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INJECTOR FOR L E P

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Summary

Two alternative 15 GeV injectors have been considered for the 15 to 100 GeV, four-bunch version of the e^+e^- storage ring LEP[1]: i) a synchrotron operating with four bunches and cycling at a rate of 0.4 Hz, and ii) a storage ring (SR) which is capable of holding the full charge of one LEP beam in 48 bunches. The e^+ are slowly accumulated in the SR during running of LEP for high-energy physics experiments, i.e. prior to LEP's refill. The synchrotron system is designed to provide a ∿15 min filling time of LEP; the SR would reduce it to ∿5 min for a scheduled fill. The design considerations are outlined and the merits of the two systems are discussed.

1. Requirements

The choice of the injection energy for LEP is the result of a compromise. Higher injection energies are preferred, as these would minimize remanent field effects and provide stronger magnetic fields for the distributed ion pumps. The beams are also more stable at higher energies. However, cost and complexity of the injector favours a low energy. Consideration of all these factors leads to the choice of 15 GeV for the nominal energy of the injector.

The average luminosity of LEP is an important parameter for physics experimentation. It is lower than the peak luminosity due to the finite lifetime of the beam and the filling time, but can be maximized by proper choice of the time between successive refills. Figure 1 shows the result for LEP indicating that a filling time of about 15 min is desirable in order to provide adequate average luminosity. The optimum physics running time is 1.5 h at 70 GeV.

Given the relatively high bunch charge in LEP and the difficulties in handling high beam intensities at low energy, one cannot envisage an injector which would provide all four complete LEP bunches per pulse or even only one bunch.

The final bunch will be made up of many injector bunches, which in turn are the result of an accumulation process at lower energy. Since the bunches are added in betatron phase space to those already stored, the total acceptance of LEP together with the equilibrium emittance of the stored beam define an upper limit to the emittance of the beam accepted from the injector. The maximum energy spread accepted by LEP imposes a further constraint on the injector.

2. Injectors

Given the requirements, various injection schemes can be examined, all involving i) a large circular machine (the cost of a 15 GeV linac is prohibitive); ii) charge accumulation at low and at high energy by adding the new beam to the stored one in betatron phase space and by subsequent compression through radiation damping. Two solutions are retained for closer scrutiny:

i) A 15 GeV electron synchrotron accelerating only a fraction of LEP's charge but cycling many times. In order to limit its repetition rate, the bunch charge should be fairly high. This is achieved by collecting and storing many pulses from a small linac operating with a higher repetition rate than the synchrotron. A small accumulation ring[2,3] acts as a buffer between linac and synchrotron, so that the latter may cycle slowly. Accumulator and synchrotron operate with the same number of bunches as LEP, which makes beam transfer between the three machines straightforward and very fast.

ii) A storage ring[4] of 15 GeV which accumulates all the particles of one kind at low energy and accelerates them slowly to LEP injection energy. The accumulation proceeds in two steps: collection of the total charge in many bunches at low energy in the storage ring itself, and combination into four bunches during injection into LEP. Operating with many bunches avoids high bunch charges, and the storage ring offers a large number of collecting buckets so that its injector can run at a high repetition rate. The pre-injector consists of a linac and a small synchrotron. The bunches of the storage ring are combined in LEP by injecting them sequentially into the four collecting buckets of LEP.

Both solutions have their merits and shortcomings. In order to explore the influence of a particular choice on LEP performance and cost, it was decided to study both systems in more detail.

2.1 Injection system with a 15 GeV synchrotron

Positron generation, which is the bottleneck during LEP fills, determines the layout and the parameters of the pre-injector which consists of an S-band linac feeding the small accumulation ring (ACR). The system is designed to provide a positron filling time of about 10 min for LEP. Every 20 ms the linac produces a train of four 6A electron pulses, each 6 ns long to match the bucket length in ACR. After conversion to positrons and acceleration in the positron linac, these four pulses are put into one of the four collecting buckets of ACR by multi-turn injection. The next pulse train is placed into another bucket and so on. Thus, the damping rate required in ACR is only a fraction of the average pulsing rate of the gun and, consequently, the energy of ACR and of the positron linac can be low. During the electron fill, the electrons pass through both linacs, with two sections passive and the converter removed; they are accumulated in the same manner as the positrons. The ACR is a separated function machine with its circumference determined by the minimum risetime of the kickers which have to act on individual bunches for injection and ejection. Table I gives the main parameters of the front-end machines which are described elsewhere in detail[5].

