Simulation of Stability Thresholds in LEP

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Abstract

Multi-particle simulation of electron or positron motion in LEP has been redone using both a new tracking program and an improved estimate of the wake fields caused by the RF cavities and the shielded bellows. The wake potentials of very short bunches were obtained with a new version of the code ABCI [1] which uses a moving mesh and thus permits much smaller mesh sizes. The results obtained with this approach are compared with experimental data obtained during dedicated machine development sessions. For tunes chosen between synchro-betatron resonances, transverse mode coupling appears quite close to the current thresholds observed in LEP. However, these thresholds are strongly reduced for tunes near those resonances by the appearance of coupling with new modes. The rather good agreement obtained so far between simulation and experimental data gives us some confidence that it will be possible to obtain meaningful predictions for the future operation of the LEP2 machine, where increased bunch intensities are a key issue for successful operation.

1 INTRODUCTION

The successful operation of the LEP2 machine requires a significant increase of bunch intensities compared to those used presently in LEP, where an increase would lead to limitations by the beam-beam effect. This ambitious objective is hoped to be achieved by a combination of different actions, such as removing some of the high-impedance Cu cavities now installed in the machine (replaced by SC cavities in LEP2), operating with a higher synchrotron tune Q_s at injection, and possibly by a novel reactive feedback system. Whatever the final configuration, collective effects will be dominant in limiting the bunch current and have therefore to be studied carefully. In order to do this, the new simulation program TRISIM [2] has been developed at CERN. This computer program uses the same description of beam dynamics as the somewhat older code HERSIM2 [3], but a completely new approach for the expansion of the bunch distributions and wake fields. At the same time a number of new features and better graphics have been incorporated.

The new program has been successfully tested on experimental data of the existing LEP, and we therefore assume that it can be used for LEP2 with some confidence. This report presents a brief description of this simulation program as well as some of the results obtained for LEP.

2 THE SIMULATION CODE

As far as the description of the beam dynamics is concerned, the program uses the same formalism as HERSIM2[3] which was derived from the predecessors SIMTRAC[4] (with a super-particle approach), and HERSIM[5] (using a development into Hermite polynomials). The main new feature of the code TRISIM is the expansion of the particle distribution and of its first moment into a basis of linear interpolating functions consisting of equilateral triangles.

The wake potentials of an arbitrary distribution can then be obtained from a superposition of wakes of the basis function. If all triangles are equal in width, only a single table is needed rather than one for each Hermite polynomial, which saves in memory space and computing time needed for interpolations between tables. By increasing the number of basis functions used - typically between 20 and 50 - this approach permits improving the description of the distribution, in particular near the instability thresholds where it is usually quite non-Gaussian. At the same time, a reduction of the required computing time of up to one order of magnitude could be achieved.

2.1 Wakefield representation

The computation of the wake contribution is based on an approximation of the actual distribution by a sum of triangular shaped basis functions of constant width Δ and variable height. The longitudinal coordinate 's' is divided into a number of discrete values (index k) $s_k = k\Delta$ where $\Delta \approx \sigma_s/2$ to $\Delta \approx \sigma_s/4$ have been found acceptable choices for initially Gaussian distributions.

We develop the two continuous functions which are presently used for the simulation, namely the charge distribution $q(s)$ and its dipole moment $d(s)$ according to :

$$q(s) = \sum_k q_k f_k(s) \quad \text{and} \quad d(s) = \sum_k d_k f_k(s) \qquad (1)$$

where each f_k is an interpolating function

$$\begin{aligned} f_k(s) &= 1 - \frac{|s - s_k|}{\Delta} \quad \text{for } s \in [s_{k-1}, s_{k+1}] \\ &= 0 \quad \text{for } s \notin [s_{k-1}, s_{k+1}] \end{aligned} \qquad (2)$$

and the expansion coefficients are given by

$$q_k = \sum_i q_k^i, \qquad d_k = \sum_i z^i q_k^i \qquad (3)$$

with

$$
\begin{aligned}
q_k^i &= \frac{Q}{N\Delta}\left(1-\frac{|s^i-s_k|}{\Delta}\right) \quad \text{for } s^i \in [s_{k-1}, s_{k+1}] \\
&= 0 \quad\quad\quad\quad\quad\quad\quad\quad\quad \text{for } s^i \notin [s_{k-1}, s_{k+1}] \quad (4)
\end{aligned}
$$

