THE DETERMINATION OF THE LEP ENERGY IN THE 1995 Z^0 SCAN

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The procedure of the LEP collision energy determination is explained. Discussion is given to the new phenomenon observed during the 1995 Z^0 scan that the beam energy rises during a fill. One consequence of this discovery is that the energies of previous years must be revised. The interaction point specific corrections to the collision energy in 1995 are briefly described. The preliminary systematic errors from the energy on M_Z and Γ_Z are given.

1 Importance of Energy Determination

The primary achievement of the LEP 1 physics programme has been a series of precision measurements of the Z^0 resonance parameters, in particular the mass, M_Z, and width, Γ_Z. These are determined by performing a scan of the resonance. With the high luminosities delivered by LEP in recent years, accurate knowledge of the collision energy ($E_{\rm CM}$) at each scan point has become essential to benefit from the large statistics. After the scan of 1993, the preliminary combined LEP values for M_Z and Γ_Z had associated errors of 2.2 MeV and 3.2 MeV respectively. The contribution of the energy uncertainty to these errors was 1.5 MeV and 1.7 MeV [1].

2 Principle of Energy Determination

The technique of *resonant depolarisation* provides an instantaneous and precise ($<$ 1 MeV) calibration of the beam energy ($E_{\rm b}$). However the depolarisation procedure carries certain practical overheads. Typically several hours are required to unambiguously locate the resonance. Furthermore, the measurement has only succeeded with separated beams outside of physics conditions. Calibration therefore has been restricted to the end of fills (EOF), after physics, or occasionally at beginning of fill (BOF), before collisions. As the beams may be lost before or during the calibration a significant fraction of fills go uncalibrated. A full discussion of resonant depolarisation at LEP is given in [2].

The energies of the calibrated fills show a large scatter. For instance, the RMS of the EOF calibrations in 1995 was 5.0 MeV in $E_{\rm b}$. This demonstrates that the energy of LEP does not remain constant, but shows significant variation. Two classes of effect contribute to these changes in $E_{\rm b}$. Even with a constant magnet current, the dipole field itself may vary. Changes in temperature, for example, are important, causing a fractional variation in field of 0.0001/° C. In addition, the quadrupole magnets can also lead to energy shifts if the average beam position varies. The magnitude is approximately 1 MeV per 13 μm of transverse movement. Such off-centre trajectories can occur if the shape of the LEP ring is distorted, for instance by earth tides. The various sources of energy variation as understood after the 1993 LEP scan are discussed in [3].

At a given energy point, the calibrated fills can be taken as unbiased estimators of the mean energy of all fills. With the scatter coming from the energy variation, however, this mean energy has an unacceptably large uncertainty. Therefore, it is desirable to develop a model which parameterises the factors driving the variation. This model can be directly compared to measurement at each EOF calibration, and thus its validity assessed. With complete knowledge the scatter of the residual of the model and the calibrations would be zero. With present understanding the 1995 scatter is 1.9 MeV.

The ability to cross-check model and calibration ensures a powerful test of the understanding of LEP's behaviour. Note however, that with calibrations at the EOF only, this test has relatively little sensitivity to any energy variation during the fill itself.

At each experiment $E_{\rm CM}$ is twice $E_{\rm b}$, plus interaction point (IP) specific corrections. These corrections are explained in section 5.

3 1995 Scan

As in 1993, the 1995 Z^0 scan was made at peak and at two points approximately ~ 1760 MeV either side of peak. The offpeak luminosity was $\sim 18\,\mathrm{pb}^{-1}$, delivered over 52 fills and evenly distributed between each point.

Attempts were made to calibrate every offpeak fill after physics collisions. This was realised for $\approx 70\%$ of the offpeak integrated luminosity, to be compared with the figure of $\approx 40\%$ achieved in 1993. This improvement lessens the dependence on the model in determining the mean energy, and leads to an error of 0.25 MeV in $< E_\mathrm{b} >$.

Of these fills with EOF calibration, 4 fills were also calibrated at BOF. Such BOF/EOF fills had not been performed previous to 1995, and were of great interest for studying any energy change during a fill. In addition, two machine development fills had an extended series of polarisation measurements, giving 6 BOF/EOF fills in total.

The 1995 scan also benefitted from additional instrumentation. NMR probes were installed in two dipoles in LEP to provide a direct measurement of the bending field. In 1993 there had only been a measurement of the field in a reference magnet outside of the tunnel.

