PREPARATIONS FOR HIGH-LUMINOSITY LEP

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Abstract Plans to increase the luminosity of LEP by means of a "pretzel scheme", permitting a much larger number of bunches to be stored and collided, have been described previously. This paper provides an update on these plans in the light of developments and further studies since LEP was turned on. Although the potential gain in luminosity diminishes with increasing energy, the scheme still appears useful above the threshold for W-pair production. A better understanding of multi-bunch instabilities and beam-beam effects of separated bunches has also been gained. The hardware implications (particularly separators and superconducting RF) and compatibility with other upgrades of LEP are discussed.

1 Introduction

LEP, the largest e^+e^- storage ring ever built, is now operating successfully with a substantial fraction of its "design" luminosity. This design value was calculated assuming that the machine would run in a mode similar to most of the earlier generations of e^+e^- colliders. Building on the experiences of its smaller predecessors, improved simulation capabilities and improved understanding of how beam-dynamics limit luminosity, the predictions of the luminosity for LEP were made rather realistically. At the same time, budget constraints and the need to keep the project well-defined for the large community of users, meant that more exotic, untried modes of operation were not considered as options for the first phase of running.

Now, as the physics motivations become clearer and our understanding of the machine steadily advances, we are in a better position to evaluate options such as Z^0-factory operation with more than the nominal 4 bunches per beam and correspondingly higher luminosity. The possibility of implementing a "pretzel" scheme, following the example of CESR [1], has been described in previous papers [2,3]. The purpose of the present paper is to review progress made in the meantime [4] and provide answers to some of the questions which were left open.

2 Implementation

Despite the fact that the focussing structure and layout of the straight sections of LEP will have to be changed [5] to accommodate the superconducting RF cavities to be installed for the energy upgrade (LEP200), it has proved possible to maintain the layout of the pretzel scheme essentially as proposed in [3]. Space is being reserved for the horizontal electrostatic separators just before the first quadrupole (QS11) of the dispersion suppressors in each experimental straight section. Of course, the installation of these pretzel separators remains contingent upon the removal of some of the normal-conducting RF cavities which presently occupy these spaces. Ways of ensuring compatibility with the possible installation of spin-rotators [6] are also under study. However it is considered very unlikely (virtually impossible in the case of vertical separation) that it would ever be possible to maintain longitudinally polarized beams in a pretzel scheme.

In high-energy operation, the emittance will be kept within the dynamic aperture limit by using the high-tune (90° betatron phase advance per FODO cell) version of the LEP lattice which is also very suitable for the pretzel scheme. All the calculations of [3] have been repeated for the latest optics and more favourable results have been obtained (see Table 1).

If it were feasible, vertical separation would have the advantage that the existing design of LEP's electrostatic separators could be used, cutting the lead time for installation of a pretzel scheme. Since experience has shown that it is very difficult to inject onto vertically displaced orbits and no solution has been found to the problem of *simultaneously* compensating the betatron coupling induced by pretzel orbits in the sextupoles *for each beam*, we continue to focus on a pretzel scheme with horizontal separation.

3 Parasitic beam-beam effects

The optimum number of evenly-spaced bunches in a given pretzel optics depends on a kind of interference among the various optical functions (β_x, dispersion η_x, and the pretzel orbits $x_\pm$). In [3], we described a method for choosing k_b based on the evaluation of the contributions of the long-range beam-beam forces to the tune-spread in the beams. The additional tune-spread should not amount to more than the synchrotron tune $Q_s \simeq 0.1$.

On the basis of various physical arguments or experience [7], it is possible to advance other criteria. For example, stability might be determined by the closest encounter X between bunches or by this same quantity expressed in units of beam size X/σ_x or, again, by the largest individual tune-shift $\xi_{x,y}$ occurring.

Table 1 shows computed parameters (see [4] for further details) related to the different stability criteria for all the allowed bunch numbers using identical pretzel orbits of amplitude $\hat{x}_\pm = 15\,\mathrm{mm}$. It is evident that, on the whole, application of one of the other criterion would lead to similar results as far as selecting good values of k_b goes. Given an adequate pretzel amplitude, the favourable bunch numbers stand out quite clearly.

