PROGRESS REPORT ON THE LEP PRE-INJECTOR

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Abstract

The LEP Pre-injector (LPI) provided very reliably positrons and electrons at 500 MeV for the LEP injector chain during the first LEP injection tests. Later, experiments were performed with the LEP Injector Linacs (LIL) to verify the influence of various parameters on the positron current and on the conversion efficiency. We also report experiments done with the Electron-Positron Accumulation ring (EPA) operating at 500 MeV concerning trapping, accumulation, and equilibrium beam parameters. Cutting of the 8 bunches by a thin electrostatic septum to produce two batches of 8 bunches was successfully tested. First runs with e^+ and e^- at 600 MeV showed that LPI behaves also at this energy as expected.

1. Introduction

The LEP Pre-Injector provided beam for three SPS cycles in the 14.4 s long SPS supercycle in July 1989 during the LEP injection tests[1]. The LEP injector chain operated in the interleaved mode during the fixed-target proton runs of the SPS as foreseen in the LEP Design Report. The positrons were accumulated during the SPS proton cycles in the 8 buckets of EPA. Four of the 8 bunches were ejected for the first SPS cycle; the remaining 4 were used for the second SPS cycle. Bunch cutting (see point 3.6) in EPA was not available but also not required as PS, SPS and LEP operated with only 4 bunches. Four electron bunches were used in the whole chain for the third SPS cycle. They were used for tests in the SPS. The number of e^+ and e^- per bunch was 2×10^{10}. A description of LPI and typical performance figures have been given at EPAC88[2] and, in more detail for LIL, at the last linac conference[3]. Here we report results of machine experiments done in the second half of 1988. Since not all LIL klystron modulators have yet been upgraded, nearly all experiments were performed at 500 MeV. First tests at the nominal energy of 600 MeV were however possible showing that LPI behaves as expected also at this energy. A specific experiment was set up to produce LIL pulses containing only one e- at 180 MeV for calibration of the BGO crystals which will be part of the electro-magnetic calorimeter of the LEP L3 experiment. The details of these runs where EPA was used as a spectrometer and for which a new ejected beam line had to be built, are given elsewhere[4].

2. LIL Experiments

Positrons are normally produced by an intense electron beam of 0.22 GeV hitting a tungsten target at the end of the first linac (LIL-V). They are accelerated by a second linac (LIL-W) to 500 MeV (nominal 600 MeV). In order to investigate the importance of the prebuncher parameters, the unresolved positron current was measured at 500 MeV as a function of prebuncher phase and electric field. Fig. 1 gives the e+ current obtained with the optimum phase versus the electric peak field. The current was low because LIL-W was not well adjusted. The energy gain is 40 keV for $\beta = 1$ particles in the prebuncher at E = 3 MV/m; the output pulse charge of the buncher was 40 nc in 20 ns; the gun voltage was 70 kV. Fig. 2 shows the output charge of the buncher versus electric field in the prebuncher according to earlier measurements[5] and calculations[5-6]. The phase in these cases is adjusted for maximum transmission from gun to buncher output in a rf phase bite of ± 5°, and the gun voltage was 80 kV. Comparison of Fig. 1 and 2 indicates a positive correlation between e+ output current and e- transmission through the buncher.

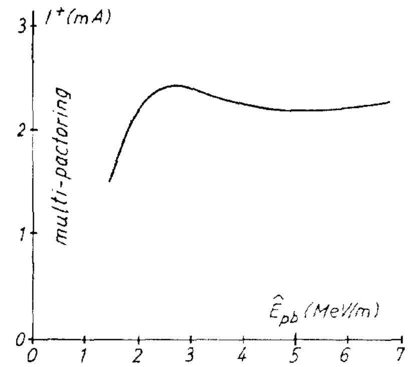

Fig. 1: Positron output current of LIL-W at 500 MeV versus the peak elec. field in the pre-buncher of LIL-V.

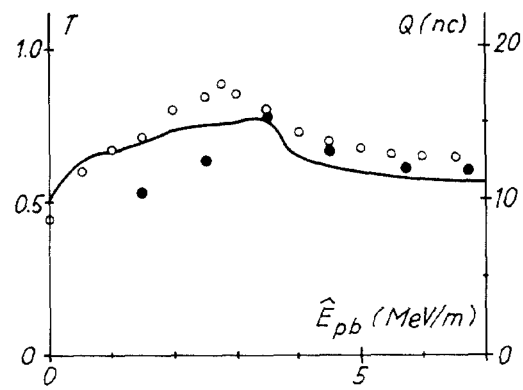

Fig. 2: Measured electron output charge of the buncher of LIL-V[5] (full line), simulations at LAL[5] (dots) and at CERN[6] (circles) of the e^- transmission between gun output and buncher output versus peak field in the pre-buncher.

