BEAM TRANSFER FROM SPS TO LEP AND LEP INJECTION

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Abstract

The 20 GeV positrons and electrons are fast-ejected from the CERN Super Proton Synchrotron (SPS). Each kind of particle is transferred along separate, about 400 m, resp. 660 m long beam lines to the LEP injection points situated 37 m, resp. 50 m below the SPS in two adjacent LEP arcs. The optics is designed to allow different matching conditions at the LEP injection points and provides the possibility to exchange horizontal with vertical emittance. A concise description of the LEP injection system is included, and first measurements of injection efficiency and of related parameters are reported.

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 continued 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 batch 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 filling of LEP does not interfere with the Fixed-Target Programme of CERN. Since the injector chain can provide more than 2 x 10e^{10} particles per bunch at 20 GeV[4], the nominal LEP injection rate is reached with 4 bunches. This is sufficient for the moment and the originally foreseen but more complicated operation with 8 bunches has not yet been required.

The emphasis of this report is on the beam transport system between SPS and LEP including a brief description of the fast ejection system of the SPS and the LEP injection system[5]. Design concept, layout and the most important components are described. 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 $e^{\pm}$ beams are ejected in long straight section LSS6. The e^+ beam is ejected in the horizontal plane and follows the existing 450 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 within 1% which is adequate for transfer and injection into LEP. The current pulses are sinusoidal of an amplitude of 6 kA, the rise and fall times are 1.6 μs[6].

Two new tunnels are made to transfer the $e^{\pm}$ beams from LSS6 to the LEP injection points, situated symmetrically with respect to the intersection point P1 in the beginning of the regular arcs. For cost reasons it was interesting to reduce length an diameter of the tunnels. Since they descend towards LEP, the minimum length is limited by the maximum slope which is practical for installation and maintenance of the beam line equipment and the minimum diameter by the space required for the transport devices. This resulted in a tunnel length and slope for the e^+ beam (TI18) of 225 m and 15.5% and for the e^- beam (TI12) of 540 m and 10.3%; the tunnel diameter is 3.5 m. A schematic layout of the lines is shown in Fig. 1.

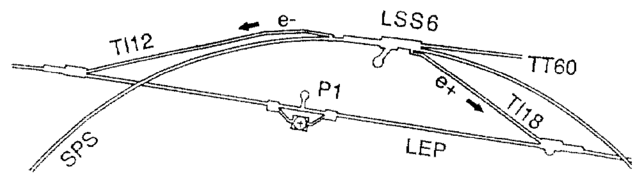

Fig. 1 - Schematic layout of SPS-LEP transfer lines

The geometry of the lines is dominated by lumped bends at given positions at both ends, mainly the bends on top of the SPS and LEP main rings which make the beam leave or join the respective machine tunnels and the main vertical bends, placed as far apart as possible, to reduce tunnel slopes. The sum of all horizontal and vertical deflections in both lines is about 100° requiring strong bending magnets. Wherever 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 ε_{xo} = .094 μm and ε_y = .019 μm at 20 GeV and to accommodate an energy spread of σE/E = .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_x 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 them tuned to a phase advance of 90 degrees[7],
- the matching section composed of 8 separately powered 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 : D_x = 7.8 m and D_y = 5.8 m and for TI18 : $D_x = 7.3$ 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 TI12 and 100 m in TI18) but suffer a blow up in the matching section which grows with increasing squeezing of β_x at injection (up to about 1 km in TI12 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-interceptive 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 1 : Results of measurements with beam in TI12 and TI18

Values for 20 GeV	TI12 Design/meas.	TI18 Design/meas.
Dispersion at coupler or SEM (m)	Hor. : 7.1 /6.9 Vert.: 3.9 /3.3	7.3 / 7.4 6.4 / 6.5
Emittance 1 σ (μm)	Hor. : .09 / .06 Vert.: .02 / .07	.09 / .06 .02 / .05
Energy spread (σ E/E)	: .06%/. 06%	.06%/ .05%
Momentum passband of monoenergetic beam	: .7 %/	.5 %/
Id of actual beam	: .5 %/> .2	.25%/ .2%

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 steel 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 led to the design shown in Fig. 2.

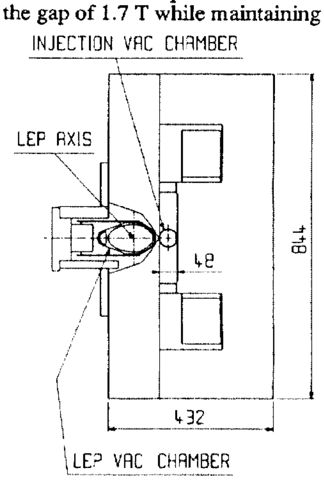

Fig. 2 - Cross section of Steel septum magnet

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[5]. 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 π orbit bump in the horizontal plane. The horizontally deflecting copper septum magnet is placed immediately downstream of the central kicker (Fig. 3).

