Polarized Electron Beams and Energy Calibration

Beam Dynamics & Technologies
for Future Colliders

21 February -
6 March, **2018**
Crowne Plaza Hotel
Zurich, Switzerland

J. Wenninger
CERN Beams Department
Operation Group

Introduction

Radiative polarization in storage rings

Beam energy measurement techniques

Beam energy at – LEP/FCC-ee

From beam to center-of-mass

Polarized beams - definition

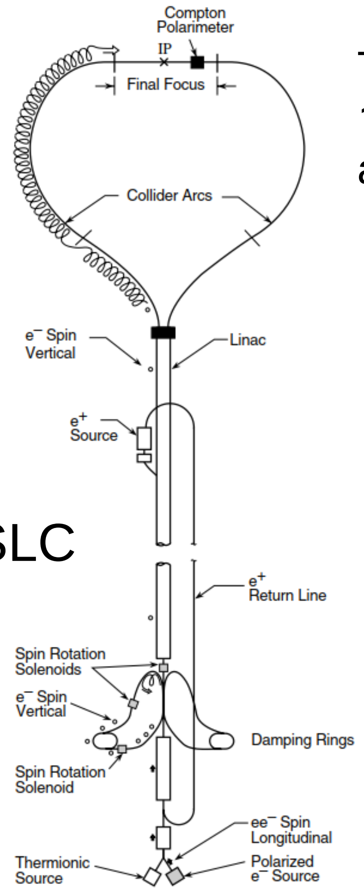
- Beam polarisation can be used as probe for physical processes, for example the electro-weak interaction, but it is more rarely used at colliders compared to other goodies like highest beam energies or luminosity.
- A beam is considered to be polarized if there is an asymmetry in the orientation of the particle spins in the beams:

$$P = \frac{N^+ - N^-}{N^+ + N^-} \neq 0$$

$N^{+(-)}$: number of particles with spins oriented along the +(-) direction

- The direction of the spins may be transverse or longitudinal (wrt particle direction) or a mixture of both.
- Polarization is either established at the source (polarized beam sources for hadrons or e^-) or may be build up spontaneously (e^+e^- beams – in damping rings or in the main machine).

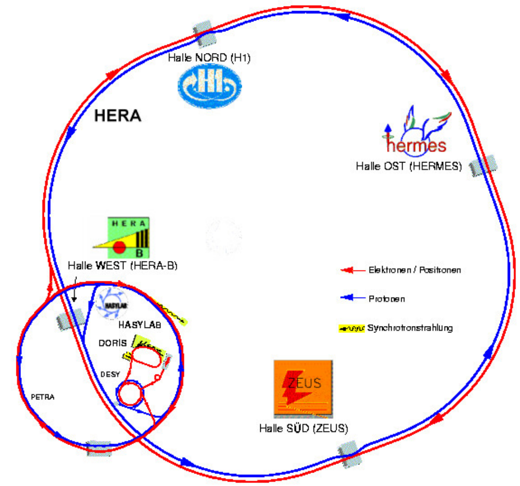
Examples of “polarized” colliders



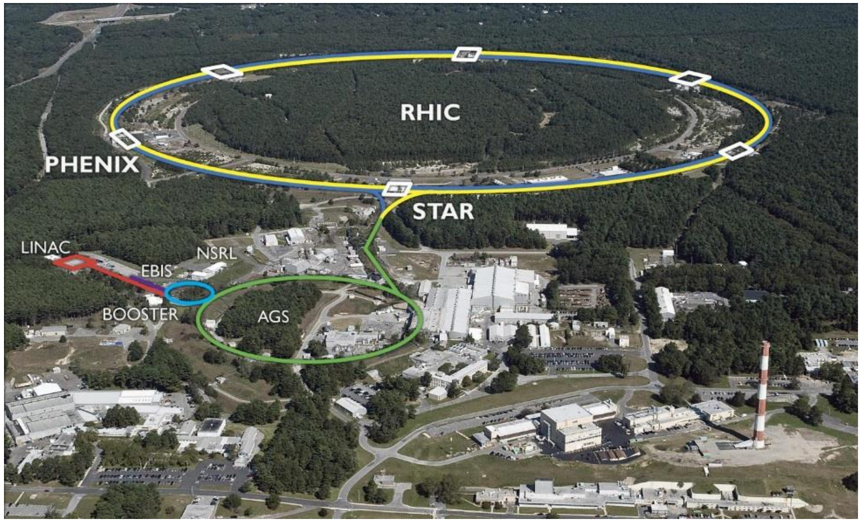
SLC

The **SLC** (Stanford Linear Collider), operated in the 1990’s collided longitudinally polarized e^+e^- beams at ~45 GeV (Z resonance).

HERA (DESY), operated between 1992 and 2005, collided 920 GeV proton beams with longitudinally polarized e^+ or e^- beams at 27.5 GeV.



RHIC (Relativistic Heavy Ion Collider) at BNL, in operation since the early 2000’, can be operated with polarized proton beams of up to 250 GeV.



Content of this presentation

- This presentation will be focused on transverse polarization build-up in e^+/e^- storage rings.
- Besides the option of using such polarization for physics measurement – e.q. HERA – one of the key interests of polarization is its use for precise calibration of beam energies. The second half of this presentation will describe energy calibration techniques for storage rings.

Introduction

Radiative polarization in storage rings

Beam energy measurement techniques

Beam energy at LEP/FCC-ee

From beam to center-of-mass

- **Transverse polarization builds up spontaneously** in e^+e^- storage rings due to the emission of synchrotron radiation, the final state with e^+e^- spins aligned along the bending having a slightly higher probability to occur.
  - Spin flip during photon emission is rare, but favours one spin direction.
  - This effect was first predicted by Sokolov and Ternov in 1964.
  - First observations at the ACO (1971) and VEPP-2 (1972) rings.

- The maximum equilibrium polarization level P_{ST} and the polarization risetime τ_p are given by:

P-REV

$$P_{\mathrm{ST}} = \frac{8}{5\sqrt{3}} \simeq 92.376\% \qquad P(t) = P_{ST}\left(1 - e^{-t/\tau_p}\right)$$

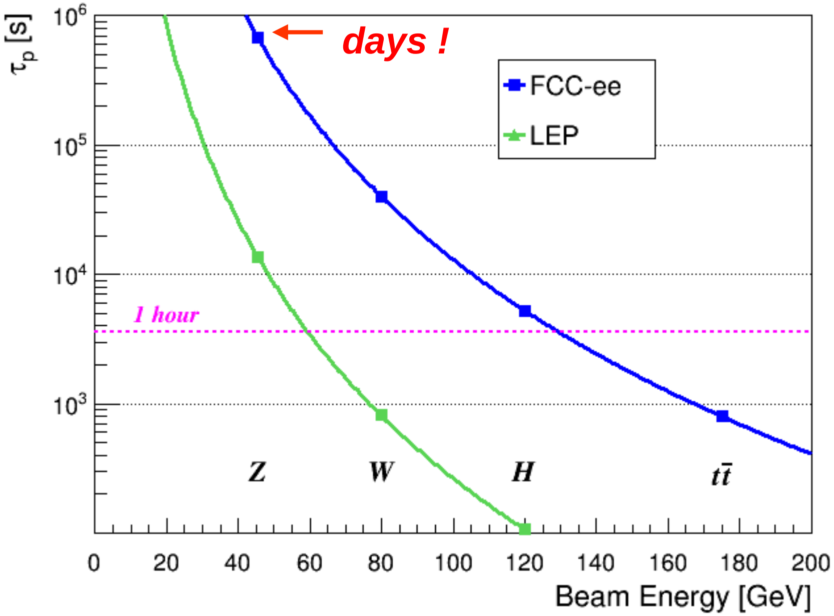
$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e \gamma^5 \hbar}{m_0 C}\oint \frac{ds}{|\rho|^3} \qquad \frac{1}{\tau_p} \propto \frac{E^5}{\rho^3}$$

- For a storage ring of **radius** R ($C=2\pi R$), mean **radius of curvature** ρ, **energy** $E=\gamma m_0$ and **dipole field** B:

$$\tau_p(s) \cong 3654 \frac{(R/\rho)}{[B(T)]^3[E(GeV)]^2}$$

Polarization time scales

- For large e^+/e^- colliders like LEP and FCC-ee, the build-up of polarization is a rather slow process because ρ is large !
  – This renders polarization build up delicate and prone to perturbations.
  – The rise time can be reduced with dedicated wigglers ($1/\tau_p \propto 1/\rho^3$).

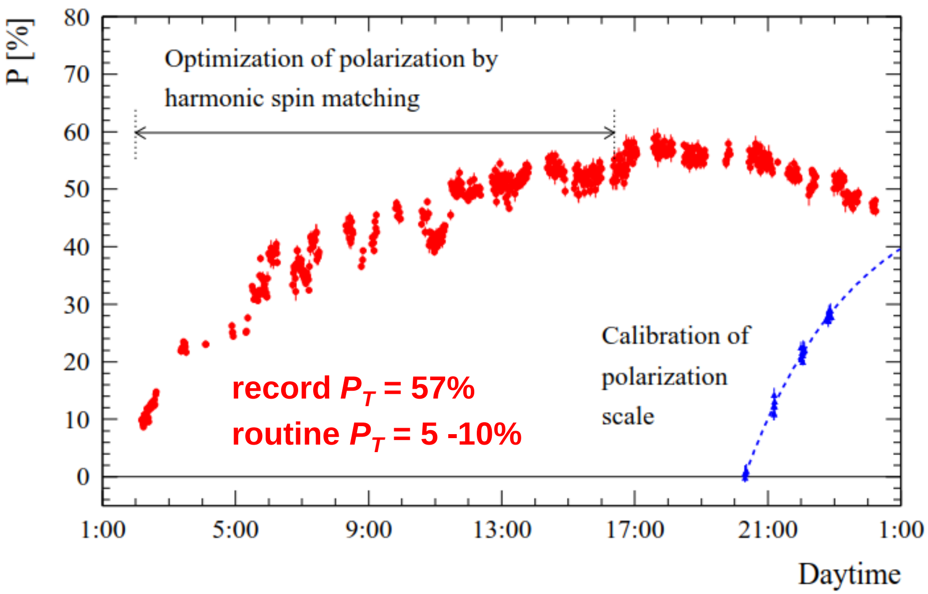


Polarization risetimes at LEP and FCC-ee (from bending dipoles only)

The difference between the two machines is due to the difference in bending radius (3 km for LEP versus 11 km for FCC-ee).

P-LEP1

Polarization build up at LEP (~45 GeV)



- The **spin precession** in the electromagnetic fields of the storage ring is described by the Thomas-BMT (Bargmann-Michel-Telegdi) equation:

$$\frac{d\vec{S}}{dt} = \vec{\Omega}_{BMT} \times \vec{S}$$

$$\vec{\Omega}_{\mathrm{BMT}} = -\frac{e}{\gamma m}\left[(1+a\gamma)\,\vec{B}_{\perp} + (1+a)\,\vec{B}_{\parallel} - \left(a\gamma + \frac{\gamma}{1+\gamma}\right)\vec{\beta} \times \frac{\vec{E}}{c}\right]$$

$a = (g-2)/2$ = magnetic moment anomaly

$\vec{E} =$ electric field

$\vec{B}_{\perp}, \vec{B}_{\parallel} =$ transverse and longitudinal components of the local magnetic field

- For a uniform transverse magnetic field the revolution and precession frequencies of the particles are given by:

$$\vec{\omega} = -\frac{e}{\gamma m}\vec{B}_{\perp} \quad \text{and} \quad \vec{\Omega}_{BMT} = -\frac{e}{\gamma m}(1+a\gamma)\vec{B}_{\perp}$$

- The number of spin precessions per machine turn (**spin tune** ν) is:

$$\nu = a\gamma$$

proportional to the particle energy !

Spin tune

- The number of spin precessions per turn (**spin tune ν**) is related to the beam energy though the magnetic moment anomaly and the particle mass:

$$\nu = a\gamma = a\frac{E}{mc^2} = \frac{E}{(mc^2/a)}$$

Symbol	Anomaly $a = \frac{1}{2}(g-2)$	Accuracy	Mass (MeV)	$\Delta E = mc^2/a$ (MeV)
$e^{\pm}$	$1.159\,652\,1859 \times 10^{-3}$	$\pm 3.8 \times 10^{-12}$	510.9989×10^{-3}	440.65
$\mu^{\pm}$	$1.165\,9208 \times 10^{-3}$	$\pm 6.0 \times 10^{-7}$	105.658	90 622.24
p	1.792 847 351	$\pm 2.8 \times 10^{-8}$	938.272	523.34
d	−0.142 9878	$\pm 5.0 \times 10^{-7}$	1875.613	13 117.30

- For a beam energy of 45.5 GeV (Z boson resonance) the value of the e^+/e^- spin tune is ν = 103.3.
  - The factor ***mc^2/a*** is a number known to **very high accuracy** – opens the door to accurate energy determinations.

- In a perfectly planar ring with vertical bending fields the spins align along the vertical direction, but in a real machine fields may point along other directions. The spins will be **rotated away from the vertical direction** by (for example):
  - **Solenoids** with longitudinal fields (particle physics experiments !),
  - Horizontal magnetic fields due to **vertically misaligned quadrupoles**.
- For transverse fields: **spin deflection = ν × particle deflection**.
  - This property, which is detrimental in case or machine errors, can be used to manipulate the spins ('spin rotator').
- In analogy to the closed orbit, there exists a periodic spin orbit vector n_0 that corresponds to the equilibrium direction of the spin vectors satisfying:

$$\vec{n}_0(s) = \vec{n}_0(s+C)$$

- To ensure a high level of polarization the direction of n_0 must be as close as possible to the direction of the bending field.
  - To achieve **high equilibrium polarization the direction of polarization growth (// bending field) must coincide with the equilibrium direction n_0** !

