# Presentation 46

# Present Status


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### 46.1 Magnetic measurements

The energy of LEP is read from a moving coil in a reference magnet and displayed on the *field display*. This magnet does not have any concrete between the laminations. The reproducibility of the field display is about $0.5 \cdot 10^{-4}$ over a short term of about a day during which the magnet is not turned off and about $1.0 \cdot 10^{-4}$ over a longer term of up to two weeks.

The iron-concrete magnets in the LEP tunnel go through an aging process which involves changes of the dimensions, the permeability and the remanent field not seen by the reference magnet. For this reason a calibration of the field display is carried out about once a month with the *flux loop*. This loop consists of wires installed on the lower poles of all the dipole magnets in the ring. By cycling the magnets symmetrically between -2900 and +2900 A and measuring the voltage induced in the flux loop, an absolute calibration is obtained. However this calibration does not include effects due to the earth magnetic field (which is not cycled) and due to the Nickel layer between the aluminum and the lead (the loop is outside the vacuum chamber). Furthermore the flux loop itself undergoes some dimensional changes during the aging of the magnet. As a result the relative accuracy of the energy determination with the flux loop and the reference magnet is about $5 \cdot 10^{-4}$. The results of such flux loop calibrations are presented in Figure 46.1 which clearly shows the aging process. The lower part of the figure gives the relative calibration between 20 GeV and 45 GeV which we will use later to extrapolate the absolute calibration done at 20 GeV with protons to the physics condition at 45 GeV.

### 46.2 Determination of the central orbit

The magnetic measurement gives the energy of a beam on central orbit, i.e. a beam going in average through the centre of the quadrupoles. We have to determine how far the orbit of a physics run deviates from this central orbit. This average horizontal deviation $< x >$ is related to the energy deviation from the central energy $E_c$ by the horizontal dispersion $D_x$

$$\frac{E_{ph} - E_c}{E_c} = \frac{< x >}{< D_x >} = \frac{< x >}{\alpha R} \tag{46.1}$$

where $\alpha$ is the momentum compaction, $E_{ph}$ the energy during the physics run and $R$ the average radius of LEP. We can change the average horizontal deviation $< x >$ by changing the RF-frequency which forces a different circumference on the beam

$$\frac{< x >}{R} = -\frac{\Delta f_{RF}}{f_{RF}}. \tag{46.2}$$

We now change the RF-frequency until the beam is on central orbit. This determines the central RF-frequency $f_{RF_{ce}}$ which can be compared with the frequency $f_{RF_{ph}}$ used in physics runs and the energy difference evaluated.

$$\frac{E_{ph} - E_c}{E_c} = -\alpha \frac{f_{RF_{ph}} - f_{RF_{ce}}}{f_{RF}}. \tag{46.3}$$

We cannot easily determine when the beam goes in average through the centre of the quadrupoles. However, the sextupole magnets are very well aligned with respect to the quadrupoles. We can find out when the beam goes in average through the sextupole centres since a change of the sextupole strength will in that case not result in a tune change. This experiment is done as follows. We measure the betatron tunes as a function of RF-frequency as for a measurement of the chromaticity. This is repeated for different settings of the sextupole strength. The lines $Q(f_{RF})$ should cross at the point which corresponds to a beam going in average through the centre of the sextupoles. This determines the central RF-frequency. Such a measurement is shown in Figure 46.2 and the results are summarised in Table 46.1.

| Date | Dec. 89 | May 90 |
|---|---|---|
| $f_{RFce}$ from $Q_x$ Hz | 352254156.0 ±3.8 | 352254168.8 ± 7.0 |
| $f_{RFce}$ from $Q_y$ Hz | 352254149.4 ± 2.3 | 352254177.1 ± 4.7 |
| $f_{RFce}$ average Hz | 352254151.7 ± 5 | 352254172.9 ± 9 |
| circumference mm | 26 658 873.7 ± 0.4 | 26 658 872.1 ± 0.7 |
| $f_{RFph} - f_{RFc}$ Hz | 68.3 ± 5 | 47.1 ± 9 |
| $(E_{ph} - E_c)/E_c$ $10^{-4}$ | -5.0 ± 0.4 | -3.5 ± 0.7 |

