PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

LEP: A Historical Introduction [and Discussion]

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LEP: a historical introduction

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On 13 August 1989, close to midnight, the electron and positron beams in LEP, the largest research device ever built, collided for the first time. Only ten minutes later the control-room telephone rang and one of the four experiments announced the detection of the first Z-event. This was the culmination of a project that had started 14 years ago had been brought to a full success thanks to the devotion and enthusiasm of physicist, engineers, technicians and administrators. The development of our field is so breath-taking that events of 10 years ago already are almost forgotten. Not only for the historical record but also for future projects it may be useful to report some of the experiences which were encountered during the realization of LEP.

1. The prelude

It is the tradition in elementary particle physics that the big laboratories involve future users from universities and national laboratories in the conception and decision process for new facilities. LEP is a particular good example for such a procedure.

It is not clear who first suggested the construction of LEP at CERN. Anyway this was a rather trivial idea since it is an obvious continuation of the European line of e^+e^- colliders ADA, ADONE, ACO, DORIS and PETRA. First studies for this large electron–positron collider started at CERN as early as 1976 in parallel with deliberations for other machines, such as a larger proton–proton collider as a follow-up of the ISR and an electron–proton collider CHEEP. CERN hesitated somewhat to leave the domain at which it had excelled so well, the construction of proton machines, and gave in only slowly to the pressure of the physics community to look into electron machines. Eventually an electron–positron collider with a circumference of about 40 km was studied. But because of technical and financial problems encountered the LEP study group issued in August 1978 a design (the Blue Book) for a smaller collider ring of 22 km circumference which could reach beam energies of 70 GeV. This design was discussed by an ECFA–LEP working group which concluded among other things that the machine should be able to reach 85 GeV with conventional copper cavities.

The physics goals were quite obvious. In a first stage one wanted a machine for the copious production of Z-particles, i.e. about 50 GeV per beam, and in a second stage the pair production of W was envisaged requiring more than about 90 GeV. Everybody agreed that from the physics point of view LEP was a fascinating facility with no competition for a long time to come. The continuous enthusiasm and unanimous support of the user community was an essential and necessary, if not sufficient, condition for achieving the authorization of LEP construction.

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As a result of the discussions with ECFA a new design was presented by the LEP study group (led jointly by E. Keil, W. Schnell and C. J. Zilverschoon) in the summer of 1979 (the famous Pink Book) for a machine with a circumference increased to 30.6 km. Three energy shapes were considered: a 1/3 Stage with a beam energy of 62 GeV and a Stage 1 with an energy of 86 GeV per beam, which in Stage 2 could be raised to about 130 GeV by using superconducting cavities. Eight experimental halls of four different types were proposed. The later possibility of colliding electrons from LEP with protons from the SPS was also discussed.

From the conceptual point of view LEP is a relative conservative machine since it can be considered as an upgraded PETRA. However, the extraordinary size presented a challenge since it entailed many technical problems with the additional condition that ways had to be found to reduce the cost. A number of ingenious solutions were found, like the RF storage cavity system or the 'concrete magnets', to mention only two. Also the required precision was remarkable, e.g. the tolerance on the particle orbit was ± 2.5 cm out of 26.6 km (from the circulating beams it was found that the deviation was only 8 mm).

This design study was presented by the Directors-General J. Adams and L. van Hove in the second half of 1978 to the subcommittees of the CERN Council. The whole year 1979 was spent in discussions whether and how LEP could be realized. In February 1980 I was appointed by Council as new Director General after I had been interrogated in detail how I would handle the LEP project. In a very agreeable and efficient collaboration with John Adams and Leon van Howe we prepared an official proposal to Council which was submitted by my predecessors in June 1980. This definition of LEP Phase 1 was based on the earlier Pink Book design (circumference 30 km) with one major modification. The group responsible for the injection system had proposed to use the SPS and the PS as preaccelerators.

This helped to reduce the cost of the project to a tolerable level but had also political consequences. No longer was LEP considered as a separate programme but Council decided in June 1980 that it should be integrated in the Basic Programme of CERN and a rather complicated procedure for the approval of LEP was decided in December 1980. An essential sentence read: 'If the inclusion of the LEP Project ... in the Scientific Activities and Long-Term Budget Estimates is agreed by the Council *with no Member State voting against*, this will constitute approval of the LEP Project ...'. This clearly meant that a unanimous decision was required. I was asked by Council to present in June 1981 a definite project proposal and a financing scheme providing the integration of LEP into the Basic Programme with no additional project funds.

