Chapter 2
The Difficult Decision of LEP's Size and Energy

When the decision has been taken as to which type of facility has to be realized, many questions concerning the details of its concept remain to be decided. For a machine designed for fundamental research, the following issues have to be taken into account:

- Will the machine be able to provide answers to the scientific questions raised by the scientific community in order to penetrate deeper into unexplored territory?
- Are the technologies available to realize such a facility or do new technologies have to be developed?
- Are the necessary scientific and technical staff available with the appropriate experience and competence?
- Last but not least, are there good chances that the necessary financial resources may be found?

Before a project can be proposed in a definite form, many discussions between scientists, engineers and politicians are needed. The final aim is, of course, to obtain a facility with the best performance at minimal cost. Since LEP was the largest device ever built, the answers to these questions were particularly pertinent and the choice of its parameters (size, energy) was important and was the most pressing decision to be taken.

2.1 The Optimization of Construction Cost

There is a fundamental difference for proton and electron storage rings. For a proton machine the highest achievable energy is determined by the bending power of the magnets which keep the particles in a circular orbit; hence, the most powerful proton rings use superconducting magnets which provide high magnetic fields. The conditions are different in the case of electrons. Electrons in a circular orbit emit (owing to the centripetal acceleration) a type of electromagnetic radiation, called

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'synchrotron radiation'.[1] The energy loss E_{rad} due to this radiation is given by the relation $E_{\mathrm{rad}} \sim (E/m)^4/R$, where E is the energy of the circulating electrons, m is their mass[2] and R is the radius of the orbit. This implies that the radiation losses increase very sharply with the energy E, whereas increasing the radius has relatively little effect. One has to fight against the fourth power of the electron energy with a linear dependence on the radius.

The radiation losses must be continuously compensated for by radio-frequency (rf) accelerating cavities which are fed by rf power supplies. If superconducting cavities are employed, the losses in the cavities can be neglected and for a given radius the rf power P_{rf} has to increase with energy as $P_{\mathrm{rf}} \sim E^4$. This was the case for LEP 2. If copper cavities are used, as was the case for LEP 1, there are additional losses in the walls of such cavities which increase with E^2 and consequently one obtains the overall relation $P_{\mathrm{rf}} \sim E^8$. In both cases the rf power P_{rf} must increase very steeply with the maximum electron energy for a fixed radius. This is costly both for the construction of the accelerating cavities and for the operation, which requires considerable electric power. The total construction cost is composed essentially of two elements: the cost of components, which is proportional to the circumference of the machine and hence to its radius (tunnel, magnet ring), and the cost of the rf system, which scales as $1/R$, as shown above. Optimization of the construction cost with respect to the radius shows that in the case of superconducting cavities both the radius and the construction cost increase with E^2, i.e. the radius of the machine should approximately increase with the square of the maximum energy. However, this relation is only very approximate and to find the most efficient parameters for an optimized electron–positron collider for a particular physics programme is not easy and requires compromises depending on the local and actual conditions.

The arguments given above apply, of course, only to a circular machine. If two linear accelerators with opposing beams are used instead, the synchrotron radiation losses are negligible and the length is roughly proportional to the desired energy (a fixed cost has to be added which is practically independent of the energy). The relations are shown schematically in Fig. 2.1 taking into account realistic prices for the various parts of the facilities.

It turns out that at a certain energy there is a crossover of the construction cost for the two types of machine, with linear accelerators being more economical. This crossover occurs at different energies depending on whether copper accelerating cavities or superconducting ones are used in the circular machine. Below a design energy of about 300 GeV a circular machine is more economical, whereas for higher energies two colliding linear accelerators are more advantageous. For

[1] This kind of radiation was observed in 1946 for the first time at a particle accelerator called a 'synchrotron' and hence its name [1]. Nowadays special storage rings are built to exploit this radiation for research and technical applications. It also plays a major role in astrophysics.