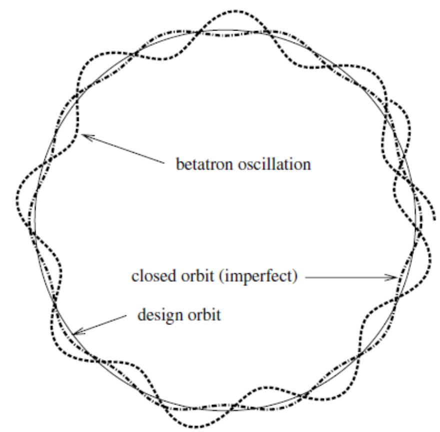
Realistic rings II

- As the beam particles follow the closed orbit of the storage rings, the spin vectors are subject to perturbations and resonances. To obtain high polarization, the spin tune should not match the resonance conditions:

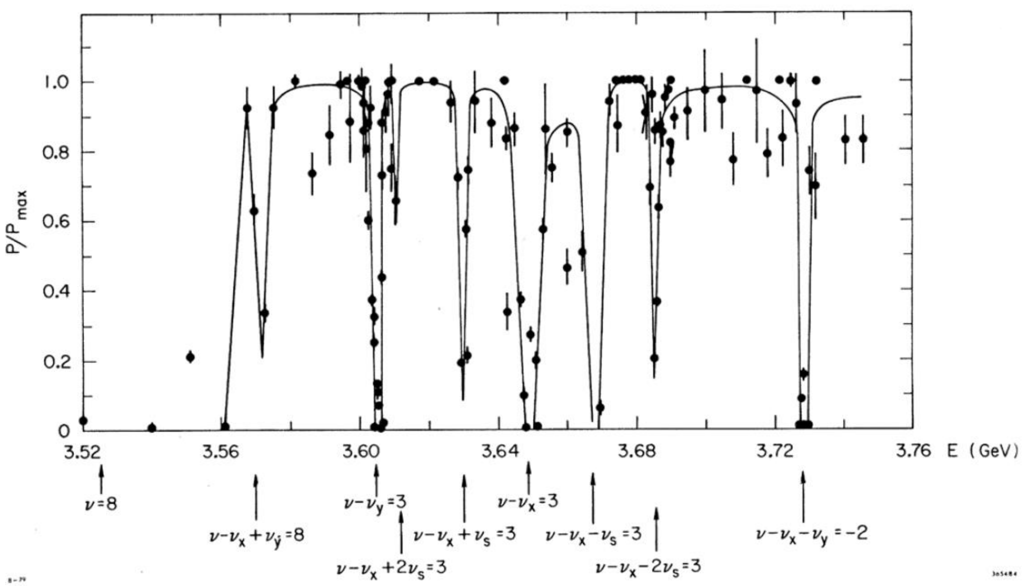
$$\nu = k \pm k_x Q_x \pm k_y Q_y \pm k_s Q_s$$

k, k_i = integer numbers

Q_i = betatron/synchroton tune



Polarization versus energy at SPEAR



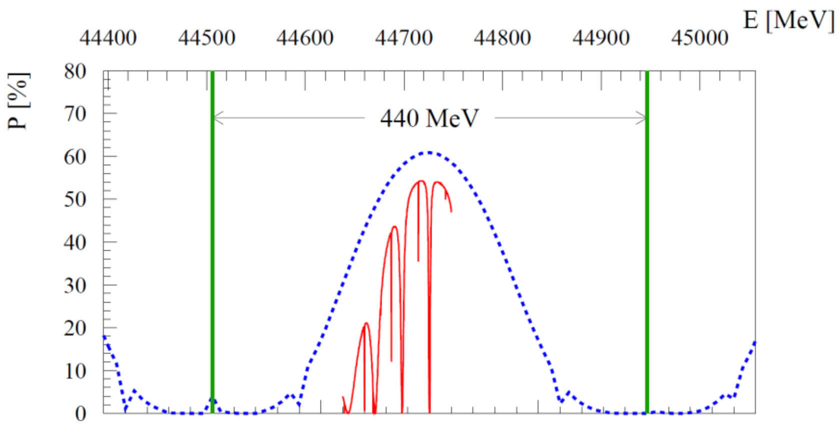
P-REV

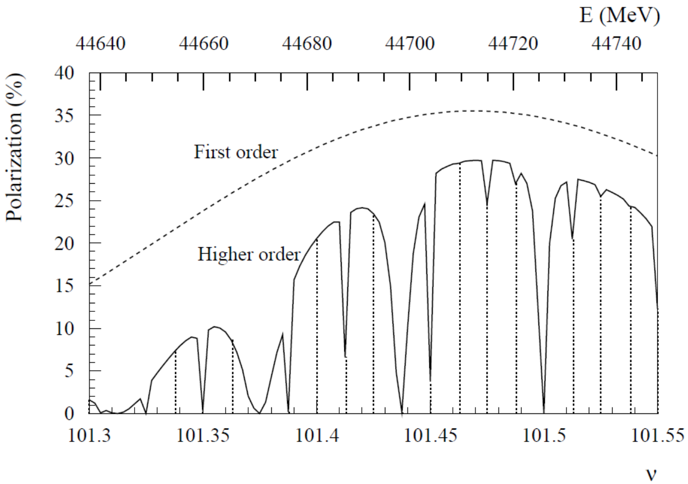
- The highest polarization is usually obtained for ν far away from an integer spin tune, i.e. in the vicinity of :

$$\nu = n + \frac{1}{2} \qquad n = \text{integer}$$

- Tune working points away from the half-integer and with overlapping spin resonances reduce the number of resonance lines.
  - For example LEP used Q_x=0.1, Q_y=0.2.
- It is also favourable to select betatron and synchrotron tunes such that upper and lower sidebands overlap:
  - Q_i versus 1-Q_i .

Polarization simulations for LEP



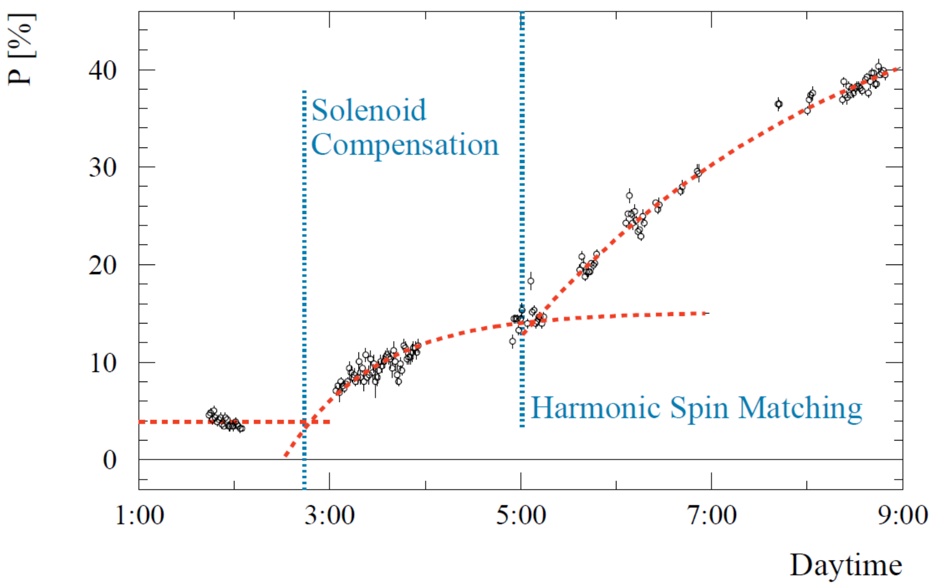


P-LEP1

Polarization optimization

- A well corrected vertical orbit (and a well aligned machine) improves the achievable polarization levels.
  - Optimized beam position monitor layouts and phase advance per cell (60°) help in achieving high(er) polarization through improved orbit correction quality (no hidden bumps…).
- Solenoidal fields must be compensated with anti-solenoids or with orbit bumps ('spin rotators') that compensate the rotation due to the solenoids.
- The orbit resonances driven by the harmonics around the spin tune (ν and ν+1) generally dominate depolarization. They can be compensated by dedicated (harmonic) orbit bumps – harmonic spin matching.

Polarization optimization at LEP



The polarization is first improved by compensating the experiments solenoids with orbit bumps.

This is followed by optimizing the strength of 4 vertical orbit bumps configurations (Harmonic Spin Matching): sinus and cosinus components at ν and $\nu + 1$.

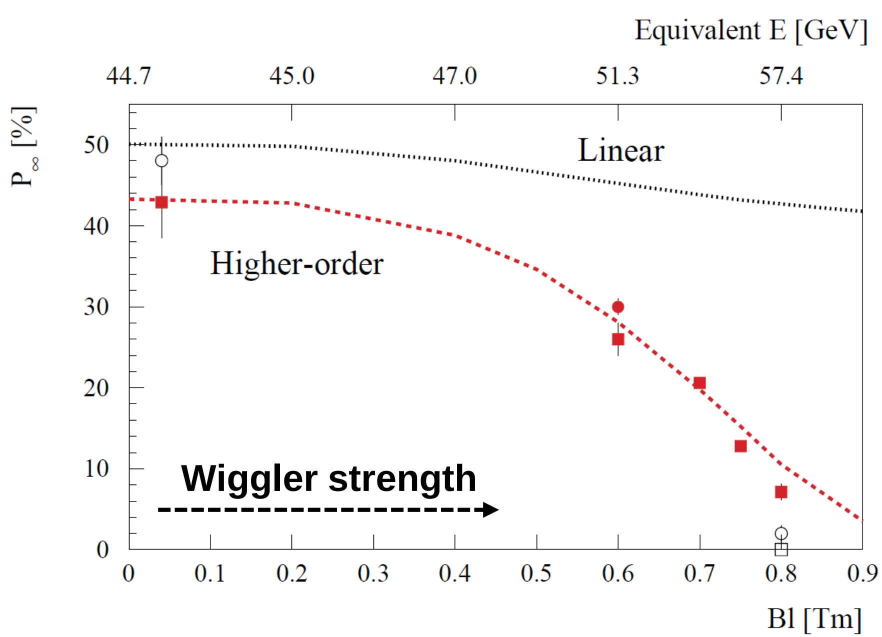
P-LEP-REV

- The relation between spin tune and energy has an important impact for longitudinal/energy oscillations.
  - Energy oscillations lead directly to spin tune oscillations,
  - Energy spread leads to spin tune spread (of the particle ensemble that makes up the beam).
- Intuitively it can be observed that when the energy spread of the beam is comparable to the integer resonance spacing of 440 MeV, it is likely that the polarization may be affected significantly due to the nearby integer resonance.

Peak polarization at LEP as a function of wiggler strength

Under identical machine conditions, the polarization drops due to the increase in energy spread as the wiggler strength is increased.

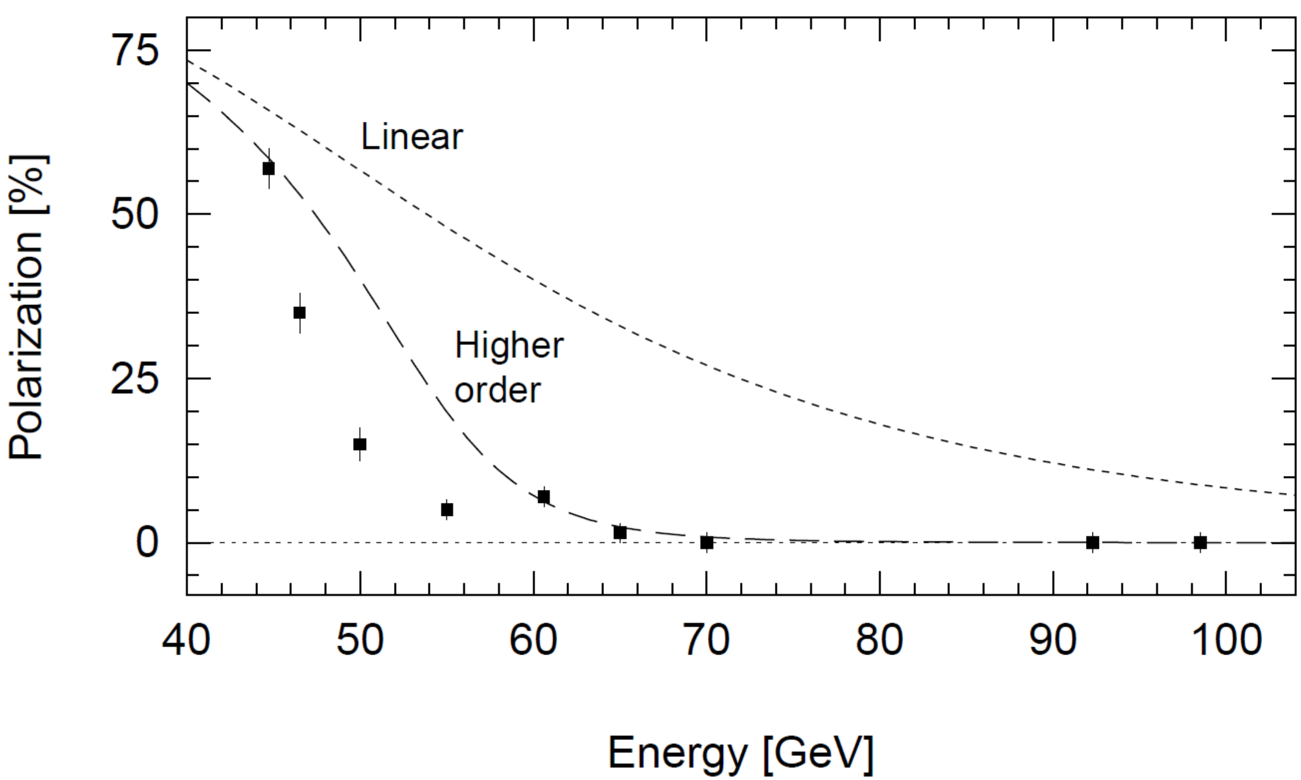
P-LEP1



Polarization at LEP

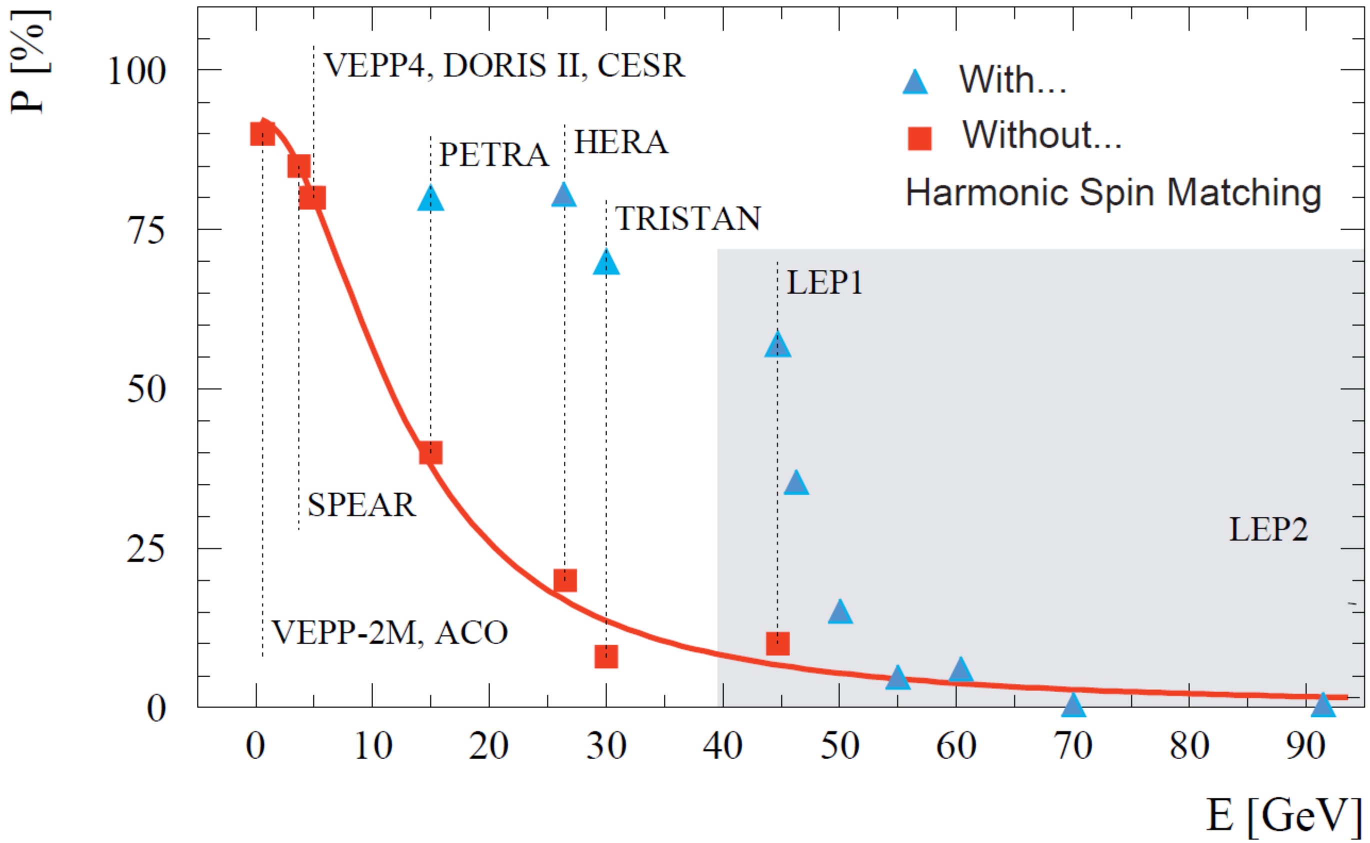
- LEP probed a range of high beam energies with increasing energy spread.
- As the energy was increased a drop of peak polarization was observed around **55-60 GeV** corresponding to an energy spread **σ_E ~ 50-55 MeV**.
  - Can be mimicked with wiggler generating the same energy spread (see previous slide).