Table 46.1: Central RF-frequency and circumference

## 46.3 Absolute energy calibration with protons

We start by finding the central orbit and the corresponding central RF-frequency ($f_{RF_{ce}}$) with positrons using the method explained in the previous section

$$f_{RFce} = h_e f_{0e} = \frac{h_e \beta_e c}{2\pi R} \approx \frac{h_e c}{2\pi R}. \tag{46.4}$$

Here $f_{0e}$ is the revolution frequency of the positrons on central orbit. It is related to the RF-frequency by the harmonic number $h_e$ which has not been measured but is known since a change of one unit would mean an error of more than one percent in the energy which is way outside the error of the orbit measurement. The harmonic number in LEP needs some further explanation. LEP has a double RF-frequency system with two frequencies corresponding to the harmonic number $h = 31320 \pm 4$. During all experiments the higher of the frequencies was recorded which has the harmonic $h_e = 31324$. During physics runs the RF-frequency was $f_{RFp}$=352254220 Hz. If LEP were operated in a single frequency mode with positrons the harmonic number would be $h_e = 31320$. This is the case for the superconducting cavities.

The experiment is repeated with the same magnetic configuration using protons giving the new central RF-frequency

$$f_{RFcp} = h_p f_{0p} = \frac{h_p \beta_p c}{2\pi R}. \tag{46.5}$$

In this case the RF-system operates with a single frequency having a harmonic number of $h_p = 31358$ at 20 GeV. Substituting the circumference $2\pi R$ from the positron measurement we get for the normalised proton velocity $\beta_p$

$$\beta_p = \frac{f_{0p}}{f_{0e}} = \frac{f_{RFcp} h_e}{f_{RFce} h_p}. \tag{46.6}$$

and the proton momentum which has to be the same as the electron momentum since both particles have the same orbit in the same magnetic configuration

$$p_p = p_e = p = m_0c^2\beta_p\gamma_p = m_0c^2\frac{\beta_p}{\sqrt{1-\beta_p^2}}. \tag{46.7}$$

Examples of such measurements for protons are shown in Figure 46.3 and the results are summarised in Table 46.2. This method becomes less accurate for higher energy protons since their velocity will approach the one of light. The relative error of the momentum determination is related to the one of the velocity measurement by

$$\frac{\Delta p}{p} = \gamma^2\frac{\Delta\beta}{\beta}. \tag{46.8}$$

At higher energy this calibration is probably better done with deuterons or other ions.

| Date | 11.12.89 | 21.05.90 |
|---|---|---|
| $f_{RFcp}$ from $Q_x$ Hz | 352249435.3 ± 190.6 | 352249247.5 ± 19.0 |
| $f_{RFcp}$ from $Q_y$ Hz | 352249478.7 ±42.3 | 352249237.7 ± 18.0 |
| $f_{RFcp}$ average Hz | 352249471.5 ± 70 | 352249242.6 ± 20 |
| $\beta_p$ | 0.9989025 ±2.1 $10^{-7}$ | 0.9989018 ±5.7 $10^{-8}$ |
| p(x=0) GeV/c | 20.0102 ±1.0 $10^{-4}$ | 20.0038 ±0.3 $10^{-4}$ |
| p(field display) GeV/c | 20.007 | 20.009 |
| (p(0)-p(fd))/p(fd) | $(1.6 \pm 1.0)10^{-4}$ | $(-2.6 \pm 0.3)10^{-4}$ |