In the mean time I had won E. Picasso as project leader. Many were surprised about this choice since they had expected a real accelerator expert to lead the LEP crew. However, I was conscious that to realize LEP required much more than just technical skills. I had no worry about the necessary technical competence since excellent CERN groups were already engaged in the LEP design. But the staff and the funds for LEP had to be found within the available resources of the laboratory and hence somebody who had the full confidence not only of the accelerator people but of the whole staff was needed. Indeed it turned out that human problems, e.g. arising from the need to transfer about one third of the staff to new tasks implying the rupture of human relations which had developed over several decades, were sometimes much more difficult to handle than technical problems. Emilio Picasso did an excellent job and I enjoyed the cooperation with him through all the eight

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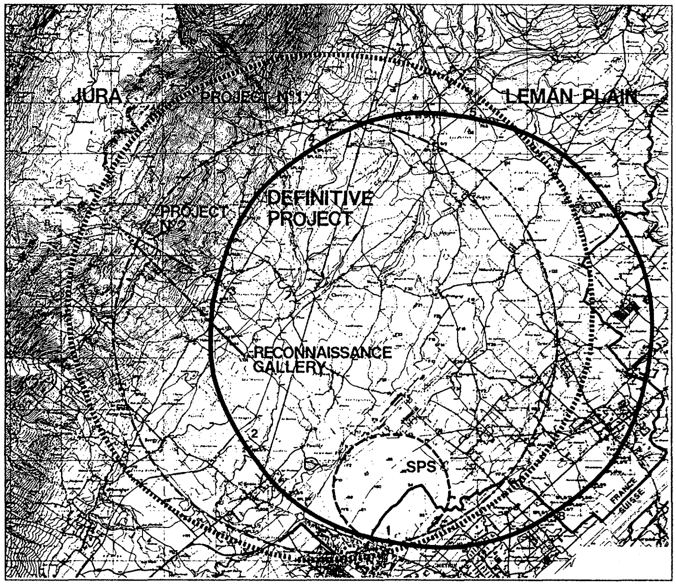

Figure 1

years and sometimes we had to take very lonely decisions. But of course, many other scientists and engineers played a key role, in particular the members of the LEP Management Board and the staff responsible for the injection system.

Our first important task was to fix definitely the main parameters of LEP and its precise location. For more than two years test borings had continued to explore the underground of possible LEP positions and a reconnaissance tunnel was being excavated to study the critical transition between sandstone and limestone which seemed to be unavoidable. It turned out that the rock right under the Jura range was very bad for tunnelling and also the long access galleries foreseen to reach some of the experimental halls appeared as a considerable disadvantage (figure 1). After long discussions we decided to reduce the circumference of LEP from 30 to about 27 km and to move it somewhat out of the Jura to reduce the geological risks. Fortunately the reduced circumference did not result in a reduced energy since meanwhile the LEP group had found a more favourable tune of the machine which allowed to reach the design energy with the RF power originally foreseen (16 MW) for Phase 1. It became also obvious at that time that the use of superconducting cavities would offer a much more economic solution to go to energies beyond Phase 1.

2. The approval by Council

To obtain the required unanimous decision I travelled in the beginning of 1981 to most capitals of Member States to convince the politicians of the soundness of our project. To my surprise I found that most of the opposition came from colleagues in other fields who feared that the construction of LEP within a constant budget was unrealistic and that once approved CERN would come with additional requests which could have negative effects on other sciences. I recognized that all efforts would have to be made to avoid such a development and that LEP would have to be built strictly within the given boundaries in order not to damage the credibility of CERN.

With this in mind we submitted in June 1981 the final proposal ('Green Book' CERN 2444, 1981) with a detailed cost estimate. To have a chance for a positive decision of Council a new approach had to be adopted which became known as the 'stripped-down LEP' and which consisted of the following main elements.

1. LEP was presented as an evolving machine which implies that only the absolute minimum of components would be installed for Phase 1, just sufficient to produce Z-particles. The completion of the machine should be decided later.

2. In spite of this saving concept future potentialities should not be impaired. This meant in particular no further decrease of the circumference (for which some colleagues were pushing hard) and no reduction of the tunnel cross section to keep the space for a second magnetic ring.

