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Effects of Terrestrial Tides on the LEP Beam Energy

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Abstract

The circular e^+e^- collider LEP located near Geneva is used to investigate the properties of the Z boson. The measurements of the Z boson mass and resonance width are of fundamental importance for the Standard Model of the Electroweak Interactions. They require a knowledge of the LEP beam energy with a precision of $\sim$ 20 ppm, which is provided by a measurement of the electron spin precession frequency. To extrapolate beam energy calibrations over a longer period of time, effects causing energy changes have to be taken into account. Among these are the terrestrial tides due to the sun and moon which move the Earth surface up and down. The lateral components of this motion modify the 26.7 km LEP circumference by about 1 mm. This change in length results in variations of the beam energy up to 120 ppm. We present results of measurements on the influence of terrestrial tides on the LEP beam energy that have been performed in 1992 and 1993.

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1 Introduction

As carrier of the Weak Neutral Current, the Z boson plays a central role in Electroweak Interactions [1, 2]. It is directly produced and studied in great detail at the Large Electron Position Collider (LEP) at CERN. The production rate of Z bosons exhibits a resonant behaviour when the centre-of-mass energy of e^+e^- collisions is in the vicinity of the Z mass. The mass, m_Z, of the Z boson and its resonance width are extracted from a fit to the resonance [3]. The Z mass is one of the fundamental ingredients of the Standard Model of Electroweak Interactions and the Z resonance width provides a very sensitive test of the theoretical model. Both must be known to the highest possible accuracy. This requires a precise knowledge of the LEP beam energies. The precision of the measurements providing the absolute energy calibration of the LEP electron beam was significantly improved in 1991 when calibration by resonant depolarization was implemented [4, 5]. It is the most accurate method for calibrating the beam energy of e^+e^- storage rings. In 1991 this resulted in a Z mass measurement by the LEP experiments of $m_Z = 91187 \pm 7$ MeV/c^2 [6], where the error is dominated by the knowledge of the absolute energy scale.

The analysis of the 1991 beam energy data suggested that previously unforeseen effects contribute to the LEP energy reproducibility. The hypothesis that tidal forces might be responsible for it was suggested by theoretical and experimental studies [6, 7]. Based on this evidence, a first dedicated experiment was performed on November 11th 1992 during a full moon phase which confirmed the hypothesis of "tidal energy variations" [8, 9]. This effect was studied further during the 1993 LEP physics run.

2 Particle Orbits in Storage Rings

The LEP storage ring is composed of a regular lattice of horizontally deflecting dipole magnets and of alternating focusing and defocusing quadrupole magnets. Such a structure, called "strong focusing lattice", keeps the particles oscillating on stable orbits around the ring. The particular orbit passing on average through the centre of all quadrupoles is called the central orbit. Particles moving on this orbit are only deflected by the dipole magnets because there is no magnetic field on the quadrupole axis. The nominal beam energy is set by the total bending field from about 3300 dipole magnets seen by the particles on the LEP central orbit.

Particles circulating in the LEP ring are ultra-relativistic and for all practical purposes, it can be assumed that they move at the speed of light. On a stable orbit the particles are synchronous with the frequency f_{RF} of the accelerating Radio Frequency (RF) fields which is a multiple of the revolution frequency. The RF fields compensate the energy losses from synchrotron radiation. Since the speed of the particles is constant to a very high accuracy, the length of their orbit is fixed by the frequency f_{RF} which can be adjusted to bring the particles on the central orbit.

Due to ground motion, the position of the magnetic elements in an accelerator can change with time. The length of the actual orbit of circulating particles being fixed by the frequency f_{RF}, the change in the ring circumference forces the particles to move off-centre through the quadrupole magnets which try to bend the particles back towards the central orbit. This results in an extra deflection leading to a change in energy (figure 1). The energy change $\Delta E(t)$ is related to the difference in circumference $\Delta C(t)$ by the momentum compaction factor α :

