Der lange Weg zu 200 GeV :
Luminosität und höchste Energien bei LEP

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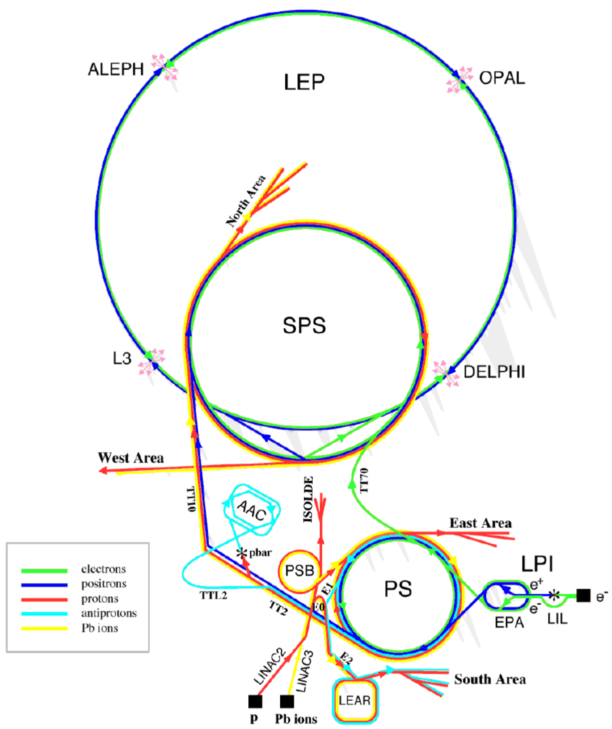
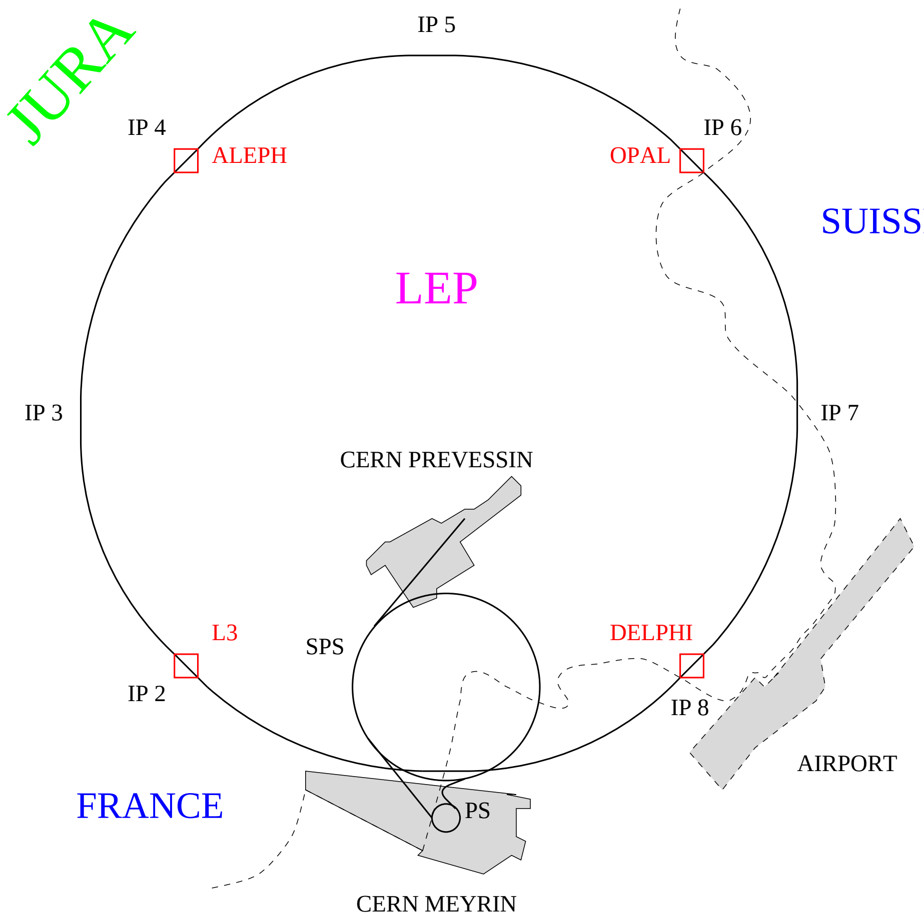
CERN SPS/LEP Operation



- Introduction
- Beam energies of 100 GeV and more...
- Luminosity performance
- Beam energy calibration
- Outlook

The LEP Ring

LEP = Large Electron Positron Collider

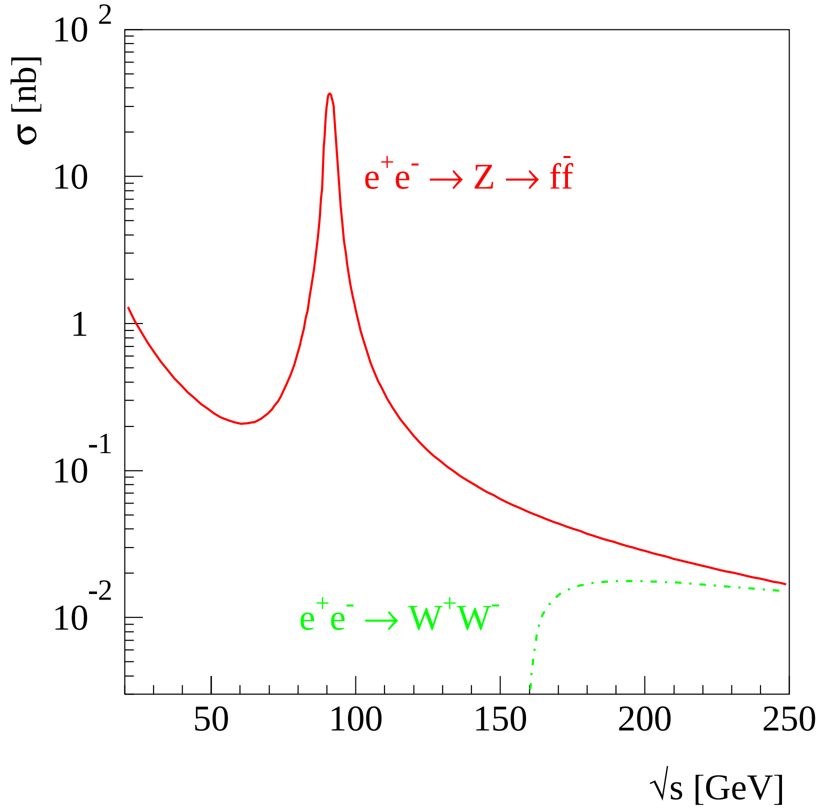


LEP Tunnel :

- Length : 26.7 km
- Depth : 50 to 175 m below the surface
- 8 arcs and 8 straight sections
- 4 experiments : L3, ALEPH, OPAL and DELPHI
- Revolution frequency $f_{rev} = 11.2$ kHz

LEP Energy Range

LEP was designed to cover a beam energy range of 20 to ≈ 100 GeV for Z and W bosons studies.



- 1989-1995 : Z resonance study (LEP 1/ LEP 100)
  - $M_Z = 91.19$ GeV/c^2 ⇒ E ≃ 45 GeV
  - Large statistics : ≈ $16 \cdot 10^6$ decays observed !
- 1996-2000 : W pair production (LEP 2/ LEP 200)
  - $M_W = 80.5$ GeV/c^2 ⇒ 80 GeV > E ≤ 100 (?) GeV
  - Small statistics : ≈ $4 \cdot 10^5$ decays expected !

Energy Loss

A unique feature of LEP are the large effects of
Synchrotron Radiation

The energy lost per turn ΔE_{loss} depends on the beam energy E and the bending radius R (= 4.2 km) :

$$\Delta E_{loss} \sim E^4/R$$

E (GeV)	ΔE_{loss} (MeV/turn)	$\Delta E_{loss}/E$ (%)	Power per 1 mA (MW)
22	7	0.03	0.007
45	120	0.27	0.120
90	1919	2.13	1.919
100	2925	2.95	2.925

Note : 1 mA $\Rightarrow 5.5 \cdot 10^{11}$ particles

Obviously ΔE_{loss} must be compensated by the Radio-Frequency (RF) system with an accelerating voltage U_a :

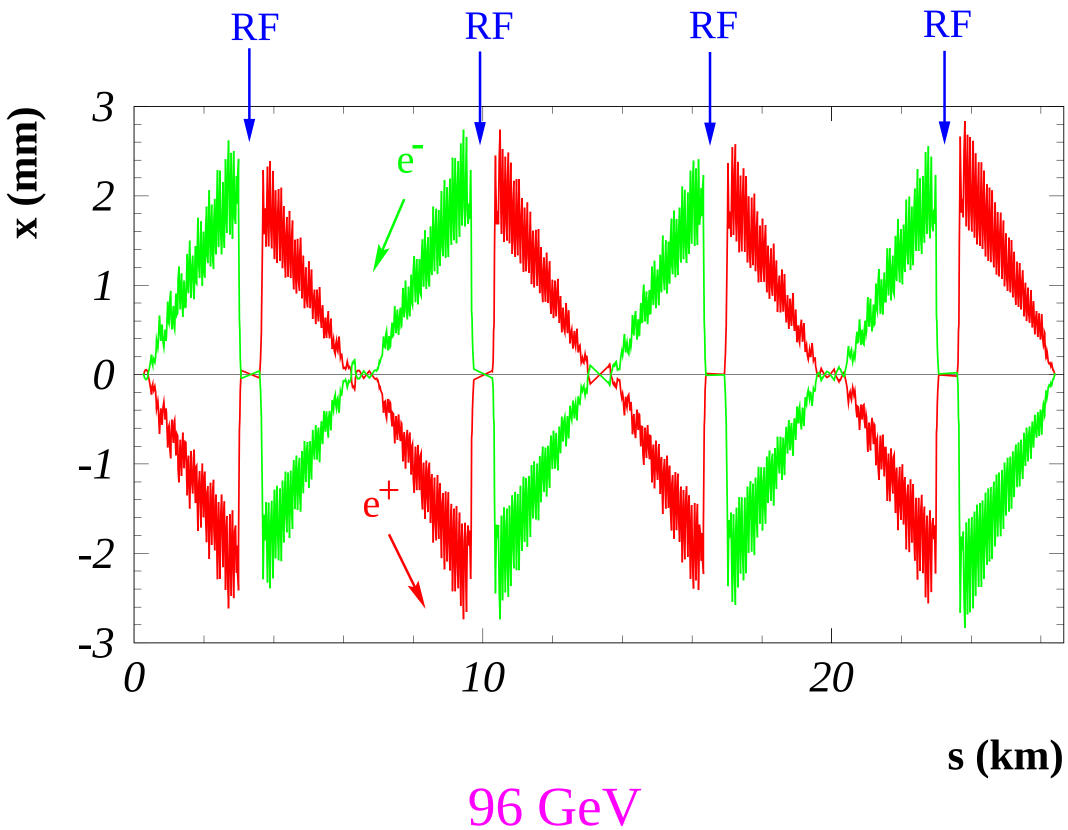
$$eU_a > \Delta E_{loss}$$

The very large ratio $\Delta E_{loss}/E$ has important consequences for the two beams in the pipe :