Two innovations in LEP operation distinguished the 1995 running from previous years. Firstly, superconducting RF cavities were operated for the first time in preparation for LEP 2. Secondly, in a bid to increase luminosity bunch train running was used throughout the scan. The electrons and positrons were distributed in four trains of three wagons, rather than the eight equally spaced bunches of previous years. To avoid parasitic collisions between wagons, electrostatic deflections ('bumps') were applied on either side of the IP's.

4 Energy Rise in Fill

4.1 NMR behaviour

The NMR's installed in the tunnel for the 1995 scan exhibited two unexpected characteristics.

Anticorrelated short term noise
Frequent spikes and spikes in the field were seen. This activity was strongly anticorrelated between the two devices. Furthermore the noise was much reduced between the hours of 00 : 00 and 05 : 00.

Field rise during fill
Over the course of a fill the NMR's showed a significant field rise. The integrated rise averaged over all fills is shown in figure 1. This plot is already corrected for the small variation in the magnet core temperatures. The rise was steepest at start of fill and diminished with time. When analysed as a function of time of day the rise was found to be smallest at night.

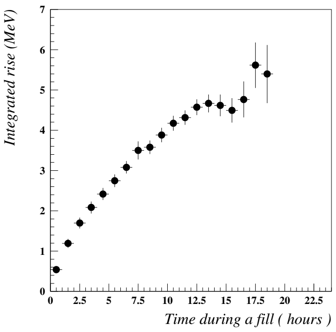

Figure 1: Effective E_b rise from tunnel NMR's.

In previous years noise, jumps and long term drift had been observed in the reference magnet NMR. This was also the case in 1995. In contrast to that behaviour seen in the tunnel NMR's, however, the reference NMR was much more stable. The field rise was of a much reduced amplitude, the noise less frequent, and no distinctive 'day-night' variation was present.

4.2 BOF/EOF experiments

Conceivably, the field rise seen in the two tunnel NMR's was instrumental, or limited to these two magnets and not seen as an energy rise by the beam itself. A direct test of this was provided by the 6 BOF/EOF calibration experiments. These calibrations confirmed that E_b rises during the fill. This rise was of order $4-5$ MeV after 15 hours in fill, in agreement with the average NMR behaviour.

4.3 Understanding and modelling the energy rise

In seeking to understand the NMR noise, a discovery was made of a current flowing on the LEP beam pipe. This current fluctuates in amplitude with time and position around the ring, with typical amplitude of ~ 1 A. It enters close to IP 1 and flows in both directions, exiting near the Versoix river at IP 6. The current's behaviour at the positions of the NMR's is consistent with the anti-correlated noise seen in these devices. Furthermore the current activity is highest during the day, but much reduced between 00 : 00 and 05 : 00.

Investigation eventually revealed the source of this current to be from passing trains on the Geneva-La Plaine line. A fraction of the current powering the trains leaks to earth when returning to the generator station and passes on to the LEP beam pipe. The quiet period after midnight is a consequence of the absence of trains at this time. That the trains cause the noise observed in the NMR's was demonstrated by an experiment which monitored the voltage between the train rails and ground, the beampipe voltage and the NMR field. The clear correlation is shown in figure 2.

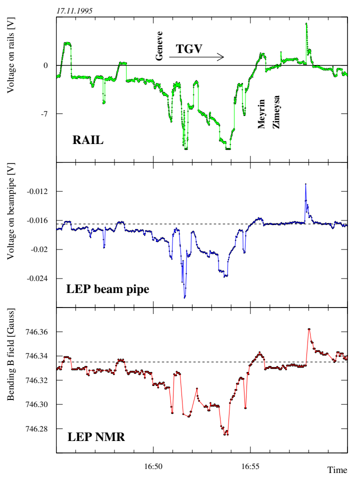

Figure 2: Correlation between train (TGV) rail voltage, beampipe voltage and tunnel NMR behaviour.

It is believed that the current flowing on the beampipe perturbs the equilibrium of the magnetic domain of the LEP dipoles. At the start of fill these dipoles are not at the top of their hysteresis cycle. The excitation of the beampipe current induces a rise in field.

In an effort to improve the understanding of dipole behaviour, a series of dedicated laboratory experiments are being conducted with a single magnet in an environment which closely resembles the LEP tunnel. These experiments have strikingly confirmed the 'train effect'. Figure 3 shows that if the same beampipe current is applied to the laboratory magnet as was recorded in the LEP tunnel, a field rise is observed of very similiar nature to that seen by the tunnel NMR's. The experiments have also demonstrated that other sources possibly contribute towards the energy rise; in particular it has been learnt that the temperature dependence of the field cannot be adequately described with a single coefficient and the temperature of the magnet core alone, but that the temperature gradient between the core and the cooling water enveloping the magnet coil must also be considered. This work is in progress.