The 15 GeV synchrotron (ISY) has fourfold symmetry: two RF stations and two straight sections for beam transfer are foreseen as shown in Fig. 2. The effective length of the RF and the bending radius in the dipole magnets are the result of a cost and performance optimization. The exact circumference of the machine is determined by the requirements of bunch transfer to

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Table I. Pre-injector to 15 GeV Synchrotron

Energy of electron linac (loaded)	140 (133)	MeV
Energy of positron linac	460	MeV
Repetition rate of linacs	50	Hz
Resolved positron peak current	5	mA
ACR Circumference	81.35	m
Number of bunches	4	
Bending radius	1.27	m
Transverse damping time	80	ms
RF	58.97	MHz
Max. number of particles	$4 \cdot 10^{11}$	

LEP. A separated function lattice is chosen with uniform betatron focussing around the whole ring. The RF equipment (24 five-cell cavities, six klystrons rated at 1 MW) is the same as in LEP. The vacuum chamber is made of corrugated steel with a wall thickness of 0.4 mm to reduce eddy current effects during initial acceleration. The repetition rate of ISY is given by the rate at which ACR has to be emptied to avoid beam instability. Since electrons can be produced much faster, it is the required e^- filling time of LEP which determines the repetition rate. Choosing 1 min for the LEP e^- fill, a reasonable cycling rate of 0.4 s^{-1} is obtained. Table II gives the key parameters.

Table II. Parameters of 15 GeV Synchrotron (ISY)

Circumference	1057.52	m
Betatron tune	14.2	
Hor. damping time	2.4	ms
Bending radius	90.4	m
Max. circulating current	18	mA
Number of bunches	4	
RF	354	MHz
Peak RF voltage	65.1	MV
Effective length of RF	51	m
Repetition rate	0.4	s^{-1}

2.2 Injection system with a 15 GeV storage ring

The approximate circumference of the storage ring should be about 1300 m to minimize construction cost, but there are other factors which determine the exact size. In order to shorten the accumulation time it is advantageous to have as many collecting buckets as possible. However, sufficient space must be left between these buckets to accommodate the kicker risetimes, which limits the bunch number to about 50. Choosing 48 bunches and the same RF frequency for SRI as for LEP implies that the circumference can only be one of a few discrete values. Adopting a circumference corresponding to 48×35 RF wavelengths meets all these requirements and ensures correct bunch synchronism with LEP for transfer. The overall layout is shown in Fig. 3. Four straight sections with zero dispersion provide space for two RF stations and for the beam transfer equipment in the separated function lattice. In order to reduce cost, as many of the LEP components as possible are used, e.g. the dipole will be a single 6 m LEP dipole magnet with a different coil, and the quadrupoles have the same yoke shape as the LEP quadrupoles. The standard RF equipment of LEP is used; each RF station houses ten five-cell cavities and five klystrons (1 MW each). The extruded Al vacuum chamber is the same as in LEP. Table III gives the main parameters of SRI.

The injection energy (2 GeV) of SRI is determined by the stability requirements of the intense bunches. A booster synchrotron (BSY) is proposed to bridge the gap between a low-energy positron linac and SRI. Limiting the repetition rate of BSY to 12.5 Hz avoids the complications of a fast cycling machine.

