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Measurements of coherent damping and tune shifts with amplitude at LEP

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Abstract

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Measurements of Coherent Damping and Tune Shifts with Amplitude at LEP

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Abstract

The coherent damping offers the possibility to study various machine parameters such as head-tail damping, radiation damping and the horizontal detuning with amplitude. At the LEP electron-positron collider the beam orbit system is able to store the beam positions over 1000 turns following a deflection by a horizontal kicker. A precise analysis of such data for many beam position monitors was used to study the dependence of head-tail damping on beam parameters. The tune dependence on the horizontal amplitude was determined during the decay of the beam oscillation for various LEP optics. This parameter turned out to be an important issue for the LEP high energy optics.

1 1000-TURN MEASUREMENTS

The starting point for all studies described in this paper are “1000-turn” measurements. A coherent horizontal oscillation is excited by a single kick and the centre-of-charge position of the bunch is observed over 1024 consecutive turns. Figure 1 shows such a 1000-turn measurement for one BPM. The moment of the kick is clearly visible. A“global” fit to these data using a damped oscillation with amplitude dependent frequency (see fig. 2) yields the coherent damping time τ. The coherent damping at LEP is composed of radiation and head-tail damping:

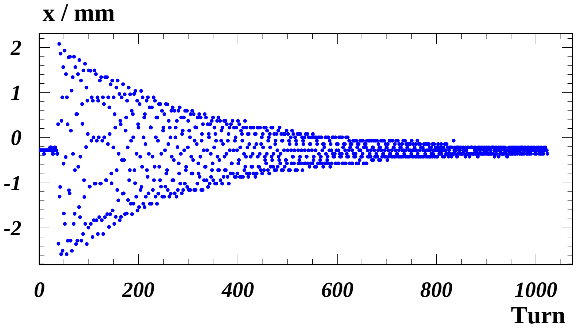

Figure 1: *Centre-of-charge position of a bunch versus turn number at an arc monitor. The kick and the subsequent damped oscillation are clearly visible.*

$$1/\tau_{\text{coh}} = 1/\tau_0 + 1/\tau_{\text{head-tail}}$$

with

$$1/\tau_{\text{head-tail}} \sim \frac{Q'}{E_0} I_{\text{b}}$$

where Q' is the chromaticity, I_{b} the bunch current and E_0 the beam energy. This relation holds down to very low bunch currents No filamentation effect is observed down to the smallest measurable currents. In general the head-tail effect is the dominating damping mechanism (see also fig. 3 and fig. 4).

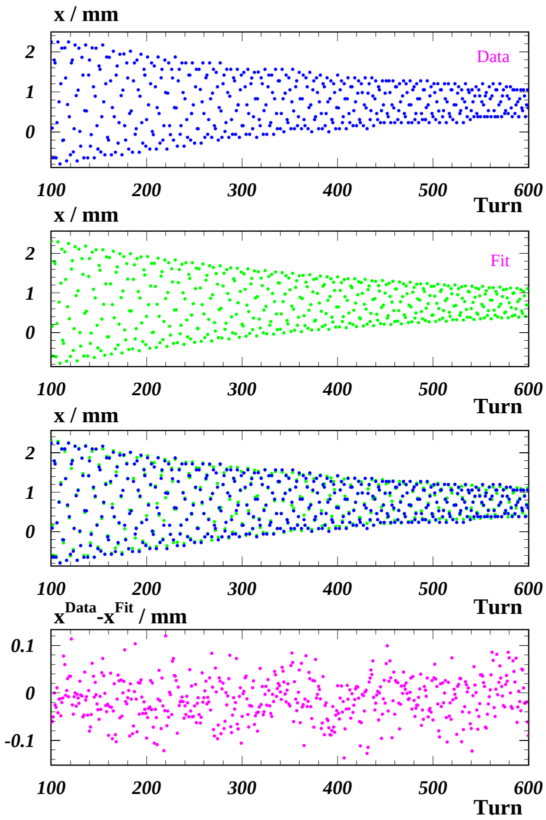

Figure 2: *Centre-of-charge position of a bunch versus turn number at an arc monitor. The upper two plots show data and the results of a “global” fit to the oscillation. The third plot is an overlay of data and fit results and the fourth shows the difference.*

2 RADIATION DAMPING AND J_X

During dedicated studies the coherent damping rate was measured for various sets of parameters. Figure 3 shows measurements where bunch currents and chromaticities Q' had been varied at a beam energy of 45.6 GeV. The dependence of the damping rate on current and chromaticity is clearly visible as expected for a head-tail dominated regime. The radiation damping rate can be extracted by an extrapolation (straight line fit) to zero bunch current. Table 1 shows the results of these extrapolations for measurements at 45.6 GeV and at 60 GeV and the corresponding predictions of the MAD program [1]. Differences between measurement and simulation are caused by tidal and geo-

