EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - SL DIVISION

Energy Calbration with Resonant Depolarization at LEP in 1993

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Abstract

An important goal for the 1993 LEP running was the improved measurement of the mass and the resonance width of the Z boson. Regular and accurate calibration of the LEP beam energy by resonant depolarization was essentially needed to reach the required precision. We show how energy calibration was achieved on a regular basis and for all three operational LEP beam energies in 1993. The results taken over the year are presented. Possible systematic errors on energy calibration are very important and were studied in detail. As an interesting side effects measurements of tidal changes of the beam energy are shown.

Geneva, Switzerland
5 August, 1994

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Abstract

An important goal for the 1993 LEP running was the improved measurement of the mass and the resonance width of the Z boson. Regular and accurate calibration of the LEP beam energy by resonant depolarization was essentially needed to reach the required precision. We show how energy calibration was achieved on a regular basis and for all three operational LEP beam energies in 1993. The results taken over the year are presented. Possible systematic errors on energy calibration are very important and were studied in detail. As an interesting side effect measurements of tidal changes of the beam energy are shown.

1 INTRODUCTION

Transverse beam polarization opens up the possibility for accurate measurements of the average beam energy in LEP. The reachable precision is at least 40 times higher than the precision offered by other existing methods. The procedures to establish polarized beams for energy calibration in LEP are described elsewhere [1].

2 PRINCIPLE

The motion of a classical spin vector $\vec{S}$ of a relativistic electron in electromagnetic fields is obtained by solving the Thomas-BMT equation. For electrons that only see the vertical bending field of the storage ring $\vec{S}$ precesses $a\gamma$ times in one machine turn. a is the magnetic anomaly and γ the Lorentz factor of the electron. The *spin tune* is defined as $a\gamma$. Its average value ν_0 for all electrons is proportional to the average beam energy E:

$$\nu_0 = a\gamma = \frac{E[\text{MeV}]}{440.6486(1)}$$

The vertical component of $\vec{S}$ is completely conserved in an e^+e^- storage ring with purely vertical magnetic fields. Stable polarization can therefore only be along the vertical. The polarization vector $\vec{P}$ is defined as the ensemble average of all spin vectors and due to the Sokolov-Ternov effect vertical polarization can build up to a maximum of 92.4%. Any non-vertical magnetic fields reduce the equilibrium degree of polarization and perturb the spin precession.

An oscillating radial field from an RF-magnet is used for the resonant measurement of the spin precession frequency at LEP. If the perturbation from the RF-magnet is
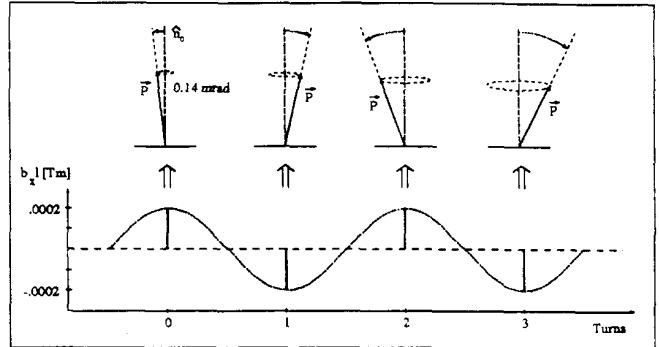
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Figure 1: Resonance condition between the nominal spin precession with $[\nu] = 0.5$ and the radial perturbation $b_z l$ from the LEP RF-magnet. After being tilted $\vec{P}$ precesses with $[\nu]$ about its initial direction. $\vec{P}$ is resonantly rotated away from the vertical direction.

in phase with the spin precession then the spin rotations about the radial direction add up coherently from turn to turn and about 10^4 turns ($\approx$ 1 second) are needed to bring the polarization vector into the radial plane, or twice as much to flip its sign. This is demonstrated in fig. 1. Due to random synchrotron radiation the beam polarization in e^+e^- storage rings can at most partially be flipped. With f_{dep} being the frequency of the RF-magnet the resonance condition between the perturbation $b_z l$ and the nominal spin precession reads $f_{dep} = [\nu] \cdot f_{rev}$, where f_{rev} is the well known revolution frequency of the particles. $[\nu]$ denotes the non-integer part of the spin tune. Its integer part n is known from the setting of the bending field.