3. Only four instead of eight experimental areas were planned.

4. The total investment for the project was reduced to 910 MSF (in 1981 prices as compared to about 1300 MSF of the Pink Book Project) which included 20 MSF for experimental area infrastructure but did not contain the salaries of the CERN staff. A financing period of eight years was foreseen from the date of approval. However, every effort was promised to complete the machine as early as technically possible. No additional staff was asked for.

5. No contingencies were foreseen with the argument that the main uncertainty was in the civil engineering and those risks were almost unpredictable in view of the difficult geological situation. Any major problems in tunnelling would unavoidably lead to delays and hence the financing period would automatically be extended. 'Time is contingency' was our slogan.

6. No provision was made for the experiments since it was not known yet how many experiments would be approved and to what outside contributions could amount to.

7. I proposed three alternative levels for a constant budget which would allow to build LEP and to continue the other programmes at corresponding levels.

When in June 1981 this proposal was put to a vote in Council presided by Jean Teillac, eight Member States (Austria, Belgium, Germany, France, Greece, Italy, Switzerland and U.K.) cast a positive vote, Denmark gave a positive vote but 'ad referendum' and three countries (The Netherlands, Norway and Sweden) declared that their internal decision procedure was still going on. It was decided that the voting procedure was not closed but that it would be completed at a special Council Meeting. Hence for a few months the trembling continued, but finally on 30 October 1981 the unanimous decision in favour of LEP was taken.

Unfortunately a difficult condition was attached to this decision. Of the three different budgets levels not even the lowest of 629 MSF was accepted but the budget was fixed at 610 MSF. Integrated over the construction period of LEP this reduction corresponded to about 20% of the project cost. I argued that such a level could only be accepted if at least the full cost variation index would be given for the material budget during the project period and I asked if not for a formal but a gentleman's agreement on this topic. The answer unfortunately was that the budget had to be negotiated every year again with a unanimous decision required to increase it whereas a 2/3 majority sufficed for a reduction. These boundary conditions implied difficult years ahead, not only with the Member States but also with the staff and the users. Indeed I was criticized for accepting these conditions but it was the only way to get LEP approved. During the most critical years some colleagues expressed the view 'never again' whereas it seems that everybody is quite happy now to have this excellent machine.

I always thought that one of the most valuable assets of CERN was its broad programme covering the whole range of energies from atomic physics at ISOLDE to the highest collision energies of protons and antiprotons in the SPS. It was clear that the non-LEP programme would have to suffer but I thought that also LEP should take its share in unhappiness. Hence we decided that the construction period of LEP should be extended by one year and operation should start at the end of 1988 instead of 1987 which really meant a start-up in spring 1989 because of the usual winter shutdown. This postponement was later occasionally misunderstood as a delay in the construction whereas it had been so decided already at the time of authorization. Indeed with the first collisions in August 1989 a delay of only a few months occurred, an excellent achievement in view of the geological difficulties.

With the help of the Experiments Committees and the Scientific Policy Committee was tried to balance the non-LEP programme. First priority was given, of course to the exploitation and upgrading of the proton–antiproton programme, with good success as is generally known. Unfortunately we had to close down the pioneering ISR, the only pp collider ever built, the bubble chamber BEBC, the European Hybrid Spectrometer and many other beans and smaller experiments, much to the dismay of many CERN users. Nevertheless we were able to respond positively to some new initiatives, the most important being the start-up of the relativistic heavy ion programme and the second phase of LEAR. The doubling of the number of users proved that the non-LEP programme not only maintained but increased its attraction.

3. The construction of LEP

Unfortunately the formal procedure for the authorization for civil engineering could only be started after the approval of the project. Although everything had been prepared in the best possible way we had to go through a sometimes painful procedure which lasted longer than we had hoped. In Switzerland the legal conditions are such that no major difficulties arose. In France, however, the ownership of ground extends to the centre of the Earth (but minerals belong to the state!) and we had to obtain the agreement of more than 2000 proprietors to tunnel under their property. Each of them could have stopped the project by going to court. To avoid this we had to obtain the 'declaration d'utilité publique' by the highest court in France which required quite an effort by itself.

