The Performance of LEP and Future Developments

S. Myers,
CERN, CH-1211 Geneva 23, Switzerland

Abstract A description is given of the evolution of the performance of the LEP collider from the first injection in July 1989, through to the first collisions less than a month later and finally to the present. The major factors related to each significant improvement in performance are described, as well as the present day limitations to performance. In addition the time schedule and performance estimates for the planned upgrade in LEP energy to allow study of W pair production are reported. Finally the beam dynamics and technical issues associated with the proposed multi-bunch "pretzel" and polarization schemes are addressed.

Preparation and Commissioning

The first injection into the LEP collider took place on July 14 1989, one day earlier than scheduled. First collisions of electrons and positrons were provided almost exactly one month later on August 13, 1989. In the following four months of interleaved operation for physics and machine studies the collider performance allowed more than 30,000 Z^0 particles to be detected in each of the four experiments. During the first seven weeks of operation for physics in 1990, the LEP performance allowed the detection of a furthur 50,000 Z^0s.

The speed and efficiency with which the LEP collider was commissioned was the result of careful planning and co-ordination of the testing of components as they were installed in the tunnel, and later, the extensive programme of global testing without beam, just before the official turn-on date. In the nine months before July, more than 24 kilometres 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 super-heated 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 co-ordination of all work was essential in order to avoid conflicts between testing of the different systems and the transport needed for installation of the final octant 3 $\rightarrow$ 4.

In parallel with hardware installation and testing, a great effort, with limited manpower, went into the preparation of the software necessary for the operation of LEP. The software was prepared in close collaboration with the accelerator physicists and the collider operators. This allowed a clear definition of priorities so as to ensure that software became available as it was needed.

On the 7th 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 14th July turned out to be a "hot check-out", since beams of positrons were already available from the SPS injector.

The period between July 14 and August 13, was at the same time crucial and exciting for LEP collider. The accelerator work done during this period brought about the transition between sucessful 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 18 Capture of the beam by the RF system. This gave around 100 turns.

July 20 Beam Orbit Monitoring (BOM) system used to measure and correct the single turn trajectory.

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

July 22 Measurement and correction of the betatron tune values.

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

July 25 Successful injection of electrons.

July 30 Closed orbit measurement and automatic correction.

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

July 31 Synchrotron light beam monitor commissioned and allows "real time" observation of the beam cross-section.

August 1 Injection studies give good accumulation rates and a record current of 500 μA.

August 2 Chromaticity correction with the six sextupole families.

August 3 Energy ramp to 47.5 GeV. Electro static separators commissioned.

August 5 Transverse impedance measured to be only 65% of estimated value.

August 8 Compensation of transverse coupling due to the experimental solenoids by use of the skew quadrupole system. Accumulation of record current of 850 μA with solenoids at nominal settings.

August 10 Energy ramp to 47.5 GeV followed by β squeeze to 42 cm under physics conditions.

August 12 Accumulation of both electrons and positrons.

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

Following the first stable beams run of August 13, a pilot physics run was scheduled to cover a five day period. Due to various technical problems, only 15 actual hours physics were possible during the scheduled five day period. Nevertheless this pilot run allowed the "debugging" of the experimental detectors with a maximum luminosity of 5×10^{28} cm^{-2} s^{-1}. Around 20 Z^0s per experiment were successfully detected during this period.

A period of three weeks of machine studies was scheduled after the first pilot physics run. The accelerator performance was greatly improved during this period. In particular, the low β was reduced to the "back-up" design value of 20 cm, a new optics with less transverse coupling was commissioned, and injection studies gave higher filling rates and maximum intensities. The very last shift of this period was foreseen as a physics preparation run and gave a maximum total beam current of 1.6 mA at 45.5 GeV with the low β squeezed to 20 cm.

The first LEP physics run started on September 20, 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 physics running period was subdivided into three types of running. The first sub-period lasting for five days was scheduled for operating at the Z^0 peak (45.5 GeV per beam). During the second sub-period a mini-scan of the Z^0 was performed involving five different beam energies $\pm$ 1. and $\pm$ 2 GeV (centre of mass) around the peak. The final and longest period was devoted to scanning the peak by spending 50% of the time on the peak and 50 % off peak. The maximum luminosity achieved during this period was $\sim 5 \times 10^{30}$ cm $^{-2}$ s^{-1}, about one third of the design luminosity.

