THE CERN LEP PROJECT

by

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1. **Introduction**

A Large Electron Positron project has been discussed by the European High Energy physics community in general \(^1\) and at CERN in particular \(^2\) since 1976. The European Committee for Future Accelerators (ECFA) has organized a number of studies on the physics programme which could be carried out with an electron-positron collider with beam energy around 100 GeV and, in parallel, feasibility and design studies \(^3,4,5\) have been carried out at CERN with the collaboration of a number of other European Laboratories.

The LEP project has now reached a rather advanced stage and was officially presented to the CERN member states at their June meeting of this year.

This report outlines the reasons why the European High Energy Physics community has chosen to construct LEP, the general features of the machine with emphasis on the latest developments, a brief review of the experimentation which has been discussed in the various studies and finally the status and timescale of the project as at July 1980.

2. **General Physics**

This section will be rather brief as the reasons are very similar to those given for the choice of topic for this year's Summer Institute. Recent progress in the unification of the Weak and Electromagnetic interactions and the emergence of the Gauge Theories has made it extremely important to test these theories in the energy region where the interaction strengths become comparable. In the energy range up to 200 GeV, the standard Weinberg-Salam model \(^6\) predicts the existence of both the neutral \((Z^0)\) and charged \((W^\pm)\) bosons which are needed to damp the rising Weak cross section.

The presence of the \(Z^0\) pole will have a particularly spectacular effect as illustrated by the ratio \(R\) of the total to the point like cross-section, shown in figure 1. At present energies, as measured at
PETRA, R has a value of $\sim 4$ but will rise to over 4300 at the $Z^0$ mass value of 92 GeV in the Weinberg-Salam model with $\sin^2\theta_W = 0.23$. With the same parameters, the charged boson $W^\pm$ is expected to have a mass of 81 GeV \(^7\).

However, since the large machine under discussion will take several years to build, it is anticipated that the existence of these particles will have already been established by experiments at the $p\bar{p}$ collider \(^8\) at present under construction at CERN. The role of LEP will therefore be to carry out the detailed studies needed to verify or disprove the theories, detailed measurements which it will be impossible to make at the $p\bar{p}$ collider because of the "hadronic background".

An important question, to which there is no precise answer in the Gauge Theories, is how many quark-lepton families are there in nature?

$$
\begin{bmatrix}
v_e \\
v_\mu \\
v_\tau \\
u \\
\nu_3 \\
\nu_1 \\
\nu_2 \\
\nu_4 \\
s
\end{bmatrix}
\begin{bmatrix}
u_e \\
u_\mu \\
u_\tau \\
u \\
\nu_3 \\
\nu_1 \\
\nu_2 \\
\nu_4 \\
s
\end{bmatrix}
\begin{bmatrix}
(\nu_e) \\
(\nu_\mu) \\
(\nu_\tau) \\
(\nu) \\
(\nu_3) \\
(\nu_1) \\
(\nu_2) \\
(\nu_4) \\
s
\end{bmatrix}
\begin{bmatrix}
? \\
? \\
? \\
? \\
? \\
? \\
? \\
? \\
?
\end{bmatrix}
$$

Experimental evidence exists for five quarks but so far the expected sixth or top quark has not been seen at PETRA and PEP and it is conceivable that LEP will be the first machine to observe the "toponium" states due to this quark. Further, complete families cannot be excluded and may well exist within the energy range up to 200 GeV in the centre of mass.

Another particle which is required by the theory in some form or other is the Higgs boson needed to induce symmetry breaking and generate the mass spectrum of the known quarks and leptons. Although it probably has a mass too high to be directly produced in a 200 GeV machine, it cannot be excluded that effects due to its existence could be observed.

These major predictions \(^6\), which must all be verified in as detailed a manner as possible in order to constrain the theories, have set the energy scales for LEP, with a centre of mass energy of 100 GeV one studies the $Z^0$, with 180 GeV, one studies $W$ pair production and the maximum possible beam energy, is required for the Higgs Boson or Bosons.

