RF System Calibration Using Beam Orbits at LEP

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Abstract

The target for beam energy calibration at LEP 200 is to achive a relative accuracy of approximatively 10^{-4} for energies above the W pair production threshold. A variety of calibration methods have been used for that purpose, one of them being based on a spectrometer magnet. The spectrometer is using six dedicated high resolution BPMs to measure the beam energy through the deflection angle around a dedicated and calibrated dipole magnet. To obtain the average beam energy, local deviations at the spectrometer due to the energy sawtoothing must be taken into account. The local energy shift depends on the energy loss in each arc as well as on the details of the RF voltage distribution. Local phase errors and longitudinal misalignements affect the local energy and must be taken into account. This note describes a method to determine some overall RF parameters for each interaction point of LEP to improve the accuracy of the local energy prediction. It is based on a MAD model of the RF system which is calibrated by dedicated experiments.

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1 Introduction

For beam energies up to 60 GeV, very accurate measurements of the average beam energy are possible at LEP using the technique of resonant depolarization [1, 2]. Unfortunately no direct beam energy measurement is available at LEP for beam energies above the W pair production threshold of 80 GeV. The determination of the beam energies in this regime relies on a variety of calibration methods which are all based on the extrapolation of the accurate calibrations by resonant depolarization to high energy [3]. The target of the energy calibration is to achieve an accuracy of better than 2×10^{-4}. One calibration strategy is based on the spectrometer principle where beam angle variations across a calibrated dipole magnet are tracked using two triplets of beam position monitors on either side of the magnet. The LEP spectrometer, which is installed near interaction point (IP) number 3, aims for a relative accuracy of the beam energy of 10^{-4}. Contrary to the other methods the spectrometer is only able to determine the local beam energy which depends on the LEP energy sawtooth. Due to the huge ~ 2 GeV energy loss by synchrotron radiation over one machine turn above 100 GeV, the deviation of the local beam energy at the spectrometer with respect to the average beam energy can be quite significant. In addition it is sensitive to longitudinal alignment, phase and voltage calibration errors of a large number of RF units. This problem can in principle be avoided by measuring systematically the energy of both beams at the same time, because their local energy shifts are anti-correlated. Unfortunately spectrometer measurements with two beams were not possible, due to hardware problems with the BPM electronics.

For the last LEP run in 2000, a realistic model of the RF system, including imperfections like longitudinal misalignments, was implemented in the MAD program. This allowed online predictions of local energy shifts at the spectrometer based on the actual RF configurations and accurate predictions for off-line analysis. In addition the RF model was tuned using a novel procedure to determine some RF system uncertainties using beam orbit measurements.

2 The RF System Model

To make accurate prediction of local energy deviations (energy sawtooth), the machine model must include alignment, phase and voltage calibration errors of each RF unit in addition to a precise description of the synchrotron radiation losses. In the first LEP years, a dedicated program, including a detailed description of the RF system [2], was developed to calculate the local energy corrections at the LEP IPs for physics and calibrations fills. The effects of the LEP wiggler magnets, which were used to control the bunch length at injection and the beam emittance during collisions around the Z resonance, were also taken into account. Concerning energy loss by synchrotron radiation, the machine model was however based on a simple global loss for each LEP octant. The main aim of this program was the prediction on centre-of-mass energy shifts at the LEP IPs.

The details of the RF system and the energy loss due to synchrotron radiation can also be modelled with the MAD program [5]. Using MAD the local energy deviations with respect to the average energy can be determined at any place in the ring. The energy loss around the ring is modelled more precisely and in more detail than the standard LEP RF system program. Other relevant parameters like synchrotron tune, bunch length, etc... are also easily available. For those reasons a detailed model of the LEP RF system was implemented inside MAD using
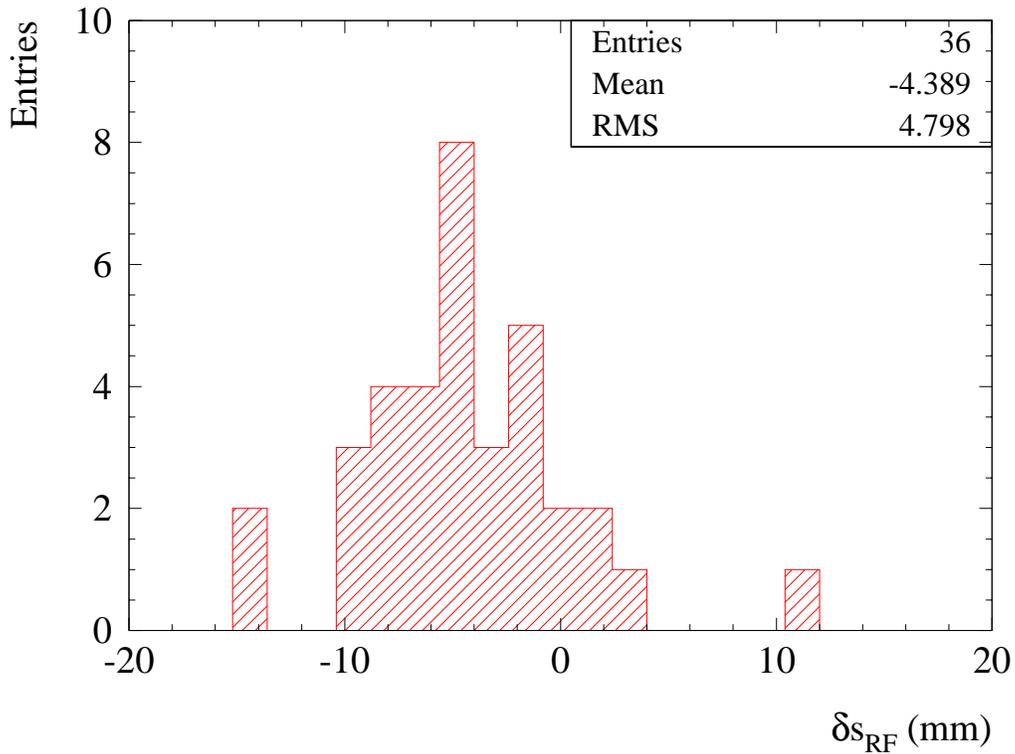
Figure 1: Distribution of longitudinal misalignments relative to the nearest IP of the LEP SC RF units. The measurements were performed at the beginning of the LEP run in 2000. The reproducibility of the measurement is $\sim \pm 1$ mm. For negative values of δs_{RF} the RF unit is too close to the IP.

