Measurements of Beam Energy

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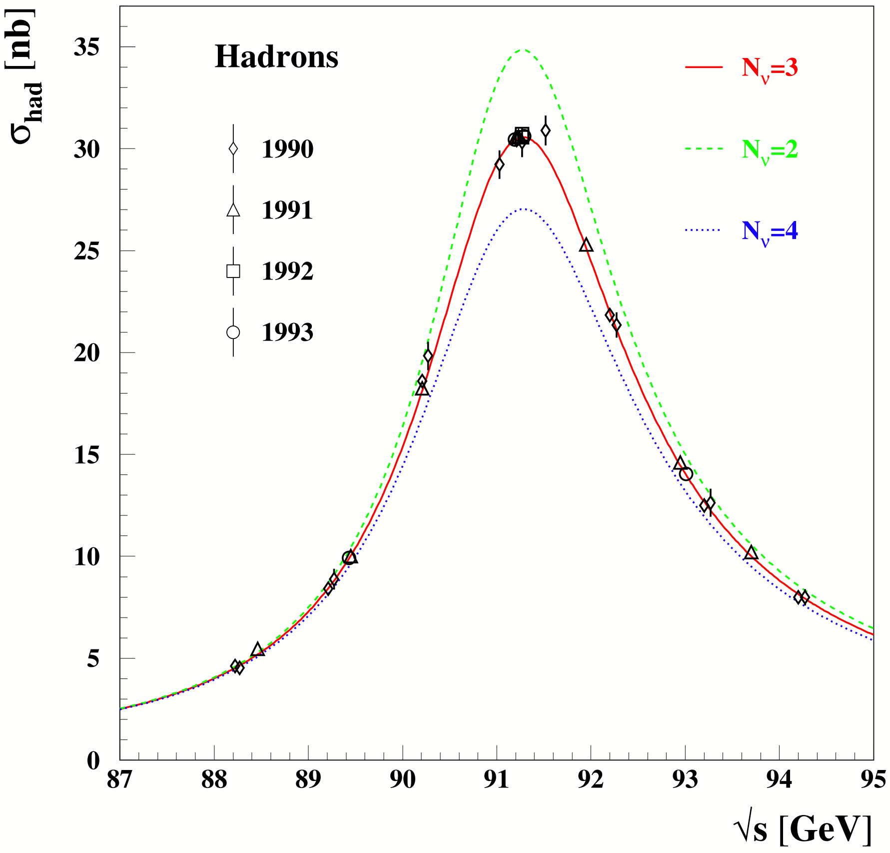
Outline

- Introduction
  - ➜ Why do we need to know the beam energy?
- Methods of energy calibration
  - ➜ classical: spectrometers
  - ➜ exotic: from particle/nuclear physics processes
  - ➜ photon based measurements
  - ➜ energy measurements from central frequency
  - ➜ best precision: resonant depolarisation
  - ➜ energy from energy losses
- Applications and results
  - ➜ Beam parameters
  - ➜ LEP energy calibration
- Summary

What for?

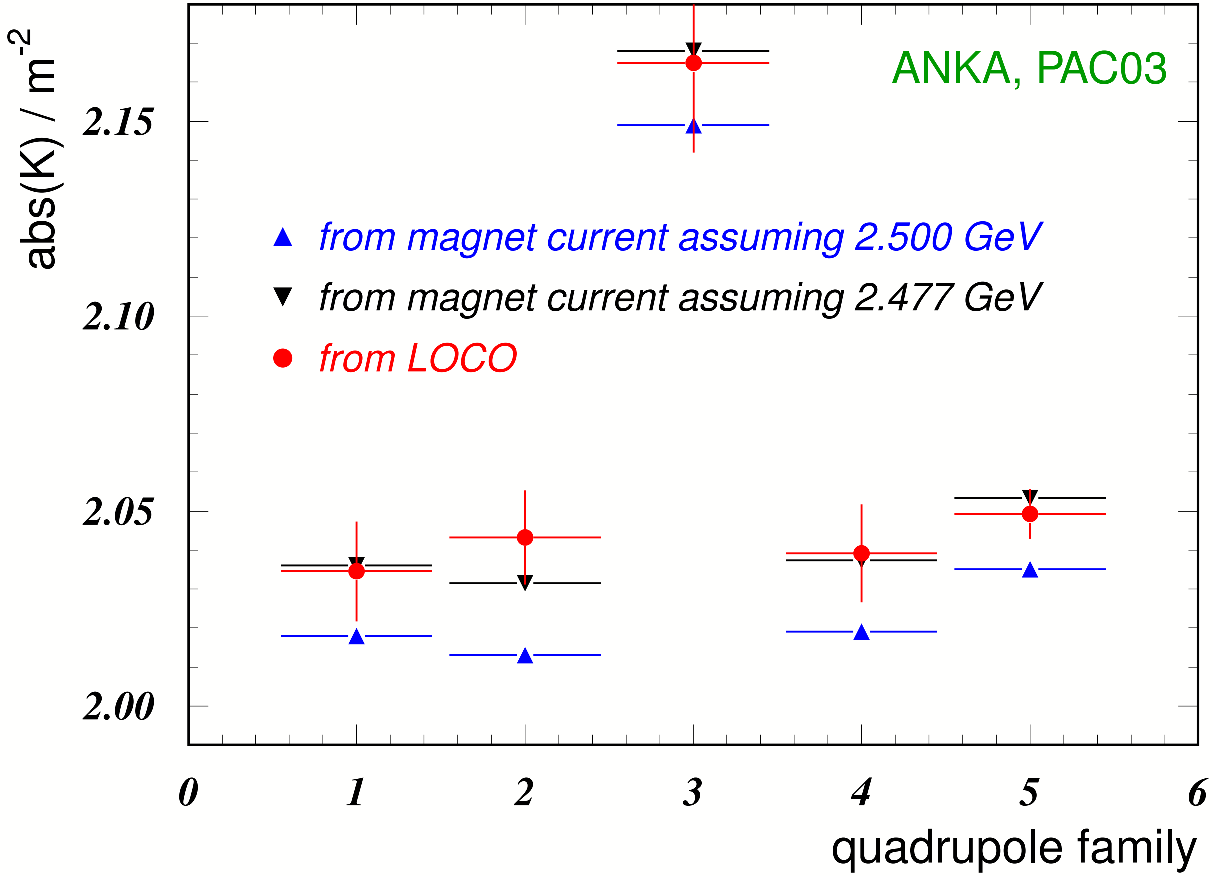
- Example 1 (LEP):
  For precise measurements of Z mass/width and cross sections a beam energy needs to be known
- Example 2 (LEP2):
  E_0 for determination of m_W
- Example 3 (Syn. Light Sources):
  for insertion devices: $\epsilon_\gamma \propto E^2$
  1% $\Delta E/E$ ➜ 2% $\Delta\epsilon_\gamma/\epsilon_\gamma$
- Example 4 (e.g. Tandem):
  For resonances in nuclear physics in “ion beam on fixed target” configurations

LEP Electroweak Working Group



“most precise measurement of the number 3”

For Optics Measurements



- Measurements of quadrupole gradients show systematic offset relative to the model if the beam energy is wrong ....
- This effects both lepton and hadron accelerators....

Beam Energy Determination using Spectrometers

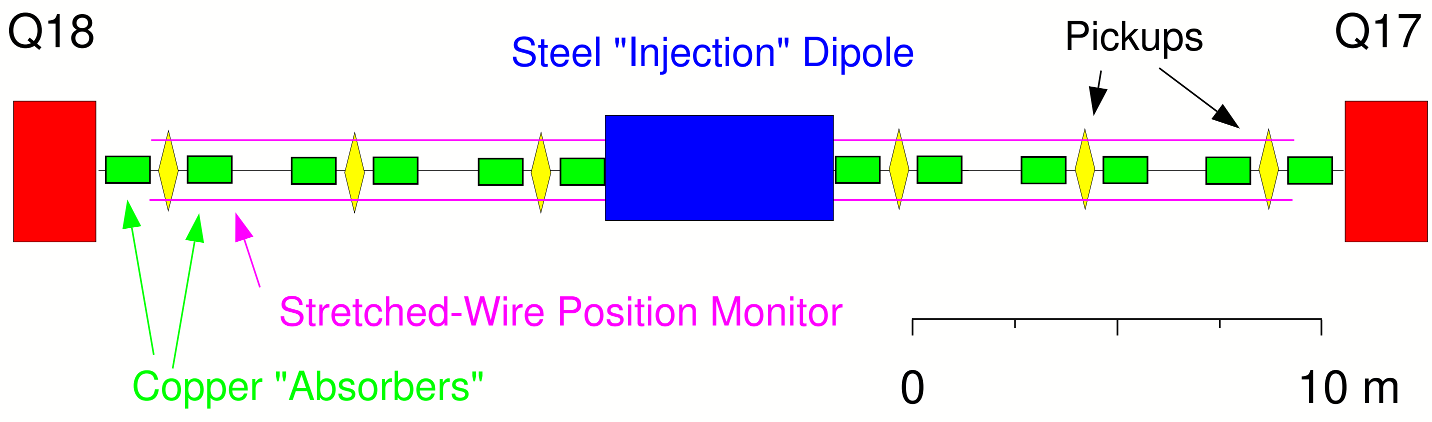
Spectrometer

- Spectrometers measure the particle momentum by precisely determining the angle of deflection in a dipole magnet

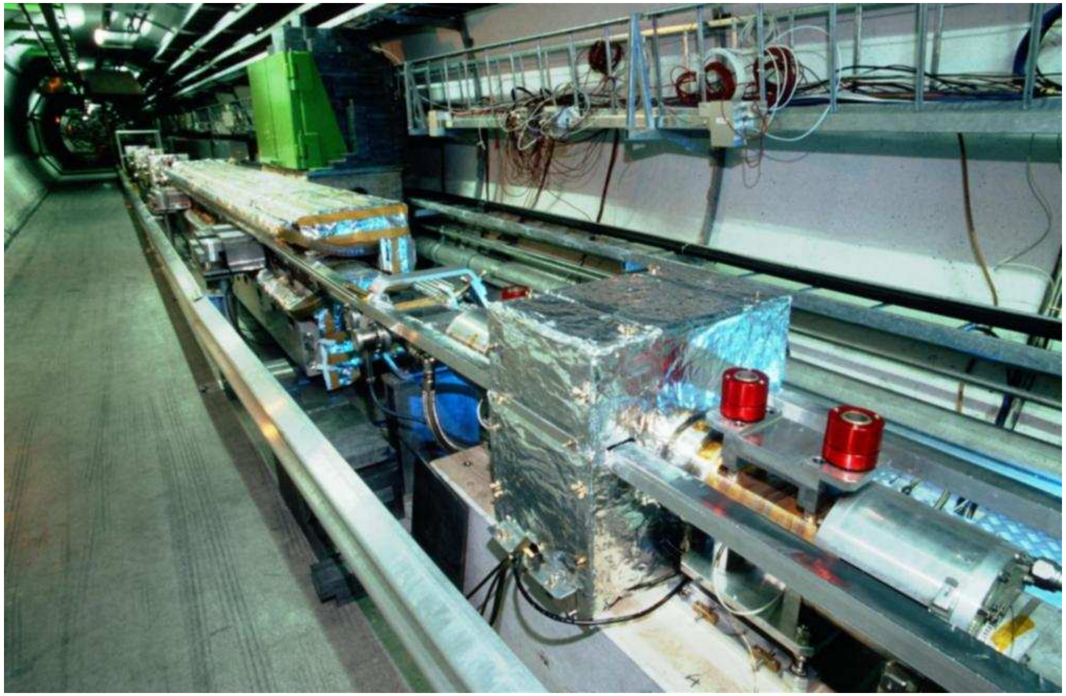
$$\theta \propto \frac{1}{E_0} \int B ds$$

- Ingredients:
  - ➜ beam position ($\mathcal{O}(1\,\mu m)$) at entrance and exit of analysing magnet
  - ➜ magnetic field ($\mathcal{O}(10^{-5})$ or better)
- Single pass systems
  - ➜ position measurement with position sensitive detector at the beam stop (possible attenuation)
- Storage rings
  - ➜ no beam stop therefore position measurement with beam position monitors following the deflection

