DAMPING OF LONGITUDINAL COUPLED DIPOLE BUNCH OSCILLATIONS IN LEP

J.C. Juillard and E. Peschardt

CERN, 1211 Geneva 23, Switzerland

Summary

Dipole coupled bunch oscillations are observed in LEP at bunch currents above $\sim 150\,\mu A$. These oscillations are damped with a feedback system. The phase between the sum signal from a pick-up and the RF frequency is measured. After processing the error signal is used to modulate the RF stable phase angle. Two feedback systems, each acting on different cavities, have been installed, one for electrons and one for positrons. The systems are decoupled by dephasing of the RF system in such a way that the synchrotron tune is different for e^+ and e^-. Longitudinal feedback is used routinely during physics runs and increases substantially the maximum currents which can be accumulated.

Introduction

Longitudinal instabilities were not expected in LEP before the bunch current was approaching the nominal value of 0.75 mA [1]. However, during the commissioning of the accelerator strong dipole oscillations were seen at bunch currents higher than about 0.15 mA. Although the accelerating cavities were carefully detuned to cure the Robinson instability the oscillations did not disappear. As a separate wideband damping cavity system has not been installed in LEP a system which acts on the phase in the accelerating cavities has been developed. A fundamental limitation of such a system is the small bandwidth of these cavities. To damp all dipole modes the maximum modulation frequency f_{max} is, with a four-bunch beam (Fig. 1):

$$f_{max} = 2 \times f_{rev} - f_s$$

where f_{rev} is the revolution frequency and f_s the synchrotron frequency. In LEP $f_{max} \cong 21.5$ kHz. At this deviation from the carrier the LEP RF cavities attenuate the signals about 13 dB. This is not a serious limitation. However, with two counter-rotating beams and the cavities located near an intersection point (IP) the time between the passage of an electron bunch and a positron bunch is only between 1.0 and 1.6 μs. Unavoidably a signal which acts on one bunch will also excite a bunch of the counter-rotating beam. As particles only respond to longitudinal excitation near their synchrotron frequency or an harmonic thereof, this unwanted coupling can be reduced in LEP by making the synchrotron tune different for the two beams.
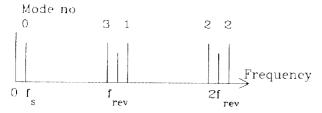

Fig. 1. Spectrum showing all the dipole modes of oscillation for a beam of four bunches.

Contrary to the case with other lepton accelerators, this is possible in LEP because the cavities are excited at two frequencies, $f_1 = 352.20904$ MHz and $f_2 = 352.29900$ MHz [2].

With the cavities aligned for one frequency, f_1, the phase error for the second frequency increases linearly with the distance from an IP. When the RF phases are correctly adjusted (Fig. 2) the error is the same for positrons and electrons and the voltage loss is only 3.5%. If all the RF voltage vectors are aligned for, say, positrons, the RF sum voltage seen by electrons is 13.3% lower and the phase oscillation frequency shifted downwards. The nominal synchrotron tune of 0.08 is decreased to 0.074.
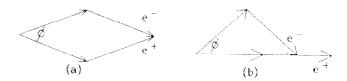

Fig. 2. Vector diagrams showing the addition of the voltage vectors for two RF units located symmetrically around an intersection point. In (a) the RF phases are correctly adjusted and the total voltage is equal for electrons and positrons. In (b) the phase of f_2 for one unit has been adjusted to maximise the voltage for positrons. The sum voltage for electrons is decreased by a factor $\cos \phi = 0.734$ for an average cavity position. As half the RF power is generated at f_2 the voltage loss for electrons is 13.3%.

System description

The longitudinal dipole oscillations are detected by a pick-up sensitive to energy variations. Basically two detection schemes can be used:

a) The oscillations are picked up by a horizontal position monitor located where the dispersion is large.

