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LEP2 Present and Future Performance and Limitations

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A brief review of the performance in 1997 is given where LEP was operated up to 92 GeV per beam. The upgrading in the past and next winter shut-down is described which allows to raise the beam energy to 94.5 GeV in 1998 and to gradually approach 100 GeV from 1999 onwards. Preparatory work and studies are summarized which aim at this further increase in beam energy with adequate luminosity. The initial performance in 1998 and the expected performance in the following years are reviewed.

1 INTRODUCTION

The Large Electron-Positron collider (LEP) at CERN operated at a beam energy of 46 GeV for collisions at the Z^0 resonance between 1989 and 1995 providing an integrated luminosity of 200 pb^{-1} to each of the four experiments.

In order to fully exploit the design potential of LEP, it was decided as early as 1989 to upgrade LEP to a collision energy well above the W-pair threshold of 80.5 GeV by supplementing the room-temperature rf system with a superconducting rf system, both operating at 352 Mhz [1]. Based on the results of a previous R&D programme, initially a batch of 20 Nb-sheet cavities was produced starting from 1990 and, after the decision in 1990 to switch to the more performing technology, the production concentrated on cavities featuring a thin Nb-film on copper substrate [2]. The first superconducting cavities were installed in 1993 in the LEP tunnel. The installation of the last 16 cavities before the LEP run in 1999 will result in a complement of 288 superconducting cavities and terminate the upgrade programme which concerned also many other systems [3].

The step-wise increase in the available rf voltage allowed to operate at higher energies than 46 GeV per beam from 1995 onwards and to collect the integrated luminosity shown in table 1.

Table 1: Integrated luminosity per collision point at the different beam energies

E(GeV)	Int.L dt (pb^{-1})	Year
65-70	13.5	1995, 1997
80.5	12.1	1996
85-86	11.3	1996
91-92	63.5	1997

The beam energy is 94.5 GeV in 1998 and the aim is to collect in this second long production run about 150 pb^{-1} . From 1999 onwards all the hardware will be installed so that the beam energy can gradually approach 100 GeV in 1999 and 2000. Originally, LEP was scheduled to stop

in 1999 but given its scientific potential it has recently been decided to extend its operation into 2000. This extension is compatible with the schedule of the Large Hadron Collider (LHC) under construction at CERN which requires the removal of LEP after the run in the year 2000. The civil engineering work for the detector caverns of LHC is supposed to start already in 1998 but can be scheduled such that the impact on LEP and its injector, the Super Proton Synchrotron (SPS), is acceptable provided precautions are taken in LEP and SPS [4].

2 OPERATION AND PERFORMANCE IN 1997 [5,6]

After a start-up delayed by 35 days due to a fire in one of the auxiliary buildings of the SPS, the last accelerator in the injector chain of LEP, and after having provided 2.3 pb^{-1} at the Z^0 resonance for detector calibration, LEP operated in a first period mostly at 91.5 GeV. Only a few runs had slightly lower energies (4.6 % at 91.0 GeV, 0.3 % at 90.5 GeV) which is a good indication of the reliability of the rf system. In order to repeat previous data taking, one week was spent at 65 and 68 GeV in this period. The well-tried optics with 90° horizontal and 60° vertical phase advance per cell in the arcs was used during the whole first period. Table 2 shows the peak luminosity and typical parameters used with this optics.

Table 2: Peak performance and parameters for $90^\circ/60^\circ$ optics

Peak luminosity	$L = 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
Integrated luminosity	$\int L dt = 1.9 \text{ pb}^{-1}/\text{d}$ ^{a)} $1.3 \text{ pb}^{-1}/\text{d}$ ^{b)}
Current in both beams	$2I_0 \leq 5.0 \text{ mA}$
Bunches per beam	$k_b = 4$
at interaction point	$\beta_x^*/\beta_y^* = 1.5 \text{ m} / 5 \text{ cm}$
Emittance ($J_x = 1$)	$\epsilon_{x0} = 37 \text{ nm}$
Damping partition	$J_x \leq 1.6$
Emittance ratio	$\kappa = \epsilon_y / \epsilon_x \leq 0.5 \%$
Beam-beam tuneshift	$\xi_y \leq 0.055$

