USPAS 2019: Knoxville

Spin Dynamics, Energy Calibration, Acceleration of Polarized Beams

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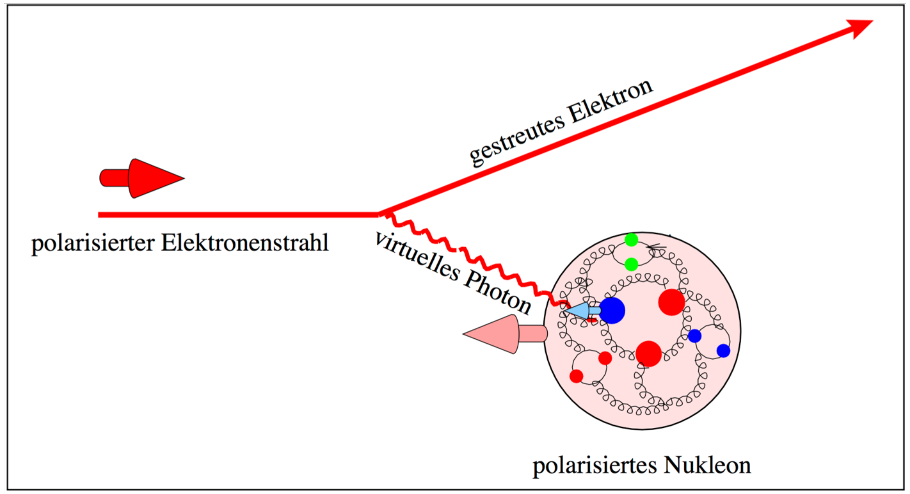
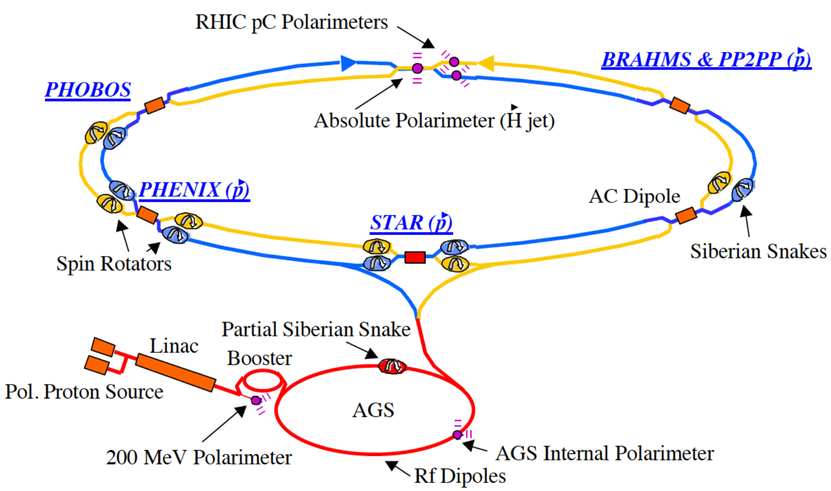
Outline

- Introduction
  - Applications of Spin in Accelerators
  - Spin dynamics
- Accelerating Polarized Beams
  - Electrons
  - Protons
- Beam Energy Stability
  - Energy Calibration
  - Tides, TGV, …
- Summary

