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

The LEP Machine: Present and Future

Stephen Myers

Phil. Trans. R. Soc. Lond. A 1991 **336**, 191-200
doi: 10.1098/rsta.1991.0072

The LEP machine: present and future

By Stephen Myers

SL Division, CERN, CH-1211, Geneva 23, Switzerland

A description is given of the status of commissioning of the LEP collider from the first injection in July 1989 with first collisions for physics about a month later to the first year of operation. During this time the LEP luminosity has reached more than half of the design value and more than 900000 Z^0 particles have been generated, detected and analysed. The major factors related to each significant improvement in performance are reported. The present day limitations to performance are analysed, and the foreseen improvements aimed at raising the performance are discussed. The future possible LEP upgrades are outlined; the approved energy upgrade, studies to increase the luminosity by increasing the number of bunches, and studies aimed at producing transversely and longitudinally polarized beams for physics.

1. The design of LEP: energy and luminosity

The two fundamental parameters in the design of any particle collider are the beam energy range and the 'luminosity'. In the case of LEP the energy was clearly defined by the energy of the Z^0 and the $W^{\pm}$ particles and resulted in a range of $40 \rightarrow 100$ GeV per beam. Having decided upon the energy the next question in the design procedure is to optimize the physical size of the collider so as to minimize the capital and running costs. The crucial component in the definition of the circumference of LEP is related to the mechanism of synchrotron radiation. When charged particles are bent to form a circular orbit, they radiate a fraction of their energy by emission of photons. If this energy were not replenished then the particles would rapidly decelerate in a spiral and finally be absorbed on the inside of the vacuum chamber wall. The radiation loss per revolution (U_0) of a particle of energy E_b being bent in a circular path of radius ρ is given by

$$U_0 = c_\gamma E_b^4/\rho, \tag{1}$$

where

$$c_\gamma = \tfrac{4}{3}\pi r_e/E_0^3 = 8.85 \times 10^{-5} \text{ m GeV}^{-3}, \tag{2}$$

with r_e the classical electron radius $= 2.8 \times 10^{-15}$ m and E_0 the rest energy of the electron $= 0.511$ MeV.

1.1. RF *power requirements*

The energy loss provoked by synchrotron radiation is replenished by the radio frequency system of resonating cavities (the RF system). Clearly the power and cost of this RF system is defined to a large extent by the radiated power due to the synchrotron radiation. The power dissipated as heat in the cavity structure is

$$P_d = V_{RF}^2/l r_s, \tag{3}$$

where V_{RF} is the peak accelerating RF voltage, l is the total active cavity length, and r_s the shunt impedance per metre of the accelerating structure.

Phil. Trans. R. Soc. Lond. A (1991) **336**, 191–200
Printed in Great Britain

The electric field in the accelerating gaps oscillates at high frequency (352 MHz for LEP) and is synchronized to a harmonic (h) of the revolution frequency of the particles. Hence the bunches traverse the accelerating gaps at a constant phase (ϕ_s) relative to the field. On average all particles gain the same amount of energy which, at a constant beam energy, must balance the loss due to the radiation, i.e.

$$eV_{RF} \sin \phi_s = U_0. \tag{4}$$

Combining equations (1), (3) and (4) gives the power dissipation in the cavity walls as a function of the relevant beam parameters

$$P_d = (c_\gamma/e)^2 E_b^8/(lr_s \sin^2 \phi_s \rho^2). \tag{5}$$

The power absorbed by the beams is

$$P_b = 2k_b I_b U_0/e = 2k_b I_b c_\gamma E_b^4/e\rho, \tag{6}$$

where I_b is the current per bunch and k_b the number of bunches per beam.

The total power needed then is simply

$$P_{total} = P_d + P_b. \tag{7}$$

For the case of room temperature accelerating cavities the power dissipated in the cavity walls is predominant. For a given maximum beam energy, from equation (5), this power may be minimized by maximizing (1) the total active length of the cavities, l; (2) the shunt impedance of each cavity, r_s; (3) the 'overvoltage factor', $1/\sin \phi_s$; (4) the bending radius of the bending magnets, ρ.

Of these parameters, the bending radius ρ is the most critical. Early studies showed that for a beam energy of around 100 GeV, the cost-optimum was for a circumference of 20–30 km, depending on assumptions about the future availability of superconducting RF cavities. For geological reasons the final choice was 26.6 km. For phase 1 of LEP, the energy needed was only around 50 GeV per beam, and required 16 MW of RF power. Consequently it was decided to buy and install only those room temperature cavities necessary for the initial phase and continue with the development of superconducting cavities. In this way both options were left open for phase two. The present scheme for increasing the beam energy to around 90 GeV requires the installation of 192 additional superconducting cavities with an additional required power of only 12 MW.

