INTENSITY LIMITATIONS AND THE IMPEDANCE OF LEP

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Abstract Both single- and multi-bunch instabilities have been encountered in the process of increasing the intensity of the beams in LEP. Here we present a survey of measurements made to date on single-beam collective phenomena. These include the dependences of coherent transverse and longitudinal mode frequencies, bunch-length and other beam parameters on intensity. Estimates of the longitudinal and transverse impedances have been obtained as fits to model impedances. The factors limiting the intensity of the beams in LEP are discussed in the context of instability theory. We compare the results with expectations and comment on the extent to which customary theories and models have been tested in the parameter range of LEP.

1 Introduction

Running-in LEP was the moment of truth for many predictions made in the design phase. Among the most vulnerable of predictions are those related to the intensity limitations by collective phenomena. Not only are the theories and simulations radically simplified models of the reality they purport to describe, but their results also depend on the distribution of coupling impedances in the storage ring. These functions (or the equivalent wakefields) are notoriously difficult to calculate with sufficient approximation over the entire frequency range. Moreover, in applying instability theories to LEP, we are forced to make considerable extrapolations in parameter range from the smaller rings which have been their testing ground up till now. We note, as an example, that although the RMS bunch length $\sigma_z \simeq$ 5–40 mm in LEP is comparable to that in other e^+e^- rings, the large circumference $C = 2.7 \times 10^7$ mm leads to a very large ratio of peak-to-average beam current.

The importance of single-beam collective effects cannot be overemphasised since they have long been expected to constitute the principal limitation of the luminosity of LEP.

In over a decade of preparation and construction of LEP, many people have worked on this subject; here we cite only a few seminal references which included the application of the broad-band impedance model to study single-bunch stability [1], the introduction of time-domain computation of wake-potentials [2] and the first systematic accounting of the impedance of all the structures seen by the LEP beam [3]. More recent updates of the impedance estimates and their consequences for beam stability can be found in [4,5,6].

The single-bunch current in LEP was expected to be limited to $I_b \simeq 0.75$ mA (with certain prospects for improvement using transverse feedback, bunch-lengthening by wigglers, etc.) by the transverse mode-coupling instability (TMCI) at injection energy (20 GeV) [5]. This value was recently attained (see Section 6).

In the 8 months that LEP has operated to date, the steady rise of the maximum beam current has depended on solutions being found to several problems, not all of which can be classed as collective effects. Among the others were the empirical adjustment of the injection bump to compensate for what turned out to be a limited dynamic aperture, the correction of the orbit, the choice of tunes, the use of wigglers, RF adjustments, etc.; these topics are treated in other papers in this conference.

2 Longitudinal phenomena

Measurements of longitudinal effects will be discussed in a future paper; here we summarise the most important points.

Coupled-bunch instability Within the first two months of commissioning it became clear that longitudinal coupled-bunch instabilities were involved in a current limitation at $I_b \simeq 0.3$ mA. This limit was only about a factor 3 less severe than had been expected [6] in the worst case of 640 identical RF cavity cells. More "realistic" expectations for the spread of cavity mode frequencies between cells had led to estimated thresholds a few times larger than the TMCI threshold. Although all such calculations contain many sources of uncertainty, it appears that the quality of construction of the RF cavities was very high! LEP was not at first equipped with a longitudinal feedback system but it was nevertheless possible to improvise one [7] at short notice to cure the problem.

Coherent longitudinal motion Persistent self-sustaining longitudinal coherent motion can be clearly observed by means of the recently commissioned streak camera [8]. This motion appears to be present at injection energy, even when there is just a single-bunch in the ring and particularly when the RF voltage is not high ($Q_s \lesssim 0.1$). This phenomenon can make it difficult to measure the bunch length, except by means of the streak camera itself.

A tentative explanation of this phenomenon is the fact that the beam-induced voltage in the cavities becomes comparable to the RF voltage itself, leading to the Robinson instability. The instability mechanism may involve the feedback systems used to control the cavity tuning, power and phase which can effectively change the impedance of the fundamental mode [6].

Bunch length Significant bunch-lengthening was expected [3,4] for $I_b \gtrsim 0.1$ mA in LEP at injection energy, even if the wigglers are not used. This has been confirmed.

