LEP Progress and Future

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Abstract

The LEP performance in 1992 and the plans for 1993 are presented and discussed. The status of the LEP 2 project aiming at an increase of the LEP beam energy beyond the $W^\pm$ threshold is discussed. A recent proposal to increase the luminosity of LEP by up to an order of magnitude by operating it with equidistant bunch trains of up to seven bunches is presented.

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1 LEP Status in 1992

Table 1 shows a comparison of performance figures for 1989–1992. Despite considerable difficulties during the start-up, the 90/90 configuration with $\mu_x = \mu_y = \pi/2$ in the arcs has been a success. The lower emittance than in the 60/60 configuration of 1991 was used to compensate for the lower than expected bunch current limit. The average vertical beam-beam tune shift $\xi_y \approx 0.032$ in 1992 was higher than $\xi_y \approx 0.022$ in 1991.

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<tbody>
<tr>
<td>Total/h</td>
<td>3107</td>
<td>3443</td>
<td>4002</td>
<td>4883</td>
</tr>
<tr>
<td>Physics/h</td>
<td>1321</td>
<td>2504</td>
<td>2762</td>
<td>3439</td>
</tr>
<tr>
<td>Actual Coast/h</td>
<td>469</td>
<td>1048</td>
<td>1242</td>
<td>1742</td>
</tr>
<tr>
<td>Efficiency/%</td>
<td>35</td>
<td>43</td>
<td>45</td>
<td>51</td>
</tr>
<tr>
<td>MD/h</td>
<td>454</td>
<td>689</td>
<td>997</td>
<td>935</td>
</tr>
<tr>
<td>$\int L dt/\text{pb}^{-1}$</td>
<td>1.7</td>
<td>12.1</td>
<td>18.9</td>
<td>28.6</td>
</tr>
<tr>
<td>$\bar{L}/\text{µb}^{-1}s^{-1}$</td>
<td>1.0</td>
<td>3.2</td>
<td>4.2</td>
<td>4.6</td>
</tr>
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</table>

The luminosity $L$ was more constant during coasts because $\epsilon_x$ was reduced at lower bunch current by exciting emittance wigglers less. Using only one configuration for physics with or without pretzel, MD and LEP 2 studies improved the efficiency of LEP operation because of less time lost in transients between configurations and the more rapid build-up of experience in the PCR. The luminosity lifetime is now dominated by beam–beam bremsstrahlung.

1.1 Pretzels

In a pretzel scheme the $e^+$ and $e^-$ beams are separated over most of the circumference by exciting forced horizontal closed orbit oscillations with electrostatic separators. The beams collide head-on in the even pits. The bunch spacing is arranged such that beam–beam collisions in the arcs occur only where orbits are well separated. A pretzel scheme was first used and nicknamed in the CESR storage ring at Cornell University [1, 2]. The pretzel scheme for LEP was proposed by Rubbia [3] and added as an afterthought [4, 5]. Machine development with partial pretzels was done in 1991 [6, 7] and with full pretzels in 1992 [8]. The number of bunches is limited to $k = 8$ because of the Cu RF cavities which are coupled to storage cavities with a beat frequency corresponding to $k = 8$. Triggers for the LEP experiments happen to be OK. More than $k = 8$ bunches would require drastic modifications to the RF system and the detectors. Commissioning was much easier with the new configuration. Pretzels were used for physics during the last five weeks of 1992. The luminosity was slightly higher than without pretzels. While the bunch current is typically limited at 0.55 mA with four bunches, it is limited at 0.32 mA with eight bunches. This reduction is due to the mid-arc collisions. The luminosity is smaller than that expected from the bunch current because of the horizontal miscrosings at the even pits which are also caused by the separated mid-arc collisions.
1.2 Polarization and Energy Calibration

Polarization was not achieved with the 90/90 configuration. The reasons can be understood from simulations which predict a drop in $P$ from about 10% to about 2.5% when changing the configuration from 60/60 to 90/90, and show vertical orbit bumps which are not seen by the beam position monitors, and therefore cannot be corrected. Polarization was achieved with the 60/60 configuration as in 1991, and with a 90/60 configuration similar to that to be used in 1993.

![Energy Calibration Graph](image)

Figure 1: Energy Calibrations in 1992

Figure 1 shows the energy calibrations in 1992 by resonant depolarization. The differences are larger than expected, indicating that the LEP energy is affected by parameters which are not yet identified, and therefore uncontrolled. A measurement of the effect of tides in the Earth’s crust is in good agreement with expectations and demonstrates the stability of the energy calibration over a day. Figure 2 shows the results.

