Single-Bunch Intensity Limitations in Low-Emittance Lattices for LEP

G. Sabbi, A. Wagner

Abstract

Single-bunch collective effects at injection are discussed for the low-emittance 108°/60° and 135°/60° LEP lattices. In particular, calculations of bunch length at high current, and calculations of threshold current for vertical stability as function of synchrotron and betatron tunes are presented and compared with measurements. Comparisons with the present 90°/60° lattice are also performed, and the effect of polarization wigglers is investigated. These results have been obtained using the multi-particle tracking program TRISIM; the impedance model corresponds to the machine status during the 1994 run, and the β function values at the impedances are those of the optics which were used for the 1994 machine experiments.

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1 Introduction

In present LEP operation near 46 GeV/beam, the bunch current is limited by the beam-beam effect: in these conditions, a higher luminosity can only be obtained by increasing the number of bunches, as it has been done by operating the machine with the “Pretzel” and the “Bunch Trains” schemes. However, at the higher energy of about 90 GeV/beam (which can be obtained with the additional RF power generated by the superconducting cavities now being installed in the frame of the LEP2 project), the beam-beam limitation to the bunch current is shifted to higher values. Moreover, at LEP2 the total beam current will be limited by the synchrotron radiation energy loss (which has to be compensated by the available RF power) and by the limited amount of cooling provided by the cryogenic system. As a consequence of these new boundary conditions, it is no more attractive to operate the machine with a large number of bunches: on the contrary, the optimal luminosity would be achieved using a small number of bunches with the highest possible intensity. On the other hand, this strategy encounters a major obstacle due to collective instabilities at injection, which presently limit the bunch current to values lower than those required in order to reach the design luminosity in 4-bunch operation [1].

Since the beam-beam effect is not expected to be a limitation at an energy of about 90 GeV, a significant luminosity gain can be achieved by reducing the emittance of the bunches. This can be obtained with a high tune lattice [2]. Two possible candidates, with a horizontal phase advance of, respectively, 108° or 135° per cell, have been extensively studied [3, 4], and their performance has been tested in several experiments [5, 6, 7, 8, 9, 10]. Both lattices have a vertical phase advance of 60°. Theoretical studies have shown that the ultimate gain in luminosity is as high as a factor 2.3 with respect to what can be achieved with the present 90°/60° lattice; however, because of the increased sextupole strength, some difficulties arise [11] in controlling the single-particle dynamics (chromaticity correction leads to nonlinear resonances, off-center orbits result in larger stopbands for linear resonances): these difficulties have been circumvented in the case of the 108°/60° lattice, while the 135°/60° lattice, which gives about the smallest emittance possible in a regular FODO-lattice, is still at a less advanced stage of development.

Also intensity limitations due to collective effects are generally more severe in a low-emittance lattice: in fact, the threshold for TMC (transverse mode coupling) instability, which is presently limiting the bunch current at injection, is decreased by the reduction of synchrotron tune and of bunch length due to the smaller momentum compaction factor. These effects could significantly reduce the luminosity gain expected from emittance considerations. The reduced bunch length is also potentially dangerous from the point of view of SC cavity operation, as it can enhance the excitation of high-frequency modes and possibly cause damage to the HOM couplers. Following these considerations, it becomes clear that single-bunch collective effects at injection will be a potential performance limitation for LEP2, and have therefore to be studied carefully.

The current limitation due to TMC instability in both the 108°/60° and 135°/60° lattices has already been studied theoretically [12], and a few relevant experiments concerning the 108°/60° lattice have been carried out [6, 7]: a very good agreement between theoretical predictions and measured values has been obtained so far. These results are promising, as the maximum bunch intensity is not much reduced with respect to that attained with the present 90°/60° lattice. However, more subtle effects have not yet been investigated: in particular, the longitudinal effects at high current, and the influence of betatron tune on the stability threshold
could not be studied in detail during the experiments due to the limited time available, and at the same time were not included in the theoretical model. The multi-particle tracking program TRISIM [13], which is based on a new formalism allowing an accurate and fast calculation of the wakes, and which includes a refined model of the impedance of LEP, has been successfully tested on the experimental data of the 90°/60° lattice [14]. We therefore assume that it can be used to predict the performance of the new low-emittance lattices with some confidence. In this report, the results from simulation will be presented, and compared with the available experimental data.

