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CERN SL Division

CERN SL / Note 95-21 (OP)

Radial Deformations of the LEP ring

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Abstract

The LEP beam orbit measurement system has been used to study the evolution of the LEP circumference. Radial deformations can be detected with an accuracy of about 20 μm. In addition to the periodic and well known tidal distortions, slow variations of the storage ring circumference of about 2 mm are observed. These deformations lead to significant variations of the beam energy and play an important role for energy calibration. We will show the results of orbit measurements performed in 1993 and 1994 and discuss a possible correlation with the water level of the nearby Lake Leman.

Geneva, Switzerland

24 February 1995

1 Introduction

The knowledge of the LEP circumference is an important ingredient for the energy calibration of the beams. The first measurements of the LEP circumference through the central frequency were performed in 1990 [1]. The accurate energy calibration of the beams by resonant depolarization [2, 3, 4] revealed unexpected variations of the beam energy that could be traced to tidal deformations of the ring. Tides from Sun and Moon create periodic ground distortions in the horizontal plane of the ring. This leads to beam energy variations ΔE of up to 10 MeV peak-to-peak ($\Delta E/E = 2.2 \cdot 10^{-4}$). Dedicated energy calibration experiments demonstrated this effect [5].

In addition to this regular tide motion, a slow ring deformation was observed during the LEP running period of 1993. It was first revealed by unexpected variations of the beam energy [4, 6]. These energy variations were traced to slow changes of the ring circumference [7].

I will present the observed evolution of the LEP circumference ground motion that has been observed over two years and show possible causes for these slow deformations.

2 Effects of ring distortions

The energy of the beams is not constant around the ring due to synchrotron radiation. On each turn, electrons and positrons loose about 125 MeV of energy on their path through the dipole fields of the LEP magnets. This energy loss is compensated by the RF cavities located around L3 and OPAL. The revolution of the particles is synchronous with the frequency f_{RF} at which the RF system is operated. During the two years of observation covered by our data sample, LEP has been running in physics with a constant frequency f_{RF} of 352 254 170 Hz. Because the particles circulating in LEP are always ultra-relativistic, the orbit length does not depend on beam energies and is only determined by f_{RF}.

The beam optics is matched for particles having a nominal energy E_0 and circulating on the central orbit. A particle with an energy $E_0 + \Delta E$ will, on the other hand, move on a dispersion orbit. The radial displacement Δx of this particle from the ideal orbit in the horizontal plane is given by the horizontal dispersion D_x :

$$\Delta x(s) = D_x(s)\,\frac{\Delta E}{E_0} \tag{1}$$

D_x is a periodic function of s, the path length along the ring.

Let us examine the situation where the circumference C is modified by ground motion. Because the length of the orbit is determined by the constant frequency f_{RF}, the horizontal deformation forces the beams to move off-center through the magnetic elements and through the Beam Orbit Monitors (BOM), since these are mounted on the quadrupole magnets. This leads to a change in the average beam energy of :

$$\frac{\Delta E}{E_0} = -\frac{1}{\alpha}\,\frac{\Delta C}{C} \tag{2}$$

α is the momentum compaction factor. It is a function of the horizontal dispersion and of the bending radius ρ :