Here N is the total number of (super)particles, Q the total charge, and the index 'i' refers to the i-th particle of the distribution (i=1,...N). The longitudinal ($m = 0$) and transverse ($m = 1$) wake potentials are then obtained as:

$$
\begin{aligned}
W_L(s) &= \sum_k q_k w_L(s - s_k) \\
W_T(s) &= \sum_k d_k w_T(s - s_k) \quad\quad (5)
\end{aligned}
$$

when w_L and w_T are the wake potentials of the (triangular) basis function, travelling through the impedance with unit off-axis displacement. These wake potentials have been computed for various components of the LEP vacuum enclosure, such as RF and SC cavities, shielded and unshielded bellows etc. with the mesh program ABCI, assuming rotational symmetry. In Fig.1, the transverse wake potential of a Gaussian with $\sigma = 50ps$ is compared with that of the superposition of wakes of triangles of width $20ps$.As can be seen, it is hard to distinguish the two curves from each other.

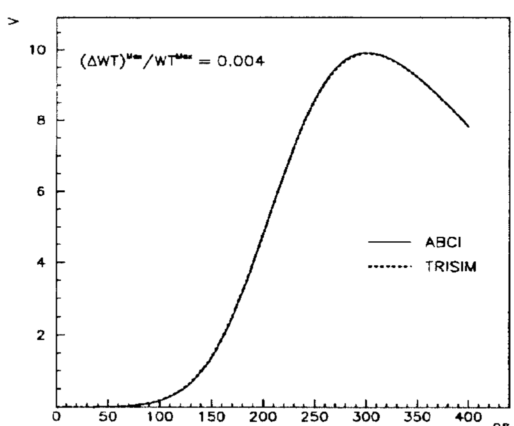

Figure 1: Comparison of wake potentials

2.2 *New Features*

Compared to its predecessor, this new code has been significantly improved in a number of areas. In addition to the introduction of simpler basis functions, a large effort has been made to improve its portability, the input-output commands have been simplified, new graphics based on PAW[6] have been added, and an option to run the code without pre-computed tables of wake potentials has been included for broad-band resonator impedances. The larger inherent speed of computation permits use of more realistic machines composed of many different elements. Pick-ups and kickers have been introduced in order to simulate feedback systems which might be useful for increasing the instability thresholds.

3 THE IMPEDANCE MODEL

The ability to predict the performance of LEP2 will depend critically on the precise knowledge of the machine impedance. For this reason, an attempt was made to refine the model used in previous simulations.

The major contributions to the impedance in LEP come from two components, namely the RF (copper) cavities and the shielded bellows, mainly due to their large number. For the transverse planes, it is possible to obtain a rather accurate description of the impedance as a superposition of two broad-band resonators corresponding to these two components. It is worth mentioning that the respective resonant frequencies of these resonators happen to be very different (around 2 GHz for the first and above 100 GHz for the second one), which explains the observations that the effect of the surroundings on the beam crucially depends on the actual bunch length. Unfortunately, it was not yet possible to establish a correspondingly good model for the longitudinal plane. Consequently, it was decided to directly use ABCI for the computation of the reference potentials required by the simulation program. At present, ABCI is used to compute the wake potentials of the reference triangular function for both one RF cavity cell and one shielded bellow. The two are subsequently superposed, accounting for both their respective average beta-function and their number of occurrences in the machine. This results in a single wake potential which can be directly applied in the simulation code.

4 SIMULATION RESULTS

In order to test the different new features of the program, it was decided to simulate the LEP machine and to compare the predictions with experimental observations. As shown in the following, the code did not only reproduce quite satisfactorily the instability thresholds, but even shed some light on possible new instability mechanisms.

4.1 *Transverse Mode Coupling Instability*

This fast transverse instability is known to be the main intensity limitation of LEP at injection. In order to reach the minimum objectives of the LEP2 project, it is foreseen to circumvent the present limitation by accumulating with a much higher synchrotron tune Q_s. This procedure has been both tested experimentally and simulated with TRISIM. The results are presented in Fig.2, where it can be seen that the predictions are in reasonable agreement with experimental data. It also indicates that we may be slightly underestimating the impedance of the machine. Actually this could be easily explained by the fact that the bellows are probably not perfectly aligned w.r.t the beam axis, so that their contribution is slightly larger.