2 Machine model

The geometry of LEP has been modelled by a ring divided into 5 sectors, each of which is composed by a point-like element followed by an arc section in which the motion is assumed linear. This machine representation is illustrated in Fig. 1: the first element is placed at the position conventionally indicated as “start LEP” (IP1), and represents a pick-up which collects, at each turn, the relevant bunch data; the second element (clockwise) and the fourth one represent the accelerating RF stations in IP2 and IP6, and also include the effect of the impedance of the straight sections (copper and superconducting cavities, separators and the associated bellows and tapers). The two remaining elements account for the impedance of the curved sections (shielded bellows).

![Figure 1: The LEP machine model A](image)

The motion of a set of macroparticles in this virtual machine is then simulated, in a 2D longitudinal-vertical plane, for a suitable number of turns: the beam dynamics includes synchrotron radiation loss, radiation damping, quantum excitation, sinusoidal RF, while the effects of chromaticity and beam loading, which are also included in the simulation program, were not investigated in this application; the wakefield effects, which depend on the particle distribu-
tion, are represented as kicks, lumped at some of the point-like elements. A detailed discussion concerning the equations of motion, the wakefield representation technique, and the efficiency of the described model in representing the real machine can be found in [14].

For what concerns the impedance model, several elementary structures are considered: one cell of the copper cavity, a four cell superconducting cavity, an electrostatic vertical separator, the different bellows and tapers which connect these structures to the vacuum chamber, and a shielded bellows for vacuum chamber interconnections in the arcs. For each structure, the wake potential for a reference (basis function) distribution, having a triangular longitudinal shape and a multipolar dependence on the azimuth, has been computed using the electromagnetic mesh code ABCI [15]. The so obtained reference wake potentials have then been combined in "effective wakes" for the point-like elements, by taking into account the number of structures in each impedance class, and the average values of the (vertical) $\beta$ function at each class. These data are reported in table 1: they correspond to the machine status during the 1994 run, and to the optics which have been used during the experiments.

<table>
<thead>
<tr>
<th>Structure</th>
<th>N</th>
<th>$&lt;\beta_y&gt;$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper cavity cell</td>
<td>600</td>
<td>40.6</td>
</tr>
<tr>
<td>Four cell SC cavity</td>
<td>20</td>
<td>51.3</td>
</tr>
<tr>
<td>ZL tank &amp; electrodes</td>
<td>36</td>
<td>66.4</td>
</tr>
<tr>
<td>Separator tapers &amp; bellows</td>
<td>47</td>
<td>56.1</td>
</tr>
<tr>
<td>Straight section bellows (L)</td>
<td>128</td>
<td>40.6</td>
</tr>
<tr>
<td>Straight section bellows (S)</td>
<td>160</td>
<td>40.6</td>
</tr>
<tr>
<td>SC module taper</td>
<td>5</td>
<td>51.3</td>
</tr>
<tr>
<td>Shielded bellows (arc)</td>
<td>2668</td>
<td>108°/60°/60°/60°</td>
</tr>
</tbody>
</table>

Table 1: Impedance model of LEP: the elementary structures which have been taken into account, their number, and the average values of the (vertical) $\beta$ function are reported. For the straight sections, the $\beta$ function values have been assumed to be the same as those which have been computed by A. Verdier for the 90°/60° (1994) lattice.