Present Performance and Limitations

TABLE 1

Parameter	ACHIEVED	DESIGN
Current per bunch (mA)	0.753	0.750
Total current per beam (mA)	2.88	3.00
Total current in both beams (mA)	4.3	6.0
Vertical beam beam strength parameter (ξ_v)	.02→.03	.04
Horizontal beam beam strength parameter (ξ_h)	$\sim$ .035	.04
Emittance ratio ($\frac{\epsilon_v}{\epsilon_h}$)	$\leq$ .040	.040
Luminosity ($10^{30} cm^{-2} s^{-1}$)	$\sim$ 5→8	16.0
Betatron amplitude function at the IP (β_v^*) cm	4.3	7.0

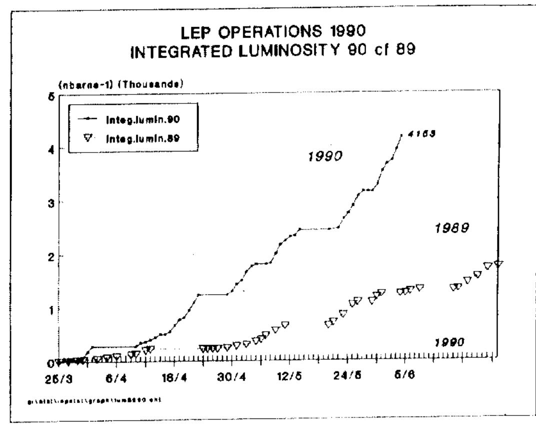

Figure 1: Evolution of the integrated luminosity during 1989 and 1990

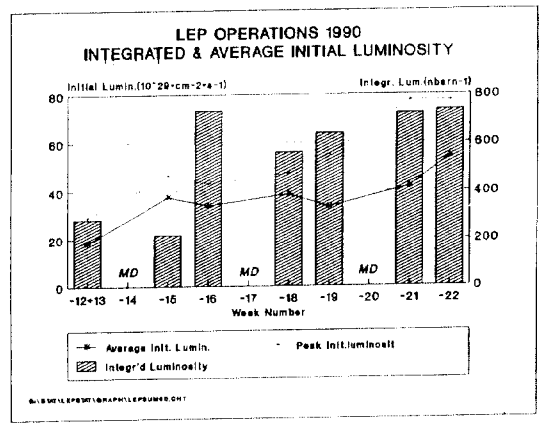

Figure 2: Integrated luminosity per week during 1990

Operational Performance 1989 and 1990

The operational performance of the LEP collider has been gradually increasing since the first run in September 1989 (see Fig 1). The integrated luminosity during the first 8 weeks in 1990 is more than a factor of two more than that achieved in the 14 weeks of operation in 1989. It should be noted that the absolute values shown in Figure 1 are optimistic by 20% → 30% 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 750 nb^{-1} as compared with the best in 1989 of around half that value.

This excellent performance is a direct result of the speed with which improvements in machine studies have been efficiently incorporated into operational procedures and the quality of the operations staff. In Figures 1 and 2 the average performance numbers are recorded, however it is also useful to record the maxima yet achieved in LEP in comparison with design values. Table 1 gives such a comparison. Unfortunately not all maxima have yet been achieved simultaneously.

Limitations to Performance

The provision of high energy, high intensity beams involves four major steps. Firstly the injection and accumulation of the maximum current at injection energy of 20 GeV, followed by ramping this current with minimum loss to Z^0 energy. Then the the betatron amplitude function at the collision points (β^*) are "squeezed" to their minimum values. Finally the beam cross-section must be minimized in collision so as to maximize the beam–beam strength parameters (ξ). The problem areas associated with each of these steps is discussed in the following subsections and where appropriate the solutions are outlined.

Injection and Accumulation at 20 GeV

During the commissioning of LEP several intermediate intensity limitations have been encountered and solved by one means or another.