P-LEP-REV



- Overview of peak polarization as a function of energy at a variety of storage rings:

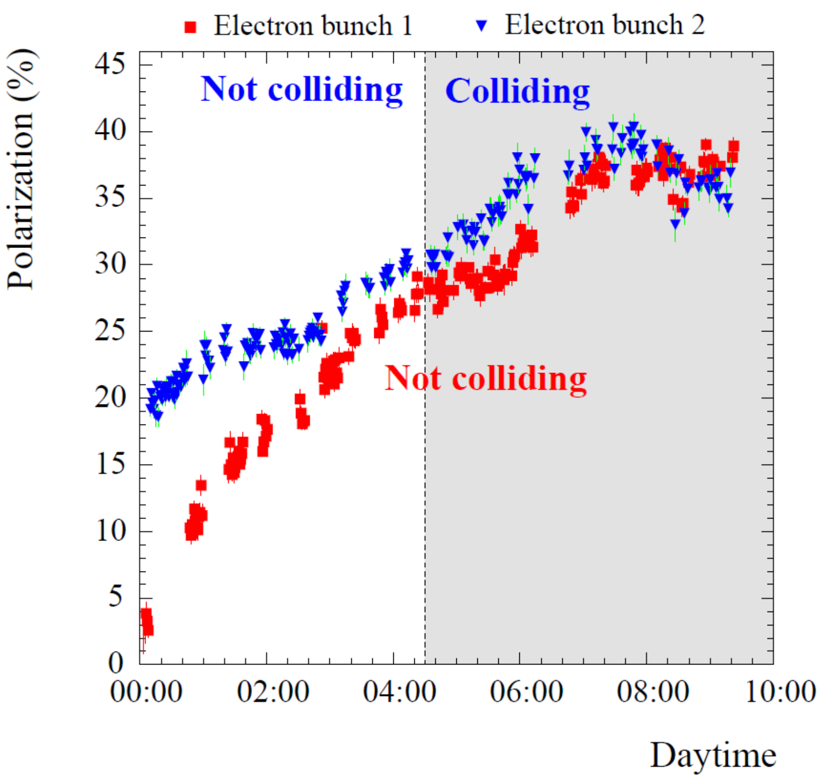
P-LEP-REV



Polarization and beam-beam

- The beam-beam force at IPs enhances betatron resonances and spin depolarization and only few studies were made on this subject.
  - At HERA the beam-beam tune shift was small.
- For energy calibration non-colliding bunches are generally used to reduce the complexity and obtain higher polarization levels.

Colliding beam polarization test at LEP



In some LEP studies it was possible to collide bunches with close to 40% polarization.

Non-colliding witness bunches indicate no loss of polarization with beam-beam parameter of ~0.04 – not too bad !

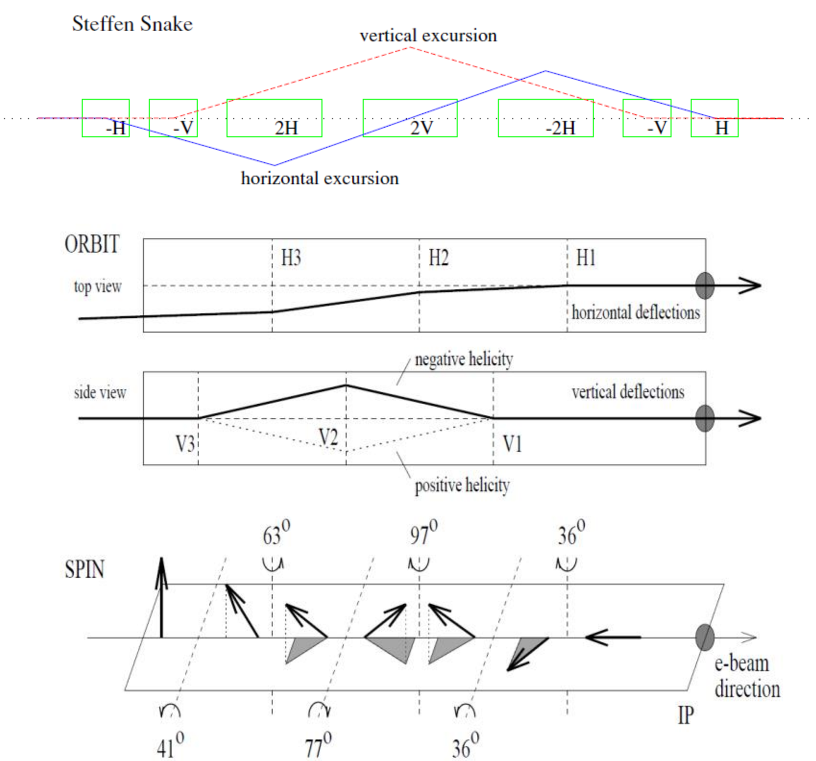
For the routine usage of polarization at LEP, only non-colliding beams were used.

P-LEP-REV

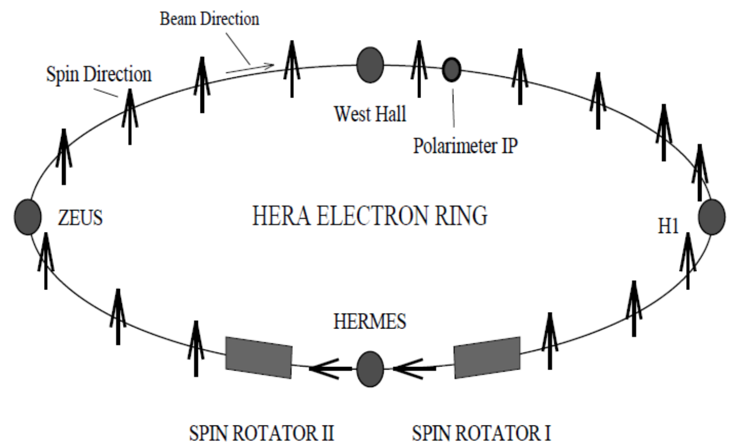
Longitudinal P and spin rotators

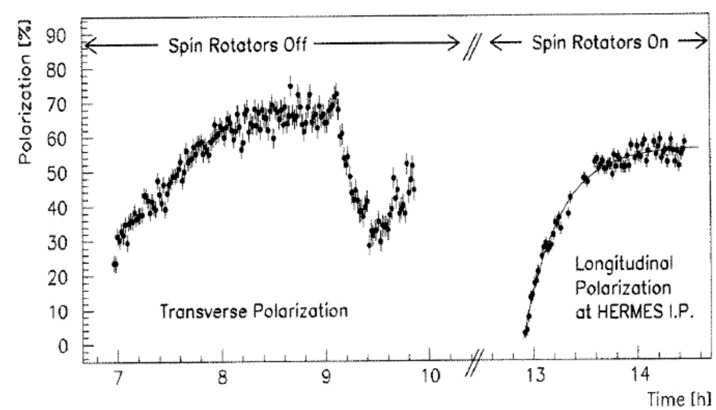
- At HERA the spins were **rotated into the longitudinal plane** with **spin rotators** (interleaved H and V bends) installed around one experiment.
- Polarization levels above 50% were obtained routinely during HERA operation with such manipulations.

HERA spin rotator concept



P-HERA **P-HERA-ROT**





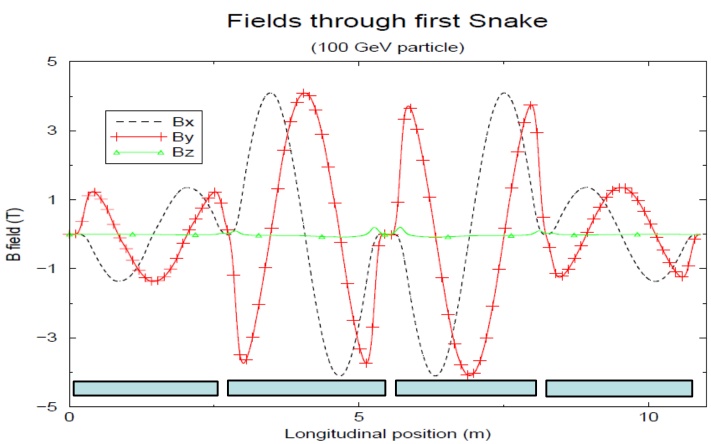
Snakes

P-REV

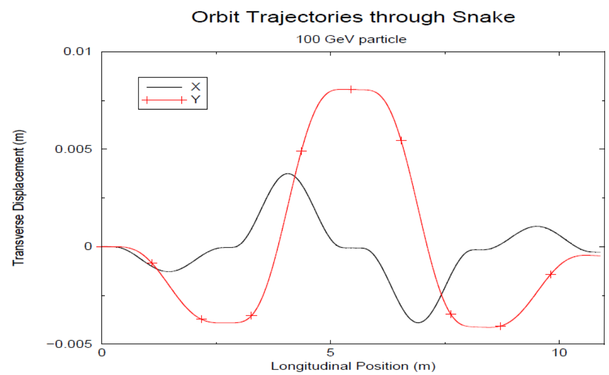
- The concept of the **Siberian Snake**, introduced in 1976, defines an ‘object’ that **rotates the spins by 180°** around an axis in the horizontal plane without affecting the beam orbit (identity map for orbital motion).
  - A solenoid with appropriate field can function as a snake.
  - Helical wiggler magnets with a cork screw orbit can act as snakes, employed for example for RHIC.

P-SNAKE_RHIC

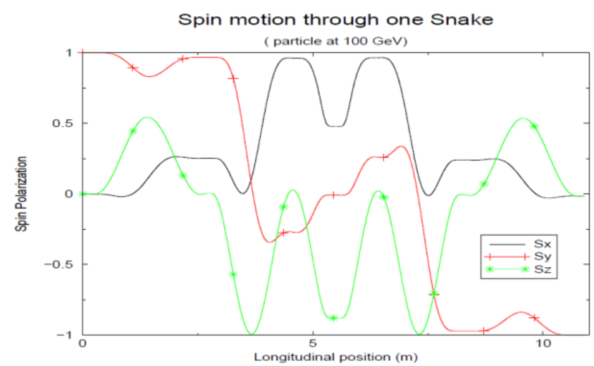
RHIC helical snake



Field map at 100 GeV for a 4 magnet superconducting snake

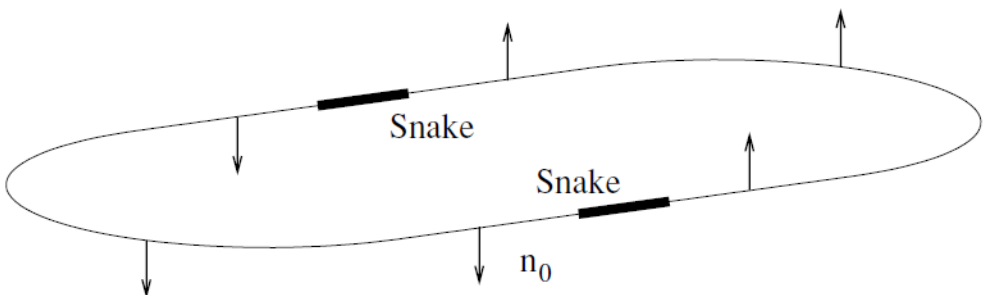


No orbit perturbation outside of snake

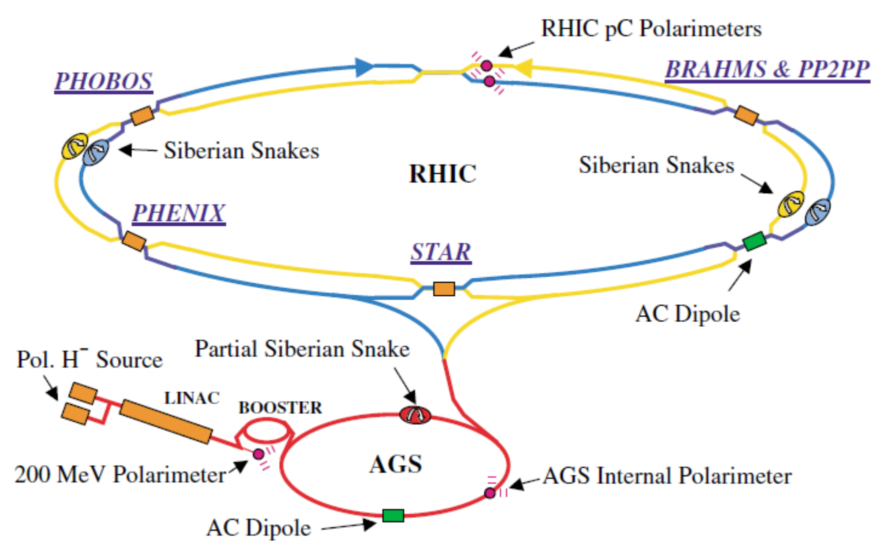


Vertical spin flip

- With 2 Siberian snakes installed in a ring, each one rotating the vertical polarization by 180° around the longitudinal axis, the spin tune over the ring is forced to a constant value of **½**.
  - This concept can be used to overcome spin resonances and can be used to maintain the spin tune at the fixed value while the beam energy is ramped.
    - Without snake the spin tune would have to pass many resonances.
  - The RHIC polarization program is relying heavily on snakes.

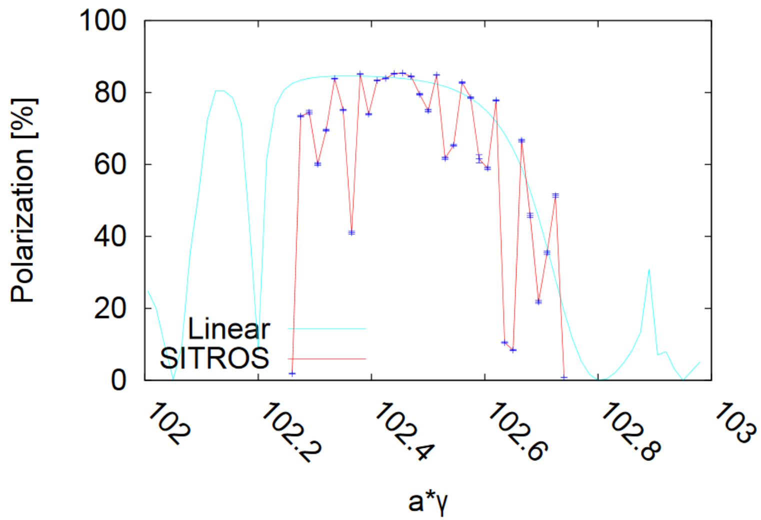


P-SNAKE_RHIC-2



- Due to its very large bending radius, $\rho \cong 11$ km, the polarization rise time at 45 GeV (Z resonance) is longer than 100 hours !
- The rise time can be lowered with wigglers, but their energy loss is not compatible with the 100 MW SR budget.
- The current operation concept in view of **energy calibration**:
  - A few 100 non-colliding bunches are injected first with wigglers on until a few percent polarization is obtained (~1-2 hours),
  - Then the wigglers are switched off and the main beam is injected (and kept at constant intensity with top-up injection).
  - Cohabitation of colliding bunches and non-colliding energy calibration bunches.

FCC-ee polarization simulations at Z pole



Polarization simulations with machine mis-alignments for Qx =0.11, Qy =0.18 and Qs =0.05.

The low-beta quadrupoles are not misaligned !