<table>
<thead>
<tr>
<th>Wiggler Excitation</th>
<th>Damping</th>
<th>Radiation loss/turn</th>
<th>Energy spread</th>
<th>Damping time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>MeV</td>
<td>MeV</td>
<td>s</td>
</tr>
<tr>
<td>520</td>
<td>0</td>
<td>6.94</td>
<td>22.8</td>
<td>0.255</td>
</tr>
<tr>
<td>520</td>
<td>500</td>
<td>14.97</td>
<td>36.4</td>
<td>0.119</td>
</tr>
</tbody>
</table>

Table 2: Beam parameters for nominal wiggler currents [16].

More details about the impedance model and the calculation of the reference wakes are provided in [14], where a discussion concerning the possibility of representing the effect of different structures as an "effective wake" lumped at a point-like element can also be found.

For what concerns the other input parameters, table 2 reports the values of the zero-current
energy spread, of the radiation energy loss, and of the radiation damping time, depending on
the excitation of the wiggler magnets [16], while the momentum compaction factors for the
three lattices are reported in table 3.

<table>
<thead>
<tr>
<th>Lattice</th>
<th>$90^\circ/60^\circ$</th>
<th>$108^\circ/60^\circ$</th>
<th>$135^\circ/60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1.86 \times 10^{-4}$</td>
<td>$1.38 \times 10^{-4}$</td>
<td>$0.98 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 3: Momentum compaction factors for the three lattices.

The number of macroparticles has been chosen according to the criteria formulated in [14].
A few thousands particles have been used for currents below the threshold of longitudinal
turbulence, while above this threshold between 3000 and 5000 particles were used; some runs
with 10000 particles were also performed in order to check the stability of the results, which has
been found to be very good. The half-width of the basis function was 10 ps for bunch lengths
in the range of 20-40 ps, while for longer bunch lengths a basis function with an half-width of
20 ps has been selected. The tracking was performed for a number of turns corresponding to
3-4 damping times, and the average values were calculated over the last damping time.

3 Longitudinal effects

Longitudinal collective effects have not been directly responsible for bunch current limitations
in LEP so far, but they strongly influence the onset of transverse instabilities, both because of
the dependence of the tranverse loss factor on bunch length, and because the coherent motion
in the longitudinal plane may result in coherent synchro-betatron resonances; in particular,
stronger resonances may appear above the threshold for longitudinal turbulence, when the
bunch starts to perform high-order oscillations (quadrupole, sextupole...) due to longitudinal
mode coupling. This phenomenon provokes violent bunch shape oscillations, which could be
clearly observed on the LEP streak camera in several experiments [17, 18].

Although very little data are available concerning longitudinal collective effects in the
$108^\circ/60^\circ$ and $135^\circ/60^\circ$ lattices, detailed checks of simulation results obtained with TRISIM
against experimental observations relative to the $90^\circ/60^\circ$ lattice have been carried out, as re-
ported in [14]: the code could not only reproduce quite satisfactorily the observed behaviour,
but also helped to explain some puzzling phenomena, like inductive longitudinal coupling for
short bunches and appearance of additional lines on the longitudinal spectra. These good re-
results obtained so far give us some confidence in the capability of the code to deliver meaningful
predictions for LEP operation at higher $Q_\beta$ and with high-tune lattices.

Figure 2 illustrates the simulation results concerning the high-current (800 $\mu$A) bunch length
dependence on synchrotron tune, for both the $90^\circ/60^\circ$ and the $108^\circ/60^\circ$ lattices, when damping
and polarization wigglers are excited at nominal settings. The bunch current value of 800
$\mu$A was chosen because it is close to the one which will be necessary for reaching the design
luminosity at LEP2 in 4-bunch operation: although the minimum intensity required is not the
same for the different lattices (due to the different emittances), it was decided to use a unique
current value to be able to carry out a consistent comparison. It should be noted, however,
that an intensity of 800 $\mu$A would be, in several of the cases considered, above the threshold
for vertical stability (see section 4): for this reason, in order to avoid transverse instabilities, the simulations have been carried out with the transverse wake switched off.