In the very early commissioning days it was found impossible to accumulate more than $\sim$ 0.1 mA per bunch. It was discovered empirically that by increasing the injection "bump" of the already stored beam, and thereby reducing the betatron injection amplitude of the injected beam, then the saturation level increased. Subsequent machine studies clearly indicated that the dynamical aperture for LEP was and still is significantly less than foreseen. Recent measurements [1] at 20 GeV indicate that the dynamic aperture is only $\sim$ 13 mm compared with the expected value of $\sim$ 40 mm. At higher energy the dynamic aperture is somewhat greater. With the present injection settings however, this effect does not limit the LEP intensity at injection. The source of the reduction ins dynamic aperture is not yet fully understood, however there is some suspicion that higher order multipoles generated because of magnetization effects in the dipole vacuum chambers may be contributing to the problem.

The second intensity threshold was encountered at around 0.2 mA per bunch (less than one third of design) and was accompanied by the observation of dipole longitudinal motion on the bunches. This coupled bunch behaviour was not expected by theory due to the very large spacing of nearly 7 km between the LEP bunches. Consequently no longitudinal feedback was available at that time to damp the longitudinal oscillations. However it was possible to quickly build an improvised feedback system. [2] which used existing high power elements in the acceleration system. This system, in order to treat the electrons and positrons differently, requires that their synchrotron frequencies are different. Fortunately this was possible by dephasing the voltage envelope of the coupled cavity system [3]. This system has now been commissioned and is used operationally for every fill.

The next major intensity threshold occurred at $\sim$ 0.3 mA per bunch and was observed to result in a saturation of the accumulation rather than a hard threshold. This effect is not yet fully understood but appears to be due to synchro–betatron resonances driven by dispersion and closed orbit deviations in the RF straight sections. Studies of this effect [4] have shown the surprising fact that the coherent betatron tune values as well as the single particle ones are relevant in the resonant condition

$$mQ_x + nQ_y + lQ_s = p \tag{1}$$

where m, n, l and p are positive or negative integers. This added complication means in practice that there are two groups of resonances to be avoided, one associated with the incoherent (zero current) tune and one associated with the coherent tune which is intensity dependent. Since the intensity of each bunch is not always equal due to many spurious effects such as injection, losses, etc then the avoidance of all synchro–betatron resonances is a very complex procedure.

Subsequently a search for a better tune range was initiated which resulted in the possibility of accumulating $\sim$ 0.55 mA per bunch. At these same tune values, and by taking great care to minimise the global orbit distortion in the vertical plane the maximum current per bunch increased to $\sim$ 0.6 mA per bunch. Finally, steering the closed orbit through the centres of all the RF cavities with good precision allowed a maximum bunch current of 0.67 mA.

Very recently during machine studies the design current of 0.75 mA was achieved at injection energy by operating with an increased synchrotron frequency (Q_s = 0.135). The large value of Q_s provides more space between the synchro–betatron sidebands and thereby allows a larger tune shift with increasing intensity before either the coherent or incoherent tunes approach a resonance.

The ultimate solution to the problems associated with large splits between the coherent and incoherent tune values will be to equalize the two under all conditions. The controls of the reactive feeedback system [5] , designed to fight the Transverse Mode Coupling Instability, are now being modified so as to produce intensity dependent coherent tune shifts for each bunch so that the coherent and incoherent tunes will remain equal during accumulation.

Ramping to Z^0 Energy

The ramping procedure in LEP [6] has been designed so that the beam sees the same magnetic fields at a given energy irrespective of whether the fields are being ramped or in a stationary state. This procedure was adopted so that measurements made at intermediate stops would be valid during actual ramping. This greatly facilitates the procedure for the manufacture of the ramp files. One simply ramps in small energy increments and at each intermediate stop, measures the relevant parameters, applies the corrections and saves the values in a file. Future ramps are done by linear interpolation between the power supply settings in the files.

However, this procedure is complicated by the intensity dependent coherent tune shifts which are also energy dependent. Consequently bunches with different intensities are ramped with different and varying tunes. In LEP the measured vertical tune dependence on intensity, at 20 GeV, is

$$\frac{\Delta Q_v}{i_b} = 120.0 \tag{2}$$

and about half as much in the horizontal plane. This effect is taken care of my preparing the ramp files with low intensities, and using differences in magnet currents as a function of energy, with respect to injection energy. In this way, for high intensity fills, the change in the quadrupole fields which compensates the effect of current at injection energy is maintained constant throughout the ramp. Hence the energy dependence of the intensity tune shift is automatically compensated.