P-FCCEE

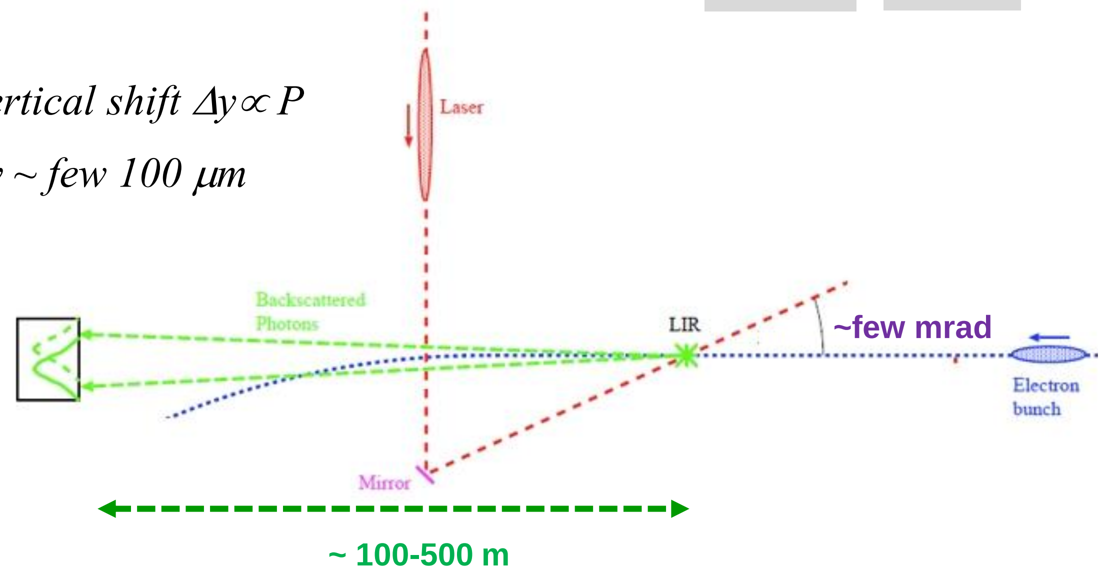
Polarization measurement

- At high energy rings the transverse polarization is typically measured by **Compton scattering of laser photons** on the beam.
  - Take advantage of the spin dependent Compton cross-section.
- Circularly polarized laser pulses (visible light) collide with the e+/e- beams at a small angle. In the presence of transverse beam polarization, the scattered photon beams (GeV !) distribution is shifted vertically when the laser polarization is inverted.
- More advanced concepts where the scattered electrons are also measured are studied for FCC-ee.

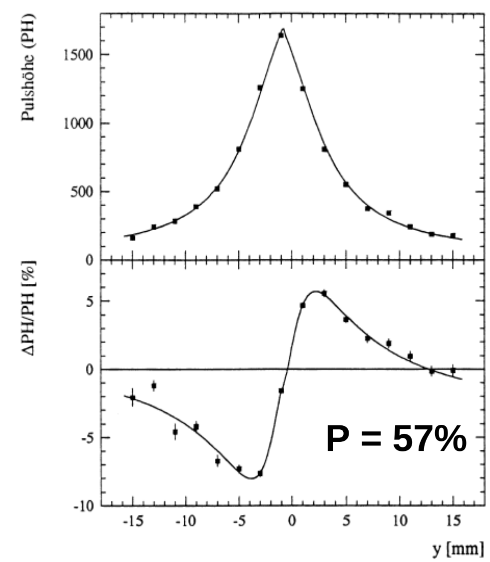
P-LEP1 P-REV

Vertical shift $\Delta y \propto P$

$\Delta y \sim$ *few* $100\ \mu m$



γ profile and asymmetry (R/L laser helicity) at LEP



Introduction

Radiative polarization in storage rings

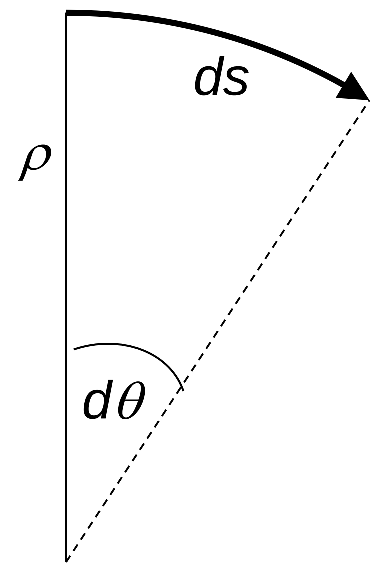
Beam energy measurement techniques

Beam energy at LEP/FCC-ee

From beam to center-of-mass

- The deflection angle $d\theta$ of a particle with charge *Ze* and momentum *P* in a magnetic field *B(s)*:

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



- Integrated over the circumference:

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

- The momentum is defined by the **integrated magnet field** along the closed orbit:

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

LHC: 1232 14.3m long dipoles, 8.33 T $\Longrightarrow$ $P = 7.0\ \mathrm{TeV/c}$

Which magnetic fields contribute to ∫Bdl?

- In the ideal flat storage ring only dipoles contribute.
- In a real machine the contributions to the integral (typical values) are:
  - Dipoles ≥ 99.9%
  - Quadrupoles few 0.01%-0.1%
  - Dipole correctors few 0.01%
  - Higher multipoles < 0.01%
- For a **target accuracy** at the level of **~0.1%, only the dipoles and quadrupoles matter** – the rest can be lumped into the systematic error.
- For **target accuracies of 10^{-6}** (FCC-ee) **everything matters** !
  - Including very subtle **breaking of the relation** between ν and E !

Energy measurement techniques

- A variety of techniques may be used to calibrate the beam energy depending on the desired accuracy.
- It is possible to obtain the energy directly from the **magnetic field measurements** of the machine magnets. In that case the relative accuracy is typically **~few 10^{-4} to 10^{-3}**.
  - The LHC for example reaches 0.1%.

E-LHC

- **Resonant depolarization** relying on the measurement of the spin tune ν achieves accuracies of **10^{-5}**.
  - LEP, VEPP4M, PETRA, light sources, etc.
  - Planned for FCC-ee aiming for less than **10^{-5}**.

E-OVER-LEP

- Comparison of the **RF / revolution frequencies** of particles with different **charge over mass** (Z/m) ratio. Accuracy reach **~ 10^{-4}** .
  - Used at LEP, SPS, LHC – usable at mainly hadron colliders.

E-LHC

Energy measurement techniques II

- Measurement of the **Compton edge of backscattered laser photons** with relative accuracies of **~few 10^{-5}**.

  E-COMPT

  - Works at lower energy e^+e^- colliders (VEPP-4M, VEPP 2000, BEPC) and synchrotron light sources up to energies of ~2 GeV, because the scattered photons should be in the MeV range (Germanium detector).

- **Spectrometer systems** based on dipole magnets with bending field known to high precisions surrounded by high precision BPMs have achieved relative accuracies of **~10^{-4}**.

  E-FINAL-LEP2

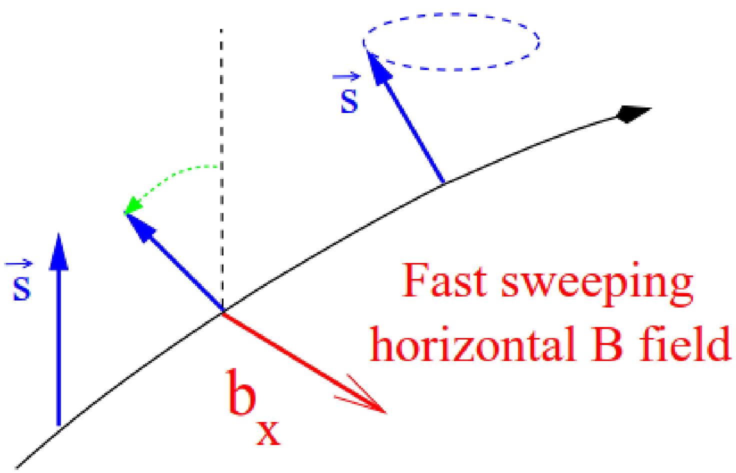
  - Used at LEP to interpolate energies into a range not accessible by polarization.

- More exotic methods like a relative calibration using the **synchroton tune** taking advantage of the dependence of energy loss scaling with E^4 that achieved relative accuracies of **~10^{-4}**.
  - Used at LEP to interpolate energies into range not accessible by polarization.

E-FINAL-LEP2

- Resonant depolarization takes advantage of the fact that the **spin tune ν** is propositional to the beam energy:

$$\nu = a\gamma = a\frac{E}{mc^2} = \frac{E}{(mc^2/a)} = \frac{E}{440.6486[MeV]}$$



Principle of **resonant depolarization**:

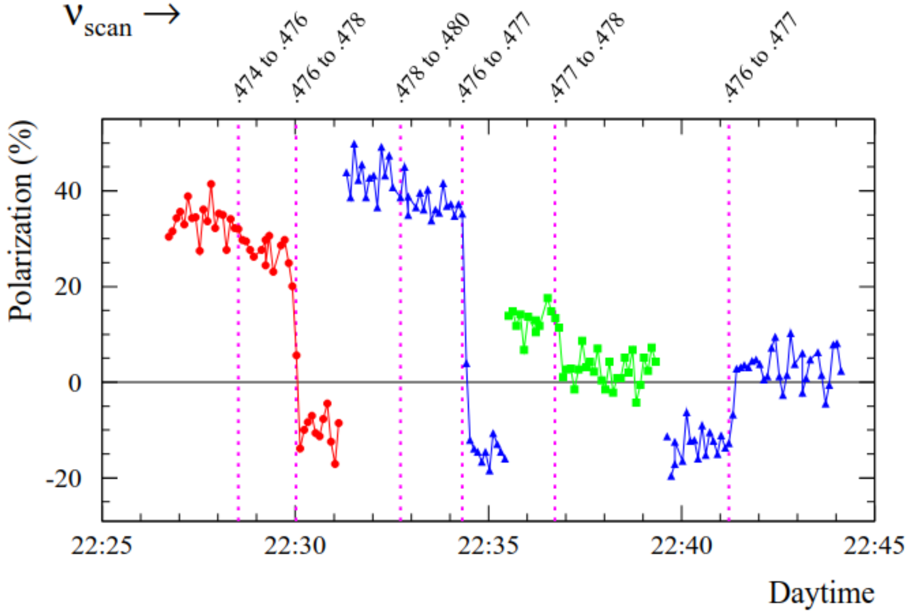
- The field of a fast pulsing magnet ("kicker") is swept in frequency over a certain range of fractional spin tune.
- If kicker frequency and fractional ν match, P_T may be rotated away from the vertical axis if the kicker strength is well chosen.
- The kicker magnet is typically similar to a transverse feedback system magnet.

- Only the **fractional part of the spin tune** may be determined by this technique. The **integer part** must be deduced from the magnetic field …

Resonant depolarization II

E-OVER-LEP

RDP example from LEP

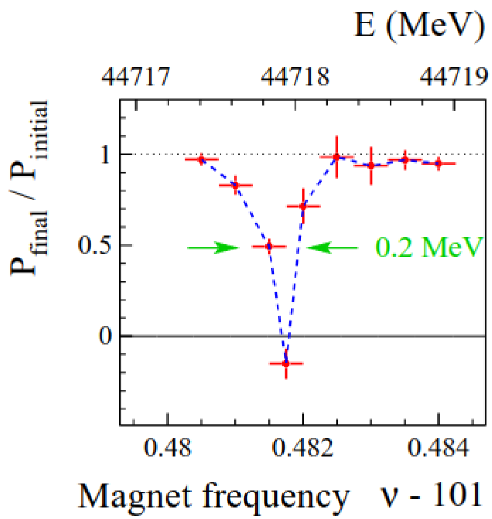


The kicker frequency was swept over a selected interval, typically ~ 22 Hz ($\delta\nu$ ~ 0.002).

P_T could be destroyed or flipped when the kicker was in resonance with the fractional spin tune.

Achievable accuracy :

$\Delta E/E \leq 10^{-5}$



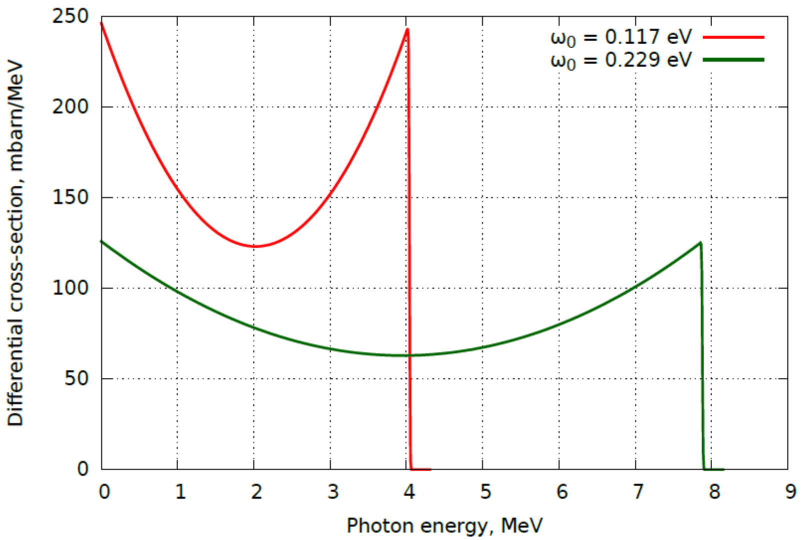
*For a non-planar ring (misalignments !) the **relation between ν and E breaks down** (non-commutation of rotations), systematic effects must be evaluated and simulated carefully – applies when **relative accuracies of 10^{-6} are targeted** like for FCC-ee !*

- Scattering photons with energy ω_0 on an $e^{-(+)}$ beam produces backscattered Compton photons with a maximum energy of:

$$\omega_m = \frac{E\lambda}{1+\lambda} \cong 4\frac{E^2\omega_0}{m^2} = 4\gamma^2\omega_0 \qquad \lambda = \frac{4E\omega_0}{m^2}$$

- **Infrared laser photons** (μm wavelengths) yield maximum scattered photon energies in the **MeV range**, well suited for measurements by high purity Germanium semiconductor detectors (HPGe).
  - Detector calibration with well known nuclear gamma ray lines.

Photon spectrum for scattering on 1.5 GeV beams



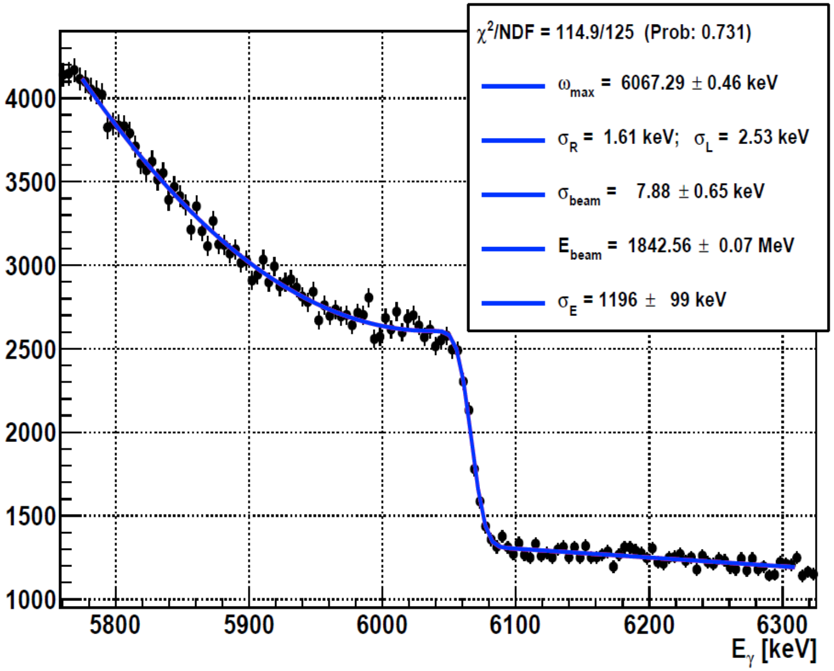
E-COMPT

Compton backscattering II

- The measurement technique requires an excellent understanding of the detector (response, resolution, noise…).
  - The width of the edge may be used to determine the beam energy spread.
- Relative accuracies of **2-5×10^{-5}** have been achieved for machines with beam energies up to ~2 GeV.

