

The LEP Impedance Model

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Abstract

The bunch current in LEP is limited by collective effects slightly below its design value. To understand this limitation, a set of experiments has been carried out to obtain a model of the impedance seen by the circulating beam. From measurements of the current dependence of the synchrotron and betatron frequencies information about the longitudinal and transverse reactive impedance has been obtained. The growth rate of the $m=1$ head-tail instability has been observed to gain some knowledge of the resistive transverse impedance. The dependence of the transverse mode-coupling threshold on bunch length has been measured. The energy loss per turn of a stable bunch is given by the longitudinal resistive impedance and has been measured by recording the change of the synchronous phase angle with current. All these quantities represent integrals over products of bunch mode spectra and impedances. By measuring them for different bunch lengths the frequency dependence of the impedances can be estimated. From these results a model of the LEP impedance has been obtained which can be used to estimate the current limitation under different operating conditions.

I. INTRODUCTION

Single bunch instabilities, in particular transverse mode coupling at injection energy, are limiting the current and hence the luminosity of LEP[1]. To understand - and possibly overcome - this limitation, we have computed the impedances of various components of the vacuum chamber wall. Their interaction with charged particle bunches can be described quite well by a number of broad-band resonators.

The largest impedance in LEP is due to the RF cavities, in particular the 5-cell copper cavities, of which 128 were installed originally. Their transverse broad-band impedance is computed from the dependence of the transverse loss factor on bunch length [2], which yields a value for R/Q of about $11.8 \text{ K}\Omega$ per cavity, with a resonant frequency slightly above 2 GHz .

Eight of the 350 MHz copper cavities have since been replaced by four 1 GHz feedback cavities (7 cells each). in

our calculations. Furthermore, a small number (2 modules of 4 cavities each) of superconducting (SC) 4-cell cavities have been added so far, with many more to come for LEP200. The transverse broad-band impedance of these cavities is much lower ($R/Q = 1.88 \text{ K}\Omega$ per cavity), as well as their resonant frequency (0.71 GHz), due to the larger beam tube holes and smoother shapes. For simplicity we just retain the original number of cavity cells

The second most important impedance in LEP is caused by the vacuum chamber bellows, of which there are a very large number because of the large circumference of the machine. All of those which connect oval chambers with small height (70 mm) have been shielded with sliding finger contacts to reduce their effect on the beam (2800). There are also almost 400 unshielded bellows between circular chambers of larger diameter (100 mm). Their transverse impedance, inversely proportional to the third power of the beam hole is hence smaller, and we simply increase the number of shielded bellows to 3000.

Due to the small size of the cross-section variations, the broad-band impedance of the bellows is expected to have a rather high resonant frequency. In principle, it can be estimated from the position of the maximum of the transverse loss factor. However, until recently the size limitations of our mesh codes (a few 100.000 mesh cells) did not permit us to find this maximum, and thus only a lower limit of 8 GHz could be given for the resonant frequency[4]. A recent improvement of the code ABCI, introducing a so-called "moving mesh", permits the use of much finer meshes. With a mesh size corresponding to 7 million mesh cells in a static mesh code, the maximum of the loss factor was finally found, corresponding to a frequency of almost 120 GHz , ten times above the previous limit. However, this value is important only for extremely short bunches which are of little interest in LEP.

For the longitudinal impedance, the contribution of the unshielded large bellows is also important. Nevertheless, the total longitudinal loss factor is some 20% too small for bunches of $\sigma_s \leq 10 \text{ mm}$, probably due to many other small impedances which have been neglected. Such components include the electro-static separator plates, (about 40 pairs), pick-up buttons, collimators, flange gaps, pump connections etc. For the transverse threshold calculations, it is sufficient to include the RF cavities and bellows to

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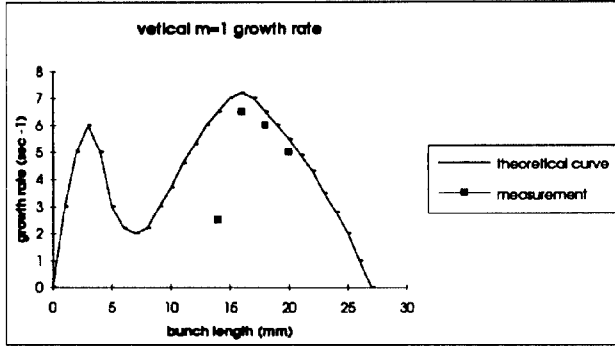


