Energy Calibration and Stray Fields at LEP

Spins, Tides

and

Vagabond Currents

J. Wenninger

LEP in one slide

The **Large Electron Positron collider** (LEP) was build in the 1980's and operated between 1989 and 2000 at beam energies from **~43 GeV to 104 GeV**.

Four large experiments (ALEPH, DELPHI, OPAL and L3) were installed in LEP, their experimental programs included the detailed **study of Z and W bosons**.

- *The maximum centre-of-mass energy of ~208 GeV was not sufficient to discover the Higgs as $e^+e^- \rightarrow HZ$ which requires ~215 GeV.*
- *The Z boson mass and width measurements, relying on an accurate determination of the beam energy, were an important part of the experimental program.*

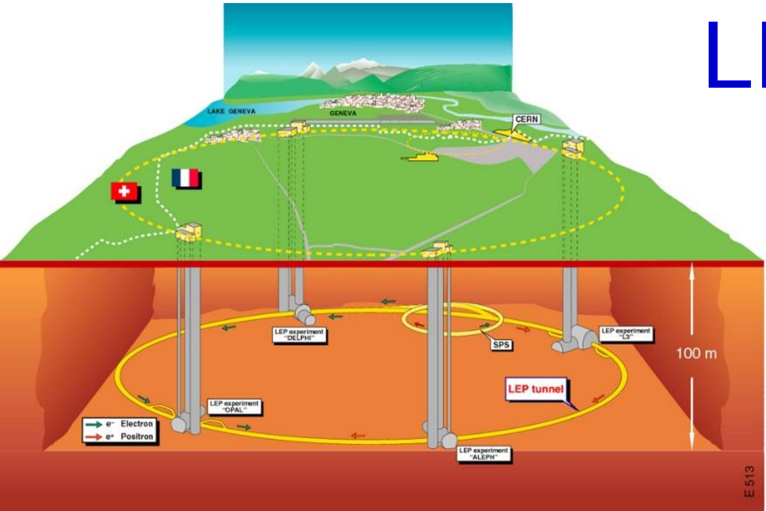
Since energy losses by synchrotron radiation is a concern for circular e^+e^- colliders, the effective LEP bending radius was large, ρ = 3026 m.

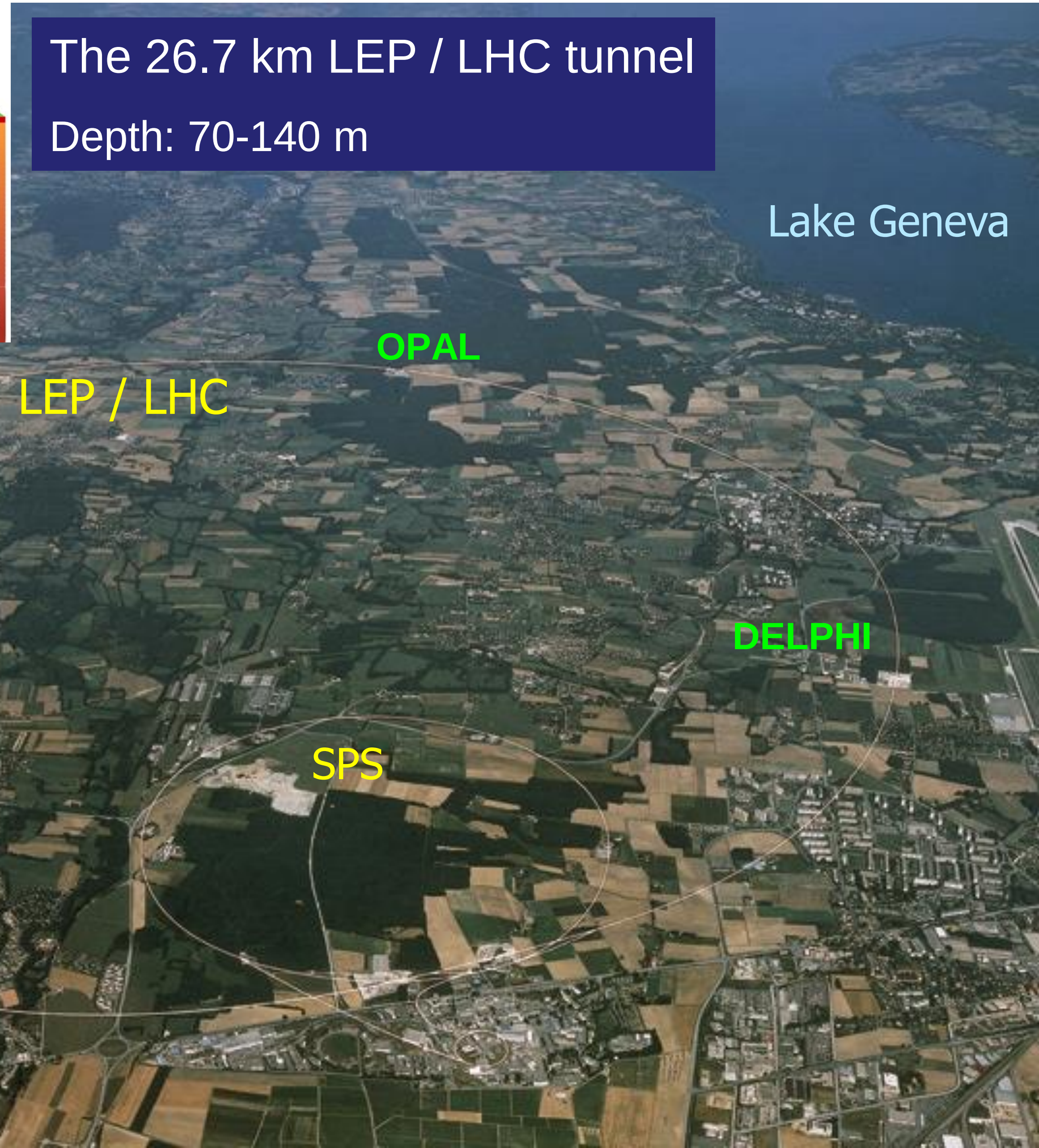
The dipole bending field of LEP was consequently very low, **B ≈ 50 – 120 mT**, rendering the machine more sensitive to stray fields.

LEP / LHC Layout

The 26.7 km LEP / LHC tunnel

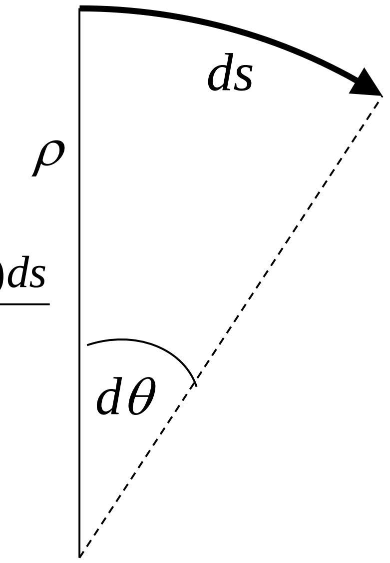
Depth: 70-140 m





Beam energy

The average beam energy in a ring is given by the integrated magnetic field along the path of the beam(s).