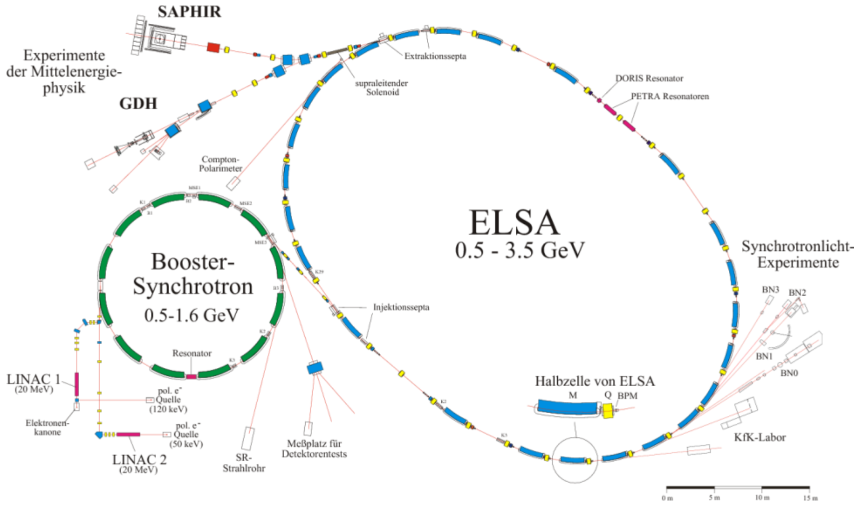
Introduction





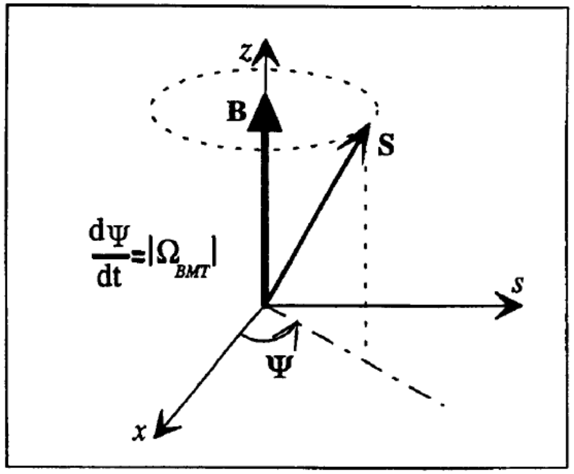
- Spin is a fundamental property of elementary particles (like charge)
  - Guiding fields in accelerators (magnetic and to lesser degree electric fields) also determine spin dynamics
- Interactions between particles depend on this property (scattering cross sections)
  - Includes the emission of synchrotron radiation
- Often desirable to study scattering processes (particle/nuclear physics) in spin dependent way
  - This usually requires polarized beams/targets

Example Applications



- Two main classes of applications of polarized beams in accelerators
- Producing polarized Beams at a source and crossing potentially many polarizing resonance
  - Protons
  - Electrons if used for external targets
- Self Polarization of Beams at final energy
  - Electrons/Positrons (Colliders)

Spin Dynamics



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

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

for $\gamma \gg 1$

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

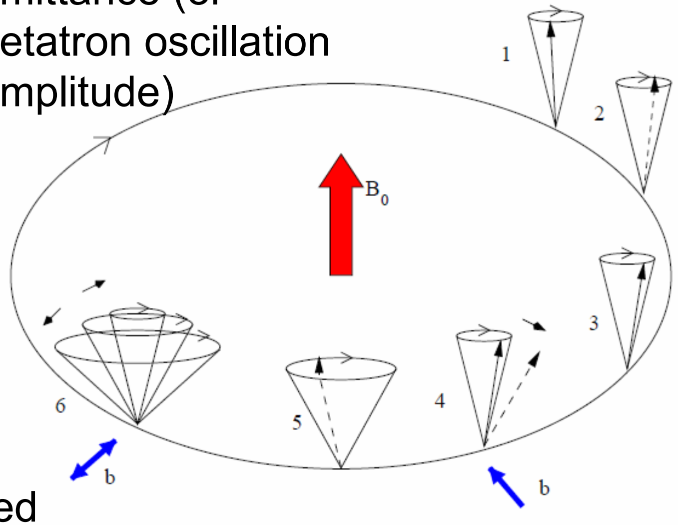
a: gyromagnetic anomaly $a = 1.159652 \cdot 10^{-3}$ for electrons and 1.792846 for protons

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

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

Scales with beam emittance (or betatron oscillation amplitude)



Scales with closed orbit error amplitude

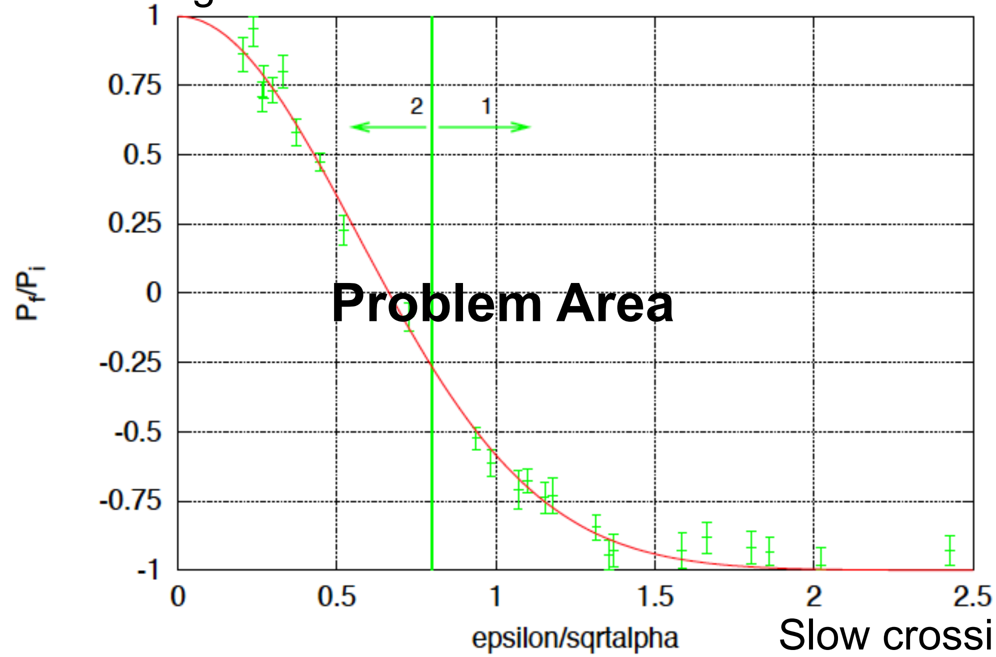
Resonance Crossing

- final polarization level after linear crossing of isolated resonance can be analytically calculated (Froissart-Stora)

$$\frac{P_f}{P_i} = 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1$$

$$\alpha = \frac{\dot{\gamma} a}{\omega_{rev}} \pm \frac{\dot{Q}_z}{\omega_{rev}}$$