$$\alpha = \frac{1}{C}\oint \frac{D_x(s)ds}{\rho(s)} \tag{3}$$

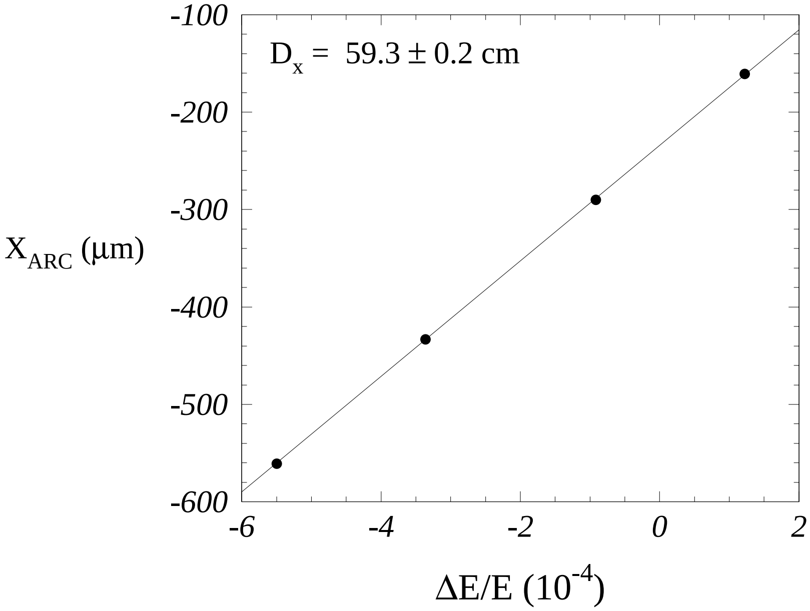

Figure 1: Variation of the horizontal orbit position in the LEP arcs as a function of the energy. The energy change was obtained by a variation of the RF frequency. The slope is given by the average dispersion D_x^{pu} at the pickups.

By design, the horizontal dispersion vanishes in the straight sections of LEP. For this reason, we concentrate our analysis on the 240 BOM monitors installed in the LEP arc cells. The apparent change of the average horizontal beam position measured by these monitors is :

$$\Delta X_{ARC} = -\frac{D_x^{pu}}{\alpha}\frac{\Delta C}{C} = \kappa\,\Delta C \tag{4}$$

where D_x^{pu} is the average horizontal dispersion at the pickups. For the LEP optics used in 1993 and 1994, the values of the two parameters are $\alpha = 1.86 \cdot 10^{-4}$ and $D_x^{pu} = 59$ cm. These numbers lead to a sensitivity of :

$$\Delta X_{ARC} = \kappa\,\Delta C = -0.119 \cdot \Delta C \approx -0.75 \cdot \frac{\Delta C}{2\pi} \tag{5}$$

ΔX_{ARC} is not equal to the change of the average radius because the regular arc cells only cover about 85% of the LEP arcs and because the average horizontal dispersion in the arcs is ≈ 75 cm. The sign change is due to the fact that we are measuring the position change of the beam relative to the (moving) monitors. The energy change corresponding to such a circumference variation is :

$$\Delta X_{ARC} = D_x^{pu}\,\tfrac{\Delta E}{E} = 13.0\,[\mathrm{MeV}/\mu\mathrm{m}]\cdot\Delta E \quad \text{for E} = 45.6 \text{ GeV} \tag{6}$$

Tides, for example, lead to energy variations of $\Delta E = 10$ MeV and to observable beam position variations of $\Delta X_{ARC} = 130\ \mu$m. Such energy changes are large compared to the 1 MeV accuracy of energy calibration by resonant depolarization [4, 6]. Figure 1 shows the result of a controlled variation of the orbit length by a change in f_{RF}. The response of the beam orbit follows the expected linear behavior and sensitivity.

3 Analysis of beam orbits

The analysis of the beam position is based on orbits acquired during physics conditions in 1993 and 1994. The beam energies were distributed between 44.7 and 46.5 GeV. To avoid a