These considerations have prompted the study of three different machines since 1976. The first was a feasibility study for a 50 km circumference machine with a beam energy of 100 GeV obtained with conven-
tional room temperature RF cavities. This machine was extremely expensive and had a number of unsolved technical problems. The next had a circumference of 22 km and a beam energy of 70 GeV and was very successful from the machine point of view. It became the basis for the present design for a circumference of 30 km with a beam energy approaching 90 GeV with room-temperature RF cavities and the possibility to reach 130 GeV if superconducting cavities become technically feasible. The design report for this machine was published last year and, in what follows, emphasis will be placed on developments since that report.


The present LEP machine whose main parameters are given in Table I, has been optimized for a beam energy around 90 GeV and a luminosity of $10^{32}$ cm$^{-2}$sec$^{-1}$ to be obtained with room temperature RF cavities, this results in a circumference of 30.6 km. Physics experiments will be possible at eight interaction points of which half will have the design luminosity and a free space between low beta quadrupoles of $\pm 5$ m, while the rest will have half the luminosity but a larger free space for experiments, $\pm 10$ m.

The desirability of installing the enormous RF system in stages, with a view to the use of superconducting cavities as soon as they become available, has been considered from the start. Recently, this staged installation has been coupled with arguments to start physics as soon as possible with a minimum machine capable of studying the $Z^0$ with only four equipped interaction regions. This minimum machine has been called phase I and corresponds to the installation of 1/6th of the RF as shown in Table II. Further stages corresponding to 1/3rd and the complete 96 MW of RF are also shown. The final column corresponds to the performance when all the room temperature cavities have been replaced with superconducting cavities with 5 MV/m field gradients such that all the 96 MW is available for beam power.

The luminosity performance of the machine over its complete energy range is summarized in figure 2 where it can be seen that it is hoped to be able to limit the fall-off with energy $E$ below the design maximum to be not faster than $E^2$ by the use of wigglers to maintain the optimum
beam size. A possible improvement in luminosity, at low energy, when maximum use is made of the machine aperture after correction of the orbit, is also indicated.

The whole machine, including experimental areas, will be constructed underground according to the layout of figure 3.

The tunnel is tangential to the CERN SPS and slightly below it so that it will be possible to inject protons from the SPS into a possible future proton ring (1 TeV per Tesla) in the LEP tunnel and also to allow e⁻ p collisions at one interaction point, by constructing an SPS by-pass. A third overriding reason for this location results from a recent decision to use the existing PS and SPS complex as part of the electron-positron injector for LEP.

The ringed numbers on figure 3 show the positions of test drillings which have already been made to determine the depth of the molass rock which the tunnel will be cut in, as for the CERN SPS, by means of full face boring machines. The part under the Jura mountains will be in limestone and the dotted line indicates the trajectory of a reconnaissance tunnel which will be started shortly to obtain, as early as possible, information for this less well understood part of the tunneling programme. Approximately one-third of the tunnel will pass through limestone including interaction points 3, 4 and 5.

The cross section of the 4 m diameter standard tunnel is shown in figure 4. The details of this layout have been carefully studied to allow maximum space for installation in view of the 4 km between access points. Space has been reserved for a future proton machine as already mentioned and for the helium gas lines which will be needed for the superconducting RF cavities.

The underground experimental halls are proposed to be of similar design to that now under construction for the SPS collider at LSS4, but are somewhat longer as shown in figure 5. Access to halls 1, 2, 6, 7 and 8 will be by vertical shafts between 45 and 90 metres deep while halls 3, 4 and 5 which are deep under the Jura, will be reached by a combination of vertical shafts and nearly horizontal tunnels.

The magnet structure of LEP is a separated function FODO lattice with a cell length which has been made as long as possible on the argument that focussing elements are more expensive than dipoles. This is particularly true as it is intended to use an unconventional construction method for the dipoles which will halve the price. The field in the C shaped dipoles is only 0.123 T at 130 GeV and the return
yoke of a conventional magnet would be far from saturated. A technique
has been developed whereby conventional stamped laminations are given
raised points in a number of places so that when stacked on
prestressing rods the 1.5 mm thick laminations are spaced 4.1 mm
apart. These spaces are then filled with concrete so that an extremely
stable mechanical structure is obtained (figure 6). Two such full size
dipoles 10 have already been built, tested and measured both
mechanically and magnetically. Similar magnets built by industry will
be delivered shortly.

