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Measurement of LEP Beam Energy by Resonant Spin Depolarization

The LEP Polarization Collaboration

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Abstract

A transverse beam polarization of around 10% was reproducibly observed in LEP in 1991. Resonant spin depolarization was performed at four occasions, from September 16 to November 11, providing measurements of the beam energy with a precision of $\pm 1.5 \cdot 10^{-5}$. Several cross-checks were performed to ascertain that the observed resonance corresponds to the fundamental spin precession frequency. The variability of the results, $\pm 6 \cdot 10^{-5}$, is consistent with the expected stability and reproducibility of the machine.

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1 Introduction

The Z boson mass and width are fundamental parameters of the electroweak theory. Their experimental determination is based on measurements of e^+e^- annihilation cross-sections as a function of center of mass energy. The exact knowledge of the energy of the beams is essential: if one combines the results published for 1989-1990 data by the four experiments [1], at the CERN Large Electron Positron Collider LEP, the statistical precision is ± 5 MeV on M_Z , ± 9 MeV on Γ_Z , whereas the systematic error due to beam energy uncertainties is ± 20 MeV on M_Z and ± 6 MeV on Γ_Z . The Z mass error is dominated by the knowledge of the absolute energy scale, while the Z width error stems from possible uncertainties in the differences between the various center-of-mass energies.

Beam polarization was observed in LEP for the first time in 1990 [2]. This letter reports on its use for improved beam energy calibration by measurement of the spin precession frequency. This method has been used previously in e^+e^- storage rings, providing accurate measurements of the masses of the ω , ϕ , J/ψ , ψ' , Υ , Υ' and Υ'' , at VEPP2 and VEPP4 in Novosibirsk [3,4,5], at DORIS in Hamburg [6], and CESR in Cornell [7].

The spin precession frequency is determined by resonant depolarization. It is equal to the product of the revolution frequency, known to 1 part in 10^9 , by the spin tune ν , directly related to the beam energy by the anomalous magnetic moment $a_e = \frac{g_e - 2}{2} = 1.1596521884(43)10^{-3}$ [8] and the mass $m_e c^2 = 0.51099906(15)$ MeV of the electron:

$$\nu = a_e \gamma = \frac{g_e - 2}{2} \frac{E_{\text{Beam}}}{m_e c^2} = \frac{E_{\text{Beam}}}{0.4406486(1)} . \quad (1)$$

A spin tune $\nu = 105.5$ corresponds to a beam energy of 46.5 GeV.

This letter is organized as follows: first the standard magnetic methods of energy calibration are briefly recalled, for reference. Then the conditions under which beam polarization was obtained and measured in 1991 are described, followed by the depolarizing system and depolarizing method. Finally the results are given and compared with those obtained using the other methods.

2 Magnetic measurements

A reference for the magnetic field in the LEP dipole magnets is given by measuring with a flipping coil the field in a pure iron magnet powered in series with the ring's dipoles. The beam energy derived from this measurement is continuously available and is labeled E_{FD} (for Field Display). However, the reference magnet is of different nature than the LEP concrete-iron dipoles and situated in different conditions of temperature and humidity. An absolute calibration by other methods is necessary.

A direct measurement of the field generated by the dipoles is provided by cycling the magnets and measuring the induced current in a closed electrical loop, imbedded in the LEP dipoles. This "flux-loop" method is in principle rather

Experiment	Date	$\langle y \rangle_{RMS}$	Best Polarization(%)
1	29 May	0.69	11.
2	24 June	0.76	9.
3	8 August	0.69	—
4	2 September	0.94	5.
5	16 September	0.81	10.
6	2 October	0.61	19.
7	26 October	0.75	12.
8	11 November	0.61	8.