1.2. *The beam–beam effect*

The second important performance parameter in the design of colliding beam rings is the luminosity ($\mathscr{L}$). For any physical process (such as for example the Z^0), the rate at which events are produced is given by

$$dN/dt = \sigma\mathscr{L}, \tag{8}$$

where σ is the cross section of the process.

For beams colliding 'head-on', the luminosity at any collision point is given by

$$\mathscr{L} = N_e N_p k_b f_{rev}/4\pi\sigma_x^* \sigma_y^* \tag{9}$$

with $N_{e,p}$ the number of electrons, positrons per bunch and $\sigma_x^* \sigma_y^*$ the transverse cross section of the bunches.

A fundamental limitation to all colliders results from the influence of the electromagnetic fields associated with each beam on the motion of the particles in the

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

'other' beam. This 'beam–beam effect' is quantified by the beam–beam strength parameter (ξ), i.e.

$$\xi_y = -(\beta_y^*/\pi)(\Delta y'/y_0), \tag{10}$$

where $\Delta y'$ is the angular deflection ($\Delta\, \mathrm{d}y/\mathrm{d}s$) received by a particle at a vanishing displacement from the centre of the other beam, y_0; s is the longitudinal coordinate, and β_y^* is the betatron amplitude function at the location of the beam–beam interaction, this specifies the strength of focusing at that point.

Evaluation of the deflection $\Delta y'$ requires calculation of the electrical potential of the beam's three-dimensional gaussian charge distribution. For small displacements, and for $\sigma_x^* \gg \sigma_y^*$, equation (10) is given by

$$\xi_y = (N_\mathrm{b}\, r_\mathrm{e}/2\pi\gamma)(\beta_y^*/\sigma_x^*\, \sigma_y^*). \tag{11}$$

Combining equations (9) and (11) and assuming that the bunches in both beams have the same number of particles (N_b) gives the luminosity in a more useful form, i.e.

$$\mathscr{L} = (\gamma f_\mathrm{rev}\, k_\mathrm{b}/2r_\mathrm{e})(N_\mathrm{b}\, \xi_y/\beta_y^*). \tag{12}$$

From equation (12) it is apparent that the maximum luminosity is achieved when the beam–beam strength parameter (ξ_y) is at a maximum simultaneously with the beam intensity. Under the condition that the horizontal ξ must equal the vertical, equation (11) may be written as

$$\xi_y = N_\mathrm{b}\, r_\mathrm{e}/2\pi\gamma\epsilon_x, \tag{13}$$

where ϵ_x is an invariant of the horizontal motion called the emittance, and can be approximated by

$$\epsilon_x \Rightarrow \sigma_x^2/\beta_x \approx (c_q R/\rho)(\gamma^2/Q_\mathrm{h}^3), \tag{14}$$

where R is the average radius of the orbit.

Combining equations (13) and (14) gives

$$\xi_y \approx N_\mathrm{b}\, r_\mathrm{e}\, \rho Q_\mathrm{h}^3/2\pi c_q R\gamma^3. \tag{15}$$

Consequently for a given energy, equation (15) shows that, if the intensity is too low to reach the beam–beam limit, increasing the overall focusing will reduce the emittance and allow higher values of ξ. It is also evident that as the beam energy is increased, the beam–beam strength parameter decreases with the third power. For this reason two focusing optics have been foreseen; a low-energy optics with a phase advance per cell of 60° and a high-energy optics of 90° per cell.

Since the beam–beam strength parameter varies inversely with the third power of beam energy, then if the beam–beam limit is to be attained at the maximum energy it would be greatly exceeded at injection energy. This situation is avoided by separating the beams at the collision points by electrostatic plates. Experiments done at injection energy in LEP have shown that the current per bunch is limited to *ca.* 0.03 mA (compared with design of 0.75) if the bunches are not separated in the collision points.