2 LEP Plans for 1993

A new LEP configuration 90/60 is being installed during the 1992/93 shutdown. In particular, the HIBL insertions near the odd pits and many power converters are new. They are
being installed as part of the LEP 2 programme. The phase advances are $\mu_x = \pi/2$ and $\mu_y = \pi/3$ in the arcs, combining the advantages of tight horizontal focusing in a lattice with $\mu_x = \pi/2$ and small horizontal emittance $\epsilon_x \approx 12$ nm with the better orbit correction in a lattice with $\mu_y = \pi/3$ and – it is hoped – polarization. Pretzels will be in routine operation for most of 1993. The LEP physics programme calls for scanning around the $Z^0$ peak. This implies energy calibrations twice a week at the end of physics coast, and polarization in the physics configuration with solenoids compensated by orbit bumps. This works in simulation.

![Figure 2: Effect of Tides on the Energy](image)

3 LEP 2

The LEPC Minutes of November 1992 state the objectives of the LEP 2 programme: Produce about 6000 W± pairs in about three years. With $\sigma \approx 17$ nb, this implies an integrated luminosity of 500 pb$^{-1}$. The baseline performance assumes four bunches in each beam with 0.5 mA each, and a horizontal emittance 50 nm at 90 GeV. It results in an initial luminosity $L = 11 \mu$b$^{-1}s^{-1}$ at a conservative beam–beam tune shift $\xi_y \approx 0.014$. If LEP is operated for 200 days/year at 60% efficiency, the average luminosity becomes $\bar{L} \approx 80$ pb$^{-1}$a$^{-1}$, assuming
coasts of 10 h and a lifetime determined by beam–beam bremsstrahlung. Several tricks can be envisaged to double \( L \) and to complete the W physics programme in three years: (i) Remove the Cu RF cavities, install extra superconducting RF cavities, and raise the bunch current to 1 mA. (ii) Use eight bunches instead of four in each beam. (iii) Reduce the emittance by changing the damping partition numbers. This implies an increase in the momentum spread, and hence a lower maximum energy. It is unlikely that these tricks are cumulative.

New HIBL insertions were installed during the 1992/93 shutdown. New LOBS insertions will be installed during the 1993/94 shutdown. Major subsystems, i.e. the cryogenic plant, civil engineering for klystron galleries near Pits 4 and 8, new high-power klystrons, control electronics for the RF system, electric power distribution, power converters, electrostatic separators, cooling and ventilation, magnets and vacuum, are all on schedule. Delays have occurred with the superconducting (s.c.) RF cavities. However, 19 s.c. RF cavities have been accepted; the higher-order mode coupler problem is believed to be solved; the power coupler problem is under investigation. The acceptance rate of bare s.c. cavities is now about 30%, but improving. The forward planning assumes 60% acceptance in 1993, and 80% in 1994. We hope to get a Nb-Cu module with adjustable power couplers into LEP during the 1992/93 shutdown, and five more during technical stop in June 1993. The commissioning of all 192 s.c. RF cavities is scheduled for October 1994. Operation of LEP 2 above the \( W^\pm \) threshold is foreseen from 1995 onwards. The beam energy will be about 88–89 GeV with all s.c. and Cu cavities, assuming 5 MV/m for 32 s.c. cavities near Pit 2, and 6 MV/m for all other s.c. cavities.

4 Bunch Trains

I propose to operate LEP with \( j = 2, 4, 6, 8, 10, \ldots \) equidistant bunch trains instead of equidistant bunches. In order to be quantitative I discuss one specific set of bunch train parameters. There are other sets. The bunch trains consist of up to \( k = 7 \) bunches. The bunch spacing \( s \) is determined by the RF harmonic numbers in LEP and its injectors. I propose \( s = 21 \lambda_{\text{RF}} \approx 17.875 \) m. The maximum length of a bunch train becomes \( l \approx 107.25 \) m. I assume that the bunch trains collide in the even pits with a full horizontal crossing angle \( \alpha = 1 \) mrad. I discuss in Section 4.1 the criteria for choosing \( \alpha \). I assume that the bunch trains are vertically separated in the odd pits if beam–beam collisions must be avoided there, i.e. if their number \( j = 4, 8, 12, \ldots \). I assume that beam–beam collisions in the arcs which are possible if \( j = 6, 8, 10, 12, \ldots \) are avoided by a horizontal pretzel scheme. Bunch trains for LEP were proposed earlier [9], and are being studied for CESR. Table 2 shows the parameters assumed in my calculations.