Fast crossing / Small Resonance Strength

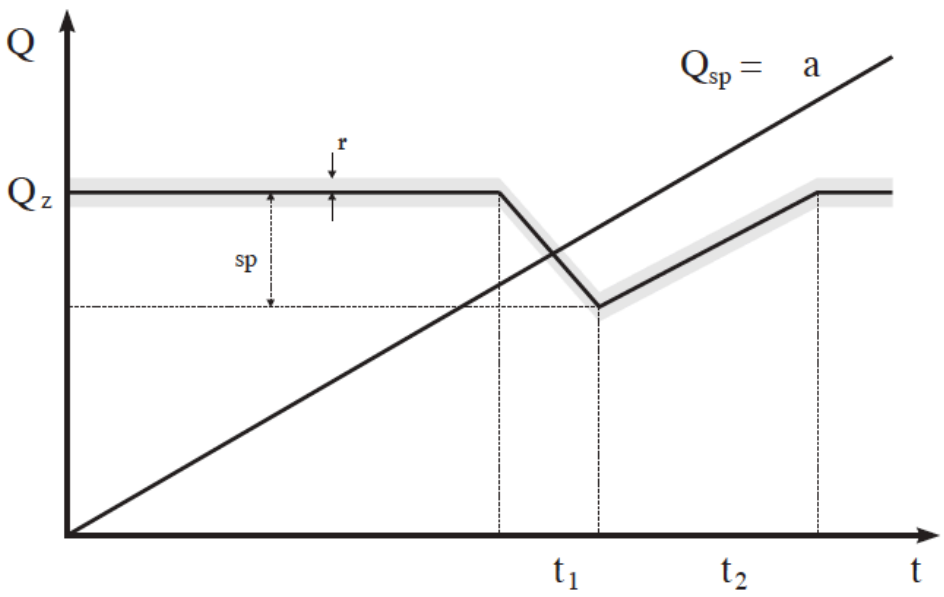


Slow crossing / Large Resonance Strength

$$\epsilon_r = \frac{1}{2\pi} \oint \frac{1}{B\rho} \left((1+\gamma a) B_{\perp,II} + (1+a) B_{||,II} \right) \exp(iQ_r\theta)\, \mathrm{d}\theta$$

Possible Correction Methods

- intrinsic resonances: betatron tune jump using pulsed quadrupoles



- imperfection resonances: decreasing or increasing the resonant magnetic field component

Polarimeters

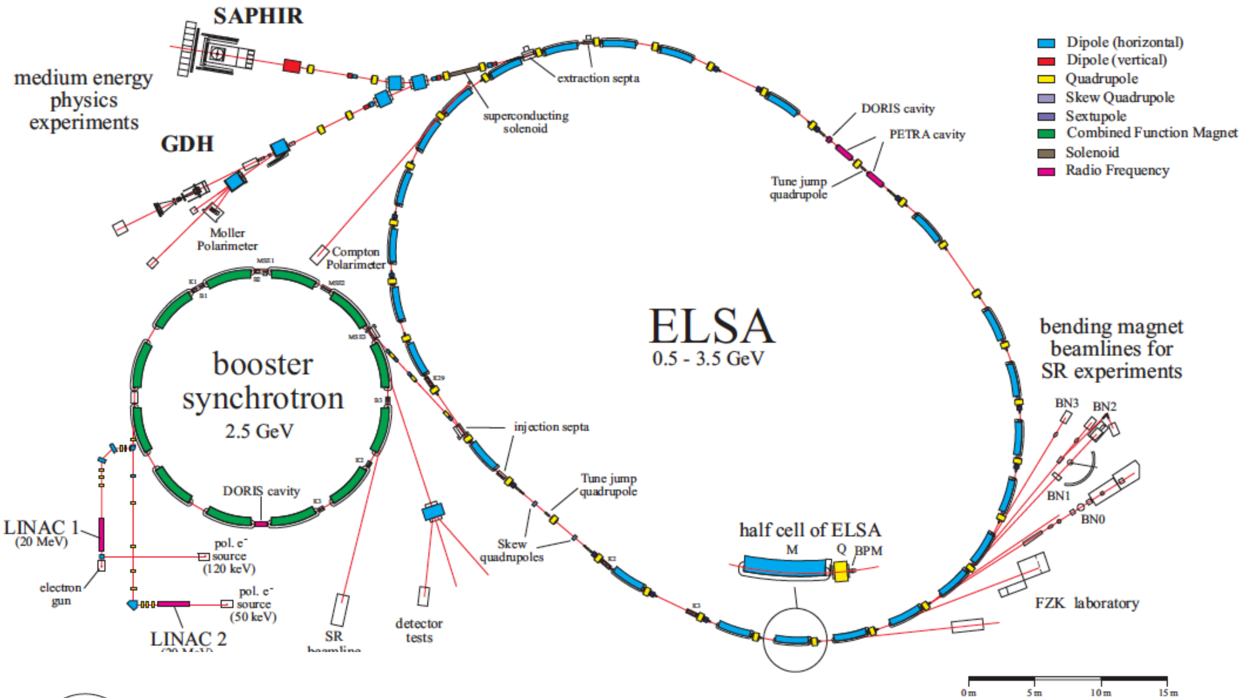
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\cdot\left(1 + P_T P_B A_{zz}(\theta)\right)$$

