LEP STATUS AND PLANS

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Abstract

A description is given of the present performance of LEP. The major factors related to the limitations are discussed as are the measures currently used to overcome them.

The results from the "pretzel" scheme operation in 1994 are presented as well as a brief description of the new bunch train scheme. This scheme should ultimately allow the luminosity to be doubled by increasing the number of bunches per beam to sixteen (four trains of four bunches).

The results and limitations from the energy calibration by resonant depolarization are summarized.

A review is then given of the performance limitations, hardware requirements, and machine studies associated with operation of LEP at energies above the W± threshold. Finally the present plans for the LEP2 timescale are given.

I. INTRODUCTION

The CERN Large Electron Positron (LEP) collider is a 26.6km circumference e^+e^- storage ring which has, until the end of 1994, operated with 4 and 8 bunches per beam in an energy range of 20 to 50 GeV (see previous conference reports, [1],[2],[3],[4]).

LEP obtained its first circulating beam in July 1989 and performed collisions one month later in August. Since then, operation has been a mixture of physics data taking around the Z^0 energy (45.6 GeV) and machine studies aimed at performance improvement, beam energy calibration, and future upgrades. During 1994, LEP was operated for physics with a pretzel scheme and 8 bunches per beam and it is foreseen to further increase the number of bunches during 1995 by the use of a bunch train scheme [5].

For the second phase (LEP2) the collider will be operated at an energy of about 90 GeV with an expected luminosity $\sim 7 \times 10^{31}$ cm^{-2}s^{-1} to produce W pairs. This will be made possible by the addition of 224 superconducting cavities giving a total voltage of more than 2.2 GV. A total RF-power of about 30 MW will be available for the beam, which, with an energy loss of about 1.9 GeV per turn, will be sufficient to store a current of ∼8 mA per beam.

II. PRESENT PERFORMANCE

For LEP1 the most critical parameters are the integrated luminosity, which dictates the number of Z^0s, and the precision with which the beam energy can be calibrated, which determines the mass and the width of the Z^0 interaction. Figure 1 shows the increase in the daily integrated luminosity over the past 6 years. The integrated luminosity has been increasing by about 50% per year over the past 3 years. Since there has been no significant increase in the current per bunch this increase is due to three main factors.

1. Improvements in the operational efficiency,

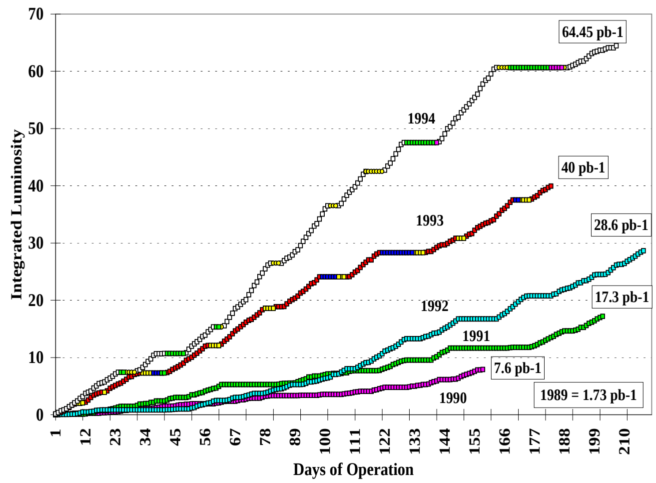

Figure. 1. Daily Integrated Luminosity

2. Optimization of the beam-beam tune shift by emittance control, and
3. Increasing the number of bunches by the use of the pretzel scheme.

A. Improvements in the Operational Efficiency

The operational efficiency in LEP (defined as the ratio of the actual hours spent in physics to the scheduled hours) has steadily increased from about 40% in the first year of operation to about 61% during 1994. It should be noted that due to the finite refill time the efficiency can never be 100% (a realistic upper limit is ∼ 85%), and that the efficiencies of all injectors in the LEP injection chain are included in this figure. The improvement in the operational efficiency is due to two main components

1. Improvements in the reliability of all hardware. This has been done by identifying the least reliable components and improving their design as well as doing preventative maintenance.
2. Reduction of the refill time. The accumulation time has been reduced by improving the injection efficiency by better diagnostics and by using synchrotron injection [6] [7]. In addition the applications software has undergone enormous improvements which greatly speed up all "measure and correct" manipulations.