$$\frac{\Delta E(t)}{E_0} = -\frac{1}{\alpha}\frac{\Delta C(t)}{C_c} \tag{1}$$

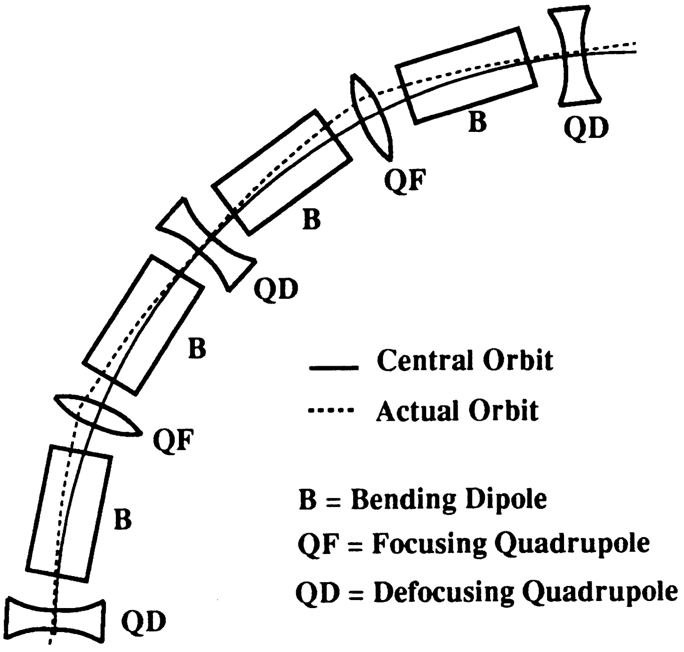

Figure 1: This figure shows the average particle motion in the horizontal plane of a strong focusing particle accelerator, which is composed of a sequence of bending dipole magnets interleaved with focusing and defocusing quadrupole magnets. The solid line corresponds to the central orbit that passes through the centre of all quadrupoles and on which particles are only deflected in the dipole magnets. If the radius of the accelerator is reduced by ground motions (or if the length of the actual orbit is increased), the particles have to move off centre through the quadrupoles (dashed line) and receive additional deflections.

where E_0 is the energy of particles on the central orbit of length C_c in the absence of deformations. Due to the strong quadrupole focusing of LEP $\alpha = 1.86 \cdot 10^{-4}$. Therefore, tiny changes of the circumference are enhanced by 4 orders of magnitude and result in measurable changes of energy.

3 Earth Tides

The gravitational attraction from the moon and the sun is not uniform over the surface of the Earth because of the $1/r^2$ dependence of the gravitational forces, where r is the distance between two interacting bodies. As a consequence the gravitational and centrifugal forces are not everywhere in equilibrium, which results in a small elastic deformation of the Earth's body producing two daily tide bulges. The lunar and the weaker solar tides interfere to produce tide bulges that can move the crust up and down by up to 25 cm at the location of the LEP ring at a latitude of 46°15' North. Such crust deformations are of the same origin as the well known water tides of the oceans. Any observer far from the equator sees asymmetric amplitudes due to the inclination of the Earth rotational axis ($\epsilon_E = 23°26'$) and of the lunar orbital plane ($\epsilon_M = 5°8'$) (figure 2). The 49 min difference between the periods of the lunar and solar tides modulates the global tide amplitude. Highest tides occur about twice a month at full or new moon phases, when moon, sun and Earth are aligned. A wide spectrum of periodicities, including eccentricity and oscillations of the Earth's and moon's orbits, make the full picture