the MAD script language. Phase errors of RF units can be added using the phase lag parameter of MAD, but longitudinal misalignments of RF cavities are not supported. Such misalignments can however be faked since a longitudinal misalignment of δs_{RF} is equivalent to a phase lag of

$$\delta\phi_z = 2\pi\frac{\delta s_{RF}}{\lambda_{RF}} \tag{1}$$

for one beam, and of opposite sign for the counter-rotating beam. λ_{RF} is the RF wavelength (85.2 cm for LEP). Misalignments can be easily converted to phase errors using the MAD script language, including the correct signs for the 2 counter-rotating beams.

Scripts were developed to load individual voltage calibration factors, misalignments... into MAD and compute the energy deviations with respect to the average beam energy anywhere along the ring. RF configurations logged in the LEP databases could be retrieved and loaded to reconstruct the orbits, energy sawtooth and other parameters related to the RF system for any given point in time. The scripts could be run online during machine experiments to obtain quick estimates of the local energy deviation at the spectrometer from the actual RF voltage distribution.

In 1991 it had been realized that the LEP Copper (Cu) RF cavities were longitudinally misaligned with respect to their operating RF frequency. This misalignment resulted in ~ 16 MeV

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higher centre-of-mass energies in IP2 and IP6 compared to IP4 and IP8 [2]. The influence of the Cu cavities became gradually weaker at LEP200 since the RF voltage of over 3 GV was mainly produced by the superconducting (SC) RF system. Some Cu RF cavities were even removed from the machine to free space for additional SC cavities. The Cu cavity misalignment depends on the distance to the IP. For the LEP run in 2000, the effective distance corresponds to 225 m. At such a distance the Cu cavities are 2.87 cm too far away from the IP.

At the beginning of each LEP run, all RF units are phased one with respect to the other. The longitudinal alignment and voltage scaling factors are determined at injection by comparing synchrotron tune measurements performed with electron and positron beams. For more details on those procedures, see for example Ref. [4]. For LEP200, the alignment errors of the SC cavities are in the range of ± 15 mm, for a measurement reproducibility of approximately ± 1 mm. The distribution of the misalignment is shown in Figure 1. Since on average the cavities are shifted towards the IP by ~ 4 mm, the energy at the LEP IPs is systematically lower than the centre-of-mass energy obtained by addition of the average single beam energies. The shift due to the SC cavities is of opposite sign to the shift due to the Cu RF system.

Predictions from the RF program developed for LEP energy calibration and from the MAD RF model have been compared for a number of standard configurations and energies. The agreements were always excellent, in general much smaller than 1 MeV for centre-of-mass energy shifts at the IP. The predictions for sawtooth energy shifts at the location of the LEP spectrometer agreed within 0.1-0.5 MeV at 50 GeV and within 1-2 MeV around 100 GeV.

In the following sections of this note, all results are implicitly based on a complete model of the RF system, including the measured misalignments and voltage scale factors determined at the beginning of the LEP run in the year 2000.

3 Local Beam Energy Measurements with Closed Orbits

The energy sawtooth of the beams can be measured by the beam position monitors in regions of non-vanishing horizontal dispersion. The local energy offset translates into a horizontal beam position that is proportional to the local horizontal dispersion and energy offset. When a single beam orbit is being considered, the sawtooth signal is smeared out by the closed orbit deviations around the ring. On the other hand, the sawtooth appears very clearly on the difference orbit between the two beams since closed orbit contributions cancel almost completely. An example in shown in Fig. 2. Due to the limited accuracy of the beam position monitors, uncertainties on the exact value of the energy loss... it is not simple to make a precise prediction and comparison of the sawtooth itself.

