Precise determination of the Center of Mass energy for the experiments at LEP

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The progress in understanding the LEP energy behaviour following the 1995 Z lineshape scan is presented. The major change in the model of the LEP energy stems from the discovery of an unexpected rise of the bending field during a physics run. Preliminary estimates of the errors on the collision energies for the datasets relevant for the Z parameters (1993,1994,1995) are reported.

1 Overview

The Center of Mass energy for the LEP experiments is a fundamental parameter in the determination of the mass and width of the Z resonance. The LEP beam energy can be determined with high precision using the technique of resonant depolarization [1](200 KeV resolution). Unfortunately, this measurement has only been commissioned in accelerator conditions without colliding beams, typically at the end of a physics fill. A model is then necessary to follow the evolution of the energy during a fill: this model will provide the instantaneous energy through a set of *corrections* to the absolute energy determined by the resonant depolarization method. [2]. The corrections can be broadly grouped into two main categories: those affecting the mean LEP energy of the electron and positron beams and the ones causing offsets between the positron and electron beam energies locally at individual Interaction Points (IP) hence causing local corrections to the CM energy. This paper presents the progress and the changes in the 1995 scan campaign compared to the one in 1993 [2].

2 The 1995 scan

As in 1993 the 1995 Z scan was made at three energy points, peak ('P') and at approximately $\pm$ 1760 MeV from the Peak ('P-2' and 'P+2'). The offpeak integrated luminosity delivered was $\approx 20pb^{-1}$ over 52 fills equally distributed between the two off peak energies. Attempts were made to calibrate every off peak fill, after physics collisions, at the End Of Fill ('EOF') using the resonant depolarization technique [1]. The calibrated fills represent 70% of the off peak luminosity to be compared with 40% achieved in 1993. In 1995 for the first time two of the 3600 LEP dipoles were equipped with NMR probes capable of monitoring the magnetic field behaviour in the region just outside the vacuum pipe. In 1995 a number of physics fills were calibrated also at the Beginning Of Fill ('BOF') before the beams were brought into collision. Last but not least a dedicated team of physicists took shifts to control the quality of the recording of the accelerator parameters and, in particular, of the RF system. Contrary to 1993, when a stable RF configuration was a precondition to run off-peak, in 1995 the need to commission the first complement of Superconducting RF modules made high quality parameter logging essential to track the details of RF distribution around the ring.

3 Determination of the mean energies of LEP

The practical impossibility to calibrate each fill and the fact that most calibrations happen at EOF, after the collisions have taken place, require a model to follow the evolution of the energy during a fill. In ref. [2] some of the energy time variation related to magnet temperature, tides and geological effects are discussed in detail.

The newly installed NMR probes immediately revealed some bizarre behaviour. The measured field was jumping up and down during most of the day, being quiet between midnight and 5 am, and in general showing an underlying slow drift saturating after 10 to 12 hours to a level equivalent to an energy change of around 5 MeV. A sample fill spanning all of these periods can be seen in fig. 1. The major source of this behaviour was traced, after a few months of investigation, to the phenomena of *vagabond currents*. The return current of electrical trains is intended to go back to the power supply along the iron railtracks. In reality, part of this current follows a more erratic path in the ground surrounding the railroad. If, in the vicinity, there is a good underground conductor (like the LEP beam pipe) these currents will preferably follow it. The proof of this hypothesis came after the observation, during the transit of trains on the railway along the CERN sites, of the perfect time correlation of (i) the voltage drop between the rails and ground, (ii) the voltage drop between the LEP beam pipe and the surrounding ground and (iii) the reading of the NMR probe as shown in fig. 2. The worrisome feature in fig.1 is the substantial drift. The

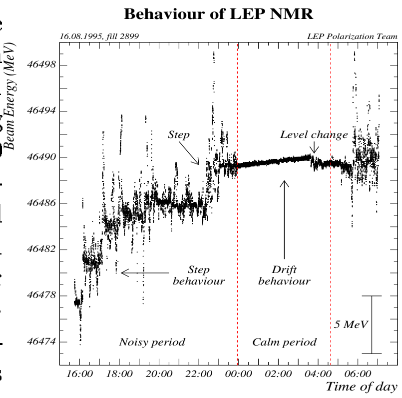

Figure 1: Typical NMR output during a physics fill

instantaneous spikes should not affect the energy as the current splits around IP1 and IP6 to circulate in opposite directions. A large fraction of the drift is most likely caused by the magnets *monodirectional walk* along their histeresis curve, caused by the current spikes. The change in field has been confirmed by 6 fills where either BOF and EOF calibration were performed or the energy calibration repeated after several hours. With this hindsight the few Machine Development studies ("MD") performed in 1992 and 1993 when the beam polarization was repeated during extended periods of time (hence the energy monitored in time) were reinterpreted. Within the limited statistics they confirm the effect observed in greater detail in 1995. Prior to 1995 no direct monitoring of the field in the tunnel was available, so any model aiming to apply the newly acquired knowledge to the 1993 and 1994 datasets could not be based on the NMR direct measurements. A parametrization of the rise as a function of the time into the fill, time of day and ring temperature has been developed to reproduce the 1995 data. This model can be applied to the 1993, 1994 and 1995 datasets in a coherent way.