Six of these magnet cores needed between each pair of quadrupoles,
will be energised by two water cooled aluminium bars in place of
conventional coils. The bars are situated above and below the median
plane so that their insulation, consisting of clamp-on extruded plastic
shells, will not be damaged by synchrotron radiation. Similar return
conductors on the front of the magnets will compensate the stray
magnetic field.

The cores of the quadrupoles and multipoles are of more
conventional design but, for the coils, it is proposed to use anodised
aluminium strip with water cooling on the outside. The quadrupoles and
sextupoles have been designed to allow a beam energy up to 130 GeV.

The LEP vacuum chamber will be an aluminium extrusion with a
linear ion pump, using the main magnetic field, similar to that of
other electron machines 11) (figure 7). A special problem at LEP
results from the higher critical energy of the synchrotron radiation
\( \varepsilon_c = 400 \text{ KeV at } 86 \text{ GeV and } \varepsilon_c = 1.4 \text{ MeV at } 130 \text{ GeV} \). Cooling of the
chamber will require three water channels to avoid buckling due to
uneven heating by the synchrotron radiation. A lead shield, as
indicated in figure 7, will also be needed which will be applied by
pressing preformed lead strips onto the chamber at temperatures just
below the melting point of the lead.

The quantities of ozone and corrosive substances like nitric acid
which will be produced by radiation escaping from this lead shield have
been estimated 12) and are well below the acceptable limits. The
production of neutrons in the vacuum chamber structure has also been
estimated 13) and found to reach \( 10^9 \) neutrons/metre of bend/sec at
130 GeV. This neutron production starts just above a beam energy of 60
GeV due to the process \( \gamma + d \rightarrow n + p \) on the naturally occurring
deuterium in the cooling water of the vacuum chamber. This level of
neutron production will not be serious for the machine but at high
energy a neutron shield will probably be needed at the end of the RF straight section to prevent background problems in the experimental areas.

The distributed ion pumps have also required a special development. They will be constructed in one metre lengths from five stainless steel strips with 5 cm diameter holes punched out to form the pump cells when the strips are assembled between titanium cathodes. The large diameter pump cells are needed to maintain adequate pumping in the low dipole field at injection.

The RF system of LEP has to make up for an energy loss of 1.37 GeV per turn at a beam energy of 86 GeV, making a total synchrotron power loss of 25 MW. The frequency of 353 MHz has been chosen for economic and beam dynamical reasons. It is proposed to use 768 five-cell cavities fed by 96 1 MW klystrons. Each five-cell cavity will be coupled to a low loss spherical storage cavity \(^{14}\), as shown in figure 8. The stored RF energy then oscillates between the coupled systems spending on average half its time in the low loss environment of the storage cavity. This method decreases the power dissipation in the cavities by a factor of 1.5 allowing a higher beam energy to be reached for a given total power. The coupling of the cavities must of course be adjusted to ensure proper synchronisation with the bunch passage. The principle of operation has already been tested at low power and a 500 MHz storage cavity has been built to enable high power tests with an existing five cell cavity and klystron to start shortly.

Work on developing suitable superconducting cavities has started at both Karlsruhe and CERN. A single cell cavity constructed at Karlsruhe \(^{15}\) will soon be installed in the storage ring DORIS at DESY while at CERN \(^{16}\) accelerating fields of 4.6 MV/m have already been achieved in a single cell axial coupled model cavity.

A recent development in the machine project has been the adoption of a scheme \(^{17}\) using the CERN PS and SPS as injectors for LEP. The electrons and positrons would still be produced in a 600 MeV Linac and accumulated in a small DC accumulator ring \(^{18}\). These two machines are being designed by the Linear Accelerator Laboratory at Orsay. Electrons or positrons from the accumulator ring which will have 1/7th the circumference of the PS, will be injected into the PS in opposite directions and accelerated to 3.5 GeV (figure 9). The positrons will be extracted from the PS and injected into the SPS via the existing proton transfer line for acceleration to 22 GeV. The electrons will pass via
the transfer line TT70 at present under construction for the antiproton project.