By changing the frequency f_{dep} of the perturbing radial field and by measuring the beam polarization the resonance condition is looked for. After observation of resonant depolarization the spin tune and the beam energy can be calculated from the measured f_{dep} and the known f_{rev} and n. The method is often referred to as *energy calibration by resonant depolarization*. The quantity which is measured is the precession frequency of the polarization vector over one turn. The polarization vector is the ensemble average over all spin vectors. Therefore the measured beam energy is to a very good approximation independent from betatron and synchrotron oscillations of the individual particles and its accuracy is not limited by the beam energy spread (30 MeV). This can be verified by measuring the FWHM of the resonance, which is as small
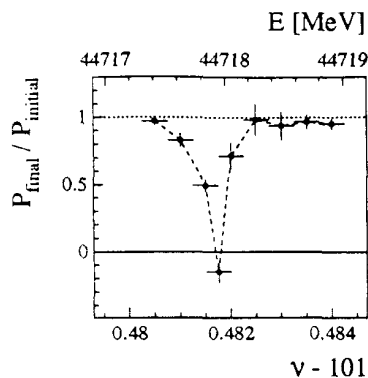
E [MeV]

Figure 2: A measurement of the artificially excited spin resonance for a standard energy calibration at LEP is shown. The slightly asymmetric resonance shape is due to tidal changes of the beam energy during the 12 minutes of measurement.
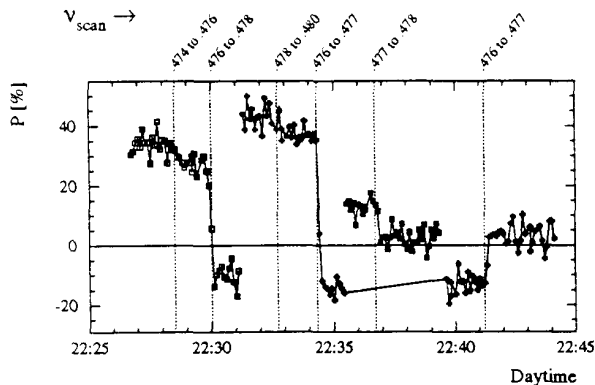

Figure 3: Example of energy calibration. Several bunches are used to measure the non-integer part of the spin tune. Spin flip to negative polarization was observed and checked by flipping it again.

as 200 keV for the standard LEP energy calibrations (see fig. 2). Local energy variations like the energy sawtooth modulate the spin phase advance. They do not bias the measured beam energy, which is determined from the total spin phase advance over one full turn.

At LEP the frequency of the RF field is slowly varied with time over a given range. The difference $\Delta\nu_{scan}$ in frequency between start and end of the "sweep" in practice determines the resolution of the spin tune measurement and is chosen small enough to match the requirements of precise energy calibration. For standard energy calibrations $\Delta\nu_{scan}$ was set to .002, which corresponds to 0.9 MeV in beam energy. However, on some occasions the beam energy was measured with a better resolution, down to 0.22 MeV. An example of energy calibration by

resonant depolarization is shown in fig. 3. To uniquely determine the beam energy two additional measurements are required. The so-called "mirror-ambiguity" and the locations of synchrotron satellites must be resolved [2].

3 ACCURACY

The sources of systematic errors on energy calibration by resonant depolarization and their magnitudes were studied in detail for LEP [2, 3, 4]:

1. Electron mass: $\Delta E/E = 2 \cdot 10^{-7}$.

2. Revolution frequency: $\Delta E/E = 1 \cdot 10^{-10}$.

3. RF-magnet frequency: $\Delta E/E = 2 \cdot 10^{-6}$.

4. Width of resonance: $\Delta E/E = 2 \cdot 10^{-6}$.

5. Interference of resonances: $\Delta E/E = 2 \cdot 10^{-6}$.

6. Spin tune spread: $\Delta E/E = 1 \cdot 10^{-7}$.

7. Longitudinal magnetic fields: $\Delta E/E = 1.1 \cdot 10^{-7}$.

8. Horizontal magnetic fields: $\Delta E/E = 2 \cdot 10^{-6}$.

The total systematic error on a single energy measurement is estimated from experimental and theoretical results to be about 200 keV for LEP at 45.6 GeV. There is an excellent reproducibility and short-term stability of the measured beam energy. This can be seen most clearly from the measured variations of the beam energy due to tidal deformations of the LEP circumference (see fig. 4). The systematic error was verified experimentally with limited accuracy and an experimental upper bound for the systematic error of 1.1 MeV was established. The requirements for energy calibration in 1993 have thus clearly been met. The average beam energy was determined at least with a precision of better than 1.1 MeV.

4 RESULTS

The beam energy of LEP was accurately measured in regular intervals during 1993. The beam energies E were corrected to a common reference, taking into account changes of the magnet temperature, tidal changes of the LEP circumference, changes of the magnetic field and a few other parameters [2]. If this model of energy variation were complete the corrected beam energy would be stable within a few MeV.