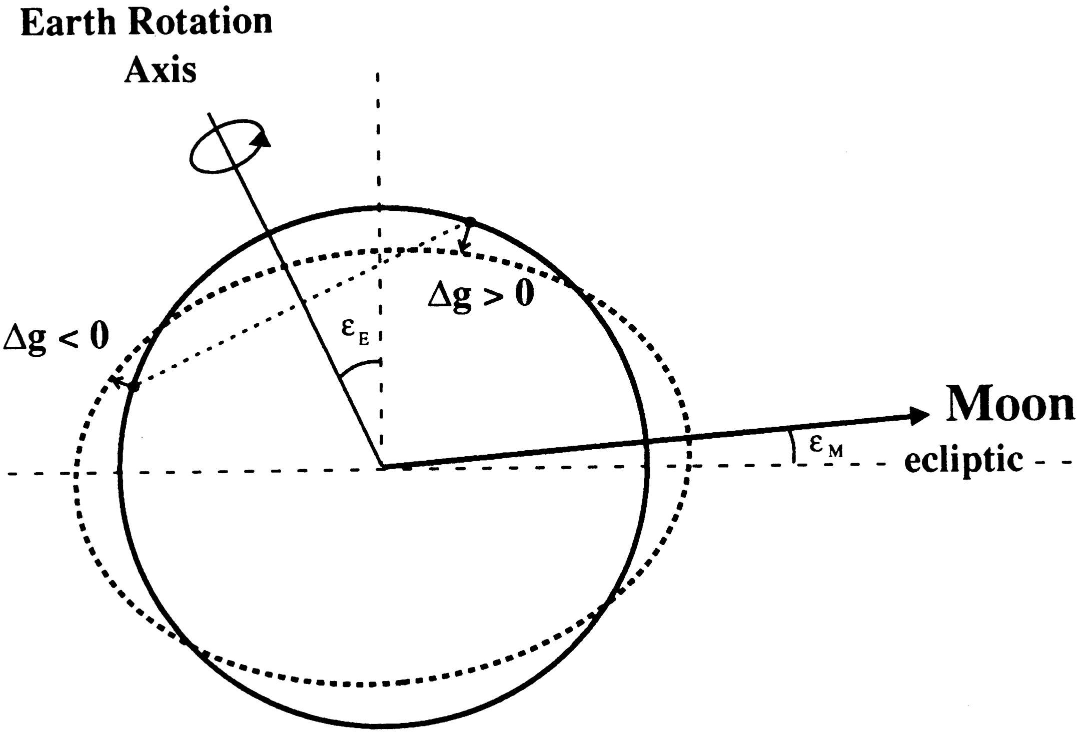

Figure 2: Tidal deformation of the Earth crust due to the presence of the moon. One tide bulge is formed in the direction of the moon and another one just opposite of it. The changes in gravity associated to the tidal deformations Δg are indicated for an observer at a latitude of about 45°. The sun tides have not been drawn. They create a tide bulge along the plane of the ecliptic. Their amplitude is 45% of the moon tides.

more complex and add a large number of harmonics to the frequency spectrum of the tides.

Two important observables are associated to the above phenomena : the local strain and the gravity variations. The strain is a tensor describing the local elongation of the Earth's crust due to the gravitational stress. Monitoring the crust strain is complicated, but the time-dependent gravity variation $\Delta g(t)$ is simpler to measure and to predict. Using estimates for the elastic properties of the Earth [10], the largest resulting strain is estimated to $\sim \pm 2 \cdot 10^{-8}$, which corresponds to a change of the 26.7 km LEP circumference of ± 0.5 mm. To a good accuracy the horizontal strain is proportional to the gravity variation $\Delta g(t)$ and can be related to it through

$$\alpha_{str} = \frac{\Delta C(t)/C_c}{\Delta g(t)/g_0} \tag{2}$$

which measures the fraction of gravity change that couples into the strain. g_0 is the unperturbed local gravity, $g_0 = 980$ gal (1 gal = 1 cm s^{-2}). $\Delta g(t)$ reaches about 140 μgal at high tide in the Geneva area and 15 % couples into lateral motion.

To analyse our experimental beam energy data we use predictions for the tide amplitudes $\Delta g(t)$ based on a Cartwright-Tayler-Edden (CTE) potential [11]. This model includes the 505 main harmonic components of the tide potential. We can relate energy variations to gravity