For what concerns the 90°/60° lattice, at low $Q_\ast$ the effect of the wake field is to shorten the bunch with respect to its zero-current length, while at higher $Q_\ast$ this effect tends to be reduced and an opposite behaviour emerges: such observations are in agreement with the standard theory of potential well distortion applied to the LEP impedance model [19]: for bunch lengths of 15-20 mm, the capacitive contributions of the accelerating cavities and those of the separators dominate, while for shorter bunches the inductive contributions of the bellows start to become important and tend to compensate the effect of the cavities. In the chosen conditions, no higher-order bunch shape oscillations or "bunch widening" (increase of the energy spread) indicating the onset of longitudinal turbulence appear as far as the 90°/60° lattice is concerned.

A similar behaviour is observed for the 108°/60° lattice up to a $Q_\ast$ of 0.12; above this value, longitudinal turbulence starts to set on: at $Q_\ast=0.14$, the bunch exhibits quadrupolar shape oscillations with a longitudinal RMS length varying between 24 and 28 ps, and the energy spread is about 38 MeV, to be compared to a zero-current value of 36 MeV.

![Graph](image)

Figure 2: Bunch length at high current as function of synchrotron tune: comparison between the 90°/60° and the 108°/60° lattices. Damping and polarization wigglers excited at nominal current. Transverse wake switched off.

The results concerning the 135°/60° lattice are illustrated in figure 3: here the bunch exhibits longitudinal turbulence for all the $Q_\ast$ values which have been considered. This effect becomes stronger as $Q_\ast$ increases: for $Q_\ast=0.14$, the energy spread reaches 46 MeV, to be compared with a zero-current value of 36 MeV, and the bunch length oscillates from a minimum close to the zero-current value to a maximum which is about 50% higher. A similar behaviour appears in the simulations concerning the 108°/60° lattice with only damping wigglers switched on, as
reported in Fig. 4: in the latter case, the dependence of the bunch length oscillation amplitude on \( Q_s \) is weaker; on the other hand, the "bunch widening" shows a steady increase from 27.5 MeV at \( Q_s=0.08 \) to 38 MeV at \( Q_s=0.14 \), to be compared with a zero-current value of 22.8.

![Figure 3: Bunch length at high current as function of synchrotron tune for the 135°/60° lattice. Damping and polarization wigglers excited at nominal current. Transverse wake switched off.](image)

![Figure 4: Bunch length at high current as function of synchrotron tune for the 108°/60° lattice. Only damping wigglers excited. Transverse wake switched off.](image)
4 Transverse effects

Two machine experiments aiming at measuring the maximum single-bunch current with the 108°/60° lattice have been carried out during the 1994 LEP run [6, 7]. The outcome of these experiments is summarized in table 4, where three measured points, corresponding to different machine settings, are reported: the first value has been obtained with damping wigglers only and $Q_x=0.08$, the others with damping and polarization wigglers on and a $Q_x$ of either 0.093 or 0.097. The position of the coherent vertical tune at maximum current can have, in some situations, a rather strong influence on the stability threshold; for this reason, the zero-current tune for the simulation (indicated as $(Q_x)_0$ in table 4) was chosen in such a way as to obtain a high-current coherent tune similar to the one observed during the experiment.

<table>
<thead>
<tr>
<th>Reference SL/MD Note</th>
<th>Machine settings</th>
<th>Maximum current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D-wig</td>
<td>P-wig</td>
</tr>
<tr>
<td>138</td>
<td>520 A</td>
<td>off</td>
</tr>
<tr>
<td>139</td>
<td>520 A</td>
<td>500 A</td>
</tr>
<tr>
<td>139</td>
<td>520 A</td>
<td>500 A</td>
</tr>
</tbody>
</table>

Table 4: Maximum bunch intensity for different machine settings: comparison between simulation and experiment.