Path / orbit closure

$$\oint_C d\theta = 2\pi = \frac{Ze}{P}\oint_C B(s)ds \qquad d\theta = \frac{ds}{\rho(s)} = \frac{Ze\,B(s)ds}{P}$$

And therefore

$$P = \frac{Ze}{2\pi}\oint_C B(s)ds = Z \times 47.7[\mathrm{MeV/(cTm)}]\oint_C B(s)ds$$

It is challenging to determine the energy by simple 'summing up' of all fields when accuracies of $\Delta P/P \sim 10^{-5}$ are requested.

Polarization at LEP

As a side effect of synchrotron radiation emission, e^+/e^- beams polarize spontaneously (align their spins) in the transverse (vertical) direction, i.e. along the direction of the bending field.

Polarization is however a slow and delicate process which requires a lot of care in machine setup and special conditions.

Ideal machine :

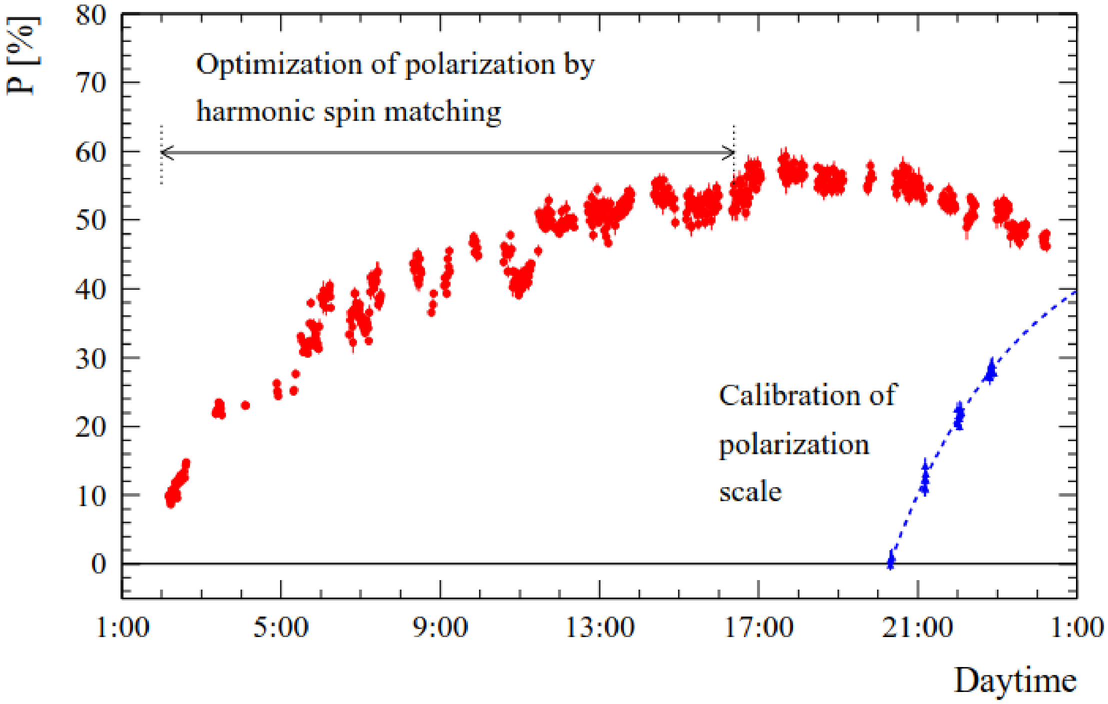
$P_T^{max} = 92.4\%$

At LEP :

record $P_T = 57\%$

routine $P_T = 5$ -10%

Up to 60.6 GeV



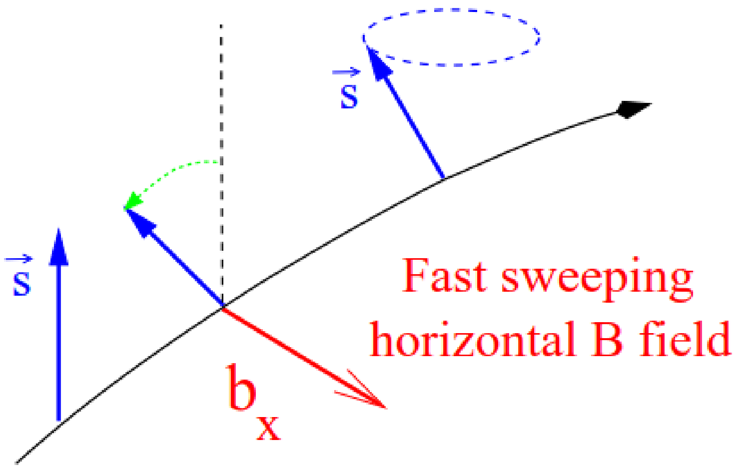
Resonant Depolarization

The interest of P_T : magnetic moments precess in B-fields

The **number of precessions/turn** ν, called the spin tune, is **proportional to the energy** :

$$\nu = \frac{g_e - 2}{2}\frac{E}{mc^2} = \frac{E[\text{MeV}]}{440.6486(1)[\text{MeV}]}$$

To determine the energy → **Measure ν**



Principle :

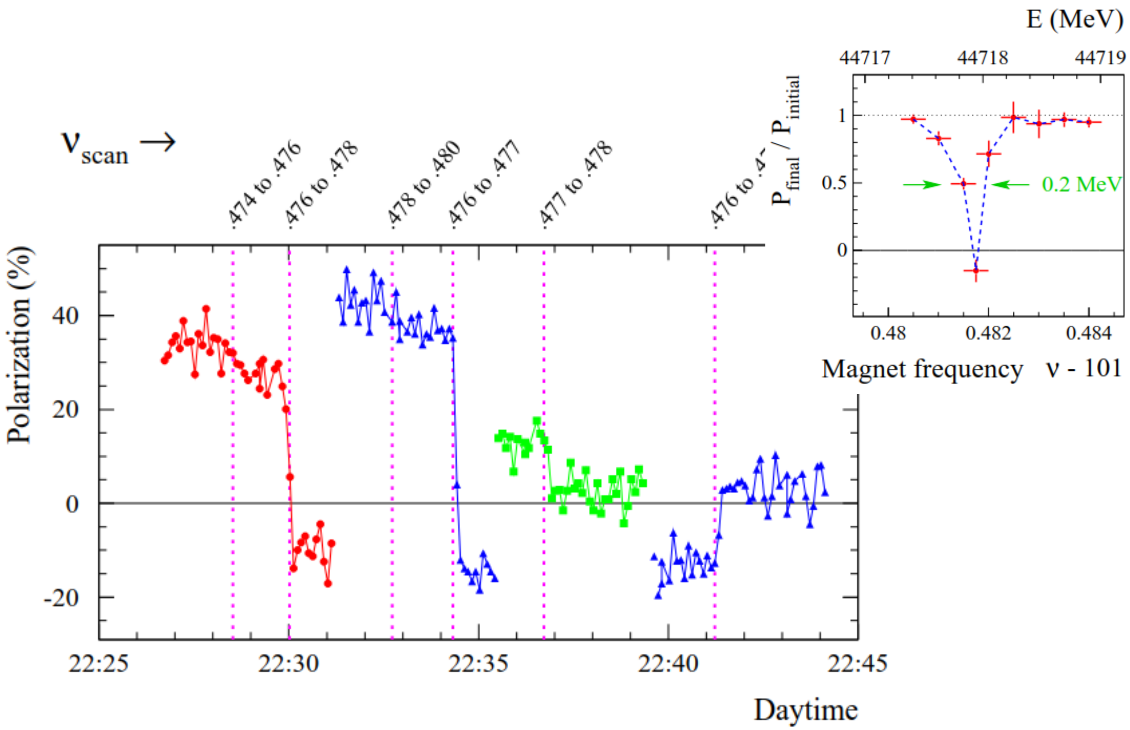
- Sweep the B-field of a fast pulsing magnet (“kicker”) in frequency and observe P_T,
- If kicker frequency and ν match, P_T is rotated away from the vertical axis.