- Different orbits ("orbit sawtooth")
- Different local energies ("energy sawtooth")
- Different beam optics ($\rightarrow$ beam sizes,...)
- Very strong damping of oscillations

Energy and Orbit Sawtooth

The electron and position horizontal orbits with respect to the magnet axis look like "sawtooths" along the ring :



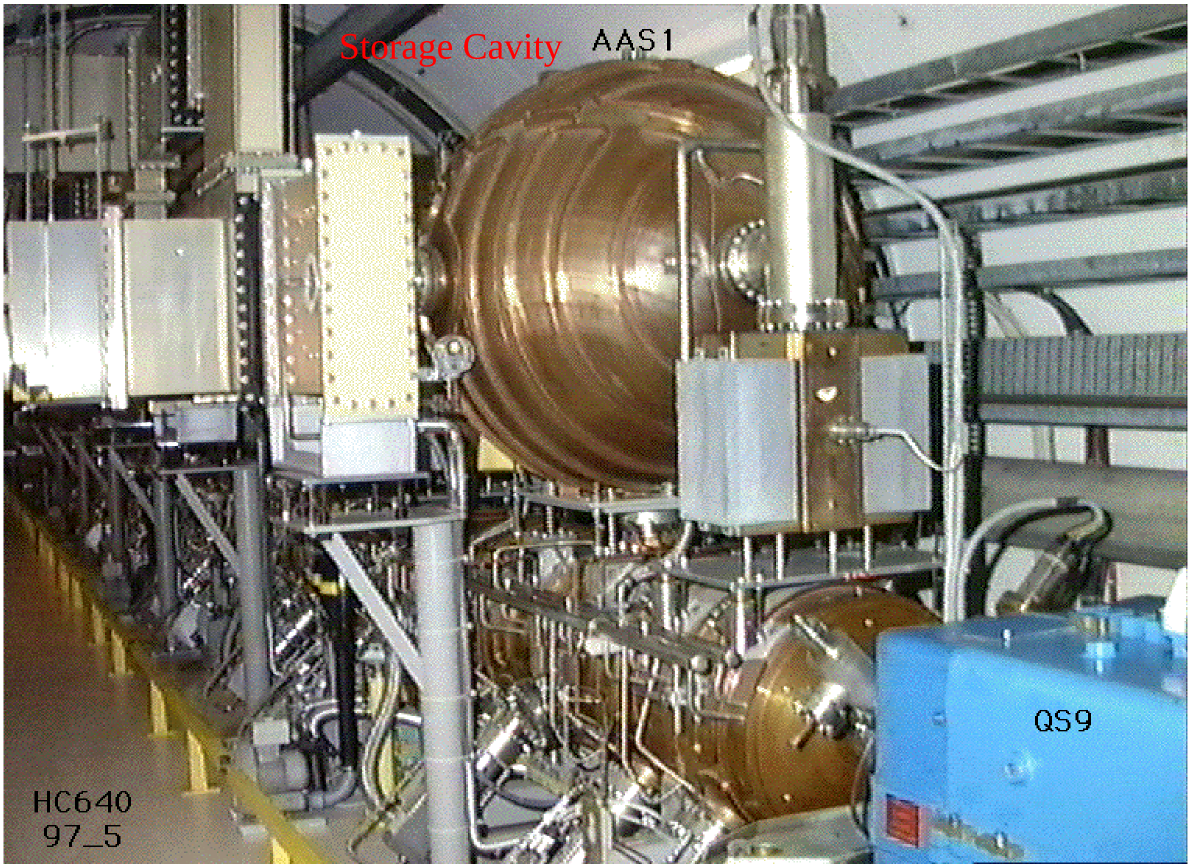
The sawtooth is due to :

- Continuous energy loss in the arc sections
- Localised energy gains in the RF system

When :

- x > 0 ⇒ local energy > average energy
- x < 0 ⇒ local energy < average energy

The LEP1 RF System



The Copper RF cavities for LEP1 :

- Maximum field gradients $E_a = 1.4$ MV/m
- Total length of the cavities = 252 m
- Maximum RF voltage $U_a = 350$ MV
- Only ≈ 10% of the energy is transfered to the beam ... the rest is heating the walls ...
- The energy oscillates between the RF cavity (high losses) and the storage cavity (low losses) ⇒ 50% reduction of the losses.
- Presently 50% of the cavities have been removed to make room for superconducting ones.

The LEP2 Superconducting RF System

For beam energies of 80-100 GeV it is excluded to use Cu cavities :

- There is not enough free space.
- The power requirement would be to high.

Therefore the choice of a superconducting RF system for LEP2 was natural and necessary :

- For Niobium gradients can reach 50 MV/m before super-conductivity breaks down (B field at super-conductor surface).
- In practice gradients are limited to lower values :
  LEP E_a = 6-7 MV/m
  TESLA $E_a \simeq$ 20-30 MV/m

The LEP technology is based on SC films. A 1.5 μm superconducting Niobium film is deposited on a Copper substrate :

- The thermal conductivity of Cu is a factor 5 to 10 higher than that of Nb :
  $\Rightarrow$ better heat evacuation
  $\Rightarrow$ less sensitivity to quenches
- The material cheaper
- Production is very delicate (thin surface)

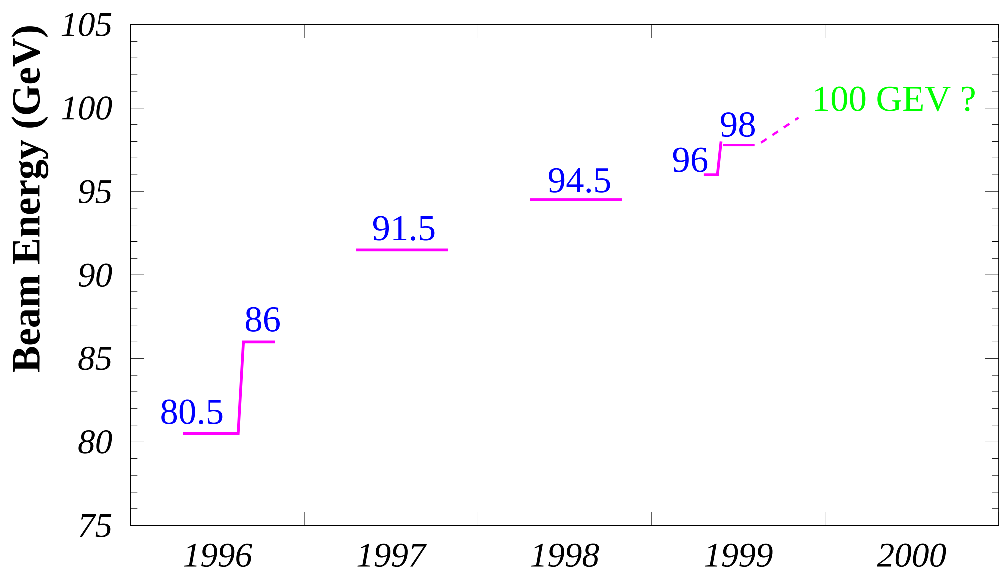
Superconducting RF Cavities

A LEP SC cavity module

- Design gradient is $E_a = 6$ MV/m.
- With beam the highest average E_a over 8 cavities is 6.5 MV/m.
- All cavities have been conditioned to 7.0 MV/m.
- Up to 100% of the energy can transfered to the beam.
  The overall efficiency reaches $\sim 75\%$.
- In 1999 the SC cavities will provide $U_a \geq 2.8$ GV.
- The total SC area is 1600 m^2 !

Energy Upgrade

The LEP beam energy has followed the progressive installation of new RF cavities and the improved reliability of the RF system :



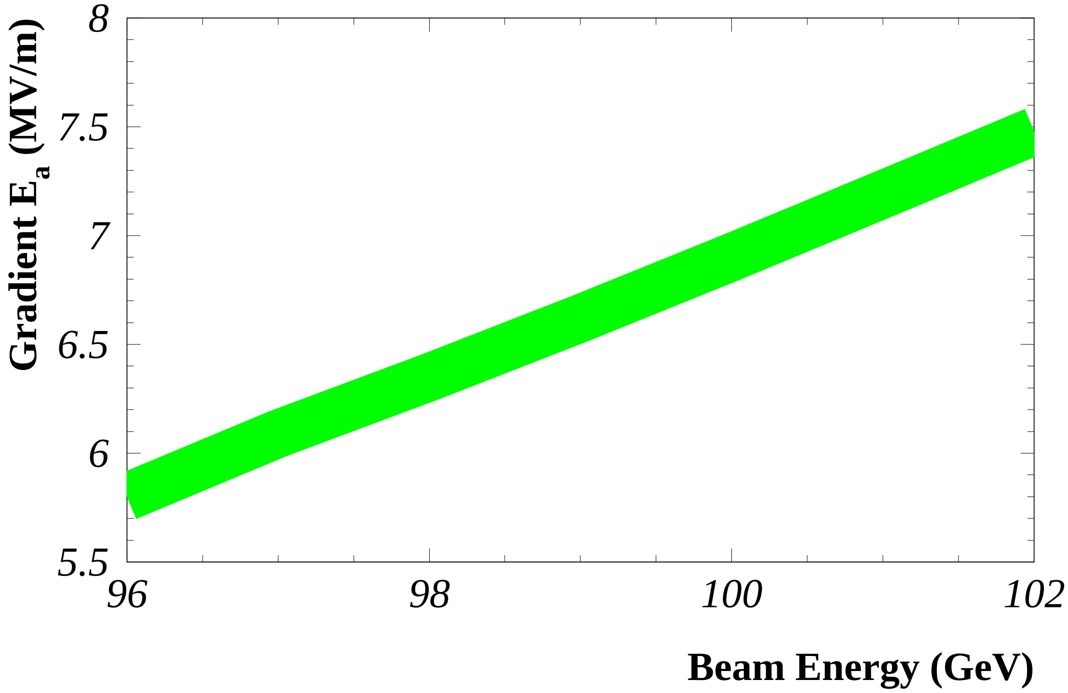
Up to about 96 GeV the energy gain is obtained by adding new SC cavities. In 1999 LEP will have a nominal U_a of 3.03 GV :

Type	Number	E_a (MV/m)	U_a (MV)
Cu	48	1.2	120
Nb	16	5.0	136
Nb-Cu	272	6.0	2774
Total			3030

Typically $\sim$ 95% of the voltage is available.

To reach energies beyond 96 GeV the gradient must be increased above the design value of 6 MV/m !