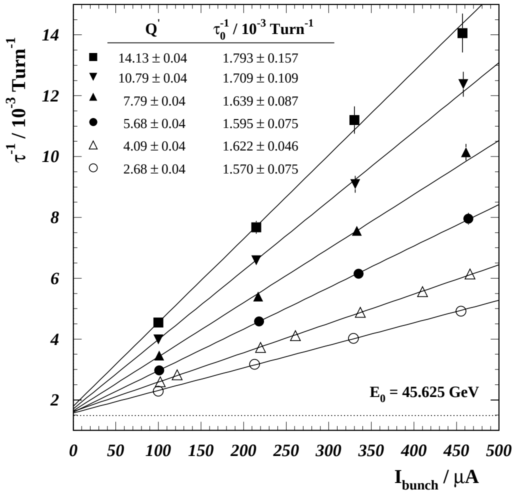

Figure 3: *Coherent damping rate as function of bunch current measured at a beam energy of* 45.625 *GeV for several chromaticities* Q'*. The straight lines are fits to the individual samples. The table gives measured chromaticities and 'zero current' damping rates.*

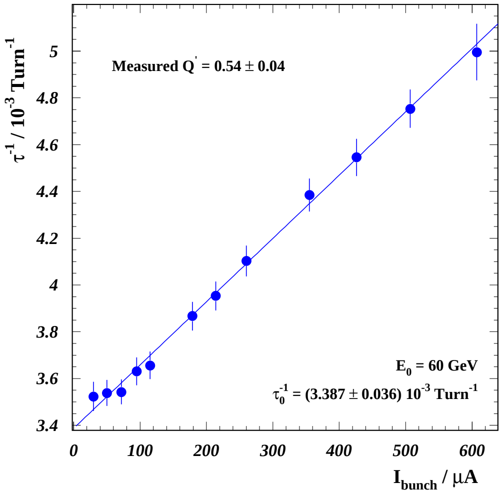

Figure 4: *Coherent damping rate as function of bunch current measured at one BPM with* 60 *GeV beam energy. The straight line is a fit to the data.*

logical distortions of the LEP circumference [2].

The measurement at 60 GeV (shown in fig. 4) yields a very precise value of the damping rate at zero current. A comparison of measurement and simulation allows the extraction of the horizontal damping partition number J_x since

$$\tau_0^{-1} = \frac{1}{2}\frac{U_0 f_{rev}}{E_0} J_x$$

where U_0 is the energy loss per turn and f_{rev} the revolution frequency.

Energy [GeV]	$1/\tau_0$ [10^{-3}/turn]	
	MAD	Measured
45.625	1.39	1.45 ± 0.10
60.000	3.16	3.39 ± 0.04

Table 1: *Results and* MAD *predictions of the radiation damping rates at 45.6 and 60 GeV beam energy.*

The measured J_x is $J_x = 1.072 \pm 0.013$ with an expectation of $J_x = 1.066 \pm 0.006$ from direct measurements of the circumference using beam position monitors and tide models [3]. The precise value of J_x is important for the understanding of the LEP beam energy since the J_x shifts are accompanied by an energy shift.

3 DETUNING WITH AMPLITUDE

The search for a good high energy optics has revealed the importance of the horizontal detuning with amplitude (anharmonicity) to guarantee a sufficient aperture for the beam. This is due to the fact that with the regular tune working point at LEP (the fractional part of Q_H is about 0.28) a large detuning with amplitude drives particles on the third integer resonance.

The horizontal detuning with amplitude can be extracted from 1000-turn measurements with a series of fits. Using the damping time from the previously described "global" fit, the tune evolution with time is obtained from subsamples of several turns. The results of such fits to the data of fig. 1 are shown in fig. 5. The horizontal detuning with amplitude ($\partial Q_x/\partial W_x$) is given by the dependence of the tune Q on the Courant-Snyder invariant W. The latter is easily calculated from

$$W = \frac{1+\alpha^2}{\beta}x^2 + 2\alpha x x' + \beta x'^2 \quad \approx \quad A^2/\beta$$

with

$$A = A_0 e^{-t/\tau}$$

where τ is the damping time and A_0 the zero turn amplitude. x stands for a single particle position and A denotes