LIL-V has 4 TW accelerating sections after the buncher, all powered from one klystron which is equipped with a SLED-type rf pulse compressor (LIPS). The beam energy was measured by a spectrometer at the end of LIL-V as a function of the klystron power. The energy gain per section averaged over 3 measurements and normalized to 1 MW klystron output power is 11 ± 0.5 MeV/$(MW)^{1/2}$, which agrees well with the calculated value of 11 MeV/$(MW)^{1/2}$ [7] corresponding to 66 MeV per section for a 4.5 μsec long klystron pulse of 35 MW. The experimental error is mainly due to the inaccuracy of the rf power measurement. The timing of the 180° phase jump of the klystron input and of the beam passage in the section was optimized for maximum energy gain in this experiment as was done in the calculation.

The conversion efficiency of e^- to e+ is one of the important figures of merit. Thus an effort was made to understand how a variety of parameters would affect it. All experiments were done with the relative phase of LIL-V and LIL-W such that the positrons are first decelerated in LIL-W, which gives a higher positron current than the phase relation where the positrons are accelerated immediately. No time was available to explore the second mode of phasing in detail.

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The target is followed by a short pulsed solenoid as in DESY (B_{1max}/I_1 = 3.3 x 10^{-4} T/A; $\int B_1.ds$ = 1.8 x 10^{-5} Tm/A; I_{1max} = 5.5 kA) for transverse matching of the e+ emerging from the target to the admittance of the downstream accelerating section. The first two sections are immersed in a longitudinal field (B_{2max} = 0.33 T) produced by solenoids. Measuring the resolved ($\Delta E/E=\pm$ 1%) e+ current versus the field B_1 with B_2 as parameter yields B_2 = 0.31 T (0.65 kA) as the optimum value. Using somewhat different fields (0.30 T, 0.32 T) in the two sections further improves the e+ current by about 10%. The e+ current saturates in both cases at B_1 =0.83 T (2.5 kA), which is plausible according to calculations based on a simple model of the matching ($\lambda/4$ transformer). With these parameters, the invariant transverse admittance of LIL-W is A/π=5.8 x 10^{-3} rad.m, and the model predicts that the matching device accepts e+ with 4 ± 0.5 MeV emerging within $r \leq 3$ mm, $\theta \leq 14°$ from the target. The measured primary beam spot is about 1 mm (FWHH). Taking this value as 2.4 σ of the primary beam and adding the widening by scattering (σ = 0.7 mm) gives a total secondary beam radius (2 σ) of about 1.6 mm. The radius of the tungsten target is 2.5 mm. Scanning the radial acceptance with a small beam and simultaneously measuring the e+ current verified the acceptance of $r \geq 2.5$ mm.

Fig. 3 shows the number of e+ in the LIL-W output pulse, unresolved and resolved ($\Delta E/E=\pm$ 1%), versus the number of e^- hitting the target (LIL-V output). The conversion efficiency is 0.43%, resp.0.31% (resolved); the latter is close to the nominal efficiency 0.32%. The zero-current e^- energy was 0.26 GeV in this experiment. Lowering this energy to 0.21 GeV did not change the efficiency significantly. The conversion efficiencies normalized to 1 GeV incident are 1.8% and 1.4% (resolved) at the nominal number of e+ per pulse (6.0 x 10^{-8}). The pulse length was 20 ns (total charge/peak current) with about 8 ns rise-time and 4 ns fall-time. The accelerating gradient in the 2 sections following the target is about 10 MV/m. It can be seen from Fig. 3 that the linac can produce 50% more e+ than nominal. The plot does not indicate any saturation. The e^- charge was limited in this experiment by a conservatively set interlock on the vacuum pressure in the converter box.

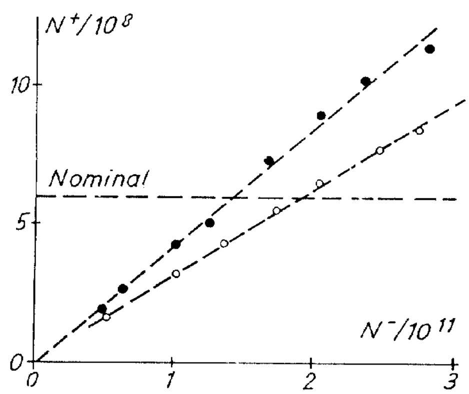

Fig. 3: Number of e^+ per LIL-W pulse at 500 MeV versus number of e^- hitting the target. Dots: unresolved e^+; circles: resolved e^+ ($\Delta E/E=\pm 1\%$); horizontal line: nominal number of e^+ per pulse.