Higher gradients



Various factors limit the gradients of the SC RF system :

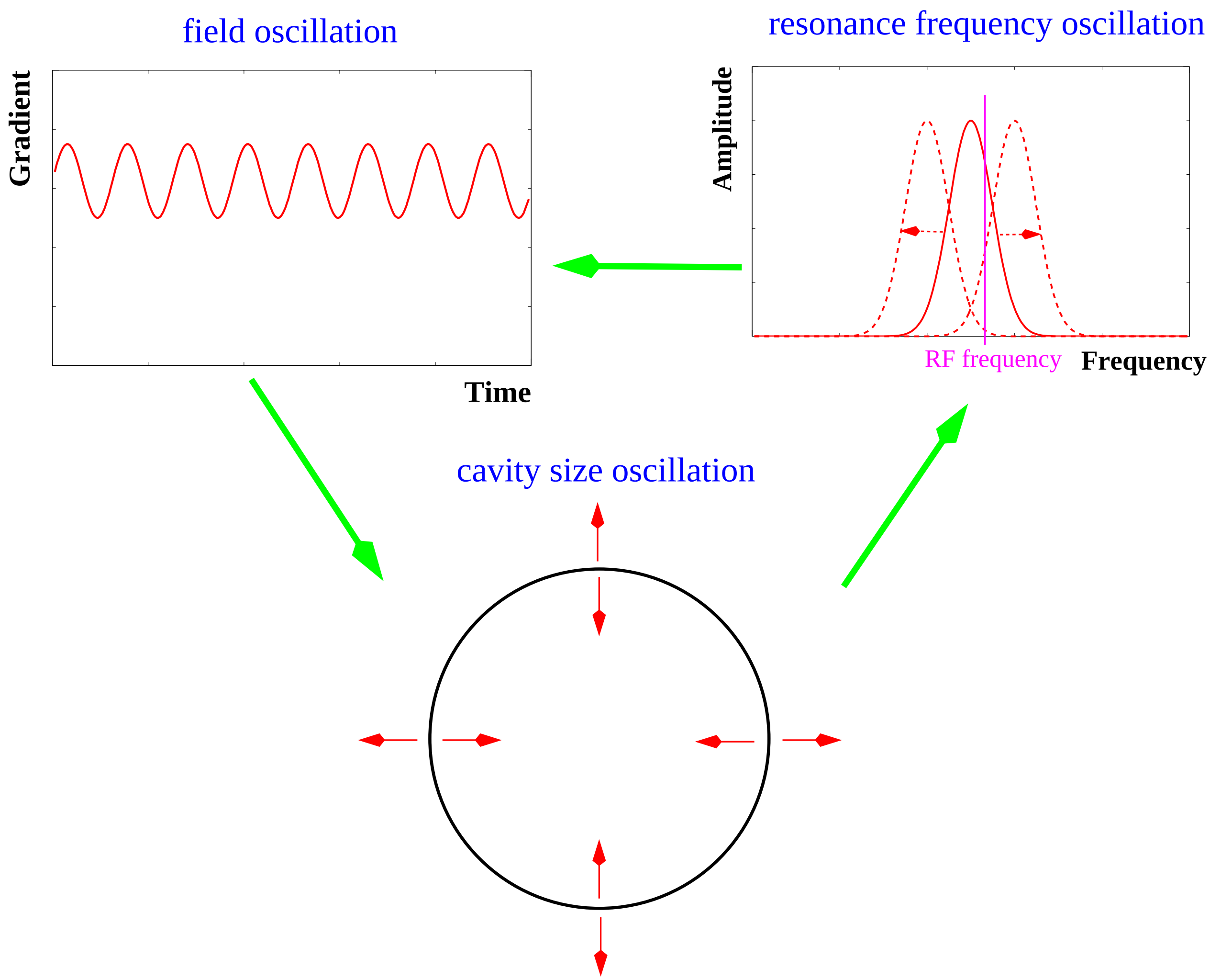
- Gradient differences in nearby cavities due to the distribution of RF power through the waveguides.
- Between 6 and 7 MV/m strong field emission sets in and becomes the main energy dissipation (and destruction) factor in the cavities :
  - Radiation (many kRad/hour !)
  - Cryogenic cooling power $\Rightarrow$ limits E_a to $\sim$ 7.6 MV/m
- Field oscillations $\Rightarrow$ beam instabilities

After a large effort to equalise fields in nearby cavities, each individual cavity was run above 7.0 MV/m without beam.

Ponderomotive Field Oscillations

Cavity field instability “loop” : a surprise for the RF experts !

- field amplitude oscillations
- mechanical oscillations driven by an external source or by the field itself (“ponderomotive” oscillation)
- cavity resonance frequency oscillations



The strength of the instability is $\sim E_a^2$ which makes operation with larger gradient even more difficult.

$\longrightarrow$ Delicate cavity tuning at high currents and gradients

Luminosity Performance

A collider performance is judged by its luminosity $\mathcal{L}$:

$$\mathcal{L} = \frac{\mathrm{k I_b^2}}{4\pi \mathrm{e^2 f_{rev}} \sigma_x \sigma_y} = \frac{\mathrm{k N_b^2 f_{rev}}}{4\pi \sigma_x \sigma_y}$$

k = number of bunches/beam = 4

N_b = number of particles/bunch

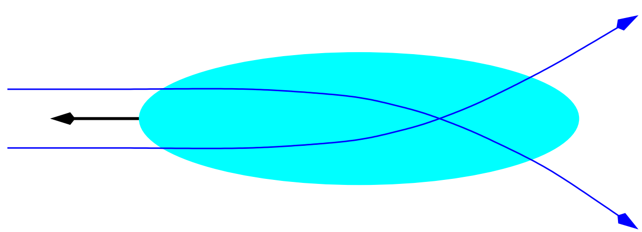
I_b = bunch current = e N_b f_{rev} $\Rightarrow$ 1 mA $\equiv 5.5 \cdot 10^{11}$ particles

$\sigma_{x(y)}$ = horizontal/vertical beam size (collision point)

From this formula it seems at first sight that $\mathcal{L}$ could grow without limits for adequate intensities and sizes...

Unfortunately when the mutual interaction of the two beams at the collision point (beam-beam effect) is too strong, the beams blow up and become "unstable" (tails, backgrounds) and $\mathcal{L}$ is limited. For a given beam optics the strength of the lens at the collision point depends on :

$$\xi \sim \frac{1}{\mathrm{E}} \frac{\mathrm{N_b}}{\sigma_x \sigma_y}$$



For constant σ_x and σ_y :

- for a fixed $\xi \Rightarrow N_b \sim E \Rightarrow \mathcal{L}$ increases with E
  The beams become "stiffer" as the energy increases !
- ξ can reach larger values at higher energies because of the stronger damping.

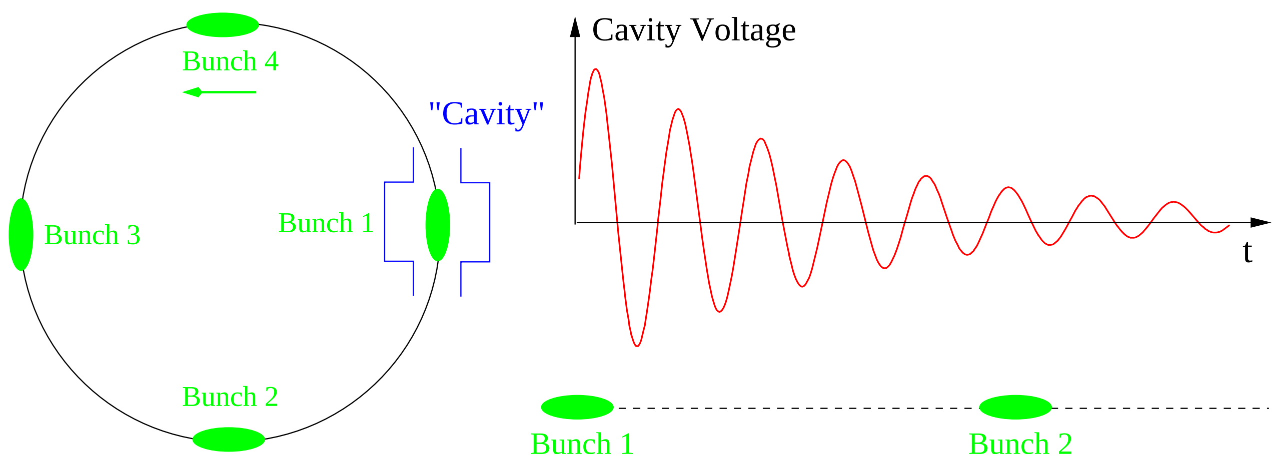
The LEP luminosity is expected to increase significantly with energy !

Current Limits

LEP has now two fundamental current limits :

- RF power limit at 100 GeV :
  11 mA of total current for a 34 MW klystron power.
- Instability limit at 22 GeV (injection) of 1 mA/bunch.

The current at injection is limited by the feedback of the beam induced fields in the vacuum chamber surrounding :



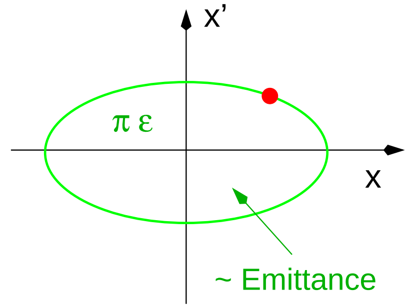
- Discontinuities act like low Q (quality factor) "cavities". Induced fields act back on the beam and can cause instabilities.
- The vacuum chamber should be as smooth as possible !
- The LEP Cu cavities are the dominant cause of current limitations. The removal of 50% of the cavities for LEP2 has helped to rise the instability threshold current.

Beam Sizes

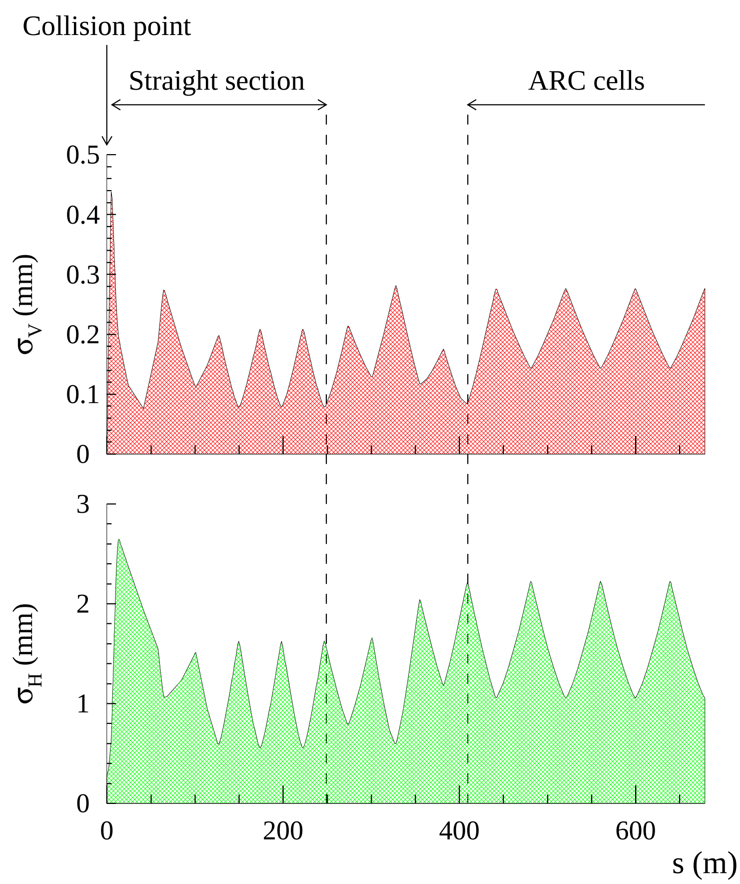
The beam size σ at any position in the ring depends on :