Table 46.2: Calibration with protons

## 46.4 Results

To get the energy for the physics conditions we use the proton results for the calibration of the field display at 20 GeV. The flux loop calibration is used to extrapolate to the physics energy of 45 GeV. From Figure 46.1 we find that this scaling involves a correction of $(-5.75 \pm 1) \cdot 10^{-4}$. There is a further correction due to the reduced effect of the Nickel at higher energy of $(+5.0\pm2)\cdot10^{-4}$ obtained from magnetic measurement in the laboratory and a small correction due to the earth magnetic field of $0.3 \cdot 10^{-4}$. This results in a total correction of $(-0.45 \pm 2.2) \cdot 10^{-4}$ for the scaling from 20 to 45 GeV. We then make a correction for the fact that the physics runs were carried out with an RF-frequency slightly different from the one of the central orbit. The horizontal corrector magnets represent some additional bending field which can lead to a slight change of the energy. This effect is difficult to correct for since some corrector magnets are used to compensate the bending due to a misplaced quadrupole or to cancel the effect of the earth magnetic field in the long straight sections. Other correctors actually make up for a lack of bending field in the LEP dipole magnets. The first group should not be included in the energy calibration unless one also includes the earth magnetic field in the straight sections and the effect of the misplaced quadrupoles. However the second group should be included in the overall bending field. It is not possible to separate these functions completely. The calibration with protons includes of course all effects. However the scaling to 45 GeV could be affected by the correctors since not all of them are ramped with energy and the flux loop does not include the field of them. The corrector setting is also different from run to run. To estimate this effect the total bending of all correctors has been registered for several runs. The effect was usually smaller than $5 \cdot 10^{-5}$. We took this number as a possible error introduced by the correctors. Furthermore, a small correction was made for the 1989 data since most of them were taken earlier than the calibration in December. It was estimated from the slope of the flux loop calibration shown in Figure 46.1. All these effects are summarised in Table 46.3 giving on the last line the correction to be applied to the field display in order to get the true energy of the physics run. The final correction for the 1990 data is $(-6.55 \pm 2.4) \cdot 10^{-4}$, however it was decided to take a correction of $(-6.4 \pm 2.4) \cdot 10^{-4}$ instead which has been used earlier and which has only a small difference (well inside the error) form the value in the table. More details about the energy calibration are given in [1] and [2].

| Date | | 11.12.89 | 21.05.90 |
|---|---|---|---|
| $\frac{p(0)-p(fd)}{p(fd)}$, 20 GeV | $10^{-4}$ | $1.6 \pm 1.0$ | $-2.6 \pm 0.3$ |
| effects of correctors etc. | $10^{-4}$ | $0.0 \pm 0.5$ | $0.0 \pm 0.5$ |
| scaling to 45 GeV | $10^{-4}$ | $2.3 \pm 2.4$ | $-0.45 \pm 2.2$ |
| p(0)-p(fd)/p(fd), 45 GeV | $10^{-4}$ | $3.9 \pm 2.6$ | $-3.1 \pm 2.3$ |
| p(phys)-p(0)/p(0) | $10^{-4}$ | $-5.0 \pm 0.4$ | $-3.5 \pm 0.7$ |
| time of physics correction | $10^{-4}$ | $+0.5 \pm 1.1$ | $0 \pm 0$ |
| p(phys)-p(fd)/p(fd), 45 GeV | $10^{-4}$ | $-0.6 \pm 2.7$ | $-6.4 \pm 2.6$ |

Table 46.3: Calibration for physics conditions

## References


[1] R. Bailey et al. Proc. of the 2nd European Particle Accel. Conf. EPAC 90, Nice (June 1990), 1765.
[2] V. Hatton et al., CERN LEP Performance Note 12, 1990.