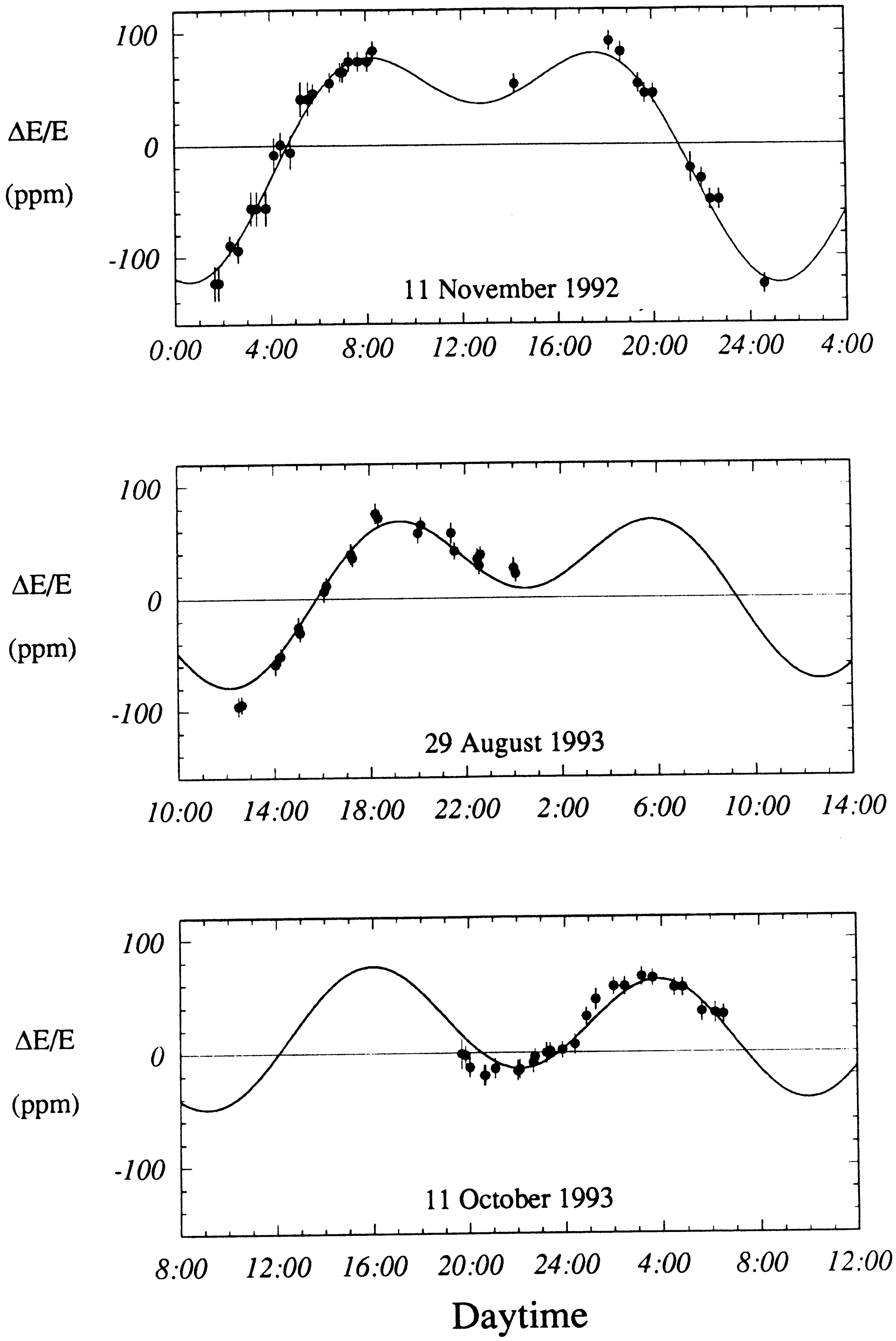

Figure 3: The evolution of the relative beam energy variation due to tides is shown as a function of time for three periods with stable beam conditions. The solid line is calculated using the CTE tide model with the average coefficient from equation 4. The top picture corresponds to full-moon, the bottom picture to a time close to half-moon. Relative beam energy variations of up to 220 ppm are observed on November 11^{th} 1992.