3. EPA Experiments

The closed orbit at 500 MeV was remeasured after an error in the monitor electronics had been corrected. The peak to peak value is 12.5 mm in x and 5.8 mm in y; the rms distortion is 3.1 mm in x and 1.6 mm in y. EPA operated for the first time at 600 MeV. The closed orbit showed no significant deviation from the orbit at 500 MeV, and the machine tunes were within ± 0.5% of the predictions by the optics model[8]. The beam decay-rate $1/\tau$ depended linearly on the total number of circulating particles N according to $1/\tau = k_1 N + k_2$ as found earlier[9]. Table 1 gives the coefficients measured at end of 1988. The ion clearing system was on.

Table 1, Coefficients of beam decay rate

	Positrons		Electrons	
E(MeV)	k_1 (s^{-1})	k_2 (s^{-1})	k_1 (s^{-1})	k_2 (s^{-1})
500	4×10^{-16}	3×10^{-5}	9×10^{-16}	1×10^{-5}
600	9×10^{-16}	2×10^{-5}	1×10^{-15}	3×10^{-5}

It can be inferred from the table that the beam life time is more than one hour for the nominal N =2×10^{11}. Preliminary measurements at 500 and 600 MeV indicate that the e^- emittance still suffers the same amount of intensity-dependent blow-up by ions as before[9], though the voltage is now raised from 3 to 5kV also for the clearing electrodes installed in the elliptic vacuum chambers in the bending magnets. Given the large admittance of EPA and of the ejection channel, this blow-up is tolerable. Removal of ions by vertically exciting the beam with a single frequency close to the eigenfrequency of the ions in the beam was successfully tested[10].

In order to fight the longitudinal dipole (m=1) oscillations of the beam occurring with 8 bunches, setting in when the total number of particles exceeds 4×10^{11}, a preliminary version of a feed-back system having 3 channels has been tested at 500 MeV. Each channel can handle 2 of the coupled-bunch modes (n = 0,1..7). The beam was stable up to the highest number of particles which could be stored (7×10^{11}). The layout of the electronics follows the design proposed by F. Pedersen for NSLS/BNL. The final version is now being implemented.

3.1 Injection and accumulation

EPA has a separate injection system for e+ and e^-. The principle of injection is based on stacking in betatron phase space with more than one radiation damping time elapsing between two injections into the same bucket. The circulating beam is moved by a slow bump and a superimposed $\lambda/2$ fast bump close to the septum during injection of the beam pulse from LIL. The fast bump is switched on for less than 2 bucket-to-bucket distances (2 x 50 ns).

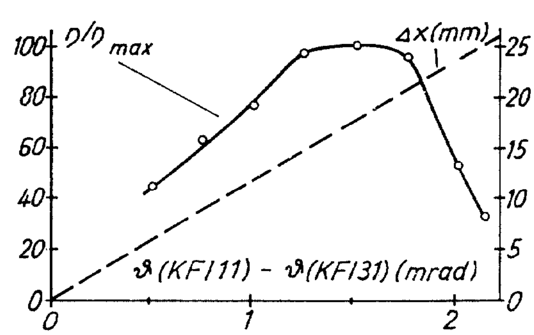

Fig. 4: Normalized accumulation efficiency of e^+ at 500 MeV (full line) and amplitude of the residual coherent oscillations of the stack at the septum (dashed line) versus the difference in the deflection of injection kickers.

With the present closed orbit and slow-bump it was noticed that the accumulation efficiency reaches a maximum when the two injection kickers have a different amplitude such that the stored beam makes a residual coherent betatron oscillation outside the fast bump with a phase shift of π relative to the injected beam. Fig. 4 shows the normalized accumulation efficiency and the residual amplitude of the stored beam versus the difference in kickstrength. If the difference is too big, particle loss from the stored beam occurs; if the difference is made smaller, the betatron amplitudes of the injected particles are increased and beam loss occurs because the injected beam having a large energy spread no longer fits into the dynamic aperture. However, if large currents have to be accumulated, the difference in kickstrength has to be reduced at the expense of the initial accumulation rate in order to avoid too early levelling off in the accumulation rate at high current. A typical value for the accumulation efficiency is 45% (65% peak).