Table 1: Compilation of LEP polarization experiments in 1991. All experiments were performed at a beam energy of 46.51 GeV.

photons is the quantity of interest and is recorded in a plane of horizontal strips with a 2 mm pitch, situated 4.5 radiation lengths inside the calorimeter. The vertical profile has a typical width of 4 mm RMS. Transverse polarization $\mathbf{P}$ of the electron beam is seen as a shift $\Delta\langle Y \rangle$ of the center of gravity of the vertical profile upon reversal of the laser helicity from $-\xi$ to $+\xi$:

$$\Delta\langle Y \rangle = \kappa \xi \mathbf{P} \quad (3)$$

where κ is the analyzing power of the polarimeter, estimated by monte-carlo simulations [12] to be $\kappa = 500 \pm 30 \mu\text{m}$.

The vertical profiles were recorded separately for the alternating light helicities over 2500 successive laser shots, and the averages and widths separately calculated. The number of backscattered photons associated with each data point was of the order of $2.5 \cdot 10^6$. An estimate of the error on each data point was inferred from the scatter of the 10 partial results (hereafter referred to as "data set") based on 250 laser shots each. The polarimeter was substantially improved in 1991, giving a reduction by a factor 3 of the statistical errors. Systematic errors on the polarization are estimated to be $\Delta\mathbf{P} = 0.5\% + 12\%\mathbf{P}$.

A compilation of the polarization results is shown in table 1. Polarization was observed every time except in the August run, where no significant signal could be established. The validity of the polarization signal was verified each time by exciting a static depolarizing resonance $\nu=106$, and letting the beam repolarize thereafter. An example is shown in figure 1. Observations were in agreement with expectations, allowing cross-checks i) of the zero polarization point, and ii) of the factor κ by comparing the fitted polarization rise-time, which is proportional to the asymptotic polarization degree, to the observed value of $\Delta\langle Y \rangle$.

To find the resonance, the horizontal field of maximum integrated strength bl is excited at a slowly varying frequency, in such a way as to cross the resonance condition. The expected signal for resonance crossing is a steep variation of the polarization degree, in a way that depends on the rapidity with which the equivalent spin tune is swept, $\frac{\Delta\nu}{\Delta t}$ [13]:

$$\frac{P(\text{final})}{P(\text{initial})} = 2e^{-\chi} - 1 \quad (4)$$

$$\chi = \frac{(\pi\nu \cdot \frac{bl}{BL})^2 \times f_{rev}}{\frac{\Delta\nu}{\Delta t}}, \quad (5)$$

where BL is the integrated guide field of LEP.

Formula (4) is derived for proton accelerators. Its application for e^+e^- storage rings is not straightforward, because of the excitation of energy oscillations of particles due to emission of synchrotron radiation. This effect leads to decoherence of the polarization component in the plane of the ring (horizontal component), with a decay time constant which is not yet well known. If this decay time is much longer than the resonance crossing time, a value of $\frac{P(\text{final})}{P(\text{initial})}$ of -1 can be obtained, leading to polarization reversal or "Spin-Flip". On the other hand, a short decay time of the horizontal polarization component would limit $\frac{P(\text{final})}{P(\text{initial})}$ to 0, i.e. depolarization.

4.2 First attempt

In runs 1, 2 and 4 the horizontal field was generated by the vertical kicker magnet used for betatron tune measurements, producing a maximum field of 1.6 Gm. The frequency sweeps were engineered to explore a spin tune range of $\Delta\nu=0.01$, for a duration $\Delta t=100$ ms. The frequency range was swept back and forth at that rate for 5 minutes. According to formula (4), each sweep under these conditions reduces the vertical component by $\delta P/P=7 \cdot 10^{-4}$. Assuming, as in ref. [14], that the horizontal component of the polarization loses coherence in one damping time (45 ms), the effect of successive sweeps should add up, reducing the initial polarization to 10% of its value in 5 minutes.