In order to check the accuracy with which TRISIM is able to reproduce the machine behaviour, an accumulation process in steps of 10μA and with the same settings of the experiments was simulated: the last column in table 4 reports the highest current which could be reached without losing particles. As can be seen, the threshold current obtained from the calculations is close, but somewhat higher than the measured one: this discrepancy, which has also been found when comparing the simulated and measured threshold currents for the 90°/60° lattice [14], is mainly caused by the contributions to the machine impedance which have not been taken into account in the model. In any case, this is not a major point of concern as the relative difference remains approximately constant for the different machine configurations: the simulation results can therefore be easily corrected in order to obtain more accurate values.

![Figure 5: Transverse oscillation modes at high current. LEP 108°/60° (1994), $Q_x=0.08$, $(Q_x)_0=76.18$, damping wigglers at 520 A, polarization wigglers off.](Image)
Some additional simulation results, relative to the calculation of the threshold current with damping wigglers only (first line in table 4), are presented in Fig. 5 and 6: in the first picture, the vertical spectrum at high current is reported, showing the $m=0$ and the $m=-1$ modes approaching each other. At the threshold current of 520 μA the two modes couple, their frequencies become complex-conjugate and the amplitude of the transverse oscillation increases exponentially, as shown by the plots of Fig. 6.

Figure 6: Threshold current for TMC instability. LEP 108°/60° (1994), $Q_x=0.08$, $(Q_v)_o=76.18$, damping wigglers at 520 A, polarization wigglers off.
On the basis of the good agreement observed so far between the simulation results and the available experimental data, it is now possible to extend the analysis in order to investigate the machine performance in different configurations. Various methods to increase the single bunch current have been proposed in the past [20]; the changes in the machine parameters which are likely to raise the stability threshold are suggested by the following approximate formula [21]:

\[ I_{th} = \frac{8Q_s f_s E / e}{\sum \beta_i k_{si}(\sigma_s)} \]  

where \( Q_s \) is the synchrotron tune, \( k_{si} \) is the (bunch length dependent) transverse loss factor for the \( i \)th impedance, \( \beta_i \) is the (optics dependent) vertical \( \beta \) function at the location of the \( i \)th impedance, and \( E \) is the operating energy. For a given optics and injection energy, the most effective strategies to increase the maximum bunch current are the following:

- Lengthen the bunches by using wigglers: this reduces the total loss factor, which decreases with \( \sigma_s \) in the range of interest [22].
- Increase the synchrotron tune: the effect of a change of \( Q_s \) is not obvious from equation 1, because an increase in \( Q_s \) is likely to result in a reduction of the bunch length and in a consequent increase of the loss factor; however, by evaluating the expression 1 for different values of \( Q_s \) and by making use of loss factor dependence on bunch length quoted in [22, 23] it has been shown [12] that the net effect of an increase of \( Q_s \) is indeed positive both for the 90°/60° lattice and for the low-emittance 108°/60° and 135°/60° lattices; this result has also been confirmed experimentally for the 90°/60° lattices with damping and polarization wigglers on: in these conditions an increase of the synchrotron tune from 0.095 to 0.125 resulted in an increase of the maximum bunch current from 650 µA to 820 µA [24]. In a similar experiment carried out with damping wigglers only [25], an increase of \( Q_s \) from 0.083 to 0.101 resulted in an increase of the stability threshold from 540 µA to 615 µA.
- For what concerns the 108°/60° lattice, the few measurements available are not sufficient to draw conclusions: the two measured points obtained with damping and polarization wigglers on and with different values of \( Q_s \) [7] confirm the theoretical prediction that an increase of \( Q_s \) should produce an increase of the maximum current (table 4); however, in a previous experiment [6] carried out with damping wigglers only, both a reduction and an increase of \( Q_s \) with respect to a value of 0.08 resulted in beam losses.