Figure 1: Growth rate of the m=1 head-tail mode

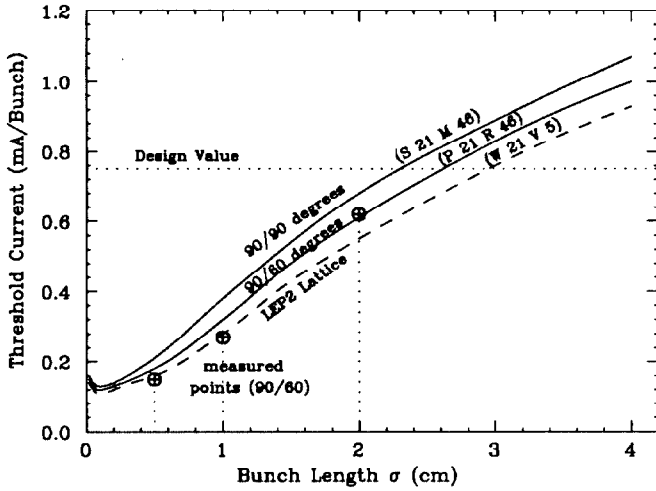


Figure 2: TMC threshold current vs. bunch length

obtain satisfactory agreement with measurements.

II. CURRENT DEPENDENCE OF BETATRON TUNES

A simple measurement which yields the imaginary part of the transverse impedances is that of the change of the betatron tunes with current[3]. However, the measurement should be made at constant bunch length in order to get a model-independent result. Fortunately, the bunch length is (almost) independent of current when the bunches are lengthened by excitation of the wigglers, and longer bunches can be measured up to quite high currents. For shorter bunches one has to stay below the "turbulent threshold". We have thus obtained a set of values for the "tune-slopes" dQ/dI , in both the horizontal and the vertical planes, over a range of bunch lengths of interest for LEP (5 - 20 mm).

The tune-slopes are proportional to the sum of the prod-

ucts of the beta functions and "effective" impedances

$$\frac{\Delta Q}{\Delta I} = \frac{R}{2\pi\sigma_s E} \sum \langle \beta \rangle_i Z_{\perp eff}^{(i)} \quad (1)$$

where the effective impedances are given by the overlap integrals of the impedance and the spectrum of the bunch oscillations. For gaussian bunches oscillating in a dipole mode, and a broad-band resonator impedance, one can approximate the result for short bunches ($\omega_r \sigma_s / c \ll 1$) by $Z_{\perp eff} = 2(\omega_r \sigma_s / c)^2 (R/Q)$, while $Z_{\perp eff} \approx R/Q$ for longer ones.

The difference between the tune-slopes in the horizontal and vertical directions also permits an estimate of the contributions of the RF-cavities - which have circular beam holes - and of the bellows (resp. the rest of the oval vacuum chamber), where the vertical dimension is about a factor two smaller than the horizontal one.

The measured "slopes" (depending on bunch length) are of the order $(\frac{\Delta Q}{\Delta I})_H \approx 60-70 A^{-1}$, $(\frac{\Delta Q}{\Delta I})_V \approx 100-130 A^{-1}$. These values agree quite well with the predictions, and were thus a first confirmation of the impedance model.

III. GROWTH RATE OF M=1 HEAD-TAIL MODES

At injection, LEP is normally operated with a slightly positive ($Q'=1$) chromaticity in order to avoid the m=0 head-tail instability. For a chromaticity of $Q'=2$ or higher, the vertical m=-1 mode becomes unstable before the transverse-mode-coupling threshold is reached. Due to eddy currents, the chromaticity is hard to control to a precision better than ± 1 at the start of the ramp. Hence it was important to determine the growth rate of the m=-1 mode as a function of bunch length.

The experiment was performed in two steps. For each bunch length (the bunch length was varied using wigglers) the single particle damping time was measured. A bunch with very low intensity ($50 \mu A$) was used and the chromaticity was rigorously set to zero. In this way any Landau damping or space charge effects could be ignored. We then measured the response of the beam to an excitation with a single frequency that was swept through the betatron frequency. From the width of the response we could determine the damping time. Then the chromaticity was set to +4 and the intensity was slowly increased until the m=-1 mode became unstable. In this way we could determine the intensity at which the m=-1 growth rate was equal to the measured damping time.

Assuming a linear dependence of the growth rate on intensity, we could normalize the measured growth rates to a fixed intensity of $250 \mu A$ per bunch, for which current

the calculations had been done with the LEP impedance model. The measurements and calculations are compared in fig.1.

