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DESIGN STUDY OF A LARGE ELECTRON-POSITRON COLLIDING BEAM MACHINE - LEP

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1. Introduction and Summary

Early in 1976 a study group at CERN began to examine design concepts[1] for a Large Electron-Positron storage ring, LEP. At that time, 50 km circumference and 100 GeV per beam - to be obtained with a conventional radio frequency system - were chosen. This first study was terminated[2] with several problems still unsolved, including extreme sensitivity of orbit stability to closed-orbit tolerances, operation in collision mode with electrostatically separated beams and technical difficulties due to the low magnetic field at injection. In addition, the estimated cost was considered high. A fresh start was made in the second half of 1977. In order to explore the variation of difficulties and cost with machine size and in an attempt to arrive at a solid base for an entirely feasible machine, it was decided to reduce the nominal energy to 70 GeV while retaining the target for maximum luminosity at $10^{32}cm^{-2}s^{-1}$. The optimum radius for this design - later confirmed by the outcome of the study - is 3.5 km. This phase of the study ended in August 1978 with the issuing of a detailed Design Report[3] including a cost estimate. The conclusions are that such a machine is not only feasible but that it can be developed to reach 100 GeV per beam when suitable superconducting cavities become available. In fact, the design is made such that this extension of energy requires no major change other than the substitution of cavities.

Meanwhile the design study continues. Following strong encouragement by ECFA, the European Committee on Future Accelerators, a somewhat larger machine composed however of similar building blocks to those described in the Design Report[3], is being studied. Tentative parameters of this new version - called "Version 8" - are described below. In addition, further reductions of cost are being sought by detailed improvements and the application of novel solutions to some components.

2. Main Parameters of LEP Version 8

A nominal energy of about 85 GeV at $10^{32}cm^{-2}s^{-1}$ maximum luminosity is to be obtained with copper cavities but the design of at least the magnet system and the vacuum system should permit extension to 130 GeV by means of superconducting cavities. The optimum value of circumference is about 30 km. The exact value has been chosen so as to permit ep collisions[4] in a bypass to the CERN SPS[5], respecting the different radio frequencies and bunch numbers in the SPS and in LEP. Of the eight interaction regions foreseen four are designed for a nominal luminosity of $10^{32}cm^{-2}s^{-1}$ with a free space of ±5 m. Detailed studies have shown that this is adequate for most foreseeable experiments. However, the other four interaction regions are designed for ±10 m free space, albeit at half luminosity. A study of the tolerance problems with electrostatic (or RF) beam separation at unwanted crossings made us decide that such crossings should be avoided by limiting the number of bunches to four, in spite of the high resulting bunch charge. Table 1 gives some general machine parameters.

Table 1. LEP Version 8 at 85 GeV

Machine circumference		30.608 km
Number of interaction points		8
Number of bunches		4
Circulating current per beam		8.3 mA
Maximum luminosity	10^{32}	$0.5\times10^{32}cm^{-2}s^{-1}$
Beam-beam tune shift	0.06	0.06
Horizontal ampl. function at crossing β^*_H	1.6	3.2 m
Vertical ampl. function at crossing β^*_V	0.1	0.2 m
Free space around crossing points	±5	±10 m
Transverse damping time		13.3 ms
Horizontal betatron wave number		72.3
Vertical betatron wave number		76.2
Length of regular cell		79 m
Beam-beam bremsstrahlung lifetime		7.3 h

3. General Layout, Services and Experimental Areas

The design is based on a site near CERN. The layout of Version 8 is similar to the one shown in the Design Report[3], except that the LEP ring encompasses the SPS. A bypass[5] bridging SPS straight sections 5 and 6 would permit ep collisions in one of the LEP interaction areas. The machine is situated underground. The main tunnel will be bored by methods similar to the ones used for the SPS tunnel, and it will have the same width, viz. 4 m. Slightly enlarged tunnel sections may be required for the RF cavities, situated at either side of the interaction areas, and separate lengths of tunnel, starting from the experimental halls and running parallel to the main tunnel for about 250 m, will house the RF power sources. In order not to disturb the surface outside the immediate vicinity of the eight experimental areas, it is planned to feed the input power, the primary cooling water and all controls connections through the main accelerator tunnel. Power will be distributed at 60 kV level, most of the main transformers being placed outdoors near the access points to the experimental areas. For the main control[6] links optical fibre transmission is being studied.