The longitudinal impedance can be estimated from the measured threshold current and bunch length using the usual stability criterion for bunched beams

$$\left|\frac{Z}{n}\right| = \frac{F h V_{\mathrm{RF}} \cos\phi_s}{\sqrt{2\pi} I_{\mathrm{thr}}} \left(\frac{\sigma_z}{R}\right)^3 \qquad (1)$$

where the form factor $F = 1$ for a capacitive impedance (expected for short bunches), and about 1.4 for resistive impedances. Substituting the parameters of LEP yields the extremely low impedance of about 22 mΩ (for $F = 1$). However this is the

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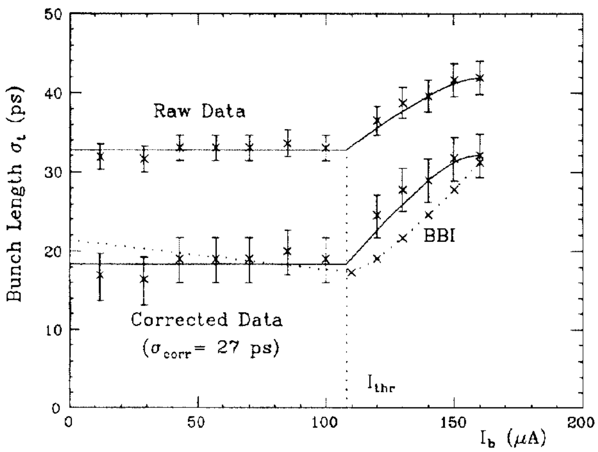

Figure 1: Bunch-lengthening in LEP; corrections have to be applied to the raw data from the pickup and sampling scope in order to produce the correct behaviour at low currents and varying RF voltage. See [10] for details; the streak camera was not yet available for these measurements.

"effective impedance" (a weighted average over the bunch frequency spectrum) acting on a very short bunch, and *not* the usually quoted low frequency limit $|Z/n|$. Assuming a resonator impedance with resonant frequency ω_r, the effective impedance of short bunches $\sigma < 1/\omega_r$ is strongly reduced by the overlap of the bunch spectrum with both the positive low-frequency inductance, and the negative high-frequency capacitance. The result is given approximately by

$$(Z/n)_{\text{eff}} = 2\,(\omega_r\sigma_\tau)^2\,|Z/n| \qquad (2)$$

for short bunches ($\omega_r\sigma_\tau < 1$), whereas for longer ones ($\omega_r\sigma_\tau \geq 1$) one should use $(Z/n)_{\text{eff}} = |Z/n|$.

In LEP, the major part of the longitudinal impedance is expected to come from the RF cavities, for which a broad-band resonator frequency of about 2 GHz has been estimated [5]. For a bunch length $\sigma_\tau = 18ps$ we find $\omega_r\sigma_\tau \simeq 0.21$, and we have to use the short bunch expression to get the correction factor for the effective impedance of $2(\omega_r\sigma_\tau)^2 \simeq .09$. The low-frequency limit of the impedance then becomes

$$|Z/n| = 0.25\,\Omega \qquad (3)$$

somewhat less than the predicted value $\simeq 0.9\,\Omega$ [9]. Since this result depends both on the form factor and on the assumed resonator frequency, it may be larger (since $F > 1$ and ω_r may be smaller than the 2 GHz assumed).

We have also computed the bunch length as function of current with the program BBI, which has the Hofmann-Maidment model[1] as one of its options. The result for an impedance of 0.25 Ohm is shown in Figure 1 in addition to a set of measured values.

Measurements of the frequency shift of the longitudinal quadrupole mode with current and scaling from the measured transverse impedances have given independent estimates of $|Z/n|$ which agree quite well with the one obtained above.

3 Transverse impedance

Transverse mode frequency shifts with current can be used to estimate the transverse impedance. However the impedance is also proportional to the bunch length which must be known.

The tune shift caused by N impedances can be written

$$\frac{dQ}{dI} = \frac{R}{2\pi\sigma_z E/e}\sum_{i=1}^{N}\langle\beta\rangle_i\, Z_{Ti}^{\text{eff}} \qquad (4)$$

where $\langle\beta\rangle_i$ is the average beta function at the i-th transverse impedance Z_{Ti}. The effective transverse impedance for a Gaussian in a resonator impedance can be expressed as

$$Z_T^{\text{eff}} = Z_T F(\omega_{res}\sigma_\tau) \qquad (5)$$

where the form factor can be approximated by $F(x) \approx 2x^2$ for $x < 1$ (bunches short compared to the resonant wavelength), and by $F(x) = 1$ for $x \geq 1$ (long bunches or high resonant frequency).