[2] The total power emitted by synchrotron radiation is proportional to $1/m^4$. Since protons are about 2,000 times heavier than electrons, the synchrotron radiation of protons is much weaker (about 10^{-13}) and becomes noticeable only at extremely high energies, such as those at the LHC.

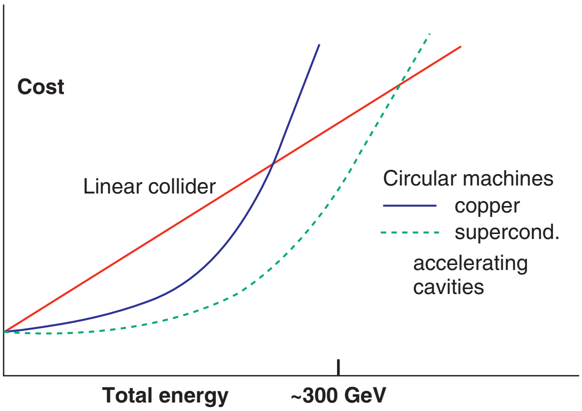

Fig. 2.1 The construction cost of circular and linear electron–positron colliders as a function of the maximum energy of the facility. For the circular machines, the cases for copper and superconducting accelerating cavities are shown

a machine with only 3 times the energy of LEP the radius of a circular machine becomes unrealistic (several hundred kilometres in circumference). Since the design energy of LEP was well below the crossover of about 300 GeV, only a circular machine had to be considered, no matter what kind of accelerating cavity was considered.

On the other hand, for the next step in the development of electron–positron colliders only two colliding linear accelerators are feasible. Such a machine is presently considered as a world machine for a beam energy of more than 500 GeV with a total length of 30–40 km, the International Linear Collider (ILC) [2]. The disadvantage of linear colliders is that the particles in two opposite beams have only a single chance of colliding, whereas in a circular machine they can circulate many times, thus increasing enormously the chance of collisions. To obtain a sufficient number of collisions in a linear collider, very high beam currents (implying a large power consumption) are necessary and in addition the beams must be strongly focussed at the collision point. These requirements present serious technical and economic problems. To solve them further technical developments are necessary, and these are happening in a concerted way on a worldwide scale. A decision will only be taken after the results of these activities have come to fruition and when the results from the LHC are known.

Considering the arguments mentioned, it is not surprising that it took some time to agree on a final energy for LEP; the values suggested for energies oscillated up and down, leading to different circumferences for the ring. A first study group [3, 4] was formed at CERN in 1976 to examine the feasibility of a large electron–positron collider with a beam energy of 100 GeV (hence a total energy of 2×100 GeV) and a circumference of 50 km which was called LEP 100. When the technical study was terminated around the middle of 1977, several basic problems remained unsolved and the cost was considered to be very high. A new study had to be made.

2.2 The LEP Studies

In August 1978 the LEP Study Group issued a new design, LEP 70 (the 'Blue Book' [5]), for a smaller collider ring with a circumference of 22 km which could eventually reach beam energies of about 70 GeV. In a second stage the energy could be increased by replacing the accelerating copper cavities by superconducting ones if and when these became available. Since CERN always attaches great importance to having the support of future users, this design was presented to the European Committee for Future Accelerators (ECFA) and was discussed in ECFA-LEP working groups [6, 7] in September 1978, in Rome in November 1978 and in Hamburg in April 1979. The main conclusions were that from the physics point of view the machine should be able to reach an energy of 85 GeV per beam with conventional accelerating cavities made of copper. Secondly, it was stated that the underground area for at least some of the experimental halls should be larger than planned. Hence, the Blue Book design was not accepted.