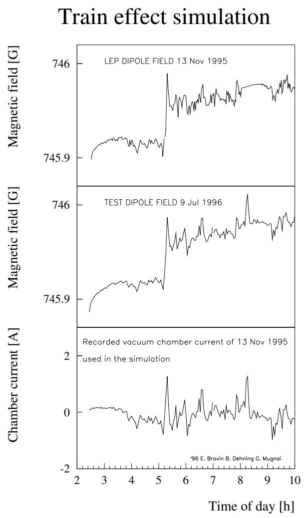

Figure 3: Simulation of 'train effect' in laboratory.

The energy rise in a fill was incorporated in the model by histogramming the average behaviour of the tunnel NMR's as a function of time in fill and of time of day, and referring to these histograms to obtain corrections to E_{b} in each fill. The preliminary systematic uncertainty on the absolute magnitude of the rise, and thus on M_Z, was assigned to be 1 MeV. This came from comparison of the modelled rise and the observed rise in the 6 BOF/EOF fills. Comparison of the NMR behaviour at the two offpeak points allowed a preliminary error of 0.6 MeV to be assigned to Γ_Z. Additional small contributions came from different approaches to the modelling of the rise.

4.4 Consequences for previous years

The energy rise must be included in the 1993 and 1994 analyses, as the effect was almost certainly present in these years also. This leads to a shift of the preliminary value of M_Z obtained from the 1993 scan, and a revision of the accompanying errors presented in [3].

Despite the fact that there were no BOF/EOF calibrated physics fills prior to 1995, there do exist machine development experiments with extended periods of calibrations. These can be reinterpreted to give confidence that the energy rise was indeed present and of similar magnitude to that observed in 1995. From this comparison, a preliminary error of 2 MeV was assigned to the rise in 1993.

5 Interaction Point Specific Corrections

5.1 RF corrections

The energy loss due to synchrotron radiation is compensated by RF stations located at IP2 and IP6. $E_{\rm CM}$ shifts are induced at each experiment of $\sim$ 10 MeV. The precise magnitude is dependent on many factors, including the absolute voltage scale, phasing and alignment of the cavities. Cavity trips result in significant short term changes.

With logged parameters as input, the RF system can be modelled and $E_{\rm CM}$ corrections calculated. The validity of the modelling can be verified by comparing calculation and observation in other RF sensitive variables. These include the synchrotron tune, the longitudinal vertex position at the IP's and the transverse separation between the beams either side of the RF stations. This enables the model to be refined and allows errors to be assigned to the $E_{\rm CM}$ corrections.

The RF modelling in 1995 was particularly challenging on account of the hybrid mixture of superconducting and conventional copper cavities, and the bunch train running. The preliminary errors on M_Z and Γ_Z from this source were 0.5 MeV and 0.4 MeV respectively.

5.2 Opposite sign vertical dispersion

The bunch train bumps applied to the beams in 1995 generated a vertical energy dispersion of opposite sense for the electrons and positrons. Such a dispersion, combined with any vertical offset between the beams at collision leads to a shift in $E_{\rm CM}$. The shift is ~ 1.5 MeV per μm of offset.

This potentially large effect was controlled through a programme of Vernier scans. In a Vernier scan the beams are swept against each other vertically in a sequence of steps. The luminosity is measured at each step and the position of maximum luminosity determined. The beams are then set to this position. By maximising the luminosity, the offset and thus the $E_{\rm CM}$ shift is minimised.

To calculate any residual bias and assign systematic errors it is necessary to know the dispersion itself. This is determined by changing the RF frequency (and thus the energy) and observing the shift in optimal Vernier position. Dispersion effects contributed only 0.3 MeV to the preliminary errors on both M_Z and Γ_Z.

6 Summary

To take account of the energy errors when fitting the experimental data, uncertainties are assigned to each energy point. Correlations must be considered between the energy points, the IP's and the years. For the preliminary results presented at this conference and summarised in [4] the assignments for 1993 and 1994 were revised with respect those used in previous fits.

Fitting all the analysed LEP data gives a preliminary error on M_Z of 2.0 MeV and on Γ_Z of 2.7 MeV. The contribution of the energy uncertainty to these values is 1.5 MeV and 1.7 MeV respectively. These may decrease with further analysis of existing data, and improved understanding of dipole behaviour from ongoing experiments.

Acknowledgements

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References

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