RECENT RESULTS ON ENERGY CALIBRATION AT LEP

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Abstract

The determination of the centre-of-mass energy at the four experiments installed on the CERN Large Electron Positron (LEP) collider is one of the major ingredients in the Standard Model investigations being carried on in the context of the experimental programme. Severe depolarising effects at beam energies beyond 60 GeV limit the application of the Resonant Depolarisation (*RD*) method, which provides an energy uncertainty of about ± 1 MeV at the Z^0 resonance. Extrapolation techniques from magnetic field measurements are used to obtain beam energies in the W-pair region, aiming at a total energy error $\leq$15 MeV. Consistency checks over a large range of precisely calibrated energies are mandatory to contain systematic errors from extrapolation. Progress obtained in extending the polarisable energy range in the 1997 LEP Run and the preliminary extrapolation errors are reported.

1 BEAM ENERGY DETERMINATION

1.1 Resonant depolarisation

Resonant depolarisation (*RD*) [1] provides the most accurate determination of the average beam energy in a storage ring via the measurement of the energy-dependent spin precession frequency of a polarised $e^+(e^-)$ beam. A vertical orbit kick from a frequency-controlled radial RF magnetic field causes the particle spin to precess away from the vertical axis with a precession frequency $\Omega_\mathrm{s} = 2\pi\,\nu_\mathrm{s}\,f_\mathrm{rev}$ where ν_s is the energy-dependent spin tune and f_rev the revolution frequency. A depolarising resonance occurs when the perturbing field oscillates at the frequency Ω_s and the knowledge of the perturbing frequency $f^\mathrm{res}_\mathrm{dep}$ provides a measurement of the spin tune and hence of the beam energy:

$$\nu_\mathrm{s} = a_\mathrm{e}\gamma = \left(N_\mathrm{s} + \frac{f^\mathrm{res}_\mathrm{dep}}{f_\mathrm{rev}}\right) = \left(\frac{a_\mathrm{e}}{m_\mathrm{e}\,c^2}\right) E_\mathrm{beam} \qquad (1)$$

where a_e is the $\mathrm{e}^\pm$ gyromagnetic anomaly, γ the Lorentz factor and $m_\mathrm{e}\,c^2/a_\mathrm{e} = 440.6486$ MeV.
The integer N_s is determined from magnetic calibration of the main dipoles.

1.2 Polarisation limitations beyond the Z^0

Several parameters affect the Sokolov-Ternov (ST) radiative polarisation process of a beam in a circular accelerator. The asymptotic polarisation level P_∞ is determined by depolarising effects of different nature:

$$P_\infty = \frac{8/5\sqrt{3}}{1+\sum\limits_\mathrm{sources}\left(\frac{\tau_{ST}}{\tau_\mathrm{d}}\right)_\mathrm{s}} \leq \frac{92.4\%}{1+\left(\frac{\tau_{ST}}{\tau_\mathrm{d}}\right)_\mathrm{opt}+\left(\frac{\tau_{ST}}{\tau_\mathrm{d}}\right)_\mathrm{syn}} \qquad (2)$$

where τ_d is the global depolarisation time, τ_{ST} the radiative Sokolov-Ternov time (320 min for LEP at the Z^0 energy)

$$\tau_{ST} \;=\; \underbrace{\frac{8}{5\sqrt{3}}\,\frac{m_\mathrm{e}}{\hbar r_\mathrm{e}}}_{2.832\cdot 10^{18}\ \mathrm{s\,m^{-3}}}\ \left(\frac{\rho^3_\mathrm{eff}}{\gamma^5}\right), \qquad (3)$$

$\hbar$ is the reduced Planck constant, r_e the classical electron radius and ρ^3_eff is the radiation integral I_3 in units of the ring circumference C :

$$(\rho^3_\mathrm{eff})^{-1} = \frac{I_3}{C} = \frac{1}{C}\oint \frac{ds}{|\rho(s)|^3}\,. \qquad (4)$$