The beam energy being set to $E_{FD}=46.51$ GeV the spin tune was expected to be 105.481 ± 0.025 , according to formulae (1) and (2). The frequency range $\delta_s=.41$ to $.51$ was swept. If one includes the mirror frequency $1-\delta_s$, this covers the expected range with a safety margin of more than three standard deviations. No depolarization was observed.

It was verified that the kicker was indeed acting on the bunch on which polarization was monitored, by exciting it at the vertical betatron frequency, with reduced intensity. Strong coherent beam motion was observed, and some depolarization occurred.

One possible reason for the failure of this method could be the inadequacy of the hypothesis that the horizontal component of the beam polarization decays in a beam damping time. In fact this hypothesis is challenged in [15]. If the

sweep number	time (hr:min)	δ , range		$P(\%)$		Δf_{RF} (Hz)	Comments
		start	end	initial	final		
1	1:24	.4625	.5125	8.3 ± 0.5	8.1 ± 0.5	-	No Depolarization
2	1:35	.4250	.4750	8.1 ± 0.5	-0.8 ± 1.0	-	Depolarization
3	2:13	.4500	.4800	5.2 ± 0.4	2.2 ± 0.7	-	Partial Depolarization
4	2:59	.4250	.4550	5.7 ± 0.4	4.7 ± 0.7	-	No Depolarization
5	4:38	.4500	.4600	7.0 ± 0.5	3.2 ± 1.0	-	No Depolarization
6	5:07	.4660	.4760	7.6 ± 0.4	6.7 ± 0.5	-	No Depolarization
7	5:18	.4700	.4800	6.7 ± 0.5	7.5 ± 0.3	-	No Depolarization
8	5:30	.4500	.4600	8.1 ± 0.5	-2.9 ± 0.7	+14	Spin Flip
9	6:55	.4600	.4700	7.0 ± 0.8	-1.1 ± 0.7	-	Spin Flip
10	7:45	.4650	.4700	7.8 ± 0.4	5.7 ± 0.8	-	No depolarization
11	7:55	.4600	.4650	5.1 ± 0.5	-2.0 ± 0.5	-	Spin Flip
12	9:20	.4600	.4700	8.0 ± 0.6	-1.4 ± 1.0	-	Spin Flip
13	9:53	.4600	.4700	6.6 ± 0.4	-1.0 ± 0.3	-	Spin Flip
14	10:23	.4600	.4650	5.7 ± 0.9	7.3 ± 0.5	-	No Depolarization
15	10:38	.4650	.4700	7.3 ± 0.5	-1.8 ± 0.8	-	Spin Flip

Table 2: Compilation of the frequency sweeps performed on 16 September 1991.

mirror solution.

The whole set of measurements is shown in figure 2 and summarized in figure 3. For the first 8 hours of the run, from 1 a.m. to 8 a.m., the spin tune was in the range 105.4600 to 105.4625, i.e. 105.4612 ± 0.0012 , or the beam energy $E_{\text{Beam}} = (46.4713 \pm 0.0006)$ GeV. However, the last measurements 12 to 15 indicate that, even though no other parameter was changed, the spin tune had changed three hours later to the range 105.465 to 105.470 or $E_{\text{Beam}} = (46.4741 \pm 0.0011)$ GeV.

Since the field display energy read during this experiment was $E_{FD} = (46.509 \pm 0.001)$ GeV, calibrations of the LEP energy scale $E_{\text{Beam}} - E_{FD} = (-37.1 \pm 1.4)$ MeV and $E_{\text{Beam}} - E_{FD} = (-34.9 \pm 1.4)$ MeV were obtained.

4.4 Analysis of the results

In view of this positive result, several remarks can be made:

- The observation of spin flip is consistent with the hypothesis that, indeed, the horizontal component of the polarization has a much longer life time than the damping time. To account for the observed spin flips, the life time of the horizontal component of polarization must be at least a few seconds. This might explain a posteriori the failure of the first attempts.
- Even though a clear resonance was encountered, it remained to prove that it was the main spin resonance and not one of its satellites, e.g. $\nu_{res} = \nu \pm Q$, where Q would be one of the beam tunes, the most likely candidate being the synchrotron tune Q_s .