Since the RF cavities have circular beam holes, their contributions to the horizontal and the vertical shift must be equal, i.e. they must be less than the smaller of the two shifts. Since the frequency of the equivalent broad-band resonator used to describe the RF cavities is estimated at about 2 GHz, the "short bunch" expression applies when the bunches have only $\sigma_\tau = 18\,$ps. This brings about a strong reduction of the effective impedance by a factor of about 9. The average β-function in the RF cavity region has been kept less than 40 m in order to maximize the threshold of the TMCI.

Much effort has been spent on shielding the vacuum chamber bellows, of which there are almost 3000 in LEP. They have a chamber height slightly more than half their width. Since the transverse impedance varies with the second to third power of the radius, we expect their effect on the vertical tune shift to be about 5 times larger than on the horizontal one. The broad band resonant frequency of the bellows has been estimated to be larger than 8 GHz[5], and hence their effective impedance will be equal to their true impedance, even for the rather short 18 ps bunches. Furthermore, the average beta function at the bellows is about 75 m in both planes, almost twice the value at the RF cavities.

Substituting these conditions into the above expressions, we find two equations with two unknowns for the (vertical) transverse impedances of the RF cavities and the bellows, which we expect to be the two main contributors in LEP:

$$\begin{aligned} -\frac{dQ_x}{dI} &= \frac{R}{2\pi\sigma_z E/e}\left[2(\omega_r\sigma_\tau)^2 Z_T^{\text{cav}}\langle\beta\rangle_{\text{cav}} + 0.2 Z_T^{\text{bel}}\langle\beta\rangle_{\text{bel}}\right] \\ -\frac{dQ_y}{dI} &= \frac{R}{2\pi\sigma_z E/e}\left[2(\omega_r\sigma_\tau)^2 Z_T^{\text{cav}}\langle\beta\rangle_{\text{cav}} + Z_T^{\text{bel}}\langle\beta\rangle_{\text{bel}}\right] \end{aligned} \qquad (6)$$

Summarising the results of several experiments at 20 GeV with $\sigma_z \simeq 0.54\,$cm, we find the measured frequency shifts to be

$$\frac{dQ_x}{dI} = -0.06 \pm 0.01\,\text{mA}^{-1}, \qquad \frac{dQ_y}{dI} = -0.12 \pm 0.01\,\text{mA}^{-1}. \qquad (7)$$

Solving (6) and (7) yields

$$Z_T^{\text{cav}} \approx 2.0 \pm 0.7\,\text{M}\Omega/\text{m}, \qquad Z_T^{\text{bel}} \approx 0.18 \pm 0.06\,\text{M}\Omega/\text{m}. \qquad (8)$$

to be compared with the figures 1.51 MΩ/m and 0.32 MΩ/m predicted in [5]. Although the value for the bellows is smaller, their contribution to the vertical tune shift for the natural bunch length at injection is just as large as that of the RF cavities. The total transverse loss factor is only slightly higher than the original estimate so we expect that the threshold for transverse mode-coupling instability will be near the estimated value of $I_b \simeq 0.75\,$mA, if the bunches are lengthened to $\sigma_z = 4\,$cm with the wigglers.

To predict the TMCI threshold more exactly, it would be useful to measure the frequency shift of the lower synchrotron sideband (i.e. the $m = -1$ mode). It is not easy to excite this mode, even with chromaticity increased up to $Q' = 20$. The chromaticity required can be estimated as a reasonable fraction (e.g. 1/4) of the value where the chromatic frequency becomes equal to the peak of the bunch spectrum, i.e., when $Q' \simeq \alpha R/\sigma_z$. For a large machine with short bunches this value may be quite high, and is about 160 for the parameters of LEP at injection energy. These sidebands have occasionally been observed at higher current levels ($\gtrsim 1$ mA in 4 bunches) when the bunches are lengthened with the wigglers.

4 Synchro-betatron resonances

Although this topic is covered in a separate paper [11] we mention it here because the present current limitation in LEP is closely associated with the large vertical dispersion around the whole ring but especially in the RF cavities. Coupling of incoherent longitudinal motion into the transverse degrees of freedom through dispersion at the cavities had been expected to drive synchro-betatron resonances in LEP, as in other large rings. However it was a surprise to discover that current limitation and blown-up vertical beam profiles occurred when the *coherent* vertical tune satisfied conditions like $Q_y^{(\mathrm{coh})} - 3Q_s = p$.