The eight experimental areas are also underground. In Version 8 (and in contrast to the smaller machine of the Design Report[3]) three areas are situated in the flank of a mountain and will be accessible via individual, roughly horizontal access tunnels. The LEP ring will be tilted in such a way that at least two areas come close to, and can be excavated from, the surface. The remaining ones will be accessible via vertical shafts; Fig. 1 shows a possible layout, that has been studied in great detail[3]. The two latter types of underground experimental area will be similar to the two colliding-beam halls now being constructed for the $p\bar{p}$ project at the CERN SPS.

4. Lattice

Figure 2 shows the lattice in the neighbourhood of a maximum-luminosity point. The sensitivity to closed orbit distortions - apparent from PETROS[7] computer runs - still makes tunable insertions[3,8] a necessity. These permit injection at three times the nominal value of β*, followed by orbit corrections and a gradual reduction - with circulating beam - of β* to its final value. The dispersion suppressor shown is

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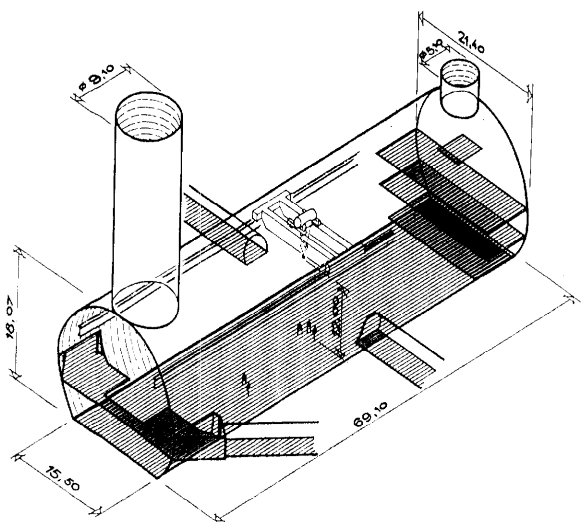

Fig. 1. Layout of underground experimental hall (dimensions in metres).

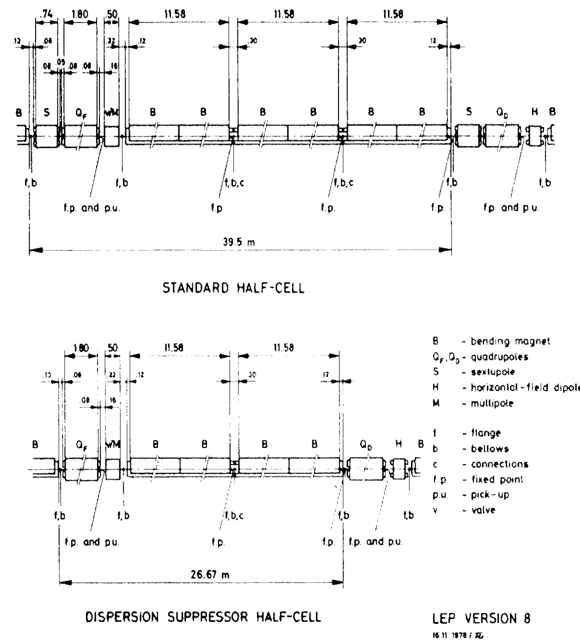

Fig. 3. Detailed lattice layout in regular arc and in dispersion suppressor (dimensions in metres).

