Precision Measurements of Beam Energy

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Contributions from many other people:
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Topics

- Motivation/Introduction
- Spin Dynamics
- Polarimeters
- Resonant Depolarization
- Applications
- Other methods of energy measurement
- Summary

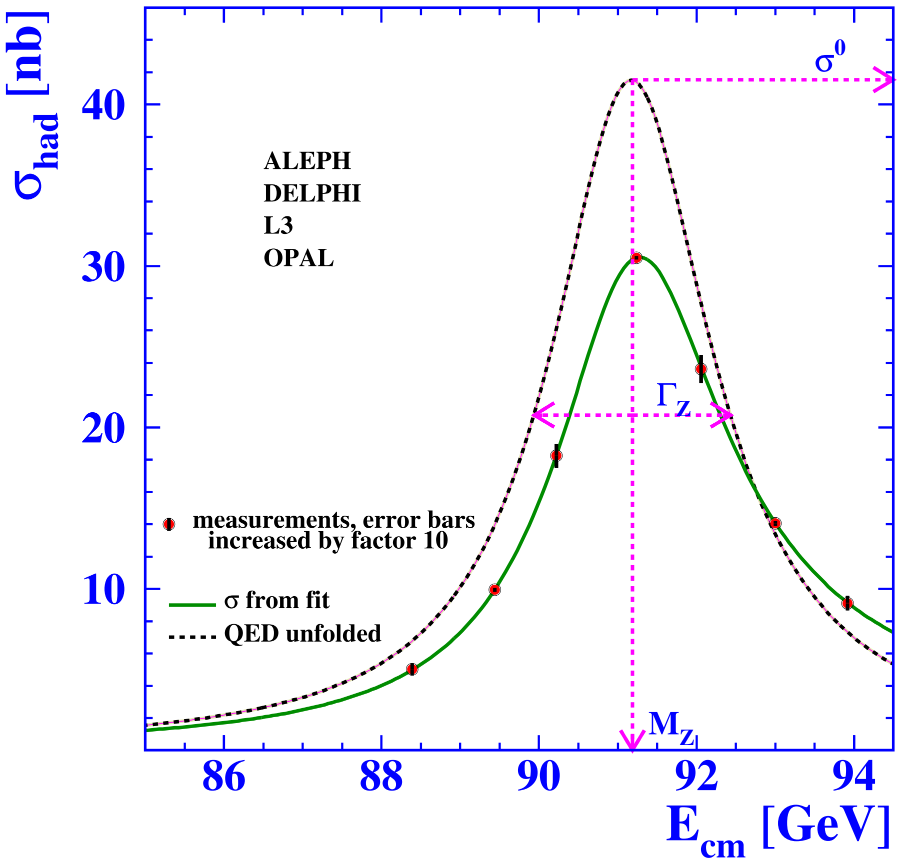
Motivation

Improvement of the determination of particle masses
obtained from resonant depolarization of polarized e^+e^- beams

Particle	World average value (MeV)	Experimental results (MeV)	Year publication	Accuracy improvement
$K^\pm$	493.84 ± 0.13	493.670 ± 0.029	1979	5
K^0	497.67 ± 0.13	497.661 ± 0.033	1987	4
ω	782.40 ± 0.20	781.780 ± 0.10	1983	2
ϕ	1019.7 ± 0.24	1019.52 ± 0.13	1975	2.5
J/ψ	3097.1 ± 0.90	3096.93 ± 0.09	1981	10
ψ'	3685.3 ± 1.20	3686.00 ± 0.10	1981	10
Υ	9456.2 ± 9.50	9460.59 ± 0.12	1986	80
Υ'	10016.0 ± 10.	10023.6 ± 0.5	1984	20
Υ''	10347.0 ± 10.	10355.3 ± 0.5	1984	20

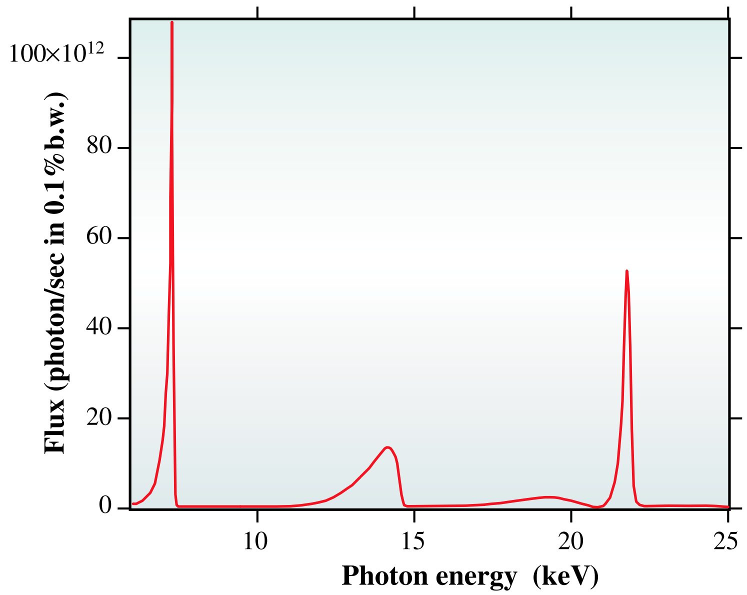
- Using resonant depolarization allows an ultra high precision measurement of the beam energy
- Many applications: precise determination of particle masses, ...