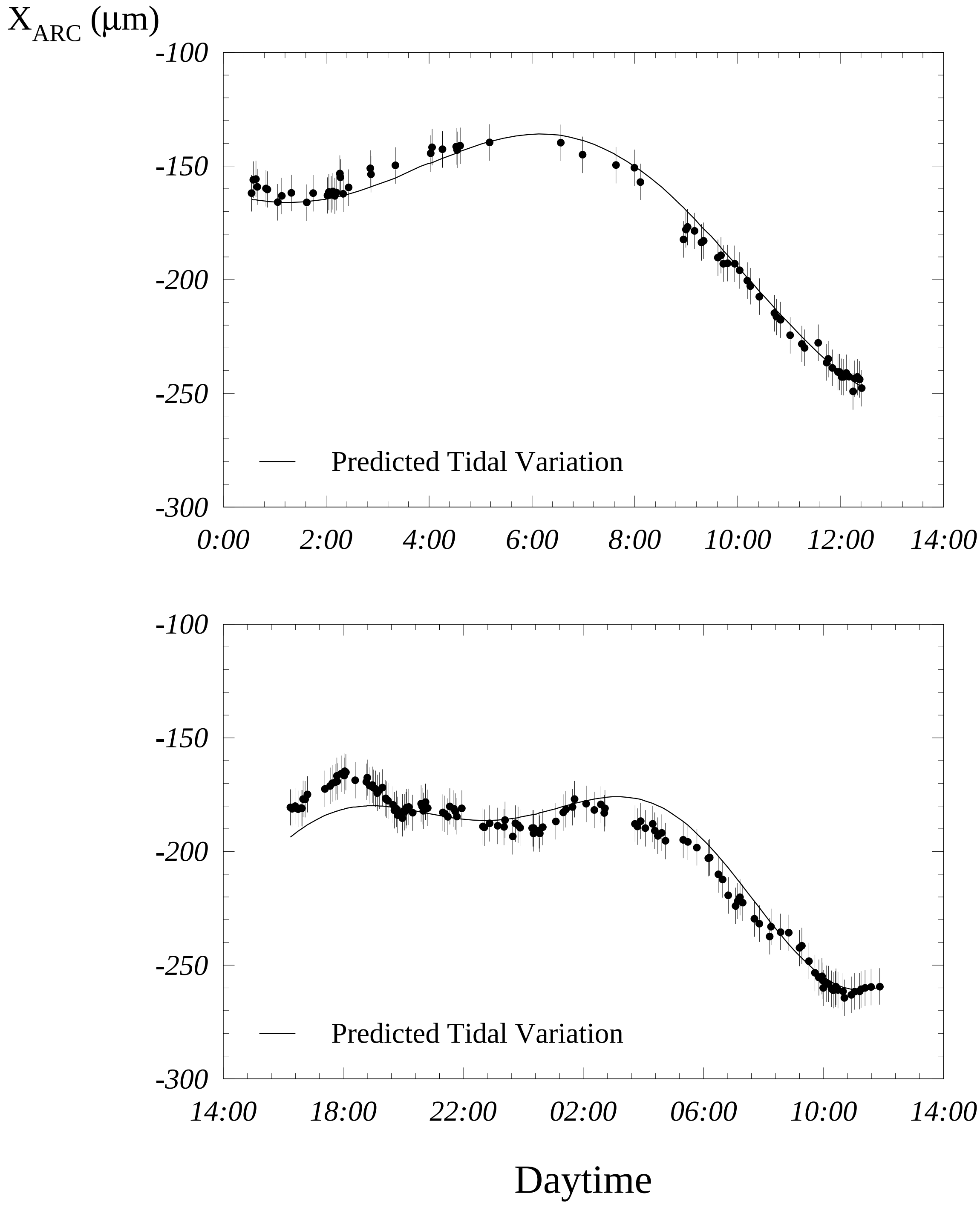

Figure 2: Evolution of the horizontal orbit position for two LEP fills. The predicted tidal variations are indicated by the solid lines. In the top figure (fill 1694), the agreement is excellent. In the bottom figure (fill 2260), the tidal effects cannot explain all the orbit movements. The errors on each point are estimates.

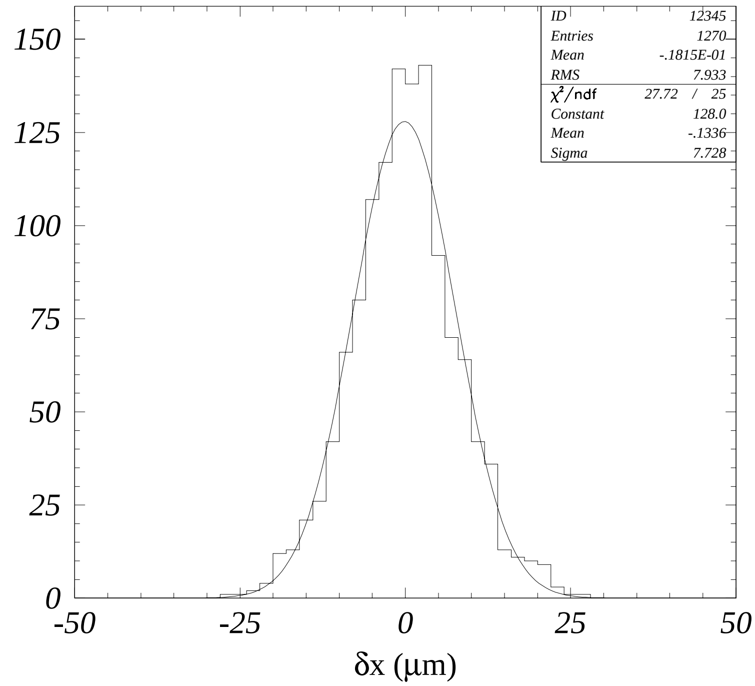

Figure 3: Reproducibility of the horizontal orbit position measurements during fills. δx represents the deviation of an individual measurement of X_{ARC} with respect to the average over the fill. This distribution contains 1993 and 1994 data.

bias of the horizontal beam position measurements due to faulty pickups, all orbits have been scanned for misbehaving monitors and a list of bad monitors has been established. The data from such monitors is rejected in all orbits. Orbits measured with additional disabled channels are completely rejected. The analysis has been carried out independently for the 1993 and 1994 data samples. About 50 pickups had to be rejected for all orbits in both data samples. For each orbit, the average beam position X_{ARC} is calculated for the horizontal plane using the valid monitors among the 240 BOM monitors installed in the regular arc cells.