B. Beam-beam Optimization

The luminosity (L) is directly related to the vertical beam-beam tune shift (ξ_y) i.e.

$$L = \frac{\gamma}{2r_e e}\frac{k_b i_b \xi_y}{\beta_y^*} \quad (1)$$

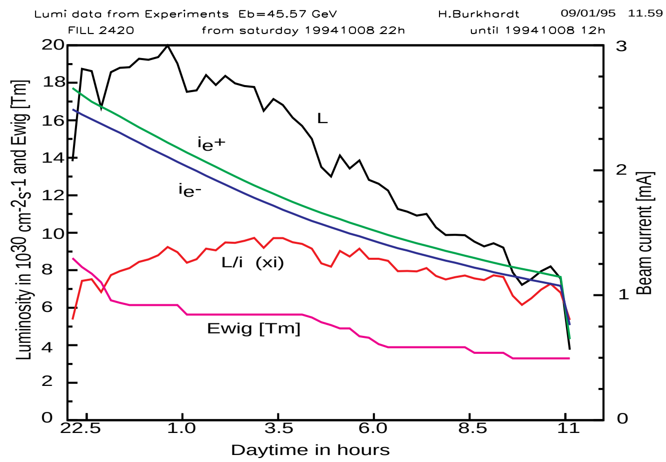

Figure. 2. Evolution of beam parameters during a typical physics run.

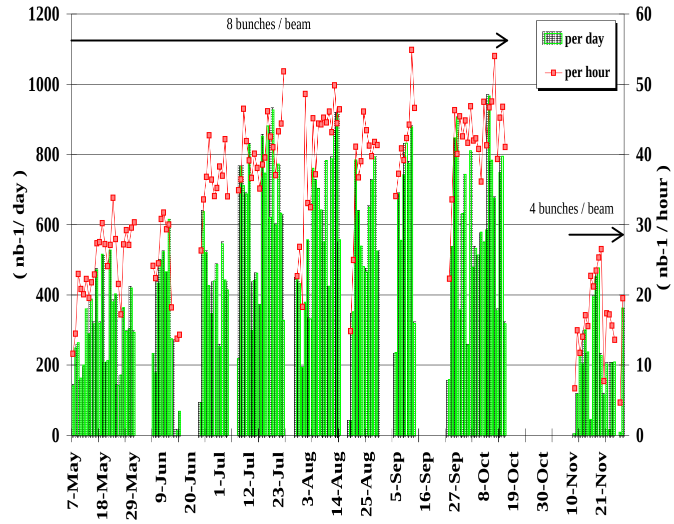

Figure. 3. Daily and Hourly Luminosity during 1994.

where γ is the relative energy, k_b the number of bunches per beam, and i_b the bunch current. The beam-beam strength parameter is approximately given by

$$\xi_y \approx \xi_x = \frac{i_b r_e}{2\pi\gamma e f_{rev}\varepsilon_x} \tag{2}$$

where ε_x is the horizontal emittance.

Clearly in order to maximize the integrated luminosity during a physics run, it is necessary to maintain the ξ_y at its maximum value independent of the bunch current which decays naturally with time. Consequently the natural emittance must be sufficiently small so that the beam-beam "limit" can still be reached with the low bunch currents at the end of the run. The natural horizontal emittance is approximately given by

$$\varepsilon_x \approx \frac{c_q R\gamma^2}{\rho Q_x^3} \tag{3}$$

where R is the average radius, ρ the bending radius, and Q_x the horizontal tune value.

In LEP the small emittances are obtained by the use of a 90^0 phase advance per cell lattice instead of the original design of 60^0. It is also clear from equation (2) that, in order to maintain ξ_y constant, larger emittances are needed at the higher currents associated with the beginning of the run. To this end emittance wiggler magnets are excited at the beginning of the run and progressively reduced during the course of the run. The evolution of the beam parameters, during a typical run in 1994, are shown in Figure 2.

C. Pretzel Operation

A horizontal pretzel scheme was developed during machine studies periods in 1993 and brought into operation near the end of 1993 [8]. The same scheme was used throughout 1994 for operation for physics and after an initial learning period resulted in an increase in luminosity which corresponded to the increase in number of bunches. This can be demonstrated in Figure 3 where the reduction in luminosity results from reverting to 4 bunch operation at the end of the year. Fine tuning of the machine was more difficult with the pretzel scheme and required very careful control of the closed orbits, the chromaticities, the horizontal and vertical separations, and the tune splits between electrons and positrons [9].