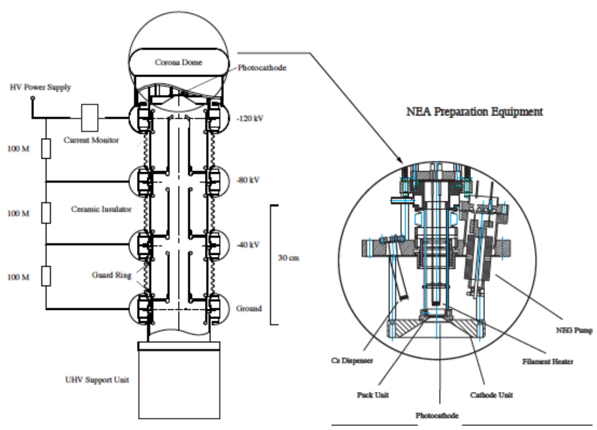
$$\frac{d\sigma_0}{d\Omega} = \left[\frac{\alpha(4-\sin^2\theta)}{2E_e^{CMS}\sin^2\theta}\right]^2$$

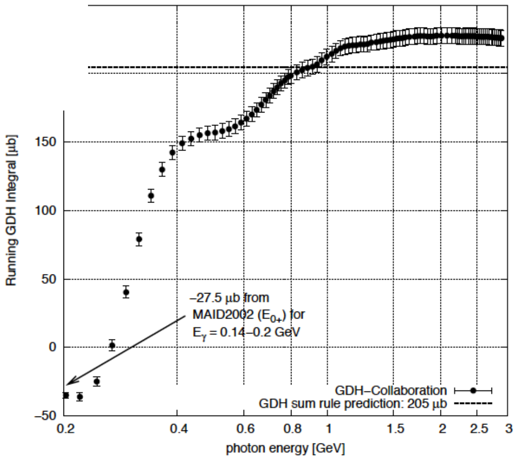
$$A_{zz}(\theta) = \frac{(-\sin^2\theta)(8-\sin^2\theta)}{(4-\sin^2\theta)^2}$$

- All polarimters use asymmetry in scattering cross sections
- Compton-polarimeters (laser photons hitting 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).
- If Touschek lifetime contribution is significant one can use simple polarimeter: Touschek scattering is Møller scattering. Møller scattering cross section depends on polarization (polarized beams have longer Touschek lifetime!).
- depolarization reduces Touschek lifetime by up to 20%

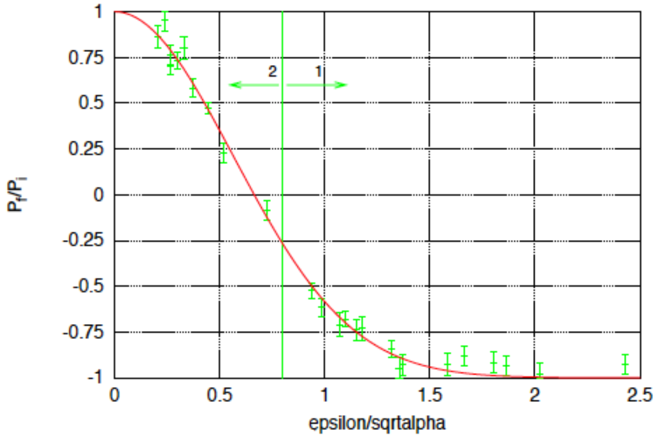
Example (1): Acceleration of Polarized Electrons