The LEP Spectrometer

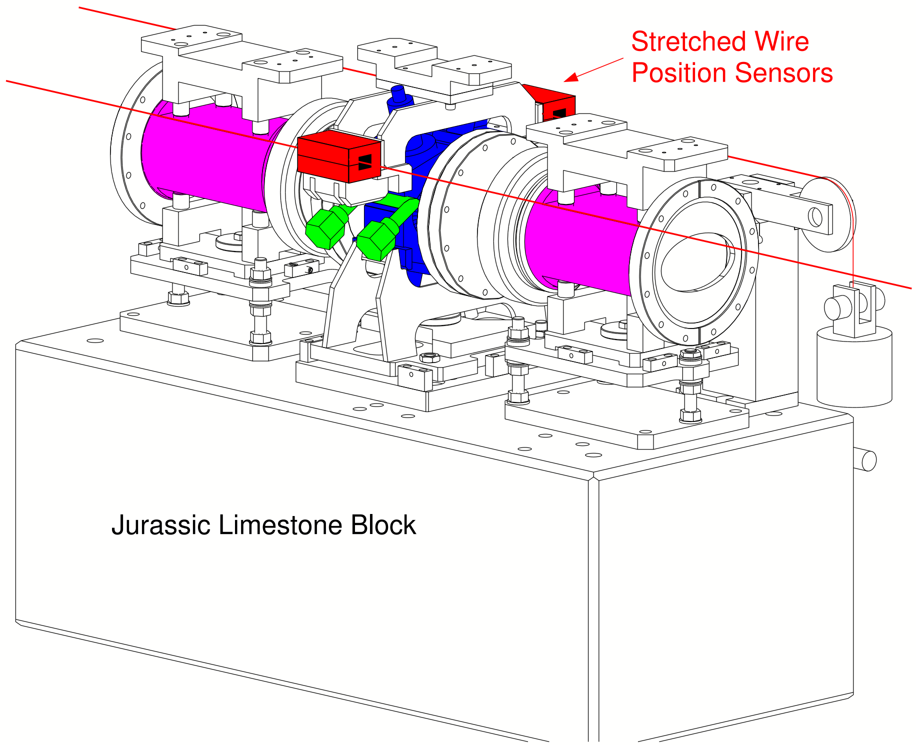


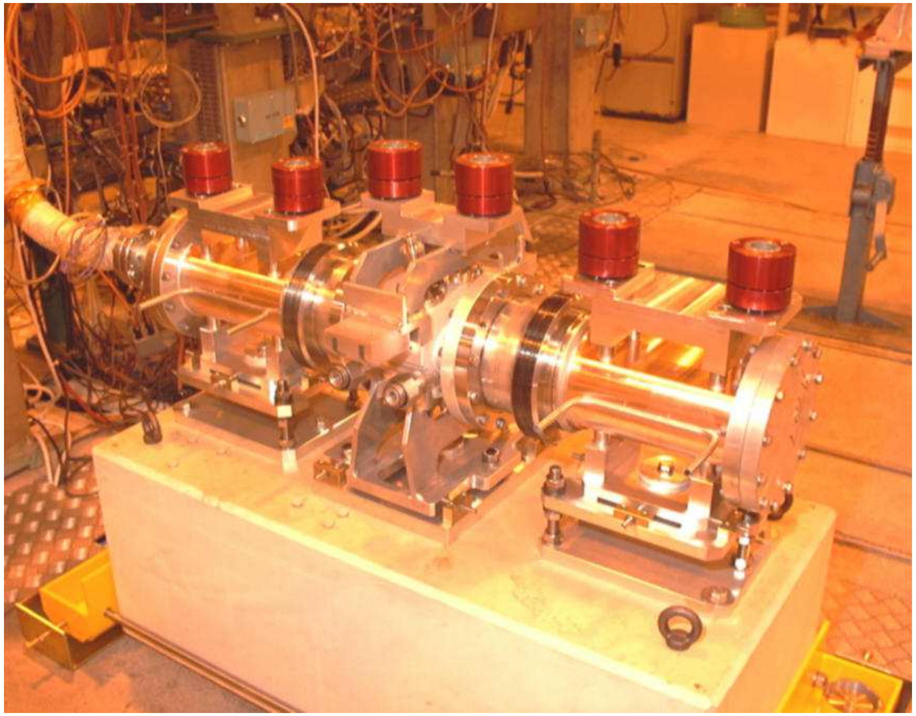
- position measurement with 1 μm
- magnetic fields $\Delta B/B = \mathcal{O}(10^{-5})$
- final energy resolution: $\Delta E/E = \mathcal{O}(10^{-4})$



The LEP Spectrometer II

- Pickup positions monitored with a stretched wire system (beware of thermal effects due to synchrotron radiation etc.)
- Take into account the local magnetic field of the earth and fields generated by close-by power lines

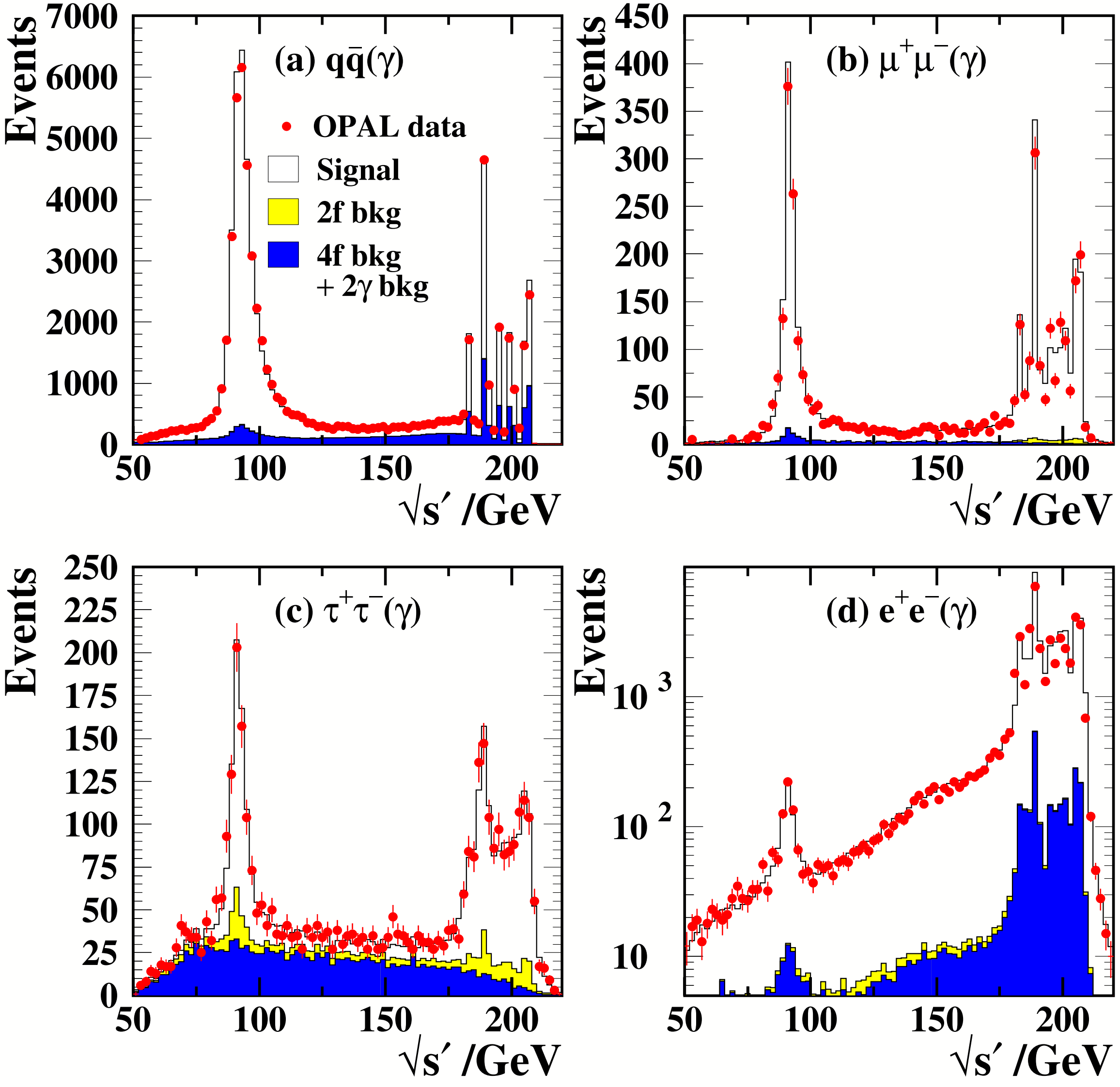




Beam Energy from Particle Physics Processes

Radiative Returns to the Z

- X-check E_{cm} using of the type $e^+e^- \to Z\gamma$, $Z \to f\bar{f}$ where the fermion f is a quark, electron, muon or τ-lepton
- From knowledge of m_Z at LEP1 invert problem and deduce initial collision energy of event
- $\Delta E/E = \mathcal{O}(3 \cdot 10^{-4})$

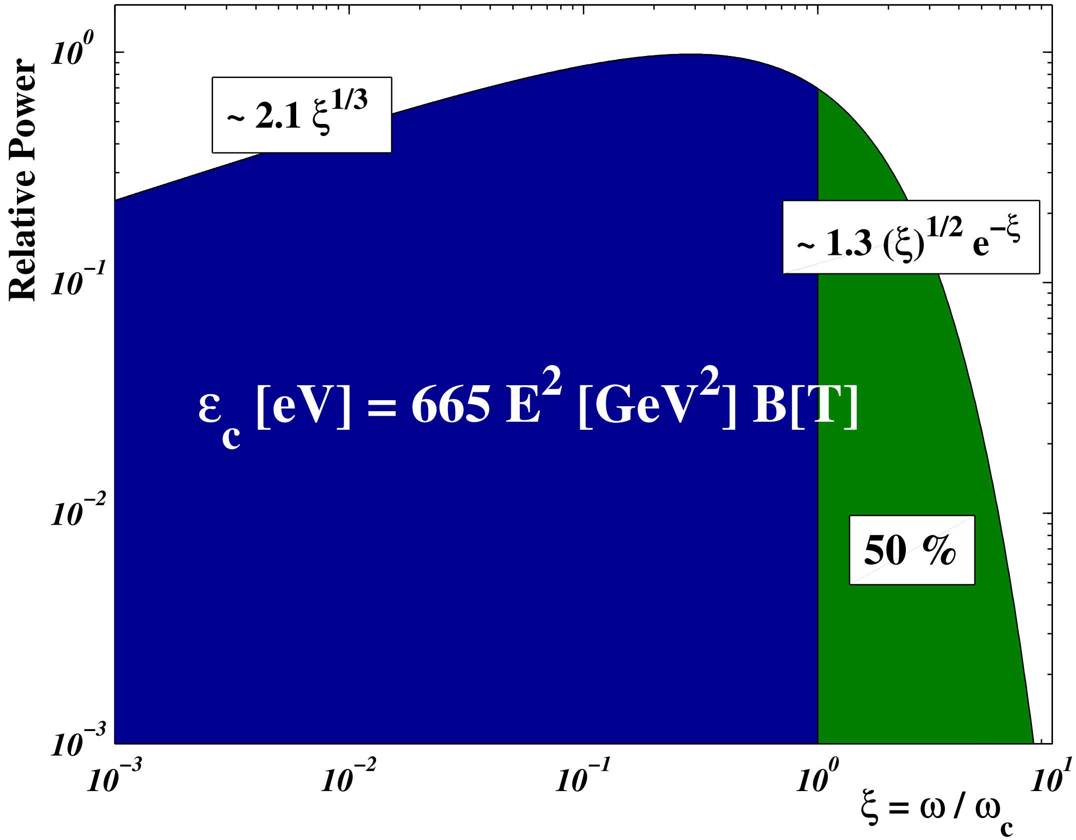


G. Abbiendi et al., Phys. Lett. B (604) 2004.

Beam Energy from Photon Based Methods

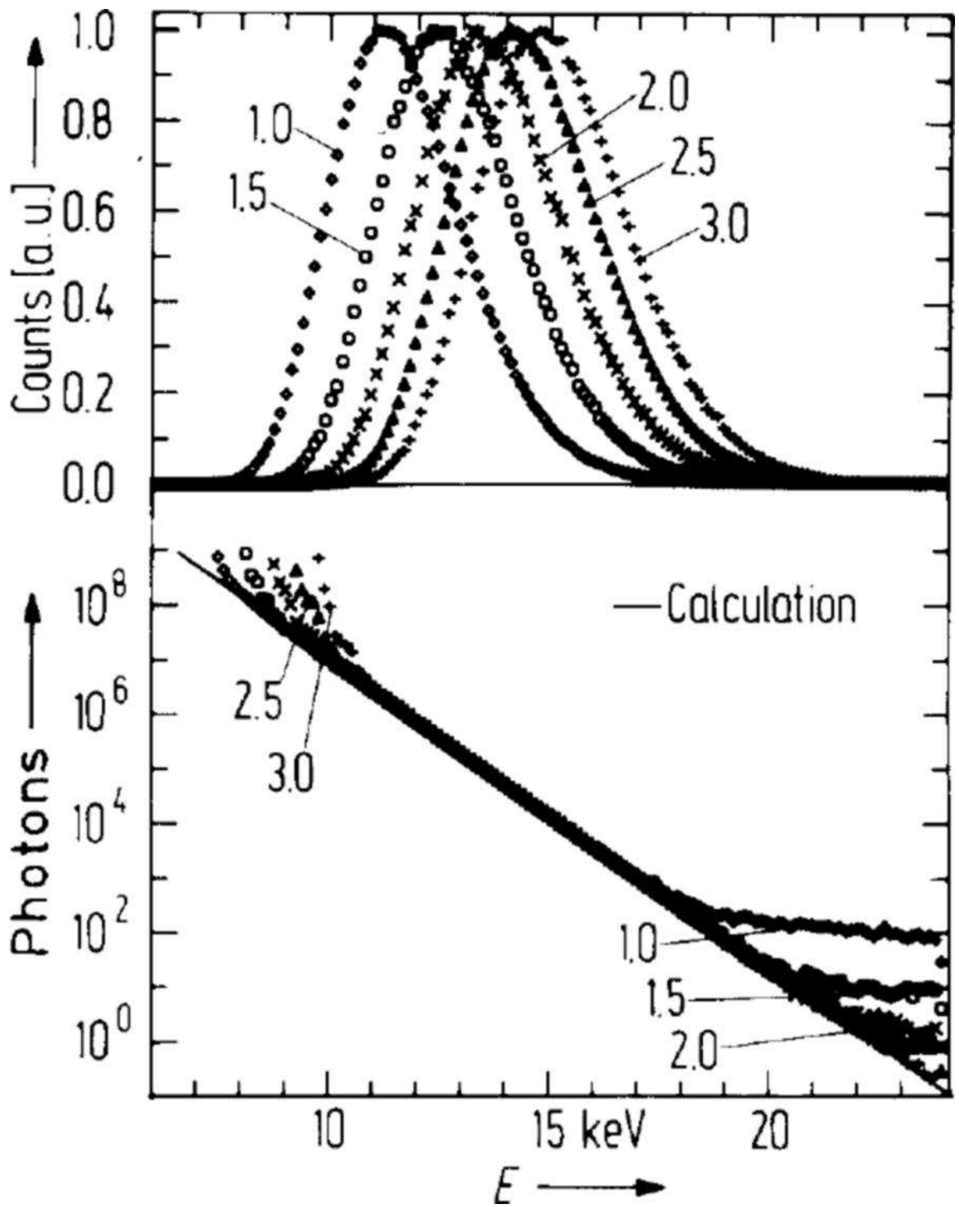
SR Spectrum

- The spectrum of synchrotron radiation has a strong dependence on the electron beam energy