^{a)} best 24 h ^{b)} average over best 10 days

Fig. 1 shows ξ_y as a function of the bunch current I_b as periodically logged during a run with many runs superimposed [7]. The value of ξ_y is calculated from the measured luminosity and beam current assuming that the vertical beam size σ_y is much smaller than the horizontal beam size σ_x at the interaction points. Lines of constant luminosity are hyperbolae in this diagram. Fig. 1 gives an idea of the spread in beam parameters and indicates that the typical value of κ was between 0.5 to 1.0 %. The vertical emittance was not caused by coupling but by the

beam-beam effect and the vertical residual dispersion around the ring. Fig. 1 also shows that the beams were dumped when the currents had decayed to about $I_b = 0.3$ mA.

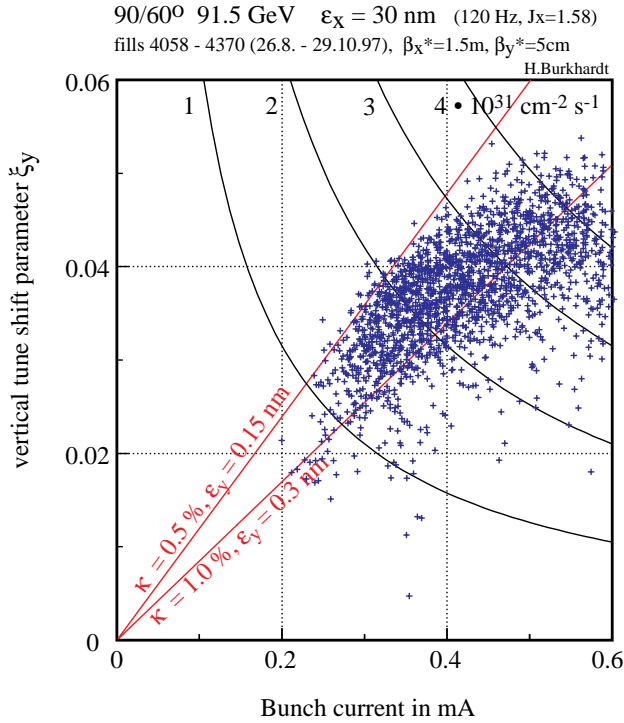


Fig. 1: Calculated vertical beam-beam tune shift as a function of bunch current. Loggings of many runs superimposed. The expected performance for two values of κ is indicated.

The typical beam lifetime varied from 7 h at the beginning of a run to 11 h at the end of the run. The duration of data taking during a run was about 7 h. The beam decay rate was dominated by the beam-beam bremsstrahlung. The average turn-around time from end of run to start of data taking in the next run was about 2 h with the record just below 1 h. During ramping β_y^* was gradually lowered from 10 cm at injection to 5 cm and at higher energy the horizontal beam size was decreased by reducing β_x^* from 2.0 m to 1.5 m and by increasing the damping partition number J_x from 1 to 1.6 through an increase of 120 Hz in the rf. The decrease in emittance resulted in a higher initial luminosity and a lower background at the experiments.

In a second, shorter period the 102°/90° optics was successfully tested. This optics holds the promise of a better performance at higher energy owing to its lower horizontal emittance being only 78 % of the emittance of 90°/60°. Furthermore, it provides a slightly higher energy (0.3 GeV per beam) for a given voltage because of its lower transition energy and, thus, the beam energy could be raised to 92.0 GeV. Although the time for tuning was rather short, the data taking period was only one week, a

peak integrated luminosity of $1.3 \text{ pb}^{-1}/\text{d}$ was achieved with beam-beam tune shifts of 0.05 and κ as low as 0.7 %.

There was evidence for a vertical blow-up of the beam at these high beam-beam tune shifts for both optics but the beam-beam limit was not reached. The horizontal beam-beam tune shift reached a maximum of about 0.03 and there was no sign of a horizontal beam blow-up.