In the present work, the effect of a variation of \( \sigma_s \) and \( Q_s \) on the stability threshold has been further investigated by calculating the maximum bunch current as function of vertical tune for the 108°/60° lattice in three different configurations: \( Q_s = 0.097 \), damping and polarization wigglers on; \( Q_s = 0.131 \), damping and polarization wigglers on; \( Q_s = 0.131 \), damping wigglers only. The interest for investigating the dependence of the stability threshold on the vertical tune derives from the following consideration: as it has been shown in section 3, both an increase of the synchrotron tune and a reduction of the momentum compaction result in shorter bunches and favour the onset of longitudinal turbulence. As a consequence, synchro-betatron resonances may be reinforced and reduce the optimal tune space available. The results of this analysis are reported in figure 7: as can be seen, in high-\( Q_s \) operation the dependence of the threshold current on the vertical tune is stronger, probably due to an increased sensitivity to the instability stop bands originating at every multiple of the synchrotron tune. As a consequence, a sensible gain in current with respect to the lower \( Q_s \) value is only obtained in a relatively narrow tune range.

\[ I_{th} = \frac{8Q_s f_s E / e}{\sum \beta_i k_{si}(\sigma_s)} \]
Figure 7: Stability threshold as function of vertical tune for different machine settings. LEP 108/60 (1994).

Figure 8: Stability threshold as function of vertical tune: comparison between the $90^\circ/60^\circ$ lattice and the low-emittance $108^\circ/60^\circ$ and $135^\circ/60^\circ$ lattices.

In figure 8, a comparison between the performance of the three lattices $90^\circ/60^\circ$, $108^\circ/60^\circ$ and $135^\circ/60^\circ$ is reported. For this comparison, it was chosen to use a machine configuration optimized for high bunch current, that is with both damping and polarization wigglers on and high
The results show that with the low-emittance lattices the stability threshold is reduced when the (coherent) tune approaches the resonant condition \( Q_0 = 2Q_s \), while no such effect is observed for the 90°/60° lattice. In the (zero-current) tune range between 76.22 and 76.24, where a similar dependence on tune is observed for all the three lattices, the reduction of the maximum bunch current with respect to the 90°/60° lattice is of about 9% for the 108°/60° lattice, of about 17% for the 135°/60° lattice.

Instability stop bands may also arise as a consequence of the coupling of mode 0 or mode -1 with higher-order (reflected) modes of the same parity [26]; for \( Q_s = 0.131 \), a resonant condition of this type occurs between the modes -1 and -3, when the fractional zero-current tune is about .26. The effect of this resonance for the different lattices was investigated by carrying out a scan of \((Q_s)_0\) around 76.26, in steps of 0.002, at a fixed current of 400 \( \mu A \); in practice, due to the shift of the modes with current, the mode coupling was found to take place when the tune is between .265 and .275, depending on the lattice considered. In order to reduce the noise in the vertical spectra, these runs were carried out with a relatively large number of macroparticles \((N=5000)\). The results can be summarized as follows: as far as the 90°/60° lattice is concerned, the resonance can be crossed without any blow-up of the transverse dimension of the bunch; the opposite is true in the case of the 108°/60° and the 135°/60° lattices, where a blow-up occurs leading to beam loss. The situation is illustrated in Fig. 9 and 10 for the case of the 135°/60° lattice: in the first picture, corresponding to a zero-current fractional tune \((Q_s)_0 = .26\), the two modes \( m=-1 \) and \( m=-3 \) are shown close to each other, but no instability occurs; by moving the zero-current tune to \((Q_s)_0 = .27\) (Fig. 10), the frequencies of the two modes are shifted to the same value, and an unstable behaviour is observed. It is also interesting to note that, when the instability occurs, the main blow-up concerns the transverse dimension of the bunch, without a correspondingly large barycentre displacement: this phenomenon was predicted by theory [26] for the case of coupling between odd modes and mode \( m=-1 \), while in the coupling between even modes and mode 0 the transverse dimensions of the bunch and the oscillation amplitude of its barycentre should be comparable. For what concerns the two peaks labelled as \( m=0 \) in the spectra, the one with a lower frequency is the coherent tune, the other is a cluster of modes also belonging to the \( m=0 \) azimuthal number, but with higher-order radial dependence, having a different frequency spectrum and therefore experiencing a different detuning [27].