The physics arguments were quite obvious. In a first stage one wanted a machine for the copious production of the still hypothetical Z particle ('Z factory'), which required about 50 GeV per beam, and in a second stage the threshold for W particle pair-production, estimated at that time to be 86 GeV, was envisaged. There was agreement that LEP would be needed even if the Z boson were discovered at the proton–antiproton collider at CERN (which happened in 1983) and if the top quark were found at PETRA in Hamburg (which did not happen). Many new results could be expected, e.g. information on the number of neutrino types, the discovery of the Higgs particle and new results on the strong interaction. Everybody agreed that such a machine would be a fascinating facility with no competitor in the whole world for a long time to come.

As a result of the in-depth discussions with the users' community, one more design was presented by the LEP Study Group (led jointly by Eberhard Keil, Wolfgang Schnell and Cees Zilverschoon) in the summer of 1979, the 'Pink Book' [8]. It was emphasized that this document was to be considered as a progress report and that the studies continued. The circumference of the machine was chosen to be 30.6 km and three energy stages were considered:

1. An initial 1/3 (zero) stage with a beam energy of 62 GeV
2. Stage 1, with an energy of 86 GeV per beam which could be reached with copper accelerating cavities
3. Stage 2, raising the energy to about 130 GeV by using superconducting accelerating cavities

In this proposal a special preaccelerator (injection) system was envisaged with two linear accelerators, an accumulator ring for the positrons and a synchrotron with a circumference of 1,741 m to be placed in a new tunnel under the Intersecting Storage Rings (ISR) site and using the ISR magnets (see Fig. 2.2 and Table 2.1).

One of the reasons why CERN originally was not considered as a good place for LEP was the fact that there was not much room between Lake Geneva and the Jura Mountains to place a tunnel with a circumference of more than 30 km. In the

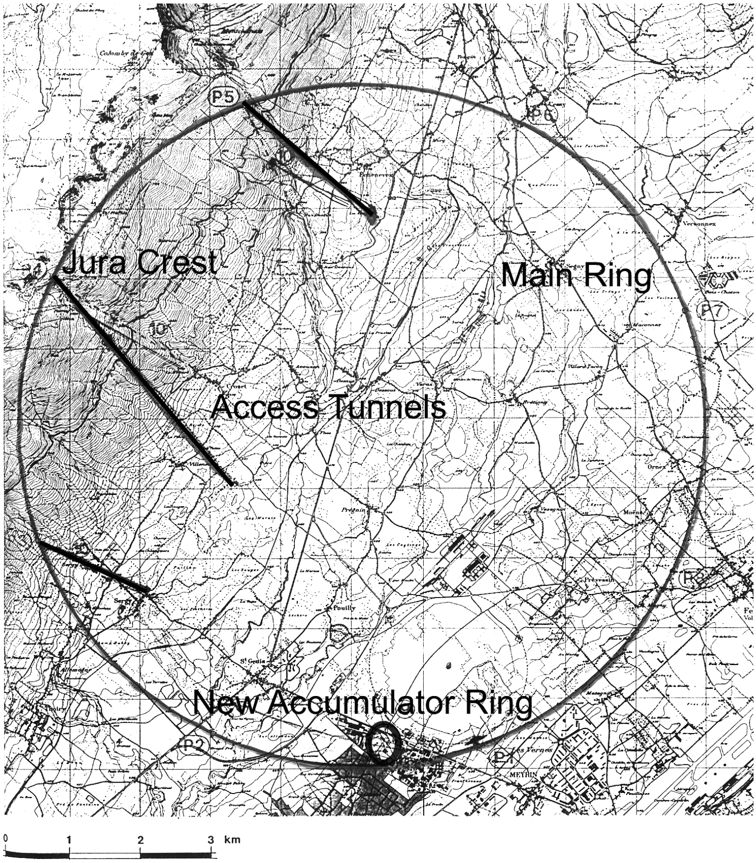

Fig. 2.2 The LEP position in the first proposal ('Pink Book'). The ring passes deep under the Jura crest; three long access galleries were necessary to provide access to the underground halls at points *P3*, *P4* and *P5*. A new accumulator ring under the old Intersecting Storage Rings (ISR) tunnel was also proposed