These results have been confirmed by an independent simulation [4].

4 Potential performance

The synchrotron radiation loss per turn is given by

$$U_0 = \frac{2}{3}\frac{r_e E^4 I_2}{(mc^2)^3}, \qquad I_2 \simeq \frac{2\pi}{\rho}. \tag{1}$$

The total beam current is limited *either* by the installed RF power (assumed superconducting) *or* the maximum current per bunch $\max I_b$ and the maximum number of bunches k_b:

$$I_{\max} = \min\left(\frac{P_{\mathrm{RF}}}{2U_0}, k_b \max I_b\right) \tag{2}$$

Luminosity at the beam-beam limit is determined by the maximum current which can be stored:

$$L_{\max} = \frac{I_{\max}(E_0/mc^2)\bar{\xi}}{2er_e\beta_y^*} \propto \frac{P_{\mathrm{RF}}}{E^3}. \tag{3}$$

k_b	min X/mm	min X/σ_x	max $\xi_x^{(j)}$	max $\xi_y^{(j)}$	$\sum_{j=1}^{2k_b-1}{}' \lvert\xi_x^{(j)}\rvert$	$\sum_{j=1}^{2k_b-1}{}' \lvert\xi_y^{(j)}\rvert$
6	12.6	5.18	0.0023	0.0003	0.0187	0.0024
8	3.05	13.5	0.0002	0.0000	0.0018	0.00007
10	1.21	10.0	0.0007	0.0005	0.0079	0.0044
12	1.21	5.18	0.0025	0.0003	0.0386	0.0046
18	1.26	5.18	0.0023	0.0004	0.0253	0.0057
20	0.88	0.71	0.0266	0.401	0.2221	3.21
24	1.21	5.18	0.0025	0.0003	0.0437	0.0049
30	2.15	1.90	0.0111	0.146	0.1278	1.1889
36	1.21	5.18	0.0025	0.0004	0.0571	0.0113
40	0.20	0.25	0.0399	0.730	0.5574	9.1

Table 1: Parasitic beam-beam effects for allowed values of $k_b > 4$ with I_b and other beam parameters kept constant. The table shows the minimum values of the separation between bunch centres or this same separation in units of the beam size, the maximum values of the beam-beam strength parameters for individual encounters and, finally, the sums of the absolute values of these parameters over all the collisions (in 8 octants). The latter quantities are roughly twice the additional tune-spread.

Another ultimate limitation is the heating by irradiation of vacuum chamber

$$h_{\mathrm{vac}} = \frac{P_{\mathrm{RF}}}{2\pi\rho} \lesssim 4\,\mathrm{kW\,m^{-1}}. \tag{4}$$

This implies that the total RF power should be $P_{\mathrm{RF}} \lesssim 64\,\mathrm{MW}$ for the present vacuum chamber.

Figure 1 summarises the potential performance of LEP at all energies up to 100 GeV per beam with a pretzel scheme. There is no need to specify the optimum number of bunches at each energy—this depends on the single-bunch current I_b which can be achieved and the power available. At 81 GeV, for example, 32 MW of RF would allow 18 bunches to be stored with almost the nominal current (0.73 mA) per bunch.

5 Electrostatic separators

Around the four even-numbered Interaction Point (IP)s electrostatic separators would be installed in the last RF cell just before the dispersion suppressor, generating horizontal pretzel orbits of opposite amplitude for the e^+ and e^- bunches. These pretzel orbits extend over two arcs and the inter-leaved straight section until the next pretzel separator set which, by arrangement of the betatron phase advances, brings them together again.

During accumulation and acceleration any collision in the eight IPs of LEP is avoided with the help of the present separation system [8] which creates closed vertical bumps at the IPs. At top energy, the bunches are brought into collision at the even IPs whereas they will be kept separated elsewhere via the combined effect of the pretzel separators and the vertical separators at the odd points.