Motivation



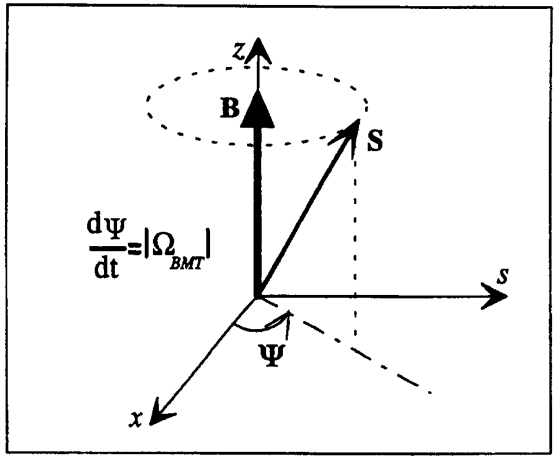
- Using resonant depolarization allows an ultra high precision measurement of the beam energy
- Another application: resonance linewidths. Example of LEP: Precision measurement of Z_0 width allowed conclusion that only 3 lepton families with light neutrinos exist.

Motivation



- In terms of accelerator physics it is often important to know beam energy precisely (cross check of magnetic measurement data, direct measurement of momentum compaction factor with high resolution).
- At synchrotron light sources a reasonable stability of the beam energy is important (energy stability of undulator beams, etc.) which can be verfied with resonant depolarization.

Spin Motion in Electromagnetic Fields



- Spin motion of non radiating electron ⇒ BMT-equation:

$$\frac{d\vec{S}}{ds} = \vec{\Omega}_{\rm lab} \times \vec{S}$$

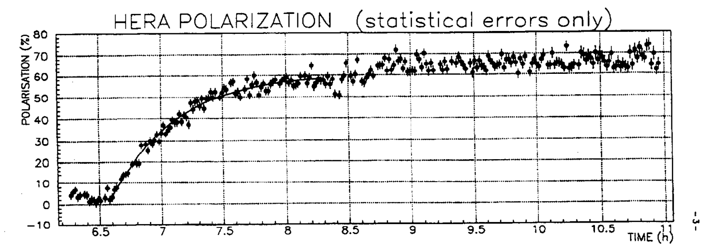
for $\gamma \gg 1$

$$\vec{\Omega}_{\rm lab} = \frac{e}{m_e\, c\, \gamma_{\rm lab}} \left((1+a)\vec{B}_{\|} + (1+\gamma_{\rm lab} a)\vec{B}_{\perp} \right)$$

a: gyromagnetic anomaly $a = 1.159652 \cdot 10^{-3}$ for electrons and 1.792846 for protons

- flat ring ⇒ $\nu_{sp} = \gamma a$
- only vertical component of spin is stable

Self Polarization in Lepton Rings



	VEPP[10]	VEPP2-M[11]	ACO[8,9]	BESSY[44]	SPEAR[45]	VEPP4[46]
E(GeV)	0.640	0.625	0.536	0.800	3.70	5.0
τ_p(min)	50	70	160	150	15	40
P(%)	52	90	90	>75	>70	80

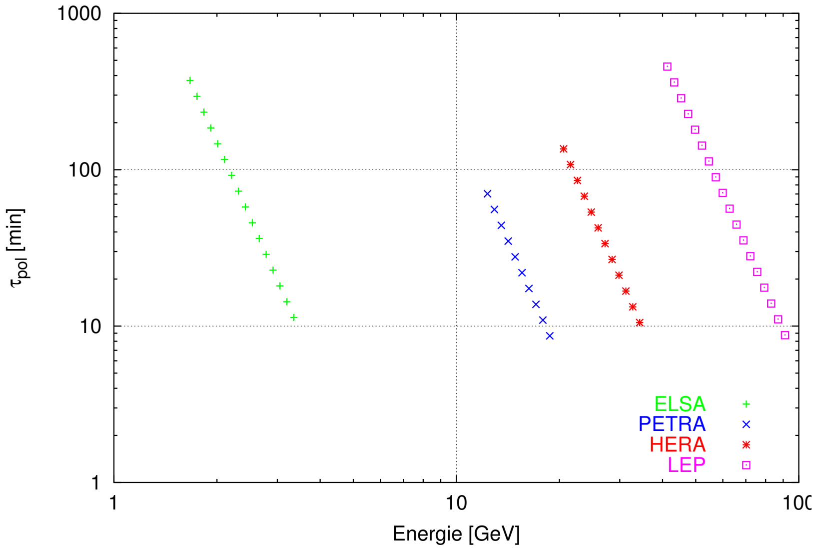
	DORIS II[47]	CESR[48]	PETRA[49]	HERA[19]	TRISTAN[50]	LEP[51]
E(GeV)	5.0	4.7	16.5	26.7	29	46.5
τ_p(min)	4	300	18	40	2	300
P(%)	80	30^{*}	80^{**}	70^{**}	75^{**}	57^{**}