Resonant depolarization

Resonant Depolarization II

In practice :

- The kicker frequency is swept over a selected interval (~ 22 Hz).
- P_T can be destroyed or flipped when the kicker is in resonance.



Intrinsic accuracy :

$\Delta E < 0.4$ MeV
$\Delta E/E < 10^{-5}$

This technique is over an order of magnitude more accurate than any other method !

But it required a large amount of DEDICATED beam time as polarization was not compatible with physics data taking !

Z Resonance Scans

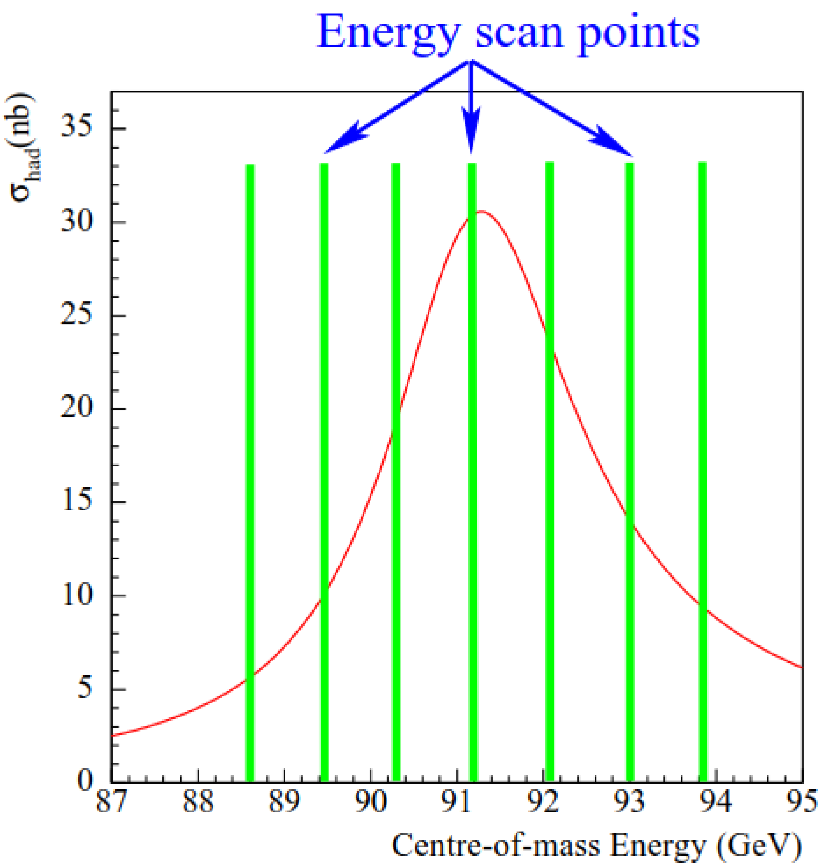
Good regions for P_T are ~ 50 MeV wide and spaced by 441 MeV.

Convenient for Z mass and width measurements !

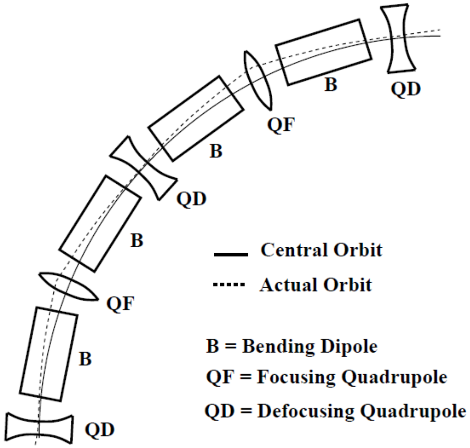
Calibrations cannot be performed during "physics" (no P_T with colliding beams)

Extrapolation in time

Beam energy model



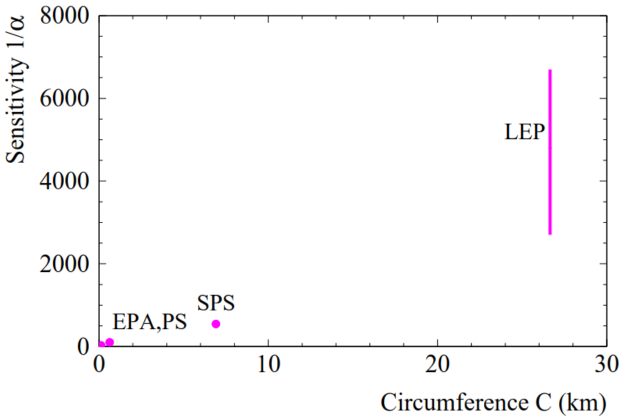
Stressed Rings



Sensitivity of the energy to circumference changes :

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta C}{C}$$

The beam receives a net dipole field from the quadrupoles



The LEP/LHC beam energy is sensitive to circumference changes of $\Delta C/C \sim 10^{-9}$!

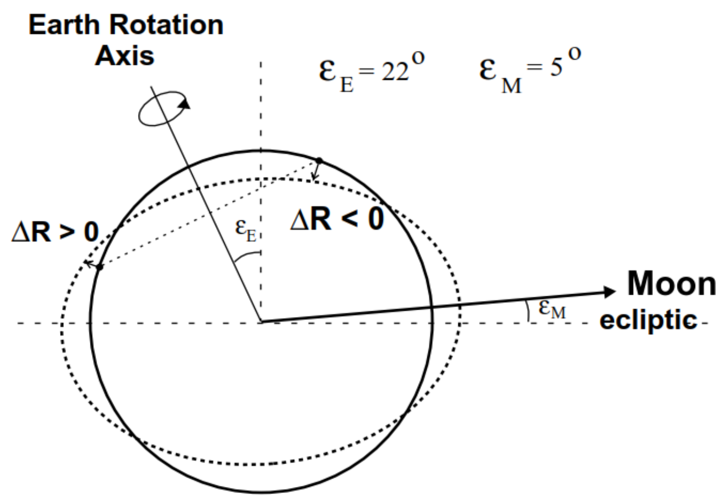
1991 : the first calibrations revealed unexplained fluctuations of the beam energy. A SLAC ground motion expert suggested… tides !