The main purpose of this proposal is an increase of the LEP luminosity beyond \( L = 100 \) \( \mu \text{b}^{-1}\text{s}^{-1} \) without the need for the LEP experiments to be substantially modified. It follows from Table 2 that the product \( jk \) must be larger than about 30. More modest variants can be envisaged: (i) Operate LEP with just two bunch trains and only four bunches in each train, thus avoiding all the complications of the vertical separation in the odd pits and of the pretzel scheme in the arcs, and still have eight bunches in each beam, and a luminosity
comparable to or better than the currently achieved values. (ii) Distribute a given current in more bunches, and operate LEP further away from the bunch current limit, at smaller emittances than those shown in Table 2, and still get the same luminosity as before. These considerations apply not only to a Z° factory, but also to LEP 2 where the severe RF power limitation excludes running with more than four or eight bunches in each beam. The SL Division has set up a study group to look into outstanding accelerator physics problems, study engineering aspects and implications for experiments, define machine development programme for 1993 and later, and study conversion of LEP 2 to bunch trains. It is unlikely that bunch trains will be operational in 1994, and that LEP 2 will be operated with bunch trains. The earliest time for the implementation of bunch trains appears to be after the completion of the W± physics programme.

<table>
<thead>
<tr>
<th>Energy $E$</th>
<th>45.6 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Current $I$</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>Horizontal emittance $\epsilon_x$</td>
<td>30 nm</td>
</tr>
<tr>
<td>Vertical emittance $\epsilon_y$</td>
<td>2.4 nm</td>
</tr>
<tr>
<td>Relative energy spread $\sigma_e$</td>
<td>$1.066 \times 10^{-3}$</td>
</tr>
<tr>
<td>Full horizontal crossing angle $\alpha$</td>
<td>1 mrad</td>
</tr>
<tr>
<td>Horizontal function $\beta_x$</td>
<td>1.25 m</td>
</tr>
<tr>
<td>Vertical function $\beta_y$</td>
<td>5 cm</td>
</tr>
<tr>
<td>Horizontal head-on beam–beam tune shift $\xi_x$</td>
<td>0.044</td>
</tr>
<tr>
<td>Vertical head-on beam–beam tune shift $\xi_y$</td>
<td>0.031</td>
</tr>
<tr>
<td>Luminosity/bunch $L$</td>
<td>$3.24 \mu b^{-1}s^{-1}$</td>
</tr>
</tbody>
</table>

**Table 2: Bunch Train Parameters**

### 4.1 Accelerator Physics of Bunch Trains

I propose beam–beam collisions between the bunch trains in the even pits with a horizontal crossing angle for the following reasons: (i) The horizontal aperture is larger than the vertical aperture. (ii) There is no increase of the vertical emittance $\epsilon_y$ due to the extra vertical dispersion $D_y$ caused by a vertical orbit bump. (iii) There is no extra $D_y$, but extra horizontal dispersion $D_x$ in the RF cavities, increasing the excitation of synchro-betatron resonances. (iv) The criterion [10] for the crossing angle $\alpha \ll \sigma_x/\sigma_y$ due to synchro-betatron resonances is more easily met in the horizontal plane. The following criteria enter into the choice of the horizontal crossing angle $\alpha$ and of the separation $x$ between the two bunch trains:

- The ratio $|x|/\sigma_x$ should be larger than some number in the range between 5 and 6 [11].
- The separated beam–beam tune shifts with $x \gg \sigma_x$, given by the following expressions, should be small compared to the beam–beam tunes shifts caused by the collisions at
the even pits:

\[
\xi_x = -\frac{N r_e \beta_x}{2\pi \gamma x^2} \quad \xi_y = \frac{N r_e \beta_y}{2\pi \gamma x^2}
\]

- The horizontal orbit distortions caused by the beam–beam kicks \( x' \) should be small enough not to cause the bunch trains to miss each other at the even pits. In order to get an upper limit on the horizontal beam separation, we compute the ratio between \( x' \) and the horizontal divergence \((\epsilon_x/\beta_x)^{1/2}\). With \( x \gg \sigma_x \), \( x' = -2N r_e / (\gamma x) \) is given by the separation \( x \) and the population \( N \) of the bunches in the other beam.