- measure synchrotron photon spectrum
- determine ϵ_c
- measure B
- derive E_0
  - ➜ the uncertainty $\Delta E/E$ is of $\mathcal{O}(10^{-3})$

SR Spectrum II



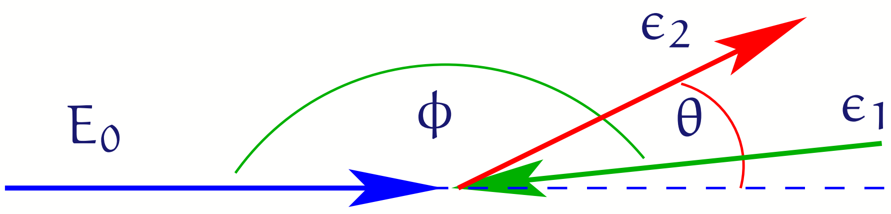
- Measure photon spectrum for different absorber (Al) thicknesses
- Integrated spectra allow to reconstruct synchrotron radiation spectrum
- Critical energy ϵ_c follows from fit according to $e^{-\epsilon/\epsilon_c}$

E. Tegeler, G. Ulm, NIM A (266) 1988.

Compton Back Scattering I

- Laser photons of energy ϵ_1 scatter with electrons of energy E_0 according to relativistic kinematics, resulting in the final photon energy ϵ_2

$$\epsilon_2 = \epsilon_1 \frac{1 - \beta \cos \phi}{1 - \beta \cos \theta + \epsilon_1 (1 - \cos(\theta - \phi))/E_0}$$



- For head-on collisions ($\phi = \pi$) and observation in direction of electron beam ($\theta = 0$)

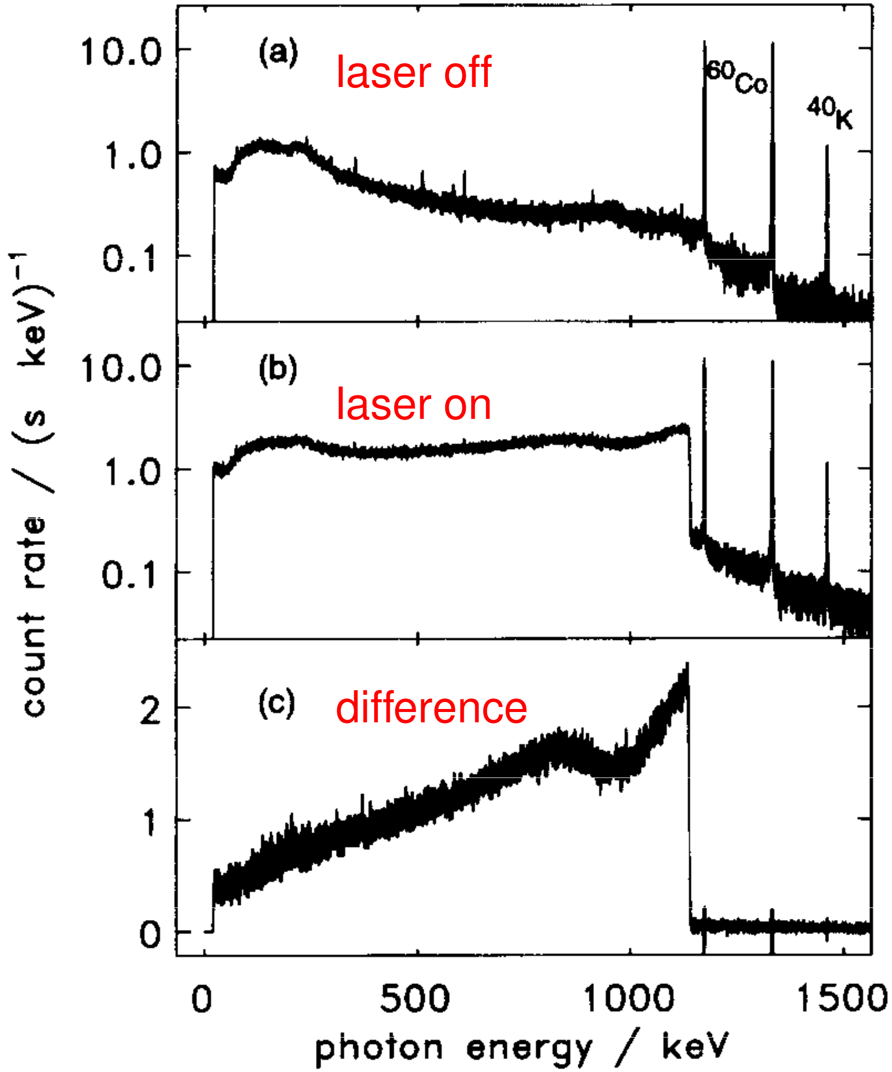
$$\epsilon_2^{max} = \epsilon_1 \, 4\gamma^2 \frac{1}{1 + 4\gamma\epsilon_1/(m_e c^2)}$$

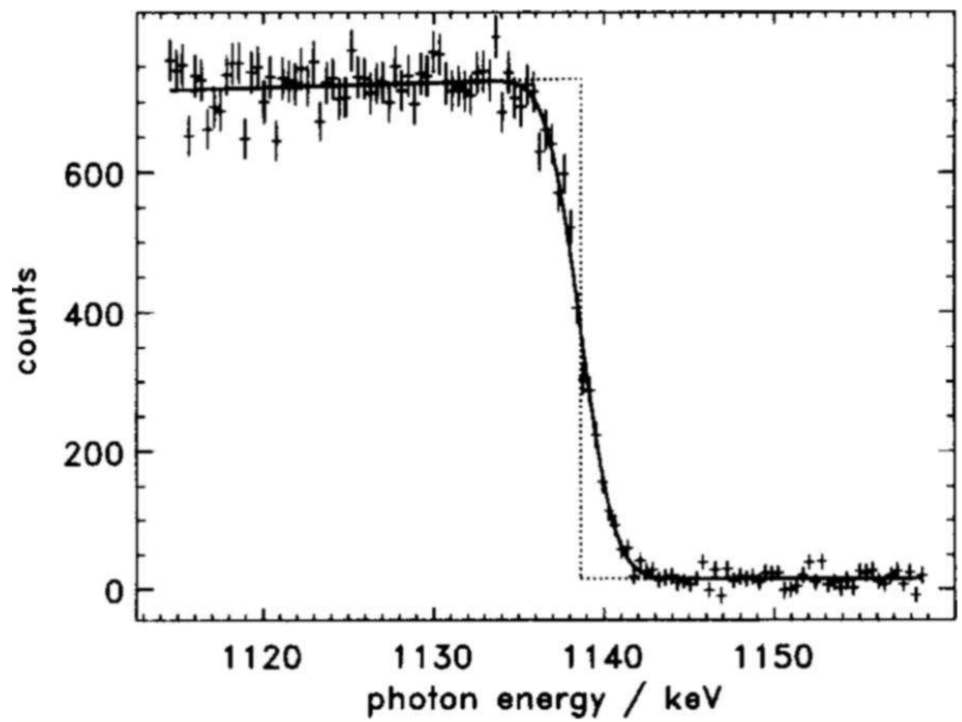
➜ determine end of spectrum ϵ_2^{max} at a detector (e.g. HPGe)

- Relative uncertainty $\Delta E/E \propto \Delta\epsilon_2^{max}/\epsilon_2^{max}$ is of $\mathcal{O}(10^{-4})$

Compton Back Scattering II

- Measurement at BESSY I (800 MeV)





➜ $E_0 = 796.88(12)$ MeV

R. Klein et al., NIM A (384) 1997.

Beam Energy from Measurements of the Central Frequency

Central Frequency and Momentum

- The speed of particles relative to c can be written as

$$\beta = \frac{C\, f_{\mathrm{rev}}}{c} = \frac{C\, f_{\mathrm{RF}}}{hc}$$

- To simultaneously determine p and C, measure f_{rev} for two particle types with different Z/m in the same machine (e^+/p, p/Pb^{53+})

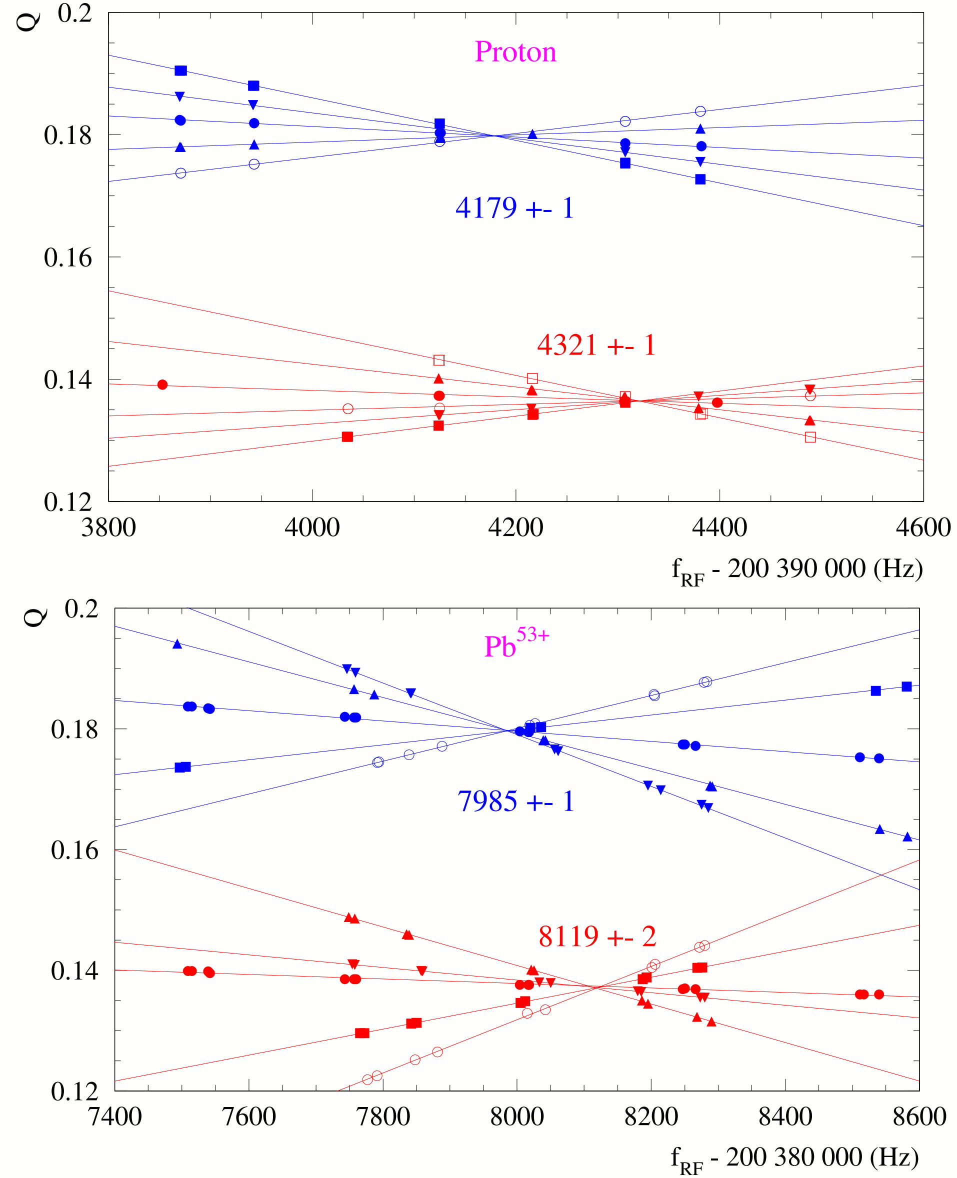
- Momentum can be written as

$$p \approx m_p c \sqrt{\frac{f_{\mathrm{RF},p}}{2\Delta f_{\mathrm{RF}}}\left[\left(\frac{m_i}{Z m_p}\right)^2 - 1\right]}$$