A tentative interpretation of this observation may be that the persistent coherent longitudinal motion is directly coupled into the transverse plane by dispersion at the cavities.

There has been partial success in trying to compensate these effects by correcting the vertical dispersion at the RF [11].

5 Dynamic aperture and wigglers

LEP was equipped with wigglers for several reasons connected with performance maximisation, among them the possibility of increasing damping rates and bunch length at injection energy to raise instability thresholds and improve accumulation rate. While LEP was running with the so-called "back-up optics" (detuned low-β sections), all indications were that these expectations were fulfilled [12]. After the transition to the "nominal optics", the beam lifetime was generally found to be very bad when the wigglers were on. Although this may be related to an increase in the average driving terms of synchro-betatron resonances arising from the increased energy spread, it is also very likely related to a poor dynamic aperture, particularly in momentum acceptance. Indeed the dynamic aperture has been found to be significantly less than expected [13].

Later optics improvements allowed the wigglers to be used again during accumulation and ramping.

6 Present maximum beam current

The steady rise of the peak beam currents in LEP have reflected continual progress in many aspects of the machine development and operational procedures. The present record beam currents achieved simultaneously on 7 June 1990, in 4 positron bunches at 20 GeV are $I_b = (0.78, 0.72, 0.75, 0.72)\,\mathrm{mA}$. The key ingredients needed to achieve this were a very high $Q_s = 0.135$, 1 T field in the damping wigglers, longitudinal feedback, a very good closed orbit and careful steering through the RF straight sections. The working point was away from coherent resonance conditions.

The value of the high Q_s seems to be twofold: it increases the space between synchro-betatron resonances and probably helps to suppress the coherent longitudinal motion since the generator voltage is much higher than the beam-induced voltages in the cavities.

The previous record single-bunch current of $I_b = 0.75\,\mathrm{mA}$ was obtained, rather surprisingly, with the coherent vertical tune close to the first synchrotron sideband of the integer. The incoherent tune was deduced to be close to the second sideband when the current saturated. Reactive feedback [14] will be used to keep the coherent and incoherent tunes together and should help to increase currents.

7 Conclusions and Outlook

Although present estimates are still subject to considerable uncertainty and are, as usual, only fits to simplified models, the longitudinal impedance appears to be rather low while the transverse is about what was expected.

The TMCI has not yet been clearly observed but we can expect to encounter it soon. Strategies are emerging for overcoming the present current limits from coherent longitudinal motion and synchro-betatron coupling.

The detailed study of collective effects makes considerable demands on beam instrumentation. LEP was designed with a superb complement of sophisticated instrumentation, which has naturally required its own commissioning—some devices have only gradually become fully operational. In parallel with this, the availability of machine study time has diminished so the full potential of these systems for studies of intensity-dependent effects is far from being realised.

We can look forward to reporting on many more measurements stemming from future efforts to comprehend and vanquish the intensity limitations, an essential component of the drive to push the performance of LEP to its ultimate limits.

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References

[1] A. Hofmann, J. Maidment, CERN LEP Note 168 (1979).

[2] T. Weiland, Proc. International Accelerator Conference, Geneva 1980, p. 570.

[3] K. Hübner, J.M. Jowett, S. Myers, CERN LEP Note 316 (1981).

[4] D. Brandt, K. Hübner, CERN LEP Note 486 (1984).

[5] B. Zotter, CERN LEP-TH/87-34 (1987).

[6] C. Pellegrini, CERN LEP-TH/86-17 (1986).

[7] J.-C. Juillard, E. Peschardt, this conference.

[8] E. Rossa et al, this conference.

[9] LEP Design Report, Vol. II, "The LEP Main Ring", CERN-LEP/84-01 (1984).

[10] D. Brandt et al, LEP Commissioning Note 21 (1990).

[11] V. Hatton, A. Hofmann, J.M. Jowett, H. Moshammer, S. Myers, this conference.

[12] K. Cornelis et al, LEP Commissioning Note 22 (1990).

[13] J. Miles et al, LEP Performance Note 30, (1990).

[14] L. Arnaudon, S. Myers, R. Olsen, this conference.