2. Commissioning and first year of operation

The first injection into the LEP collider took place on 14 July 1989, one day earlier than scheduled. First collisions of electrons and positrons were provided almost exactly one month later on 13 August 1989. In the following four months of

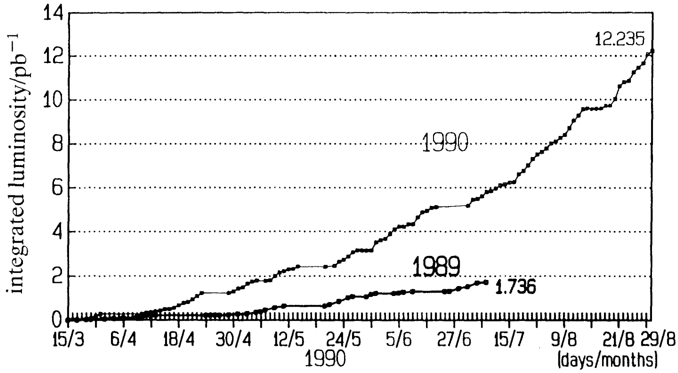

Figure 1. Evolution of the integrated luminosity during 1989 and 1990.

interleaved operation for physics and machine studies the collider performance allowed more than 30000 Z^0 particles to be detected in each of the four experiments. During operation for physics in 1990, the LEP performance allowed the detection of an additional *ca.* 200000 Z^0s per experiment.

In the nine months before July 1989, more than 24 km of equipment had been installed and tested *in situ* in the tunnel. This work involved the installation of all magnets, vacuum chambers, RF cavities, beam instrumentation, control system, injection equipment, electrostatic separators, electrical cabling, water cooling and ventilation, etc. The installation was followed by individual testing of more than 800 power converters and their connection to their corresponding magnets. Great care was taken to check and double check that all magnets had the correct polarity. In parallel, the vacuum chambers were 'baked out' at high temperature (either by superheated water or by electrical jackets) and then leak tested. The RF accelerating units situated around interaction regions 2 and 6 were commissioned and the cavities conditioned by powering them up to their maximum power of 16 MW. Careful coordination of all work was essential to avoid conflicts between testing of the different systems and the transport needed for installation of the final octant $3 \rightarrow 4$.

On the 7 July, just one week before the scheduled switch on, the whole of the LEP collider was put through a complete 'cold check-out' which involved operation of all the accelerator components under the control of the available software. In particular, the energy ramping proved invaluable for the debugging of the complete system of hardware and software. The second cold check-out, scheduled for the 14 July turned out to be a 'hot check-out', since beams of positrons were already available from the SPS injector.

The period between 14 July and 13 August was at the same time crucial and exciting for LEP collider. The accelerator work done during this period brought about the transition between successful completion of a single turn to physics data-taking. For this reason it is worthwhile to itemize the major accelerator milestones in their order of chronology.

July 14: Successful completion of a single turn by a beam of positrons.

July 22: Measurement of the revolution frequency indicates that the LEP circumference is accurate to better than 1 cm.

July 23: Circulating beam of positrons obtained with a measured lifetime of 25 min.

July 25: Successful injection of electrons.

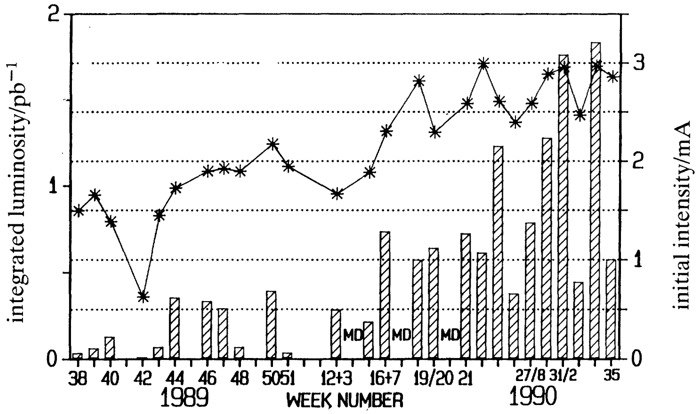

Figure 2. Integrated luminosity per week during 1990. ✱, Initial intensity (mA); ▨, integrated luminosity.

Table 1

parameter	achieved	design
current per bunch/mA	0.780	0.750
total current per beam/mA	2.88	3.00
total current in both beams/mA	4.3	6.0
vertical beam beam strenth parameter, ξ_v	0.018	0.04
horizontal beam beam strength parameter, ξ_h	$\sim$ 0.035	0.04
emittance ratio, ϵ_v/ϵ_h	$\leqslant$ 0.040	0.040
luminosity/(10^{30} cm^{-2} s^{-1})	$\sim$ 5	16.0
betatron amplitude function at the IP, β_v^*/cm	4.3	7.0

July 30: Accumulation in LEP bunches and first measurement of the effect of the beam on the vacuum pressure.