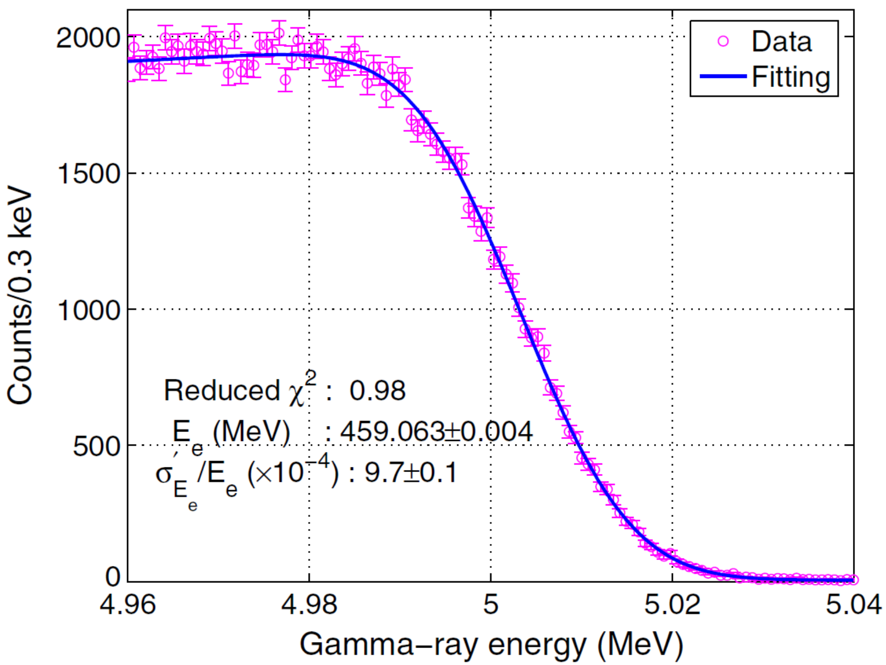
Photon spectrum and energy determination at BEPCII

E-BEPC



Photon spectrum and energy determination at Duke University γ facility

E-DUKE



RF frequency calibration

- For hadron machines it is possible to determine the beam energy if one is able to injected different ion / hadron species into the same machine.
  - The different species should be present at the same time (more than one ring) or the machine conditions must be reproduced very accurately.

- The speed β (and momentum *P*), RF frequency f_{RF} and circumference *C* are related to each other (*h = RF harmonic number*):

$$\beta c = C\ f_{rev} = \frac{C\ f_{RF}}{h}$$

2 unknowns (**C** & ***β*/P**)

- If two species of particles (for example protons and ions) are injected under ***identical conditions***, the momentum of the proton beam may be determined from the **proton-ion RF frequency difference**:

E-LHC

$$P \cong m_p c \sqrt{\frac{f^p_{RF}}{2\Delta f}(\mu^2 - 1)}$$

$$\boxed{\Delta f = f^p_{RF} - f^i_{RF}}$$

This is essentially a speed difference measurement

$$\mu = \frac{m_i}{Z m_p}$$

for protons and Pb^{82+} $\mu \approx 2.5$

RF frequency calibration II

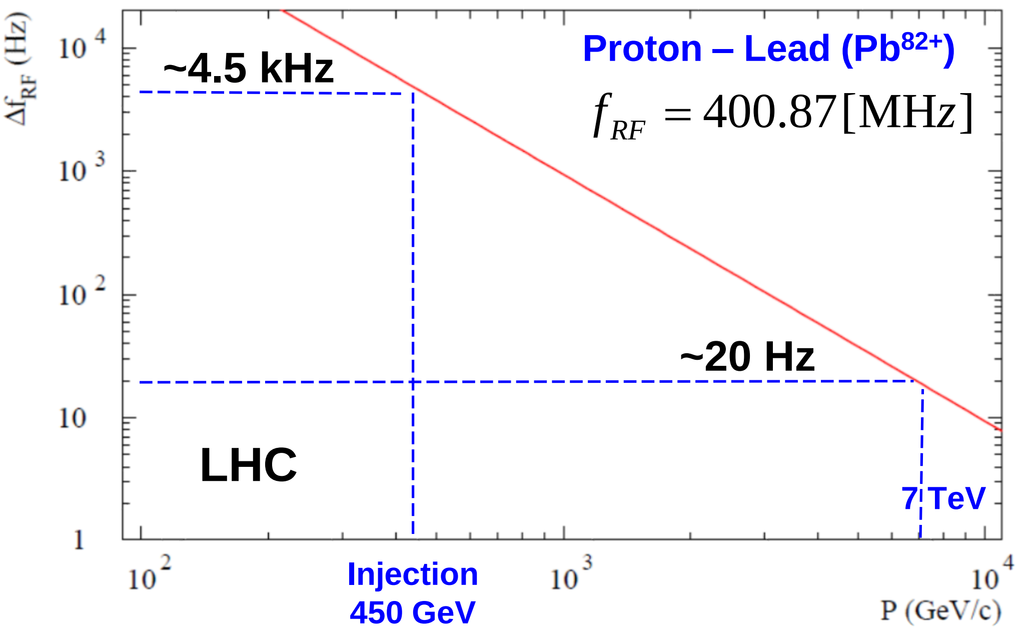
- When ions become very relativistic, the difference wrt protons decreases, the frequency difference to be measured scales $\propto 1/P^2$:

$$\Delta f = \frac{hc}{C}(\beta_p - \beta_i) \simeq \frac{h m_p^2 c^3}{2 C P^2}(\mu^2 - 1)$$

μ should be as large as possible

E-LHC

RF frequency difference between p and Pb^{82+} at LHC



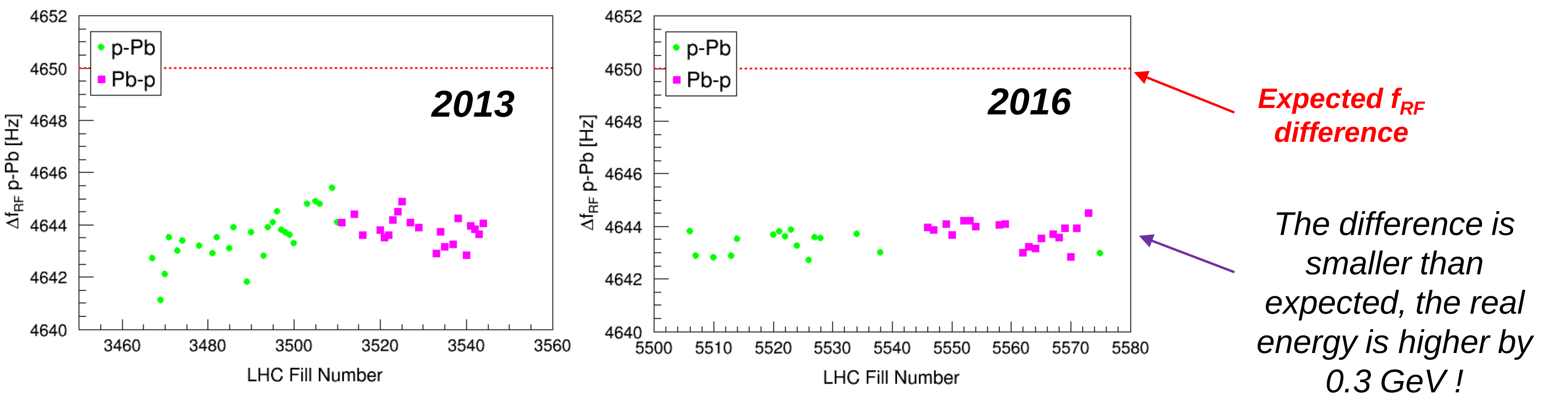
*The energy measurement at LHC top energy is challenging for the beam position monitor system as they require **μm accuracy on the mean radius** to reach 0.1% accuracy on E (< 0.1 Hz on f_{RF}).*

For FCC-hh at 50 TeV this measurement is even more challenging!

- At the LHC one can take advantage of that fact that it is possible to inject protons in one ring and Pb ions into the other ring – also valid for FCC-hh.
  - Circulate at the same time,
  - Possible to invert the beams between the ring to reduce systematic errors !

Measurement of RF frequency difference at LHC at 450 GeV

E-LHC



*Achieved accuracy at injection is **2×10^{-4}**.*

*The measurements are reproducible over 3 years to ~**10^{-4}**.*

Introduction

Radiative polarization in storage rings

Beam energy measurement techniques

Beam energy at LEP/FCC-ee

From beam to center-of-mass

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, $\rho = 3026$ m.

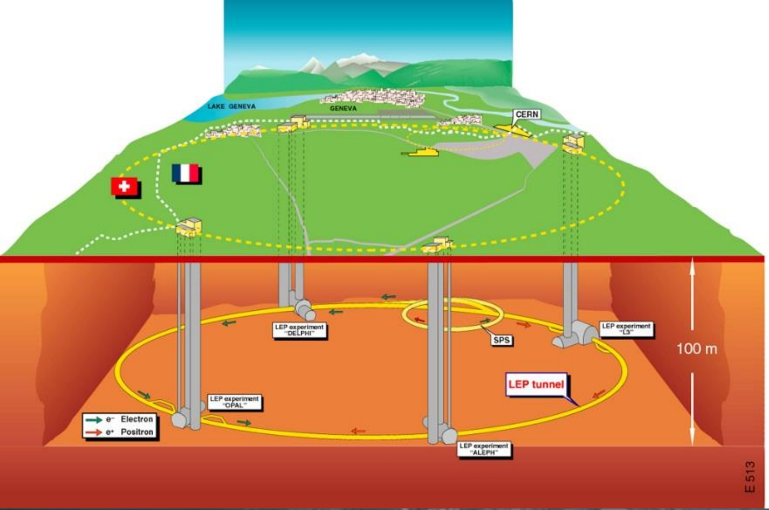
The dipole bending field of LEP was consequently very low, **$B \approx 50 - 120$ mT**, rendering the machine very sensitive to stray fields.

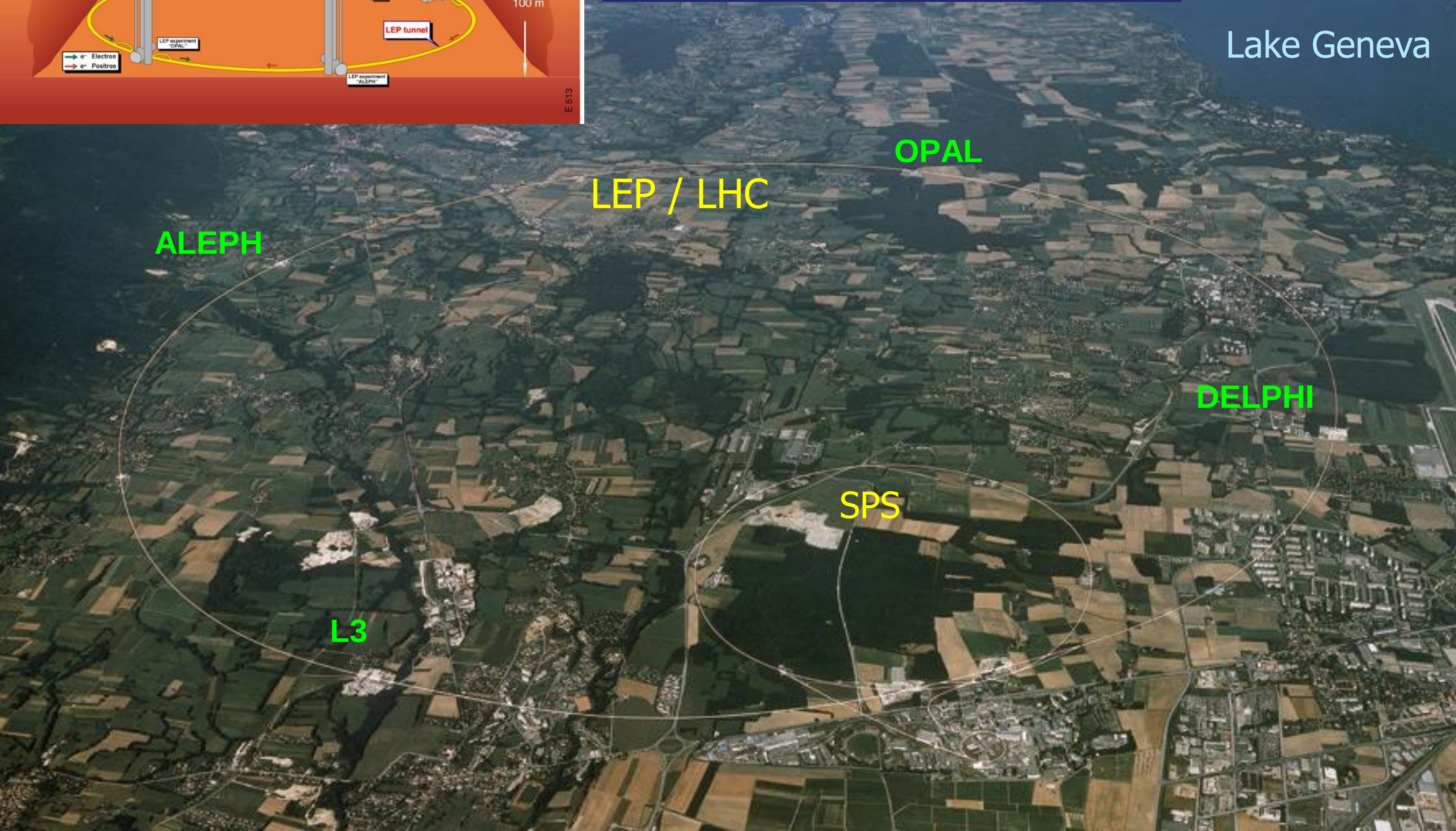
One of the aims of FCC-ee is to improve the LEP measurements by one order of magnitude.

LEP Layout

The 26.7 km LEP / LHC tunnel

Depth: 70-140 m





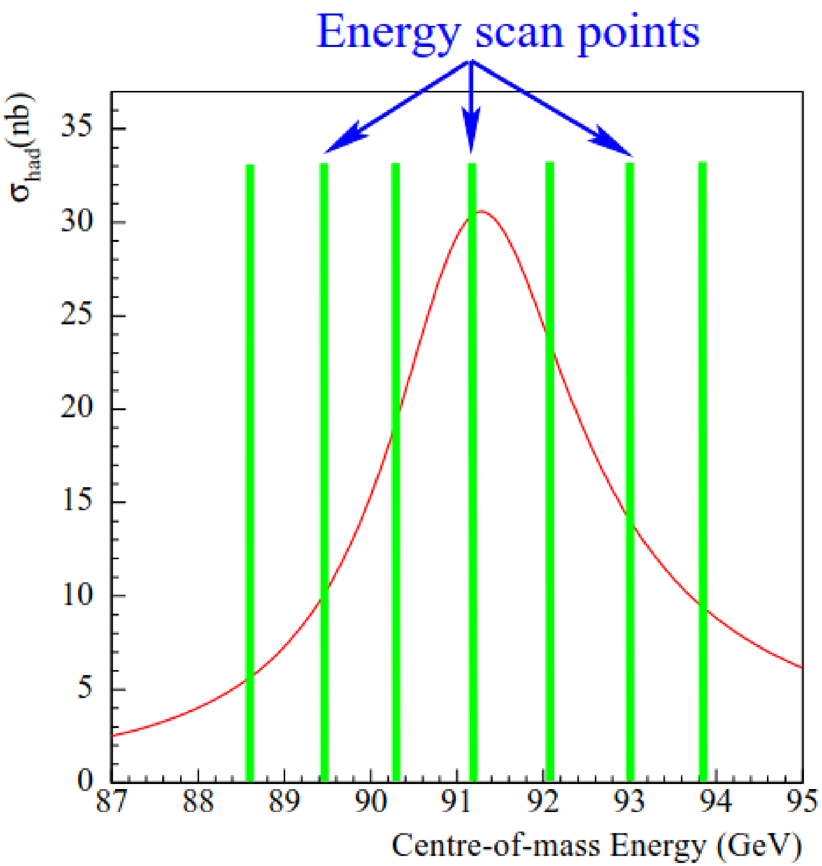
Z boson resonance scans

- LEP relied on resonant depolarization for energy calibration.
- The favorable regions for polarization are ~50 MeV wide and spaced by 440 MeV ($\nu \sim N + 1/2$): defines the operating beam energies.