However, in practice it has been found that the tunes and the orbits are not wholly reproduceable over long time scales such as several days to weeks. Consequently on average around 10% of the total intensity is lost during the ramp. For this reason a tune lock devise has been recently brought into operation. This involves measuring the tunes continuously, and correcting to a predefined value. It is hoped in the future this device will operationally reduce the losses to nearly zero.

Squeezing to Minimum β^*

After energy ramping the beams are brought into collision before reduction of the β^* from 5.0 and 0.2 metres (horizontally and vertically resp.) to the design values of 1.75 and 0.07 metres. This procedure is identical to that used for ramping except,

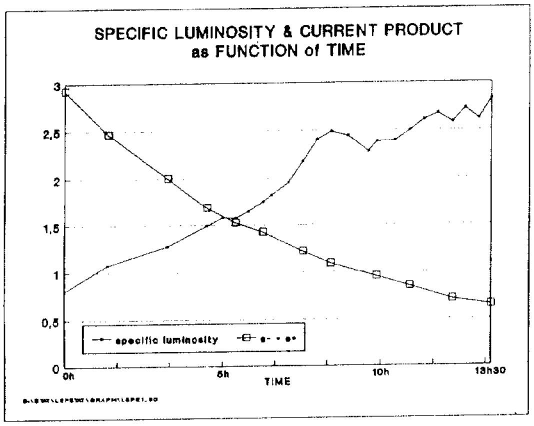

Figure 3: Specific luminosity ($\frac{\mathcal{L}}{i^2}$) and current product as a function of time during a high intensity run.

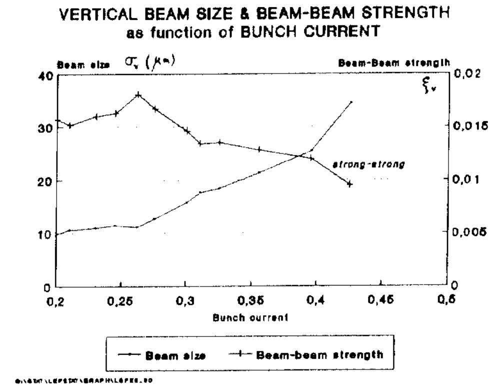

Figure 4: Vertical beam size (σ_v^*) and Beam-Beam strength parameter (ξ_v) as a function of current per bunch (i_b)

of course that the dipole fields are held constant. In the earlier commissioning days the β squeeze did result in some loss of intensity, however since the optics parameters [7] have been carefully measured and corrected, the squeeze to .07 m is now done without loss of intensity. In fact the relative ease with which the 7 cm squeeze has been attained has led to machine studies with squeezes to 4.3cm. This lower β squeeze has been successfully performed many times both at the end of physics fills and during machine studies, and will be brought into standard operation in the near future.

Maximizing the Beam–Beam Tune Shift

Very recently, analysis of the luminosity results from the four LEP experiments [8] have brought to light the fact that the specific luminosity ($\frac{\mathcal{L}}{i^2}$) decreases by up to a factor of 3 when operating with high intensity beams.This is clearly due to an increase in the beam-beam forces with increasing intensity. During the same runs, measurements of the vertical beam profiles by the wire scanners have shown that the lower intensity bunches are "blown up" by large factors. At present for the maximum intensity fills, the luminosity remains constant for around the first 5 to 6 hours in collision. For this reason the run durations are now regularly scheduled for 10 hours and on occasions the beams have been maintained for up to 15 hours. Figure 3 shows, for a typical high intensity fill, the measured specific luminosity and the product of the total current in each beam plotted during the duration of a run. It can clearly be seen that the specific luminosity increases dramatically during the first 7 hours and then stabilizes at a value of around 2.8 (the design value is 2.7 for 4% emittance coupling). This data has been analysed (see Figure 4) in order to evaluate the vertical beam size. For simplicity it has been assumed that both beams are equally blown up ("strong strong"). From these calculations it appears that above a beam-beam strength parameter of around 0.018 the bunches become badly blown up. This effect is certainly accentuated in LEP due to the fact that, until now, no effort has gone into optimization of the beam-beam effect. Following these results top priority is now being given to maximizing the beam-beam strength parameter for these intensity levels and above. This will involve a thorough search for optimum tune values in collision, the equalization of the intensity in the 8 bunches to a level of around 1%, the minimization of the betatron phase advance error per interaction point. The reduction of the dispersion at the interaction points, and the elimination of any residual separations at the collision points.