- The beam emittance ε
- The local focussing β

$$\sigma^2 = \beta\varepsilon$$



The beam sizes are modulated by the local focussing

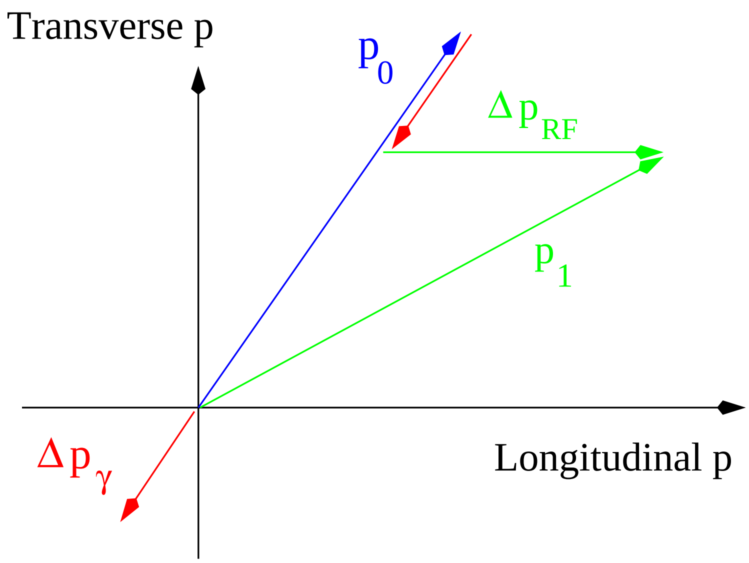


At the collision point we collide pancakes ! :

- Vertical plane : $\sigma_{\rm y} = 3$ to $5\ \mu$m
- Horizontal plane : $\sigma_{\rm x} = 150$ to $200\ \mu$m

Synchrotron Radiation Damping

In LEP the e^+ and e^- beams are subject to strong damping due to the energy loss from synchrotron radiation and to the continuous longitudinal acceleration :



- The beams have “no memory”. They forget the “past” in a few damping times (10 ms at 100 GeV). This property makes beam handling in general simpler than in the case of protons.
- ε is only conserved in a statistical sense as the mean value over many particles.

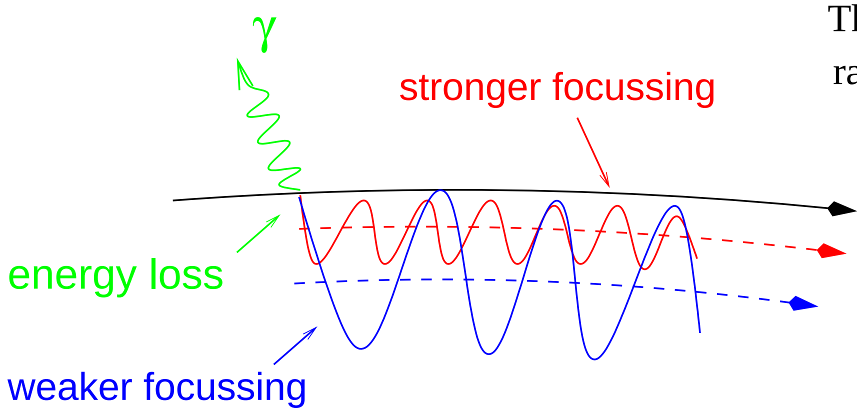
In plane e^+e^- machines the vertical beam emittance (size) :

- vanishes for a perfectly aligned machine.
- depends strongly on the beam steering in a real machine.
  $\Rightarrow$ quadrupoles are aligned vertically to 150 μm in LEP.

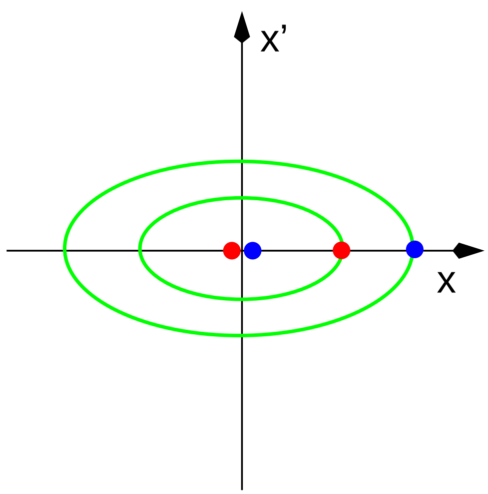
Horizontal Beam Size

The horizontal emittance ε_x :

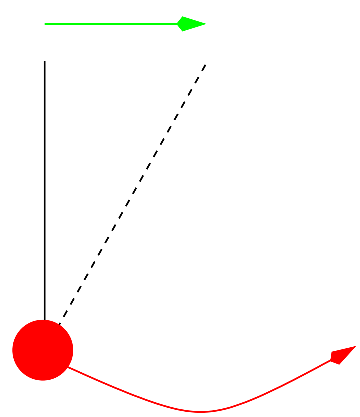
- is in equilibrium between excitation from synchrotron radiation and damping to due RF acceleration : after photon emission the particle moves towards a smaller radius until it gains back its energy.



The orbit and the bending radius depend on energy !



Mechanical Analogy :

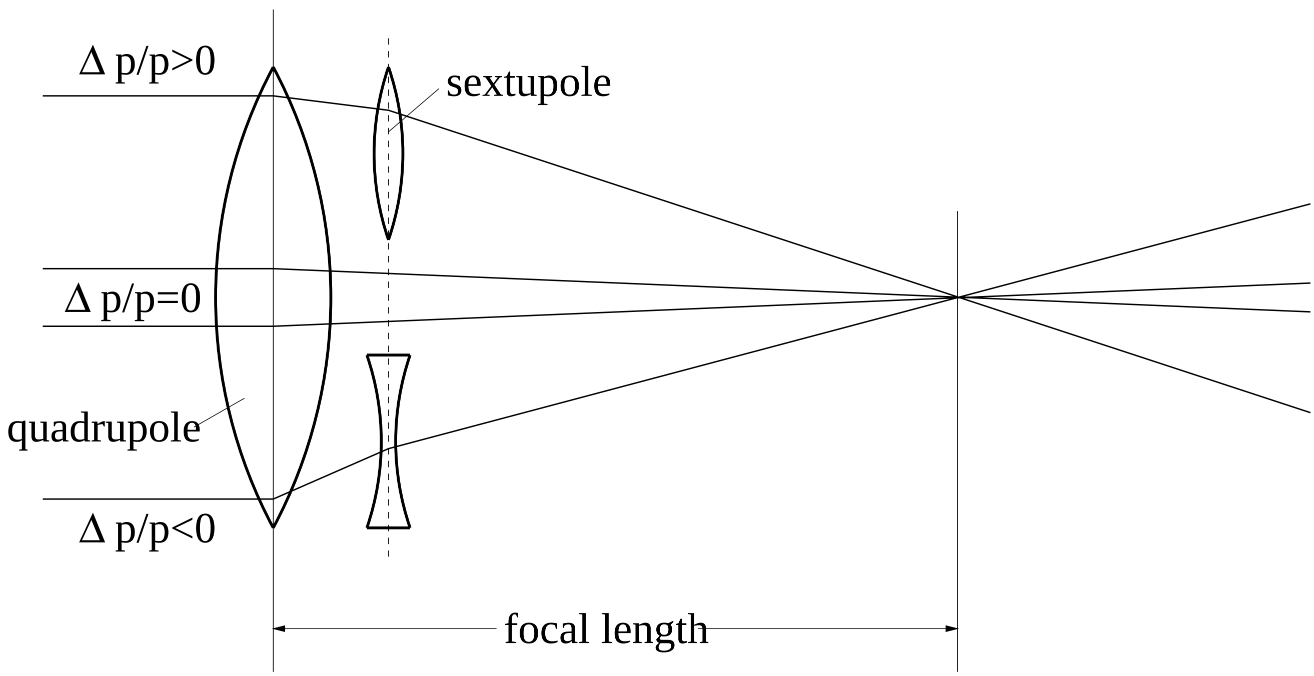


- depends on the focussing (quadrupole) strength.
- depends on the number of emitted photons : $\varepsilon_x \sim \mathrm{E}^2 \Rightarrow \sigma_\mathrm{x} \sim \mathrm{E}$

Limits of the Focussing

The focussing cannot be increased at will. For LEP one limit is drawn by the correction for "chromatic" effects :

- The focussing of the quadrupoles depends on the particle energy.
- Sextupole magnets must be used to compensate the chromatic aberrations of the quadrupoles and equalise the average focussing for a sufficiently large range of beam energies.
- When the strength of the sextupoles is too large, non-linear effects limit the aperture available for the beam. Large amplitude particles become unstable...



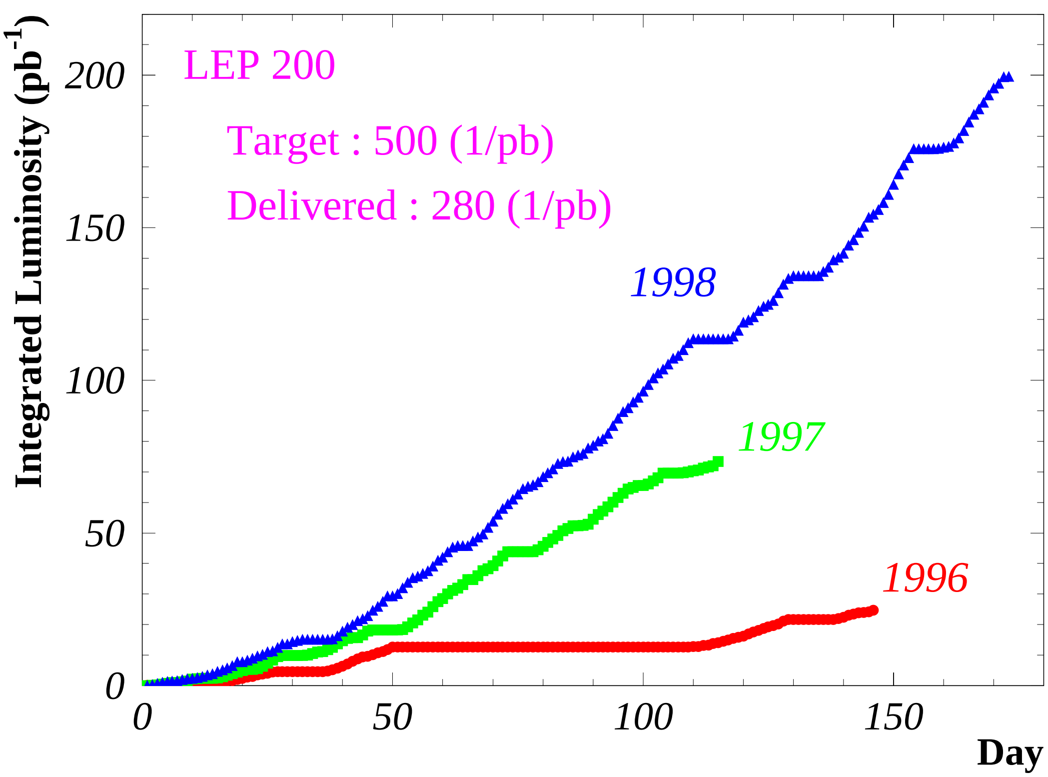
Luminosity

The luminosity of LEP has been boosted at LEP 200 :

- Higher currents at injection (removal of Cu cavities) and in collision.
- Tighter focussing at the collision points.