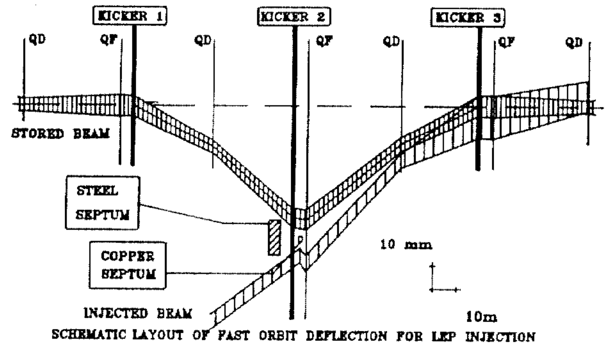

Fig. 3 - Layout of the LEP injection system

Kickers as well as the copper septum magnets are powered by pulses of about half sine shape. Rise and fall times are about 3 μs and 7 μs. The flat top time, measured between 99% amplitudes, is .5 μs. 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 μs. The actually chosen repetition time in the 4 bunches injection scheme is 467 μs.

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 $D_x = 2.2$ 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 defines 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_{max} which could be stored in this experiment, and the stacking efficiency η, defined as the ratio of stacking rate, plotted against the distance Δx_1 between the bumped orbit and the close-by edge of the septum where $\beta_x = 122$ m. The second scale Δx_2 gives the betatron amplitude of the centroid of the injected beam in LEP at $\beta_{xmax} = 136$ 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_{max} is vanishing when Δx_1 gets too small because the stored beam is scraping on the septum. With increasing Δx_1 I_{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 η is the monotonically decreasing with increasing Δx, 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 η is about 40% when I_{max} reaches the plateau. In order to have some margin, usually a larger value of Δx is selected for operation but such that η is around 30%, which is the nominal value[1].

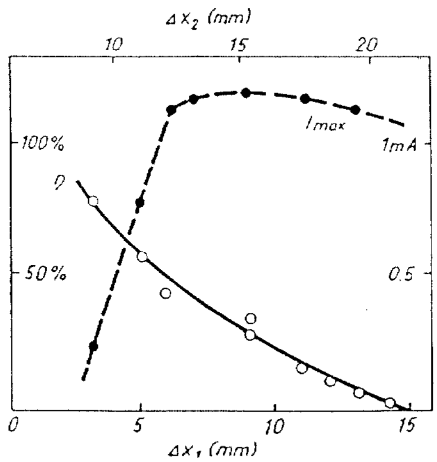

Fig. 4 - Stacking efficiency η and maximum stored current I_{max} versus distance Δx_1 of bumped orbit to septum or betatron amplitude Δx_2 of injected beam centroid at β_{max}.

If η vanishes, all particles are injected outside the dynamic aperture. The dynamic aperture based on this definition was deduced from our data and is plotted in Fig. 5 in terms of betatron amplitude at $\beta = 1$ m. Also shown are the results from particle tracking performed before the start-up of LEP that takes into account the systematic multipole errors in dipoles and arc quadrupoles as known before start-up. Including the possible range of the recently discovered additional multipole components in the dipoles produces results in the shaded area.

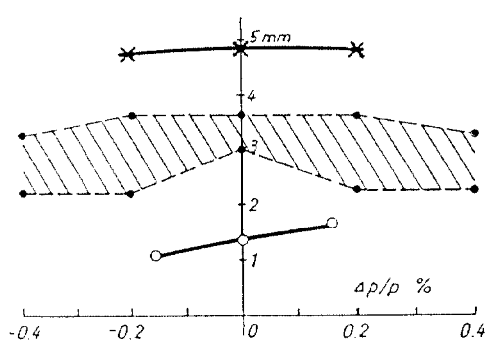

Fig. 5 - Horizontal dynamic aperture in terms of amplitude at $\beta = 1$ m plotted against initial amplitude of synchrotron oscillation; o measured values, x tracking before LEP start, shaded: tracking including all multipoles in the dipoles

Since the measured dynamic aperture is smaller than the expected one, a second experiment was performed. An electron beam of 80 μA 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 nm and an rms energy spread of 0.03% 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 ± 0.05 mm. Repeating the same experiment with a positron beam of 4 bunches gave 1.50 ± 0.04 mm with 200 μA stored and 1.54 ± 0.05 mm with 450 μA stored confirming the result obtained with the injected beam (see Fig. 5). Another test using the technique of continuous excitation of the beam confirmed also these values[11].

In the above mentioned expriments the LEP wigglers were off and the LEP optics was the nominal one[12]. One experiment was performed with the LEP "back-up" configuration having $\beta^*_y = 0.8$ m[13] in order to see the influence of the damping control wigglers on injection. Injecting only one batch of positrons per SPS supercycle the stacking efficiency η was measured. An increase in the horizontal damping decrement from 1.3 to 2.0 s^{-1} increased η from 19 to 33% though even with 1.3 s^{-1} eighteen damping times elapse between two injections into the same bucket. 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.

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