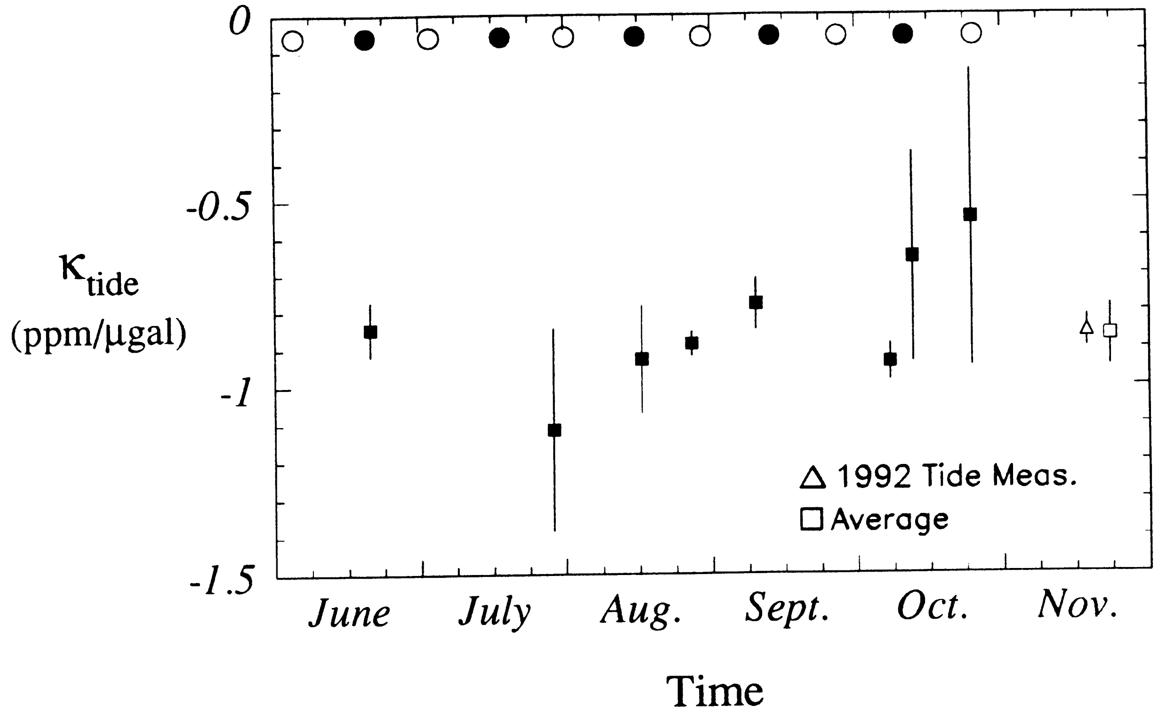

Figure 4: The coefficient κ_{tide} is shown a function of time in 1993 for the CTE model. The measurement made in November 1992 is also added on the figure. The times of full and new moon are indicated by the circles. From the spread of the data we estimate the precision of κ_{tide} to be 10%.

changes through a sensitivity coefficient κ_{tide} using (2) :

$$\frac{\Delta E(t)}{E_{tide=0}} = -\frac{\alpha_{str}}{g_0 \alpha} \Delta g(t) = \kappa_{tide} \Delta g(t) \tag{3}$$

4 Beam Energy Measurements and Observation of Tidal Effects

A vertical beam spin polarization of up to 92.4% builds up naturally in an e^+e^- storage ring [12]. This polarization can be used to measure the beam energy E very accurately because the precession frequency f_s of the spins in the storage ring is proportional to E. The frequency f_s can be measured using a controlled resonant depolarization technique [5, 13, 14, 15]. The accuracy is typically $\delta E/E = \pm$ 10 ppm.

The effects of the terrestrial tide deformations on the beam energies were observed on various occasions. In three instances, stable beams could be used to monitor energy variations due to the tides over periods of 12 to 24 hours. Figure 3 shows the evolution of the beam energy with time and the comparison with a CTE tide model. All other known machine parameters (f_{RF}, magnet temperature and dipole field) that affect the beam energy have been corrected for. One can observe small deviations from the evolution expected from the tides due probably to small uncontrolled energy fluctuations. There is good agreement between the data and the predictions from the CTE tide model. From fits to our data we obtain a factor κ_{tide}

$$\kappa_{tide} = -0.86 \pm 0.08 \text{ ppm}/\mu\text{gal} \tag{4}$$

which agrees well with the expected value of -0.9 ppm/μgal from [10]. The error includes our estimate of the uncertainty due to the use of the CTE model to predict the circumference changes. Figure 4 shows the results of fits for all the experiments. There is very good consistency of all the measurements. The effects of the tides can also be observed at LEP, although with less accuracy, from the resulting orbit distortions and the change in the length of the central orbit [15, 16, 17, 18].

5 Conclusions

Measurements of the LEP beam energy in 1992 and 1993 clearly demonstrated the effect of the terrestrial tides on the LEP ring circumference and beam energy. Terrestrial tides, that were already playing a role for astronomy and for global positioning systems, can also affect the performance of a large particle accelerator. The observed variations agree well with the expectation from tide models. The present understanding of this effect allows an accurate extrapolation of energy calibrations in time. The uncertainty on the coefficient κ_{tide} is small enough that its contribution to the total error on the mass of the Z boson is negligible.

6 Acknowledgements

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