The situation becomes much simpler when orbits are compared at a given energy for two different RF voltage distributions, as shown in Fig. 2. Since the energy loss in the arcs is only affected to higher order by a change of the RF distribution, the difference in energy gains at each IP appear on the difference orbits as step changes. In the regular arc cells where for LEP the dispersion is identical at all the monitors, one expects a constant offset for each octant. In practice a betatron oscillation can be superimposed on this constant offset. This oscillation can for example be due to an imperfect horizontal dispersion function or to more subtle effects.

To extract the energy shift δ_p between two RF configurations for a given octant from a difference orbit, the data consisting of up to 30 beam positions Δx_i is fitted to the following
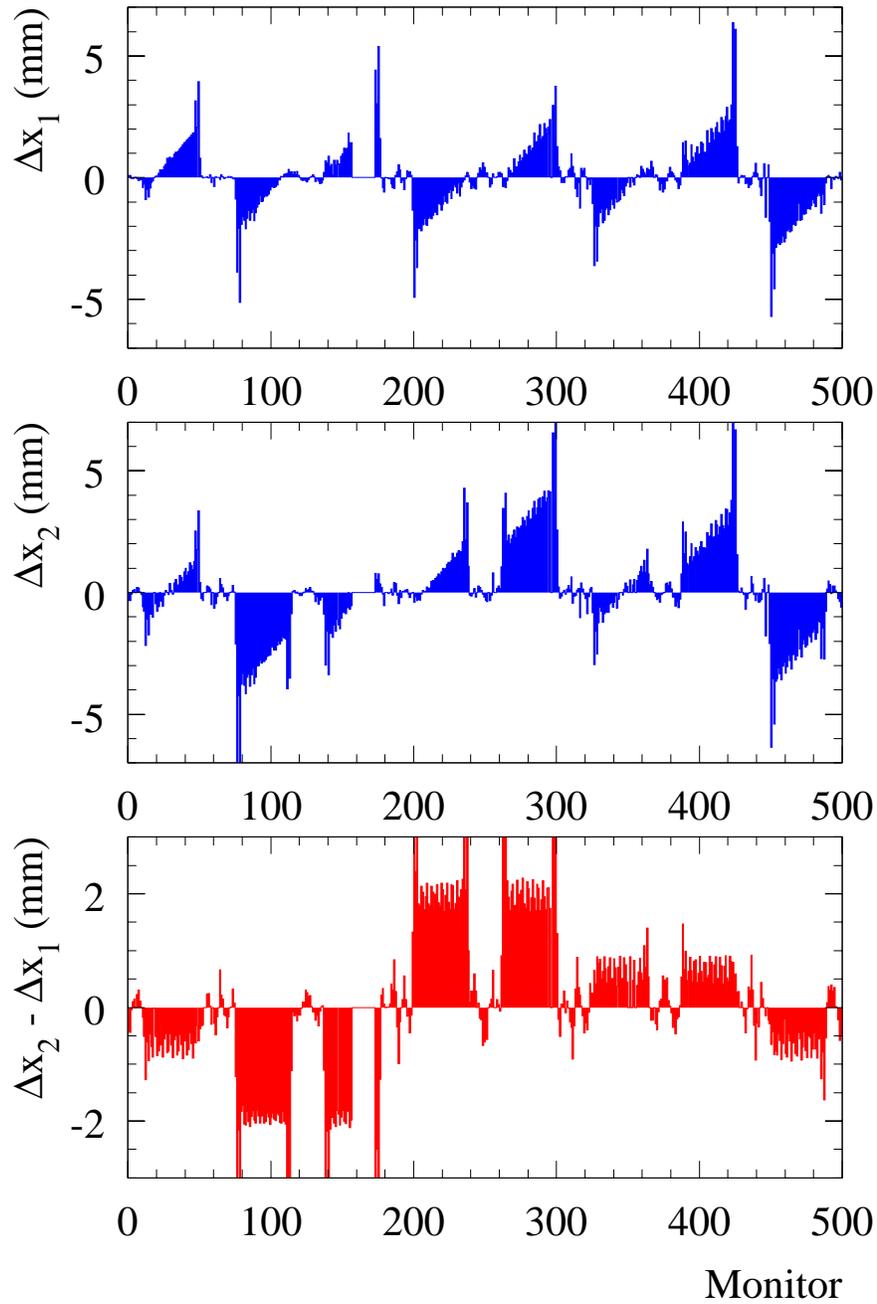
Figure 2: Example of horizontal difference orbits between electron and positron beams for two different RF configurations (top and middle). The energy sawtooth is clearly visible. The difference of the two difference orbits is displayed on the bottom plot. The step changes of the orbits in the arcs reflect the different energy gains around the 4 IPs for the two configurations. Note the missing orbit information between monitors no. 160 and 176.
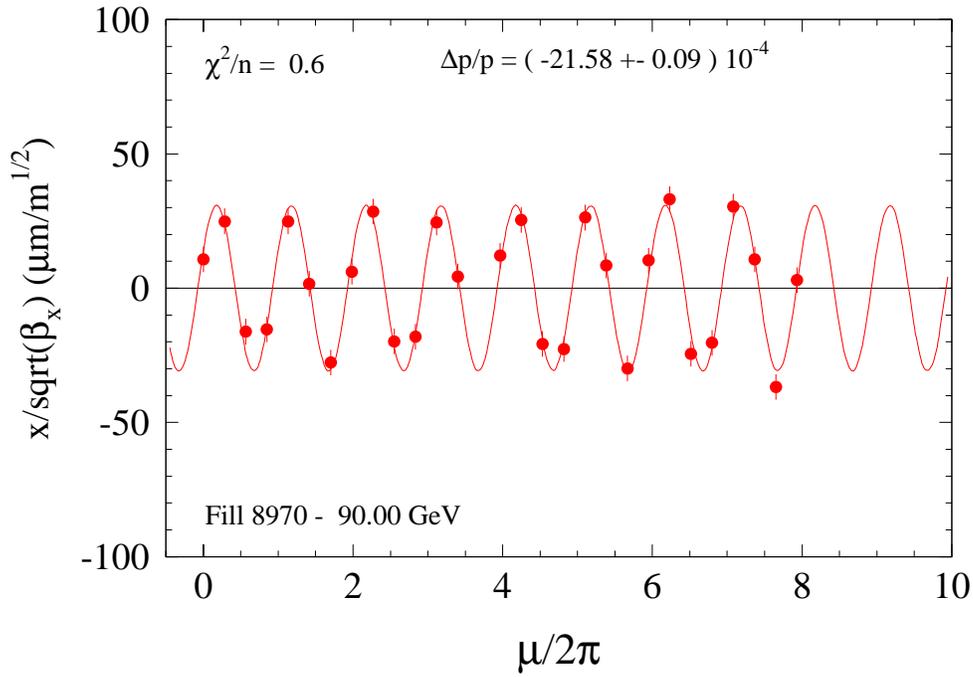
Figure 3: Example of a fit (solid line) to a closed orbit difference in one LEP octant. The vertical axis corresponds to $(\Delta x_i - D_i \delta_p)/\beta_i$, see Equation 2, which corresponds to the residual betatron oscillation. The energy offset δ_p is $(-21.6 \pm 0.1) \times 10^{-4}$ in this example.