![Graph showing beam-beam tune shifts near even pits](image)

**Figure 3:** Beam–Beam Tune Shifts \( 10^3 \xi_x \) and \( 10^3 \xi_y \) near Even Pits in the S05M46 Optics

The bunch spacing \( s \) and the length of the bunch train \( l \) are determined by the shortest \( \delta \) and the longest distance \( \delta \) to the even pits where all above criteria are satisfied: \( 2\delta \leq s \leq l \leq 2\delta \). The nominal full horizontal crossing angle \( \alpha = 1 \) mrad is large enough that the criterion \( x > 5\sigma_x \) is satisfied. Figure 3 shows the horizontal and vertical beam–beam tune shifts \( \xi_x \) and \( \xi_y \) near the even pits of the S05M46 configuration: \( \xi_x \approx 0.0012 \) is small and flat between 5 and 60 m from the interaction point, while \( \xi_y \) is small between about 10 and 50 m, and rises quickly outside this interval. It follows from Figure 3 that collisions are possible between 10 and 50 m from the interaction point. Therefore, the length of the bunch train should be \( l \leq 100 \) m, and the bunch spacing should be \( s \geq 20 \) m. My proposal approximately meets these conditions. The ratio \( x'/(\epsilon_x/\beta_x)^{1/2} \) is about 10% in the interval \( 10 \leq s \leq 50 \) m.

### 4.2 Effects of Separation on Bunch Train Parameters

The low-\( \beta \) insertions cause a lower limit \( s \geq 20 \) m and an upper limit \( l \leq 110 \) m on the bunch train length. The upper limits on \( l \leq 60 \) m with vertical separation in the odd pits and horizontal separation at the centres of the arcs are smaller than with collisions in the
even pits only. Hence, it should be possible to run LEP with \( j = 2 \) and \( k = 7 \), i.e. with a total of \( jk = 14 \) bunches, and with \( j = 8 \) and \( k = 4 \), i.e. with a total of \( jk = 32 \) bunches, respectively.

<table>
<thead>
<tr>
<th>( E_c ) / keV</th>
<th>Centered</th>
<th>Offset</th>
</tr>
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<tbody>
<tr>
<td>( P/W )</td>
<td>77 ... 95</td>
<td>253 ... 332</td>
</tr>
<tr>
<td>( 10^{-16}dN/dt/1/s )</td>
<td>148</td>
<td>1744</td>
</tr>
<tr>
<td>( 10^{-13}d^2N/ddt) / s/keV</td>
<td>3.4</td>
<td>12</td>
</tr>
<tr>
<td>( 10^{-13}d^2N/ddt) / s/keV</td>
<td>3.8</td>
<td>6.3 ... 6.7</td>
</tr>
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</table>

### 4.3 Synchrotron Radiation

The orbit offset in the QS0 and QS1 quadrupoles enhances the synchrotron radiation and increases the critical energy \( E_c \), the synchrotron radiation power \( P \), and the total and differential photon fluxes \( dN/dt \) and \( d^2N/ddt \). Table 3 shows the synchrotron radiation parameters from QS0 for one centred and offset beam and \( j = 2 \) bunch trains and \( k = 7 \). The ranges show the variation from the near to the far end of QS0. The photon flux \( d^2N/ddt \) is taken at the critical energy \( E_c \). The enhanced synchrotron radiation causes the following problems: more background in the experiments, heating of critical vacuum chambers, extra gas load due to photo desorption. To overcome these effects, modifications of collimators and/or vacuum chambers are needed, and local synchrotron radiation masks are necessary. They remain to be designed.

### 5 Higher-Mode Losses

The excitation of higher-order modes (HOM) in the s.c. cavities is a potential performance limitation. If the bunch spacing \( s \) is an exact multiple of the wavelength of an HOM, then the HOM field will grow like the number of bunches in the train \( k \), and the HOM power like \( k^2 \), because the damping by the HOM couplers is too weak. Furthermore, the fields of the HOM excited by the two bunch trains in the \( e^+ \) and \( e^- \) beam colliding close to the s.c. cavities must be added. The damping achieved by the HOM couplers is large enough that the HOM fields decay between the passages of successive bunch trains. Hence, one may add their power. The total HOM power \( P_{\text{HOM}} \) is thus \( P_{\text{HOM}} = (2k)^2 j I q k_{\parallel} \), where \( I \) is the bunch current, \( q \) the bunch charge, and \( k_{\parallel} \approx 0.22 \) V/pC is the HOM loss factor. With \( I = 0.5 \) mA, \( q = 4.45 \times 10^4 \) pC, we find \( P_{\text{HOM}} = 1920 \) W for \( j = 2 \) and \( k = 7 \), and \( P_{\text{HOM}} = 2506 \) W for \( j = 8 \) and \( k = 4 \). The HOM couplers are currently designed for 400 W. In order to stay within this limit, \( I \) must not be larger than 0.23 mA and 0.2 mA, respectively. About half of \( k_{\parallel} \) is due to a single mode at about 639 MHz. If one adds the fields for this mode only, \( I \)
increases by a factor $\sqrt{2}$. The HOM frequency cannot be controlled because the only tuner on a cavity controls the frequency of the fundamental accelerating mode.

References