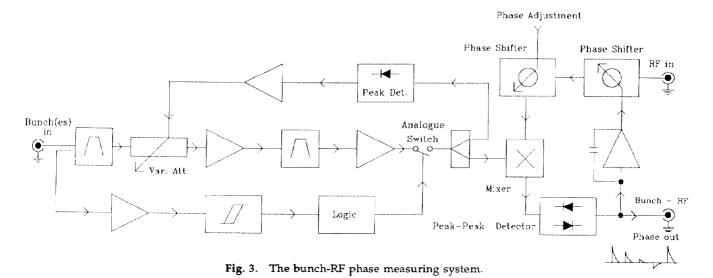b) The signal from a sum pick-up is phase-compared with the RF frequency or another harmonic of the bunch frequency.

In LEP the second solution has been chosen. The reasons are:

1. A high dispersion region is several hundred metres away from the RF straight section where the processing electronics are located. It is impractical to send pick-up signals over these distances.

2. By using the sum signal from a pick-up the horizontal betatron oscillations, which are large during injection, are not detected. This makes filtering easier.

3. The energy resolution obtained with a phase measurement using the RF frequency as reference, is better than with a position measurement in a high dispersion region. The position resolution of a LEP pick-up is about 50 μm. With a dispersion of 2.2 m the energy resolution is:

$$\frac{\Delta E}{E} = 23 \cdot 10^{-6}$$

At the RF frequency the maximum phase variation of an oscillating bunch is

$$\Delta \phi = \frac{h \cdot \alpha_p}{Q_s} \cdot \frac{\Delta E}{E}$$

Fig. 3. The bunch-RF phase measuring system.

where h is the RF harmonic number, α_p the momentum compaction factor and Q_s the synchrotron tune. The resolution of the phase measurement is 0.1 degree. The energy resolution is then (h = 31320, α_p = 3.9·10⁻⁴. Q_s = 0.08):

$$\frac{\Delta E}{E} = 11\cdot10^{-6}$$

which is a factor two better than the result obtained with a transverse pick-up.

The bunch-RF phase measuring system

Measurement of the phase between a bunch and the RF frequency is not a trivial task because of the low bunch repetition rate. With a beam of four bunches the RF frequency is 7830 times the bunch frequency. Different methods have been considered[3]. Finally a direct approach has been chosen: the sum signal from a pick-up is processed with bandpass filters centred at the 352 MHz RF frequency, amplifiers and an automatic gain control loop (Fig. 3). The resulting signal, a 352 MHz burst, is phase compared with the RF frequency and the phase difference derived from a peak-to-peak detector.

The time constant is chosen to be such that the signal decays in the time interval between the passage of two bunches. This permits phase measurement of all four bunches with one system and with only few modifications the system can be used for eight bunches.

The logic, triggered by the pick-up signal, and the analogue switch determine whether electrons or positrons selected. The disadvantage of this self-triggered system is that the feedback system cannot distinguish between electrons and positrons if only one beam is circulating. The AGC loop enhances the dynamic range. Phase differences of less than 0.1 degree at 352 MHz can be measured for bunch currents between 5 μA and 2.5 mA (Fig. 4).

The signal processor

The phase detector signal is processed using the time domain approach (Fig. 5). With the sample and hold amplifier the signal from each bunch is separated. After filtering
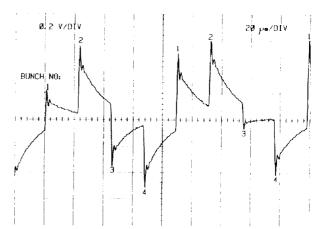

Fig. 4. Oscillogram of the signal at the output of the phase detector. The sensitivity is 250 mV/degree and the resolution better than 0.1 degree.

and phase adjustments the four channels are recombined in analogue gates. The timing (Fig. 6) is arranged to be such that the phase information from one bunch is used for correction of the same bunch one turn later. This timing is derived from the pick-up signal.