For what concerns the relevance of the observed instability stopbands to LEP operation, it should be noted that when many localized impedances are present (instead of the few point-like elements represented in the machine model used for the simulations), the growth-rate of these resonances may be weaker and become smaller than the damping rate [28]. For this reason, it was decided to repeat the simulations using a more detailed machine model, represented in Fig. 12: here the impedance of the shielded bellows is further smeared along the arc, the presence of two separated accelerating stations on both sides of the interaction points is accounted for, and the impedance of the copper cavities is separated from the rest of the straight section impedance. Since a much larger CPU time is needed in this case due to the presence of many more elements, the analysis was only carried out for the case of the 135°/60° lattice. As can be seen from Fig. 11, simulation still predicts that a beam loss will occur when crossing the resonance; however, it was also observed that the width of the stop band was decreased with respect to the case in which the simpler machine model was used: since the instability growth
Figure 9: LEP 135°/60° lattice, machine model A (Fig. 1): simulation results in the proximity of a transverse resonance involving modes $m=-1$ and $m=-3$.  

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Figure 10: LEP 135°/60° lattice, machine model A (Fig. 1): transverse instability arising from the coupling of modes m=-1 and m=-3.
Figure 11: LEP 135°/60° lattice, machine model B (Fig. 12): transverse instability arising from the coupling of modes $m=-1$ and $m=-3$. 
rate in a stop band is proportional to the its width\textsuperscript{1} [26], this result indicates that in the real machine, where many hundreds of elements are present so that the impedance is further spread along the circumference, this resonance may be crossed without beam losses.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{lep_machine_model_B}
\caption{The LEP machine model B}
\end{figure}

5 Conclusions

The results of the calculations presented in this report can be summarized as follows:

- At a given current, the machine settings which favour the onset of longitudinal turbulence are those corresponding to a short natural bunch length: high synchrotron tune, small momentum compaction factor, small (zero-current) energy spread. For the typical bunch currents which would be needed to reach the design luminosity in LEP2 with 4-bunch operation, the threshold (zero-current) bunch length below which turbulence sets in is between 8 and 12 mm, depending on the machine configuration.

- In the turbulent regime, higher-order (quadrupole, sextupole, etc.) modes of oscillation appear in the longitudinal bunch shape, and the bunch length varies from a minimum close to the zero-current value to a maximum which is up to 50% higher. Since the resulting average bunch length is increased by this effect, the effective transverse loss factor is decreased [14], and the maximum bunch current is correspondingly higher. However, in the turbulent regime coherent synchro-betatron resonances are reinforced and may cause a reduction of the available tune space. This effect could be observed in simulation for the case of an instability due to coupling between the mode \(m=-1\) and the (reflected)

\textsuperscript{1}A comparison between the rate of growth of the transverse dimension in the two cases would not be a good indicator, as it depends on the distance from the resonance.
mode $m=-3$; however, this result should be checked experimentally since the effect of such resonances may be artificially amplified in the simulation program by the concentration of the impedances in a few point-like elements.

- The dependence of the maximum bunch current on vertical tune becomes stronger when the bunch length gets shorter, while in present operating conditions with longer bunches a rather flat curve is obtained in both calculations and experiments. This tune dependence of the threshold current should be taken into account when comparing different configurations: in particular, choosing the highest possible $Q_*$ may not be the best solution for all lattices, as the optimal tune space may become too narrow; moreover, the trims which would be needed to keep the coherent tune in the optimal range may enhance the resonances due to coupling between low-order and high-order (reflected) modes, because the frequencies of the reflected modes move in an opposite direction with respect to those of the "normal" modes when such trims are made.

The results presented in this report will have to be checked during the high-intensity machine experiments which are foreseen for the 1995 run: these experiments should be performed using machine configurations similar to those which have been selected for the present study. If the experiments confirm the simulation results, the calculations will be extended to the whole range of $Q_*$ values which will be possible in LEP2 operation, with the purpose of evaluating the optimal $Q_*$ for each lattice, and the corresponding maximum bunch intensity.

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References