  ➜ for high energies difficult since $\Delta f \propto (m_i/Zm_p)^2/p^2$

  ➜ maximise m_i/Zm_p (Pb^{53+})

- $\Delta p/p$ is of $\mathcal{O}(10^{-4})$



J. Wenninger, SPS 2003: 449.16(14) GeV

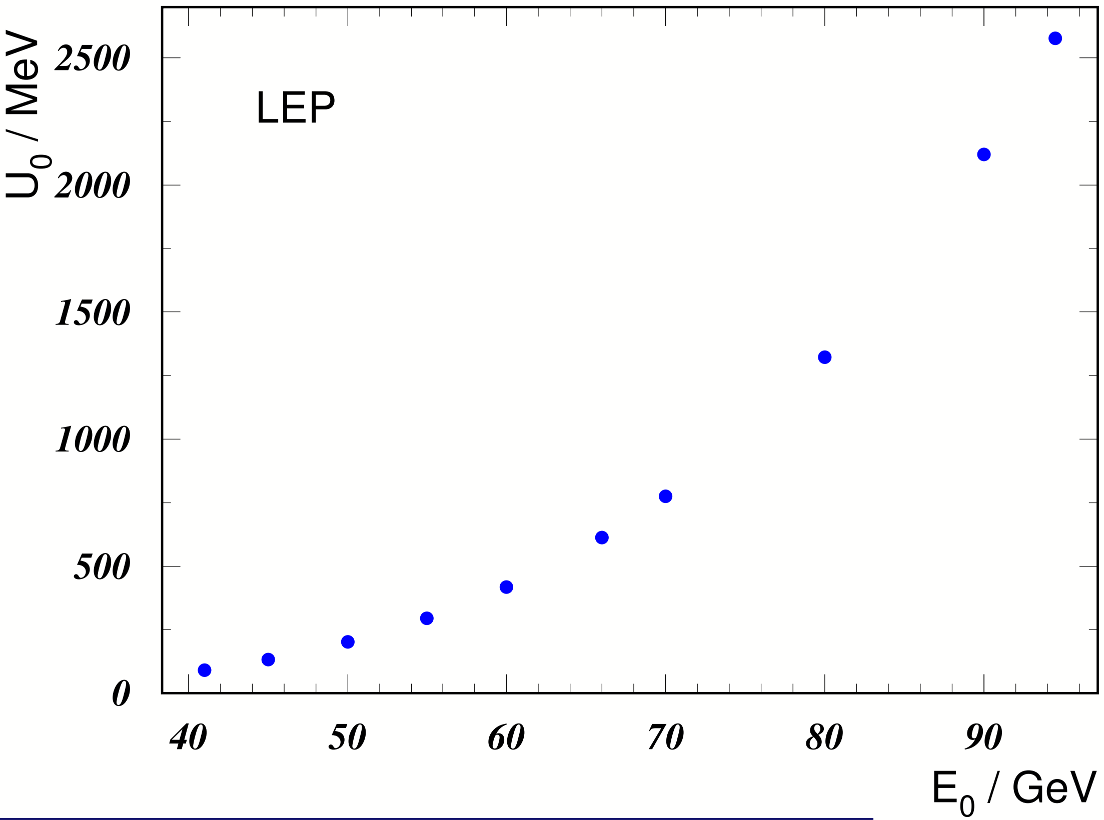
Beam Energy from Measurements of the Energy Loss

Energy from Energy Loss

- Energy loss per turn and particle:

$$U_0 = \frac{4\pi}{3}\frac{r_c}{(mc^2)^3}\frac{E_0^4}{\rho}$$

➜ high sensitivity on E!



- Quantities that depend on U_0 are e.g. radiation damping, Δx_D and Q_s

	Circumference / m	Energy / GeV	U_0 / MeV
ANKA	110	2.5	0.6
ESRF	844	6.0	4.9
LEP	26700	94.5	2576

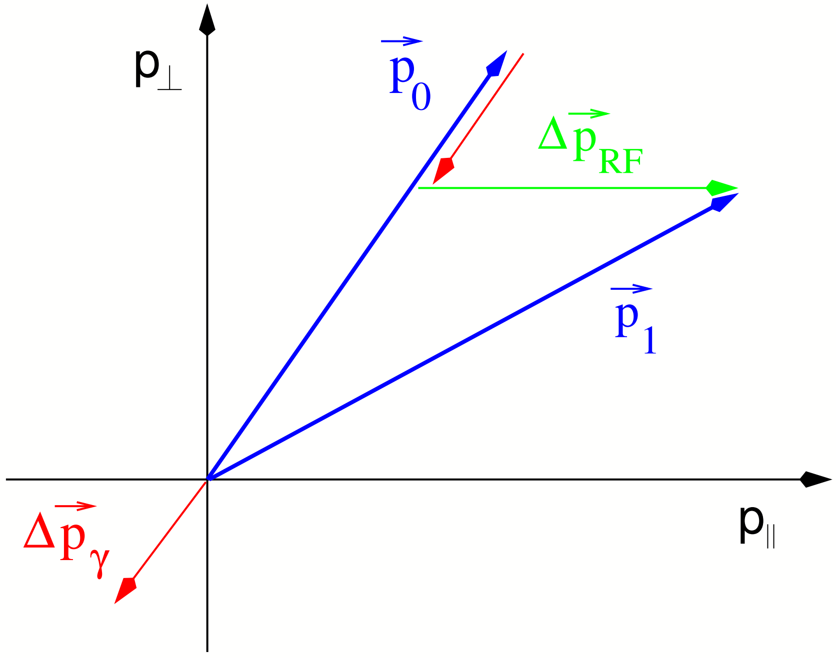
Energy from Coherent Damping

- Coherent damping at LEP
  - ➜ composed of radiation and head-tail damping:

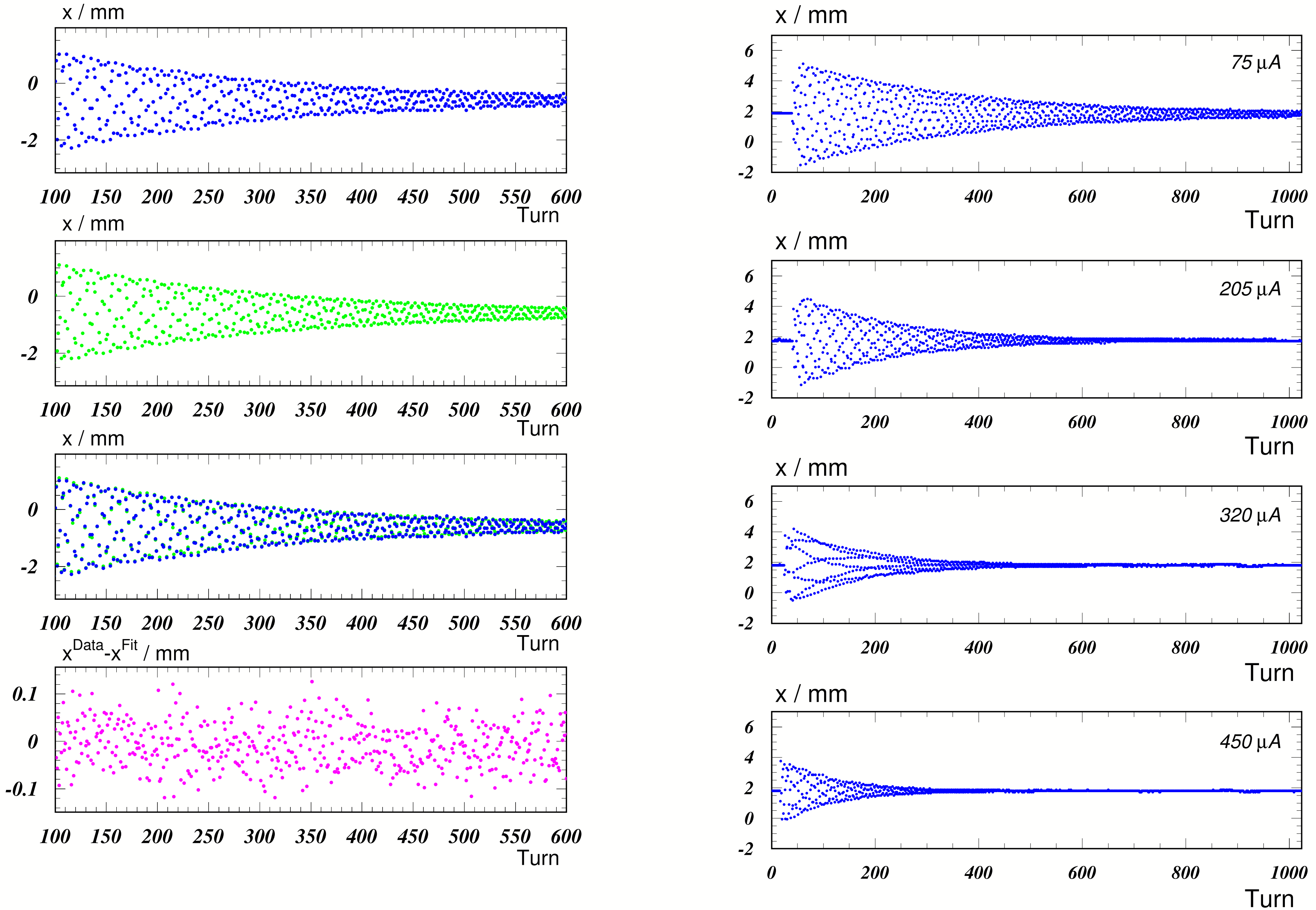
$$1/\tau_{coh} = 1/\tau_0 + 1/\tau_{head-tail}$$

$$\frac{1}{\tau_0} = \frac{1}{2}\frac{U_0\, f_{rev}}{E_0} J_x \sim E_0^3 \qquad \frac{1}{\tau_{head-tail}} \propto \frac{\sigma_s Q'}{E_0} I_b$$

- Synchrotron radiation damping
  - ➜ due to emission of synchrotron γ and RF gains
- Head-tail damping
  - ➜ depends on chromaticity and bunch current
- Beware of filamentation!



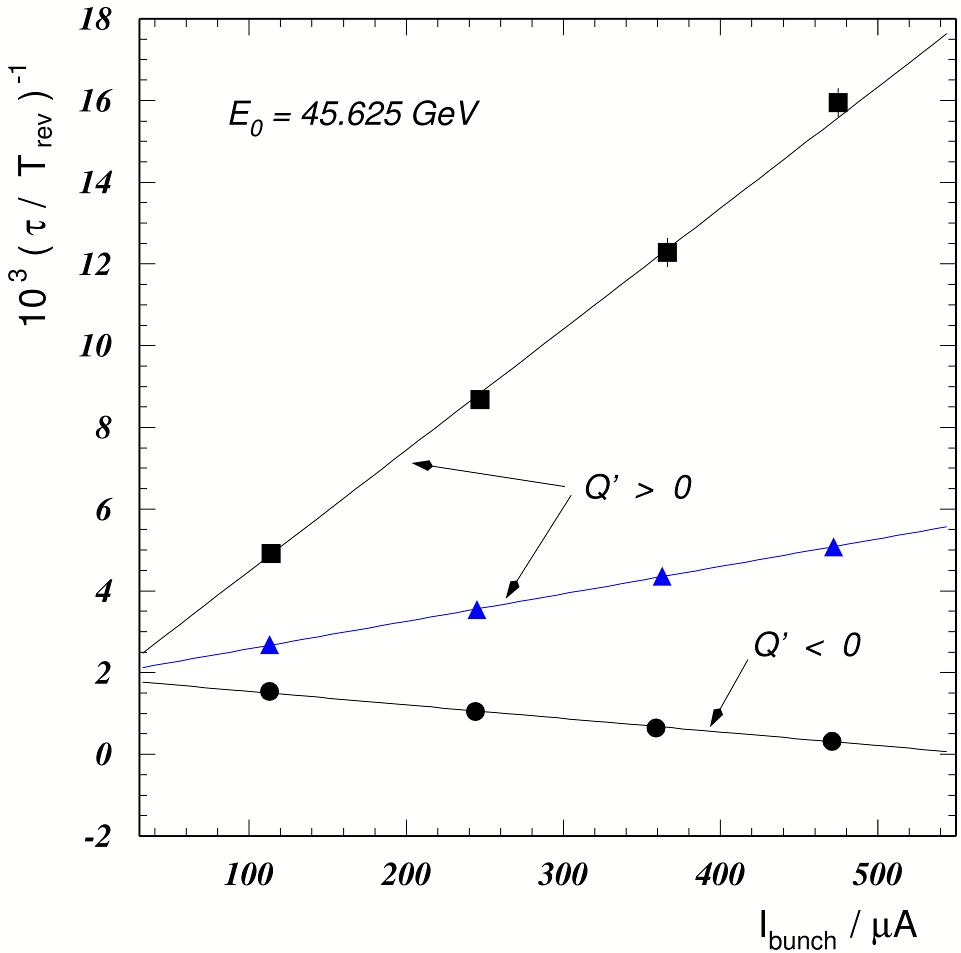
Energy from Coherent Damping II



Energy from Coherent Damping III

- Measure for different chromaticities ➜ contribution from head-tail damping varies, radiation damping stays the same as long as the energy stays the same (warning: better be finished before the tide turns....)

