increasing $\Delta x$, probably due to dynamic aperture limitations bringing about increasing losses from the injected beam circulating in LEP with a larger amplitude. It can be seen that $\eta$ is about 40% when $I_{\text{max}}$ reaches the plateau. In order to have some margin, usually a larger value of $\Delta x$ is selected for operation but such that $\eta$ is around 30%, which is the nominal value\[11\].

Since the measured dynamic aperture is smaller than the expected one, a second experiment was performed. An electron beam of 80 $\mu$A in 4 bunches was stored and the beam was given a large horizontal betatron oscillation with injection kicker IKE3 every 14.4 s. Given the horizontal emittance of 4.3 mm and an rms energy spread of 0.014% in the stored beam, the maximum available admittance can be calculated assuming that the dynamic aperture limitation acts like a scraper. The dynamic aperture turned out to be 1.37 $\pm$ 0.05 mm. Repeating the same experiment with a positron beam of 4 bunches gave 1.50 $\pm$ 0.04 mm with 200 $\mu$A stored and 1.54 $\pm$ 0.05 mm with 450 $\mu$A stored. The wigglers seem to have a beneficial effect by reducing the dwelling time of particles at large amplitudes, which also points to a dynamic aperture limitation.

5. ACKNOWLEDGEMENTS

We appreciate the advice and help by B. de Raad during the design and construction phase. We are grateful to S. Peraire for providing the beam line software and participating in the running in and to K. Cornelis for his help in the commissioning and participating in injection experiments. Also our sincere thanks to all the colleagues of the SPS and in particular of the Beam Transfer Group who contributed to the results achieved.

References

[13] D. Brandt, private communication (LEP Note 542)