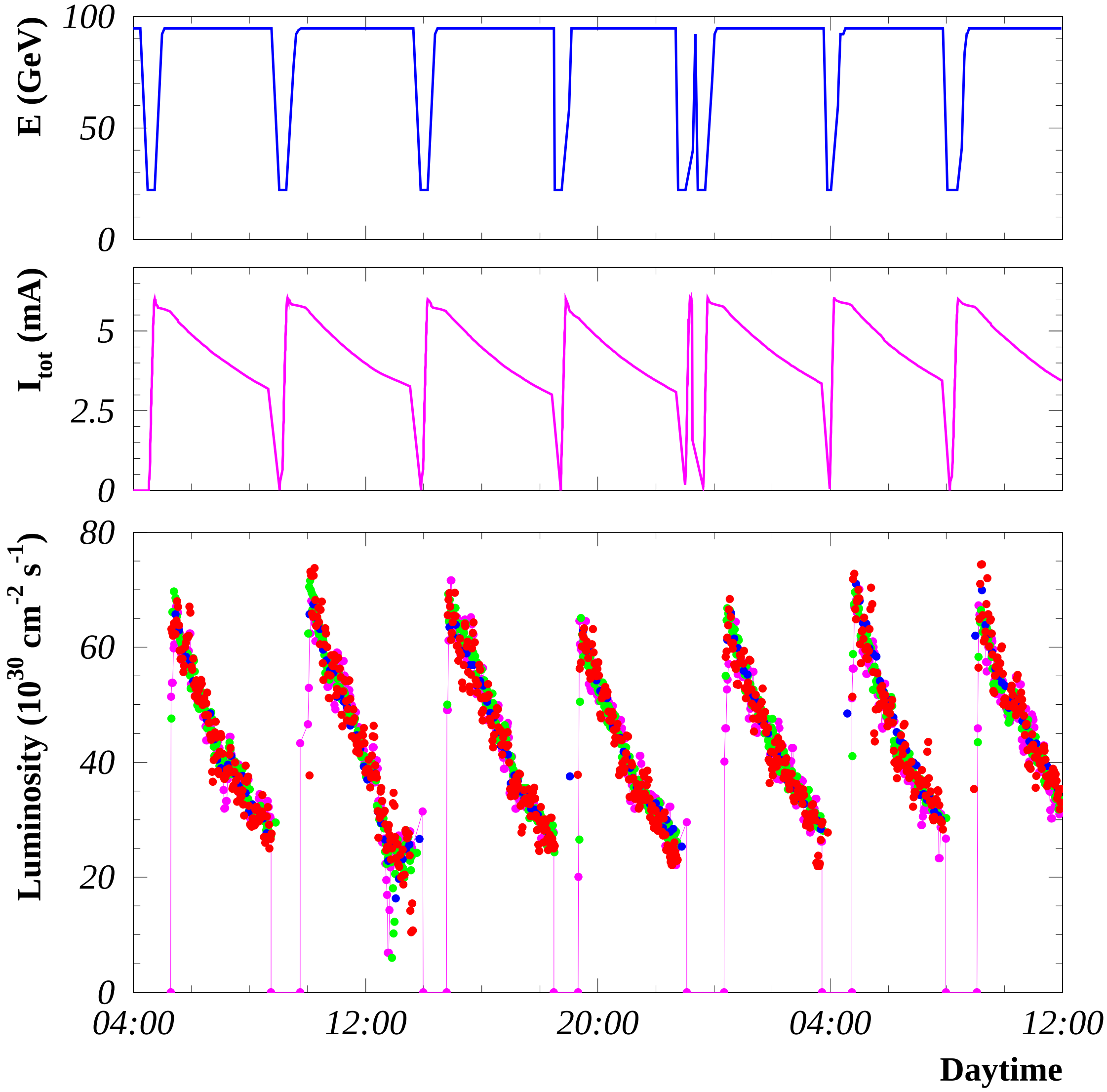
Year	$\mathcal{L}$ ($10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	k × $\mathrm{I_b}$ (μA)
LEP 1	2.4	8 × 320
1996	3.4	4 × 520
1997	5.0	4 × 650
1998	9.5	4 × 740

For 1999 we hope to reach currents above 900 μA per bunch and luminosities above $12.0 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.



A very Good LEP Day

The average efficiency of LEP is 40-50%.

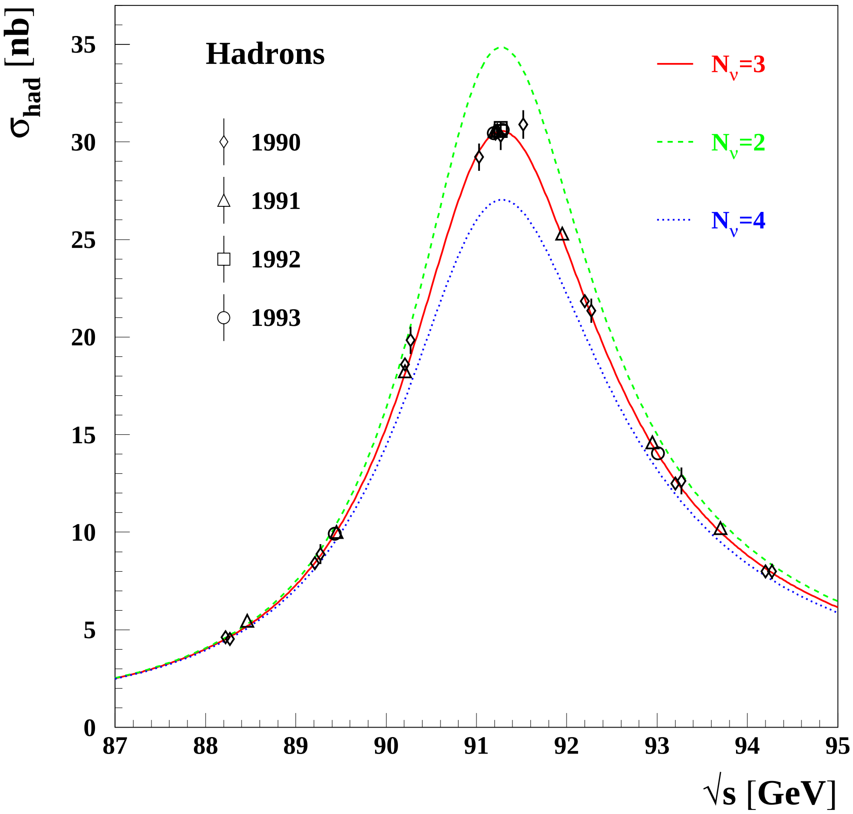


$\Rightarrow$ maximum efficiency of $\sim$ 80% !

The typical time between two physics fills is 75 minutes to cycle the magnets, inject the beams, ramp them to top energy and collide them.

Energy Calibration

The LEP experiments have measured the shape of the Z resonance :



To get the best Z mass and width measurements high accuracies are required on the cross sections and on the beam energies.

But high accuracy beam energy measurements cannot be made when the beams collide. Its is therefore necessary to be able to track the energies in time !

A 6 year effort was necessary to unveil all subtle sources of beam energy variations and to reach the ultimate accuracies :

$$M_Z = 91.1867 \pm 0.0021 \text{ GeV} \qquad \Gamma_Z = 2.4939 \pm 0.0024 \text{ GeV}$$

Transverse Polarisation

In a plane storage ring the circulating e^+e^- polarise spontaneously along the direction of the bending field :

- In the process of synchrotron photon emission there is a large asymmetry in spin (magnetic moment) flip probabilities :

$$P(\uparrow\rightarrow\downarrow) >> P(\downarrow\rightarrow\uparrow)$$

  $\Rightarrow$ the magnetic moments align along the bending field which is "breaking the symmetry".

- The maximum transverse polarisation is 92.4%.

At LEP polarisation is a very slow and therefore delicate process :

- The spin flip probability $= P(\uparrow\rightarrow\downarrow) + P(\downarrow\rightarrow\uparrow) \approx 10^{-11}$
- Rise time of transverse polarization $P_\perp$:

$$\tau_p[\text{hours}] = 6.3\,\frac{P_\perp[\%]}{92.4}\,\left(\frac{44}{E[\text{GeV}]}\right)^5$$

  $\Rightarrow$ time scale of minutes to hours !

- The highest observed polarisation level was 55%.
- The lowest useful polarisation level is $\approx$ 5%.

At LEP polarization and high luminosity are incompatible !

But polarization has a useful feature :

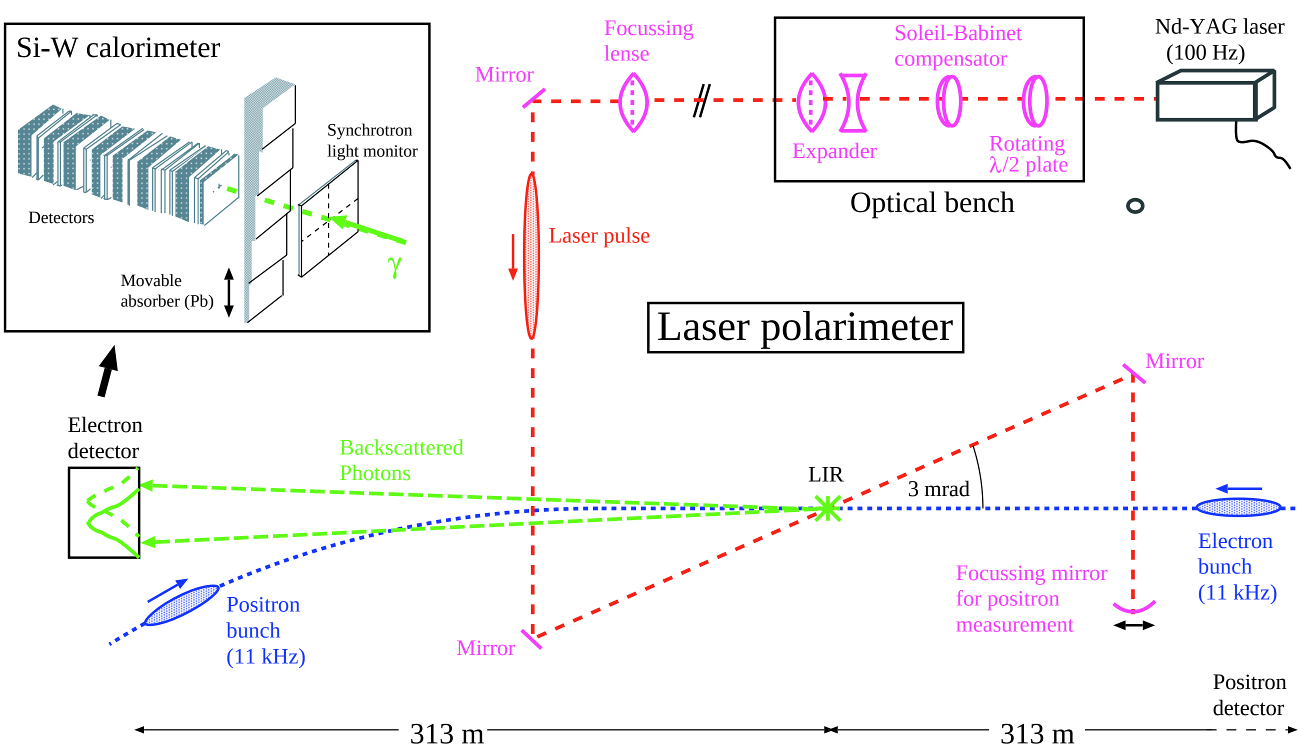
the spins (magnetic moments) precess in the vertical bending field and the precession frequency depends on the beam energy !