expression,

$$\Delta x_i = \beta_i(A\cos(\mu_i) + B\sin(\mu_i)) + D_i\delta_p \qquad (2)$$

where β_i, μ_i and D_i are respectively the betatron function, betatron phase advance and dispersion at the ith monitor. Note that in theory β_i and D_i are identical at all the arc monitors. The 3 parameters of the fit are A, B and δ_p. A fit example is shown in Fig. 3. The fits are performed individually for each octant. As a cross-check one can note that when the offsets are summed over all 8 octants,

$$\Sigma = \sum_{j=1}^{8} \delta_p^j = 0 \qquad (3)$$

by definition, unless the length of the orbit (or the machine circumference) has changed between the two orbit measurements. Furthermore, since the RF cavities are installed in only 4 IPs, the two adjacent octants between 2 even IPs have identical energy shifts. This is strictly speaking true only when the settings of the LEP wigglers are not changed between the two closed orbit measurements.

The beam position monitor calibration and the scale of the horizontal dispersion (in practice they cannot be separated) were checked with 21 dispersion measurements spread out over the LEP run in 2000. The dispersion is obtained from the difference of two closed orbits measured at two different RF frequencies. For such measurements the energy change is known precisely

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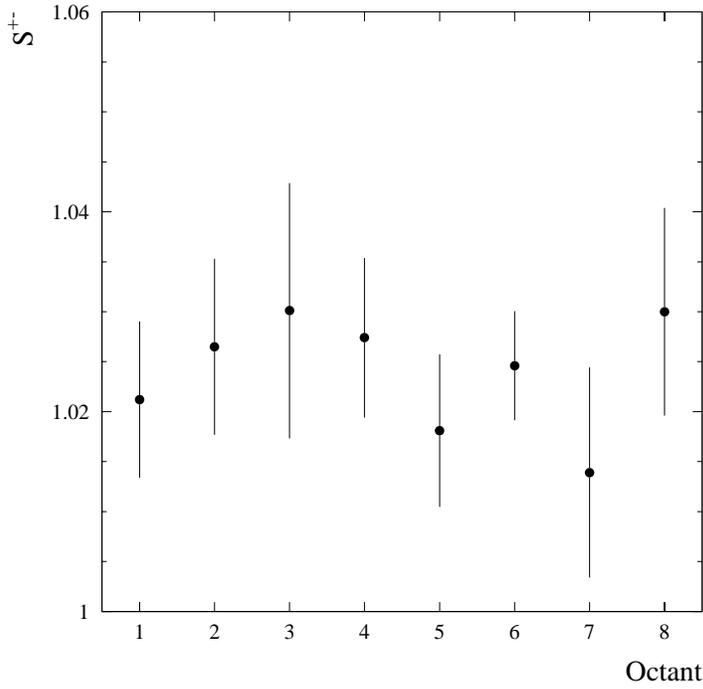
Figure 4: Average BPM scale factor as a function of the octant obtained from 21 dispersion measurements. The error bars corresponds to the r.m.s. spread of the scale factor of all measurements. The scale factor corresponds to the average over electrons and positrons.

from the RF frequency change and is identical for all octants. The energy offset obtained from the fit to the orbit difference can therefore be compared to the expected value. The ratio is an indication of the BPM scale calibration error. Figure 4 shows the results for each octant. On average the scale is shifted by 2.5%. The values are relatively stable over the run within $\pm$ 1%.