Depolarising effects from orbit errors depend quadratically on the beam energy, machine misalignments and focusing strengths of the lattice via the term

$$\left(\frac{\tau_{ST}}{\tau_\mathrm{d}}\right)_\mathrm{opt} \propto \theta^2_\mathrm{s} = \nu^2_\mathrm{s}\,\theta^2_\mathrm{p}\ \propto \gamma^2\,(k\cdot\delta y_\mathrm{rms})^2 \qquad (5)$$

where $\theta_\mathrm{p} = kL\cdot\delta y$ is the orbit kick of a particle travelling off-axis by an amount δy in a quadrupole of strength kL and $\theta_\mathrm{s} = a_\mathrm{e}\gamma\ \theta_\mathrm{p}$ is the associated spin kick.
Effects originating from the term (5) are reduced at LEP by refined orbit correction algorithms known as Deterministic Harmonic Spin Matching (*DHSM*) [3], the beam-based determination of the beam position monitor offsets [4] and the adoption of a dedicated low focusing optics [5].

Contributions from large amplitude synchrotron oscillations are described by the spin tune modulation index [2]

$$\left(\frac{\tau_{ST}}{\tau_\mathrm{d}}\right)_\mathrm{syn} \propto \left(\nu_\mathrm{s}\,\frac{\sigma_\mathrm{e}}{Q_\mathrm{s}}\right)^2 \propto \frac{\gamma^4}{Q^2_\mathrm{s}} \qquad (6)$$

where σ_e is the relative r.m.s. energy spread and Q_s the synchrotron tune.
These oscillations exhibit a severe energy dependence and are mainly responsible for the fast decay of the polarisation level attainable at LEP beyond the Z^0 resonance.
For a given beam energy improvements can in principle be obtained reducing the energy spread and/or increasing the synchrotron tune. Both involve shorter bunch lengths $\sigma_\mathrm{z} \propto \sigma_\mathrm{e}/Q_\mathrm{s}$ which in LEP cannot be reduced at will to avoid thermal problems from higher-order RF modes [6].

1.3 Magnetic methods

Magnetic measurements on the LEP dipoles are used to extrapolate *RD* calibrations to the top LEP energies. This process depends on the comparison of *RD*-measured energies with estimates from two different measurements of the magnetic field.

Local on-line field information is currently provided by 16 *NMR* probes installed in selected LEP dipoles. Continuous monitoring during physics runs and *RD* calibrations is available with a $\sim 10^{-6}$ precision but the B-field is only sampled in a very small area of a few dipoles out of the 3200 units in the ring.

A field-display loop (*FL*) [7] installed in the standard LEP dipoles measures 96.5% of the total integrated field strength [1] during demagnetisation cycles. Special *FL* measurements are taken close to physics runs with pauses in the cycles allowing the *NMR* system to lock and read for successive comparison with *NMR*. The *NMR*s system is calibrated against low energy *RD* measurements.

Cross-calibration and consistency checks of the two magnetic measurements over the LEP operational energy range together with the $E_{\rm NMR} - E_{\rm Pol}$ comparison at low energy set the uncertainty level in the physics energy region.

Extending the *RD* calibrated energy range (lever arm) is then very important to reduce the uncertainty at high energy in the extrapolation process.

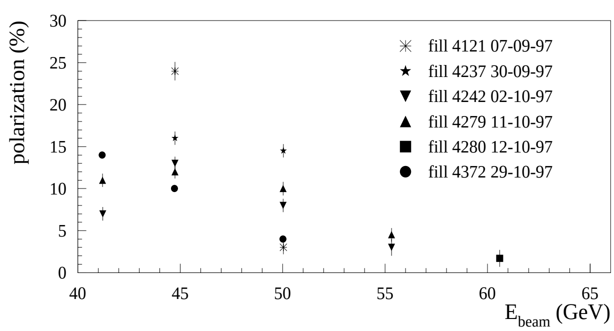

Figure 1: Polarisation measurements performed at four beam energies in different fills. Four energies were calibrated in the same fill on two occasions.