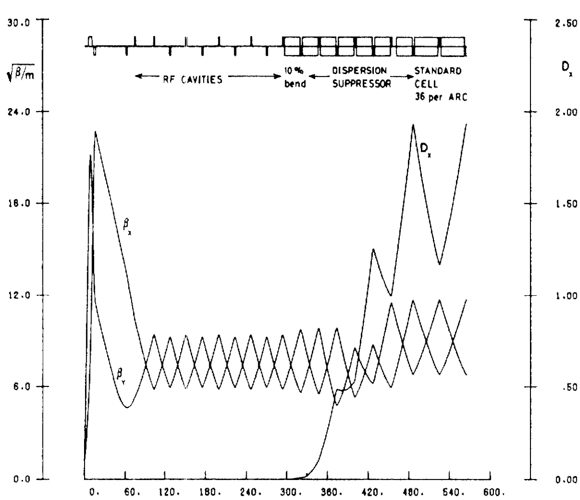

Fig. 2. Lattice layout and orbit functions near high-luminosity interaction point (horizontal scale in metres).

new. It incorporates full bending strength and it lends itself to variable tune, as required for extending the top energy to 130 GeV. The length of the lattice cells in the dispersion-free sections has been tailored to the appropriate multiple of an RF wavelength, so as to accommodate a group of eight cavities between adjacent quadrupoles without wastage of length. The regular arcs are made of a standard separate-function FODO lattice. It so happens that the length of a lattice cell increases with increasing machine size, so that the total number of cells is the same in Version 8 as in the smaller machine[3]. As the size of individual quadrupoles, sextupoles and orbit corrections does not change much either, this means approximately constant total cost for these components in spite of increasing machine size. The detailed layout of a standard lattice cell and of a dispersion-suppressor cell is shown in Fig. 3. Essentially the same building blocks are used for both cells.

To extend the energy above 85 GeV the focussing will be increased and the coupling adjusted so as to remain at constant luminosity. For colliding beams below 80 GeV wiggler magnets will be used to keep constant emittance. This yields a luminosity proportional to energy squared. The option is open to achieve the same with variable optics and hence with reduced energy spread in the beam. Once LEP is run in it might be possible to gain space for increased emittance and hence luminosity at lower energies by decreasing the allowance for closed-orbit distortions. Ultimately one may run at constant current, yielding a luminosity decreasing only linearly with energy. It is, however, unlikely that this regime can be stretched down to injection energy.

5. Magnet System

Designs for all components of the magnet system were prepared for the Design Report[3]. In Version 8 the dipole field is 0.080 T at 85 GeV and 0.123 T at 130 GeV. Contrary to the first proposal[1,2] it is now foreseen that the dipole will be built as a C-magnet (Fig. 4) in which magnetic precision depends solely on precise stamping of steel laminations. The length of a magnet core has been limited to about 6 m for reasons of mechanical rigidity. However, the low field required permits excitation by simple aluminium-bar conductors instead of the usual multiturn coils. Hence, several cores can be placed end-to-end with little or no space lost, and excited by one set of bars. A regular half-cell of Version 8 contains six dipole cores arranged in this way (Fig. 3). All dipoles of the LEP ring can be connected in series. They consume 9.2 MW of power at 85 GeV.

Recently, the development of a novel method[9] for fabricating these low-field dipole magnets has been started. While the laminations are being stamped, spacers are stamped out simultaneously (Fig. 4). After the laminations are stacked on a jig and tied together by tie rods the resulting filling factor with steel is about one third, which is more than adequate