The situation was complicated by the fact that the new socialist government had introduced the decentralization which implies that the major of each little village also had to agree. Some of them although being friends of CERN could not resist the temptation to oppose LEP since they immediately obtained an enormous publicity in the local press.

We had also to engage a campaign to convince the local population that LEP presented no danger and would not do any harm to the environment. I was surprised how little the population knew about CERN although they had lived next to it for 30 years. We had to give many talks, organize exhibitions and expose ourselves to critical discussions, in particular to the population in Meyrin and Ferney-Voltaire, two cities under which the LEP tunnel passed right through. We took measures, sometimes costly, to reduce the environmental impact as much as possible. The platform of Point 4 was lowered, some cooling towers displaced and swampy spots were found with the help of some mayors for the deposits of the excavated rock. At the end of the civil engineering work the local authorities ensured me that the trouble for the region had been quite tolerable and the economic effects on the other hand quite beneficial.

Eventually all obstacles were removed and in September 1983 the ground could be broken in the presence of President Mitterand and the President of the Swiss Confederation Aubert.

Between 1983 and 1988 LEP was the largest civil engineering undertaking in Europe. Two contracts for the excavation of the LEP tunnel and the associated shafts and caverns (in total about 1.5 million of cubic metres) had been adjudicated to two international consortia of firms. One consortium had the task to excavate about 23 km of tunnel in sandstone using three full face boring machines. The other consortium had to dig about 3.5 km in the limestone under the Jura by using the conventional method of explosives.

Several problems arose. After some running-in the boring machines worked quite well and no major technical problems appeared in the sandstone. However, the access shafts which had to traverse water levels required unforeseen measures like freezing the ground before excavation. Also the working staff of the firms went two times on strike and all this caused considerable delays. Even more serious problems were encountered under the Jura. The limestone was in some places fractured and the cracks filled with water under high pressure. In spite of careful pilot drillings several major water invasions and flooding of part of the tunnel could not be avoided. The consequence of all these problems was that the original and very detailed planning for the civil engineering had to be modified several times (figure 2) but with an enormous effort we managed to reduce the overall delays for the project to a few months.

The execution of the contracts for the different components of LEP went on with surprisingly few difficulties. I would like to mention only one incident since it gives some indications for the relations between industry and a laboratory like CERN. I insisted that the rather sophisticated control system for LEP should not be developed by CERN but should be subcontracted to a firm since industry should be more competent for control systems of complex installations. A contract was signed but resulted in a complete failure. The firm had hoped that the hardware to be developed could be used for other purposes but when another important client declined the firm lost all interest. Since the control system was on the critical path a delay of the start of LEP seemed unavoidable. Fortunately the CERN experts were able to improvise and provide a system in an incredibly short time.

During all those years we were struggling to keep the cost down. One trick we used was not to allocate definite budgets to the various project groups but we asked them to do their best to reduce expenditure. The idea was that an allocated budget would very likely be spent. Indeed most of the groups remained below the estimates which only Picasso and I knew. The Finance Committee gave us a hard time, however, since they wanted detailed cost estimates.

Another continuous problem was to accommodate the cash flow of the project with a nearly gaussian distribution within flat yearly budgets. Toward the end of the project this was only possible because some Member States (above all Switzerland) were prepared to advance their contributions. After the final counts had been closed (CERN/FC/3313, May 1990) the total cost of the machine was found to be within the