Polarisation Measurement at LEP

$P_\perp$ measurement principle :

- Collide a laser pulse ($\lambda = 532$ nm) with the beam.
- Flip the circular laser polarisation every other pulse.
- Measure the vertical profile of scattered Compton γs in a Si-strip/Tungsten calorimeter.
- $P_\perp$ is observed as a vertical shift Δy of the γ profiles between the 2 polarization states :

$$\Delta y \simeq 5\ [\mu m/\%]\ P_\perp$$



Resonant Depolarization

The spin precession frequency f_s is related to the beam energy E :

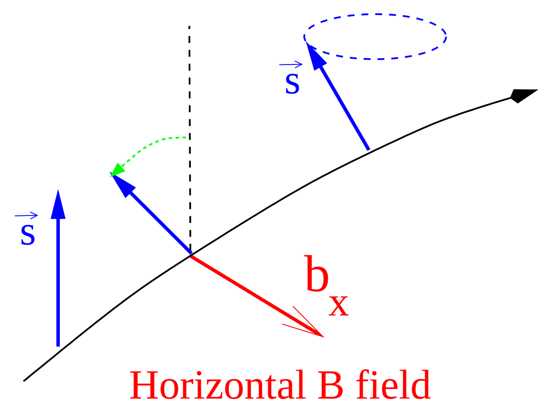
$$f_s/f_{revolution} = \nu = E\frac{(g_e-2)/2}{m_e c^2} = \frac{E}{440.6486(1)\ [\mathrm{MeV}]}$$

m_e and $g_e - 2$ are the e^- mass and anomalous magnetic moment.
$f_s \simeq 1.1$ MHz for E = 44 GeV.

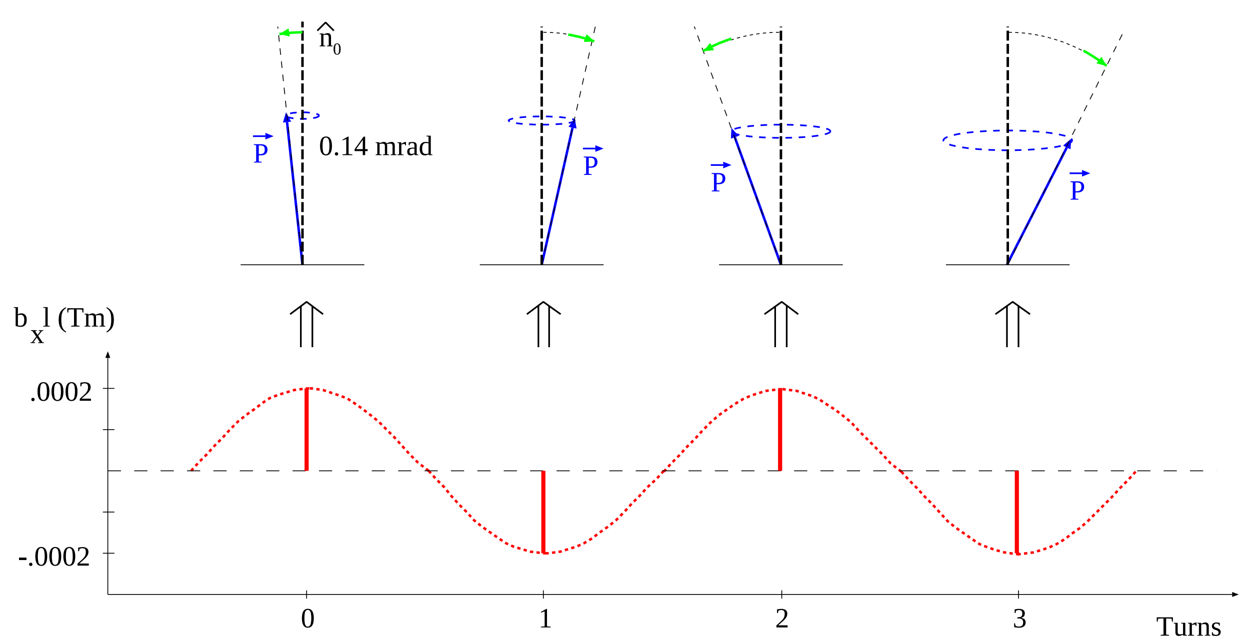
A horizontal magnetic field b_x, modulated at a frequency f_B, is applied to the beam.
Resonant depolarization occurs when

$$f_s = f_B \Rightarrow \text{determines E !!}$$

Accuracy $\delta E/E = 10^{-5}$



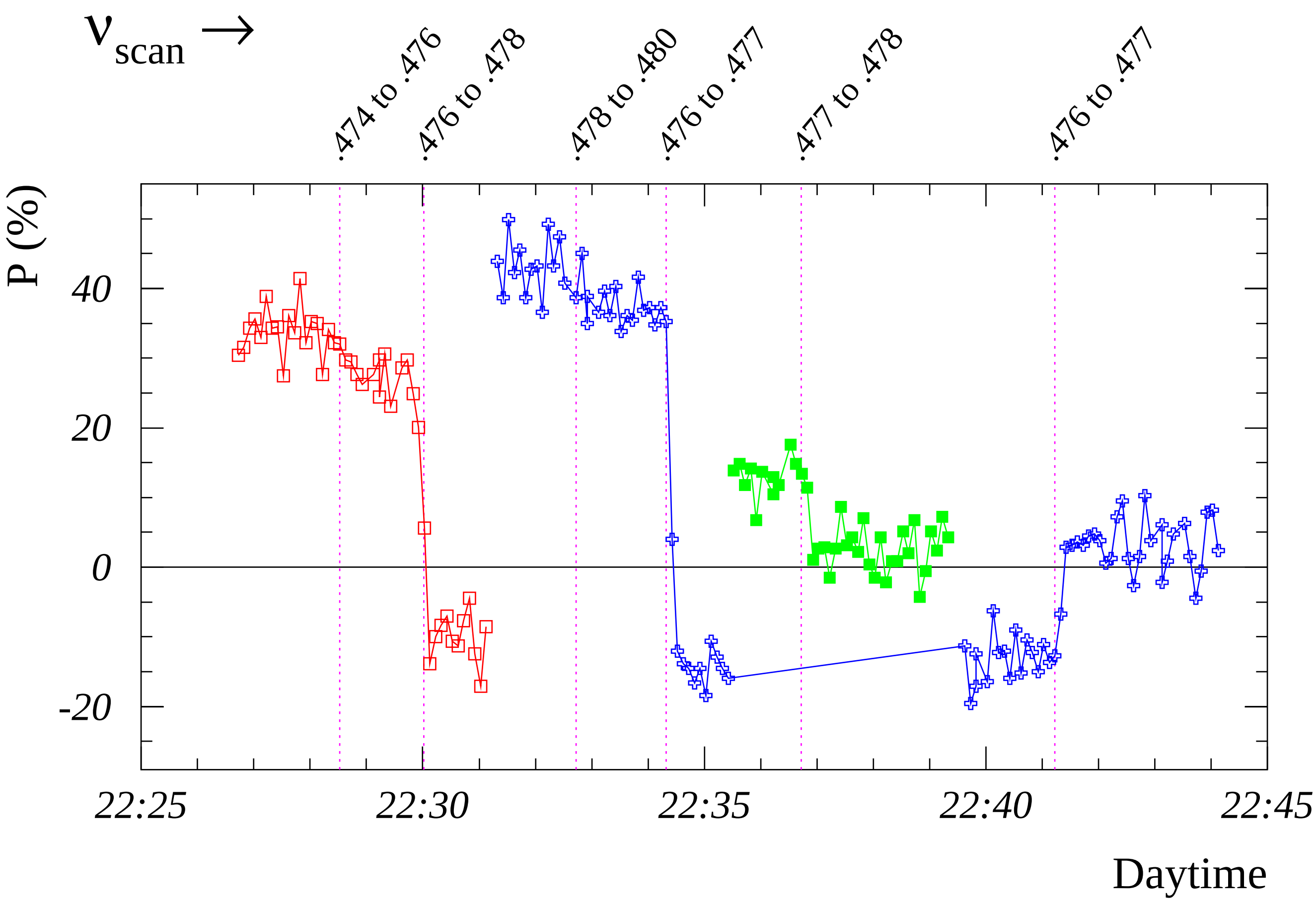
Resonant spin/polarization vector rotation for $\nu = n + 1/2$ ($n \in I$) :



Resonant Depolarization

Example of resonant depolarization on the beam.

- Vertical lines correspond to depolarization attemps.
- The frequency is swept over a range of 11 to 22 Hz.



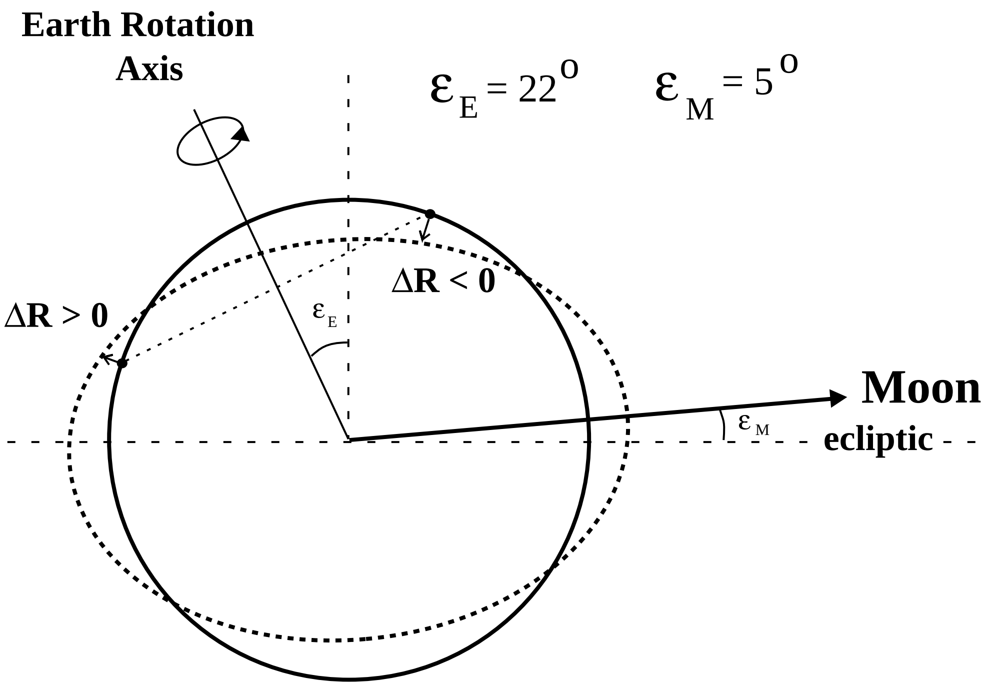
Lunatic LEP

What links LEP to ... the Moon (and the Sun) ?

