STATUS REPORT ON THE LEP PRE-INJECTOR (LPI) AND THE PROTON SYNCHROTRON (PS) AS A e^+e^- ACCELERATOR

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1. Summary

This report gives the performance of the linacs, the accumulation ring and the PS, in particular describing how the design goals for the LPI-PS chain are attained and even surpassed. The nominal linac performance has been reached for e^+ and e^-. The Electron Positron Accumulation ring (EPA) has a high accumulation efficiency (80% for e^-'s and 65% for e^+'s) and nominal intensities can be readily obtained; a maximum of 230 mA was achieved. Studies of vacuum and impedance effects show beam blow-up and instabilities at higher intensities. The beam transfer between EPA and PS is done with 90% efficiency. Acceleration and bunch shaping in the PS work as designed and e^+/e^- were already successfully ejected to the SPS at 3.5 GeV in fall 1987. Experience with the switching from e^+/e^- operation (done within 200 ms) in the LPI and in the PS is described briefly.

2. Description of the LPI

For acquiring a full picture of the LPI, the references mentioned in paper [1] can be consulted. The modifications made on the PS for e^+/e^- acceleration are given in reference [2]. To ease the reading of this paper a concise description of the LPI and the PS is presented.

The LEP injector chain consists of LPI, PS and SPS. During one super cycle, lasting 14.4 s, the PS and SPS will produce in sequence two e^+ followed by two e^- cycles (duration of each cycle 1.2 s). The production rate of LIL for e^+ is about five times lower than for e^-, and EPA accumulates e^+ during 10.8 s followed by an extraction of half of the accumulated intensity in two batches separated by 1.2 s. Two accumulation cycles of 1.2 s are used in EPA for the e^-. This mode of operation will result in that the beams in LEP will be built up simultaneously with a rate of 0.25 $mA.min^{-1}$ per beam.

The 200 MeV electron linac (LIL-V) consists of an electron gun, a standing-wave buncher and four travelling-wave S-band sections. The high current 200 MeV e^- beam, nominally 2.5 A in a 12 ns pulse and with a repetition frequency of 100 Hz, produces the e^+ in the converter target, just upstream of the 600 MeV linac (LIL-W). A low current 200 MeV e^- beam is used for further acceleration in LIL-W. The use of one gun for the e^+ and e^- production was successfully tried out last year, and this subject is discussed at some length in section 5. The four sections of LIL-V receive their r.f. power from one 35 MW klystron amplifier with LIPS (an energy storage configuration based on the SLAC-SLED arrangement). The twelve sections of LIL-W receive the r.f. power from four 35 MW klystrons of which two are with LIPS. The Electron Positron Accumulator (EPA) acts as a buffer between the fast cycling (100 Hz) but low intensity (6.10^8 e^+ per pulse) linacs and the slow cycling (0.8 Hz), high intensity (10^{11} $e\pm$ in 4 or 8 bunches) PS. It accumulates the linac pulses in betatron phase space in 1, 4 or 8 bunches at a fixed energy. The low frequency of the r.f. cavity (19.1 MHz, 50 kV) provides a long equilibrium bunch (σ_s = 21 cm). There are two identical injection systems for the two kinds of particles while a common extraction septum is used.

From the EPA (circumference 125.67 m equals one fifth of that of the PS) the bunches are extracted for a one turn injection in the PS. Acceleration to 3.5 GeV is made with two RF cavities (114 MHz, 500 kV per cavity). The damping partition numbers are controlled by Robinson wigglers to adjust the beam emittances.

3. Design goals and performances achieved

The required beam performance of the linac was derived by assuming transmission efficiencies based on data for operating electron machines and by taking into account the specified LEP filling rate. The e^-/e^+ conversion efficiency had been scaled from values attained at the linac at LAL and DESY. Table 1 gives the transmission efficiencies assumed in the LEP Design Report [3].

Table 1

Transmission efficiencies (%)		e^+ fill	e^- fill
Linac	Gun to exit of buncher	45	45
	Exit buncher to converter	90	90
	Conversion efficiency (e^+ current within $\Delta E/E \pm 1\%$ / e^- current)	0.48	-
EPA	Injection	30	30
	Transmission and ejection	90	90
PS	Injection	90	90
	Transmission, ejection and transfer	90	90
SPS	as PS		
LEP	Injection	30	30
Cumulative transmission		0.010	2.2