The correction signal is applied to a voltage-controlled phase shifter which modulates the klystron drive signal. The same phase shifter is used in the klystron phase loop which compensates for phase variations in the power generation system [4]. Two systems have been installed in LEP, one for electrons and one for positrons. Each system acts on two RF units. Common mode dipole oscillations are damped in one unit and coupled dipole oscillations in another unit.

Results

When the system was tested for the first time in September 1989 a record current of 3.8 mA (2.1 mA of positrons and 1.7 mA of electrons) was accumulated in LEP with longitudinal feedback acting on positrons. When the feedback system was switched off the positron current
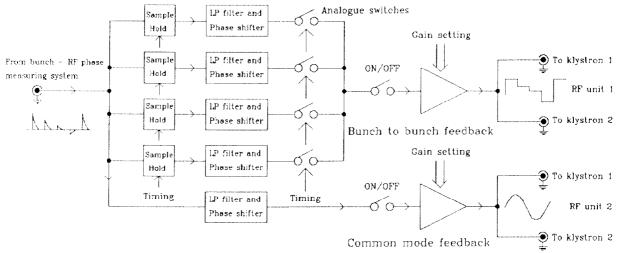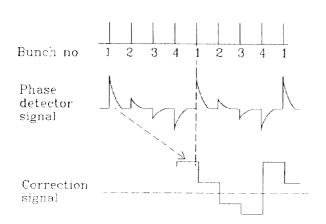
Fig. 5 Schematic diagram of the signal processor

Fig. 6 Timing diagram

Fig. 7 Bunch spectra without (upper) and with (lower) longitudinal feedback. The marker is placed on the LEP revolution frequency.

decreased to 1.05 mA. Figure 7 shows typical bunch spectra of a 1 mA beam in four bunches without and with feedback. The large signals of mode 0 ($Q_s \cdot f_{rev}$) and mode 3 [$f_{rev}(1-Q_s)$] are damped about 20 dB by the system.

At the time of writing the electron system is used routinely during operation and increases the accumulated e$^-$ current up to a factor two. With feedback on electrons the positron feedback system does not increase the e$^+$ current which can be accumulated, probably due to coupling between the two beams induced by the electron feedback system. Q_s in LEP is normally about 0.08. When longitudinal feedback is used the RF system is dephased to decrease Q_s by 0.002 for electrons. By making this difference larger the feedback systems would work better but other problems are created because the maximum bunch current is very sensitive to Q_s variations.

Longitudinal feedback is only required at the injection energy of 20 GeV. After acceleration to about 45 GeV and before physics conditions are established, the longitudinal feedback system is switched off and the RF system rephased to make Q_s equal for electrons and positrons.
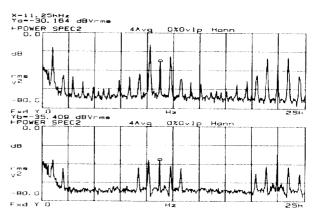
Conclusions

The present longitudinal dipole feedback system increases substantially the beam currents which can be accumulated in LEP but the performance of the system is fundamentally limited by the bandwidth of the RF cavities. Therefore a system with dedicated wideband cavities is being studied. The planned operating frequency for this system will be around 1 GHz and the maximum feedback voltage about 2.5 MV.

References

[1] C. Pellegrini, "Longitudinal coupled bunch instability for two counter-rotating beams", CERN/LEP-TH/86-17.
[2] P. Brown, E. Ciapala, S. Hansen, E. Peschardt and J. Sladen, "The LEP radio-frequency low power system", **IEEE Trans. Nucl Sci.**, NS-23, October 1985, pp. 2032-34.
[3] M. Lennholm, "Bunch-RF phase detector for the LEP accelerator at CERN", Thesis for the Master of Science Degree, submitted to Danmarks Tekniske Højskole, Lundtofte, Denmark, in 1987.
[4] J.-C. Juillard and E. Peschardt, "Phase and voltage control in the LEP radio-frequency system", **Proc. 1989 IEEE Particle Accelerator Conf.**, pp. 1639-41.