The measured variation of the corrected beam energy is shown in fig. 5 for the two off-peak energies at 44.7 GeV and 46.5 GeV. The beam energy E is given with respect to the energy E_{NMR}, which is calculated from the measured dipole field in LEP [2]. Unexpected large variations in the beam energy of up to 20 MeV have been observed in 1993. Since changes of the LEP circumference reflect in changes of the beam energy and the horizontal position of the beam in the quadrupoles they can be measured in two independent ways.
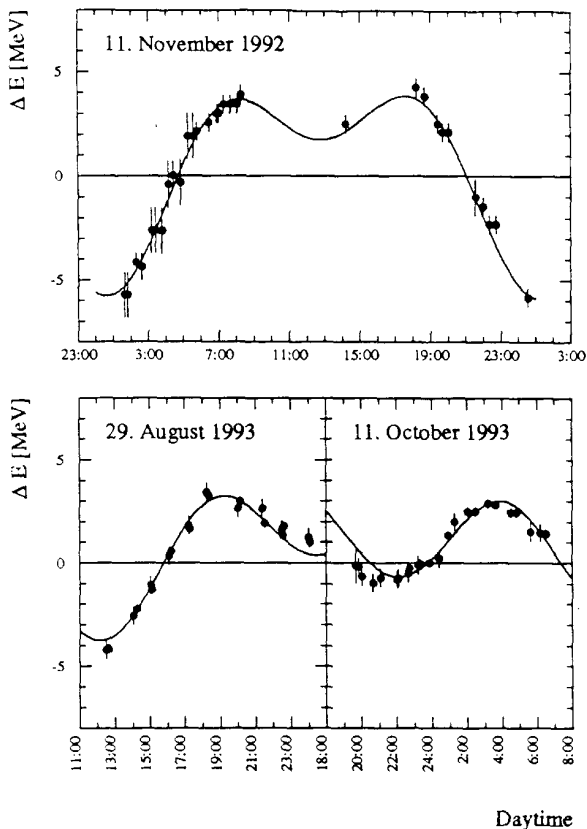
Figure 4: The measured change of beam energy ΔE is shown as a function of time for three experiments. The observed variation of beam energy fits very well with the expected change due to tidal deformations of the LEP circumference. The measurements demonstrate the excellent accuracy and reproducibility of energy calibration by resonant depolarization in LEP.

The horizontal orbit in LEP during 1993 was analyzed in [5]. From this the expected variation of the beam energy is calculated with a simple polynomial fit. Thus changes in the LEP circumference on the time scale of weeks are considered. The measurements in fig. 5 are compared to this expected variation. The variation at 46.5 GeV is almost completely explained. There are additional fluctuations at 44.7 GeV which are studied further. The physical reason for the additional variation of the LEP circumference is not uniquely determined. However, there are hints that a correlation with rainfall in the Geneva region exists.

5 CONCLUSION

The LEP beam energy was measured in 1993 regularly with a precision of better than 1 MeV. Unexpected variations of up to 20 MeV were found and confirmed by closed
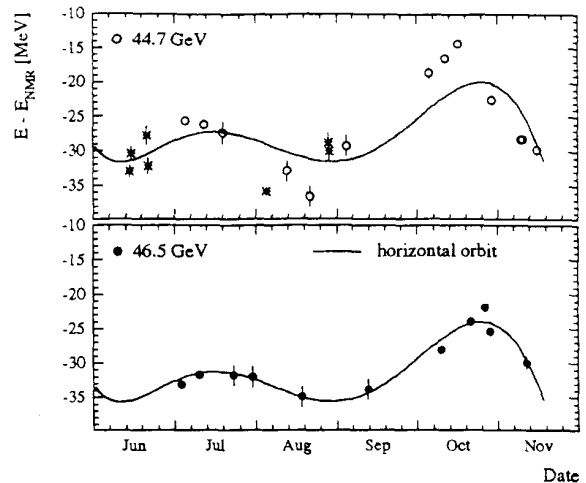

Figure 5: The measured beam energy variation $E - E_{\mathrm{NMR}}$ in LEP is shown as a function of time in 1993. The two off-peak energies are distinguished and the (*) indicates energy measurements during polarization experiments. All other calibrations were performed at the end of physics coasts. E_{NMR} is the energy variation expected from the measured dipole fields in LEP. The smooth curve indicates the expected energy variation due to changes in the LEP circumference. It is determined independently by a fit to the average horizontal position of the beam in the LEP quadrupoles.

orbit analysis. The absolute energy scale of LEP was determined accurately and a high precision measurement of the mass and width of the Z boson at LEP was made possible.

6 REFERENCES

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