- radiating leptons ⇒ polarization buildup (Sokolov-Ternov effect):

$$P = A\left(1 - e^{-\frac{t}{\tau_{\rm pol}}}\right), \quad \frac{1}{\tau_{\rm pol}} = \frac{5\sqrt{3}}{8}\,\frac{c\lambda_c r_e}{2\pi}\,\frac{\gamma^5}{\rho^3}$$

- has been observed at most lepton storage rings that have looked for the effect.

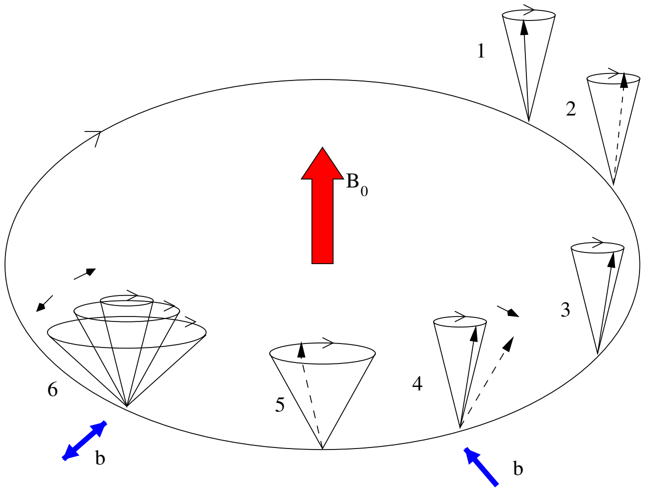
Simulating equilibrium polarization



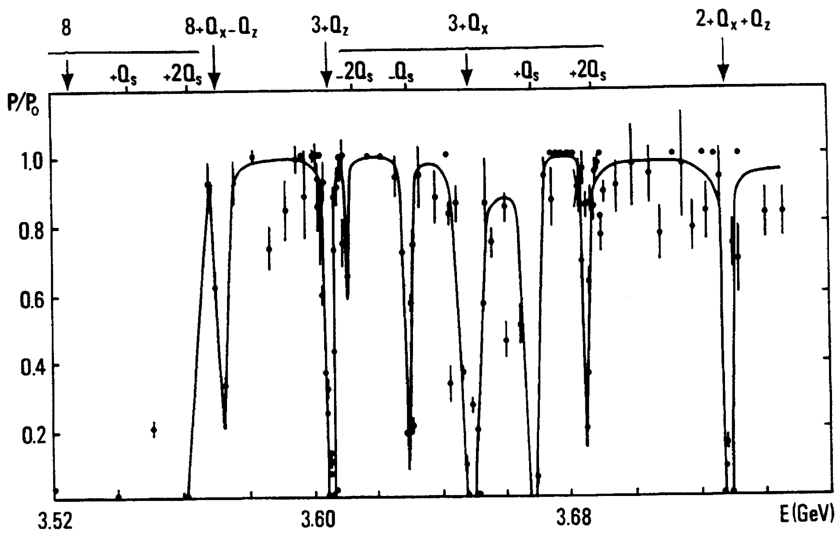
- Even though the polarization buildup time for a given ring strongly depends on the beam energy, it has about the same order of magnitude for most lepton storage rings.
- Reason is that it also scales with the bending radius and machines with higher energy typically have to have much larger bending radius to keep equilibrium emittance small and SR losses acceptable.

Depolarizing Resonances

- Depolarization due to resonant coupling of spin precession with horizontal magnetic fields
- intrinsic resonances: vertical betatron oszillations $\Rightarrow$ horizontal magnetic fields in quadrupoles (and sextupoles ...)
  resonance condition: $\gamma a = (kP \pm Q_z)$
- imperfection resonances: magnet errors (field- and position errors) $\Rightarrow$ closed orbit distortions
  resonance condition: $\gamma a = k$
- weaker resonances: gradient errors, coupling, sextupoles, synchrotron satellites