IV. TRANSVERSE MODE COUPLING THRESHOLD

At 20 GeV, the current in LEP is limited by the vertical transverse-mode-coupling instability. For the nominal synchrotron tune Q_s of .083 and a bunch length σ_s of 20mm, this instability occurs at $640\mu A$ per bunch. The closest approach between the $m=-1$ and $m=0$ modes then equals about 0.022, before they merge into a broad peak. With a Q_s of 0.04, the two modes could approach each other down to a tune difference of 0.006.

We also did measurements on the lattice that is going to be used during 1993 (90/60 degrees). The vertical TMC threshold in this lattice was found to be slightly lower than in the 1992 lattice (90/90 degrees). The smallest tune approach of the $m=-1$ and $m=0$ modes was 0.025, and the maximum current of $600\mu A$ per bunch. This is in agreement with the predictions of the LEP impedance model as shown in fig.2.

V. ENERGY LOSS PER TURN

The resistive part of the longitudinal impedance $Z_r(\omega)$ leads to an energy loss U_{pm} per turn for each particle in a bunch. It is given by the integral over the impedance times spectral power of the bunch current. The latter is usually close to a Gaussian with a width determined by the bunch length σ_s . This energy loss normalized by the bunch charge gives the parasitic mode loss parameter $k_{pm} = U_{pm}/q_b$. It was measured by observing the change of the synchronous phase angle as a function of bunch current I_b . A first method uses a streak camera with a trigger derived from the RF-system and gives the bunch position in time and its width[5]. In a second method, the bunch signal observed with an intensity monitor is filtered at a revolution harmonics and compared to a corresponding signal derived directly from the RF-system, [6] To gain in sensitivity this was done at a high frequency of 1 GHz. Such a measurement is shown in Fig. 3 where the change in synchronous phase (referred to the RF-frequency of 352 MHz) and the bunch length are plotted against the bunch current. The parasitic mode loss factor is obtained from the slope of the phase change. A set of five measurements was carried out with different values for the bunch length as controlled by the polarization (PW) and the damping (DW) wigglers of LEP. For the analysis we considered only bunches with currents below the turbulent threshold which have Gaussian form. The results summarized in Fig. 4 show the dependence of the mode loss factor k_{pm} on σ_s . It can be

fitted by a power law of the form $k_{pm} \propto \sigma_s^{-1.12}$.

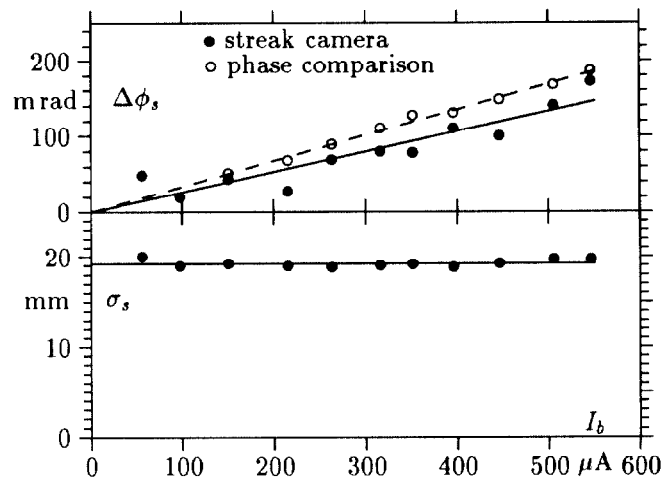


Figure 3: RF-phase and bunch length vs. current

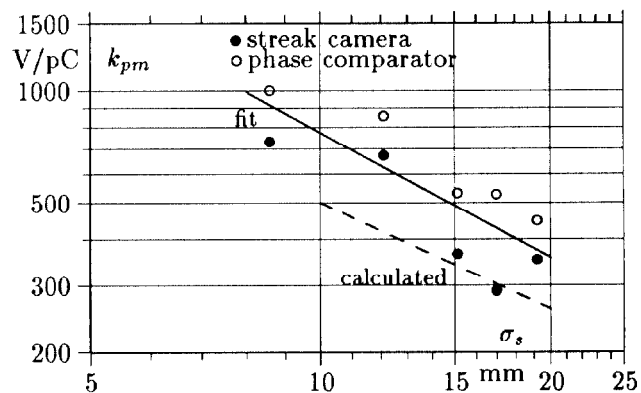


Figure 4: Parasitic mode loss parameter vs. bunch length; fit: $k_{pm} [V/pC] = 10070 \sigma_s^{-1.12} [mm]$

VI. CONCLUSIONS

The LEP impedance model, consisting of 2 broad-band resonators for the copper RF cavities and the shielded bellows, is sufficient to explain the measured behaviour of single bunch stability.

Acknowledgements

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VII. REFERENCES

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