The electrostatic field required at Z^0 energy for a pretzel orbit of 11 mm amplitude and a total electrode length of 4 m is $1.6\,\mathrm{MV\,m^{-1}}$ yielding a deflection of $\simeq 0.139\,\mathrm{mrad}$. For a pretzel scheme to be operated at W^+W^- energies a second separator unit must be installed in each of the last RF cells in order to maintain the same pretzel amplitudes.

Any High Voltage (HV) breakdown in one of the separators causes a noticeable reduction in luminosity or even a complete loss of the stored beams [9,10]. To minimize the breakdown rate the electrostatic field will be limited to $1.6\,\mathrm{MV\,m^{-1}}$ and the vacuum in all separators will be kept at the low pressure of $\leq 10^{-8}\,\mathrm{Pa}$. Therefore, the separators must be baked at a temperature of 300°C.

A separator unit consists of a pair of hollow stainless steel electrodes, each 4 m long, mounted in an ultra-high vacuum tank of about 540 mm inner diameter. Each electrode can be charged independently via its HV feedthrough.

Energy (GeV)	46.5	93.
No. of units per octant	1	2
Field length per unit (m)	4	4
Min. gap width (mm)	150	150
Max. operating field ($\mathrm{MV\,m^{-1}}$)	1.6	1.6
Max. operating voltage (kV)	±120	±120
Max. voltage for conditioning (kV)	±160	±160

Table 2: Main parameters of the pretzel separation system

Any synchrotron radiation incident on the HV electrodes could greatly increase the breakdown rate [10]. Since the synchrotron radiation arriving from the main and weak dipoles is strongly concentrated in the horizontal plane, the electrodes will be built with a longitudinal slot so that most of the synchrotron radiation is not intercepted by the electrodes, but absorbed by horizontal collimators.

Since the electrostatic separators interrupt the continuity in the vacuum chamber cross-section, there will be higher order mode losses in these units. The energy lost by the beams is mainly deposited onto the separating electrodes. In the case of $I_b = 0.75\,\mathrm{mA}$, $k_b = 36$ and a natural bunch length $\sigma_z \simeq 16\,\mathrm{mm}$, the power dissipated in both plates is estimated to be of the order of 1200 W. To prevent overheating and the resultant outgassing which might increase the breakdown rate, the electrodes and the HV feedthroughs of each separator will be connected to a closed loop cooling system. Similar cooling must be added to the present separators in the odd IPs.

The main parameters of the pretzel separators are given in Table 2.

6 Other systems

A 36-bunch pretzel scheme would require a number of upgrades to LEP equipment. However many of these (e.g., new collimators, some additional vertical separators, upgraded vacuum chamber cooling) are already foreseen as parts of the energy upgrade.

It has been shown [4] that a straightforward upgrade of the positron production rate would allow the LEP Pre-Injector complex and the rest of the Injector Chain to fill all 36 bunches in LEP without a significant increase of filling time. Bunch-cutting in the PS, a doubling of the cycle rate in the SPS and modifications of the injection kickers in LEP would also be necessary but all these improvements appear to be feasible.