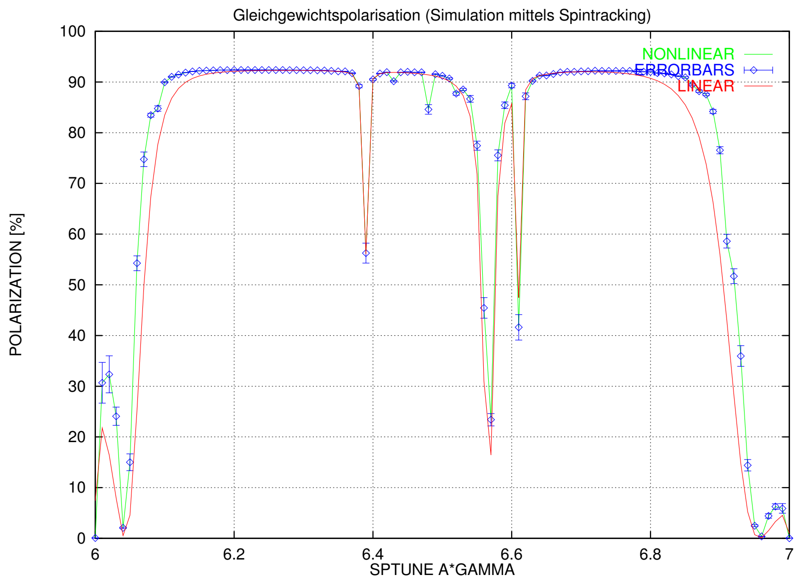


Self Polarization and Resonances



- Equilibrium of self polarization and resonances depends on energy.
- Resonance strength increases with energy.
- Imperfection resonance strength scales with the closed orbit error
- Intrinsic resonance strengths scales with the vertical emittance

Simulating equilibrium polarization



- Using spin tracking codes, one can calculate the equilibrium between polarizing and depolarizing effects.
- Using the simulations, one can optimize the correction techniques (orbit correction, harmonic spin matching, coupling correction, ...)
- Correction is much faster, if one has a good model of the machine lattice (predictive spin mathcing).

Polarimeters

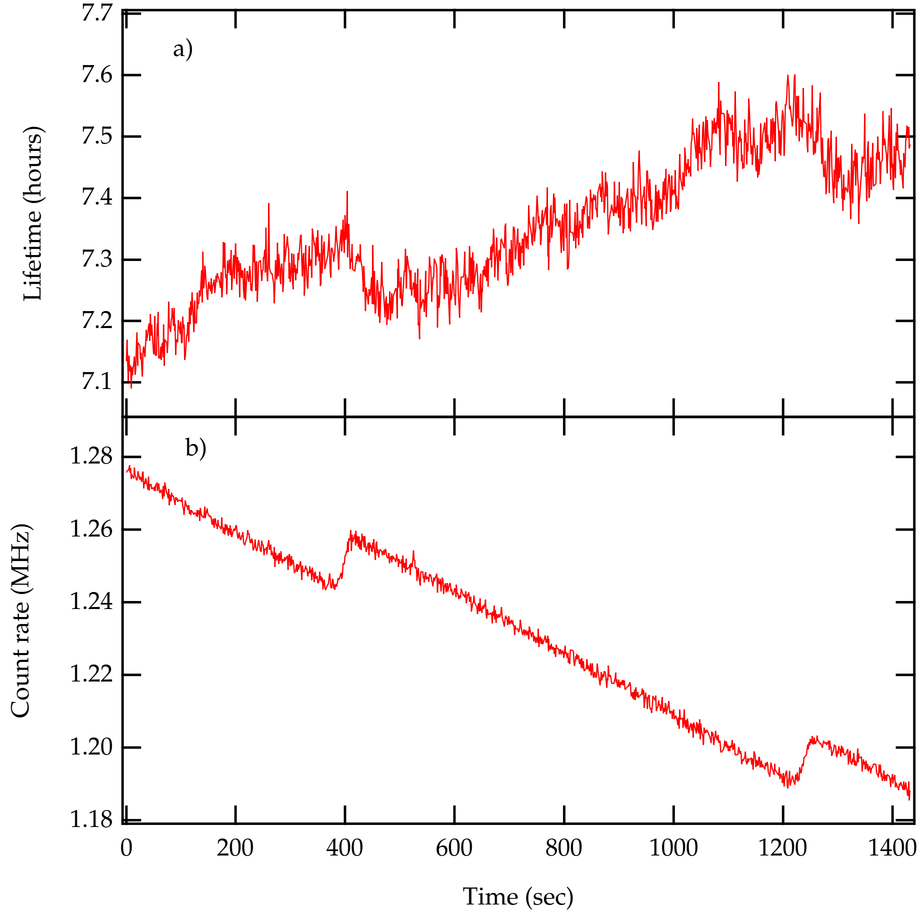
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \left(1 + P_T P_B A_{zz}(\theta)\right)$$

$$\frac{d\sigma_0}{d\Omega} = \left[\frac{\alpha(4-\sin^2\theta)}{2E_e^{CMS}\sin^2\theta}\right]^2$$