Earth Tides

Tide bulge of a celestial body
of mass M at a distance d :

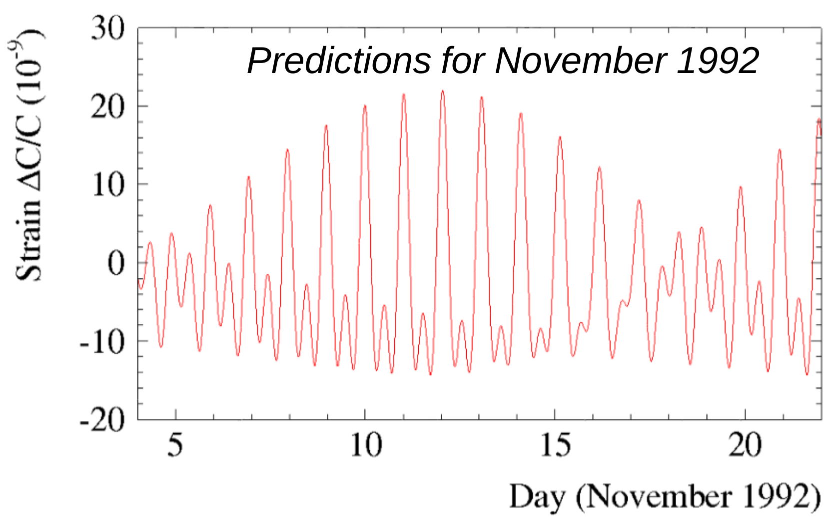
$$\Delta R \sim \frac{M}{2d^3}(3cos^2\theta - 1)$$

θ = angle(vertical, the celestial body)



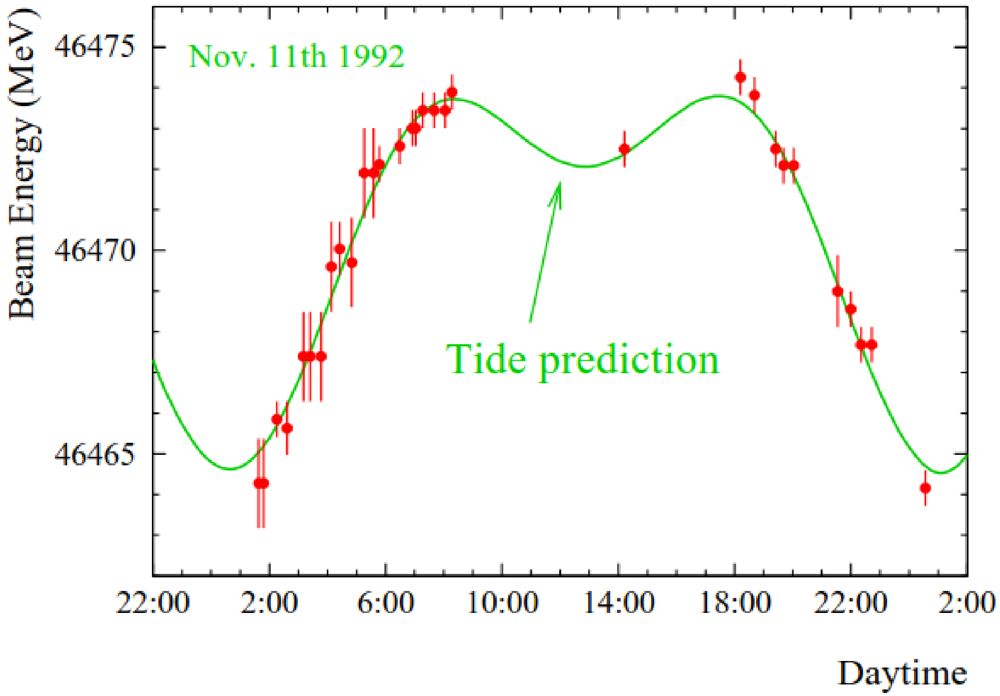
Earth tides :

- The Moon contributes 2/3, the Sun 1/3.
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions possible (~%).