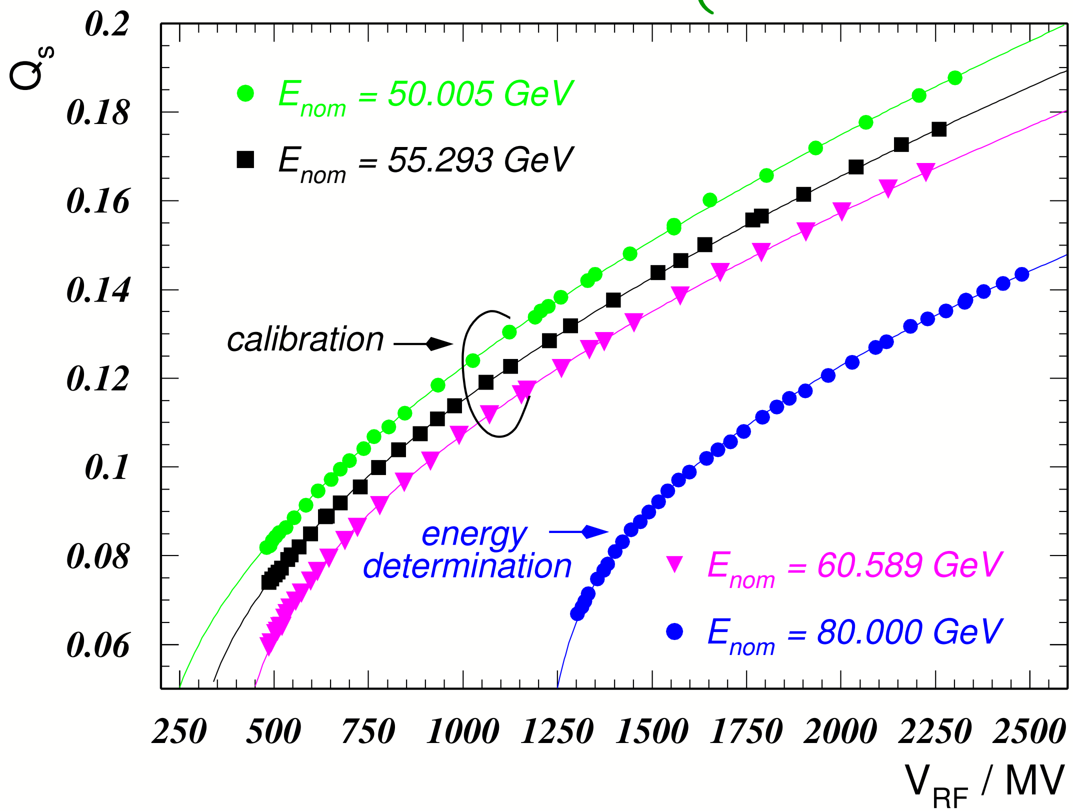
- Energy loss from comparison to MAD:
  $U_0 = U_0^{\text{MAD}} \, \tau_0^{\text{MAD}} / \tau_0^{\text{meas}}$
- Sources of uncertainty
  - ➜ J_x and central frequency
  - ➜ energy / frequency shifts due to tides
- Finally:
  - ✘ Energy uncertainty $\mathcal{O}(1\%)$
  - ➜ not sufficiently precise for E-calibration but still quite interesting



Q_s and RF Voltage

- first pointed out by H. Burkhardt and A. Hofmann as a means to determine the energy loss at LEP
- Synchrotron tune Q_s depends on total RF voltage and beam energy

$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi E}\right)^2 \left\{ e^2 V_{RF}^2 - \left(\frac{C_\gamma}{\rho} E^4 + K\right)^2 \right\} \sim \frac{a}{E^2} + bE^6$$



- X-calibrate at “low” energies with RDP and use method to extrapolate to energies where RDP doesn’t work
- Energy resolution: $\Delta E/E = \mathcal{O}(10^{-4})$

Beam Energy from Resonant Depolarisation

Transverse Polarisation

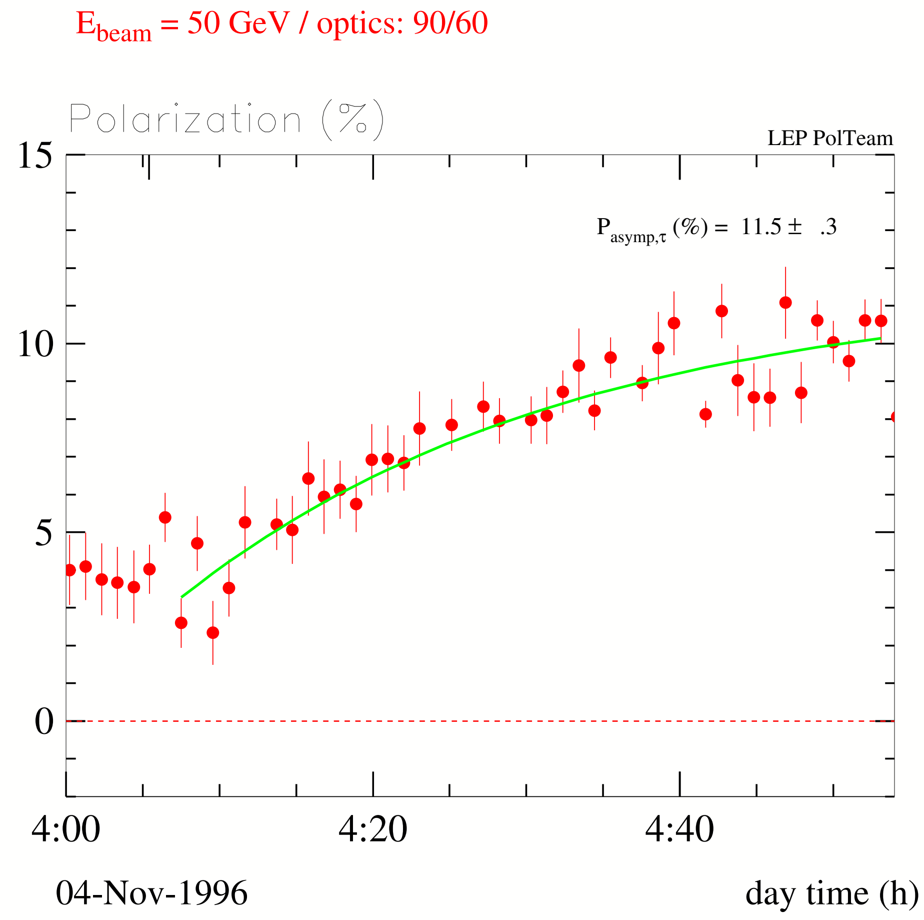
- Polarisation build-up by emission of synchrotron radiation:
  - ➜ asymmetry in spin flip probability leads to transverse polarisation
  - ➜ max. polarisation is given by size of asymmetry term:

$$8/5\sqrt{3} \approx 92.4\%$$

- Polarisation level increases exponentially with build up time

$$\tau_p = \frac{8}{5\sqrt{3}} \frac{1}{\alpha} \left(\frac{m_0 c^2}{\hbar c}\right)^2 \frac{\rho^3}{c\gamma^5} \left(\frac{R}{\rho}\right)$$

  - ➜ typical for electrons: several minutes to a few hours
  - ➜ LEP: 340′, ANKA: 10′



$$P(t) = P_0 \left(1 - e^{-t/\tau_p}\right)$$

Spin Motion

- The motion of the spin vector $\vec{s}$ of a relativistic electron in the presence of electric and magnetic fields $\vec{E}$ and $\vec{B}$ is described by the Thomas-BMT (Bargmann, Michel, Telegdi) equation:

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

- The spin precession frequency $\vec{\Omega}_{\mathrm{BMT}}$ can be written as

$$\vec{\Omega}_{\mathrm{BMT}} = -\frac{e}{\gamma m_0}\left[(1+a\gamma)\,\vec{B}_{\perp} + (1+a)\,\vec{B}_{\parallel} - \left(a\gamma + \frac{\gamma}{1+\gamma}\right)\vec{\beta} \times \frac{\vec{E}}{c}\right]$$

- $a = (g_e - 2)/2 = 0.001159652193(10)$
- The average over all particles of the number of spin oscillations per revolution is defined as the spin tune

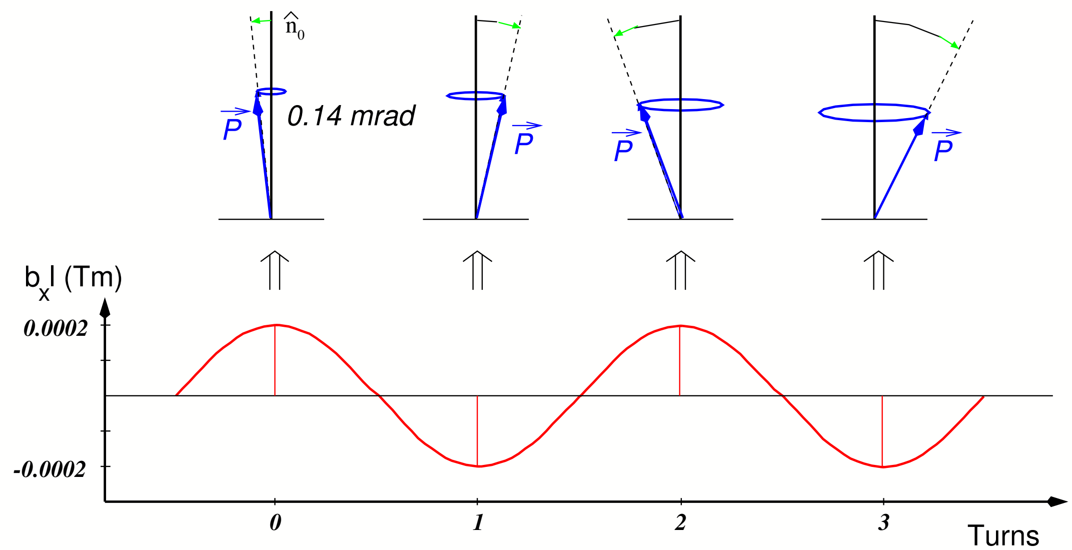
$$\nu = f_{\mathrm{spin}}/f_{\mathrm{rev}} = \frac{(g_e-2)/2}{m_0 c^2}\,E_0$$

Resonant Depolarisation

- Horizontal magn. field B_x modulated with f_{dep} is applied to the beam
- For a certain phase relation between the kicks of the depolariser and the spin tune the small spin rotations add up coherently from turn to turn and the polarisation is destroyed

  ➜ resonance condition for spin rotations

$$f_{dep} = (k \pm [\nu]) \cdot f_{rev}, k \in \mathbb{N}$$



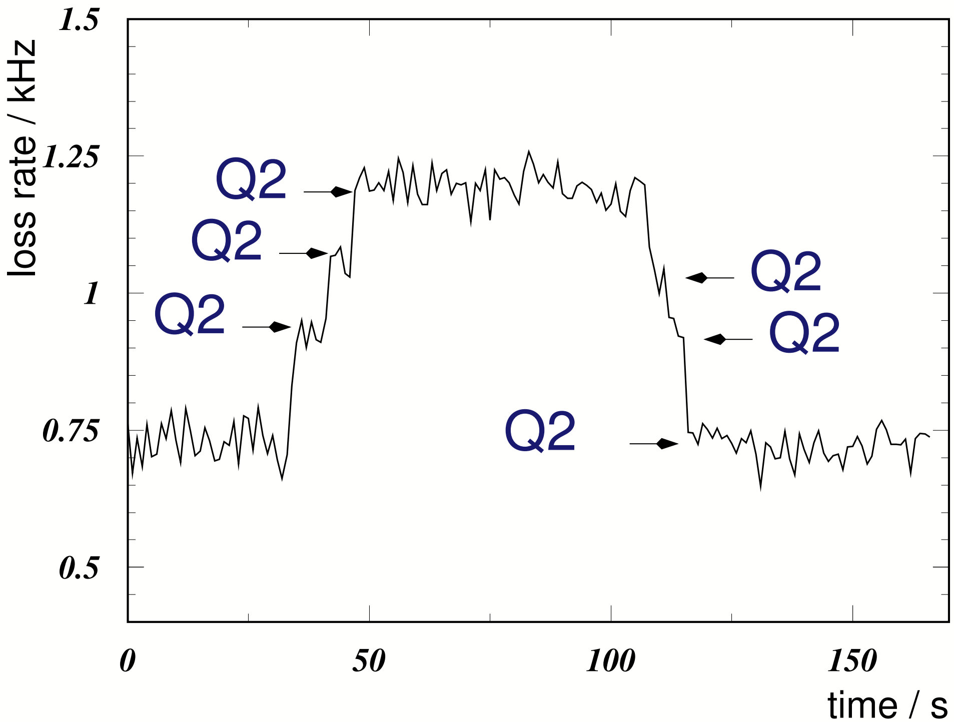
- To determine the spin tune, the frequency of the depolariser field is slowly varied with time over a given frequency range