The simulations will be soon extended to even higher Q_s values to check up to what limits the scheme can be applied. Indeed, there might be a point where the threshold could actually be lowered, since, due to the shorter bunch length, the increase in the impedance contribution might raise faster than that of the Q_s.

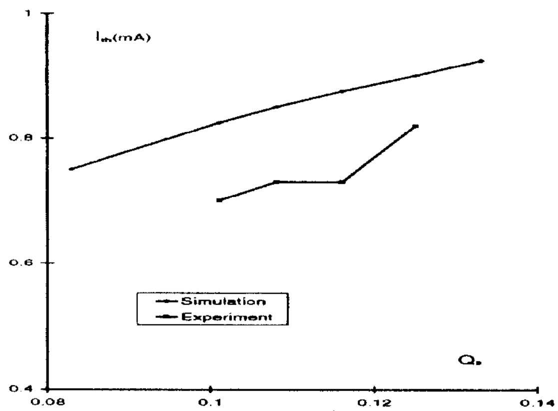

Figure 2: TMC threshold vs. synchrotron tune

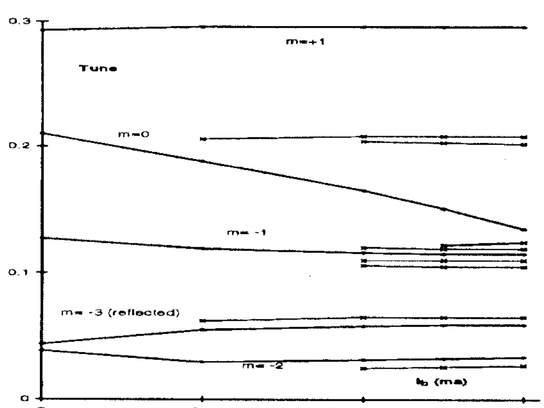

Figure 3: Mode frequencies vs. bunch current

4.2 *Synchro-betatron Resonances*

When studying the variation of the threshold intensity as a function of the (vertical) betatron tune, one observes that for short bunches it is strongly reduced when the non-integer part of the betatron tune is near to an integer multiple of the synchrotron tune (Q_β/Q_s=n). A detailed study of this behaviour yields the following picture: at low intensities, only the azimuthal modes $m = 0, \pm1$ are visible in the spectrum. As can be seen in Fig.3, at higher intensities, additional transverse modes appear (both radial and reflected[7]). Instabilities may occur from coupling of these modes with one of the synchrotron sidebands.

4.3 *Reactive Feedback*

A recent proposal for a new reactive feedback system [8] has been tested in LEP on two occasions. Despite of careful checks it has not been possible to raise the thresholds as predicted by theory. It was therefore decided to implement the feedback in the simulation program. Thanks to this new tool, it was possible to both understand the experimental problems and discover new coupling mechanisms (presently believed to be radial modes) which are in fact limiting the potential gain to much lower values than expected. In this particular case, the simulation proved to be extremely valuable, resulting in a basic modification of the theoretical model. Furthermore, it demonstrated the extreme sensitivity of the proposed feedback system to small phase errors in the pick-ups. This is likely to be the most important limitation to the successful implementation of such a system in the machine.

5 CONCLUSIONS

The simulation program TRISIM is based on a better description of the distribution of the charge density and its transverse moments than that possible with a limited number of Hermite polynomials, by expanding them into triangular basis functions. This allows a more realistic simulation of the interaction of the beam in LEP with the surrounding impedances. Using equilateral triangles of constant width requires only a single table for the wake potentials, which have been obtained directly with existing mesh codes for circular symmetric structures. Both the memory requirements and the computation time are decreased by large factors compared to the previous simulation codes.

Using improved estimates for the impedances in LEP, which are mainly caused by the RF cavities and the (shielded) bellows, it was possible to get quite good agreement with measurements in particular for the threshold of transverse mode coupling, which is limiting the single bunch current most severely. Predictions for LEP2 can thus be based confidently on this code. It has also been used to study a new reactive feedback system using additional passive oscillators and to evaluate its effectiveness and sensitivity to errors. In addition, the simulation code is a valuable tool to study and explain observations made in the control room on the real accelerator, such as synchro-betatron resonances and mode splitting at higher currents.

6 REFERENCES

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