III. ENERGY CALIBRATION

The precise measurement of the mass and width of the Z^0 resonance requires a high integrated luminosity and *a very accurate absolute calibration* of the beam energy. The average beam energy can be measured by resonant depolarization to a relative accuracy of around 10^{-5}[10]. During the physics scan of the Z^0 in 1993, all energy calibrations were performed at the end of the fills, usually with a single beam, and usually with about 12 days between calibrations. In order to estimate the average beam energy on physics fills between calibrations it was necessary to monitor all possible energy changes during the time interval between these calibrations. The average beam energy can be changed either by a modification to the integrated bending field or by a change in the length of the central orbit. The latter phenomenon results from the fact that the beam path length is fixed by the frequency of the RF system which can be held constant to around 10^{-10} . In principle, variations in the bending field should be seen by the reference magnet which is connected in series with the dipoles and equipped with flip-coil and NMR field measuring devices. However due to the large dimensions of LEP, there can be differences in the environment between the reference magnet and the main dipoles (magnet temperatures etc.) which must be carefully monitored and used in correcting the energy estimates from the reference magnet system. In addition, about once every two weeks a measurement of the total integrated dipolar field ("flux-loop") is done in order to cross-correlate with the resonant depolarization measurement. The length of the central orbit is regularly measured by changing the revolution frequency until the beam is centered in all sextupoles. The observable for this centering technique is the change in the tune value when large chromaticities are applied with the sextupoles.

In LEP the beam energy at each interaction point is different from the average beam energy as measured by the techniques described previously. This difference results from a combination of the energy "sawtoothing" and the geometrical alignment and properties of the RF accelerating system. RF phase errors and voltage asymmetries produce changes in the energies of the two beams at the collision points. The status of the RF system is an important ingredient in the final calibration of the colliding beams.

Despite all these correcting algorithms, considerable variations in the LEP energy were observed during the course of the 1993 scan. The path length variation has been identified with tidal effects and other variations on a longer time scale. More recently, other subtle effects have been investigated, such as the influence [11] of the water level in Lake Geneva and the effect of small values of dispersion at the collision points.

IV. LIMITATIONS FOR LEP1

A. Beam-beam, Background and Aperture

The luminosity of LEP1 is limited by the interplay between beam-beam effects, background in the detectors, and the aperture as set by the collimator system. Low background conditions in physics are ensured by a large number of collimators which define the LEP physical aperture, shield from synchrotron radiation and from off momentum particles generated by beam gas interactions. For geometric reasons, it is not possible to collimate a beam with a horizontal emittance greater than 45 → 50 nm. The natural emittance at Z^0 energies is around 13nm, which, at high currents is increased to around 40 nm by the use of emittance wiggler magnets.

From equation (1), with a constant value of ξ_y it appears that the luminosity may be increased linearly with the bunch current (i_b). It is also clear from equation (2) that for constant ξ_x the horizontal emittance (ε_x) increases linearly with current and for LEP reaches around 45nm with a bunch current of ∼350μA. Increasing the bunch current beyond this value would require retraction of the collimators to avoid reductions in the lifetime. This has been attempted on several occasions and always produced an increase in the background rates. Consequently the maximum bunch currents which can be collided at Z^0 energy has been limited to around 350μA for several years.

When operating at high values of ξ, the beam parameters (tunes, chromaticities, closed orbits, bunch current inequalities) must be adjusted within very tight tolerances (±.003 in tune and ±1 in Q′) in order to avoid non Gaussian tails [12]. The creation of these tails reduces dramatically the lifetime due to the aperture reasons given above.

B. Number of Bunches and β_y^*

For LEP1, when operating at the beam-beam limit, it is clear from equation (1) that the only remaining "free" parameters are the β_y^* and the number of bunches (k_b). The design value for the β_y^* was 7cm and LEP is currently operated with 5cm. On trial runs the β_y^* has been reduced to 3.7 cm but without any increase in the luminosity and resulted in much greater sensitivity of the beam to small perturbations due to the very large β values at the first two insertion quadrupoles.

The number of bunches was doubled to 8, by the use of the pretzel scheme at the end of 1993 and throughout 1994. Although the pretzel scheme could have been extended to a larger number of bunches, the detector electronics imposed a maximum of 8 equally spaced bunches. Consequently two proposals were studied to used trains of bunches. The first, which had a horizontal crossing angle was abandoned because of the large background created by passing off center in the low β quadrupoles near the interaction points. The second proposal involved separating the beams at the unwanted collision points using electro-static separators upstream and downstream of the interaction point. This scheme has been studied extensively during machine study periods [5]. The limitation to the number of bunches in the train came from the detector electronics requirement that the total length of the train be not greater than 750 ns. The minimum bunch spacing is given by the distance from the first separator to the interaction point, which sets an upper limit of 4 bunches per train. It is foreseen to operate LEP1 during 1995 with 4 trains of 4 bunches per beam unless some unexpected critical problems are encountered with this scheme.