During the periods of 1993 and 1994, LEP has been mainly running in Pretzel mode with 8 equidistant bunches per beam. To avoid systematic biases due to the large horizontal orbit deviations from the center of the pickups, the data from the electron and positron beams is averaged in our analysis. But it has been shown that the position changes of both beams are, as expected, completely correlated [7].

The terrestrial tide deformations can be easily observed during a stable run. Two examples are shown in figure 2. While in the first case, the beams follow the expected tidal deformations very accurately, the second example shows deviations from the tide predictions. Since tides can be predicted with good accuracy and since we are trying to observe non-tidal ring deformations, we will correct the measured X_{ARC} for tides. The correction is based on the CTE (Cartwright-Taylor-Edden) tide model used for energy calibration. More details can be found in [5].

The accuracy of the average beam position is not limited by the intrinsic resolution of the BOM because the average is performed over about 200 position measurements. It is affected by horizontal orbit corrections and by BOM calibrations. Due to the limited sampling, X_{ARC} depends on the detail of the closed orbit and can be artificially biased by a large horizontal orbit correction. The short term reproducibility can be estimated experimentally by comparing each individual X_{ARC} value with its average over one fill. The resulting distribution has a RMS

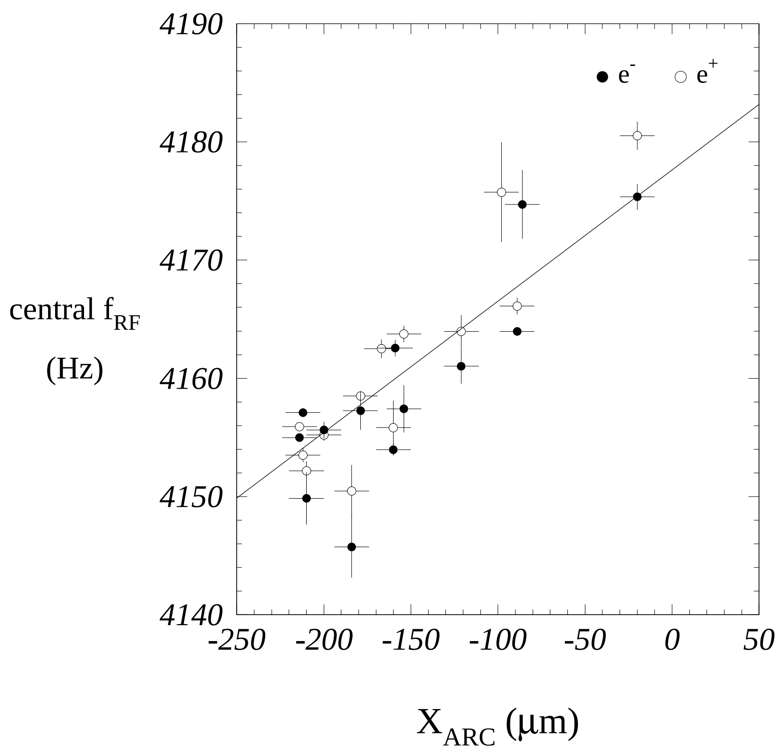

Figure 4: Correlation between the horizontal orbit position and the measured central frequencies for 1994 data. The slope has been fixed to the expected sensitivity of 0.11 Hz/μm. Only the last four digits of the RF frequency are shown.

spread of 8 μm and is shown in figure 3. The RMS represents the typical reproducibility inside a fill, but it also includes real effects from ring distortions. The reproducibility from one fill to another is evaluated by comparing the average of X_{ARC} for two consecutive fills that follow each other within 24 hours. The spread of the resulting distribution gives an estimate of the reproducibility on the time scale of a day. It takes into account systematic problems due to pickup calibrations that are performed between fills. This spread tends to give an overestimate since it also includes true position changes. This method leads to errors of 20 μm for 1993 and 10 μm for 1994. We will use these two values as our estimates for the accuracy of X_{ARC} for a fill.