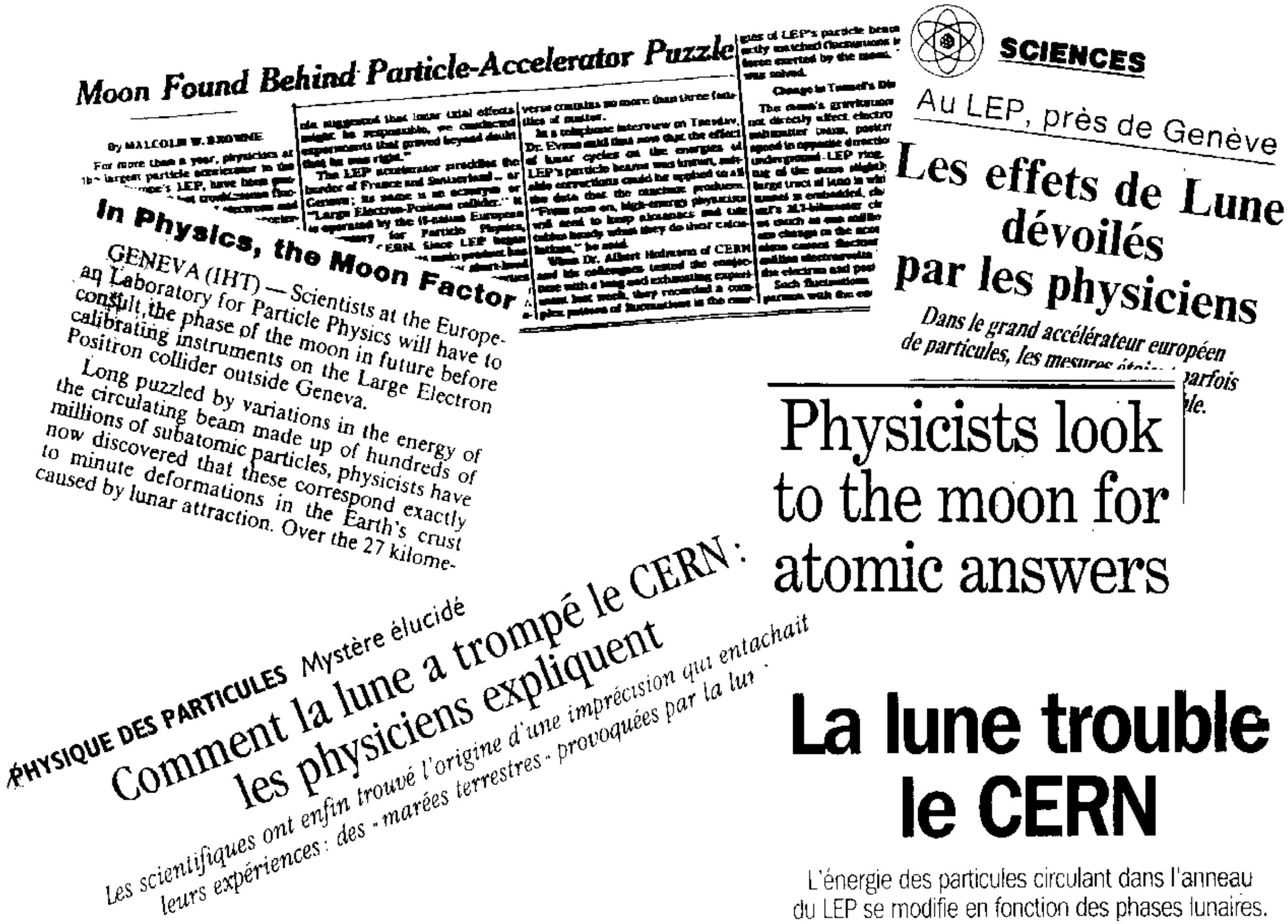
Moonrise over LEP

November 1992 : A historic tide experiment during new moon



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

Success in the Press !



Moon Found Behind Particle-Accelerator Puzzle

By MALCOLM W. BROWNE

In Physics, the Moon Factor

GENEVA (IHT) — Scientists at the European Laboratory for Particle Physics will have to consult the phase of the moon in future before calibrating instruments on the Large Electron Positron collider outside Geneva.

Long puzzled by variations in the energy of the circulating beam made up of hundreds of millions of subatomic particles, physicists have now discovered that these correspond exactly to minute deformations in the Earth's crust caused by lunar attraction. Over the 27 kilome-

SCIENCES

Au LEP, près de Genève

Les effets de Lune dévoilés par les physiciens

Dans le grand accélérateur européen de particules, les mesures étai... parfois ...le.

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

Comment la lune a trompé le CERN : les physiciens expliquent

Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences : des « marées terrestres » provoquées par la lu...

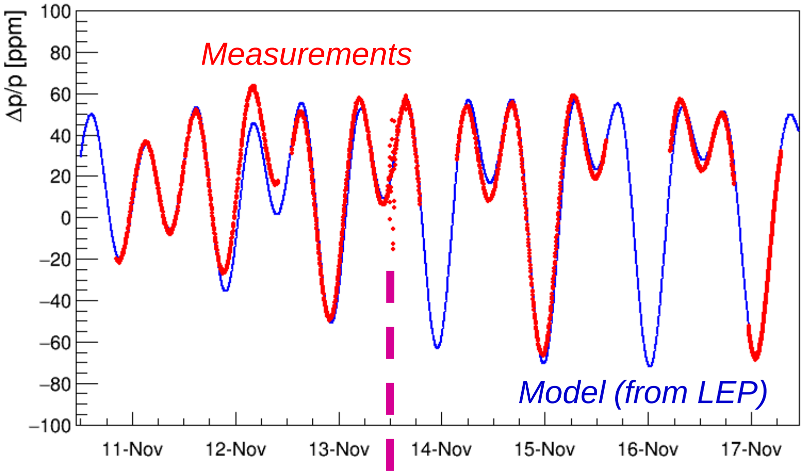
La lune trouble le CERN

L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phases lunaires.

Tides and Earthquakes at LHC

Tides are also observed very clearly on the LHC circumference since it is the same ring !.

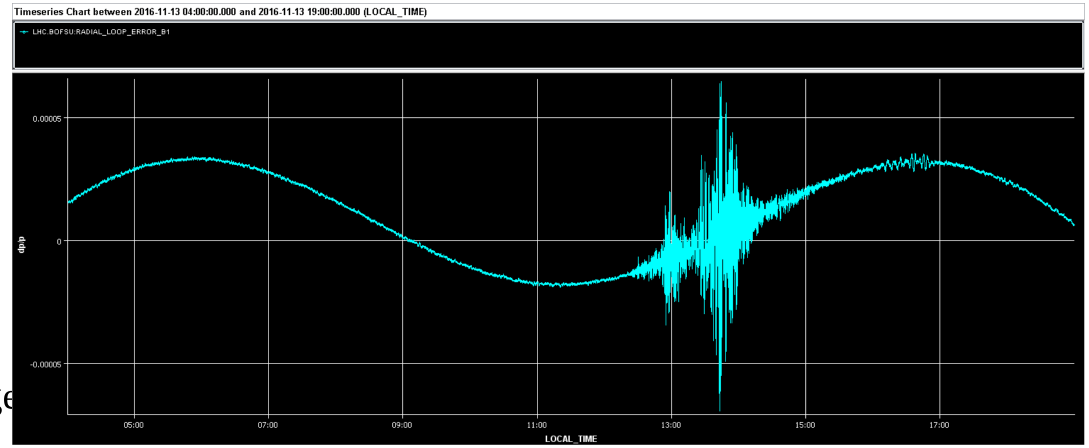
During a 6 day special LHC run in 2016 the feedback on the circumference was switched off to observe tides using the beam position monitors.



Tide observations during the 2016 pPb run at 4 TeV

Earthquake in New Zealand

The pressure waves induce a modulation of the circumference



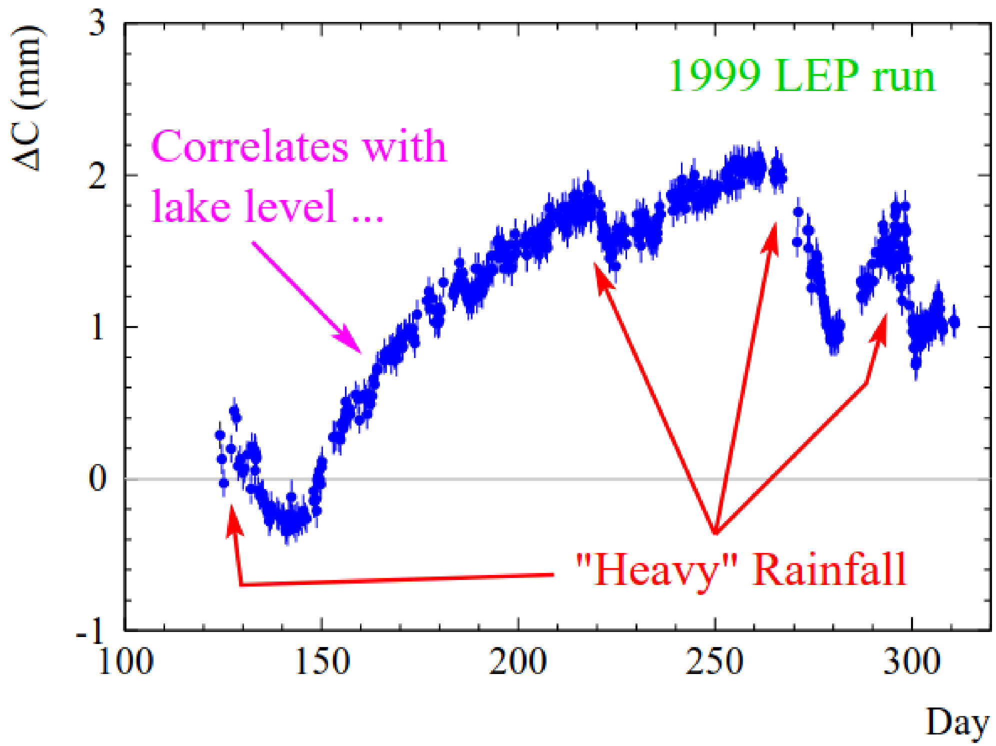
Underground Water

1993 : Unexpected energy “drifts” over a few weeks were traced to cyclic circumference changes of ~ 2 mm/year.