4 Measurement of RF System Parameters

For the large RF voltages and energy losses at high energy, even small phase or voltage scale errors can significantly bias the prediction of the local energy at the spectrometer. It is therefore desirable to verify some critical RF system parameters. Important ingredients for the prediction of the local beam energy are average phase shifts and voltage scale errors over one IP. Effects of individual RF units are not easy to measure and are, a priori, not required. At 100 GeV a phase shift of 1 degree in IP2 or IP4 shifts the energy at the spectrometer by ~ 3.5 MeV, while the same phase shift in IP6 or IP8 induces an energy change of ~ 1 MeV. The difference between the IPs is due to the fact that the spectrometer is installed between IP2 and IP4, and its local energy offset is more sensitive to uncertainties on the RF system parameters in those two "surrounding" IPs. A voltage calibration error of 1.2% has the same effect than a 1 degree phase error.

To detect errors on phase and voltage scale of a given IP, it is important to make large

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changes to its RF voltage. The measured and predicted energy shifts can be compared in each octant. The local energy gain δE_i at the ith IP with effective RF voltage U_i is given by

$$\delta E_i \simeq E_{loss} \frac{U_i}{U_{tot}} \tag{4}$$

where E_{loss} is the energy loss by synchrotron radiation over one turn and U_{tot} is the total RF voltage over the ring. A simple manipulation to force a large change of δE_i consists in ramping the RF voltage in one IP from a maximum of $800-1000$ MV to a minimum value of ~ 180 MV. This operation should be performed at the highest possible energy to maximise δE_i through E_{loss}. Errors in the RF system model appear as differences between observed and predicted energy shifts around the LEP ring. The energy shifts can be measured using the principle of the closed orbit fits on difference orbits described in the previous section.

Two machine experiments were performed in October 2000 at 90 GeV in fills 8945 and 8970. The first experiment used two beams, the second only a positron beam. The choice of the energy was dictated by the need to have a large energy loss to enhance the effects (and therefore improve the resolution). At the same time enough voltage margin was required to ramp down the RF voltage of any IP to the minimum voltage without losing the beam. During both experiments, the RF voltage of each IP was ramped down in turn to the minimum voltage (without completely switching off the RF). Orbit measurements were recorded for each RF configuration. The change in beam energy with respect to the nominal configuration is obtained for each octant from fits to the orbits and compared to the predictions of the RF model. The synchrotron tune Q_s is also recorded and compared to the predicted value. This parameter is required to set the absolute scale of the RF voltage calibrations.

For each IP it is possible to adjust an overall phase shift $\Delta\phi_z$ of that IP relative to the other IPs (or to an average phase). In addition an overall voltage scale factor f_V can also be determined IP by IP. Figures 5 and 6 show comparisons of the RF MAD model and the data before and after adjusting the phase shifts and voltage scales in each of the four even IPs. The voltage calibration factors do not exceed 3%. The phase shifts are also small, of the order of a few degrees. The optimised values for $\Delta\phi_z$ and f_V are given in Table 1. The results form the two fills are perfectly consistent. The fit uncertainties on $\Delta\phi_z$ and f_V imply an uncertainty on the local beam energy at the spectrometer of ~ 4 MeV at 100 GeV.