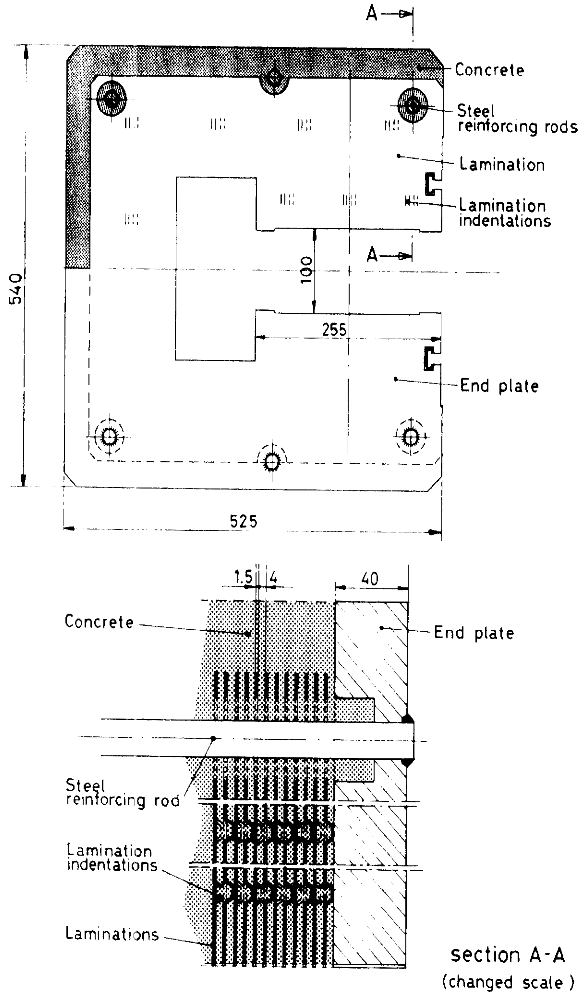

Fig. 4. Concrete-filled dipole magnet (dimensions in millimetres).

for the peak field required. Then, the stack is put into a suitable mould and all empty spaces are cast with low-shrinkage concrete. As the price of concrete is negligible compared to that of stamped steel laminations, a considerable saving results. An additional advantage of these "concrete magnets" will be their mechanical rigidity, achieved without welded-on strips or stiffening plates, and their reduced weight. So far, a model of one-half cross-sectional scale and 60 cm length has been successfully built (Fig. 5).

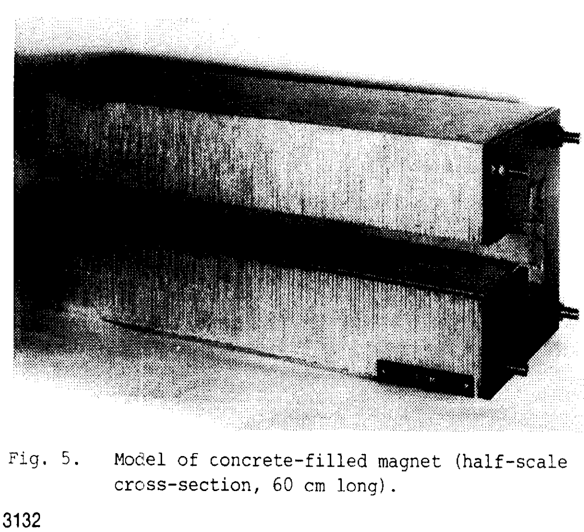

Fig. 5. Model of concrete-filled magnet (half-scale cross-section, 60 cm long).

A full-size model will be built in a few months' time.

The strength of the lattice quadrupoles is entirely governed by 130 GeV operation, requiring an increase from 4.0 T/m gradient at 85 GeV to at least 10 T/m at 130 GeV. Figure 3 shows the magnetic lengths of these elements. Anodized aluminium bands will be tried for their excitation coils.

All insertion quadrupoles can be of conventional copper-steel construction[3], but the strongest ones then become rather massive, typically 5 m long and 1.1 m wide. Clearly, these quadrupoles are candidates for superconducting magnets, to be designed in conjunction with the physics experiment and following the experience now being gained with a superconducting high-luminosity insertion in the ISR[10]. A study has shown that the solenoidal field which often forms a vital part of the experiment can be compensated by skew quadrupoles outside the central region of the insertion[3].