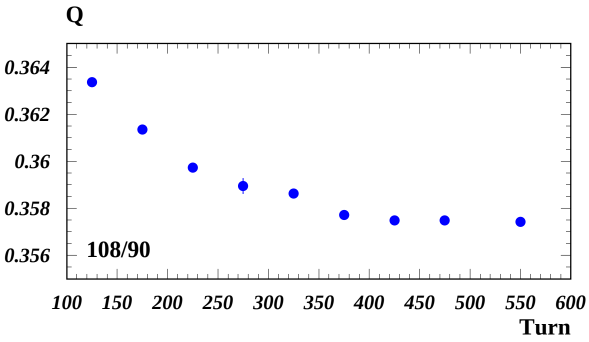

Figure 5: *Tune evolution corresponding to the damped bunch oscillation shown in figure 1.*

Optics	Energy [GeV]	$\partial Q_x/\partial W_x$ [10^3/m]	
		MAD	Measured
90/60	60.0	1.7	6.2 ± 0.8
102/90	87.0	12.2	10.6 ± 1.2
108/90	45.6	25.0	34.0 ± 1.0

Table 2: *Measured and predicted horizontal detuning with amplitude for three LEP physics optics. The energies at which the measurements have been done are given as well. The errors include statistical and systematic uncertainties.*

the measured amplitude of the centre-of-charge oscillation of a bunch. Figure 6 shows the relation between Q and W for one BPM. The detuning is given by the slope using:

$$Q = Q_0 + \frac{\partial Q_x}{\partial W_x}\, W$$

This analysis is applied to all 240 beam orbit monitors of the arcs in order to improve the statistics for a reliable measurement. Averaging over all arcs also cancels periodic perturbations like β-beating. The statistical error is given by the standard deviation of all single measurements ($\sigma/\sqrt{N}$). The systematic error is estimated by simulation studies with the MAD program which shows that the method is reliable.

Datasets for several optics have been analysed. The results are shown in tab. 2 and fig. 7. The histograms of fig. 7 represent the distributions of measurements for all arc monitors. The distributions are consistent with a gaussian shape and are clearly separated. Although the measured detuning is usually larger than the predictions for a perfect machine there is a reasonable agreement between measurements and predictions. A more detailed description of this topic can be found in [4].

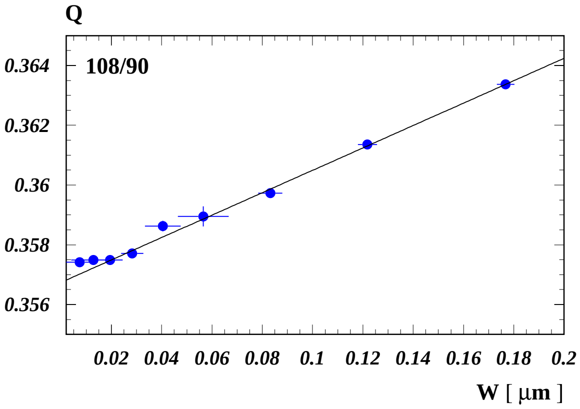

Figure 6: *Tune as function of Courant-Snyder invariant with the 108/90 degree phase advance optics at on arc monitor. The straight line is a fit to the data.*

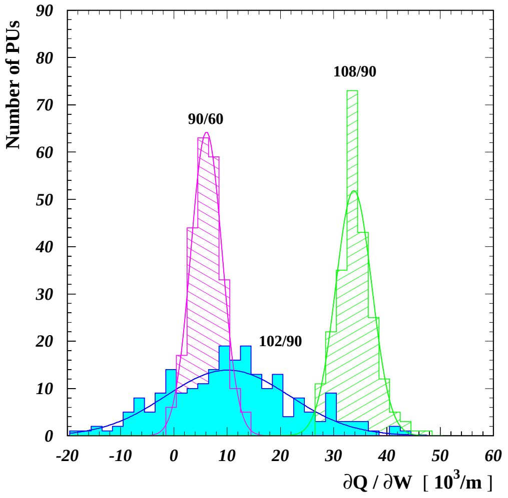

Figure 7: *Horizontal detuning with amplitude for the LEP physics optics with horizontal/vertical phase advance in the arcs of 90/60, 102/90 and 108/90 degrees. The distributions of the 102/90 measurements show a larger scatter because of the shorter damping time due to higher beam energy and the resulting fewer data points for a fit.*

4 SUMMARY

Measurements of damped coherent oscillations following a horizontal kick have been used to study the damping mechanism and the tune dependence on amplitude. The measurements confirm that at LEP head-tail damping is the dominant collective damping mechanism. Measurements of the radiation damping time allow the determination of the horizontal damping partition number, a very important parameter for the LEP beam energy. The measured tune dependence on amplitude confirms predictions of the LEP model.

5 ACKNOWLEDGEMENTS

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