After the installation of 68 additional Nb-film cavities in the shutdown 96/97, 240 sc cavities (including 16 made from Nb sheet) and 84 copper cavities were available powered by 44 klystrons (1 to 1.3 MW) providing in total a maximum voltage of 2.65 GV. The operational voltage of 2.54 GV provided still sufficient over-voltage margin so that two klystrons, each driving 8 cavities, could trip (loss of 164 MV) without creating a beam loss. A negative rf shift resulting in -60 Hz relative to the center frequency was applied in case of multiple rf trips in order to increase the longitudinal damping ($J_x = 1.6 \rightarrow 0.7$, $J_z = 1.4 \rightarrow 2.3$) maintaining a good quantum lifetime and avoiding beam loss. The Nb-film cavities operated on average around 5.9 MV/m (6 MV/m nominal), the Nb-sheet cavities at 3.6 MV/m (5 MV/m nominal). The major part (80 %) of the individual runs were regularly terminated by the operator, only 10 % were lost by an rf fault, which exemplifies the reliability of this huge and complex rf system [8] containing about 9000 rf interlocks.

The performance was initially limited by the performance of the sc rf system suffering from ponderomotive cavity oscillations, phasing and tuning errors [8]. The former are reduced by proper tuning of the cavities but the tuning window is decreasing with increasing accelerator gradient. The latter result in a spread in fields between the cavities which gets worse with more beam current.

Once these rf instabilities limiting the total current were overcome by careful, often individual tuning of the cavities and the total current could be increased to about $2I_0 = 5$ mA, the large synchrotron radiation power (10 MW) and the concurrent, inhomogeneous thermal stress revealed a number of weak points in the vacuum system, which hampered further progress. Most of the resulting leaks (7 out of 10) occurred in gaskets in insufficiently cooled or not protected places where the vacuum chamber makes a transition from one shape to another. Provisional cooling was installed in all the critical places. Despite these leaks the beam lifetime τ_{bg} , determined by bremsstrahlung on the residual gas, gradually improved under the effect of beam cleaning. The product $2I_0 \cdot \tau_{bg}$ rose from 0.50 to 0.75 Ah from the beginning to the end of the period [9].

A sharper limit on total beam current occurred at 5.5 mA because the cryogenics power due to a temporary fault could not cope with the beam-induced losses at higher currents. Since injection became somewhat difficult at 5.4 mA due to synchro-betatron resonances, it was decided

also in view of the vacuum problems to limit the total current to $2I_0 = 5\text{mA}$ and to stay with four bunches per beam in order to get maximum luminosity [5].

The precise measurement of the W mass is one of the objectives of the four LEP experiments and this requires the best possible knowledge of the beam energy at high energy. To this end, the beam energy was calibrated in 16 special single-beam runs at 41, 44, 50 and 55 GeV with the resonance depolarisation method having a precision of a few MeV. A special optics with 60° phase advance in both planes in the arcs has been developed. In addition, the closed orbit measurement and correction has been improved by installing the K-modulation equipment in all octants which permits to measure the off-sets of the beam position monitors relative to the adjacent quadrupole with a rms error of $30\ \mu\text{m}$. These two measures allowed to reach the required polarisation level (5 %) even at 55 GeV and considerably increased the polarisation rate at the other energies. Although the polarisation level reached at 60 GeV was too low (1.5 %) there are good prospects that calibration can be extended to this energy resulting in a better lever arm for extrapolation to collision energy. This extrapolation is guided by 16 NMR probes positioned in several main dipoles and the flux loop which measures 96.5 % of the total magnetic field. The preliminary estimate of the error in beam energy at 91-92 GeV is somewhat under 30 MeV but not yet at 15 MeV as desired for determination of the W mass [10].

3 EXPECTED AND ACHIEVED PERFORMANCE IN 1998

In the shutdown 97/98 the vacuum system was improved by removal of obsolete equipment, redesign of cooling and shielding of remaining transition sections, and displacement of particularly strong sources of radiation, notably wigglers [9]. These measures have been supplemented by better temperature monitoring in certain parts of the ring. The sextupole powering for the $102^\circ/90^\circ$ optics was reconfigured in order to allow for better control of the amplitude dependence of the betatron tunes $\partial Q_x / \partial \epsilon_x$ which can now be reduced to 10 % of the value used in 1997.