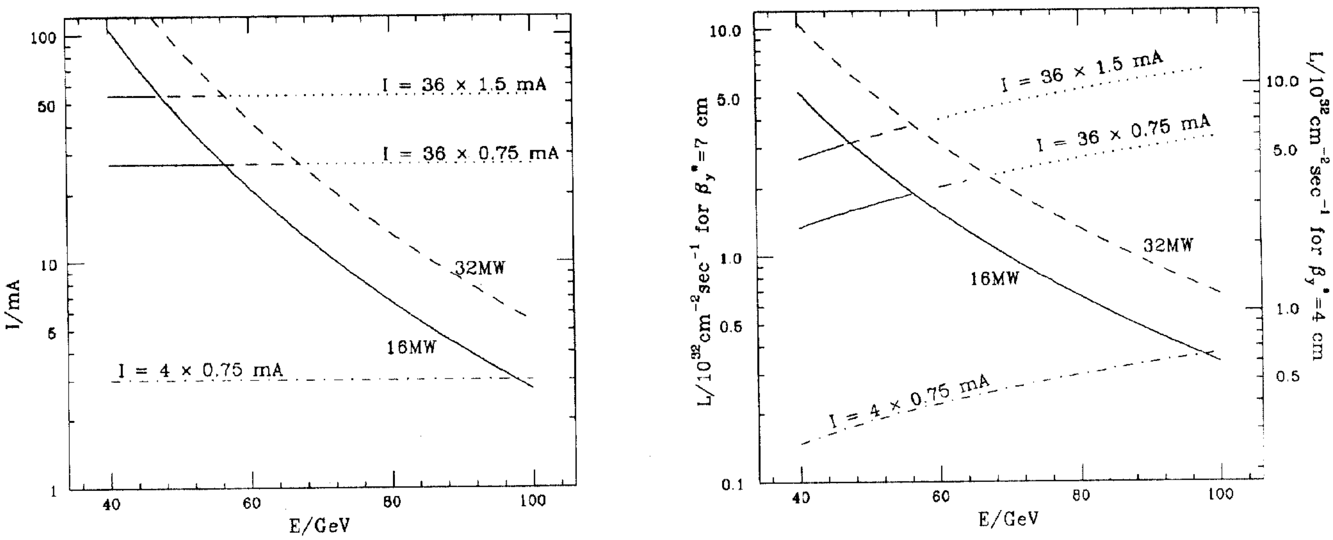

Figure 1: Ultimate limits on the total beam-current and luminosity in LEP. The limits due to total installed RF power of 16 MW and 32 MW are shown as well as the limit due to a maximum current per beam of either $36 \times 0.75\,\mathrm{mA}$ or $36 \times 1.5\,\mathrm{mA}$ (this is an optimistic upper limit for I_b). The nominal current of $4 \times 0.75\,\mathrm{mA}$ is also shown. The left luminosity axis is for the nominal $\beta_y^* = 7\,\mathrm{cm}$ and the right one is for β_y^* reduced to 4 cm.

Extrapolation of the vacuum performance and pressure rises into the future [4] shows that the beam-gas lifetime should not be a limiting factor for the pretzel scheme. It appears therefore that a high ratio of average-to-peak luminosity can be achieved.

Upgrades of various beam instrumentation and associated data-processing systems [4] are necessary and use of some systems will be restricted (e.g., wire scanners) or impossible (UV light monitors, X-ray monitors, streak camera). Most of the problems are associated with the shorter times between bunch passages or the high total intensity. The present Beam Orbit Measurement system may be adequate but only if strategies to measure the orbit at all pickups with small k_b and at just a few active pickups with large k_b can be shown to be sufficient in practice. Otherwise a costly upgrading will be needed.

The original design of input power and Higher Order Mode (HOM) couplers for the superconducting RF cavities cannot handle the HOM power levels generated by the high beam current. Measurements on the cavities already installed have confirmed computations of the loss factors [11]. However work on new coupler designs satisfying the constraints of the LEP tunnel and cryostats is proceeding with high priority. This is probably the most critical item in the implementation of the pretzel scheme at the Z^0-energy.

The LEP detectors are also examining ways of dealing with the increased interaction rates [4].

7 Conclusions

Many of the hardware and beam-dynamical questions associated with High-Luminosity LEP have now received satisfactory answers although some are still outstanding. Forthcoming experiments on the machine itself will help to answer some of the unresolved beam dynamics issues and work is proceeding towards the goal of ensuring that the superconducting RF cavities can tolerate the high beam currents.

Peak luminosity at the Z^0 resonance might be increased nearly an order of magnitude over what can be achieved with 4 bunches (provided the same values of I_b can be achieved on pretzel orbits), opening up a wide range of precise tests of the Standard Model [4]. The prospects of a factor of 4 increase over the "design" luminosity at the W^+W^--production threshold and a factor of 2 at 90 GeV are also enticing. In the event that there are difficulties in reaching design luminosity *per collision* at high energy (e.g., an insufficient dynamic aperture may not allow the emittance to be increased enough to stay below the beam-beam limit with a given I_b), the pretzel scheme, with its flexibility in the choice of bunch numbers may provide the only way of translating the installed RF power into luminosity.

Acknowledgements: We thank many of our colleagues at CERN and Cornell, in particular the contributors to [4], for information and helpful discussions.

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