Table 2.1 The various proposals for LEP; energy with superconducting rf cavities in a second stage in *parentheses*

Study	Maximum beam energy (single beam) (GeV)	Circumference (km)	Cost (millions of Swiss francs)	Year
LEP 100	100	50	Too high	1976
Blue Book	70	22	?	1978
Pink Book	86 (120)	30.6	1,300	1979
Green Book	50 (100)	26.7	910	1981

Pink Book it was proposed to place it in such a way that about 12 km would be located in the rocks of the Jura, indeed passing under the crest at a depth of 860 m. However, very little was known about the geological features of the Jura. Some general information came from some water and road tunnels built in the vicinity of the Geneva basin. The tunnel would partly be located in a kind of sandstone, called 'molasse', between Lake Geneva and the foot of the Jura and limestone and other rocks under the Jura. The preliminary conclusion was [9]:

> These studies indicate that it is probably not too difficult to construct the LEP tunnel into the Jura with a boring machine. But to improve our knowledge of the molasse/limestone contact and to verify the quality of the Mesozoic limestone, it will be necessary to bore two reconnaissance tunnels of about 0.5 to 1 km long as soon as the location of LEP is determined.

As it later turned out, this expectation was drastically optimistic, the excavation of the tunnel becoming one of the main problems in the construction of LEP! The real weak point of the proposal was that the geological risks under the Jura could not be evaluated.

Eight experimental halls (see Fig. 2.2) of different types were foreseen: two 'surface' halls to be excavated from the surface, three underground halls up to 60 m deep and three deep underground halls up to 860 m deep. To reach these three deep underground halls it would have been necessary to dig three access tunnels 1, 1.5 and 2.3 km long, respectively, sloping towards the main tunnel with rather steep gradients. In this proposal a special preaccelerator (injection) system was envisaged with two linear accelerators, an accumulator ring for the positrons and a synchrotron with a circumference of 1,741 m to be placed in a new tunnel under the ISR site and using the ISR magnets (see Fig. 2.2).

Interestingly, a later possibility of colliding electrons from LEP with protons from the Super Proton Synchrotron (SPS) by installing an external 'bypass' for the protons from the SPS was also discussed. Therefore, LEP was placed in such a way that it passed close to the SPS. This possibility was never considered again.

The cost for stage 1 was estimated at CHF 1,275.4 million and the construction time considered was 7 years. It was the first time that a facility had been proposed to Council without a special budget for the project. In the past, special funds had always been approved for each of the new facilities (see Chap. 10). It was stated that LEP should be realized within a constant CERN budget and, of course, an austerity scenario had to be envisaged.

In parallel to the technical studies, the physics arguments in favour of LEP were presented to the Scientific Policy Committee (SPC) of CERN. A report by Richard Dalitz and Valentin Telegdi [10] which was based on the results of the users meeting at Les Houches in the French Alps mentioned above was discussed in an SPC meeting in April 1979. A more formal document [11] was presented and adopted at the SPC meeting of 18–19 June 1979. The reasons for choosing an electron–positron collider were given, the physics case for the energy chosen was explained in detail and, in particular, the various stages for the increase of the energy were considered. The feasibility of constructing such a machine was pointed out, with the somewhat naive argument “since the cost of the tunnel is but a small fraction of the capital cost, its circumference should certainly be made large enough for acceleration to the highest energies discussed here”. Indeed it turned out in the end that the tunnel was the most costly and difficult part of LEP!

Contrary to the initial ideas, it was suggested in the Pink Book that LEP be built at the CERN site although “it is not yet definitely clear whether this is technically feasible, but it would in any case avoid all kinds of difficulties and delays commonly associated with site selection.”[3] It was stated that it was imperative to start constructive actions immediately and no time should be wasted and Council was asked for approval to be achieved by the end of 1981.

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[3] When a site for the SPS in another member state was discussed in the early 1970s, no agreement could be reached and in the end the SPS was built at the Geneva site.

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