6. Vacuum System

The linear density of synchrotron radiation hitting the dipole chamber is 1.1 kW/m at 85 GeV and 3.9 kW/m at 130 GeV. The critical energies are 320 keV and 1.4 MeV respectively. We propose a water-cooled chamber made from extruded aluminium and containing distributed sputter ion pumps immersed in the dipole field, as pioneered by SPEAR[11] and elaborated by PETRA[12]. However, LEP poses several new problems.

Considerable thickness of lead shielding is required to prevent an excessive fraction of the radiated power from penetrating into the tunnel air, where corrosive and toxic chemicals would be generated in intolerable doses. The lead - 8 mm thick at the sides of the chamber - will be bonded to the aluminium to obviate the need for additional cooling and to avoid the formation of acids in an interstice. Plasma spray has been tried for applying the lead to the chamber. Another method is a continuous process of melting and extrusion through a cooled orifice. For operation above 85 GeV and at full current additional lead shields will have to be installed.

Compton scattering distributes roughly half the radiated power into parts of the chamber, where it finds only indirect cooling. For operation above 85 GeV at full luminosity, three extruded cooling channels - one at the location of first incidence of radiation and two at the opposite side of the chamber - will be used to avoid excessive transverse thermal gradients and concomitant stress. Even so, the chamber has to be clamped to the magnet at roughly 1 m intervals to avoid deformation.

The pole width of the dipole magnet, determined by requirements of field uniformity inside the beam aperture, can accommodate pump cells of 50 mm diameter. These distributed pumps will ignite just below the field strength corresponding to 20 GeV injection. It is planned to use a strip-line technique for the 22 km of distributed pumps required[13]. Large and small pump cells, for different field levels, will be interlaced but, due to the high percentage of large pump cells, the pumping speed remains relatively low at higher fields. Therefore, in situ bake-out to about 150°C and in situ glow-discharge cleaning is necessary. The magnet aperture shown in Fig. 4 includes space for heat-insulation and for the lead shield. The electrical bake-out heaters will be applied to the inner side of the chamber.

7. RF System

Table 2 summarizes the most relevant RF parameters.

Table 2. RF Parameters of LEP Version 8 at 85 GeV

Synchrotron energy loss per turn		1.3	GeV
Synchrotron power (2 beams)		22	MW
Frequency		353.4	MHz
Peak RF voltage per turn	V_{RF}	1.77	G V
RF bucket height	σ_b	7.6×10^{-3}	
Stable phase (from zero crossing)		120^0	
Number of phase oscillations per turn	Q_s	0.132	
Length of active RF structure		1.629	km
Fundamental mode structure dissipation	P_d	57	MW
Higher mode energy loss per turn		235	MeV
Power loss to higher modes (2 beams)		4.9	MW
Waveguide losses		7.2	MW
Total RF generator power		96	MW

The frequency has been chosen near the economic optimum, taking into account the variation of shunt impedance (including the influence of beam aperture), of structure fabrication cost and of the cost for power sources. The chosen frequency is, however, close to the maximum permitted by beam dynamics. The resulting short and dense bunches lead to appreciable higher-mode losses (roughly two-thirds of these occur in the RF structure), a low threshold for turbulent bunch lengthening and large space-charge tune shifts. Also the value of Q_s, related to problems of synchro-betatron coupling resonances, is very high. The addition of a third harmonic to the RF to alleviate these problems is seriously considered[3]. The concentration of the circulating charge in only four bunches - required to avoid unwanted crossings - leads to appreciable but tolerable transient beam loading[14], characterized by about 40% extraction of the energy stored in the cavities by the passage of a pair of e^+e^- bunches (Fig. 7).