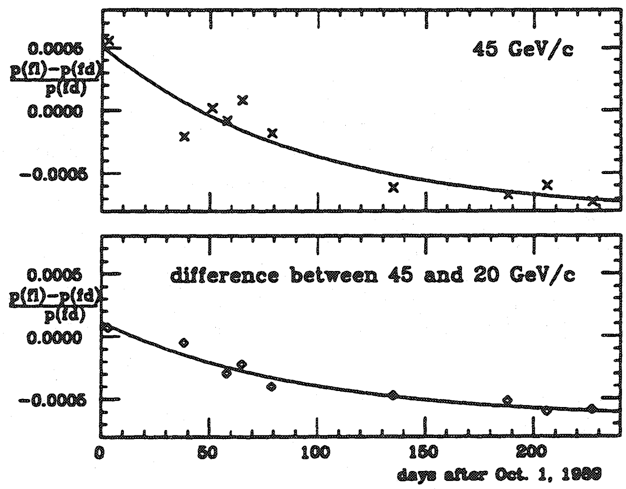


Figure 46.1: Flux loop calibration

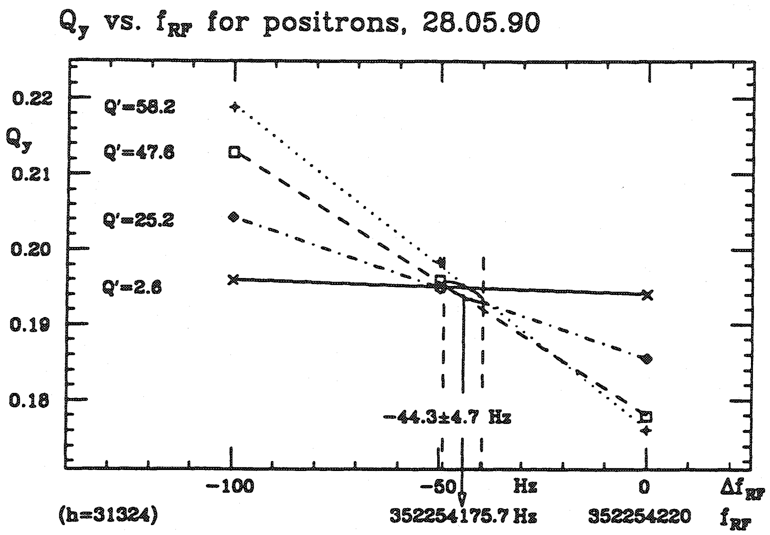


**Figure 46.2: Determination of the central orbit with positron**

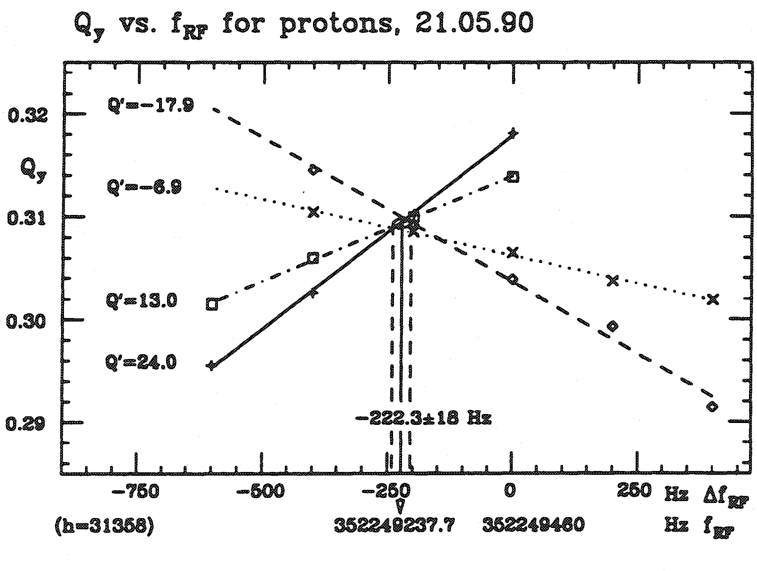


Figure 46.3: Determination of the central orbit for protons