2 DIRECT ENERGY MEASUREMENTS

Polarisation levels suitable for the *RD* method have been measured at four beam energies as shown in Fig.1. The lower point (41.2 GeV) is essentially determined by the value of the magnetic field in the LEP dipoles at which the *NMR*s still lock. The *HSM* optimisation procedure was applied at energies larger than 45 GeV and a ∼5% polarisation level was obtained at 55.3 GeV.

A 2% polarisation level, not yet useful for *RD* calibration, was detected at 60.6 GeV.

[1] The *FL* system does not measure the end-arc low field dipoles, the special injection magnets and ignores contributions to $\int Bdl$ from off-axis orbits in quadrupoles and from horizontal correctors.

On two occasions four energies could be successfully calibrated in the same fill, and the calibrated energy range was extended from 5 to 14 GeV, see Fig.2.

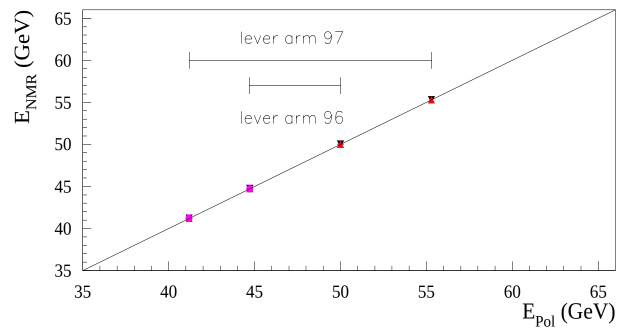

Figure 2: The improved range of calibrated energies. $E_{\rm NMR}$ represents the equivalent beam energy from *NMR* informations on the B-field in some of the LEP dipoles.

3 DATA NORMALISATION

The problematics of establishing the beam energy in the LEP2 physics range [8] by extrapolation methods based on magnetic measurements, starting from the energy scale precisely defined by resonant depolarisation around the Z^0 energies, is illustrated in the following section.

3.1 NMR/Polarisation comparison

A two-parameter linear fit to the *RD* data of the form

$$E_{\rm Pol} = a^i + b^i\, B^i_{\rm NMR}$$

is made for each *NMR* and for fills containing at least two calibrated $E_{\rm Pol}$ values. A 16-fold set of equivalent beam energies $E^i_{\rm NMR} = a^i + b^i\, B^i_{\rm NMR}$ is then associated, for each *NMR* probe, to the $E_{\rm Pol}$ data and the residuals $E_{\rm Pol} - E^i_{\rm NMR}$ derived for the measurements performed in each fill. A measurement of the non-linearity in the $41.2 - 55.3$ GeV calibrated energy range is shown in Fig.3 where the residuals averaged over all *NMR*s are plotted for the two fills with four *RD* calibrations.

Further extension of the calibrated lever arm is at a premium to reduce the uncertainties at higher energies.

3.2 NMR/Flux-loop comparison

A similar two-dimensional fit can also be applied to the *NMR* magnetic field measured during dedicated *FL* measurements. As the *FL* information on the total bending field is related to the *RD* measured energies, a good correlation is expected between the fitted slopes of the $B_{\rm NMR} - E_{\rm Pol}$ and slopes from a similar fits of $B_{\rm NMR} - B_{\rm FL}$ in the calibrated energy range. This correlation is shown in Fig.4 where the slopes of the two linear fits are presented for each *NMR*. Error bars are now given by the scatter over the dedicated *FL-NMR* measurements.