The effect of the synchrotron radiation on the machine components of the PS and SPS has been estimated \(^{19}\) and found to be acceptable with the addition of a small amount of lead shielding at specific points.

The filling of LEP via transfer lines from the SPS which have not yet been fully designed, will be possible with almost no interference with normal proton operation of the SPS. The filling times will be ten minutes for electrons and ten minutes for positrons when using a filling mode with electron pulses interleaved with proton pulses. A dedicated electron filling could be achieved in two minutes but no shortening of the positron filling would be possible, as this will be limited by the production rate.

3. **Experimentation at LEP**

There has been a wide study of the anticipated experimental programme at LEP with the active participation of a large fraction of the European High Energy Physics community. This paper cannot possibly review all the detailed work in the various study reports \(^{1,20,21,22}\) but will merely pick out a few examples to illustrate the preparations which have already been made for an exciting LEP physics programme and to demonstrate the feasibility of experiments assuming little or no development of existing particle detection techniques.

Of prime importance at any accelerator is the event rate. Figure 10 shows the total number of \(e^+e^-\) annihilation events per day as a function of energy, assuming the design luminosity. In the standard model with three quark-lepton families, one can expect nearly \(10^5\) events/day at the \(Z^0\) pole. If the \(Z^0\) is absent, the rate will be no more than a few hundred per day. The high rate at the \(Z^0\) pole will make many experiments relatively easy. The "data" points in the imaginary measurement \(^{23}\) of the forward-backward charge asymmetry \(A_{\mu}\) in the process

\[
e^+e^- \rightarrow \mu^+\mu^-
\]

shown in figure 11, represent 100 hours of running at each energy

\[
A_{\mu} = \frac{\text{Forward-Backward}}{\text{Forward+Backward}} \quad \text{and at the } Z^0 \text{ pole } A_{\mu} = \left| \frac{V}{a} \right|
\]
This experiment which is a measure of the axial and vector couplings, should be performed for all the fermions. As can be seen in figure 11, the data points close to the pole have very small error bars and precise measurements should be possible.

The charge ambiguity between the axial and vector couplings in this experiment could be resolved by measuring the helicity of the produced fermion which in the case of $\mu \pi$ would require a 30 m long polarimeter according to an early study \(^1\)). However, in the case of $e^+e^- \rightarrow \tau^+\tau^-$, there is not expected to be any great problem \(^2\), the $\tau$ lepton's helicity being measured via the momentum distribution of its decay products

$$\tau \rightarrow e^- \nu_e \bar{\nu}_e$$

or

$$\tau \rightarrow \pi^- \nu_\tau$$

The $\tau$ leptons will be produced with a high $\gamma(\sim 25)$ at the $Z^0$ peak and the decay products will be almost collinear with the parent $\tau$.

As already mentioned in the introduction, a search for new quarks will be of great interest at LEP and the methods which could be used have been extensively studied \(^24\)). At low energy, the structures in $R$ (figure 12) are extremely clear, the charm quark was first detected through the narrow $\psi$ states ($J/\psi$) preceding the step in $R$. At higher energies, such narrow states are expected to be considerably smaller and will not be easy to identify with a beam energy spread of $1.2 \times 10^{-3}$. Even with a smaller energy spread, very narrow peaks will be "washed-out" by radiative effects \(^25\)) as illustrated below. On the other hand, steps in $R$ should be easier to measure precisely because of the higher multiplicity, the sphericity method used successfully at PETRA will also be possible if a good hadron jet detector is available.

Radiation by the incident $e^+$ and $e^-$ will have extremely important effects at LEP as shown in figure 13 where the radiative effects on the $Z^0$ peak are shown. According to this calculation \(^23\)\(^26\)), 80 % of the raw events at a centre of mass energy of 140 GeV are in fact $Z^0$ production.