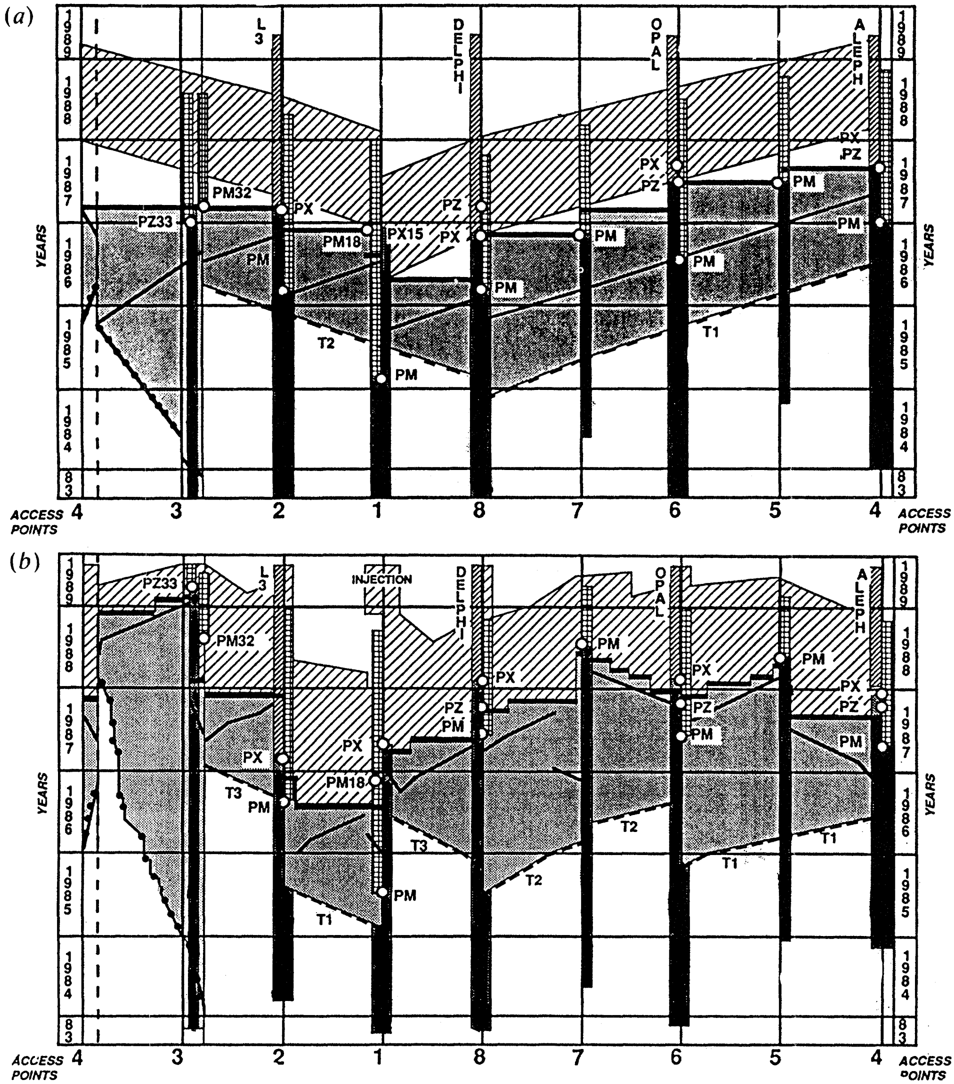

Figure 2. (*a*) LEP execution history. Civil engineering: ■, access and experimental areas: ⚃, main ring; – – –, tunnelling machines (T1 and T2 in (*a*) and T1, T2 and T3 in (*b*)); ——, vault concreting; ●—●—●, excavation (Jura); ——, availability from civil engineering; ○, availability of shafts. Installation: ▦, access shafts; ▩, experimental areas; ▨, main ring. (*b*) Initial planning for LEP work (March 1983).

approved budget within a few percent (taking into account inflation but not a pending claim by one of the civil engineering firms).

After six years of construction, a relatively short time for such a big and complex project, the first beams were turning round on 14 July 1989, the 200th Anniversary of the French Revolution.

4. The LEP detectors

It was essential to start the preparations for the LEP experiments as early as possible to allow sufficient time for the development of new techniques, to discuss the different proposals in depth, to obtain sufficient feedback to plan the civil engineering of the experimental halls and finally to organize the collaborations with the intent to allow as many physicists as possible to participate in the LEP programme.

For these reasons the discussions of the LEP experimental programme started well before its approval. A Conference on Experimentation at LEP was held as early as June 1980 in Uppsala and was followed by a number of ECFA working group discussions.

An essentially step forward was made at a meeting which was organized by ECFA (Chairman J. H. Mulvey) and CERN in June 1981 at Villars-sur-Ollon in the Swiss mountains. Although LEP had still not been approved concrete questions concerning the LEP experiments were considered and indeed some decisions were taken, if not formally but from a practical point of view.

One of the hot questions concerned the number of experiments to be approved in the first round. Several scenarios were discussed, e.g. three large and one small specialized detector, or one universal and one specialized experiment with two interaction areas left free for new technological developments, or even more than four detectors. In the ensuing discussions two things became clear: at most four interaction zones should be equipped at the beginning and everybody wanted to be ready from the start with a full-size universal detector and if possible even be first. The possibility to use existing detectors was refused.