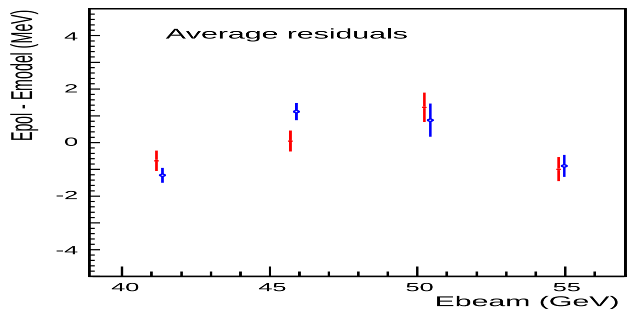

Figure 3: Non-linearity measurement in the *RD*-calibrated energy range. Residuals $E_{\rm Pol} - E^i_{\rm NMR}$ averaged over all *NMR*s for the two fills with four calibrations. Error bars are rms of residuals for each set of *NMR* measurement.

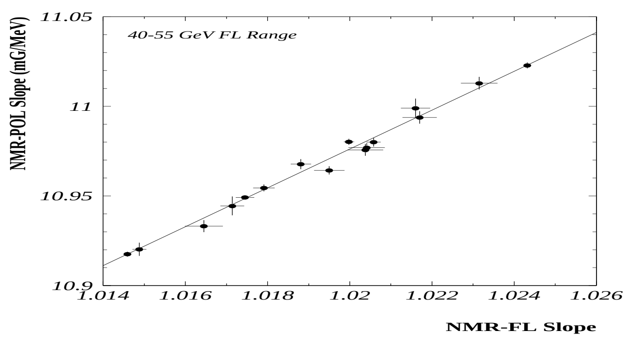

Figure 4: *NMR*/Flux-loop comparison in the calibrated energy range. Correlation between fitted slopes for *NMR* vs $E_{\rm Pol}$ and *NMR* vs $B_{\rm FL}$. One point per *NMR* probe.

3.3 Extrapolation tests

The correlation of Fig.4 can be adopted to test the extrapolation method at physics energies beyond the maximum *RD*-calibrated value $E^{\rm max}_{\rm Pol}$. Comparing the *NMR*-predicted $B_{\rm FL}$ field values with *FL*-measured ones at different dipole excitations for each flux-loop measurement produced the results shown in Fig.5 where a bias in the range $(-10 \div +20)$ MeV is predicted in the physics energy range $(90 \div 95)$ GeV. The interest in extending the *RD*-calibrated energy range is again evident from these results.

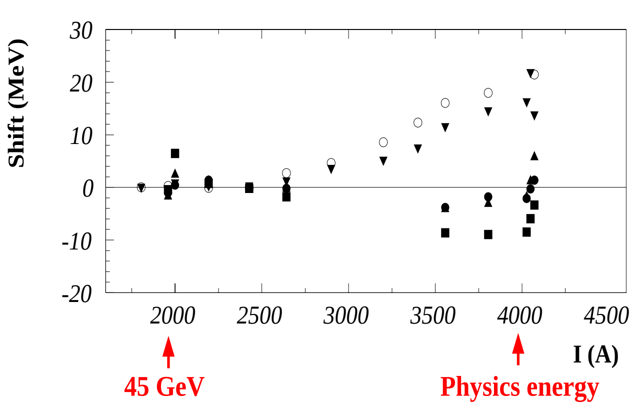

Figure 5: Example of extrapolation using *NMR*/*FL* correlation established in the *RD*-calibrated energy region.

4 ENERGY DETERMINATION AND ERRORS

The central value of the beam energy in physics is given by the actual values of the NMR fields calibrated by the RD method (Section 3). In addition, corrections to the central value must be made for energy shifts due to the RF system, earth tides, etc[8].

The aforementioned extrapolation comparison provides the largest uncertainty in the beam energy, 20 MeV. Other large sources of error are the scatter over the NMR values used for extrapolation (10 MeV) and a variation depending on which NMRs are used (5 MeV), for a total error of 29 MeV.

5 FUTURE ACTIVITIES

Plans are being developed to reach polarisation levels suitable for *RD* calibration beyond 55 GeV to extend the calibrated lever arm [9] [10].

An independent linearity check to help extrapolation at physics energies is being implemented with the installation of a magnetic spectrometer [11] to continuously monitor deviations of the horizontal orbit from the nominal value at different beam energies.

6 REFERENCES

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