With the above assumptions on the transmission and conversion efficiencies it turned out that the required e^+ pulse current of the linac was 8 mA for a pulse length of 12 ns. Given the uncertainties in the estimations on the transmission efficiencies, it was decided to aim at 12 mA as LIL design current. As the e^-/e^+ converter system chosen follows the DESY design, it was clear that we could expect to attain the design current but not to surpass it. To create some reserve in the e^+ performance of the pre-injector, the aim was to achieve an as high as possible accumulation rate in the EPA. For a given e^+ pulse current from the LIL-W the parameters available are: the pulse length and the injection plus accumulation efficiency in EPA. The frequency of the EPA, 19.1 MHz, permits us to use pulse lengths up to 25 ns before losing appreciably due to longitudinal mismatch. The acceptance of EPA has been made large enough to accommodate all possible and unavoidable errors. To take into account possible mismatch, missteering, jitters, blow-up of the beam injected into the EPA and to allow for some clearance on both sides of the injection septum, a transverse beam emittance at injection of 10 π mm-mrad has been assumed, value to be compared with 4.8 π mm.mrad of the beam at the end of the linac. Furthermore, all factors which create closed orbit distorsions were considered and resulted in a computed distorsion of ± 10 mm horizontal and ± 6 mm in the vertical plane. Finally, for the case that one damping time elapses between two successive injections into the same bunch, the required betatron admittances of EPA at injection are 100 π mm.mrad and 10 π mm.mrad, respectively horizontally and vertically. The minimum vacuum chamber apertures were made to provide these admittances (100 mm horizontally, 38 mm vertically).

The measured injection plus accumulation efficiency for e^+ is about 60%, and for e^- 80%, thus well above the 30% assumed at the conceptual design. This enhancement is welcomed in so far as it has not been possible to produce an e^+ pulse current of 12 mA within ΔE/E ± 1%; the best figure reported is 9.5 mA.

4. Optimization of the e^+ pulse current by LIL-W

From the following table it appears that LIL-V produces an e^- beam on the converter with characteristics close to the design ones.

Table 2, LIL-V Performance

Design		Operation	
Pulse current, gun	6	6	A
Pulse current, buncher	2.8	3.3	A
Pulse current, 200 MeV	2.5	2.6	A
Pulse length, 200 MeV	12	10 - 25	ns
Pulse shape, 200 MeV, rise	3	3	ns
Beam spot on converter	< 2	2 - 3	mm
Hor.ver.emitt./π, 200 MeV	< 1.3	not meas.	mm.mrad
Energy, E	200	215	MeV
Energy spread, ΔE/E	< 10	≈ 10	%

By changing the phase of LIL-V in respect to the phase of the first sections of LIL-W, two phase settings, about 200° apart, are found for e^+ acceleration. The phase setting providing the highest e^+ pulse current corresponds to one giving initial deceleration in the first LIL-W section. For this case the best matching of the e^+ flux from the converter into the section happens with a relatively low pulsed current in the solenoid just downstream of the converter; 2.7 kA. With the phase accelerating the e^+ from the start in the first section, the e^+ pulse current increases with the current in the pulsed solenoid. However the slope of this increase does not predict that if running with the design current, 5.0 kA, (at present limited by hardware to 3.5 kA), the best e^+ current can be reached with the accelerating mode. This situation is puzzling and studies have been launched to obtain a better understanding of it.

Table 3, LIL-W Performance

Design		Operation	Remarks
End LIL-W			
e^+ pulse curr.	12	9.5 (best) mA	within ΔE/E ±1%
		14.3 (best) mA	unresolved
hor./vert. emitt./π	4.8	6.4 H.mm.mrad	measured at first
		4.9 V.mm.mrad	turn in EPA
energy E	600	500 MeV	

Concerning the energy used for operating LPI. We were confronted early in 1986 with a number of reliability problems on the modulator/klystron assemblies which were voltage related. In order not to perturb the commissioning too much we tried to run LPI at 500 MeV and to inject at this energy in the PS. This operating mode was successful and we remained with it awaiting a complete hardware upgrading to guarantee a reliable operation at 600 MeV.

5. One e^- gun for e^- and e^+ beams for the EPA

In the LEP Design of 1979 it was assumed to fill LEP at first with e^+ and then with e^- beams. Consequently, for the linac design one e^- gun was proposed with the idea that during the e^- fill the e^-'s pass through both linacs with klystrons suitably phased and the converter target removed.

In the final design, the LEP e^+ and e^- fills are made quasi-simultaneously and thus, a short time lapse to commute from the e^+ to the e^- acceleration in LIL-W had to be aimed for (0.15 s). Reviewing the consequences of such a fast switching in early 1982 led to the conclusion that an off-axis gun and a bunching system (4 MeV) should be inserted between the two linacs for supplying the e^-'s for acceleration in LIL-W. This e^- injection system was used all through 1986 for the commissioning of LIL-W, EPA and PS with e^-'s. During the e^+ running-in in 1987 we tried to find experimentally how many settings would need to be changed to commute from e^+ to e^- production by LIL. We were motivated in this search as, if successful, this would open the possibility of simplifying our future maintenance charges (one gun and injection system only). Furthermore, we did not find in the time available a solution for the beam steering in the first sections of LIL-W for the low energy e^- beam if running the solenoid focusing system on these sections at the high fields required for maximum admittance of the e^+ flux.

It turned out possible to find settings for producing alternatively e^+ and e^- beams with one gun; the gun of LIL-V. Keeping the focusing and steering settings of LIL-V constant and by modulating the e^- gun pulse current with the gun bias HV, the following typical beam transmissions are obtained:

Table 4, LIL-V Electron Transmission

	Output gun	Output buncher V	Output LIL-V ("200 MeV")
e^- cycle	320 mA	140 mA	110 mA
e^+ cycle	5.2 mA	2.8 A	2.2 A

So far focusing at the end of LIL-V is set to concentrate the e^- beam onto a small spot at the converter target. As this focusing system can not yet be changed from cycle to cycle, the e^- beam traversing the 5 Ø mm hole of the converter - moved onto the beam axis during e^- cycle - is not well matched to LIL-W. Nevertheless, the transmission of the e^- beam is acceptable.