  ➜ beam energy from $\gamma = \nu/a$

  ➜ precision: $\Delta E/E \approx 10^{-6} - 10^{-5}$

Polarisation and Loss Rate

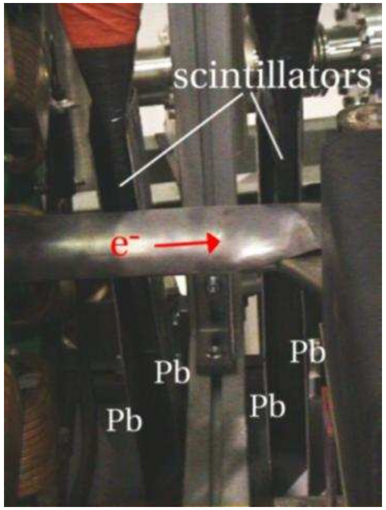
- To detect a change in polarisation, a polarimeter is needed
- Touschek cross-section depends on electron beam polarisation
  - ➜ use particle loss rate as a measure for polarisation level
- Set up a beam loss monitor in a Touschek sensitive region (low β followed by large D_x) and monitor fast loss rate changes

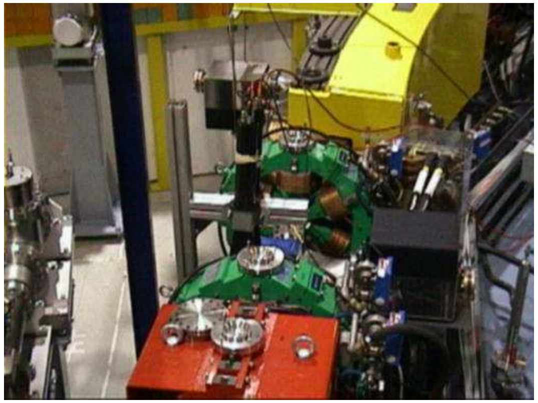


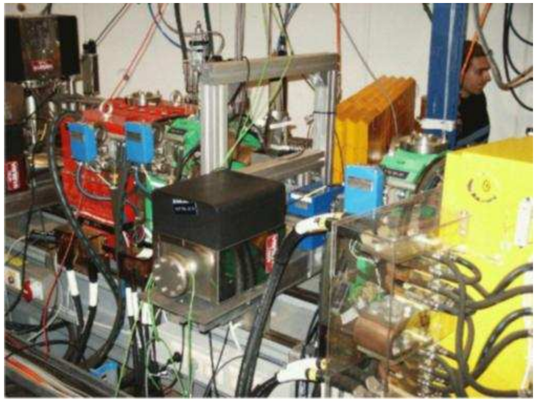
- Test detector sensitivity and setup by moving tune from and to a resonance (known impact on life time / loss rate)
- Touschek polarimtery even works for machines that are not limited by the Touschek effect

Simple Polarimeter

- E.g. with scintillators wrapped in lead sheets to suppress the contribution of synchrotron radiation to the count rate

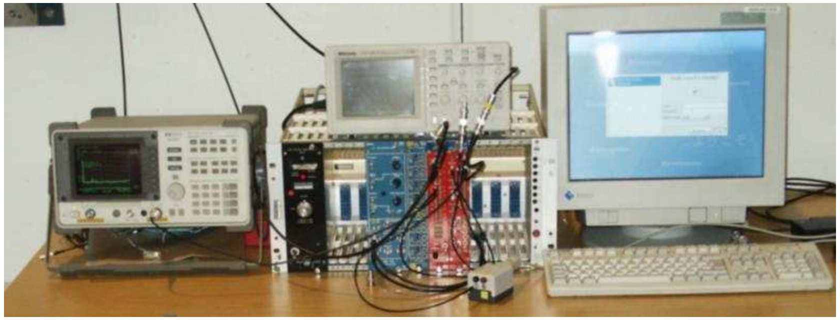






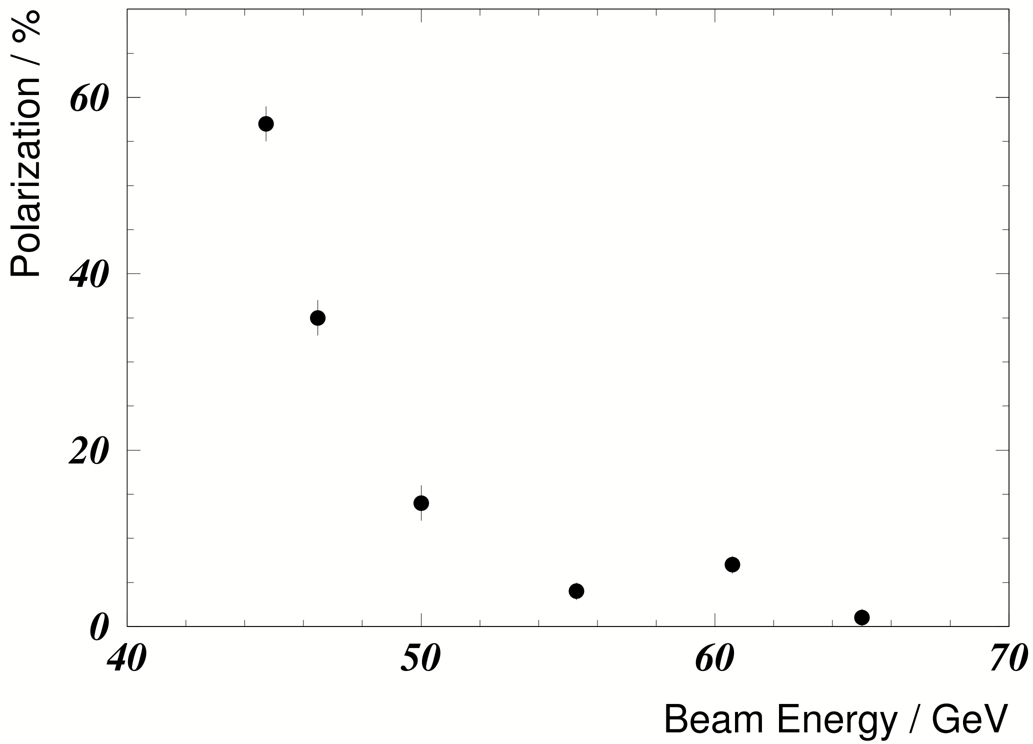
- Alterntive: Pb-Glass block with photo multiplier

- Photo multiplier pulses are converted to NIM signals and counted using a custom made interface to a Linux PC

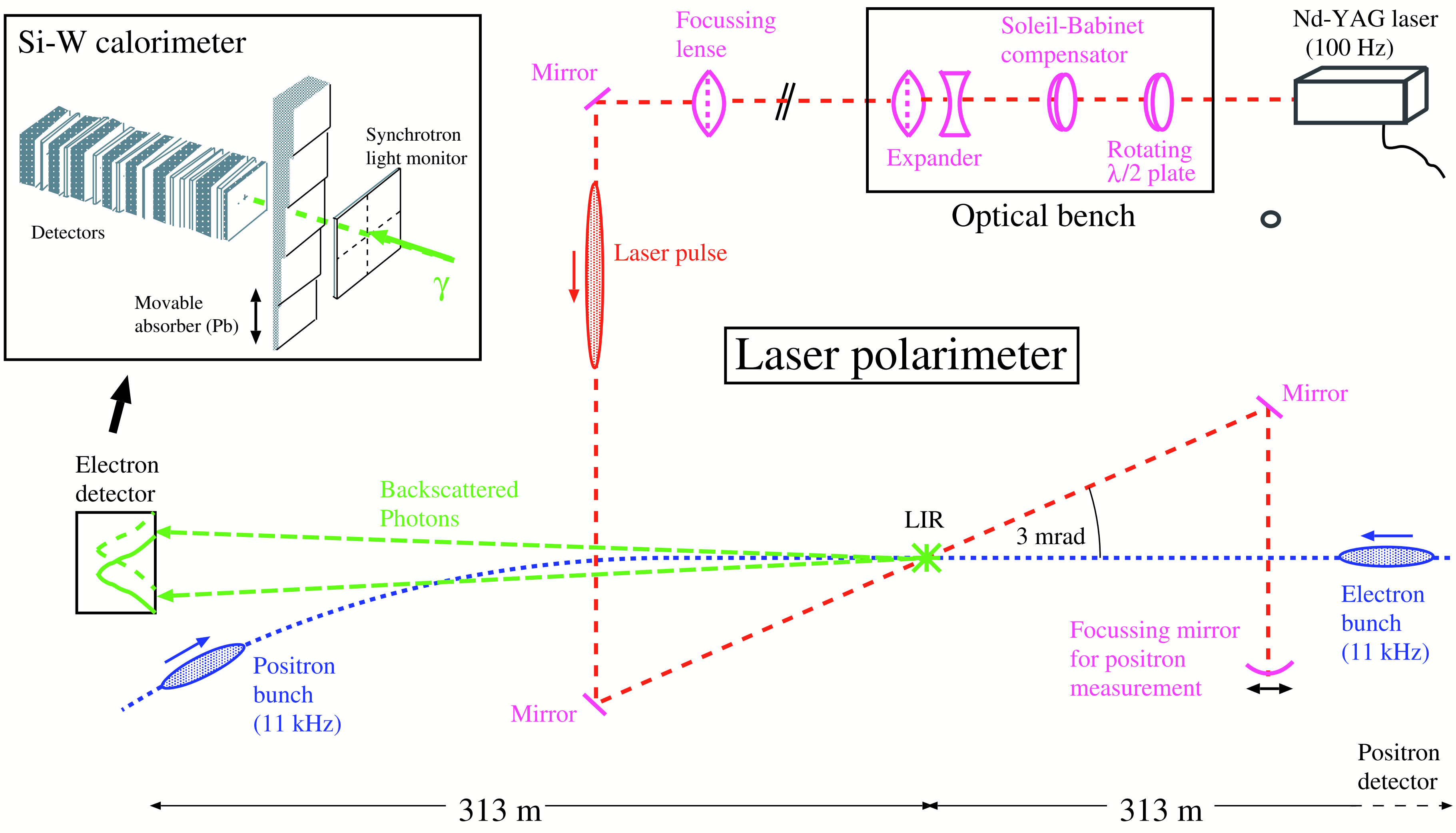


LEP Energy Calibration

- Absolute measurement of polarisation level with Compton scattering:
  - ➜ Circ. polarized laser light collides with beam
  - ➜ Measure vert. profile of γs in Si-W calorimeter
  - ➜ $P_\perp \propto$ vert. shift of γ profiles for the two pol. states
  - ➜ RDP works for $P > 5\,\%$ $\Rightarrow$ extrapolation methods necessary for higher E_0



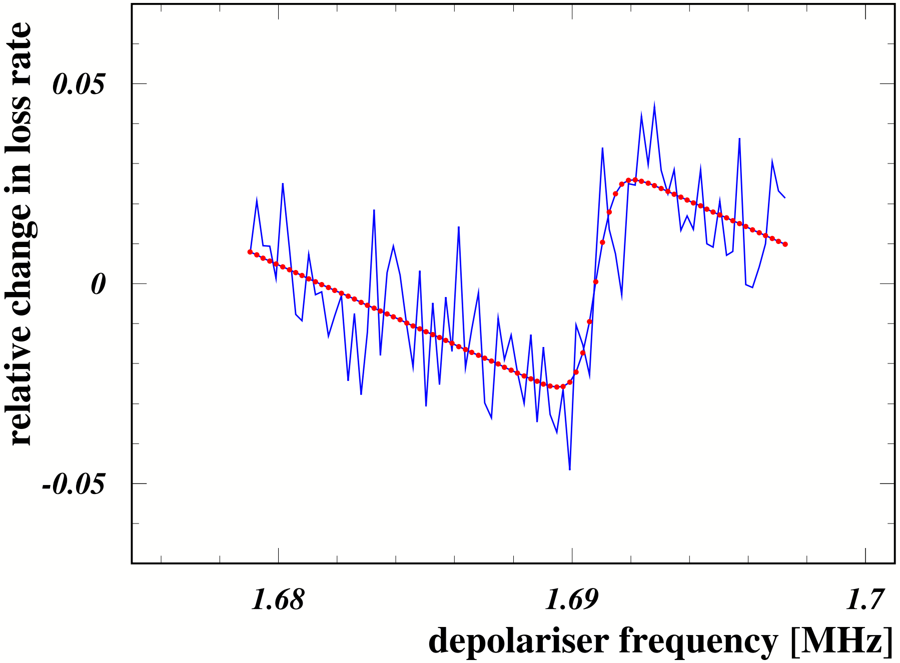
LEP Polarimeter

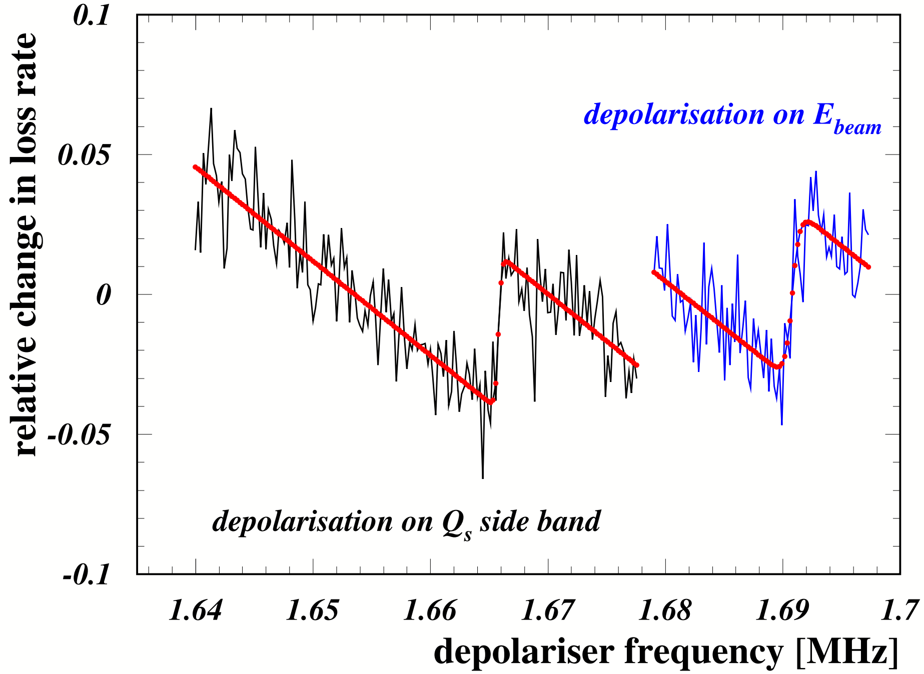


Depolarisation Scans

- scan the depolariser frequency acround the suspected beam energy equivalent
- get f_{dep} from a fit