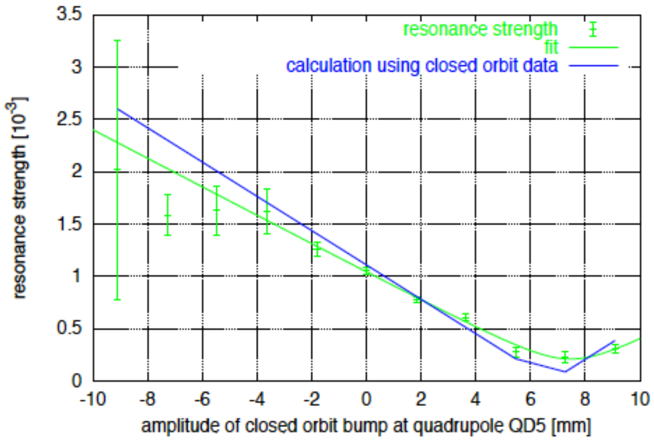






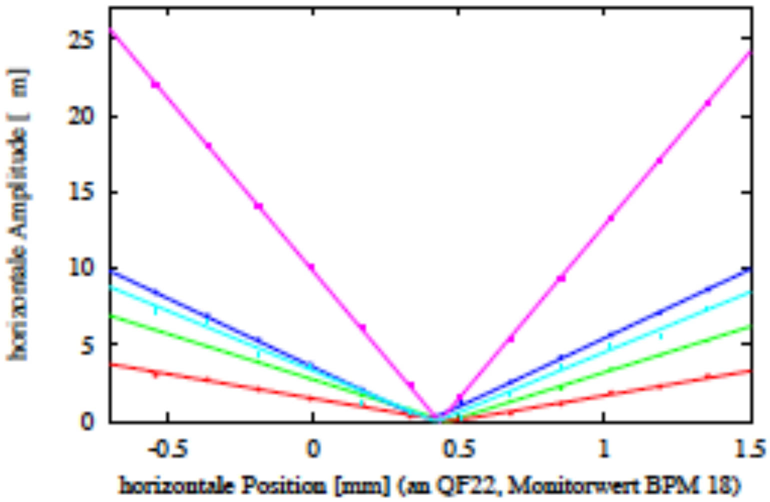
Resonance Strength Reduction

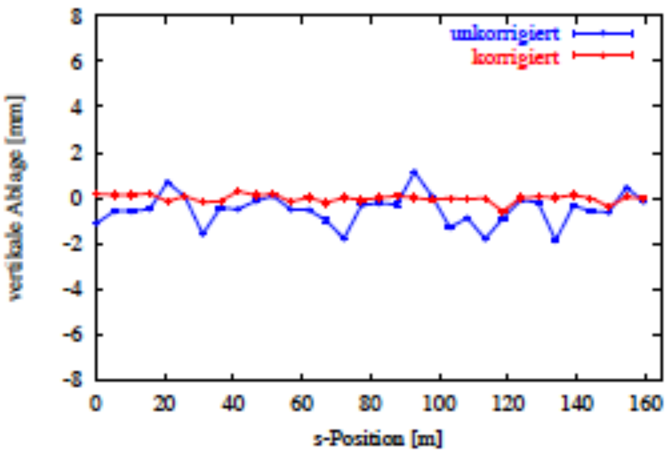




- complete spinflip possible (at 1.32 GeV)
- harmonic correction successfully applied
  Requires beam-based alignment, excellent BPMs and enough, fast corrector magnets
- measured and calculated resonance strengths agree
- intrinsic resonances at 1.14 and 1.5 GeV are weak
- complete depolarization at 2.0 GeV

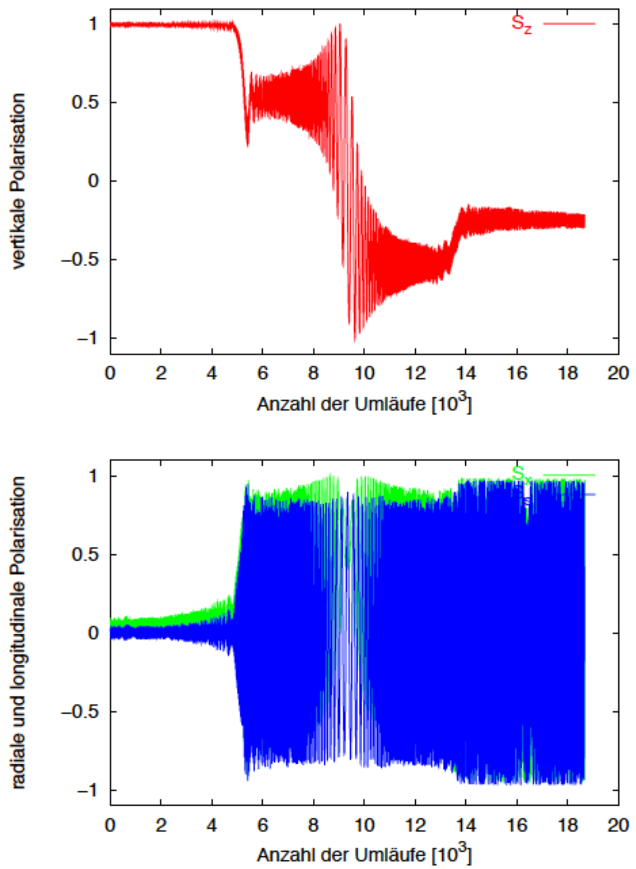
BBA / Orbit correction





- Strength of imperfection resonances not determined by deviation from BPM centers, but deviation from quadrupole centers
- Need Beam-based alignment – typical BPM offsets are up to mm
- BBA allows determination with tens of microns accuracy
- Also need fast BPMs and correctors, since correction has to be done dynamically while the machine ramps
- On top of this, one can add empirical correction with harmonic orbit bumps (based on polarization measurements)