$$A_{zz}(\theta) = \frac{(-\sin^2\theta)(8-\sin^2\theta)}{(4-\sin^2\theta)^2}$$

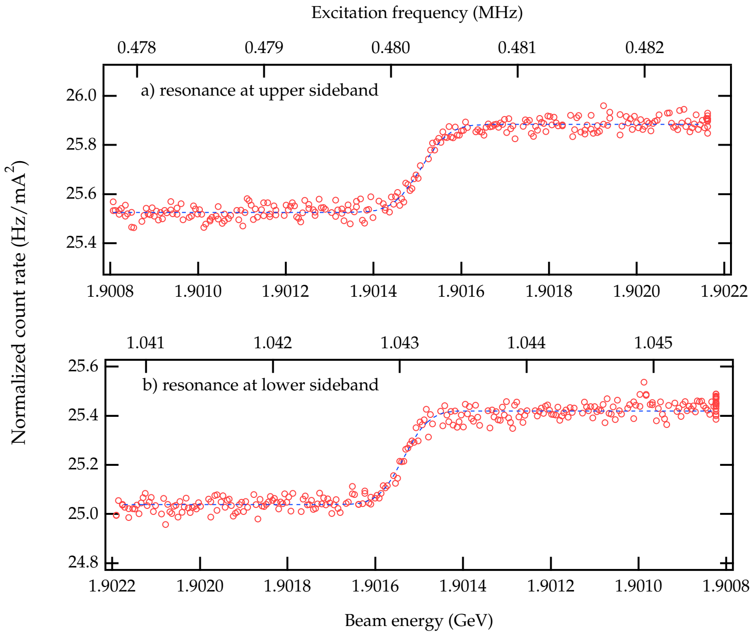
- All polarimters use asymmetry in scattering cross sections
- Types include Compton-polarimeters (laser photons head on onto beam, spatial asymmetry in backscattered photons), Møller polarimeters (polarized electrons on polarized electrons mostly in target foils), Mott polarimeters, ...
- Storage rings typically use Compton polarimeters (nearly non-destructive).
- In storage ring where the Touschek lifetime contriution is significant one can use a very simple polarimeter: Touschek scattering of two electrons within a bunch is Møller scattering. Møller scattering cross section depends on polarization (polarized beams have longer Touschek lifetime!).
- depolarization changes (reduces) Touschek lifetime by up to 20%

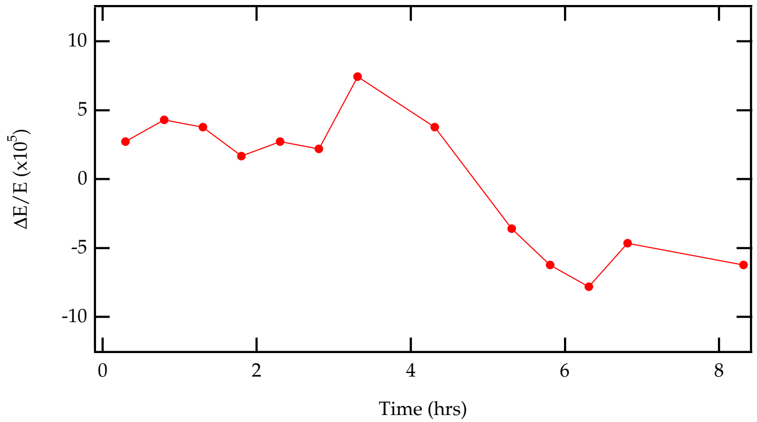
Energy Calibration/Touschek Lifetime



- Møller scattering cross section depends on polarization
- depolarization changes (reduces) Touschek lifetime by up to 20%
- experimentally simple: stripline kicker for tune measurement is sufficient + gamma telescope
- partial depolarization allows for 'fast', multiple measurements