The calibrations could not be performed during "physics" (no P_T with colliding beams)

Extrapolation in time

Beam energy model



Circumference and energy

- The speed βc (and momentum P), RF frequency f_{RF} and length of the orbit L are coupled:

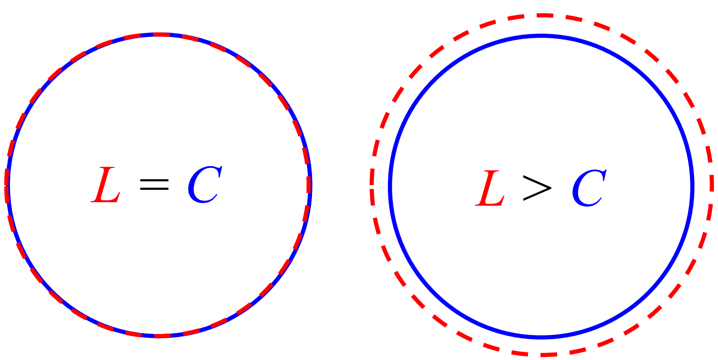
$$\beta c = \frac{L}{T_{rev}} = L\, f_{rev} = \frac{L\, f_{RF}}{h} \qquad f_{RF} = h\, f_{rev}$$

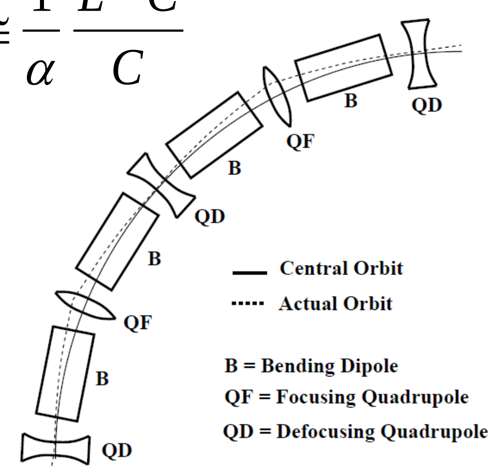
h = RF harmonic number

- In the ideal case, the orbit length L matches the circumference C *defined by the magnets*, $L=C$, f_{RF} is matched, the beam is on the design orbit.

If an external force changes the circumference of the ring, or if f_{RF} is set such that $L \neq C$, the quadrupole magnets will contribute to the field integral.

$$\frac{\Delta E}{E} = \frac{1}{(\alpha - 1/\gamma^2)} \frac{L-C}{C} \cong \frac{1}{\alpha} \frac{L-C}{C}$$

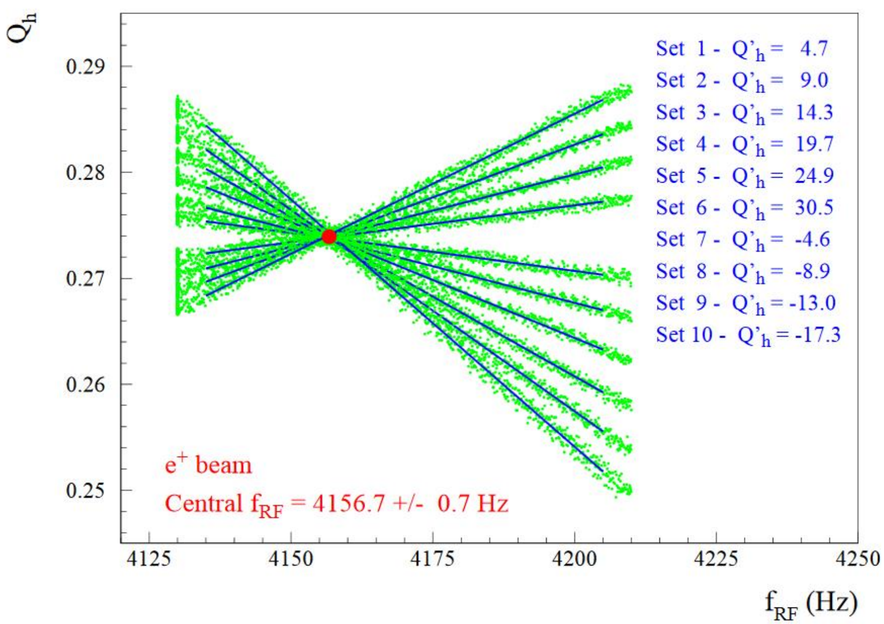




Central frequency

- The RF frequency value for which the beam is centred on average in the machine quadrupoles (in dispersive regions) is called the **central RF frequency**.

LEP central RF frequency measurement



- The central frequency can be obtained by measuring the tune Q as function of f_{RF} (resp. dp/p) for different values of the chromaticity Q':
  - For the frequency corresponding to the crossing point of all lines, the beam is centred in the sextupoles.
  - Provided there is no systematic misalignment between sextupoles and quadrupoles, this frequency is the central RF frequency.

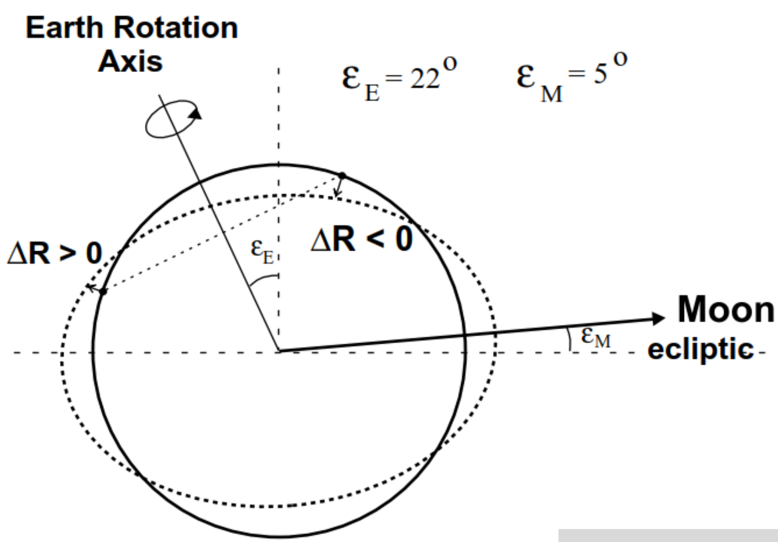
- Such a measurement may be used to calibrate the radial offset of the machine BPMs (resp define a radial reference).

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)

induces surface deformations.

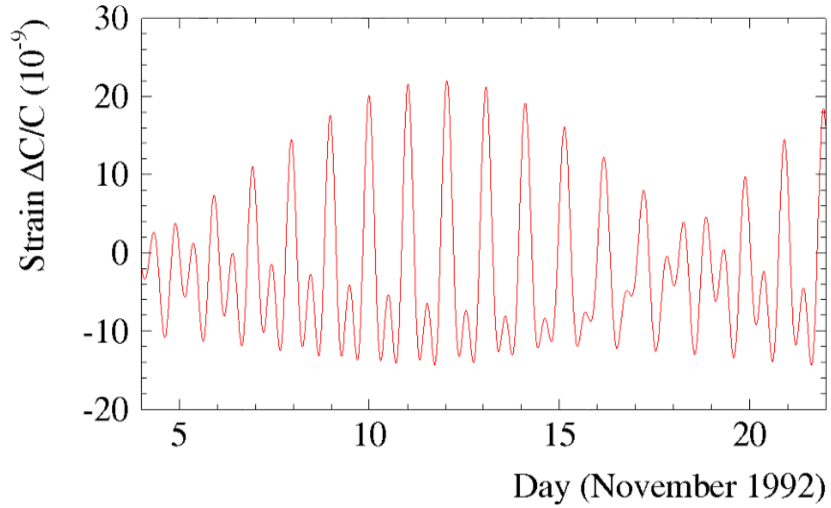


E-TIDES-LEP

Earth tides affect the accelerator circumference:

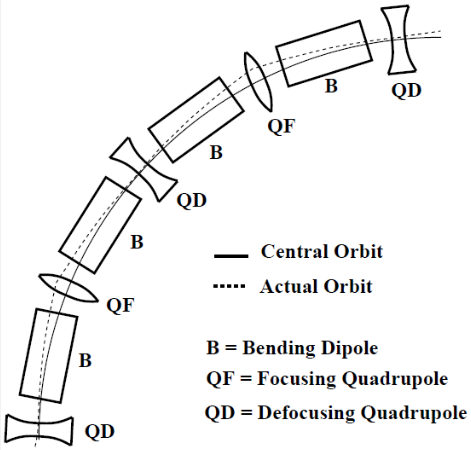
- The Moon contributes 2/3, the Sun 1/3.
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions possible (~%).

LEP tide predictions for Nov. 1992



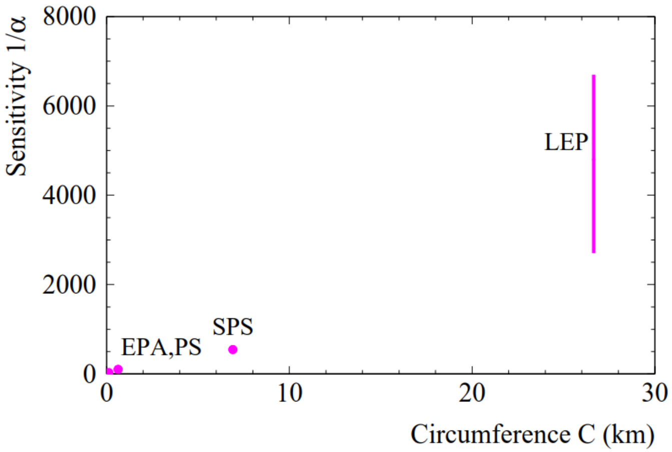
The relative circumference change amounts to ***~10^{-8}*** *!*

Gravitational waves detector *reach sensitivities of* ***~10^{-21}*** *!*



Sensitivity of the energy to circumference changes :

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



As the **machine size or the horizontal focusing** is increased, the quadrupole contribution grows:

$$\frac{1}{\alpha} \propto Q_x^2$$

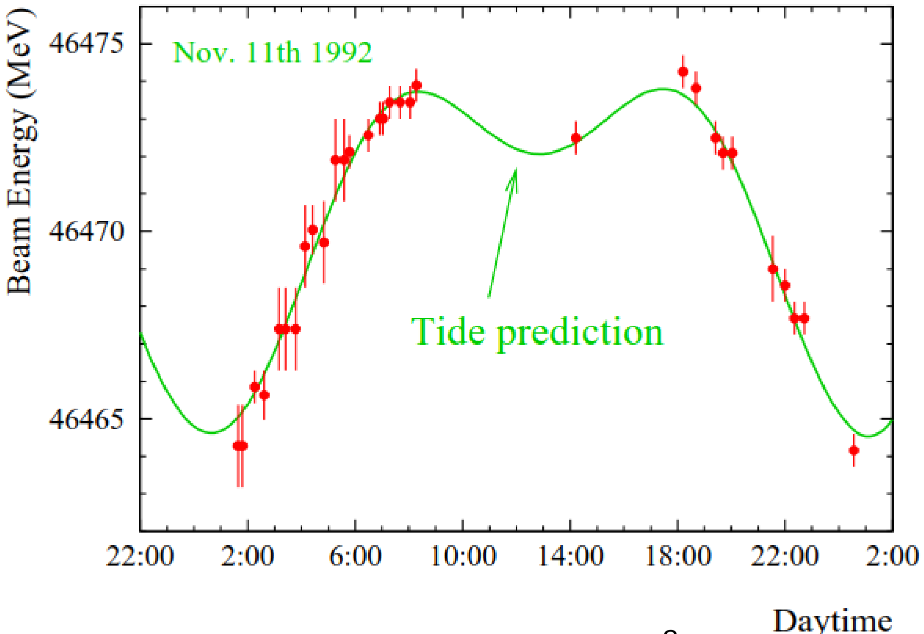
Q_x is the horizontal betatron tune

For large machines like LEP, LHC, FCC the beam energy is **sensitive to circumference changes of $\Delta C/C \sim 10^{-9}$** !

Moonrise over LEP

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

November 1992 : a historic tide experiment during new moon where the LEP beam energy was tracked over ~ 24 hours.



LEP: $\alpha \approx 2\times10^{-4}$

FCC-ee: $\alpha \approx (1-2)\times10^{-5}$

At FCC-ee the same experiment would yield an energy variation of 100-200 MeV !

The strain range is $4\text{x}10^{-8}$

($\Delta C/C$ = ~1 mm/26.7 km)

E-TIDES-LEP

Success in the press !

Moon Found Behind Particle-Accelerator Puzzle

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

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

Comment la lune a trompé le CERN : les physiciens expliquent

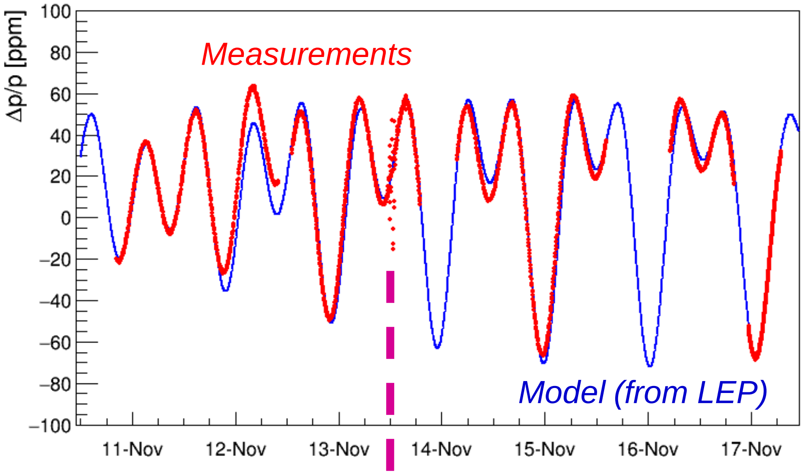
Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences : des « marées terrestres » provoquées par la lun

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 than LEP.
- 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.

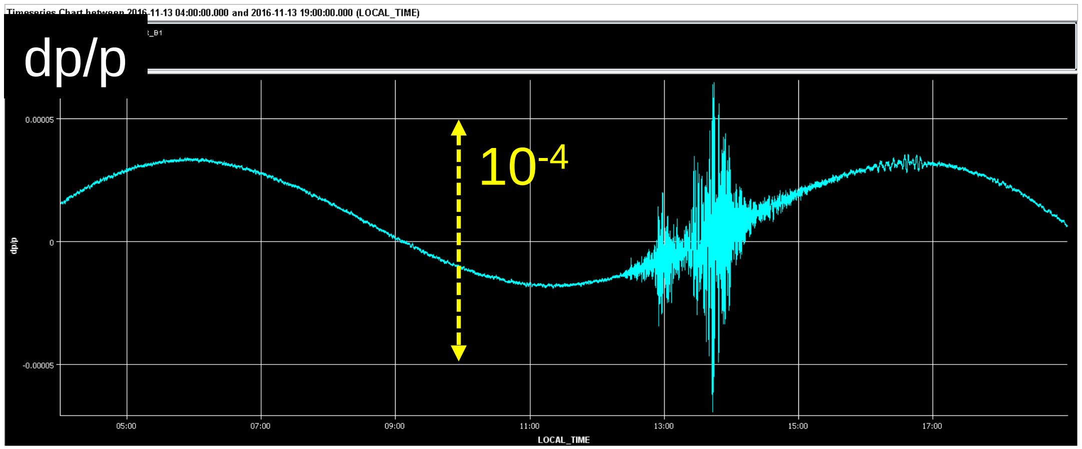


Tide observations (from orbit changes) during the 2016 LHC pPb run at 4 TeV

E-LHC

Earthquake in New Zealand

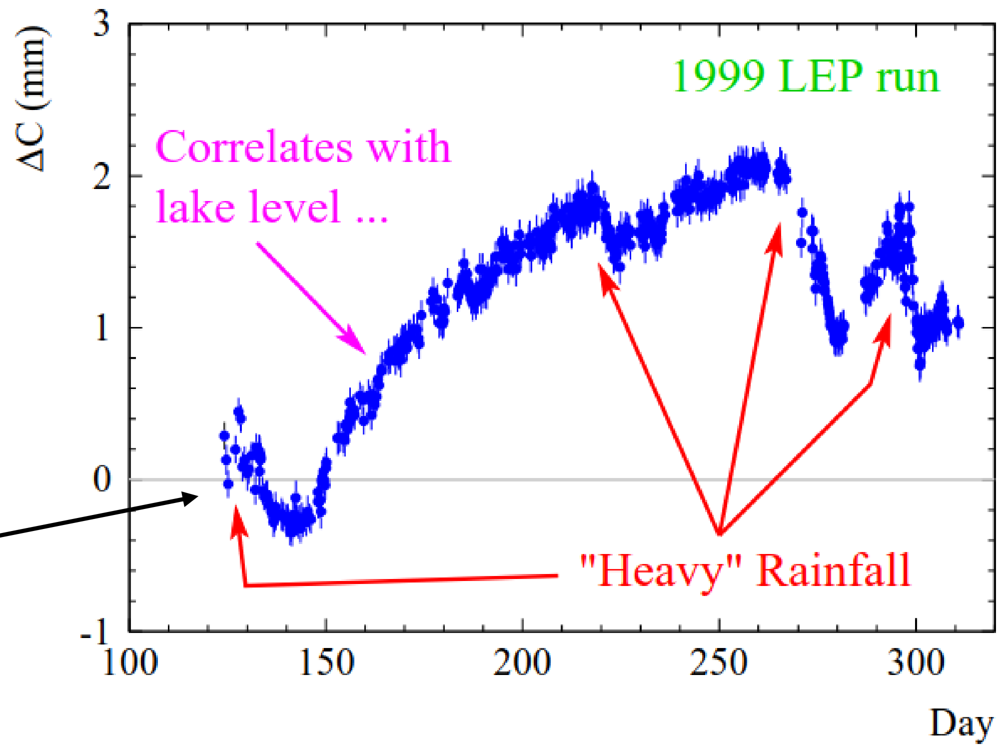
The pressure waves induce a modulation of the circumference



Underground water

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

- Rainfall (underground water) seems to play a role.
- The yearly trend is observed every year, also for LHC.