Driving “forces” :

- Underground water
  → Rainfall
- Lake levels ?
- Other ?

Circumference change measured with the beam position monitors.

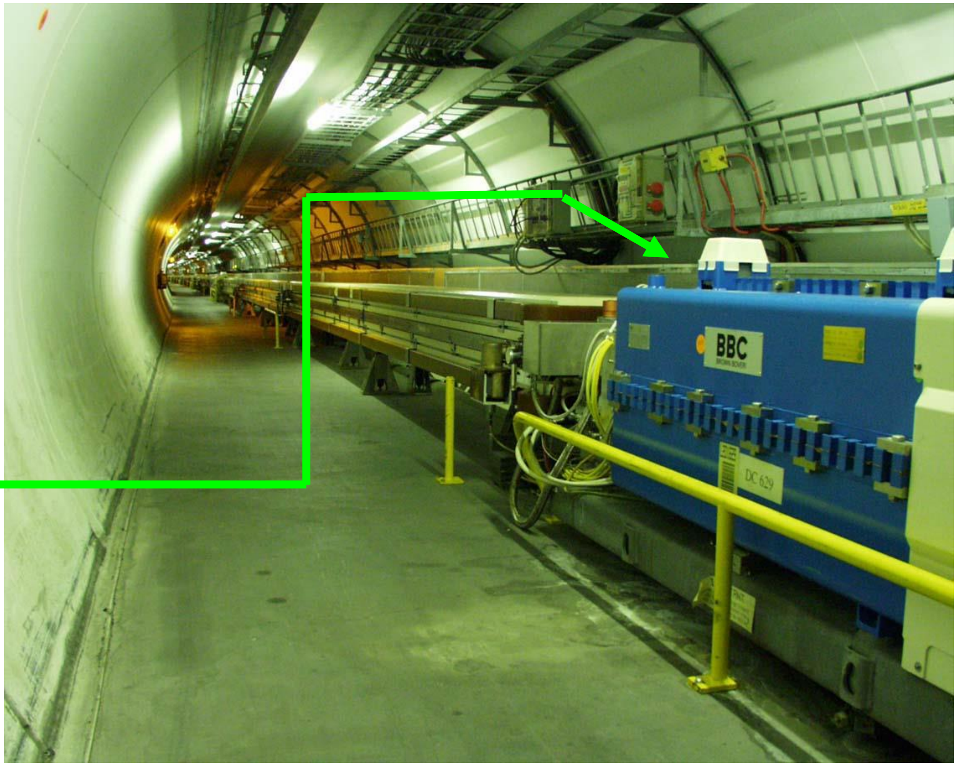


First Energy Model

1993 run : following an extensive energy calibration campaign over many fills, a first model of the beam energy evolution emerged.

The model included:

- Tides,
- Seasonal circumference changes,
- Tunnel temperature induced energy changes ($\Delta E/E \sim 10^{-4}$ / K),
- Stray fields from the bus-bars ($\Delta E/E \sim 3\times10^{-5}$),
- Reference magnet field,
- RF system corrections: from beam to centre-of-mass energy.

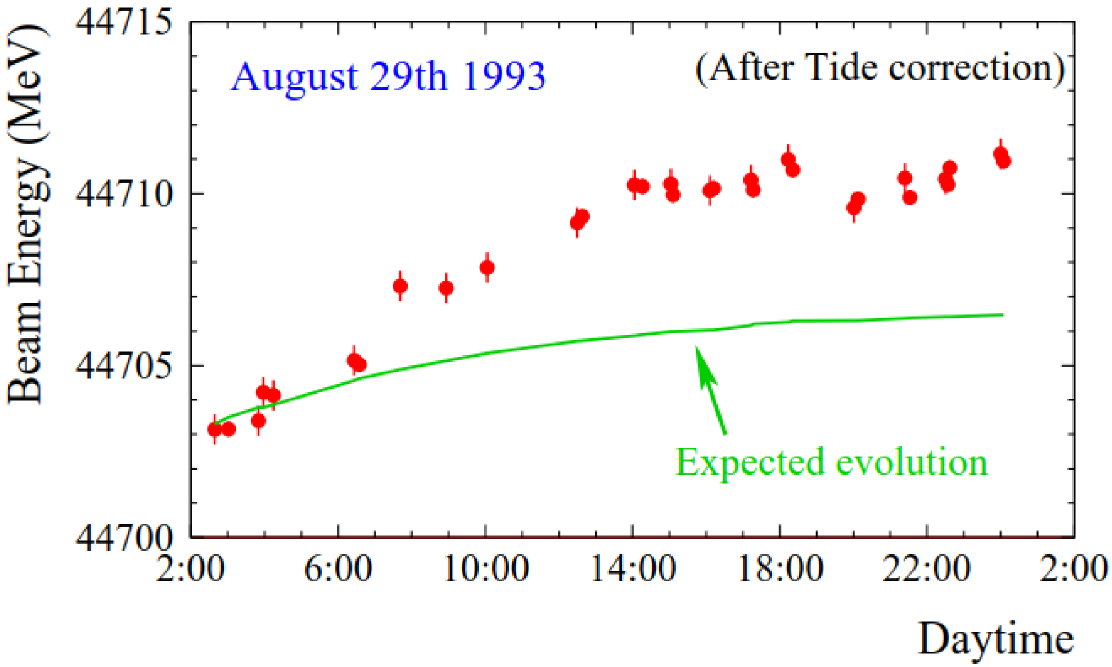


A Crack in the Energy Model

Spring of 1994 : the beam energy model seemed to explain all observed sources of energy fluctuations...

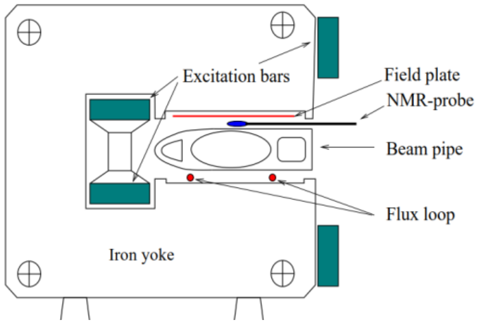
EXCEPT :

An unexplained energy increase of 5 MeV was observed in **ONE** experiment.