August 3: Energy ramp to 47.5 GeV.

August 13: Energy ramp and β squeeze to 32 cm followed by stable beams for physics with 270 μA per beam.

The first LEP physics run started on 20 September, slightly more than two months after the final testing of the installed accelerator components. The period between this first run and the Christmas shutdown was interleaved with physics data-taking and machine studies aimed at increasing the luminosity. The maximum luminosity achieved during this period was *ca.* 5×10^{30} cm^{-2} s^{-1}, about one third of the design luminosity.

2.1. *Operational performance 1989 and 1990*

The operational performance of the LEP collider has been increasing significantly since the first run in September 1989 (see figure 1). The integrated luminosity during 1990 was more than a factor of seven more than that achieved in 1989. It should be noted that the absolute values shown in figure 1 are optimistic by *ca.* 20% since the vertical blow-up due to the beam–beam effect has not been taken into account (see later).

In figure 2 is shown the integrated luminosity per week for 1990. The best luminosity integrated over a period of one week is in excess of 1750 nb^{-1}, more than four times the best achieved in 1989.

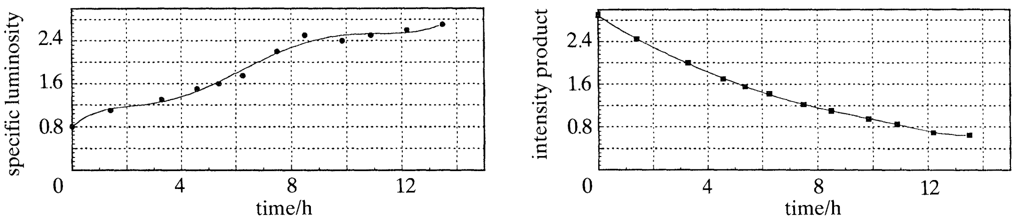

Figure 3. Specific luminosity and intensity product as a function of time.

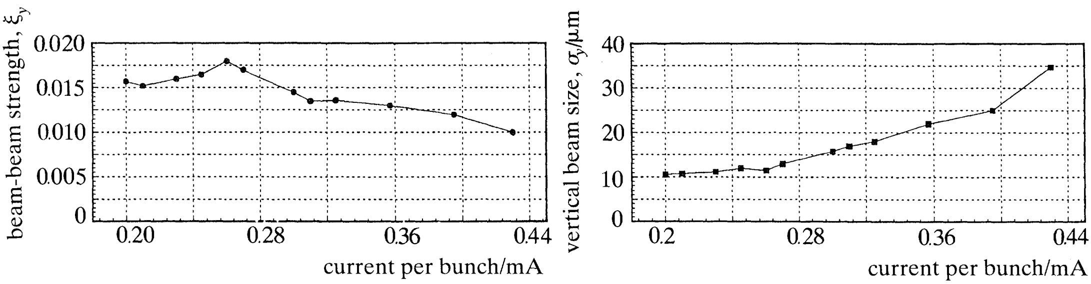

Figure 4. Beam–beam strength parameter and vertical beam size as a function of bunch current.

In figures 1 and 2 the average performance numbers are recorded, however, it is also useful to record the maximum values achieved for certain parameters and compare them with design values. Table 1 gives such a comparison and highlights the fact that many design values have already been achieved and some substantially exceeded. The most notable exception is the beam–beam strength parameter.

2.2. *The operational effect of the beam–beam forces*

It has been observed that the specific luminosity ($\mathscr{L}/i_b^2$) increases as the intensity of the bunches decreases (see figure 3). This behaviour is due to the fact that, as the beam–beam strength parameter decreases with intensity, there is a reduction in the amount of vertical blow-up. From these results one can calculate the vertical beam size and the beam–beam strength parameter as a function of beam intensity (see figure 4). The maximum value achieved is *ca.* 0.018 whereas the design value is 0.040. This low value is caused by the fact that LEP is being operated at transverse tune values which are not optimized for beam–beam effects. The reason for operating at the present tune values is to minimize the coupling between the horizontal and vertical betatron motion.

Recent beam–beam simulations of the LEP collider have shown that a significant increase in luminosity would be attained by operating LEP at slightly different tune values; above 70 and 76 (horizontal and vertical respectively) instead of the presently used 71/77. This new optics apparently satisfies the conditions for betatron coupling as well as beam–beam effects. Initial preparations have already been made to allow introduction of the new optics early in 1991.