It is difficult to estimate the long term accuracy of the position measurement. One possibility consist in estimating the error from the stability of the vertical orbit position. The problem is that there are no strong constraints on this position. A second method compares the orbit position with the central frequency measurements [8] which should give the same information than X_{ARC}. The relation between central frequency f^c_{RF} and X_{ARC} is expected to be :

$$\Delta X_{ARC} = \frac{D_x^{pu}}{\alpha} \frac{\Delta f^c_{RF}}{f^c_{RF}} = 9.01\,[\mu\mathrm{m}/\mathrm{Hz}] \cdot \Delta f^c_{RF} \qquad (7)$$

Figure 4 shows the correlation between these two measurements for 1994. Central frequency and orbit position do not agree within their respective errors, but they see the same trends. The reason for this discrepancy is not understood. The problem will be studied in 1995 during MDs. In 1993 the correlation between these two quantities was even poorer [7]. If we regard the errors on the central frequency measurements to be accurate, the error estimate on X_{ARC} for 1994 should be increased from 10 μm to about 25 μm.

4 Long term evolution of the LEP circumference

The analysis of the long term beam position evolution is based on 1270 valid orbits measured during physics in 305 LEP fills in 1993 and 1994. 65 arc pickups out of 240 have been rejected for the 1993 data sample, 40 for the 1994 sample. The beam positions have been corrected for tidal effects. Figure 5 shows the average horizontal beam positions as a function of time for each LEP fill with valid data. Variations of about 220 μm can be observed. They correspond to circumference changes of 2 mm (according to equation 5) and to a strain of $\sim 8 \cdot 10^{-8}$. We estimate that the systematic error in the scales between 1993 and 1994 is about 25 μm. A similar systematic error has to be used when the first period of 1993 (before day 140) is compared with the remainder of the year. These circumference distortions lead to beam energy variations of more than 15 MeV which have indeed been observed [4, 6, 7].

The change of X_{ARC} observed in 1993 between days 170 and 320 seems to be correlated with large amount of rainfall and a rise in the underground water table under the Jura. Fits to the 1993 orbit positions have been performed by K. Lindemann [9] using rainfall data from the Geneva airport and underground water level. The model cannot explain all details but the agreement is satisfactory.

Figure 6 shows the level of the water in the Lake Leman in 1993 and 1994. During a large part of the year, the level is almost constant. The lake is slowly emptied between January and April to produce electricity and to be ready to accept the melting water from the Alps. The level rises again in May. An interesting correlation can immediately be observed between the variations of X_{ARC} in May and the change in water level. Figure 6 shows the evolution of X_{ARC} (converted into an energy variation using equation 6), of the beam energy measured by resonant depolarization (corrected for tides, magnet temperature and hysteresis) and the water level of the lake. The correlation between X_{ARC} and the measured beam energies is excellent. The water level has been fited to the orbit data with an offset and a sensitivity factor. This factor corresponds to a $\sim -350\,\mu$m change of X_{ARC} for a 1 m rise of the lake level. As expected the radius of the ring increases (X_{ARC} decreases) when the water level is rising. The 26.66 km long LEP tunnel is located underground at a depth varying between 50 and 170 m in two geological zones. The major part, roughly 23 km, is bored through the molasse of the Lemanic Plain and the remainder through the limestone of the Jura. The plane of the LEP ring makes an angle of 0.8° with respect to the horizontal. A deformation of the molasse between the Jura and the lake due to the mass of water can be the cause of the ring extensions. With a lake area of 581 km^2, the observed 0.5 m variation in the water level corresponds to a water mass of $3 \cdot 10^8$ kg (300 Mt). It is not surprising that this can lead to ground deformation, even is this mass is distributed over a large area. One also has to bear in mind that the resulting strain of $8 \cdot 10^{-8}$ is very small.

5 Conclusions

With the help of the horizontal position of the beams in the arc pickups, it is possible to observe circumference variations of LEP with very good accuracy. Over a period of two years the LEP circumference showed periodic fluctuations of about 2 mm. These variations are confirmed by the energy calibration with resonant depolarization. The data shown in this note is used as an essential ingredient of the model for the LEP energy [6]. There is some evidence that the water level of the Lake Leman could be a cause for the circumference changes.