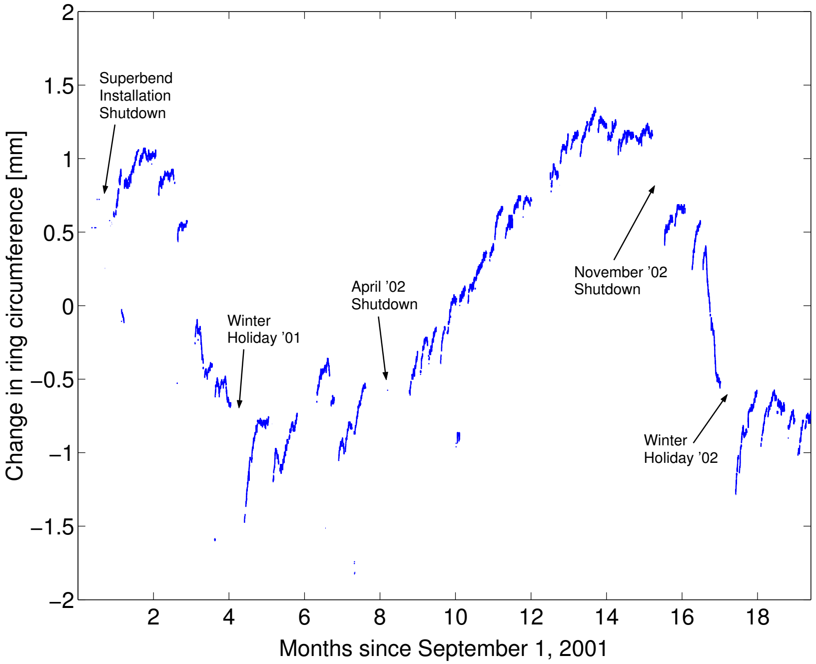
Energy Calibration II





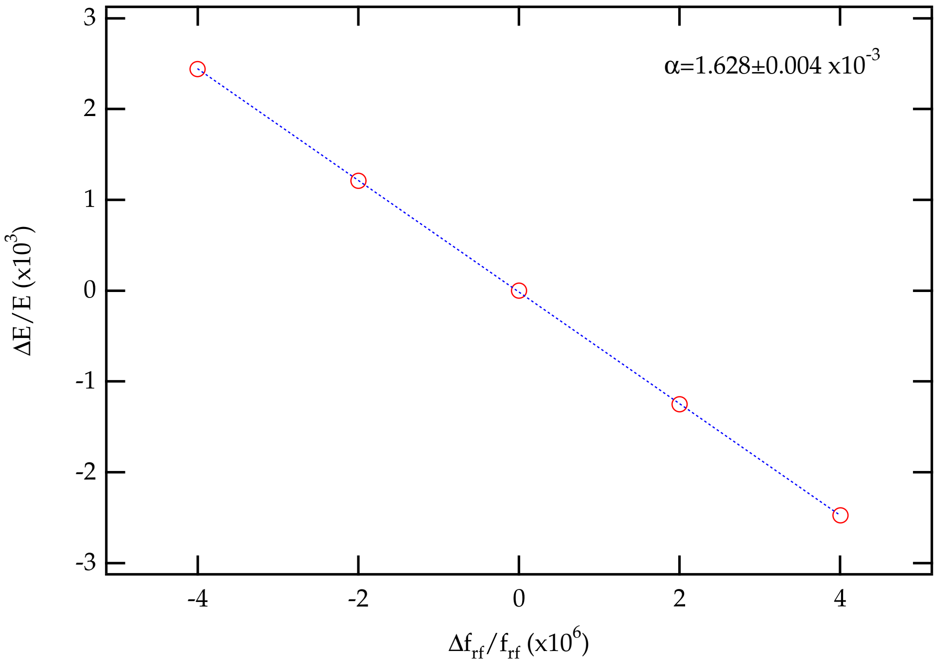
- partial depolarization allows better accuracy in sweeping measurements
- energy stable to a about $\pm 1 \cdot 10^{-4}$ within a week without rf-frequency feedback - much better with ...

RF Frequency Feedback



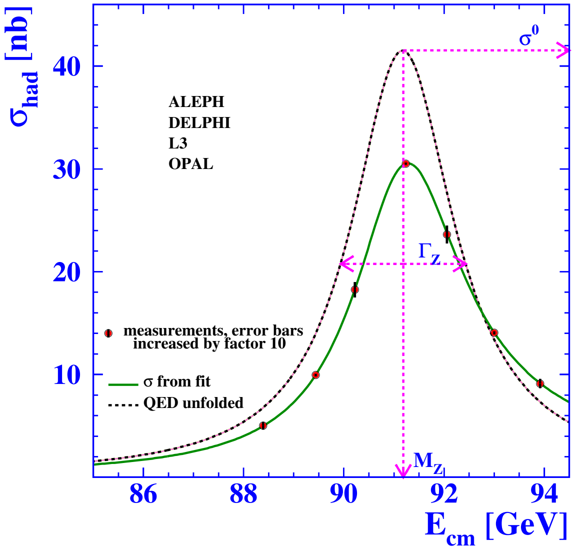
- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation,)
- RF keeps frequency fixed - beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies of all the effects in FFT (8h, 12h, 24h, 1 year)
- Verified energy stability (a few 10^{-5}) with resonant depolarization

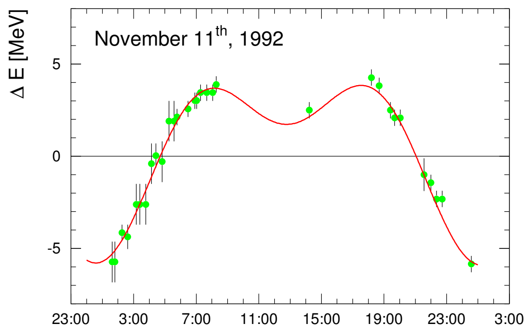
Applications: Momentum Compaction Factor



- resonant depolarization allows a precise measurement of the momentum compaction factor
- $\alpha = (1.628 \pm 0.004) \cdot 10^{-3}$
- for some machines, it could be used to measure nonlinear α terms