The accumulation rate is not affected by the LIL pulse length because the longest possible pulse (25 ns) is still short compared to the bucket length (43 ns at 500 MeV). Furthermore, provided that LIL is well tuned, the LIL pulse has a fairly small energy spread $\Delta E/E$= 1.2% (FWHH) compared to the bucket height of $\pm$ 1.2% for the usual U_{rf} = 40 kV. A 25 ns long pulse must have an energy spread exceeding $\pm$ 0.8% before any losses are expected and, even then, only the corners of the distribution are lost.

The increase in circulating bunch current in EPA per LIL pulse was investigated for 1, 4, 8 bunches with LIL operating with repetition times T_r= 10, 40, 80 and 150 ms. Since the horizontal radiation damping times τ_x are 59 ms (500 MeV) and 34 ms (600 MeV), it was possible to investigate the efficiency of the accumulation process with ratios of T_{inj}/τ_x ranging from 0.17 to 4.4, where T_{inj} is the time elapsing between 2 injections into the same bucket. Obviously, T_{inj}= $k_b \times T_r$ with k_b the number of bunches. It turned out that positron accumulation requires a ratio of at least 1; ratios larger than 1 improve the accumulation only marginally. The e^- accumulation efficiency reaches a plateau already at a ratio of 0.7. Hence, operation with T_{inj}= 40 ms instead of 80 ms with 4 bunches is possible even at 500 MeV in order to double the accumulation rate. Since LIL can deliver more e^- than anyway required, this finding is of limited use for operation.

3.9. Bunch cutting

EPA accumulates 8 e+ bunches during the 11 s long proton cycle of the SPS in the SPS supercycle. In order to be able to provide 2 batches of 8 e+ bunches for the two consecutive e+ SPS cycles, EPA is equipped to cut each e+ bunch into two halves by means of an electro-static septum. One half of each bunch is immediately ejected for the first e+ batch, the other half stays in EPA and is with the other remaining half-bunches fast-ejected 1.2 s later to form the batch of the second e+ cycle. Although the synchrotrons in the LEP injector chain will start up with 4 bunches in 1989 implying that bunch cutting will initially not be required, it was nevertheless decided to test this procedure once. The results of these first tests conducted in fall 1988 are reported.

A fast kicker (KFE49, 50 ns at base) directs the individual bunches, horizontally enlarged by a beta-bump, onto an thin (0.06 mm) electro-static septum (SEH21) where the bunch gets cut into two halves (Fig.5). The part of the bunch which experiences the kick by the electric field of the septum passes off-axis through the downstream quadrupole QCB11 which generates together with QCB31 the beta bump. Here it receives the necessary kick so that it gets into the magnetic field of the ejection septum magnet. The rest of the bunch, passing through the quadrupoles on-axis, stays in the machine and its coherent oscillation is cancelled by a second fast kicker magnet (KFE51)[11]. Two slow closed orbit bumps (3 ms at the base) and a beta-bump (β_{max} $\leq$ 120m) are needed. The first slow bump (BSW32,91) moves the closed orbit towards the ejection septum (SMH00). The second one (BSW12,32) brings the c.o. near to the electro-static septum. Simultaneously with the bumps, the beam is enlarged by a factor 2 to 3 at SEH21 by means of the pair of pulsed quadrupoles (QCB11,31) placed π/2 upstream and downstream of SEH21.

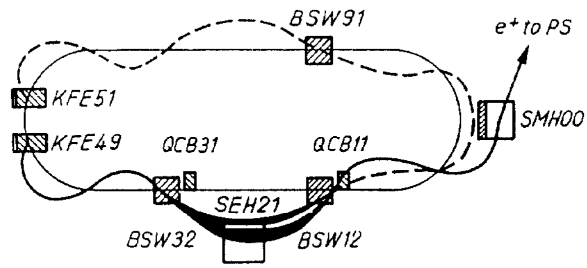

Fig. 5: Schematic beam trajectories in the horizontal plane during bunch cutting in EPA

After a very careful adjustment of the kicker amplitudes and kicker timing, any ejection ratio (beam intensity ejected/beam kept) could be chosen by varying only the slow bump at SEH21. An ejection ratio of 50 $\pm$ 3% per bunch could be obtained with all 8 (half-) bunches ejected and spaced by 262 ns, corresponding to equidistant spacing in the PS. When the kick w.r.t. the passage of the bunch was well centred in time, the ejection showed good short and long time stability. More details will be given in a forthcoming publication.

5. References

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4. Acknowledgements

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