The circumference changes are measured with the beam position monitors

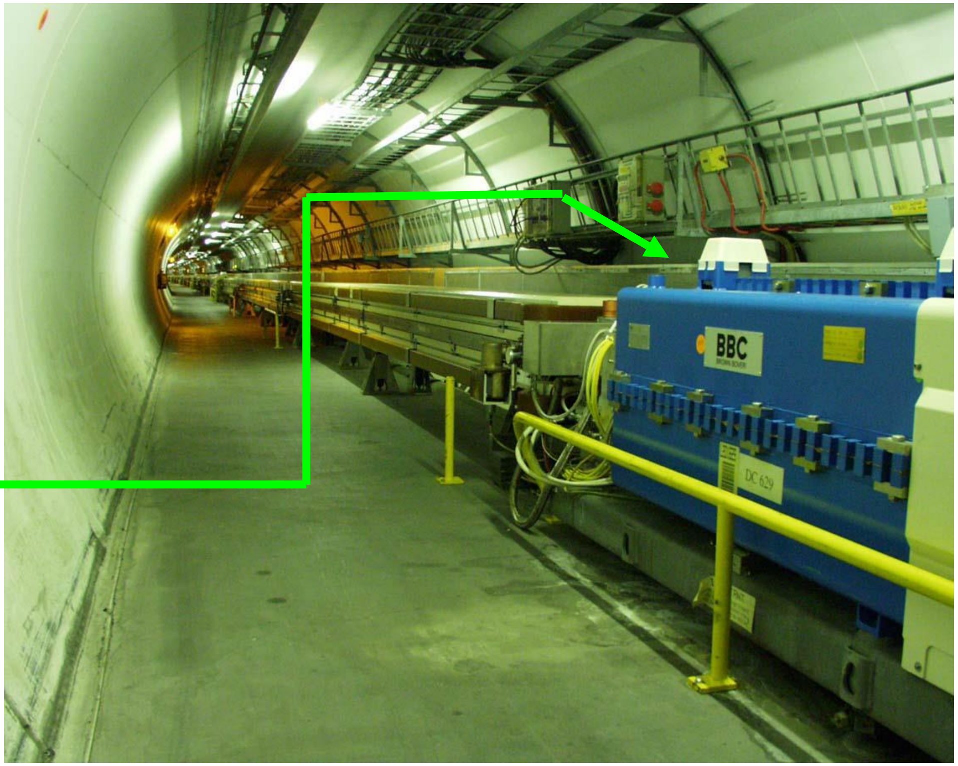
E-FINAL-LEP1

First LEP 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.

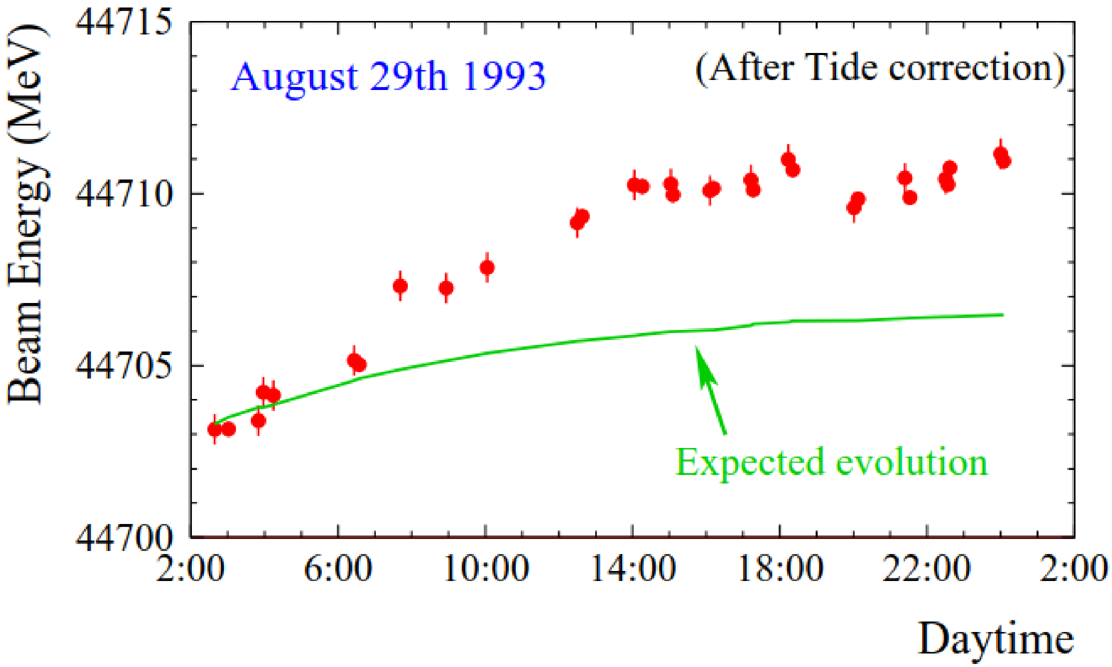


E-FINAL-LEP1

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

Exception:

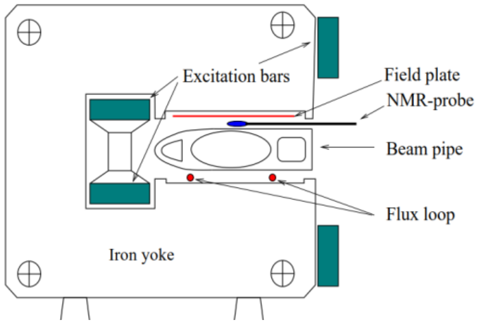
An unexplained energy increase of 5 MeV was observed in **ONE** experiment.



It will remain unexplained for two years…

E-FINAL-LEP1

The field ghost



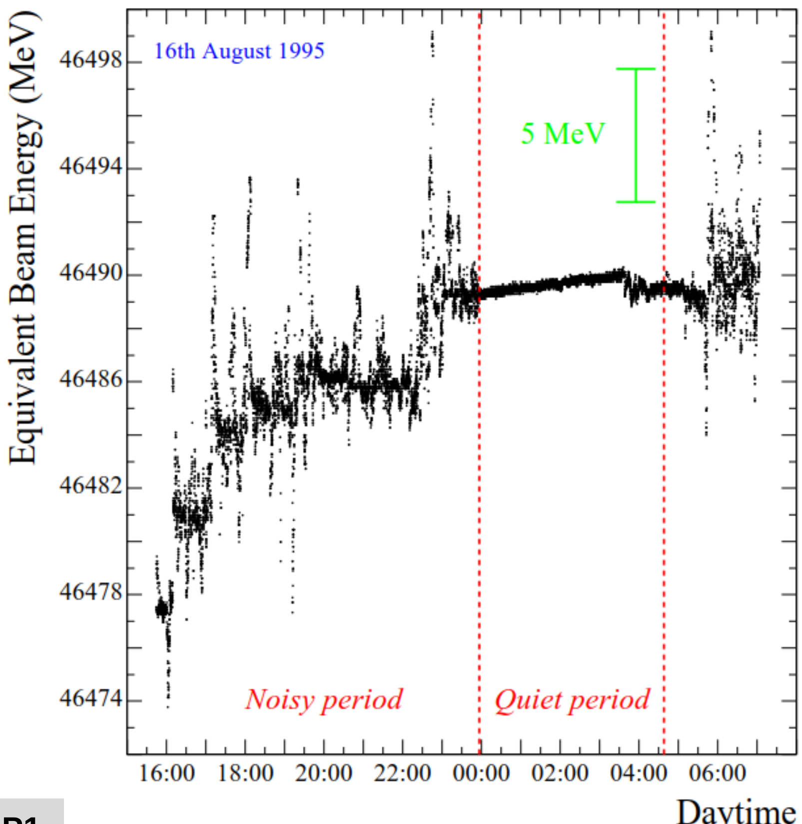
Summer 1995 : NMR probes were installed in some dipoles providing the first in-situ field measurements during operation

The data showed (unexpected) :

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

Human activity !

But which one ??



E-FINAL-LEP1

The explanation was provided by an electrician from the Swiss electricity company EOS: they know that effect very well !

DC railway

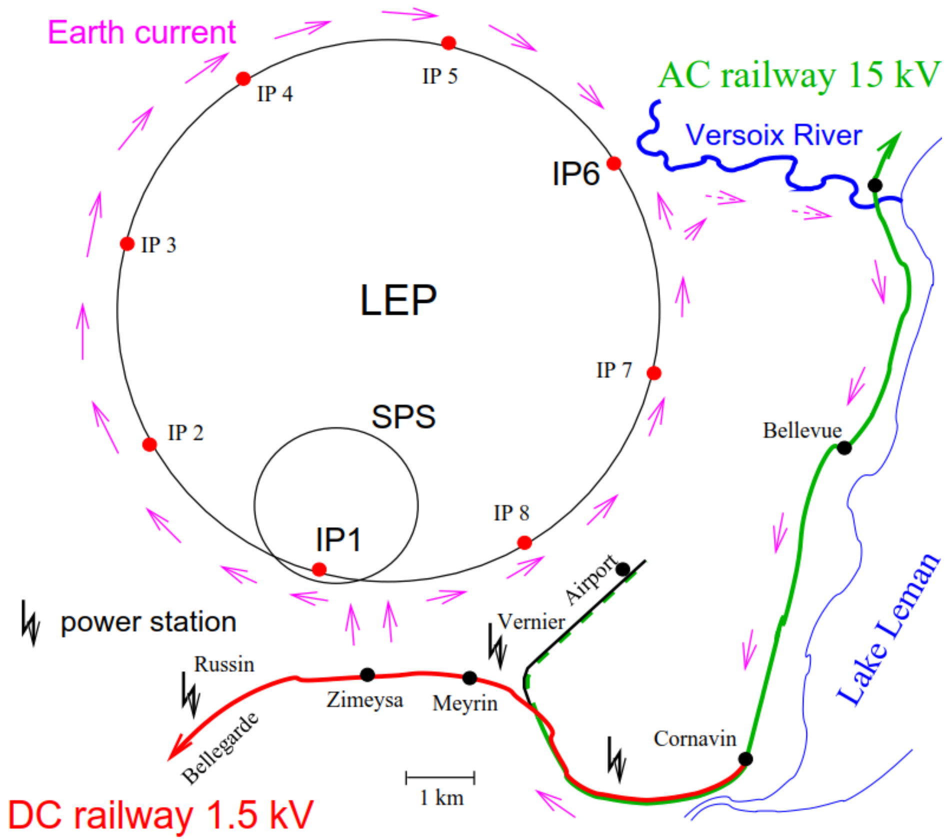
Vagabond currents from trains and subways

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

Vagabonding currents

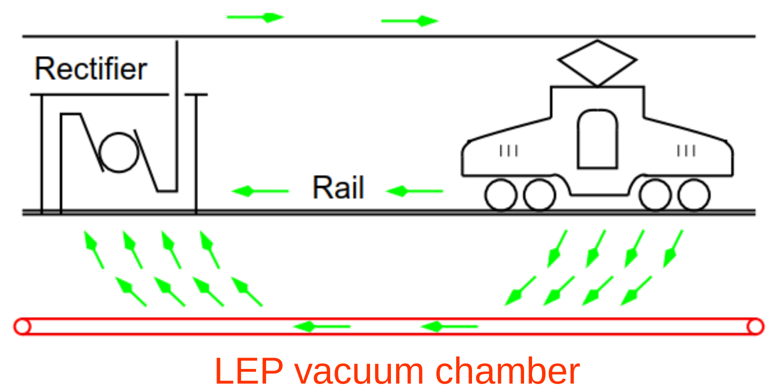
LEP was affected by the French DC railway line Geneva-Bellegarde (it was just recently upgraded to AC operation !)

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



Entrance/exit points :

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

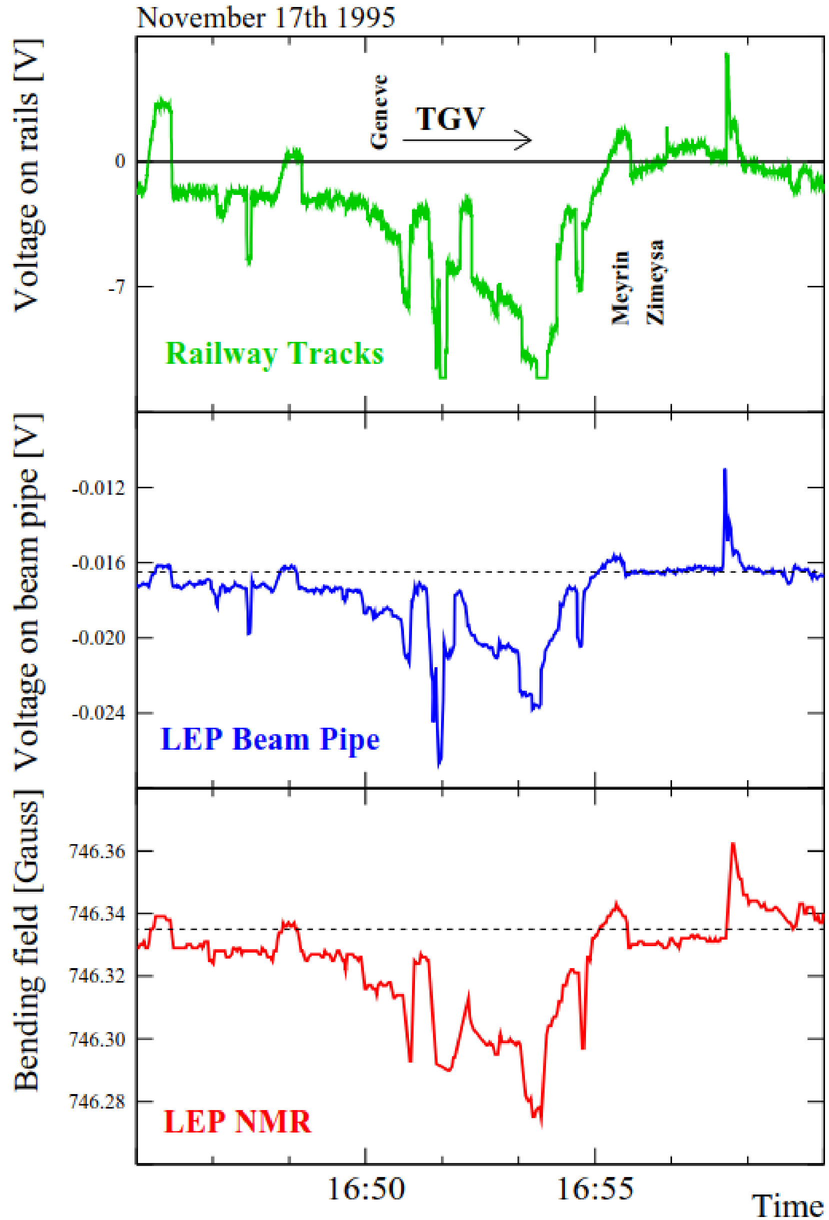


LEP Train Experiment

November 1995:

To firmly establish the effect of the trains, an experiment was organized to measure simultaneously the **voltage on the railway tracks**, on the **LEP vacuum chamber** and the **NMR field**:

- The departure of the TGV high speed train to Paris is clearly visible on the LEP vacuum chamber !