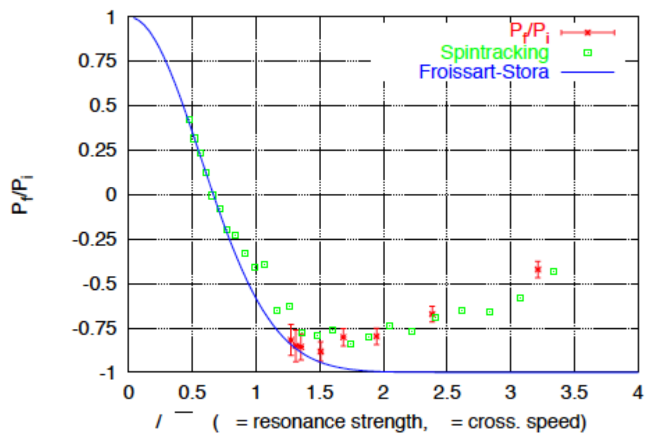
Resonance Crossing with SR

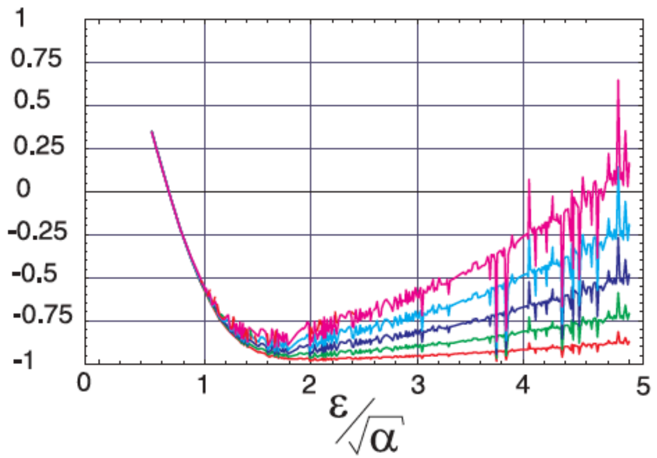


At Beam energies > 1.32 GeV, where synchrotron radiation gets much stronger:

- spinflip gets incomplete
- nonlinear crossing due to synchrotron motion
- stochastic crossing due to synchrotron radiation

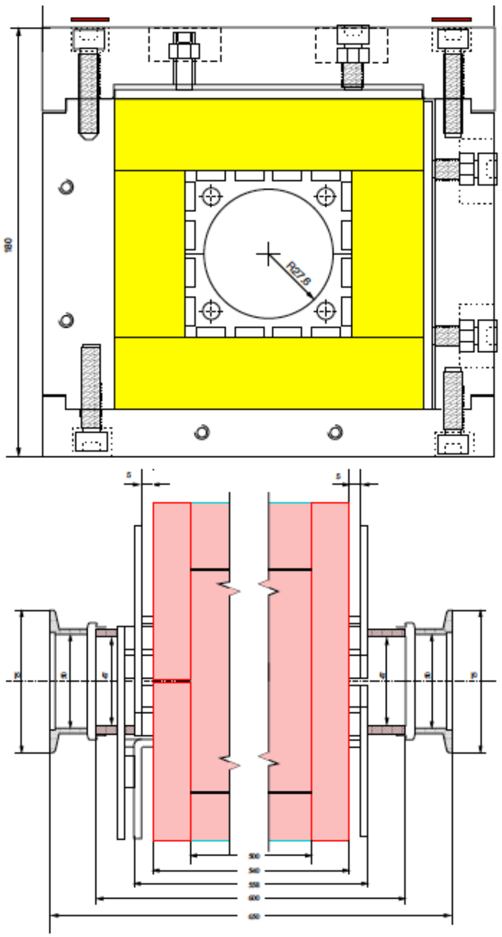
Effect of SR at higher beam energies





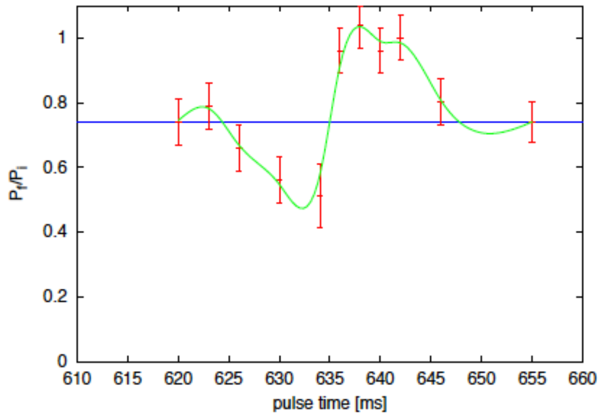
- spintracking and semianalytical calculations are consistent with measurement at 1.76 GeV (coherent longitudinal oszillation)
- prediction: complete depolarization when using adiabatic spinflip at higher energies
- ⇒ harmonic correction will be used (unaffected by SR induced diffusion)