It is a story that started in 1991 when small but unexplained variations of the beam energy where first observed ...

Earth Tides

Tides affect the Oceans *and* the Earth crust !



The local radius change ΔR due to a body of mass M at a distance d and at an angle θ with respect to the zenith :

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

Sun tides are 50% weaker than Moon tides. At the Equator full (new) Moon tides give $\Delta \mathrm{R} \simeq \pm$ 50 cm.

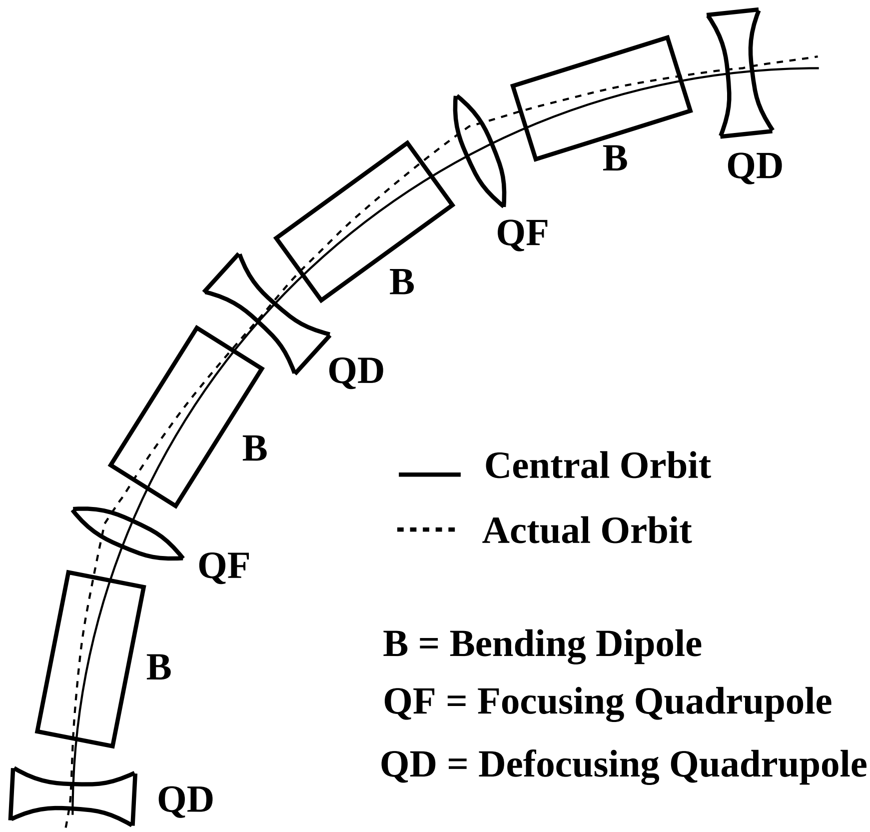
Around Geneva :

- Vertical motion of about 25 cm peak-to-peak.
- LEP Circumference change of $\simeq \pm$ 0.5 mm ("balloon effect")

Circumference Changes and Beam Energy

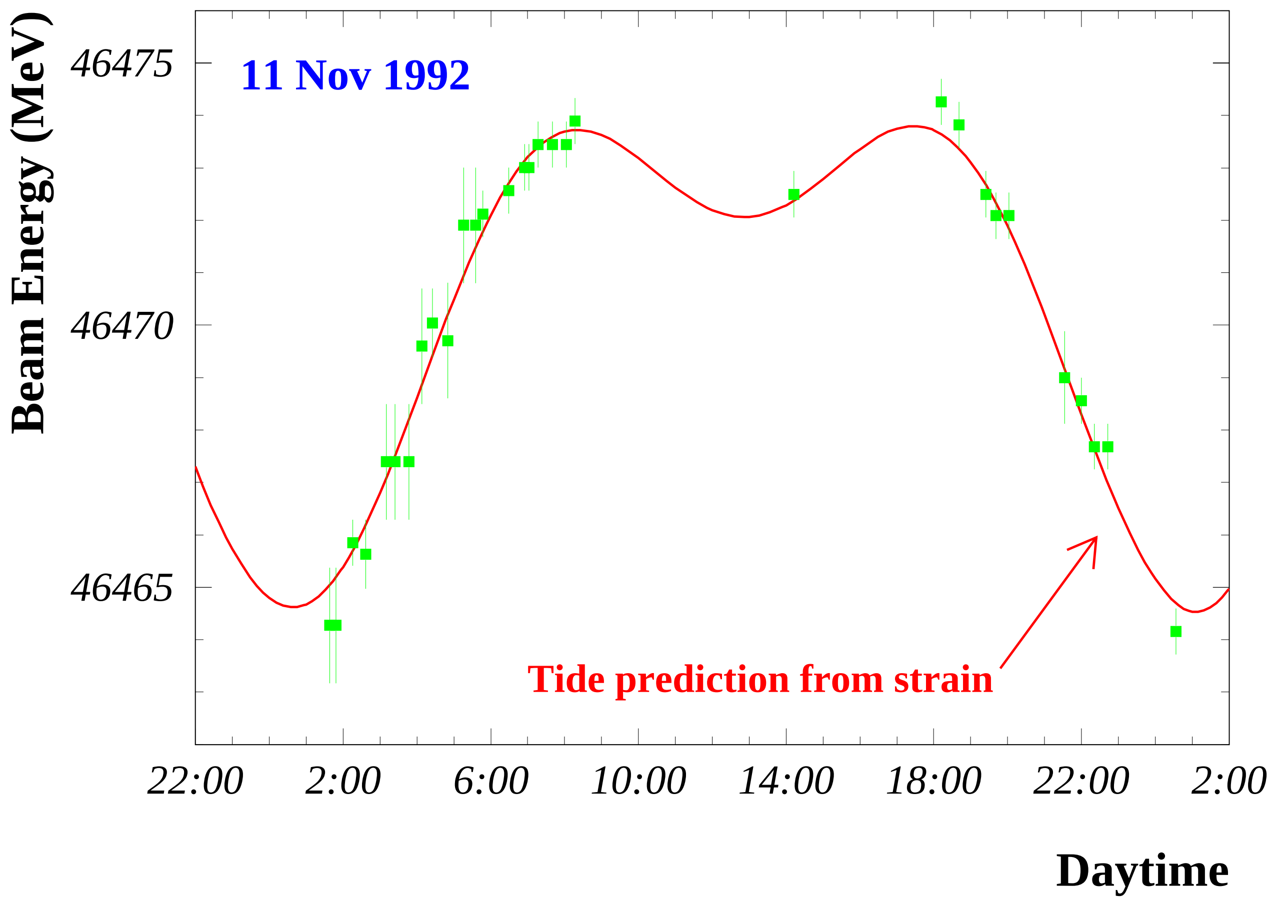
The LEP beam energy is affected because :

- The length of the actual beam orbit is fixed by the frequency of the RF system : the beam stays in phase !
- The beam has to move off-centre through the magnets when the circumference changes.
- The quadrupoles bend the beam back towards the central orbit : this additional bending changes the energy.



Earth Tides

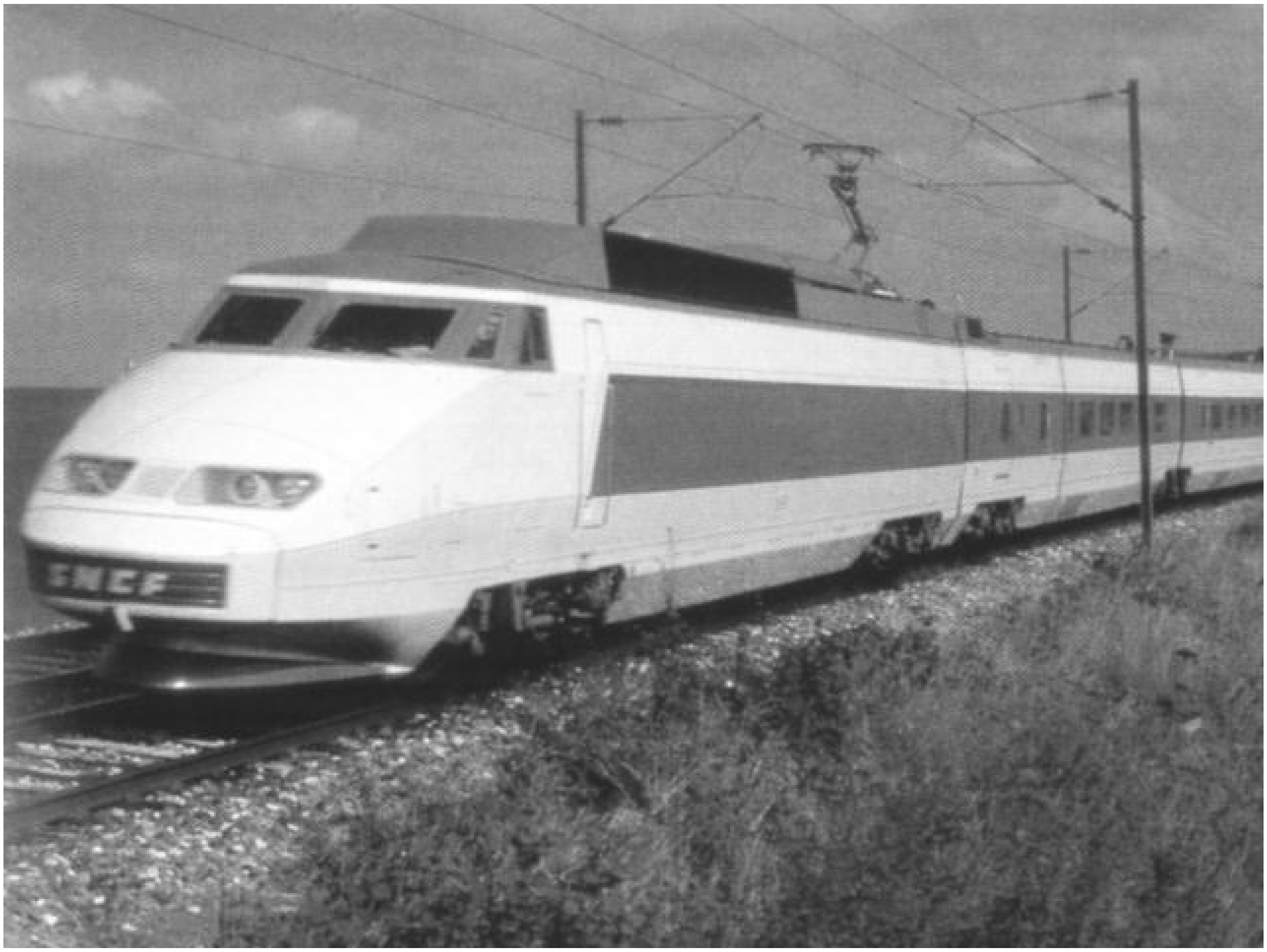
An example for the beam energy evolution at full moon compared to a geological model ...