The last 10 days of LEP operation in 1990 were devoted to studies aimed at equalizing the luminosity in all four experimental interaction points. During these studies it was found that moving the 'waist' of the low β in L3 improved the luminosity, not only in L3, but to a lesser degree in all experimental areas (see figure

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

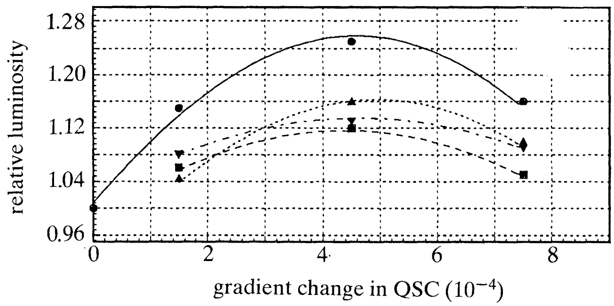

Figure 5. Luminosity as a function of position of the minimum of the low β 'waist'. ●, L3; ■, ALEPH; ▲, OPAL; ▼, DELPHI.

5). This is clear evidence that the vertical emittance was reduced by moving the waist in L3. Moving the waist varies the betatron phase advance between the collision points. Beam–beam simulations have predicted such behaviour.

In 1991 improved diagnostics and software capable of measuring the phase advance between the IPS to an accuracy compatible with maximizing the beam–beam strength parameter will be implemented.

2.3. *The intensity per bunch*

The fundamental upper limit to the LEP intensity per bunch is due to the 'transverse mode coupling instability' at injection energy. This instability results from the interaction of the particles in the bunch with its own short-term transverse wake field.

The approximate threshold for the onset of this instability is given by

$$N_{\text{th}} = 8Q_{\text{s}} E_{\text{b}}/E^2 \Sigma \beta_{\text{i}} k_{\perp \text{i}}(\sigma_{\text{s}}), \tag{16}$$

where Q_s is the synchrotron frequency, β_i is the betatron amplitude function at the location of the impedance, and $k_{\perp i}(\sigma_s)$ is the transverse loss factor of the impedance presented to the beam which decreases with the length of the bunch σ_s.

With a synchrotron frequency (Q_s) equal to the operational value of 0.09 the onset of this instability is predicted (using actual measurements of the LEP transverse impedance using the beam) at around 0.85 mA per bunch. Such high values have not yet been attained operationally. During machine studies and using a higher value of Q_s (0.135) the maximum intensity per bunch attained was 0.78 mA.

In reality the LEP intensity is limited at a somewhat lower level due to a coupling mechanism between the synchrotron motion and the vertical betatron motion. Due to the large amount of energy in the synchrotron motion, this results in a large increase in the vertical dimensions in the beam and ultimately in a reduction in the beam lifetime. The maximum intensity is reached when the injection rate is balanced by the loss rate due to the poor beam lifetime. The synchro-betatron coupling is driven by momentum dispersion at the RF cavities which converts energy gain into an increased betatron oscillation. For this reason the RF straights sections in LEP were designed to have zero dispersion; however, recent measurements with beam indicates values of dispersion which are between a factor of three and about eight above the residual value expected. The source of this residual dispersion is not yet fully understood. One basic limitation in the attempts to reduce dispersion is in its measurement. At present the dispersion cannot be measured operationally to better than about 10 cm r.m.s. However, in 1991, improvements in the beam orbit measuring (BOM) system will allow around a factor of three improvement in the measurement of the momentum dispersion.

The beams in LEP are longitudinally unstable at intensities greater than around 0.2 mA per bunch. In 1990 these instabilities were fought by the implementation of an *ad hoc* feedback system and the use of the damping wigglers. The disadvantage of this feedback system was that it required that the electrons and positrons had different values of Q_s to work properly. Operating with different values of Q_s greatly complicates the choice of suitable tunes to avoid synchro-betatron resonances. A new longitudinal feedback system is presently being developed which will treat each bunch individually and therefore not require different values of Q_s.

2.4. *The betatron amplitude function at the collision point*

During 1990 the β_y^* at the collision points was successfully reduced from 7 cm to 5 cm for operation for physics. During machine studies tests the β_y^* was reduced with low intensity beams to a minimum value of 3.7 cm. In 1991 machine studies will be performed to commission a lower β_y^* optics of say 4.0 cm. In addition studies should be performed to identify the minimum value of β_y^* possible with the present LEP parameters, in particular the influence of the bunch length on this minimum due to beam–beam effects.