Tune Jump Quadrupoles



- max. gradient 1.2 T/m (at 500 A)
- inductance 9 μH
- rise time 4–14 μs
- fall time 4–20 ms
- time between pulses > 40 ms
- complete system tested and calibrated (polarzied and unpolarized beam)

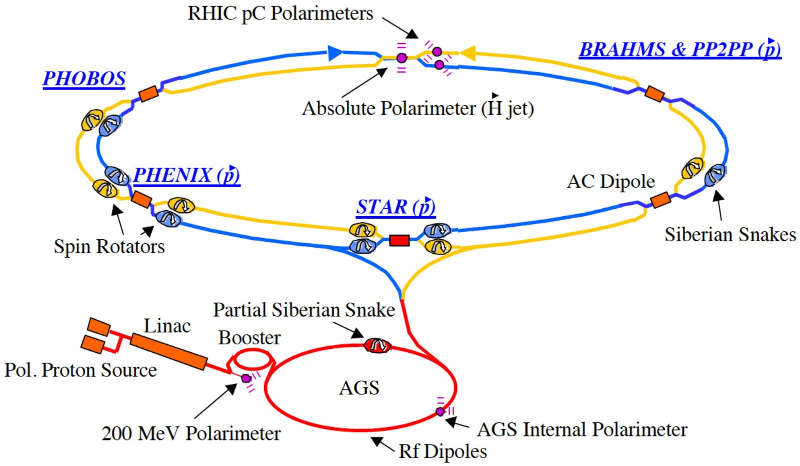
Jumping Intrinsic Resonances



- complete cure of intrinisic resonance
- needed amplitude consistent with expectation
- orbit distortion and emittance increase small

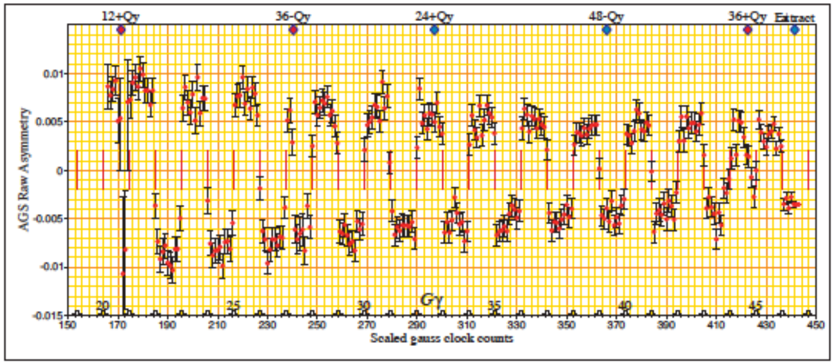
Effect of emittance increase would be much more relevant for protons, which do not have radiation damping

Example (2) RHIC



- Polarized protons
  - No synchrotron radiation
    - Usually can use spin flip
  - Much higher energies
    - Many resonances to cross – hard to empirically correct individual ones
    - Resoances get stronger with energy
  - Larger accelerators
    - Usually less correctors/BPMs per phase advance and beam-based alignment not possible everywhere

Acceleration in Pre-accelerator AGS



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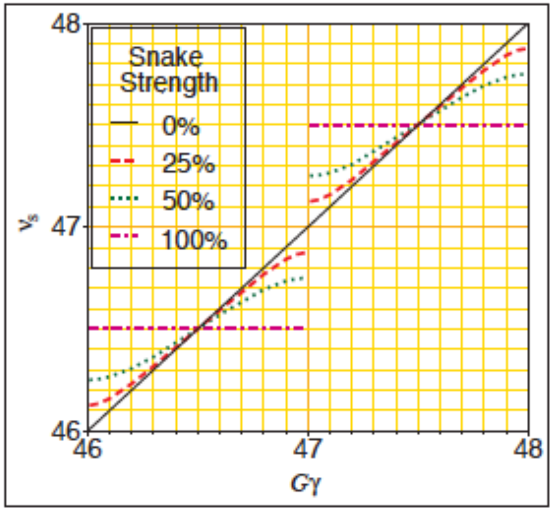
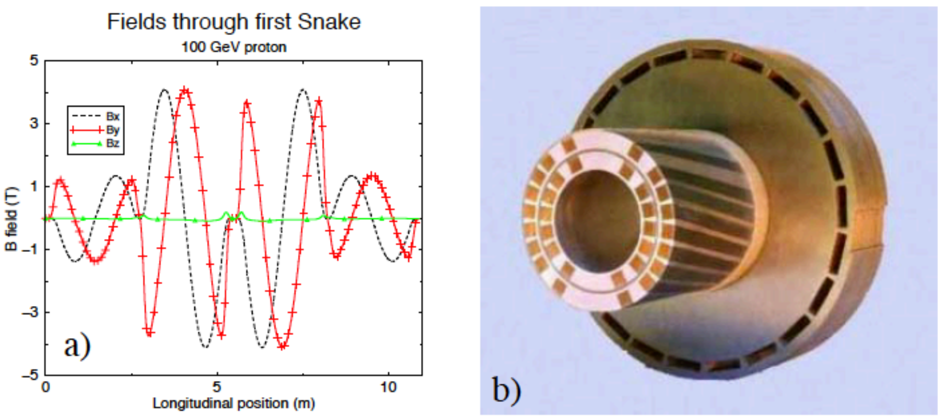
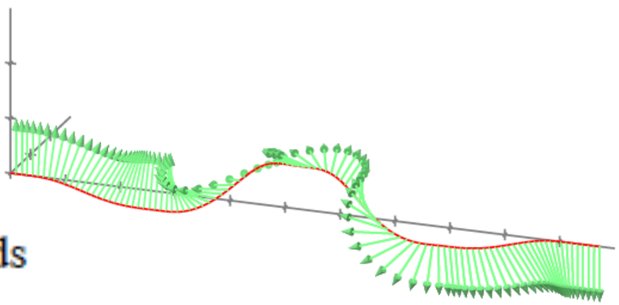