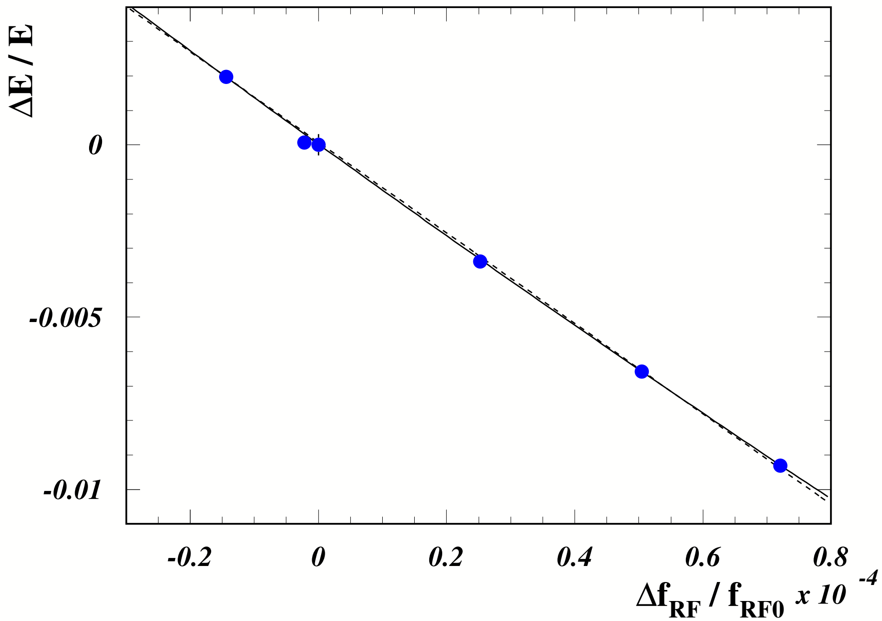
$$r = a - \frac{\partial r_I}{\partial t} t + \frac{\Delta r}{1 + \exp\left\{-\frac{t - t_d}{\sigma_d}\right\}}$$





- depolarisation can also occur on synchrotron side bands
- due to the single particle nature of the depolarisation process, this happens at $f_{dep}/f_{rev} = [\nu] \pm Q_s^{inc}$

Some RDP Applications



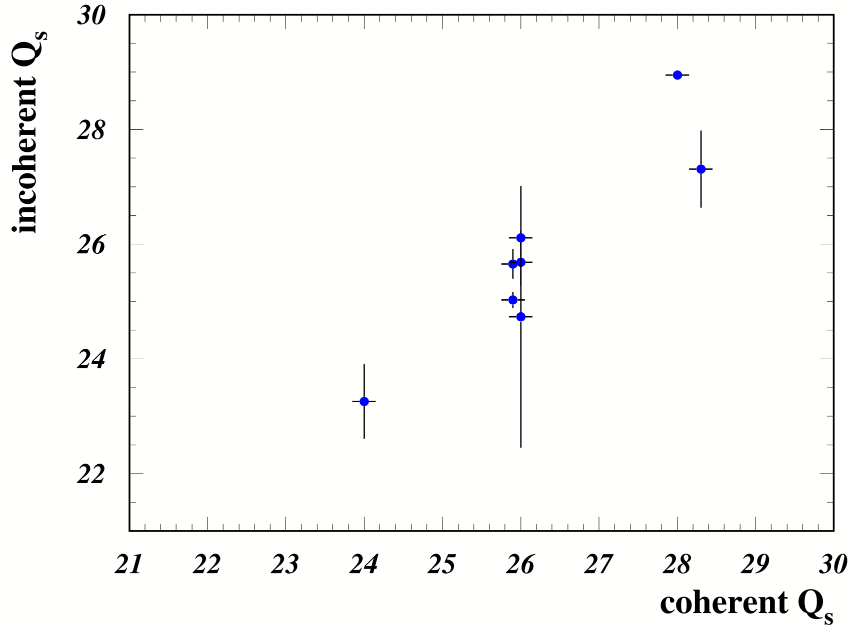
- Measure α_c using RDP scans for different f_{RF}:

$$\frac{\Delta f_{RF}}{f_{RF}} = \alpha_{c1}\,\delta + \alpha_{c2}\,\delta^2$$

- Relative precision $\Delta\alpha/\alpha \approx 10^{-3}$

- Measure simultaneously inc. (RDP) and coh. (stripline etc.)
- The coh./inc ratio is a measure for bunch lengthening with current (A. Hofmann, 1994)

$$\frac{Q_s^{coh}}{Q_s^{inc}} = 1 - \lambda I_{bunch}$$

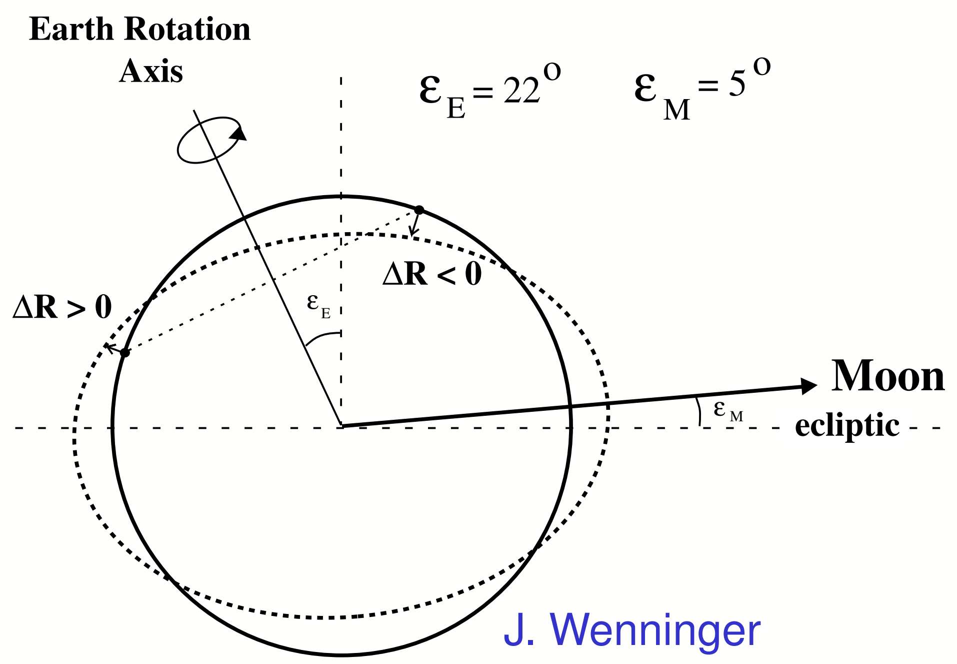



Doppelplanet © Frank Siegert

LEP and the Moon

- Tides affect both the oceans and the earth crust
- Local radius change ΔR due to mass M at distance d with zenith angle θ:

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



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- Some facts:
  - ➜ Sun tides are 50 % weaker than Moon tides
  - ➜ Full Moon tides at equator $\Delta R \approx \pm 50$ cm
  - ➜ Geneva region: vertical motion $\approx \pm 12.5$ cm
  - ➜ Change in LEP circumference of $\approx \pm 0.5$ mm

Circumference and Energy

- Impact on LEP beam energy because
  - ➜ length of actual orbit L is determined by the frequency of the RF system
  - ➜ change in circumference ΔC ➜ beam has to move off-centre through the magnets
  - ➜ additional bending field in the quadrupoles changes the beam energy

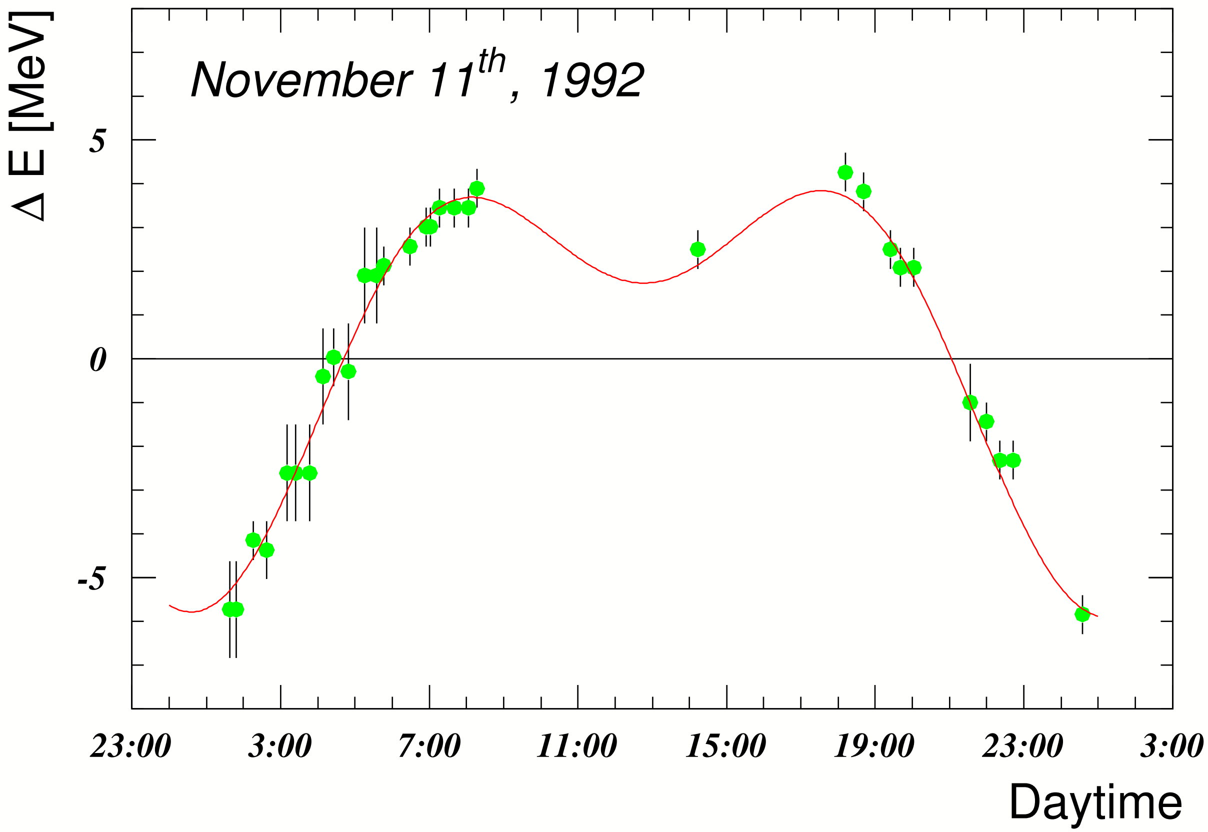
$$E \propto \oint B ds$$

- Resulting change in beam energy:

$$\frac{\Delta E}{E} = -\frac{1}{\alpha_c} \frac{(f_{RF} - f_{RF}^c)}{f_{RF}} = -\frac{1}{\alpha_c} \frac{\Delta C}{C}$$

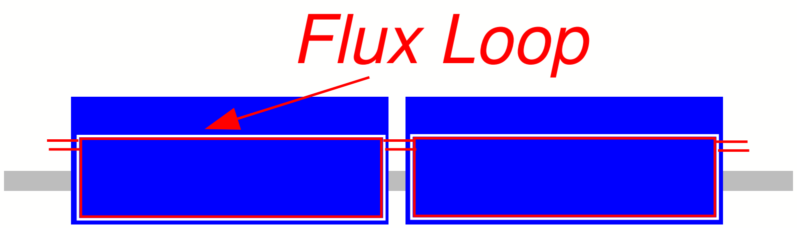
LEP and the Moon II

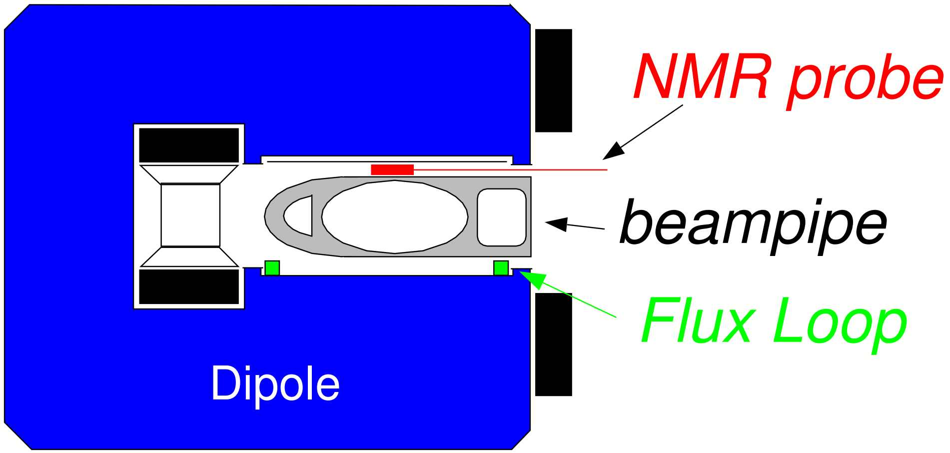
- Beam energy measurement with RDP during full moon compared to a prediction by a geological model



(L. Arnaudon et al.: *Effects of Terrestrial Tides on the LEP Beam Energy*. NIM A357, pages 249–252, 1995.)