The detection and detailed identification of hadron jets will be of prime importance at LEP in view of the production of quark-antiquark pairs $e^+e^- \rightarrow q\bar{q}$ where the final state is only hadronic jets. At higher energies, the detection of $W^+W^-$ pair production will also require a good jet detector. The $W$ pair cross section in the standard
model is shown in figure 14 where it can be seen that it reaches 1.8 x 10^{-35} \text{ cm}^{-2} \text{ at 180 GeV (design energy with 96 MW of RF)}. At a luminosity of 10^{32} \text{ cm}^{-2} \text{s}^{-1}, this gives 150 W pairs/day but with a branching ratio to hadrons expected to be around 0.8, the W pair events will yield:

- 100 "4 hadron jet" events/day
- 50 "2 jets + 1 lepton" events/day
- 5 "2 lepton" events/day

For these reasons, possible jet detectors have been extensively studied by the various working groups. The "hadronisation" of the quarks has been assumed to follow the Feynman-Feld model and the resulting hadron jets have been used in Monte-Carlo studies \(^{27}\) of the behaviour of various detector configurations. This approach allows a careful analysis of the detector requirements in terms of granularity and energy resolution.

A proposed jet detector \(^{24}\) is illustrated in figure 15 and is of a rather standard design. It is based on a solenoidal field of 1.5 T with an inner track chamber of 1.8 m radius of \(\sim 6000\) wires using Argon gas at 4 atmospheres. Such a detector would allow 100 samplings of \(dE/dx\) along a 1.25 m track to obtain good \(e/\pi\) and \(\pi/K\) separation over a wide momentum range (up to \(\sim 50\) GeV/c) \(^{28}\). An electromagnetic shower detector is placed immediately inside the magnet coil while the return yoke outside is adapted as a hadron calorimeter. An outer muon detector completes the system. The outer dimensions of this detector system are about 10 m x 10 m x 10 m and this has been used as the approximate size of experiments for the design of the experimental halls. Such a detector will fit very comfortably into the 21.4 m diameter cylindrical halls with space for transport above and around the detector. With a hall length of 60 m transverse to the beam, there will be plenty of room for electronics and cryogenic trailers.

Such a large detector would occupy the entire space between the low-\(\theta\) quadrupoles in a short insertion as shown in figure 15 where the quadrupoles are slightly inside the outer detector dimensions. For this type of installation so-called "slim" insertion quadrupoles have been designed \(^{5,29}\) based on the superconducting magnets which will be installed at the ISR this summer. Provided the proper coordination of designs is carried out, this inclusion of quadrupoles into the detector should be perfectly possible and might even be taken further. A reduction of the free space between the quadrupoles should allow an increase in luminosity. In figure 15, it can be seen that there is no provision for compensation of the detector solenoid between the
insertion quadrupoles. This will be done by means of skew quadrupoles in the adjacent straight sections.

Tagging of the forward electrons from two-photon processes, will be very important at LEP since the two-photon cross section is increasing with energy while the QED annihilation goes as $1/E^2$. At a centre of mass energy of 100 GeV

$$\frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}} \sim 3 \times 10^{-4}$$

The two-photon process is expected to be a rich field of physics at LEP but, for other experiments, it will be considered a background and for this reason studies \(^{30, 31}\) have been made of tagging efficiencies for various detector and insertion quadrupole configurations, including tagging behind the quadrupole. As an example, the tagging efficiencies which could be obtained behind three different quadrupoles are shown in figure 16. The slim quadrupole is not suited to this application but allows much better tagging around the magnet at angles in the range 55 - 300 mrad. With detectors in front of the quadrupole, angles down to 20 mrad or maybe even smaller can be reached depending on the diameter of the vacuum chamber.