In addition, a further set of 32 Nb-film cavities was installed and, in order to make space for these cavities, 36 copper cavities have been removed. This resulting complement of 272 sc and 48 Cu cavities provides nominally an rf voltage of 2.85 GV. Since it was decided to rather opt for high integrated luminosity instead of highest energy in 1998, the beam energy was chosen rather conservatively at 94.5 GeV so that the beam lifetime remains sufficiently long even with two klystrons off and some cavities temporarily detuned.

LEP is now operating at this beam energy for data taking after a fast start-up in mid-May and the usual calibration runs at the Z^0 resonance where $2.5\ \text{pb}^{-1}$ were collected. The $102^\circ/90^\circ$ optics performs satisfactorily

yielding already up to $1.2\ \text{pb}^{-1}$ per day with $J_x = 1.6$ though LEP is not yet completely tuned and still operates with $2I_0 = 4.8\ \text{mA}$ and 4 bunches per beam.

Fig. 2 shows the expected peak luminosity as a function of the total beam current. At low beam currents, the luminosity increases proportional to $(2I_0)^2$ until the beam-beam limit is reached. This diagram [11] is based on first order theory neglecting any beam-beam blow-up before the beam-beam limit of $\xi_y = 0.055$ is reached. The latter value is the highest value inferred in 1997. For higher currents, the beam is assumed to blow-up such that ξ remains constant which implies a linear increase in luminosity with current. This behaviour has been observed in LEP especially at 46 GeV. Consequently the luminosity during a run initially decays proportional to $2I_0$ and not with $(2I_0)^2$ and, hence, a higher integrated luminosity per run is obtained.

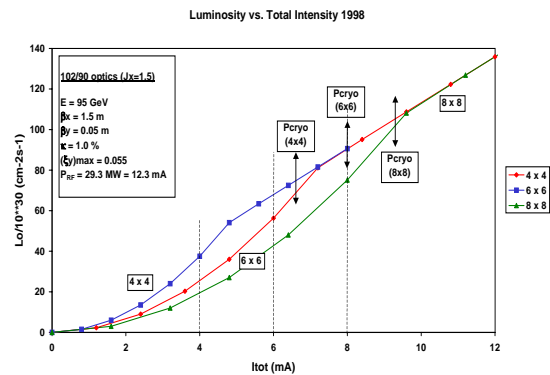


Fig. 2: Expected luminosity as a function of the total current $2I_0$ for $k_b = 4, 6, 8$. The beam-beam limit $\xi_y = 0.055$ is reached on the oblique straight line. The 1998 cryogenics limit is indicated. The rf power limit is reached at 12 mA.

It is expected that the current can be increased until the cryogenic limit is reached. This limit at $2I_0 = 6.5\ \text{mA}$ is brought about by beam-induced losses in the cavities exhausting together with the rf dissipation the liquid He cooling capacity at 4.5 K of the cryoplants. The numerical value is based on measurements of dissipation performed in 1996 and 1997 which revealed these unexpected losses in the cavities increasing strongly when the bunchlength is reduced below 1 cm. The most plausible explanation is that the two antennae mounted in each cavity pick up either directly beam signals or probe higher-order modes (hom) induced by the beam. The cables connecting them to the outside of the cryostat passing through the superinsulation dissipate a part of this power inside the cryostat. More detailed measurements are planned to confirm this hypothesis which is supported by the fact that a number of antenna cables were found to be damaged [12].

Examination of Fig. 2 shows that a record peak luminosity of about $7 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ can be expected with 4 bunches per beam. Experience has shown that the average luminosity is about 20 % of the record peak luminosity. This yields an expected integrated luminosity of 1.2 pb^{-1} per day and 150 pb^{-1} in the 125 days scheduled for high-energy operation in 1998. Fig. 2 further shows what could be gained with 6 bunches per beam and 8 bunches per beam at the cryogenics and the beam-beam limit provided the rf and the vacuum system could deal with more than 6.5 mA. Whether this potential can be used depends on the progress with the rf system which will be rather gradual in order to avoid risks.