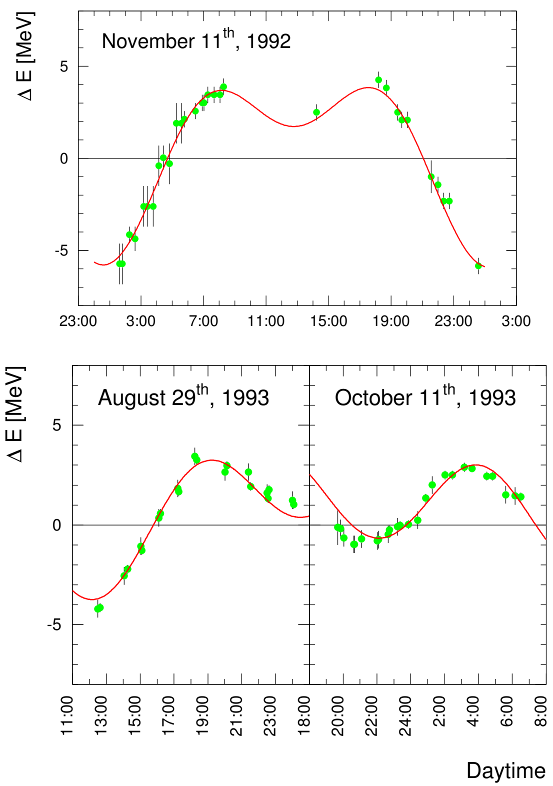
Applications: LEP





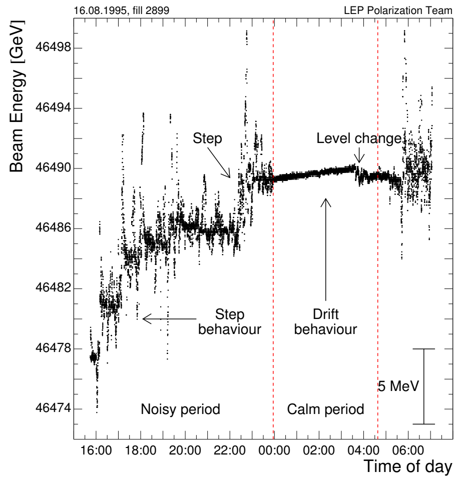
- Many electroweak precision measurements
- Precise energy calibration essential
- Found many interesting effects: Tides, Lake Geneva, TGV, ...

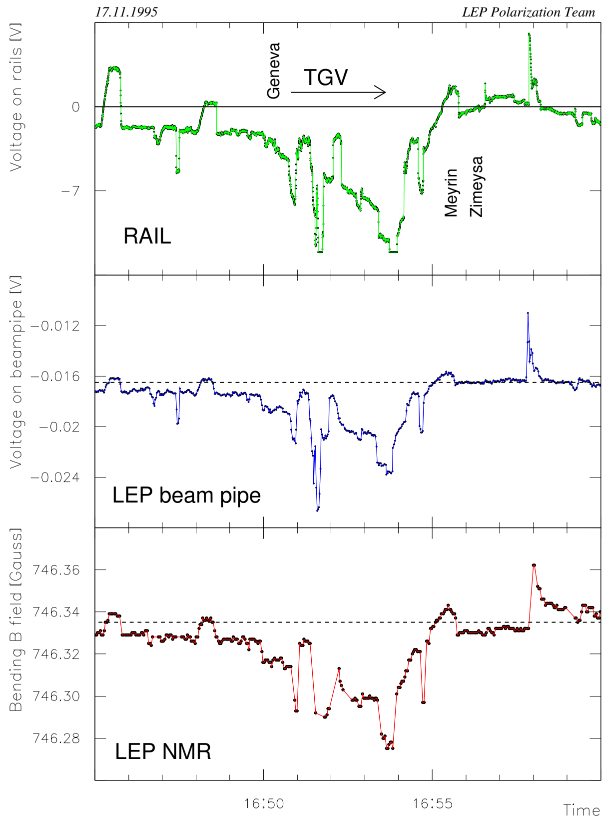
Applications: LEP



- Average tides of oceans about 0.5 m (locally much larger)
- Average tidal variation of solid ground about 1/3 of that!
- Tides cause local change in earth radius - change in ring circumference - beam energy change (scales only with momentum compaction factor, not with the size of the machine - effect is about equally strong at light sources like ESRF as it was ta LEP).
- For LEP this was very significant effect, far larger than precision of energy needed
- Measurements with resonant depolarization agreed very well with tidal predictions