In addition to event rate and suitability of detectors, it is necessary to consider backgrounds which may make experiments difficult or even impossible. As is well known, an important source of background at electron machines is the synchrotron radiation from the machine magnets. In the case of LEP, the radiation from the dipoles has a higher energy than in present machines. However, the machine layout with a 300 m straight section upstream of the crossing point will allow plenty of possibilities \(^4\) for collimators to mask the detectors; in addition, the last dipole will have a lower bending power (≈ 10 %) hence reducing the critical energy of the radiation which could reach the interaction region vacuum chamber. Much more important will be the radiation produced by the very powerful low-$\theta$ quadrupoles. The radiation from the last quadrupole has a critical energy of 0.25 MeV. Fortunately, it is produced in a reasonably small forward cone and, with a carefully designed vacuum chamber, will pass right through the interaction region. The bulk of this radiation will strike the machine vacuum chamber at distances greater than 50 m from the crossing point but even so the backscattered radiation will have to be taken into consideration when designing the interaction region vacuum chamber.
and radiation masks. The fraction of direct radiation intercepted by the vacuum chamber on the opposite side of the crossing region is shown in figure 17 as a function of the half-aperture.

Calculations\textsuperscript{30,33} have also been made of the rate of off-momentum beam particles which will be created by beam-gas bremsstrahlung in the RF straight section and final few bending magnets and which could be swept out of the vacuum chamber into detectors by the low-\(\bar{\Omega}\) quadrupoles. This rate is a linear function of the residual gas pressure, the most important region being around the last bending magnets, a special effort will be needed to keep the gas pressure as low as possible at this point. It has been found that an inner radial collimator placed approximately 75 m before the interaction region effectively intercepts the higher energy part of this background. The approximate energy spectra of off-momentum particles are shown in figure 18 where it can be seen that the total rate in the crossing region itself is no more than one particle per hundred bunch crossings, assuming residual pressures equivalent to \(10^{-10}\) torr of CO in the straight section and \(10^{-9}\) torr in the bending magnets.

A third source of synchrotron radiation\textsuperscript{5,32} comes from the crossing point itself due to the influence of the electromagnetic field of one beam on the particles of the other (sometimes called beamstrahlung). In the case of LEP, some \(3 \times 10^{15}\) photons/sec will be produced with an energy spectrum characterized by a critical energy of \(E_{C} = 2.6\) MeV. These photons will be emitted in a very small forward cone and are themselves believed to be harmless but they will contribute to a considerable \(e\gamma\) luminosity which will be as high as 5% of the \(e^+e^-\) luminosity. The \(e\gamma\) interactions may cause additional background in the detectors via

\[
\begin{align*}
e\gamma &\rightarrow e\gamma \quad \text{Compton scattering} \\
e\gamma &\rightarrow e^+e^- \quad \text{Pair production}
\end{align*}
\]

These processes have been carefully calculated\textsuperscript{34} and estimates made of the rate of particles, electrons and photons, leaving the vacuum chamber in the interaction region. High energy photons from Compton scattering could reach forward detectors but the calculated rate is only \(3 \times 10^{-4}\) per bunch crossing, the kinematics is illustrated in figure 19. A considerably higher rate (\(\sim 5/\)bunch crossing) of low energy electrons (\(< 100\) MeV) will be created by the pair production process but all these electrons will curl up inside the vacuum chamber in the presence of a solenoidal field (figure 20).
4. Realisation of the Project

The construction of LEP was officially proposed to the Council of CERN at its June meeting of this year. The machine design report for the proposal is the so-called "Pink Book" 5) to which were added proposal documents concerning budget requirements and timescale. A phase I for the project was defined and agreed upon as the 1/6 RF stage (16 MW of installed RF power) with four equipped experimental areas. The RF stations would be at interaction regions 1 and 5 and the experimental areas at 1, 3, 5 and 7. A minimum of work would be performed elsewhere. It is proposed that with these austerity measures, it will be possible to construct LEP within the total CERN budget to achieve the first beams five years after approval. It is expected that this approval will be given in June 1981 so that it is hoped to start LEP physics in 1986.

It is apparent that with this timescale, it will be necessary to call for proposals for experiments almost immediately after approval of the project so that the preparation work which has been outlined in the latter half of this paper will be extremely important. The first round of detectors at LEP will have to be constructed with today's particle detection techniques.