4 IP dependent corrections to the Center of Mass energy.

- **RF corrections:** The beam energy loss due to synchrotron radiation losses is compensated by the acceleration provided by RF cavities placed, at locations diametrically opposite, near IP2 (L3) and IP6 (OPAL). A detailed model including the measured alignement, phases and voltage curves for the RF cavities is needed to calculate the correction at each IP. The model predicts a number of observables like the synchrotron tune, the changes in the longitudinal position of the IP and the masurement of the relative radiative sawtooth amplitude of the e^+ and e^- beams at each side of the accelerating straight sections. Typical CM energy corrections for 1995 are 15.,5.,1.,1. MeV for IP 2,4,6,8 respectively.

- **Dispersion effects:** The electrostatic separation ("bump") needed to avoid parasitic collisions on either side of the IP between wagons of the same train generates opposite sign vertical dispersion for the two beams. With finite vertical dispersion the particles within a bunch are ordered vertically according to their momenta. When the sign of the dispersion is opposite a vertical offset between the colliding beams provokes a shift of the CM energy. The potential danger was realized before the scan started and a strategy was defined to monitor the offsets and to keep them below the micron level. Typically twice per fill a fine vertical scan ($\pm 4\mu$m beam excursion) of one beam against the other was performed and the luminosity curve measured. The average collision offsets were maintained at 0.5 μ m or below for each IP yielding corrections well below 1 MeV for each experiment.

5 Errors on the energy determination

In this section only error sources which are new or are better understood than in ref. [2] will be discussed. In general errors correlated between the various energy points contribute to the uncertainty on M_Z while the uncorrelated ones determine the systematic error associated to Γ_Z.

- **Uncertainties in the rise term:** The uncertainty in the absolute rise gives an error on M_Z while the systematic error associated with the assumption that this rise is the same at the two off-peak points gives an uncertainty for Γ_Z. The errors are determined from the comparison of the model predictions –derived from the NMR readings– with the energy calibrations performed at the beginning and end of physics and MD fills in 1993 and 1995. This gives errors of 1 MeV and 2 MeV from the energy rise for 1995 and 1993 respectively. The error on the assumption that the rise was the same at the two off-peak energies was estimated form the comparison of the NMR data at the two energies. This contributes an additional uncertainty of 0.6 MeV to Γ_Z. Additional contribution to the error come from the study of varying the saturation level of the rise and from varying the temperature coefficients of the magnets within safe limits.

- **Errors from orbit correctors:** The difference between the settings of the *trim* coils used to horizontally correct the orbit between physics and calibration mode contributes to the energy uncertainty. This error has been taken from the program simulating the accelerator optics. The induced uncertainty is approximately of 1 MeV on Γ_Z and 0.8 MeV on M_Z. A dedicated measurement to assess the effect and possibly reduce this error is planned.

- **Mean fill energy uncertainty:** This error accounts for the energy uncertainty in the uncalibrated fills. The error is estimated, using the calibrated fills, from the scatter between the model prediction and the calibration results. It has decreased in 1995 to approximately one half of that of 1993 due to the increased fraction of calibrated off-peak luminosity in 1995.

- **IP dependent errors:** The contribution from the RF corrections has been estimated by comparing the observables mentioned in the RF section with the predictions of the RF model. All contributions to the error[3] are well below 1 MeV with the exceptions of those related to the uncertainty in the cavity position. The largest errors amount to 1.9 MeV in IP6 and 0.8 MeV in IP2 as these are the straight sections where the RF stations are located.
  The potential error from a finite vertical dispersion of opposite sign between the two beams at the IP was kept under control. The average offset between the positron and electron beam is well below 1 μm at each IP. Center of mass energy corrections are below 1 MeV and the resulting systematic uncertainty below 0.5 MeV. [4]

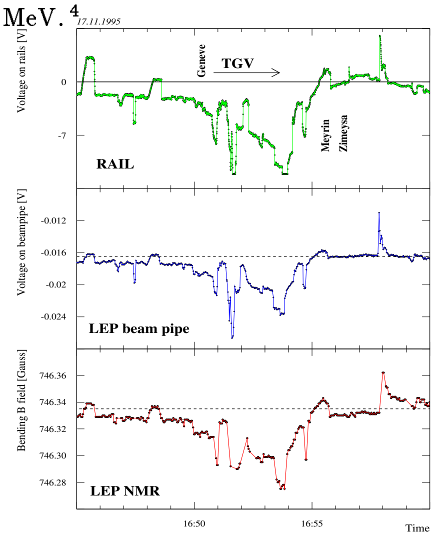

Figure 2: From top to bottom : railtrack potential, LEP beampipe potential, NMR reading

Another improvement in the final precision obtainable in the determination of the Z parameters derives form an improved determination of the beam energy spread Dedicated experiments and improved calculations have allowed to reduce the uncertainty on the energy spread to 1.3 MeV (a factor four better than previously). The preliminary energies for the 1995 scan were provided to the LEP experiments in the form of files giving the LEP energy, for each IP, every 15 minutes. Revised, but still preliminary, energy files were supplied for the 1993 scan and 1994 peak data. In addition an energy error matrix was supplied, with entries given for each energy and for both the 1993 and 1995 scans including the correlations between energy points and years. The common LEP errors are estimated to be $\Delta M_Z = \pm 1.5$ MeV and $\Delta\Gamma_Z = \pm 1.7$ MeV

6 Conclusions

The 1995 scan was a success and improves substantially the determination of the Z parameters. The newly discovered slow drift of the bending field during a fill is an important effect which, if neglected, would lead to an overestimation of the M_Z of roughly 4 MeV. It is anticipated that, with further measurements in 1996 on the magnetic and thermal behaviour of LEP, the final errors will be somewhat reduced compared to the present preliminary values.

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