LEP: TGV effect

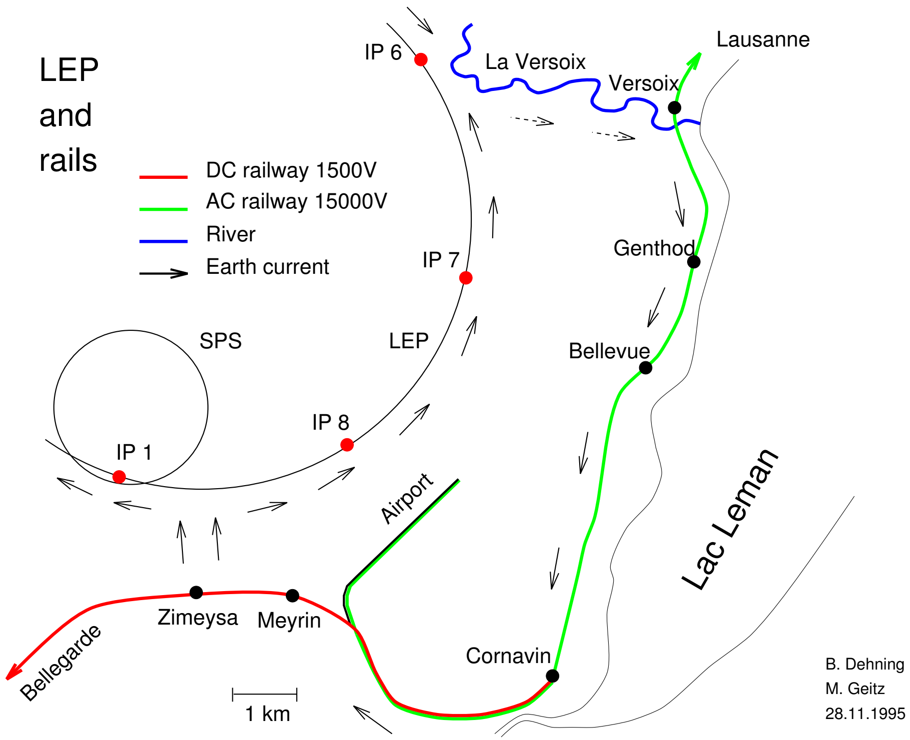




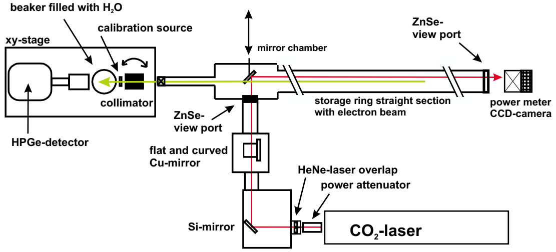
- Large noise in magnetic dipole field found
- Stopped overnight
- Intensive search - accidental discovery (on French holiday)
- Return currents of TGV

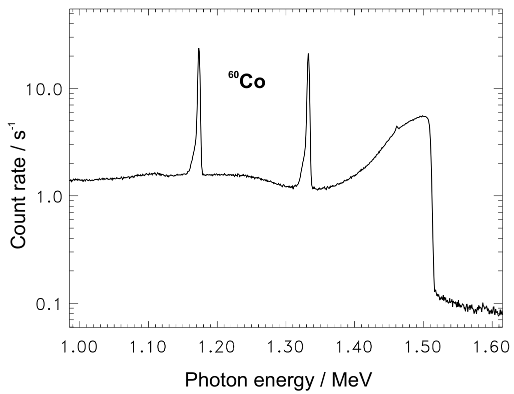
LEP: TGV effect

- Measured distribution of current on LEP vacuum chamber
- Reconstructed path of return currents from TGV



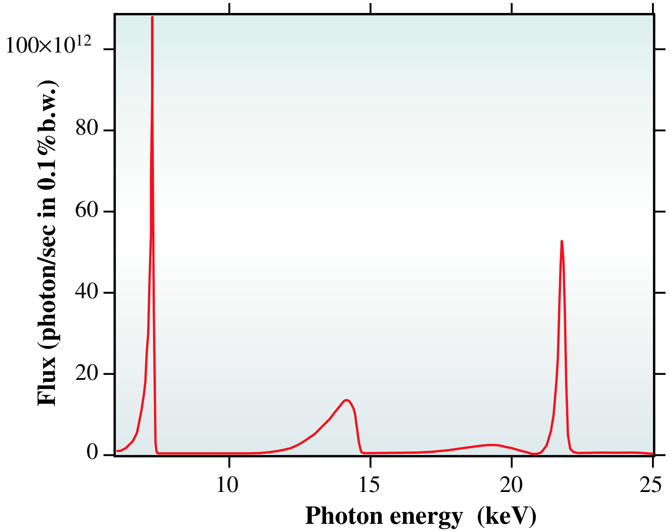
Other energy measurement methods





- Measuring energy spectrum of compton backscattered (laser) photons
- high energy edge is well defined (laser photon energy + γ^2 Lorentz boost)
- Addition of line spectrum from radioactive decay allows easy online calibration
- Advantage is relatively fast measurement - No polarizatiob necessary
- Disadvantage is lower precision

Other energy measurement methods



- Measuring the photon energy spectrum from an undulator allows fast beam energy measurement (with moderate resolution)
- Magnetic field data of undulator has to be very well known
- Monochromator has to be well understood
- Another possibility is to caclulate the beam energy based on magnetic measurements (either off-line or on-line with NMR probes) plus the readings of BPMs

Summary

- Energy calibration is a (very high) precision tool to measure some global lattice characteristics and study long term behaviour of accelerators.
- The most precise application uses reonant depolarization of a beam which typically was self-polarized because of Sokolov-Ternov effect.
- Was essential for precise determination of many particle masses and for the determination of the Z0 width, which allowed to conlude that only three (light) lepton generations exist.
- Allows absolute measurement of momentum compaction factor (otherwise fairly difficult to measure) with very high precision.