Acknowledgements

This general review describes the work of a very large number of people. For the LEP machine design, a list of names appears in the "Pink Book" 5) while the various physics study reports 1, 20, 21, 22) contain similar lists of participants and authors of particular papers.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Machine Circumference</td>
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<td>Installed RF Power</td>
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<tr>
<td>Number of Interaction Points</td>
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</tr>
<tr>
<td>Number of Bunches Per Beam</td>
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</tr>
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<td>Horizontal Tune</td>
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<tr>
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<tr>
<td>Maximum Luminosity / 10^{32}</td>
<td>1.0 0.5 cm^{-2} s^{-1}</td>
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## TABLE II

**Stages of LEP Construction**

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<th>Fraction of RF Installed</th>
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<th>Superconducting RF</th>
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<td>130 GeV</td>
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<td>Luminosity</td>
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</tbody>
</table>
Figure 1: The ratio $R$ of the total annihilation to pointlike cross section calculated using the standard Weinberg-Salam model with $\sin^2 \theta_W = 0.25$. Also shown are the weak and electromagnetic cross sections with no $Z^0$ pole.
Figure 2: Luminosity as a function of energy with 16 MW, and 96 MW of installed room-temperature RF cavities. The extrapolation to 130 GeV assumes 96 MW of power available on the beam by the use of RF superconducting cavities.
Figure 3: Layout of LEP tangential to the CERN SPS showing the eight experimental areas numbered 1 - 8. The small numbered circles indicate test drillings which have already been carried out. The straight dotted line is a possible trajectory for a reconnaissance tunnel.
Figure 4: Cross-section of the LEP 4 m diameter tunnel showing space reserved for a possible future proton machine, helium gas-lines for superconducting RF and space for installation.
Figure 5: A perspective of an underground hall 70 m long transverse to the beam which will accommodate two large experiments, counting rooms and associated electronics.
Figure 6: A cross-section of the steel-concrete dipole magnet showing construction details.
Figure 8: A five-cell slot-coupled accelerating cavity with low-loss storage cavity.
Figure 9: Schematic of the injection system using the CERN PS and SPS.
Figure 10: The total annihilation event rate at LEP with the design luminosity and the standard model with $\sin^2\theta_W = 0.2$ and three quark-lepton families.
Figure 11: Simulated measurement of the forward-backward charge asymmetry $<A_\mu>$ in $e^+e^- \rightarrow \mu^+\mu^-$ ($\sin^2\theta_W = 0.23$). Each "data" point corresponds to 100 h of running.
Figure 12: Behaviour of $R$, the ratio of the total annihilation to pointlike cross-section at a new quark threshold.
Figure 13: The event rate at LEP around the Z° pole of the standard model before and after correction for the very important radiative effects.
Figure 14: The predicted production cross section for $W^+W^-$ pairs in the standard model for $\sin^2\theta_W = 0.23$ (present world average) and $\sin^2\theta_W = 0.2$.
Figure 15: The proposed JET Detector installed between superconducting insertion quadrupoles showing the limited space available for forward tagging detectors.
Figure 16: Estimates of effective tagging efficiencies which could be achieved by placing suitable detectors behind the ±5 m insertion quadrupoles for three different quadrupole configurations.
Figure 17: The fraction of synchrotron radiation from the 5m insertion quadrupole intercepted by the vacuum chamber immediately in front of the opposite quadrupole, shown as a function of vacuum chamber half-aperture.
Figure 18: Estimated energy spectra of off-momentum electrons reaching the vacuum chamber in three regions a) immediately upstream of the insertion quadrupole; b) between the quadrupoles; c) immediately downstream of the quadrupole. The high energy component has been effectively removed by a horizontal collimator 75 m upstream of the crossing point.
Figure 19: Kinematics of the Compton scattering process $\gamma + e^{-} \gamma$ as a result of synchrotron radiation produced at the beam crossing point interacting with the opposite beam.
Figure 20: Kinematics of electron pair production resulting from the synchrotron radiation produced at the beam crossing point interacting with the opposite beam.