It will remain unexplained for two years…

The Field Ghost



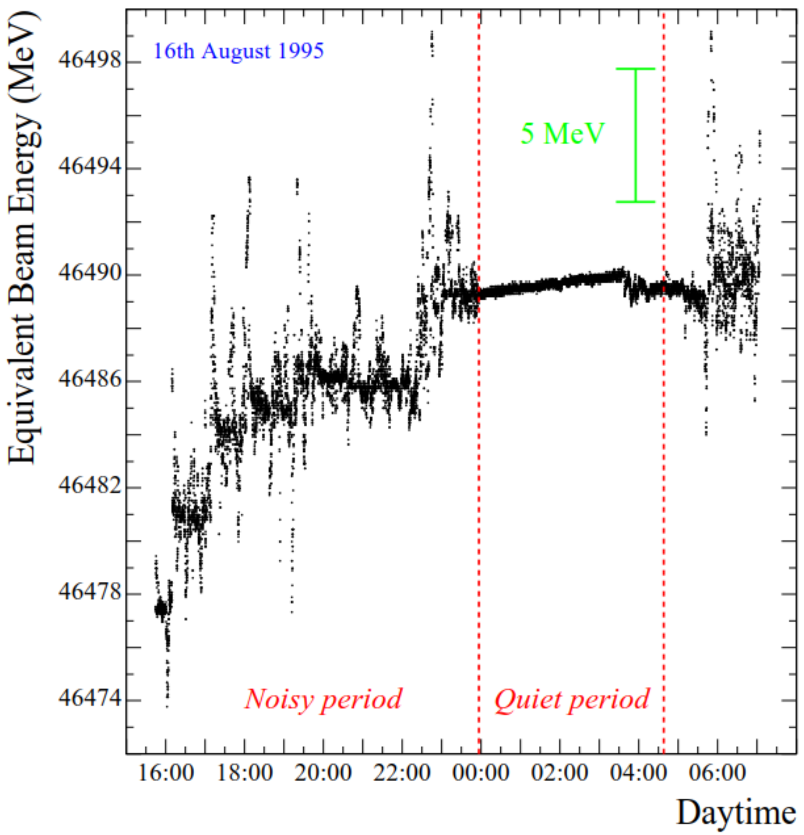
Summer 1995 : NMR probes were installed in some dipoles providing the first in-situ field measurements during operation

The data showed (unexpected) :

- Short term fluctuations,
- Long term increase (hysteresis),
- ➡ Energy increase of ~ 5 MeV over a LEP fill.
- Quiet periods in the night !

Human activity !

But which one ??



Pipe-busters

The explanation was provided by an electrician from the Swiss electricity company EOS: he knew that effect well !

Vagabond currents from trains and subways

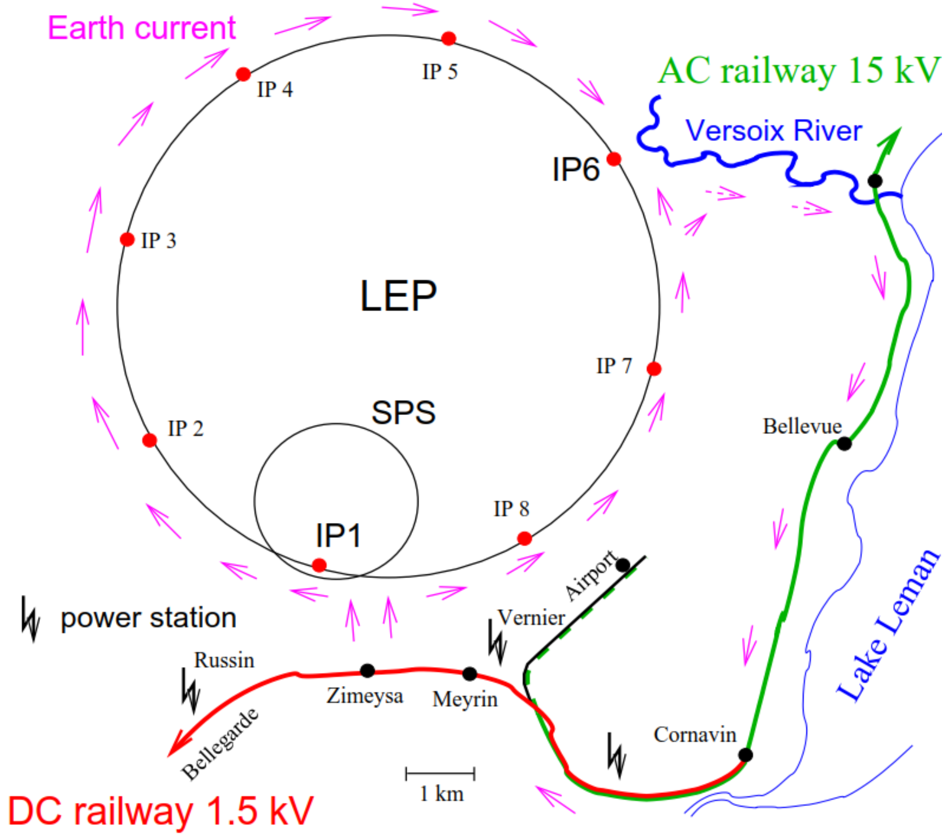
Source of electrical noise and corrosion (first discussed in 1898)

DC railway

Vagabonding Currents

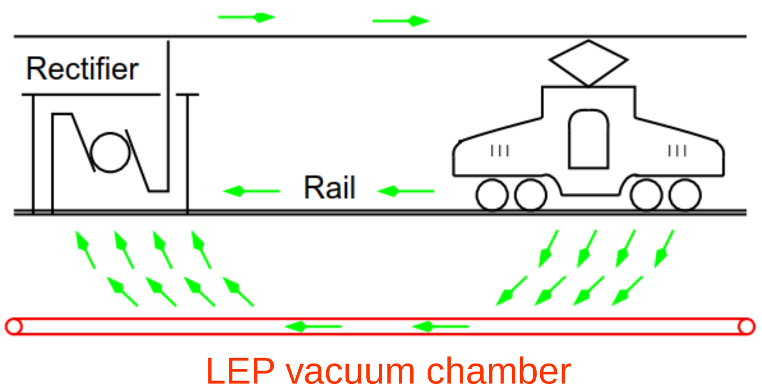
LEP was affected by the French DC railway line Geneva-Bellegarde (it was just recently upgraded to AC operation !)

→ A DC current of 1 A was flowing on the LEP vacuum chamber.