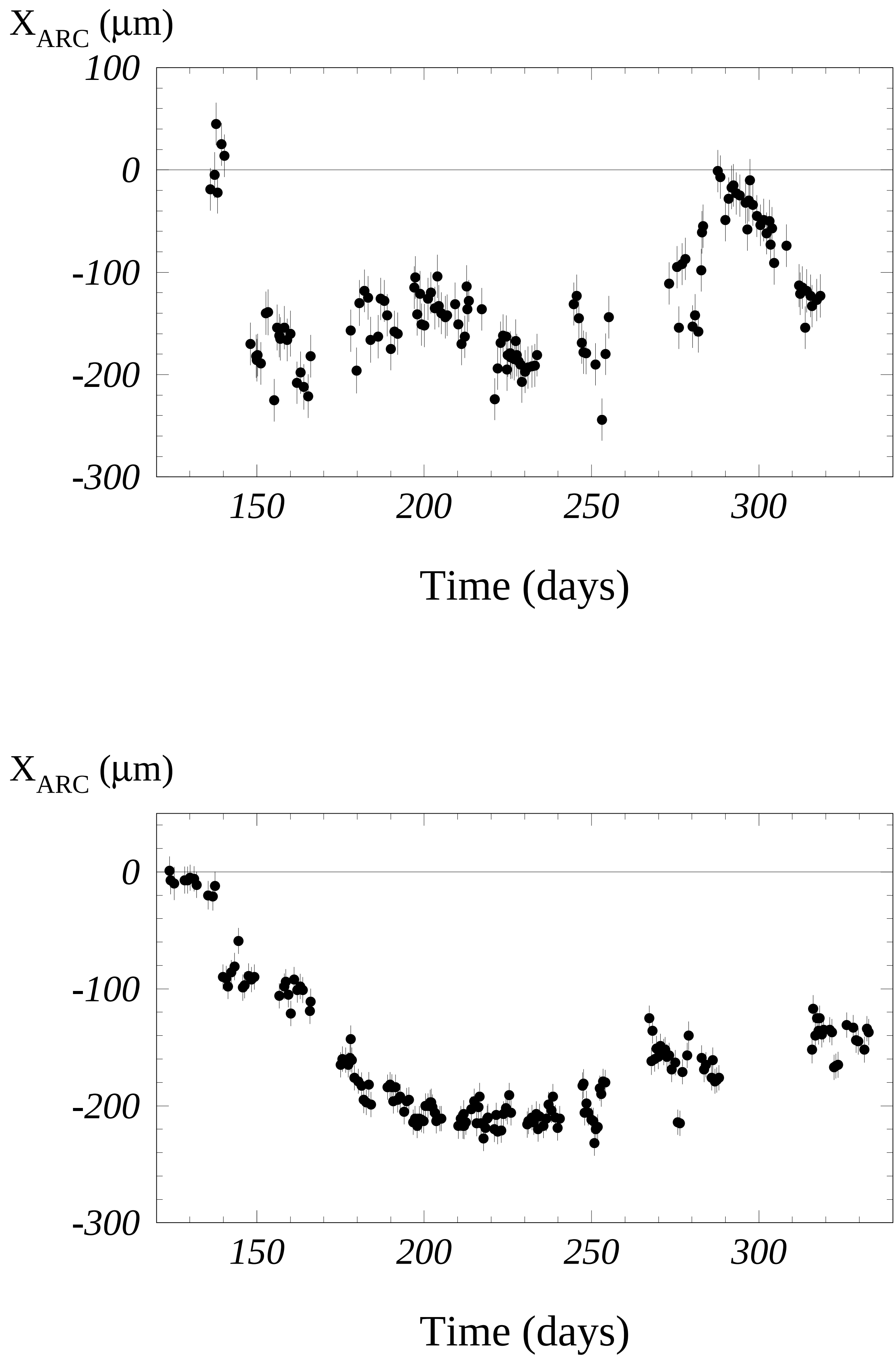

Figure 5: Evolution of the horizontal orbit position in 1993 (top) and 1994 (bottom) as a function of