The RF structure will be divided into 16 equal stations, located at either side of each crossing, where advantage can be taken of the absence of dispersion and of the infrastructure and access required there anyhow. At the present time klystrons are considered the most advantageous power sources. It is planned to install 96 klystrons - six per station - of 1 MW each and to branch out power to the cavities via a chain of hybrid dividers.

For the accelerating structure, the now customary five-cell, slot-coupled, π-mode cavities[15,16] are proposed. The cavities will be made of copper. Their detailed shape (optimized for the given beam aperture) and construction will closely resemble the PETRA[17] cavities. There will be 768 such cavities, i.e. 48 per station, eight per klystron. Taken alone, these cavities would yield only 80.5 GeV nominal energy at the RF power assumed. A calculated factor of about 1.5 in effective Q-factor and a consequent extension to 85 GeV can be gained by the addition of storage cavities[18]. The method consists of coupling a low-loss, H_{onm}-mode storage resonator to the accelerating cavity and of exciting the coupled system with both its resonant frequencies, so that the stored energy oscillates between the two resonators, spending on average half the time in the low-loss environment. The coupling is adjusted to make every second peak of the accelerating field coincide with the passage of a pair of (e^+e^-) bunches. Computations have shown that one common storage resonator is sufficient for each five-cell accelerating cavity. Figure 6 shows a conceptual design, employing a spherical storage resonator (H_{011} mode in cylindrical

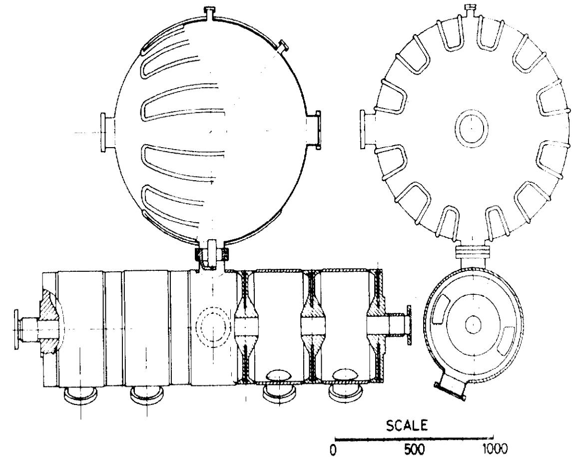

Fig. 6. Conceptual design of RF cavity with spherical storage cavity (scale in millimetres).

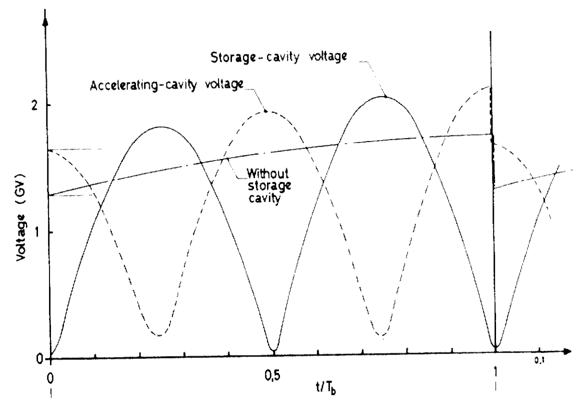

Fig. 7. Modulation of RF voltages in cavity, with and without storage cavity (computed). Horizontal axis is time normalized to bunch interval.

co-ordinates) formed from copper sheets. A feeding arrangement has been devised which permits the use of 1 MW CW klystrons in pairs, each pair driven by frequencies that differ by the bunch repetition frequency. The resulting modulation of RF fields, including beam loading, is shown in Fig. 7. Model tests of this storage method are in progress.