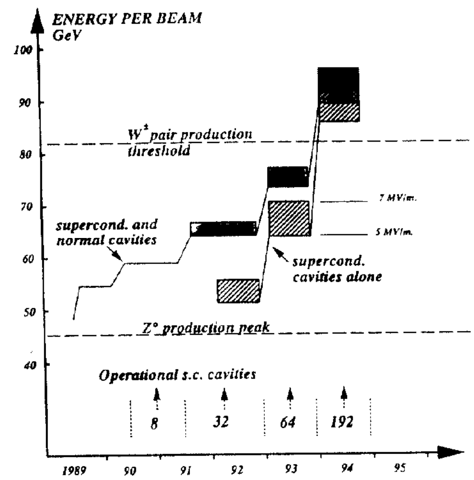

Figure 5: Programme for the installation of superconducting cavities for the energy upgrade

Future

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 at least 192 superconducting cavities from the beginning of 1990 till the first quarter of 1994 (see Figure 5).

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 reached their design gradient of 6 MV/m, it is hoped that the copper-niobium type may reach even higher gradients of 7→9 MV/m. Consequently although the first 32 superconducting cavities to be installed will be of niobium sheet, it is intended that the rest 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^{0}K, but designed for an ultimate capacity of 18 kW will be installed at the even LEP points, following the cavity installation programme.

Whilst 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, 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.

Polarization

Schemes are being studied to provide polarized beams in LEP. Transverse polarization will allow absolute calibration of the beam energy down to precisions of $\leq 5 \times 10^{-5}$. Analytical computations and simulations have predicted a very low ($2\% \rightarrow 5\%$), but measureable transverse degree of polarization, even with the relatively large spread in the beam energy. A polarimeter [9] has been designed and installed in LEP and the necessary techniques developed to increase the polarization level once it has been detected. The polarimeter has been tested and has already detected back scattered photons. Although the present yield is low ($\sim$1%), a factor of 10 improvement is hoped for by mid year.

In addition, dedicated polarization wigglers have been ordered and will be installed in 1991. These will improve the polarization growth rate to a calculated 35 minutes.

Longitudinal polarization, obtained by rotating the polarization through 90^o, would enable the study of the weak couplings at the Z^0 peak with great precision. To this end Richter–Schwitters type spin rotators have been designed and will be installed provided the outcome of the transverse polarization studies is favourable. A proposal has been made to install a prototype spin–rotator scheme in one of the non experimental collision points in order to study possible beam dynamics problems associated with such a scheme.

High Luminosity at the Z^0 Peak

By increasing the number of bunches [10] 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[11]. 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. The pretzel scheme depends on the availability of superconducting cavities foreseen for the energy upgrade. The technical details of this scheme are presented in an accompanying paper at this conference [12].

Conclusions

From a hardware point of view LEP phase 1 has been succesfully 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.

Acknowledgement

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 this conference and in learned journals.

References

[1] J. Miles et al. LEP Performance Note No 30, May 1990.

[2] J-C. Juillard and E. Peschardt; "Damping of Longitudinal Coupled Bunch Oscillations in LEP", presented to this conference.

[3] W. Schnell, CERN ISR-LTD/76-8 (1976)

[4] A. Hofmann et al. "Synchro–betatron Resonances in LEP", presented to this conference.

[5] L. Arnaudon, S. Myers, R. Olsen; "Commissioning of the LEP Transverse Feedback System", presented to this conference.

[6] E. Ciapala et al. "Energy Ramping in LEP", presented to this conference.

[7] J-P. Koutchouk and A. Verdier, "Developments of the LEP Low–Beta Optics Configuration", presented to this conference.

[8] J. Panman (physics co-ordinator for LEP), Private Communication.

[9] R. Jung et al. "Status of the LEP Laser Polarimeter", presented to this conference.

[10] C. Rubbia, "The Future in High Energy Physics", Proceedings of the First European Particle Conference, Rome, June 1988, vol 1, p290.

[11] R. Littauer, "Multibunch Operation of CESR", IEEE Trans. Nucl. Sci. NS-32 (1985) 1610.

[12] J. Jowett, S. Myers, W. Kalbreier, "Preparations for High Luminosity LEP", presented to this conference.