4 FUTURE PERFORMANCE

In order to fully exploit the potential of LEP and to reach the highest possible energy with good luminosity, it has been decided to construct four additional sc rf modules, containing 16 Nb-film rf cavities, using all available spare parts and to install them in the winter shutdown 98/99. Furthermore, the upgrade of the LEP cryoplants for LHC will be advanced to the same shutdown so that the dynamic load capacity at 4.5 K (see later) will be nearly doubled. With the further continuous improvement of the stability and reliability of the rf system and the vacuum system, reconfiguration of the power converters for the magnet system and better protection of components sensitive to synchrotron radiation, all the hardware will be ready at the start-up of 1999 to further increase the energy of LEP with the aim to eventually reach 100 GeV per beam [13]. The magnet system has been designed from the beginning to cope with 100 GeV. The beam-induced background in the LEP detectors can be controlled up to this energy with the existing masks and proper setting of the collimators[13].

Table 3 gives the required rf voltage for 24 h quantum lifetime as a function of the beam energy for the $102^\circ/90^\circ$ optics ($J_x = 1.0$). If the superconducting cavities operate at their nominal field (6 MV/m for Nb-film; 5 MV/m for Nb sheet) and the remaining 52 Cu-cavities provide 0.13 GV the maximum rf voltage is 3.05 GV. Since an operational margin is needed for the tripping of one klystron and for some cavities not being operational, it is assumed that two klystrons feeding 16 Nb-film cavities are off, i.e. a loss of 0.16 GV, which leads to an effective voltage of 2.89 GV. This is sufficient to reach 97.5 GeV. Higher energies require raising the accelerating gradient E_a , which can only be done in the Nb-film cavities, to the values given in the table (for $J_x = 1.5$ add 0.1 MV/m).

Table 3: Energy loss per turn, rf voltage and gradient in Nb-film cavities versus beam energy

E(GeV)	96	98	100	102
U_0 (GeV)	2.48	2.70	2.92	3.16
V_{rf} (GV)	2.73	2.96	3.21	3.47
E_a (MV/m)	5.65	6.19	6.75	7.36

Examination of the table shows that 6.8 MV/m are required for 100 GeV in these cavities. This average gradient has been reached during cavity conditioning in 1998 though with quite some spread. A considerable amount of further work [13] will be required to reach these values safely in operation. Although thermal quenches do not occur thanks to the copper substrate, field emission creates increased cryogenic losses and a high level of radiation leading to component damage or activation. Significant reduction in field emission can be obtained by pulsed rf power processing or He processing which can be applied in situ but these procedures need utmost care to avoid damaging the cavities, couplers or circulators. Ponderomotive oscillations (microphonics) proportional to the square of the gradient are also a serious limit but can be suppressed by operating the cavities on tune which requires close control of the tuning and entails operation with $\leq 10\%$ of the rf power reflected. A campaign has been started to reduce the imbalance in the fields of the cavities by inserting transformers in the waveguide in order to eliminate coupling errors and by improving the directivity of the magic tees. Phase errors are corrected to $\pm 1^\circ$ by adding delays (waveguide posts) [13].

The higher gradients E_a will increase the ohmic losses in the cavities described by the first term of the following equation which gives the power dissipated in one module containing 4 cavities each of them providing the voltage V_c

$$P_m = 4 \frac{V_c^2(E_a)}{(R/Q)Q(E_a)} + \frac{R_m(\sigma_s)}{n_b k_b} (2I_0)^2$$

The quality factor Q is also a function of E_a dropping due to the non-quadratic losses and field emission at higher E_a . Higher-order mode losses are characterised by a resistance R_m which has been measured to be about $16 \text{ M}\Omega$ and to increase strongly once the bunch length σ_s is lower than 1 cm. The denominator in the second term is the product of the number of beams $n_b \leq 2$ and k_b the number of bunches per beam. Since $E_a \sim E^{\frac{4}{3}}$ holds, higher energies demand a strong increase in cryogenics cooling power. Given the latter, the maximum possible current and luminosity can be calculated as a function of energy. Fig. 3 shows this limit in the luminosity-energy plane for two values of the nominal power which refers to one of the four cryoplants cooling 20 modules: 6.2 kW is the value before, 12 kW the value after upgrading, which is vital for good performance as can be seen in the figure.

Fig. 3 shows an example drawn for the most probable set of optics parameters and $J_x = 1.0$. The current and consequently the luminosity vanish when the energy requires a gradient where the ohmic losses consume all the cooling power. This yields an upper limit in energy which becomes 101.5 GeV in this example.