E-FINAL-LEP1/2

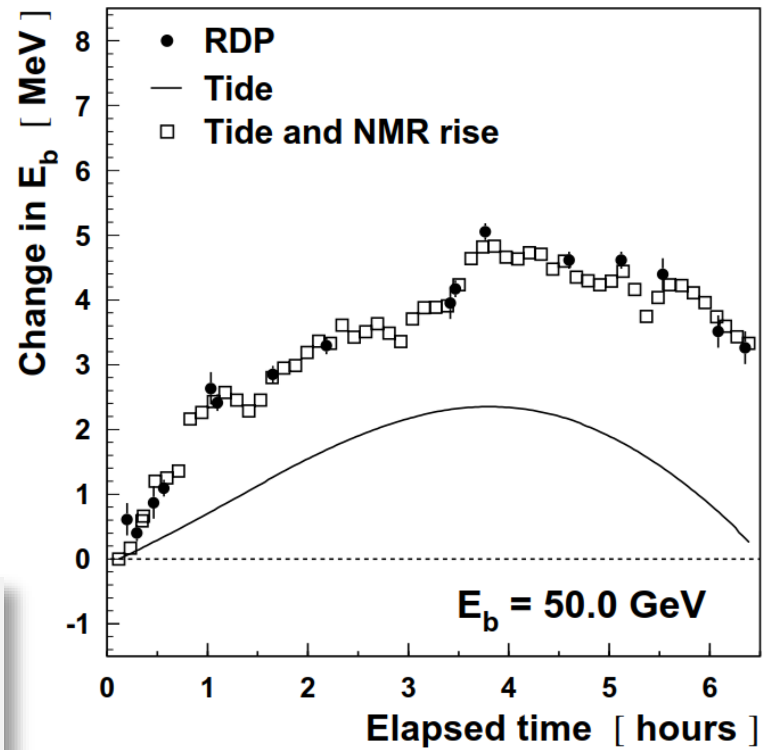
Final LEP energy model

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 it was finally possible to interpolate the LEP beam energy with sub-MeV precision !

The final LEP beam energy uncertainty was around 1 MeV

The **aim of FCC-ee is to reduce the uncertainty to < 0.1 MeV**, the lesson of LEP is that the energy must be measured in parallel to colliding beams – one will not be able to rely on a model.



E-FINAL-LEP2

Introduction

Radiative polarization in storage rings

Beam energy measurement techniques

Beam energy at LEP/FCC-ee

From beam to center-of-mass

- For the experiments installed around a collider, the **center-of-mass energy** (CM) is the relevant quantity for physics processes (and not the beam energy). To first order, neglecting the impact of a possible crossing angle at the IP, with P the relativistic momentum vector:

$$P_1 = (E_1, \vec{p}_1) \qquad P_2 = (E_2, \vec{p}_2)$$

head-on

$$\vec{p}_1 + \vec{p}_2 = 0$$

$$E_{cm} = \sqrt{(P_1 + P_2)^2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} = E_1 + E_2 = 2E_{beam}$$

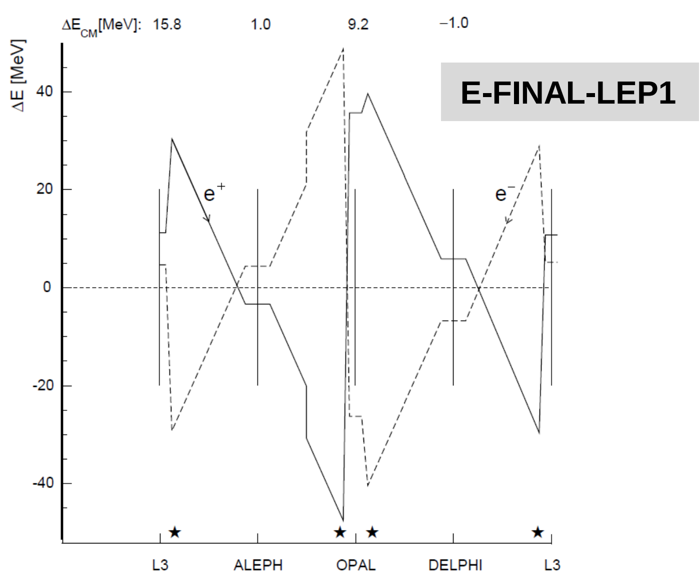
- Two important processes may induce **local shifts of the energy**:
  - **Distributed energy losses** induced mainly by synchrotron radiation (SR) → impact on the local **beam energy**,
  - **Local dispersion at the IP** → impact on the **CM energy**.

Energy sawtooth

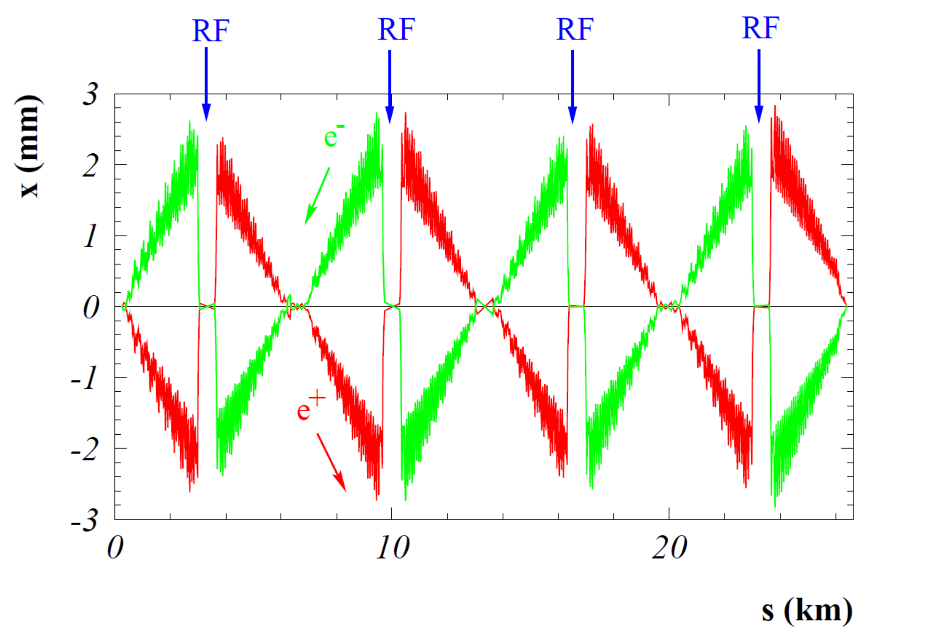
- The energy loss by SR along an e^+e^- storage ring is compensated by the RF system which is usually lumped into few straight sections, leading to a so-called **energy sawtooth** along the ring.
- The local energy at the IPs depends on the energy loss distribution and on the RF voltages and phases (and their errors).
  - At LEP RF system errors could shift E_{cm} by up to ~16 MeV, and E_{cm} uncertainties reached O(1 MeV).
  - FCC-ee aims to each uncertainties << 0.1 MeV. This is best obtained with a RF system concentrated in a single location (for each ring), as this minimizes the uncertainties due to the RF system itself (voltage and phase).

E-FINAL-LEP2

Energy sawtooth at LEP (45 GeV)

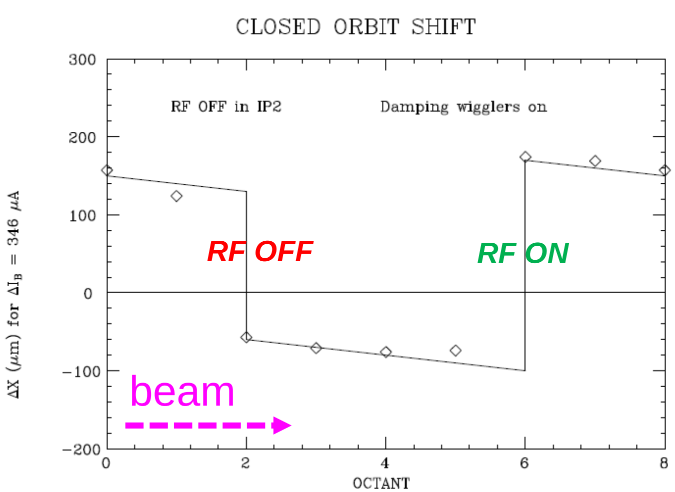


Orbit shift due to energy sawtooth at LEP (96 GeV)



- Distributed and localized **longitudinal impedances** introduce additional energy losses that affect the local energy offset along the ring.
  - A distributed impedance, for example resistive wall, can mimic a small energy sawtooth.
  - Local impedances, like collimators or RF cavities, may generate 'step-wise' energy changes.
- Such energy changes may be **difficult to predict accurately** and can affect the energy at the ~100 keV level.
  - For FCC-ee the longitudinal impedances add ~1-4 MeV energy loss to 36 MeV SR energy loss at 45 GeV.

Longitudinal impedance at LEP



Mean orbit offset in each LEP arc between a high and a low intensity bunch.

The step is due to RF cavities, the slope due to the impedance from resistive wall and from the distributed bellows.

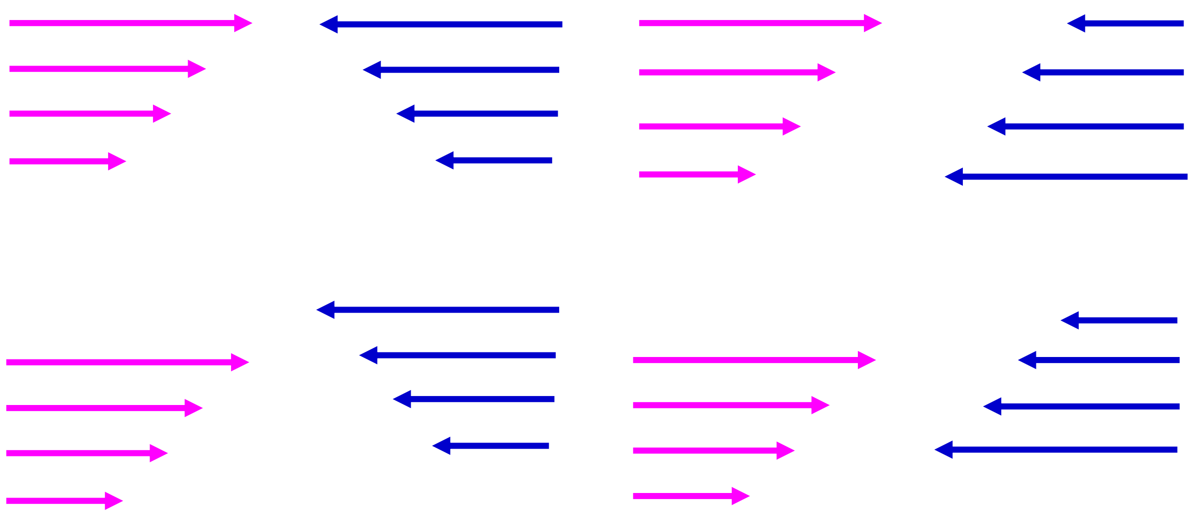
Measurements agree within ~10% with model.

Dispersion at the IP

- Despite the fact that dispersion must be well corrected in a e^+e^- collider to obtain the smallest possible vertical emittances, there can always be some **residual dispersion at the IP**.
- Dispersion sorts the particles by energy (deviation) in the transverse coordinates, and may lead to subtle biases when the **dispersion** has **opposite sign** between the two beams.

E-CM-DISLEP

Equal dispersion **Opposite sign dispersion**



Reduction of the centre-mass energy spread *due to the anti-correlation !*

Shift of the centre-mass energy *due to the anti-correlation if the beams do not collide head-on*

Dispersion at the IP II

- A difference in dispersion ΔD^* at the IP between the beams leads to energy shifts in the centre of mass:

$$\Delta E_{CM} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2}$$

E-CM-DISLEP

σ_E = energy spread

σ_U = betatron beam size

u_0 = beam offset at IP

- Even with tiny offsets corresponding to fractions of the beam size, the CM energy shift can be sizable, O(MeV). The beam overlap must be continuously controlled to avoid undesired biases !

- There is an associated impact on the CM energy spread that can be reduced (!) artificially by generating deliberately large dispersion of opposite sign – **mono-chromatization**.
  - This concept could be used to generate very low energy spread for direct H production (s-channel) at a beam energy of $m_H/2$ ~ 60 GeV.

Outlook

- The long energy calibration program at LEP was very successful, but it highlighted how much systematic effects – some of them totally unexpected – can potentially spoil the final accuracy.

- For FCC-ee the struggle to reach the 0.1 MeV scale – one order of magnitude below LEP – announces a long and even more detailed hunt for systematic effects than at LEP !

CERN

References

Polarization

[P-REV] S R Mane et al, Rep. Prog. Phys. 68 (2005) 1997–2265.

[P-LEP-REV] R. Assmann et al, Spin Dynamics In LEP With 40-100 GeV Beams, Proceedings of the 14th International Spin Physics Symposium, 2000, Osaka.

[P-LEP1] R. Assmann et al., Polarization studies at LEP in 1993, CERN SL/94-08 (1994).

[P-HERA] D. P. Barber et al., High spin polarization at the HERA electron storage ring, NIMA 338, 166 (1994).

[P-HERA-ROT] J. Buon, K. Steffen, NIM A245 (1986) 248 2,61.

[P-FCCEE] E. Gianfelice-Wendt, PRAB 19, 101005 (2016)

[P-SNAKE-RHIC] V. Ranjbar et al, FITTING HELICAL SNAKE AND ROTATOR FIELD STRENGTH MEASUREMENTS IN RHIC. Proceeding of PAC01.

[P-SNAKE-RHIC-2] V. Ranjbar et al, Phys. Rev. Lett. 91, 034801 (2003).

Energy calibration

[E-TIDES-LEP] L. Arnaudon et al., Nucl. Instr. Meth. A 357 (1995) 249.

[E-OVER-LEP] L. Arnaudon et al., Z. Phys. C 66 (1995) 45.

[E-FINAL-LEP1] R. Assmann et al., Eur. Phys. J. C 6 (1999) 2, 187-223.

[E-FINAL-LEP2] R. Assmann et al., Eur. Phys. J. C 39 (2005), 253-292.

[E-CM-DISLEP] J. Jowett et al, Influence of Dispersion and Collision Offsets on the Center-of-mass Energy at LEP, CERN SL/ Note 95-46 (OP)

[E-LHC] E. Todesco and J. Wenninger, PRAB 20, 081003 (2017).

[E-BEPC] M.N. Achasov and N.Yu. Muchnoi, JINST 12 C08007 (2017).

[E-COMPT] V.V. Kaminski et al, CERN-Proceedings-2017-001.

[E-DUKE] C. Sun et al, PRSTAB 12, 062801 (2009).

[E-IMPED-LEP] D. Brandt et al, MEASUREMENTS OF IMPEDANCE DISTRIBUTIONS AND INSTABILITY THRESHOLDS IN LEP, Proceedings of EPAC 96.