8. Superconducting RF, LEP Construction in Stages

The storage-cavity method described above is a first attempt to reduce cavity dissipation in a large ring containing only a few bunches. Modulation or pulsing with a smaller duty-cycle might become possible. The most radical progress could, however, be made with super-conducting cavities. So far, application of RF superconductivity to a storage ring project - let alone a project as large as LEP - has been prevented by a series of problems which are not likely to be overcome rapidly. Active development is, however, going on both in Europe and in the USA and the long-term prospects look very promising. LEP seems ideal for a gradual introduction of the new technology. In Version 8 a generous reserve of RF space (equivalent to 128 additional copper cavities) is foreseen, where prototype superconducting structures can be tested. Afterwards, copper cavities can be replaced by superconducting ones to extend the machine energy. If the superconducting structure worked at the same frequency, the klystrons and much of the waveguide feed system could be maintained. Replacing all copper cavities by superconducting ones and converting the entire installed RF power to beam power would lead to a maximum energy of 130 GeV at full luminosity. The corresponding gradient in the superconducting structure is 5 MV/m.

On the other hand, funding restrictions may well require that even the 85 GeV nominal energy be reached in several stages and the physics situation appears to favour such an approach. For instance, one sixth of the RF system described above would yield well over 50 GeV per beam and one third would yield just over 60 GeV. Initially only eight RF stations (with one pair or two pairs of klystrons per station) would be built and four of the eight interaction areas could remain unequipped. A decision could then be taken in the light of both physics results and technological development whether to go on installing copper cavities or to go to the superconducting option at once.

9. Injection System

There are two basic problems with the LEP injector[19].

Firstly, as the size and cost of the injector tend to increase with the square of its energy, this energy has to be chosen at the very lowest safe value. The criteria are difficulties with collective beam phenomena in LEP - e.g. space-charge tune shifts and instability thresholds[20] - in the first place and the magnetic field for the main ring distributed vacuum pumps[13] in the second. In the Design Report[3] 15 GeV was proposed and generally agreed to be a lower limit for 20 km main-ring circumference. For the larger Version 8 about 20 GeV appears to be a minimum.

Secondly, regular refills of LEP have to be fast, because of the short beam-life due to beam-beam bremsstrahlung. In fact, this lifetime simply equals $N/(\sigma_{bb}L_{tot})$ where σ_{bb} is the cross-section of the process, L_{tot} the sum of all luminosities, and N, the number of particles in the machine, is kept as small as possible because of beam power. If a ratio of average luminosity over the peak value of 75% is to be maintained during regular operation, LEP has to be refilled, and the new beam accelerated, in no more than 15 minutes every 1½ hours.

In the Design Report[3] two types of injector were presented. One is a synchrotron of 2.5 s cycle time containing four bunches like LEP but only a small fraction of the LEP charge per cycle. Hence, LEP is being filled by repetitive injection, the whole process taking about 10 minutes. The other type is a slowly accelerating storage ring containing the entire LEP charge of one polarity, albeit distributed in many bunches. This charge is then transferred to LEP in one rapid operation. At present, the synchrotron scheme tends to be preferred.

The preinjectors[21] include linear accelerators for electrons and positrons, a positron accumulation ring and - at least in the case of the storage ring injector - a small, fast-cycling booster-synchrotron.

10. Conclusions

A design[3] of considerable detail has been worked out for an e^+e^- colliding beam machine of 20 km circumference. Details of a similar design now being prepared for a 30 km machine are presented here. Much work remains to be done, but no unsurmountable technical problems have been encountered so far.

It is true that the prediction of a peak luminosity of $10^{32}cm^{-2}s^{-1}$ is based on a few basic assumptions (in particular the attainment of a maximum beam-beam tune shift of 0.06 per crossing in a machine with many crossings) which are derived from results obtained with much smaller machines. This may have to be revised in the light of results from PETRA, CESR and PEP. Quite generally, the experience now being gained with PETRA and soon to be gained with CESR and PEP will be extremely important for the LEP project.

Acknowledgement

This paper sums up the work of a Study Group based at CERN but including wide outside-CERN participation. The Study Report[3] contains a list of contributors which was valid at that time as well as a list of informal LEP-notes available on request. More such notes have appeared since and continue to appear.

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