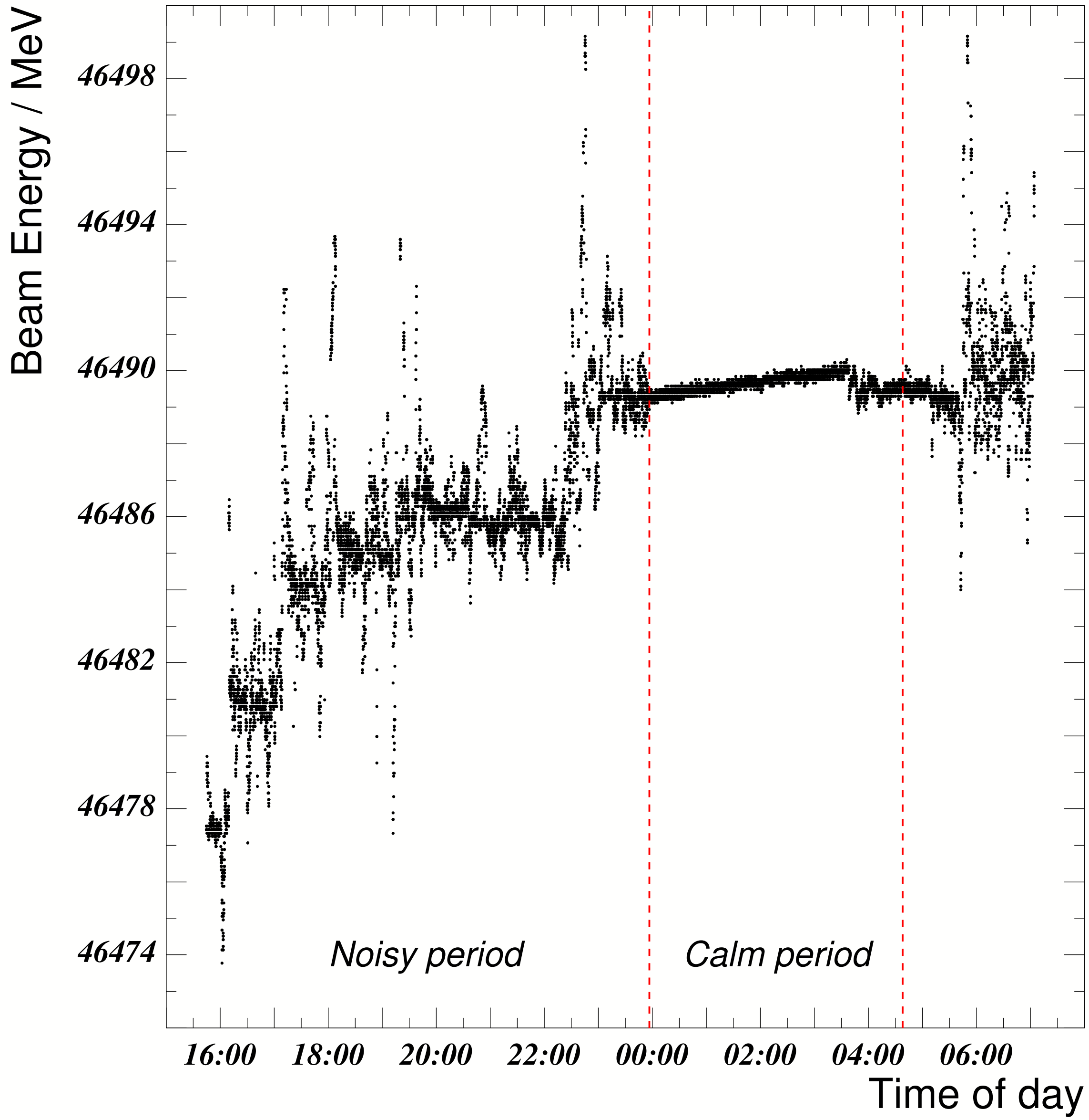
Continuous E-monitoring





- continuous monitoring of the beam energy by measurements of the bending field using $E_0 \propto \oint ds B$
- NMR probes and and flux loop cables
- field measurements calibrated for low beam energies with RDP and then used for extrapolation to high beam energies

Impact of Civilisation



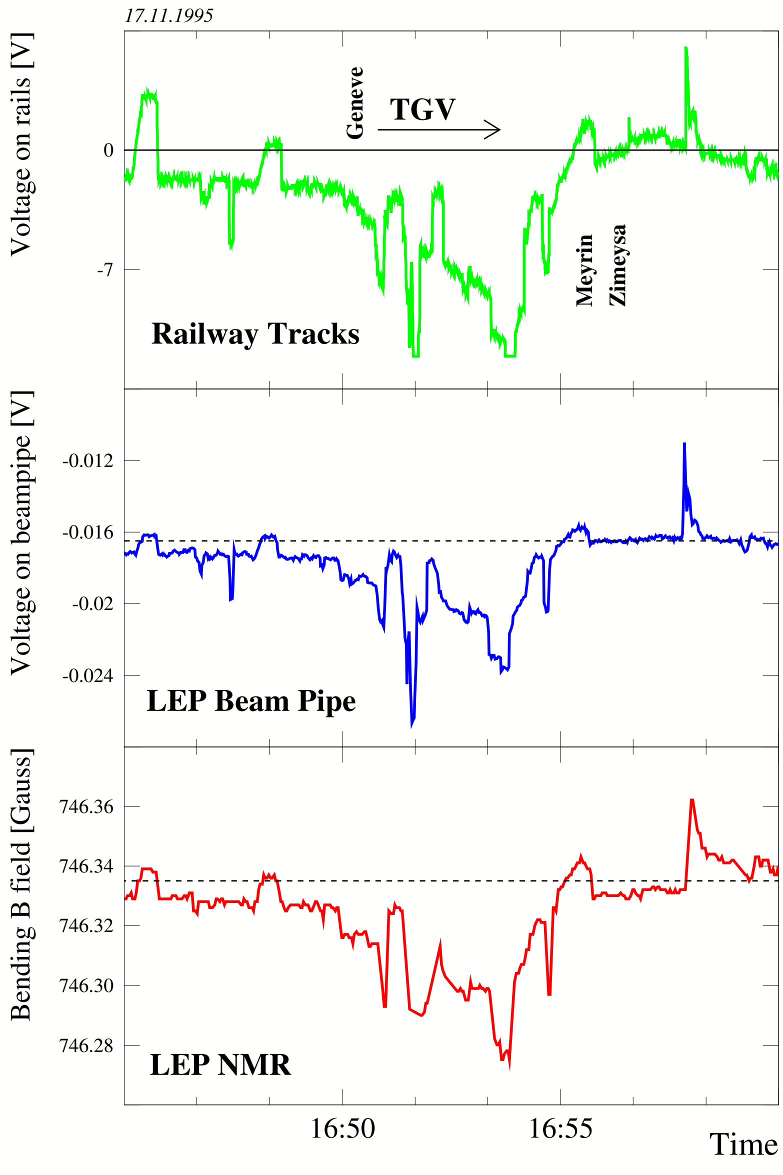
- Measurements of the LEP dipole field with NMR probes in some of the bending magnets yield variations of the beam energy since

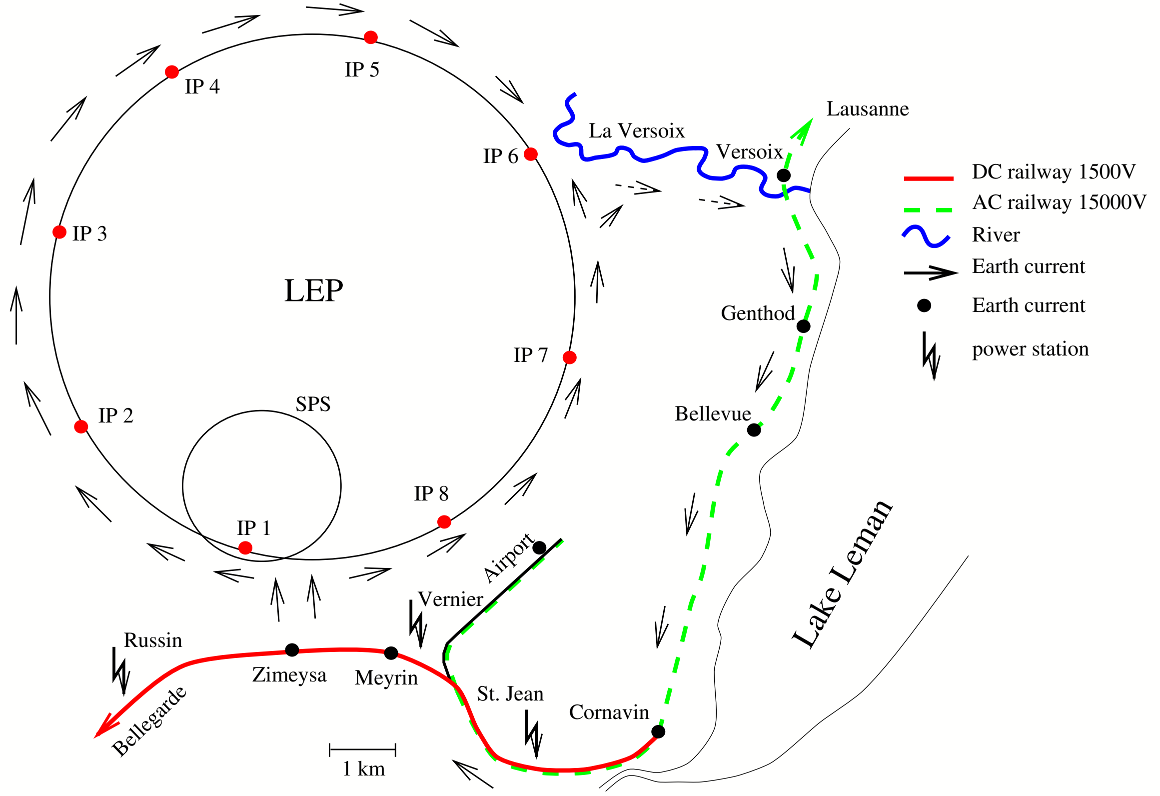
$$E_0 \propto \oint ds B$$

- correlation with human activity?

photo by S. Ingolstadt

Vagabond Currents





- about 20 % of current does not flow back to power station over the railway tracks
- in France some lines use DC currents: lower voltages ⇒ higher currents

LEP Energy: A Closer Look

- The energy model of LEP:

$$E_{beam}(t) = (E_{initial} + \Delta E_{dipole}(t)) \cdot (1 + C_{tide}(t)) \cdot (1 + C_{orbit}) \cdot (1 + C_{RF}(t)) \cdot (1 + C_{hcorr}(t)) \cdot (1 + C_{QFQD}(t))$$

Term	Physical Effect	$\mathcal{O}(\Delta E)$ [MeV]
ΔE_{dipole}	magnet temperature, parasitic currents on the vacuum chamber etc.	10
C_{tide}	tidal deformations (quadrupole contribution)	10
C_{orbit}	Circumference changes due to rainfall / underground water table height	10
C_{RF}	RF frequency change ($\sim$ 100 Hz) to reduce σ_x by increasing J_x	100
C_{hcorr}	horizontal correctors change $\oint B ds$ and ΔL	10
C_{QFQD}	stray fields of power supply cables	1

Historical Problem

- The problems with electrical trains close to physics institutes are not exactly a recent discovery...
- Journal article in 1895:

Central-Zeitung für Optik und Mechanik, XVI. Jg., No. 13, Page 151

“Nachtheile physikalischer Institute durch elektrische Bahnen”

(which roughly translates to *“Disadvantages for Physics Institutes from Electrical Trains”*)

- What happened:
  During first tests with electrical trams (instead of the horse-powered mo-dels) in Berlin it became clear that vagabond currents severely disturbed the delicate electrometers

Summary

- Beam energy is an important parameter for control room and experiment ✗
- A variety of methods exists, choose according to design precision and energy range ✔
- To achieve highest precision, a combination of several measurements might be needed ✔
- Once achieved, the high precision measurements might have some surprises in store.... ✔
- Advice: plan for long shifts... !