Entrance/exit points :

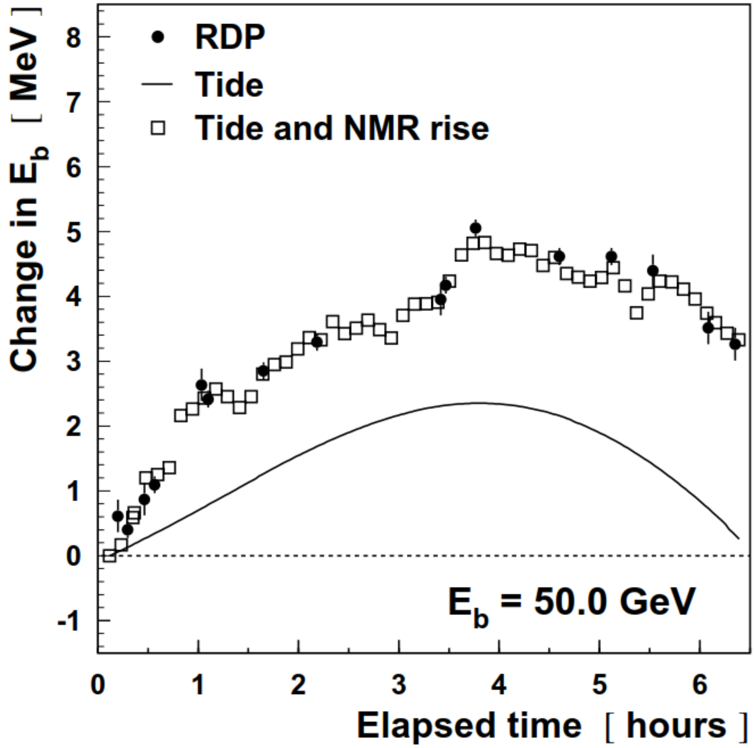
- Injection lines (Point 1)
- Point 6 (Versoix river)



Final Energy Model

1996-2000 : The LEP energy description was completed with a model of the train effects and NMR measurements.

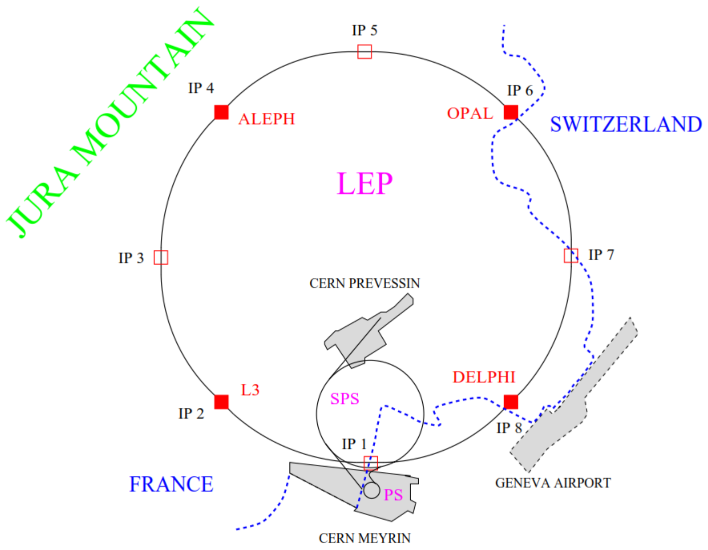
In the second half on the 1990's we were finally able to interpolate the LEP beam energy with sub-MeV precision !

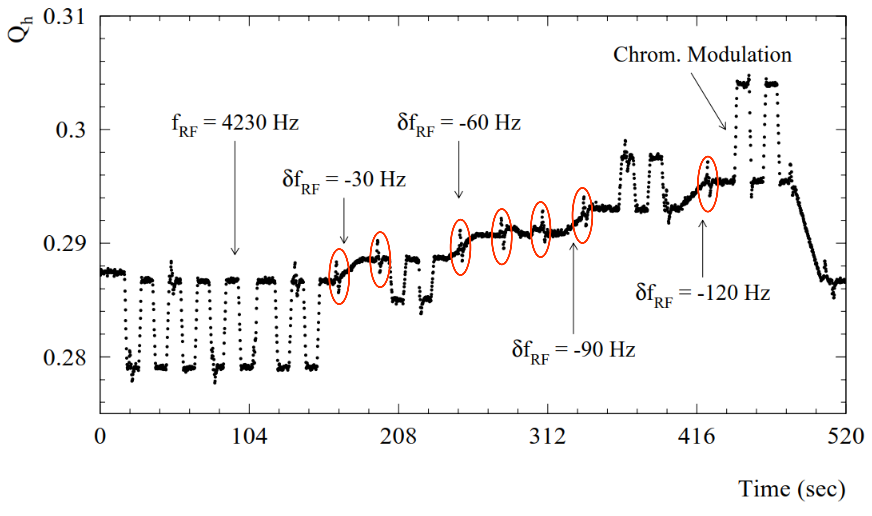


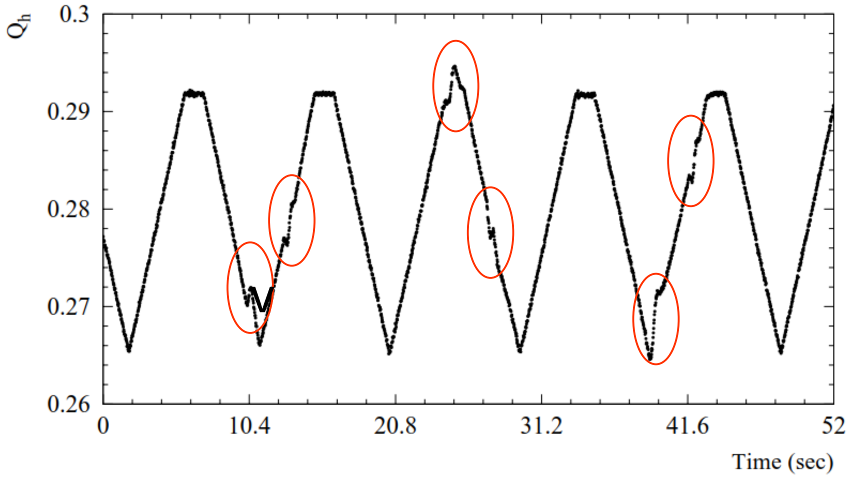
From SPS to LEP

The SPS magnetic cycle (B_{max} ~ 2 T) affected LEP by generating periodic perturbations of the machine tunes during the ramp-down phase from its flat top (at the time once per 14.4 s).

At 45 GeV the induced δQ ~ 0.002 – far from negligible !







Epilogue

- 5 years (1991-1995) were needed to unravel most of the beam energy “mysteries”.

- Many other effects besides tides and trains are included in the LEP energy model. There is not enough time to give details ...

- More than 50 24-hour days of machine time were devoted to energy calibration between 1993 and 2000...

- The mass and width of the Z boson were measured with a remarkable accuracy (see forthcoming talks). The beam energy contributes ~ 1.5 MeV to the total errors.

- The 100 km FCC-ee with 4 times lower fields aims to improve the accuracy on the Z mass by one order of magnitude.