C. Summary of LEP1 Performance

Table 1 gives a comparison of the LEP design parameters with those achieved in physics or in machine study sessions.

Table 1. Comparison of Achieved with Design

Parameter	Design	Achieved	Units
Peak Luminosity	13	24	$10^{30}cm^{-2}s^{-1}$
Luminosity/day	480*	1000	nb^{-1}
Beam beam ξ_y	.030	.049	
Bunch Current	750	820	μA
β_y^*	.07	.037	m
Total Current	6.0	10.0	mA
Energy calibration	∼25	1.7	MeV

V. FUTURE PLANS – LEP2

A. Beam Energy Limitations

The most crucial parameters for the physics to be performed above the W± threshold are the *maximum* beam energy and the integrated luminosity. The beam energy is determined by the total installed RF voltage needed to replenish the losses due to synchrotron radiation and to provide an "RF bucket" sufficiently large to provide a quantum lifetime of around 15 hours. Since the radiation losses increase with E^4 the required RF voltage increases dramatically with the beam energy needing more than 2000 MV/turn needed at beam energies of ∼ 90 GeV (see Figure 4).

B. Luminosity Limitations

Combining equations (2) and (3) gives

$$\xi_y \approx \xi_x \propto \frac{i_b Q_x^3 J_x}{\gamma^3} \tag{4}$$

Consequently, for all other parameters constant, to maintain identical beam-beam conditions at 90 GeV as at 45 GeV would require an increase in the bunch current by a factor of 8. It is therefore unlikely that LEP2 will be strongly beam-beam limited

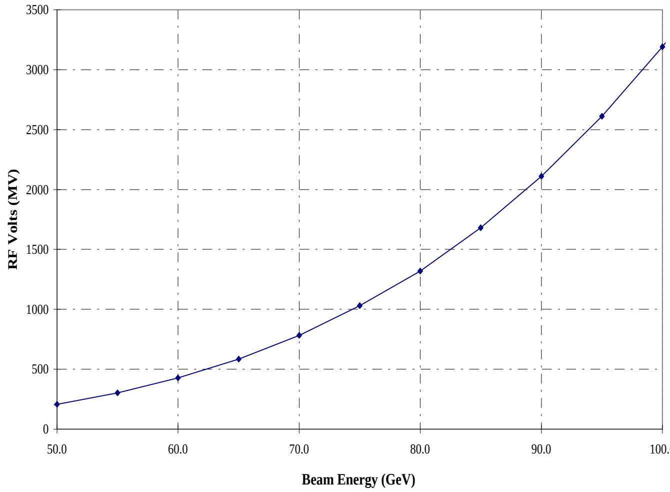

Figure. 4. RF Voltage as Function of Beam Energy.

as is the current operation of LEP1. In this case the luminosity is better written as

$$L \propto k_b \frac{i_b^2}{\sigma_x^* \sigma_y^*} = \frac{i_{total}^2}{k_b \sigma_x^* \sigma_y^*} \quad (5)$$

In LEP2 the *total* current will be limited by the required beam power which is transmitted from the klystrons i.e.

$$P_{klystron} = P_{beam} \propto 2 i_{total} U_0 \propto 2 i_{total} E_b^4 \quad (6)$$

e.g. 30 MW of klystron power allows 8 mA of beam current at 90 GeV. It is evident from equation (5) that with the total current being limited, the luminosity is maximized by storing this current in the *minimum* number of bunches k_b, or in other words maximizing the bunch current. The current per bunch in LEP is limited at injection energy by the Transverse Mode Coupling Instability (TMCI). The approximate threshold for this instability is given by [13]

$$i_{th} = \frac{2\pi Q_s E_b f_{rev}}{e \sum \beta_i k_{\perp i}(\sigma_s)} \quad (7)$$

where Q_s is the synchrotron tune, E_b the beam energy, and β_i the betatron amplitude function at the location of the transverse loss factor $k_{\perp i}$ which decreases with increasing bunch length (σ_s). In order to maximize the current per bunch for LEP2 operation, several schemes have been proposed and tested.