Compared to the ideal case ($\Delta\phi_z = 0$, $f_V = 1$ in all IPs), the phase and scale adjustments given in Table 1 cause energy shifts at the spectrometer of ~ 3 MeV at beam energies of 40 to 50 GeV and of ~ 20 MeV at 90 to 93 GeV, where most spectrometer calibrations were made. The shift at high energy is therefore similar to the target systematic error on the beam energy error and constitutes a very large correction. The predicted effect of the phase and voltage corrections is less than 1.5 MeV on the centre-of-mass energies at the four IPs in physics conditions at a beam energy of 103 GeV. If the source of the errors was concentrated on a single RF unit in each IP, the centre-of-mass shift could reach ~ 8 MeV at 103 GeV. This value is in good agreement with the systematic error on 8 MeV that was assigned to the centre-of-mass energies due to uncertainties on RF system modelling and parameters at beam energies of ~ 90 GeV [3].
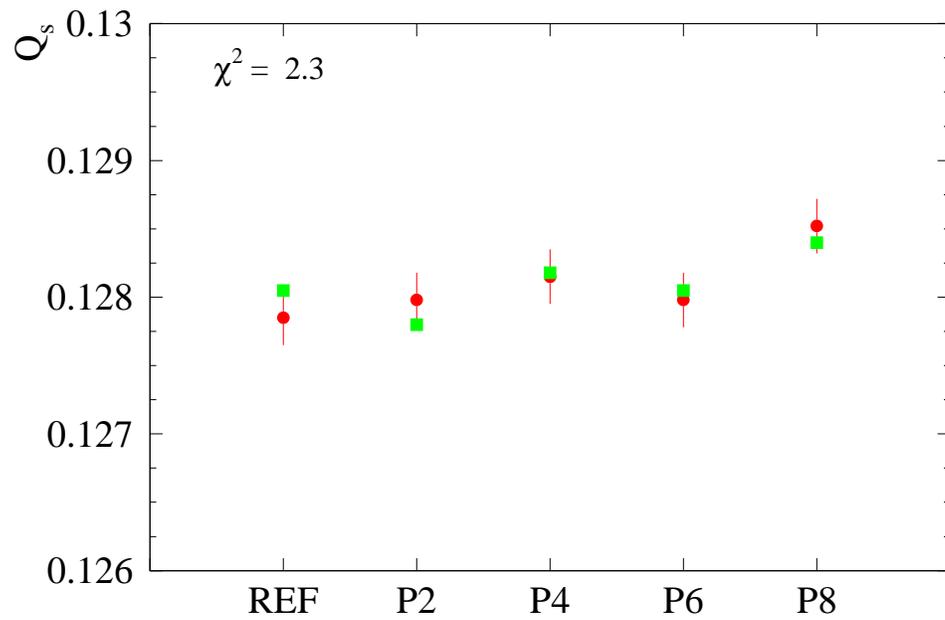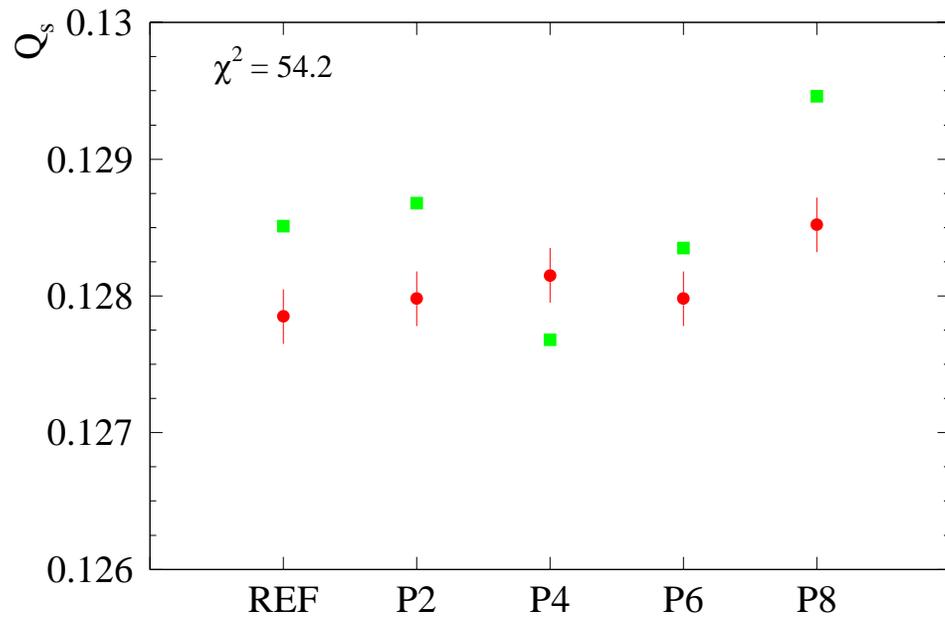
Figure 5: Measured (●) and predicted (■) synchrotron tune Q_s before (top) and after (bottom) tuning of the MAD RF model. The label REF refers to the nominal RF configuration with an equal distribution of the RF voltage in all IPs. The labels IP2, IP4,... refer to the RF configurations with the corresponding IP RF voltage ramped to the minimum voltage.
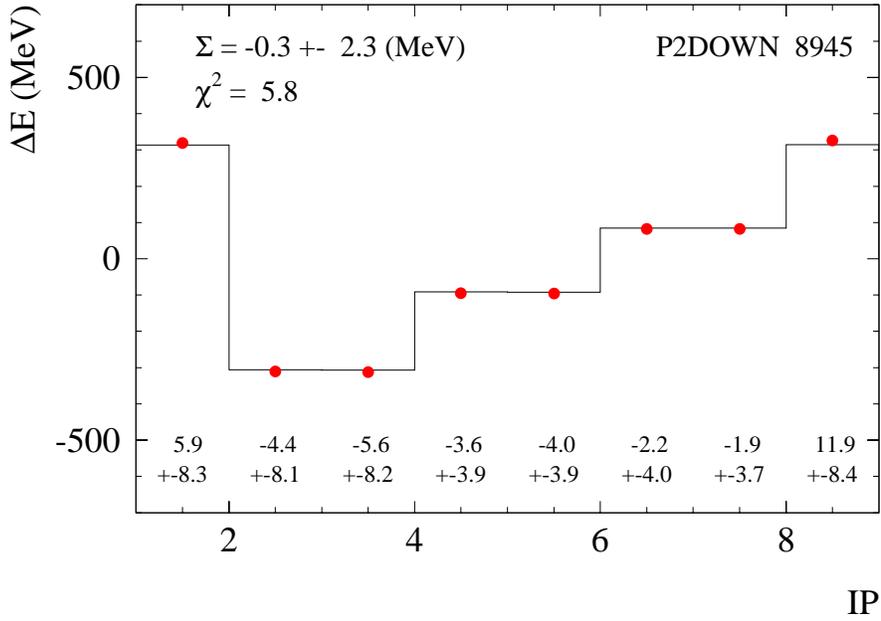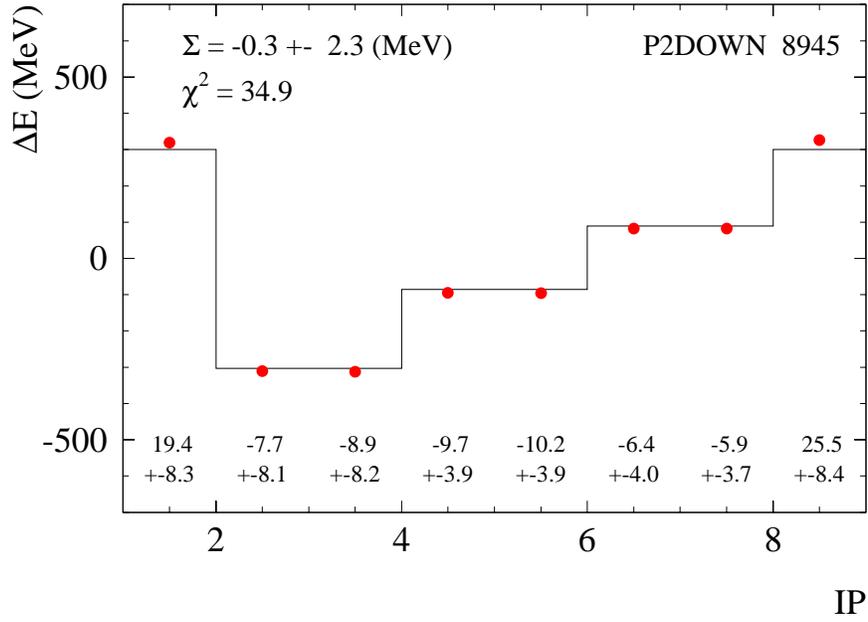
Figure 6: Energy change induced in each LEP octant by ramping the RF voltage in IP2 to its minimum. In IP2 the energy gain change is ~ 600 MeV. The points refer to the measured shifts, the solid lines are the predictions before (top) and after (bottom) fit. The numbers in the lower part of the plots indicate the difference in energy between the predicted and the measured energy shift in each octant. The errors include the uncertainty on the BPM/dispersion scale shown in Figure 4. Σ corresponds to the sum of all energy shifts (Equation 3) which should be consistent with 0.