Guidelines for the Letters of Intent and the procedure for the final approval were agreed upon. In addition to the usual conditions, such as scientific interest, technical feasibility and competent physicists, we had to introduce some novelties.

It was the first time that at an accelerator large detectors had to be installed underground. As a consequence the available space was very limited, the detector had to be designed in such a way that the largest components could be brought down through the narrow access shafts and safety regulations had to be very strict which implied no or only a small amount of explosive gases.

A new policy which was accepted by the community with great reluctance and only after many efforts of persuasion concerned the design optimization of the detectors. In the past detectors were optimized in such a way that the outside groups were facing as little a load as possible and the laboratory provided the necessary infrastructure. For example, magnets were designed according to the needs of the experiment not taking too much into account the available power sources or operating costs. Since in the case of LEP CERN did not have reserves and the total available funds from inside and outside CERN had to be optimized we requested that the detectors had to be designed taking into account not only the total investment but also the operating cost for several years. One consequence was that two experiments decided in favour of superconducting magnets, one for DELPHI was built at the Rutherford–Appleton Laboratory and one for ALEPH at Saclay, the largest superconducting solenoids ever built.

Full agreement was reached about the future procedure for the approval of the experiments. Letters of Intent were to be submitted by 6 January 1982, a LEP Experiments Committee would be installed at the beginning of 1982 and the first decisions would be taken by mid-1983 assuming that the personnel and financial problems could be solved in the mean time by the CERN management. It was also pointed out that the final composition of the collaboration would only be decided later leaving room for some negotiations. It was agreed that an effort should be made to allow those physicists whose proposals had been rejected to join other collaborations. No 'shoot out' was foreseen. The role and working conditions of groups from non-Member States were also discussed. In view of the uniqueness of LEP there was consensus that physicists from all countries should have an equal chance to participate in LEP experiments. To compensate for the fact that their countries were not contributing to the general CERN budget it was expected that they would make a larger contribution to the investment of the detectors, be it in cash or kind.

Since experiments are carried out by physicists the human element cannot be neglected and the group sociology was discussed intensely. Many worries were expressed concerning the role of individuals in large groups and in particular how young scientists can distinguish themselves and get proper recognition. Different possibilities of how to organize the groups were discussed and indeed some of the new ideas were realized later. I compared a collaboration to a convey of several ships, large and small, rather than to one big supertanker. There can be small and big ships with specialized techniques (steam, diesel or even sails) and sometimes a small but powerful tug can drag along a big immobile ship or conversely the convoy as a whole can help a sailing ship during a dead calm to get along and ships might leave or join the convoy during the trip. Looking back now I believe one might say that most physicists are relatively satisfied with the style in which the LEP collaborators have been organized. From all the problems raised it seems to me that the long time scale of an experiment covering a period of six to eight years from the conception of an experiment to the analysis of the first data is the most serious one since such a period covers an essential part of the professional life of a physicist.

At the Villar Meeting I dared to make a guess about the number of physicists who would be interested in LEP experiments and about the cost of the experimental programme – and I failed completely. Assuming four experiments with about 120 physicists per experiment I estimated the total number of physicists to be about 500 in the first stage of LEP. Today about 1600 physicists are participating in the four collaborations. Thus LEP has not become an 'elite machine' reserved to only a few privileged.

As far as the cost is concerned I estimated that three big detectors would require about 30–40 MSF each and a small detector would need an additional 20 MSF amounting to a total of about 130 MSF. The truth is that four large detectors required funds of about 500 MSF. This figure has to be used with some caution since many components were supplied in kind from different countries and a precise evaluation of the cost is difficult. It is remarkable, however, that the cost of the experiments (even without infrastructure) amounts to almost half of the investment for the machine.

Six Letters of Intent were received and the newly appointed LEP Experiments Committee under the chairmanship of G. Wolf started immediately to evaluate them. First conclusions were already reached in July 1982 and after further discussions with the groups concerned approvals were given in November. The four experiments (spokesman) ALEPH (J. Steinberger), DELPHI (U. Amaldi), L3 (a 'provisional' name meaning that it was the third LOI received) (S. Ting) and OPAL (G. Michelini) were approved. ELECTRA and LOGIC had to be refused but most of the physicists could be integrated in the approved experiments. The conditional approval implied that some physics emphasis had to be changed and tests and milestones had to be passed successfully before the final green light was given.