Exp.	Time hr:min	Q_x-70	Q_y-76	Q_s	E_{Beam} GeV	$E_{\text{Beam}} - E_{\text{FD}}$ MeV	T_8 °C	$E_{\text{Beam}} - E_{\text{FD}}$ T-Corr.
5a	5:00	.136	.203	0.083	46.4719(6)	-37.1 ± 1.2	22.4	-37.7 ± 1.2
5b	10:00	.136	.203	0.083	46.4741(11)	-34.9 ± 1.5	22.6	-36.5 ± 1.5
6	5:00	.140	.203	0.083	46.4770(6)	-32.5 ± 1.2	22.25	-32.5 ± 1.2
7	18:00	.137	.201	0.083	46.4766(6)	-31.4 ± 1.2	22.0	-30.4 ± 1.2
8a	2:00	.139	.211	0.083	46.4685(13)	-37.5 ± 1.6	22.1	-37.2 ± 1.6
8a	7:00	.136	.201	0.083	46.4729(5)	-33.6 ± 1.2	22.4	-34.2 ± 1.2

Table 3: Summary of energy calibrations with resonant depolarization in 1991. The temperature correction of 10^{-4} per °C is calculated on the basis of the average T_8 of 8 dipoles situated around LEP. The energies are corrected to the average temperature of 22.25 °C.

circulating in LEP, rendering unnecessary to wait for the beam to repolarize.

The depolarization could be located unambiguously within a sweep at several occasions, an example is shown in figure 4. This was not possible, however, when strong vertical motion was excited within the sweep. This could occur if the kicker frequency or one of its harmonics was in tune with a higher order betatron resonance. When this happened, the depolarization was not as efficient, and the polarimeter response was distorted by the oscillations of the beam, yielding large fluctuations.

The graphical summaries of these experiments are shown on figure 5. The following tests were successfully done:

- The change of beam energy by changing RF frequency, with a larger amplitude, was performed again in experiments 6 and 8.
- The synchrotron tune Q_s was changed during experiments 6 and 8. The depolarizing resonance frequency remained unchanged, indicating that the depolarization was not due to synchrotron side-bands of the main resonance, $\nu' = \nu \pm Q_s$.
- On experiment 7, these synchrotron side bands were observed where expected, figure 5b, producing reduced depolarization, by 40-50% only. This strongly supports the hypothesis that the resonance seen was indeed the main resonance.
- The chromaticity was changed during experiment 7, without modifying the depolarization frequency.

During the first and last runs evidence was seen for a variation by 3 and 4 MeV of the beam energy calibration within the same LEP fill. The difference can be partly, but not fully, explained by the variation of the magnets temperature,

Figure 5: Graphical representation of the depolarizations on 2 October(a), 26 October (b) and 11 November (c) 1991.

Full line: depolarization. dashed line: No depolarization. Thick dashed line: partial depolarization.

A diamond indicates the exact frequency of depolarization, when it could be located within the frequency sweep.

which was recorded. This observation points to short term variations of the beam energy calibration at the level of about $5 \cdot 10^{-5}$.

The five energy calibrations are summarized in table 3. The average result is:

$$E_{\text{Beam}} - E_{\text{FD}} = -34 \pm 3 \text{ MeV}, \quad (6)$$

or,

$$E_{\text{Beam}} = E_{\text{FD}} \times [1. - (7.4 \pm 0.6)10^{-4}]. \quad (7)$$

This is in good agreement with equation 2, although the energy calibration is not expected to be stable from one year to the next.

The flux loop calibrations indicate a variation of the magnets calibration with temperature [17]. The polarization data do not cover a wide enough range of temperatures to prove or disprove this observation. Applying the temperature

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