Table III. Parameters of the 15 GeV Injector Storage Ring (SRI)

Circumference	1410.89	m
Betatron tune	17.8	
Hor. damping time	3.8	ms
Bending radius	119.84	m
Circulating current	170	mA
Number of bunches	48	
RF	357	MHz
Peak RF voltage	55.3	MV
Effective length of RF	42	m
Acceleration time	1	min

Injection into BSY uses four gun pulses per linac pulse, each gun pulse going into a separate bucket of BSY (no multiturn possible because injected beam too big). In order to let the linac refill between successive gun pulses, the spacing between these pulses corresponds to three bunch spacings (294 ns) in BSY which operates with four bunches. The natural damping time (1.6 s) of SRI at 2 GeV is shortened to 0.48 s by 16 wiggler magnets so that SRI can accept four bunches every 80 ms with good efficiency. The storage ring will usually be filled with e^+ while LEP is running, so the positron filling time of SRI is not relevant except when starting up or for unscheduled fills after loss of beam. If it is assumed rather arbitrarily that the SRI has to be filled in 20 min with positrons, a 200 MeV e^- linac is required. The energy of the positron linac is determined by the acceptance of BSY at injection. Table IV summarizes the main parameters of the injection system.

Table IV. Pre-injector to 15 GeV Storage Ring

Energy of electron linac (loaded)	220 (200)	MeV
Energy of positron linac	100	MeV
Repetition rate of linacs	12.5	Hz
Resolved positron peak current	9	mA
BSY Nominal energy	2	GeV
Circumference	117.57	m
RF	51	MHz
Number of bunches	4	
Max. number of particles	$1.4 \cdot 10^{10}$	

3. Filling Procedure of LEP

Positron filling is performed first in both injector versions; the more critical setting up for the e^+ fill being done when LEP is still running for physics. The filling cycle starts with the dumping of the high-energy beams in LEP. Within the next minute the LEP magnets are taken through the appropriate cycle and the low-β insertions are detuned to reduce the machine sensitivity during injection and acceleration. In the synchrotron version, the injector then provides the positrons in 240 cycles. After setting up the linacs for electrons in about 1 min, the synchrotron accelerates 30 pulses of electrons. Assuming one minute for acceleration to high energy in LEP and for retuning of the low-β sections, LEP is ready again for physics experiments after about 14 min. In the storage ring version, all the positrons required for LEP are accumulated prior to the dumping of the beams in LEP and they are accelerated to 15 GeV during the time required to adjust the magnets in LEP to 15 GeV. The positrons are then transferred within a few seconds. After resetting of SRI to 2 GeV, the electrons are accumulated, accelerated and sent to LEP. The whole e^- fill is estimated to last 4 min. Adding 2 min for the manipulations in LEP gives in total a 6-min interruption of the experiments.

In both systems, ISY and SRI, e^+ and e^- will circulate in opposite directions in all machines. While this doubles all the low-energy transfer equipment, it reduces the switching time from e^+ to e^- operation. Beam transfer at 15 GeV has two channels anyway, the two injection points in LEP being symmetric to an interaction point.

4. Conclusions

Inspection of Table V, which gives the minimum filling times, shows that the storage ring injector (SRI) offers a filling time close to the time required for setting up LEP itself for the refill. The filling time with a synchrotron (ISY) is about three times as long but is still very short compared to the beam lifetime (≥ 5 h). For an unscheduled fill, e.g. in the case of beam loss, the filling time becomes rather long with SRI. The ISY system is cheaper by about 15% because the beam intensity in the synchrotron is much lower than in the storage ring. Consequently, the synchrotron can have a smaller radius and a less powerful RF system; also the vacuum system is simpler. However, this drawback for SRI may be offset by the higher average luminosity provided by SRI (cf. table V). Neither ISY nor SRI provides polarized beams for reasons of economy. At the moment, the synchrotron version is favoured because it is operationally much more flexible and convenient. The beam intensity is lower and the setting up of LEP injection is easier since test pulses of normal intensity are readily available in quick succession.