IP	$\Delta\phi_z$ (deg)	f_V
2	-2	1.013
4	0	0.972
6	0	0.993
8	-3	1.013

Table 1: Optimum phase shifts $\Delta\phi_z$ and voltage scale factors f_V for the 4 IPs yielding the best description of the orbit and Q_s data. The errors on $\Delta\phi_z$ is $\sim \pm 0.5$ degree, while the uncertainty on f_V is $\sim \pm 0.005$.
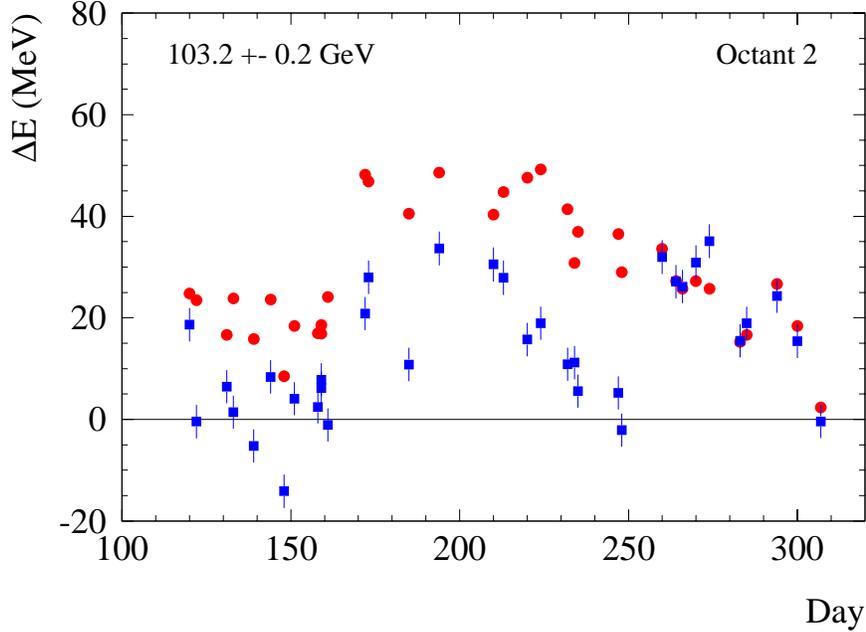
Figure 7: Evolution of the energy difference between electron and positron beams in octant 2 as a function of time for fills with energies around 103.2 GeV. The data is normalised to the model calibration fills. ($\bullet$) : MAD model prediction obtained from the RF distribution, ($\blacksquare$) : orbit measurements.