Note that sea tides have very different amplitudes and periods because of resonant amplification !

Vagabonding Currents

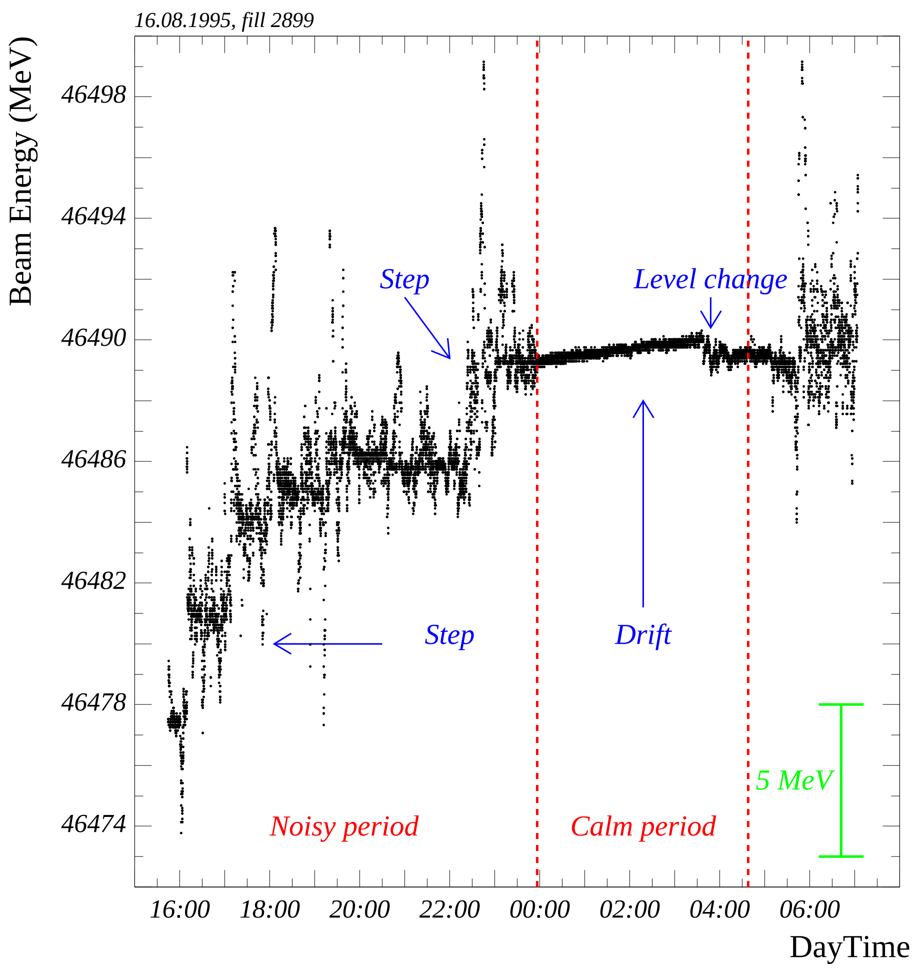
And why do we care about high-speed trains like the TGV ?



This story goes back to the early times of the European Railways !

Jumping Fields

For LEP it all started with some precise B-field measurements in 2 tunnel dipoles in 1995.



We expected some changes, but not what you see here :

- Large short term fluctuations !
- Correlation with human activity ??
- The fluctuations affect the beam energy but are too small to influence the luminosity performance of LEP.

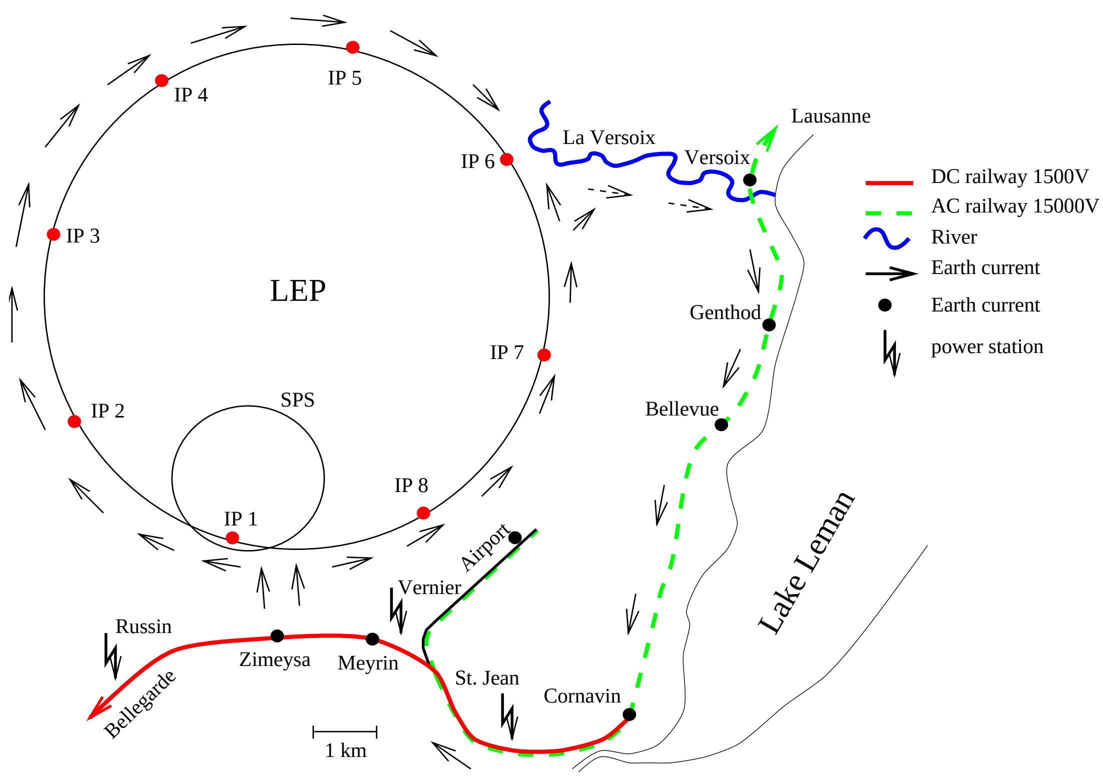
Vagabonding Currents

What happens ?

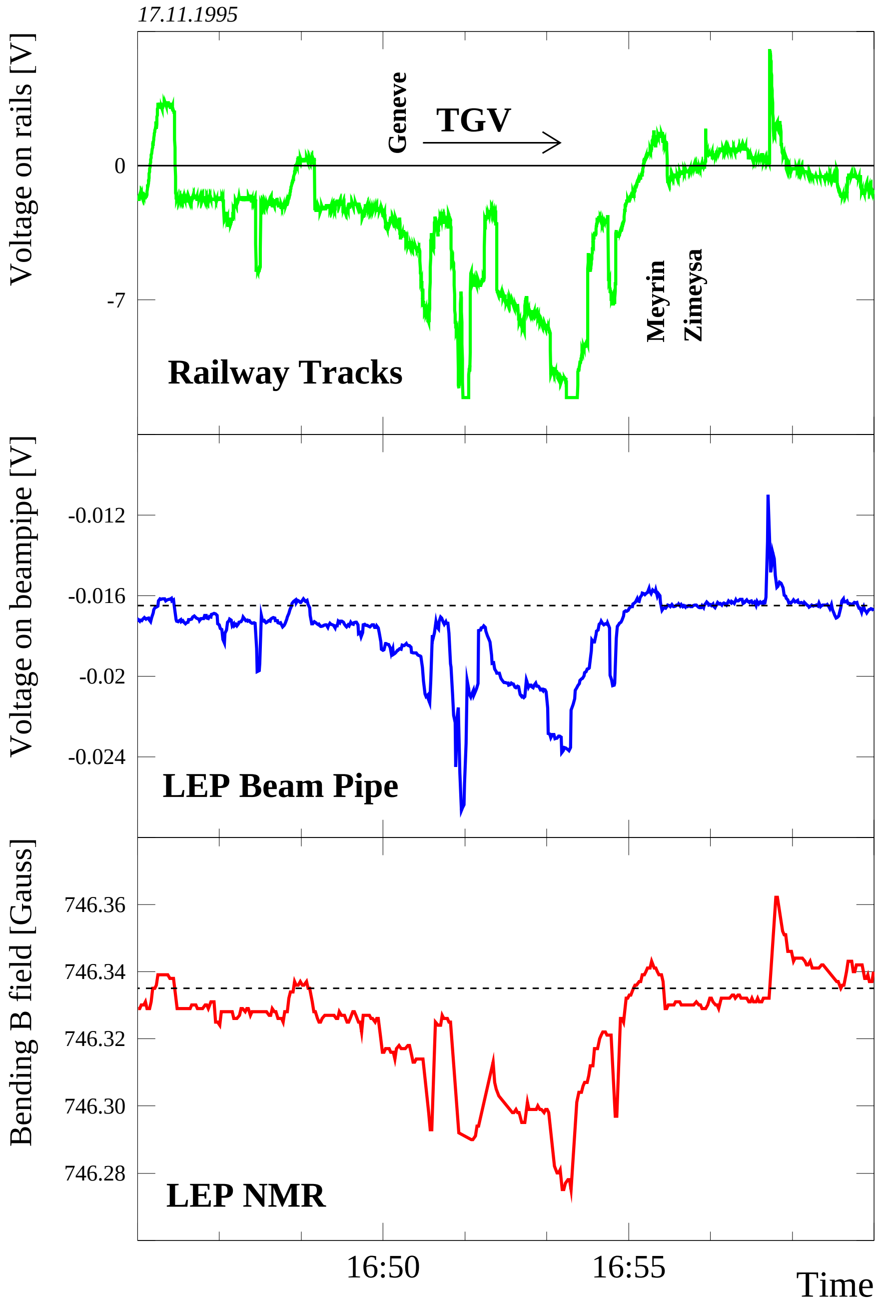
- After passing through the train engine, the current should flow back to the power station over the railway tracks.
- About 20% of the current is KNOWN to use “other roads”.

$\Rightarrow$ *VAGABOND* currents

- In FRANCE some railway lines use DC currents (history !).
- DC railways use lower voltages $\Rightarrow$ higher currents.
- Vagabond currents from French railways flow on the LEP vacuum chamber !



A Vagabonding Currents Experiment



The understanding of the bending field rise due to trains was a major breakthrough for the energy calibration !

Outlook

LEP is now reaching its final phase :

- The 1999 LEP run will be used to test the RF system at high gradient, push towards 100 GeV but maintain high luminosities.
- The 2000 LEP run will focus on top energies even if things will break...

In terms of accelerator physics the work on the LEP beam energy is standing out as one of the most interesting (and funny !) puzzles that had to be solved ! And it was a great success ! Work is going on for LEP2...

LEP will be shut down in 2000, but some of the equipment will be reused... A few ideas are on the market to take advantage of the SC RF system :

- A 2 GeV Free Electron Laser
- A 25 GeV recirculating electron accelerator (ELFE)
- An electron-proton option for LHC