Table V. Summary of Filling Time (min)

	ISY	SRI
Production time for e^+/e^-	10/1	19/2
Dwell time of LEP at 15 GeV	12	4(23)*
LEP not available for physics	14	6(25)*
Average over peak luminosity at 70 GeV	0.73	0.81(0.66)*

* unscheduled fill

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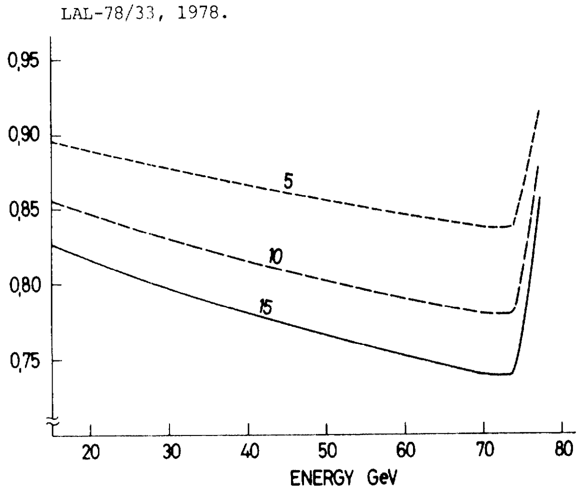

Fig. 1. Maximum ratio of average to peak luminosity. Parameter is total filling time in min.

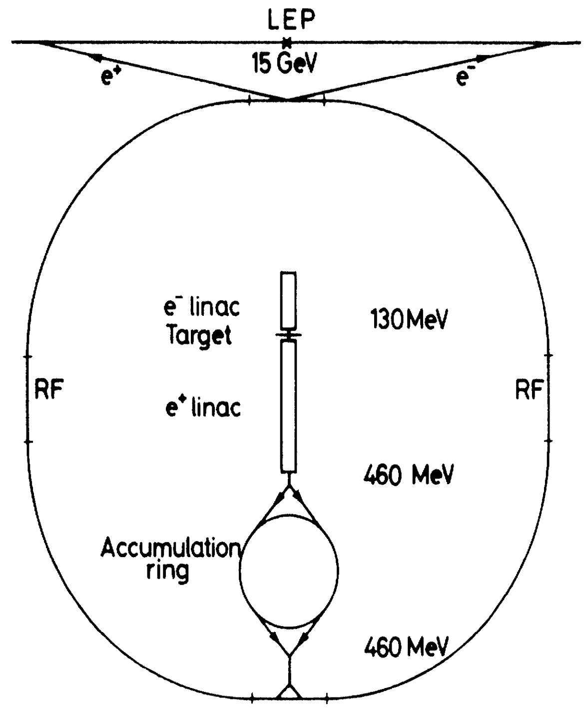

Fig. 2. Schematic layout of the injector with a 15 GeV synchrotron.

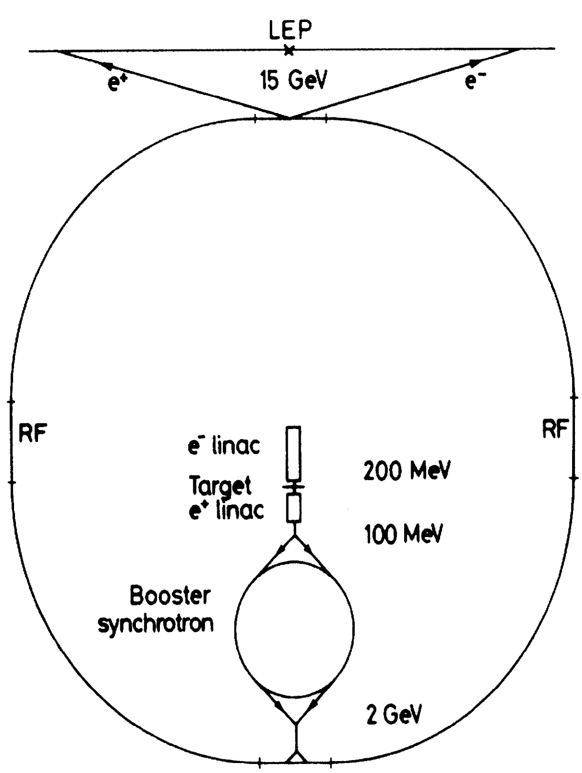

Fig. 3. Schematic layout of the injector with a 15 GeV storage ring.