3. Future plans

3.1. *Energy upgrade*

The future development of LEP to phase 2 has already been approved by the CERN Council and will take the beams up to energies to allow the study of W pairs. This will require the installation of 192 superconducting cavities from the beginning of 1990 till the first quarter of 1994.

As the thermal conductivity of these cavities is crucial for their quench behaviour two lines of development have been followed. Firstly niobium sheet metal with greatly improved thermal conductivity has been ordered from industry and secondly a successful technique has been developed to sputter the inside surface of copper cavities with niobium. Although both types of cavities have already exceeded their design gradient of 6 MV m^{-1}, it is hoped that the copper–niobium type may be operated at even higher gradients of $7 \rightarrow 9$ MV m^{-1}. Consequently although 24 out of the first 32 superconducting cavities to be installed will be of niobium sheet, it is intended that the remaining 160 will be of the copper–niobium type.

For the cooling of these cavities, four cryogenic plants with an initial cooling power of 12 kW at 4.5 K, but designed for an ultimate capacity of 18 kW will be installed at the even LEP points, following the cavity installation programme.

Although the production of the superconducting cavities is technically the most challenging aspect of the energy increase programme, many other systems have to be upgraded. In particular the superconducting low β quadrupoles must be replaced, many power converters must be modified, additional electrostatic separators must be installed, new klystrons are required to provide the power, and klystron galleries must be dug at points 4 and 8. The successful completion of this project will allow experimenters to study the physics of W pair production in 1994.

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

3.2. *High luminosity at the Z^0 peak*

By increasing the number of bunches per beam above the design value of 4, a substantial increase in the LEP luminosity may be attainable throughout the operating energy range. Increasing the number of bunches, however, automatically increases the number of unwanted collision points and thereby would generate additional beam–beam problems. One way of separating the bunches at the unwanted collision points is by means of a 'pretzel' scheme. A preliminary feasibility study of such a scheme shows that, with respect to the design values of 4 bunches per beam and 0.75 mA per bunch, the luminosity could be increased by as much as a factor of 9 (by operating with 36 bunches per beam) if operation with the pretzel scheme has no negative influence on the maximum attainable current per bunch. In addition by operating with 8 bunches per beam, a luminosity increase by a factor of 2 may be attainable at 90 GeV, if sufficient RF power is installed to replenish the beam power lost due to synchrotron radiation. For reasons of required beam power the pretzel scheme depends on the availability of the superconducting cavities foreseen for the energy upgrade.

Recently it has been decided that, from 1991 onwards, high luminsoity $p\bar{p}$ running in the SPS will cease to be a mode of operation. This has led to the possibility that the electrostatic separators used for this mode of operation could be recuperated for use in the LEP horizontal pretzel scheme. A crash study programme is now under way to investigate the feasibility of such a scheme.

The goal of this study is to provide a pretzel scheme for testing and machine studies as early as the spring of 1992.

3.3. *Polarization*

Transverse polarization (at the level of around 9%) has been observed at the end of the 1990 run. During 1991 every effort will be made to increase the level of polarization and use depolarizing effects to calibrate the energy of the beams to an accuracy of *ca.* 50 parts in a million.

Dedicated polarization wigglers have been ordered and will be installed in 1991. These will improve the polarization growth rate to a calculated 35 min.

Machine studies are planned to allow polarized beams in the presence of beam–beam forces and with the experimental solenoids operating normally. This will allow calibration of the beam energy during each LEP physics fill.

Longitudinal polarization, obtained by rotating the polarization through 90°, would enable the study of the weak couplings at the Z^0 peak with great precision. Spin rotators have been designed and will be installed provided the outcome of the transverse polarization studies is favourable.

4. Conclusions

From a hardware point of view LEP phase 1 has been successfully completed and every effort is now being made to increase the luminosity up to and hopefully beyond the design value. The future development of LEP to phase 2 has already been approved by the CERN Council and will, as previously stated take the beams up to energies to allow the study of W pairs.

The present LEP collider, its energy upgrade, and the future programmes of higher luminosity and polarization, is providing, and will continue to provide for the physicists of Europe and the rest of the world, a unique, and powerful physics tool for fundamental research in the 1990s.

This article is an overview of the work done by a very large number of scientists and technicians who dedicated a large fraction of their professional life to the successful design, construction, and commissioning of the LEP collider. More detailed information on the individual contributions can be found in specialized articles at many conferences on accelerator physics, e.g. The European Particle Accelerator Conference held in Nice in June 1990.