5 Long Term Stability of the RF System

From the two experiments described in the previous section, phase and voltage calibration corrections could be determined at a point in time very close to the end of the LEP run in 2000. There is of course no guarantee that the corrections were stable over the whole run. To quantify possible deviations, beam orbits acquired during regular physics coasts at 103.2 and 102.7 GeV were used in combination with their corresponding RF configurations. Care was taken to select data from periods without RF trips.

From this data sample, it is possible to reconstruct, again using the fits to the orbit data, how the energy offset around IP3 evolved with time relative to the moment of the two machine

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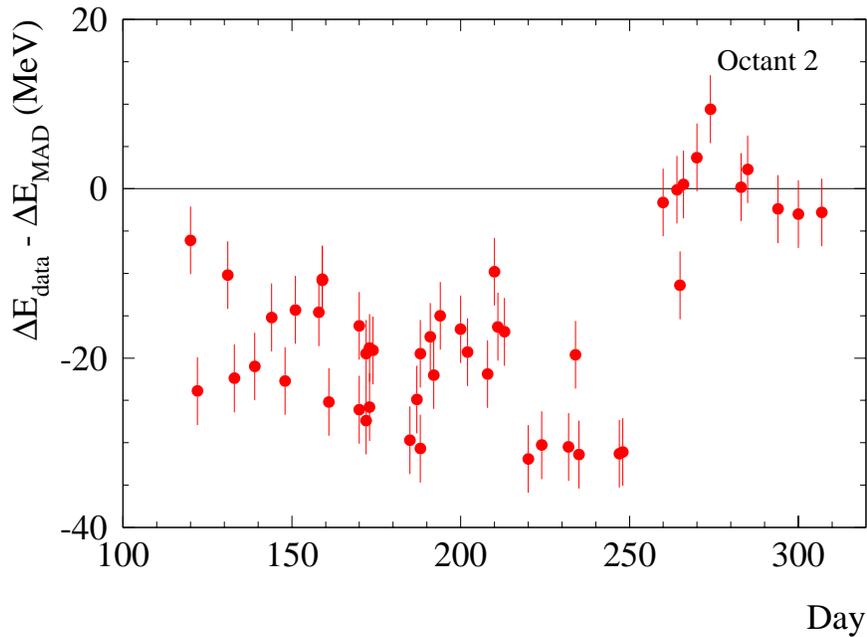
Figure 8: Evolution of the difference between MAD prediction and orbit measurements for the electron positron energy difference in octant 2 as a function of time. The data is obtained from a combination of fills at 102.7 GeV and 103.2 GeV (see Figure 7).

experiments. Figure 7 shows the change of the energy difference between the two beams in octant 2, which is relevant for the spectrometer, as predicted from the tuned MAD model and the recorded RF configurations. It also indicates energy shifts obtained directly from the orbit data. It is evident that while the predicted and measured shifts agree well in a 50 day period around the RF calibration experiments, larger deviation appears at earlier times. The difference between measurements and predictions is shown directly in Figure 8. The deviations between model and measurement reach 20 MeV in the early part of the run.

The difference observed during physics fills can in principle be used as a correction offset for the spectrometer data (it needs to be properly rescaled to lower beam energies), but such a procedure is rather delicate. Indeed the RF configurations during spectrometer calibrations often differed significantly from the nominal configurations for physics. Since the source of the observed drifts between model and measurement is not known, there is a large uncertainty on the correction factor for spectrometer data. The uncertainties on the local energy must be scaled with the fourth power of the beam energy, i.e. the systematic shifts measured at 103 GeV must be scaled to an energy E by a factor $(E/103[GeV])^4$. Since most spectrometer energy calibrations were performed around 90 to 93 GeV, the 20 to 30 MeV systematic error observed on the electron positron beam energy difference at 103 GeV translates into a ~ 7 to 10 MeV single beam systematic error for spectrometer calibration runs. It seems therefore reasonable to assign a 10 MeV uncertainty on the spectrometer energies due to the modelling of the RF for measurements performed before September 2000. For spectrometer data taken in 1999, it seems appropriate to assign a 20 MeV systematic error due to RF modelling. This corresponds to the

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size of the local energy changes induced by the phase and voltage scale adjustment determined during the two machine experiments in 2000.

6   Conclusion

A method was developed to determine effective phase and voltage calibration errors of the LEP RF system based on closed orbit measurements performed with different RF voltage distributions. This technique was used to adjust a LEP RF model based on the MAD program and improve predictions of the local beam energy for the LEP spectrometer. Changes of the local beam energy were tracked in time of the LEP run in 2000, yielding some estimate for systematic errors on such a local beam energy prediction.

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