- The "High Q_s" Scheme [14], in which the synchrotron tune is increased at injection energy and reduced in steps as the energy is increased. The highest bunch current reported in Table 1 was obtained [15] using a Q_s of .0125 at injection energy. The main anticipated problem with this scheme is the possible beam loss due to traversing (at higher energies) low order synchro-betatron resonances with high beam intensities.
- Increasing the injection energy from 20 to 22 GeV. Two new superconducting bi-modules have been installed in the SPS which will allow the extraction energy to be raised to 22 GeV. This should increase the threshold current by 10% and the luminosity by 20%. Energies higher than 22 GeV would require substantial changes to the transfer lines and an upgrade of the radiation shielding in the SPS machine.
- Reduction of the transverse impedance ($k_\perp$). The major source of transverse impedance in LEP comes from the 120 room temperature cavities (47% of the present total impedance) which could be replaced by about 32 SC cavities which have a much smaller transverse impedance (1.5%) due to their large bore diameter. This replacement, along with the other mentioned improvements should allow bunch currents of ∼0.8 mA at the LEP2 collision energies. Under these conditions and with 8 bunches per beam, a peak luminosity of $\sim 7\times 10^{31}$ cm^{-2}s^{-1} is predicted at 90 GeV.

Further optimization of the luminosity may result from a reduction in the beam size at the IP (see equation (5)). This can be achieved with a higher phase advance per cell lattice which reduces the horizontal emittance (see equation (3)). A lattice with phase advances of 108^0 and 60^0 (H and V) has been tested with beam [16] with very encouraging results. If operation is possible with this lattice and the high bunch currents described previously it is conceivable that LEP2 may produce beam-beam tune shifts of ∼.03 with a luminosity of $\sim 10^{32}$ cm^{-2}s^{-1}.

C. LEP2 Hardware

The hardware conversion to re-configure LEP1 to LEP2 has been going on for several years with the final modifications carried out during the last winter shutdown which ended in April 1995. These modifications included

- civil engineering for the new klystron galleries around IP4 and IP8.
- complete re-arrangement of the 8 RF straight sections to physically accommodate the new SC cavities.
- installation of 4 new 12kW cryogenic plants
- replacement of the superconducting low β quadrupoles
- and, an upgrade of power converters for higher energy

The final stage of the energy upgrade will be the installation of more than 200 SC cavities with their associated couplers, waveguides, klystrons and control electronics. This work will be carried out progressively until the spring of 1997 with several milestones (see later).

D. Superconducting Cavities

For the LEP2 SC cavity system three aspects can be identified as being critical.

1. Cavity production and module (4 cavities) assembly (for details see contribution to this conference [17] .
2. Design and performance of the main coupler which must be capable of passing 125kW to the beams (for details see contribution to this conference [18].
3. Higher order mode couplers. The initial design of the output lines from these couplers imposed a current limitation for LEP especially when operation was foreseen with bunch trains. Recent improvements in the design of the output lines have allowed the HOM power per cavity to be increased from the 400W "design" to 1700W which is beyond any powers foreseen with a reasonable set of parameters.

At present there are 7 SC modules (28 cavities) installed in LEP. Two of these modules were installed in Autumn 1994 and

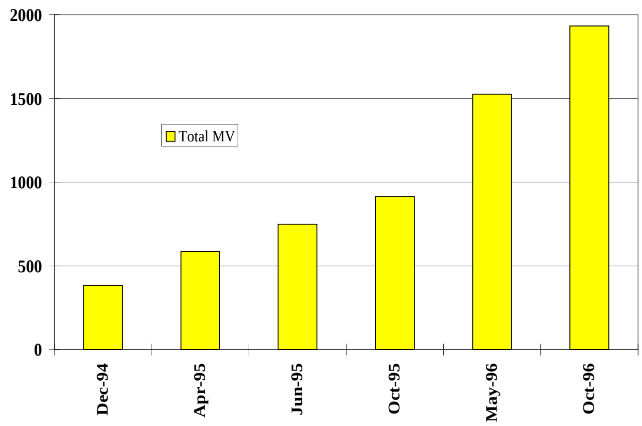

Figure. 5. Planned Available RF Voltage.

could be tested with beam during the last running period of this year. One of these modules was successfully operated for more than 70 hours at its design gradient of 6MV/m and in the presence of the normal operating intensities for LEP1.

E. Installation Plans

The planned installation (see Figure 5) of SC cavities should allow a physics data period with ∼70 GeV per beam at the end of 1995 followed by a run at 80.5 GeV in the first part of 1996 which will allow a precision measurement of the mass of the W. In October 1996 the increased RF voltage should allow phyics data taking at energies significantly above the threshold of W± production. In 1997 production physics runs will be started at the maximum possible energy .

F. Summary of Plans

In 1995 LEP1 will continue operation at Z^0 energies but using a bunch train scheme which should significantly increase the luminosity. During the first part of 1996 it is planned to perform physics data taking at 80.5 GeV/beam for precise measurement of the mass of the W. Following a shutdown in Autumn 1996, LEP2 will be operated for the first time at energies above the W± threshold. Following the 1996–1997 winter shutdown LEP2 will start an exciting physics programme at high energies which will extend beyond the year 2000.

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