The collaborations could agree rather rapidly on how to share the work and intensive activities started in many laboratories all over the world, first in developing prototypes, later to build the detector components and after testing and calibrating to deliver them to CERN. About 2/3 of the detector components were supplied by outside institutes from many countries which required a new style of international cooperation. There are many examples were parts were manufactured in one laboratory, sent for assembly with other parts to another laboratory, with perhaps testing in still another institute. All this happened with participating institutes from Europe, U.S.A., U.S.S.R., China, Canada, Israel, Poland and many others and well before Glasnost and Perestroika.

Not only in the technical field new ways of cooperation had to be tried but also new management methods had to be explored. Some experts were very sceptical that the realization of the detectors would work with CERN having only a relatively small possibility to interfere directly. In particular it seemed rather dangerous that CERN had very limited reserves in manpower or funds to step in if some outside members of the collaborations could not meet their commitments. To share the responsibility in coping with unforeseen difficulties we set up for each LEP collaboration a Finance Committee were the situation was regularly discussed with the representatives of the funding agencies and in case of problems solutions acceptable to all partners were indeed found. This way of monitoring large and complicated international technical enterprises was new and might be called the LEP Model. E. Gabathuler, I. Butterworth and J. Thresher in their function as successive Directors of Research have contributed essentially to the success of the experiments.

We had to face another difficult decision, the siting of the four detectors. The arguments for putting L3 which needed the largest hall in Point 2 were straightforward since there the tunnel was closest to the surface. Also the installation of OPAL in Point 6 could be explained by the fact that the power for the warm coil of this detector could best be provided in that area. However, no rational arguments could be found for placing ALEPH and DELPHI in Point 4 or 8. After long discussions with the spokesmen we agreed to let chance decide by tossing a coin and thus ALEPH moved to Point 4 and DELPHI to 8.

Let me mention a last problem. Because of the difficulties in tunnelling the available time for installing the experiments became very short. All kinds of arrangements had to be agreed upon to speed up the installation and additional loads had to put on the outside users and on the CERN staff. F. Bonaudi who served as an extremely efficient interface played a key role and with a common effort it was possible to keep the timetable.

If the construction of the LEP machine was a spectacular achievement I believe that the completion of the detectors in time for the first beam was even more remarkable in view of the very difficult coordination of many laboratories in many countries. An incredible effort was required by many hundreds of physicists and technicians all over the world.

5. Final remarks

Sometimes I am asked what I would do differently if I had to start again. Indeed not so much. Maybe it would have been better to engage one more consortium in the tunnelling as it had been foreseen at some time although this would have reduced the flexibility. A relatively large fraction of the total cost went into conventional equipment (power converters, cooling, ventilation, etc.) and there a larger effort and a closer relation to modern industry could have had a beneficial effect.

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I still believe that it was a right decision to approve four detectors since their potentialities will only become fully visible in the coming years when more difficult experiments will be carried out at dramatically decreasing cross sections above the Z resonance.

To have accepted to build LEP within a constant budget I would still defend. The support of high energy physics has reached a level at which a considerable further increase cannot be expected.

In summary one might state that LEP was a successful project thanks to the impressive efforts of many people inside and outside CERN. It is very gratifying to see the beautiful results already obtained after one year of operation and being a unique facility LEP should be exploited to its full capabilities. I hope that luck will be with us in the coming years and provide us with some real surprises.

Discussion

C. H. Llewellyn Smith (*University of Oxford, U.K.*). Professor Schopper referred to the circumference and radius of the LEP tunnel as assets which he was anxious not to compromise during the design stage. Would he confirm that, as I remember, it was intended from the outset that this asset should be used in due course to house a proton collider? Could he also comment retrospectively on the wisdom of the decision to approve four LEP experiments?

H. Schopper. Indeed, the purpose of making the LEP tunnel wide enough and installing the LEP magnets as low as possible had been from the very beginning to provide space for a proton ring. This seemed particularly attractive since it would offer the possibility of e–p and even Pb–Pb collisions in addition to p–p collisions. This is, of course, the basis of the LHC proposal. As to the second question, obviously four experiments can gather more luminosity and they provide necessary cross checks. They also have different detection capabilities which will become fully effective when the more difficult physics above the Z resonance will start.