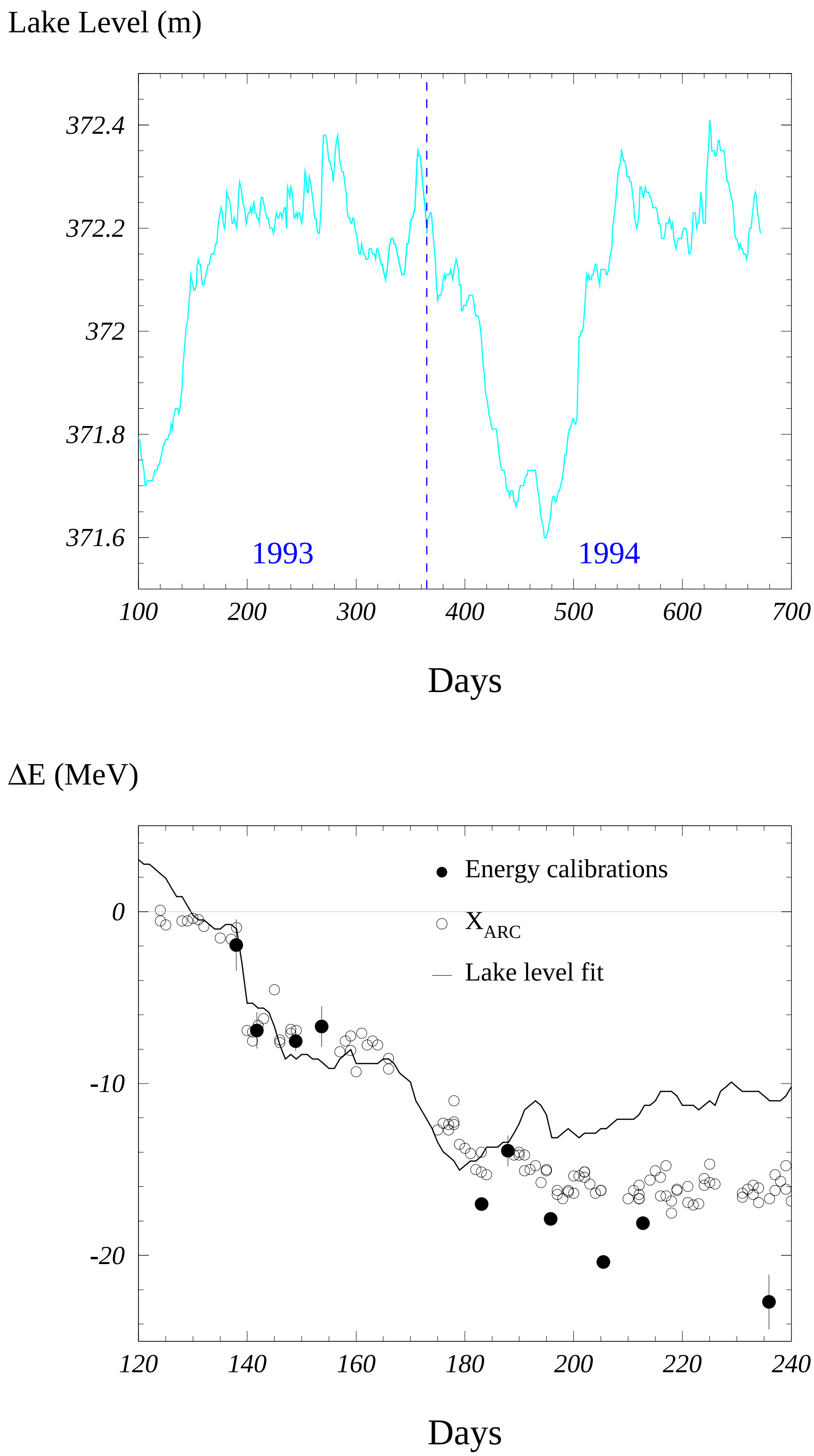

Figure 6: Evolution of the water level of the Lake Leman as a function of time in 1993 and 1994 (top). The lake is emptied between January and April and refilled in May. The lower figure shows the correlation between the orbit position (converted to energy changes), the energy measured by resonant depolarization and a fit to the lake water level for the first half of 1994. The fit is performed with an offset and a sensitivity factor. The orbit and energy measurements reflect the change in the lake level up to day 180. The time scale on the bottom figure corresponds to the period between days 485 and 605 on the top figure.

6 Acknowledgments

I thank A. Blondel for providing me the data on the water level of the Lake Leman. It was a pleasure for me to collaborate with R. Jacobsen who is one of the fathers of the “lake theory”. I thank H. Schmickler for the analysis of the central frequency measurements and for useful discussions.

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