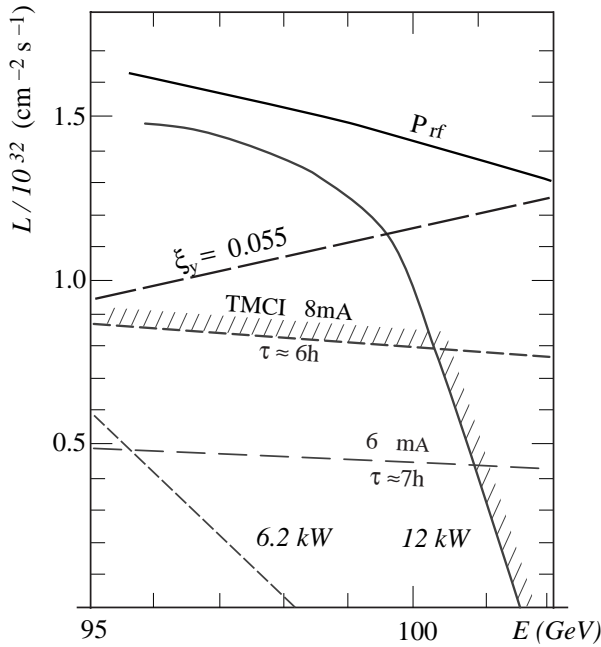


Fig. 3: Limits in the luminosity-energy plane for $J_x = 1.0$, $k_b = 4$ and $102^\circ/90^\circ$ optics. Parameters: $\epsilon_{x0} = 44.4$ nm at 100 GeV and $J_x = 1.0$, $\kappa = 1$ %, $\beta_x^* = 2$ m, $\beta_y^* = 0.05$ m. Lowest hard limits are shaded.

All other possible luminosity limits were examined in a detailed study [14]. The limits by the available rf power P_{rf} , the maximum vertical tune-shift set to $\xi \approx 0.055$, and the transverse mode-coupling instability (TMCI) are shown in Fig. 3 together with lines of constant beam lifetime of 6 and 7 h. The latter coincide with the lines of constant beam current 6 and 8 mA (also TMCI threshold) shown because the control of the rf system and of hom will become very delicate when this current range is entered. The P_{rf} limit coincides with the maximum cooling capacity of the dipole vacuum chamber. Note that the limits above the beam-beam limit are calculated under the assumption that the luminosity increases only linearly with $2I_0$ (see point 3).

Fig. 3 shows that a peak luminosity of $5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ and in turn an average luminosity of $\geq 1 \text{ pb}^{-1}/\text{d}$ can certainly be expected. If LEP is operated for 100 d in each of the years 1999 and 2000, an integrated luminosity of $\geq 200 \text{ pb}^{-1}$ at highest energy is within reach which meets the requirements of the physics community [15] [16]. The luminosity at a given energy may be further optimised by working with $J_x > 1.0$ though this lowers slightly the maximum energy. Increasing the number of bunches from 4 to 6 per beam may also be considered [11]. This seems to be an interesting option exploiting the fact that LEP is equipped with an appropriate set of electrostatic separators for operation with more than four bunches.

5 CONCLUSIONS

LEP had its first long production run at high energy in 1997 producing an integrated luminosity of 64 pb^{-1} at

92 GeV per beam. The rf system consisting of a combination of copper and superconducting cavities reliably provided an rf voltage of 2.5 GV. In 1998, after an addition of 32 Nb-film cavities, the energy has been raised to 94.5 GeV and 1.2 pb^{-1} per day has been produced in the present running period which will extend until end of October 1998. After a further addition of 16 of these cavities, the operationally available rf voltage will reach 2.9 GV in 1999. The advanced upgrading of the four cryogenic plants for LHC will double the dynamic load capacity available at 4.5 K for the LEP cavities and will permit to envisage operation at accelerating gradients exceeding the nominal 6 MV/m in order to reach up to 100 GeV per beam in the years 1999 and 2000 with an average luminosity exceeding 1 pb^{-1} per day. Thus, the potential of LEP will be fully exploited making proper use of the investment made during a vigorous upgrade programme based on R&D of rf superconducting cavities which started in the early eighties.

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