Table 5, LIL-W Electron Transmission

LIL-W:	entrance, after first	two sections	at end (500 MeV)
e^- cycle	80 mA	70 mA	65 mA

The horizonal and vertical steering coils in LIL-W can be changed from e^+ to e^- cycle. In practise, it is sufficient to change the settings of only 5 coils. The energy of the e^- beam is roughly adjusted to 500 MeV in LIL-W by delayed triggering of one klystron - LIPS system (4 sections) so that it does not provide r.f. power during the beam passage. Fine tuning of the e^- and e^+ beam energies is done with the phases and LIPS timings which can be changed from cycle to cycle.

Parameters changed from e^+ to e^- cycle:

- Bias on triode gun to modulate e^- pulse current in LIL-V
- Two phase settings in LIL-W
- One timing of the LIPS-phase inversion in LIL-W
- One delayed triggering of a KLY-MOD in LIL-W
- Five steerings in LIL-W
- Converter from target to 5 Ø mm hole.

Settings are optimised for the e^+ beam as a good reserve is present for the e^- beam. This optimisation is a difficult process as the e^- flux is high as well during converter e^+ production. In fact, the lack of an e^+ separating system in the upstream part of LIL-W is the main problem during e^+ beam optimisation.

6. The EPA with e^+'s

As expected the tuning of the injection is more critical than with e^-'s. To obtain an injection plus accumulation efficiency above 30%, the vertical closed orbit with a distorsion of 9.4 ± 1.4 mm peak to peak had to be corrected. After correction, done by a vertical displacement of one quadrupole [4], the distorsion was reduced to 6.5 ± 1.4 mm. Finally, the injection plus accumulation efficiency became 65% but lower values (45%) are typical for routine operation. The transverse beam blow-up observed with e^-'s and attributed to ion effects appeared indeed to be absent with e^+'s [5].

The observation of the behaviour of the transverse modes as a function of the beam intensity was carried out for different values of both the chromaticity and r.f. voltage in a large intensity range [6]. No instabilities due to mode coupling were detected mainly thanks to the long bunch length (> 20 cm). From the transverse measurements the longitudinal impedance could be deduced. The $[Z_L/r]$ is equal to 21.1 Ω, value found with bunch length measurements as well.

Table 6, EPA performance with positrons

	Design	Obtained
Energy	600	500 MeV
Nb, the peak bunch intensity	$2.5.10^{10}$	7.10^{10}
The number of bunches	8	8
Accumulation rate, per bunch	$2.2.10^{9}$ s^{-1}	6.10^{9}
Inject. plus acc. efficiency	30	max. 65 %
Transfer efficiency to PS	80	90 %
Bunch length at r.f. 40 kV	25	30 cm
Hor. emittance/π	0.14	0.1 mm.mrad
Vert. emittance/π	0.03	0.04 mm.mrad

7. The PS with e^+ and e^-

The PS has injected, accelerated and extracted bot e^+ and e^- provided by EPA, within two consecutive 1.2 magnetic cycles, interleaved with other types of partic les to its users, as required by the nominal LEP fillin scheme.

The e^+/e^- beams are accelerated with a new 114 MH r.f system and the required bunch dimensions are ad justed by means of Robinson wigglers. After initia tests with 2 cavities, only one is currently used. A shown in the table below, the design beam character istics have been obtained and exceeded.

The pulsed mechanical short-circuits of the high 114 MHz cavity have proved to be reliable and necessar for beam stability during high intensity proton accel eration.

As a result of the change of the PS vacuum chambe and of the vacuum system upgrading, the initial specifi pressure rise has been reduced by roughly a factor 5 down to 5×10^{-9} mbar.

At 3.5 GeV the nominal transfer scheme to the SF has been put into operation. After synchronisation c the SPS r.f. frequency, 4 out of the 8 bunches are ex tracted waiting 46 + 3/4 revolutions between two bunc extractions . The remaining 4 bunches are extracted i the same way 30 ms later which is the time required fc SPS injection kicker reloading and PS-SPS resynchronis ation.

This double batch extraction works as expected fc both e^+/e^- beams and the ejection efficiencies are ap proaching 100%.

Table 7, PS performance with e^+ and e^-

	Design	Obtained
Nb of bunches	8	8
Nb of particles/bunch e^-	1	$5 \cdot 10^{10}$
Nb of particles/bunch e^+	1	$5 \cdot 10^{10}$
EPA/PS ejection + transfer + injection efficiency	80	90%
Harmonic number	240	240
Bunch length (1σ)	0.16	0.12-0.18 m
Bunch energy spread, ΔE/E	.1	.1%
Hor. emitt./π e^-	200	250 nm
Vert. emitt./π e^-	100	100 nm
PS/transfer line efficiency	95	98%

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