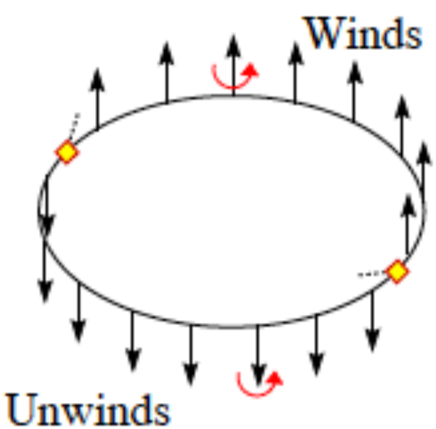
MacKay, Roser, Bai, Huang, TS, et al.

- Spin Flip used on imperfection resonances
- Partial Snake (5% or 9 degrees)
  - Snakes effect both the resonance strength, but also the spin tune
- AC dipole for some intrinsic resonances – see labels
  - increases betatron amplitude while crossing resonance to flip spin, avoids emittance blow-up
  - Adiabatic ramp up and ramp down of betatron oscillation amplitude

Additional Device - Snake

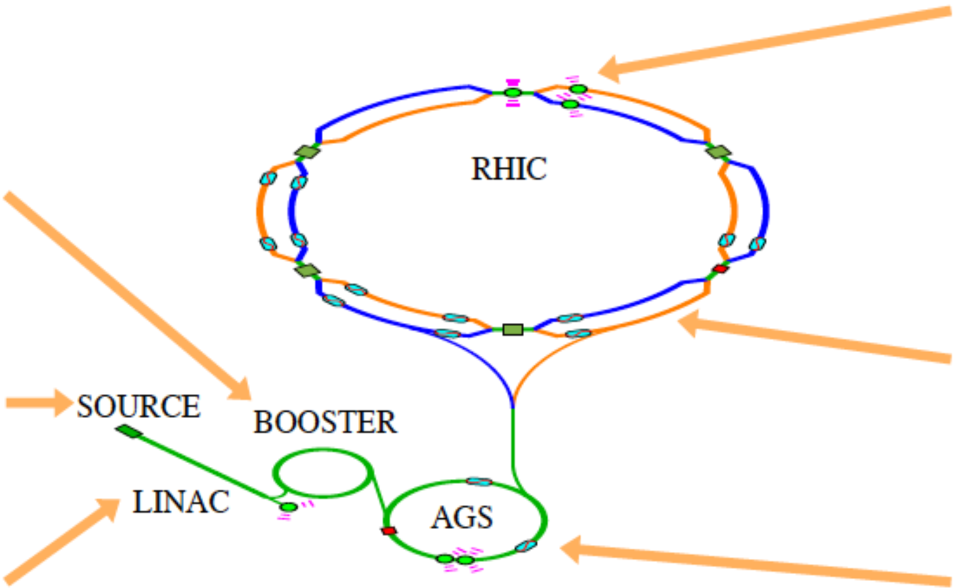


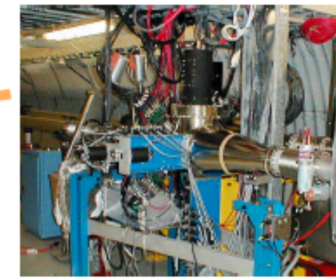


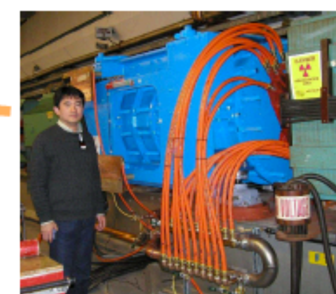


- A snake is an insertion device that rotates the spin around a horizontal axis
  – Simplest implementation is solenoid – rotation around longitudinal axis
  – For high energy rotation around transverse axis are often necessary
  Complex sequence of bending, which cancels for the particle direction, but adds up for the spin precession
- Siberian snakes rotate the spin by 180 degree in one pass
  – Fractional spin tune becomes 1/2

Some Pictures (RHIC)



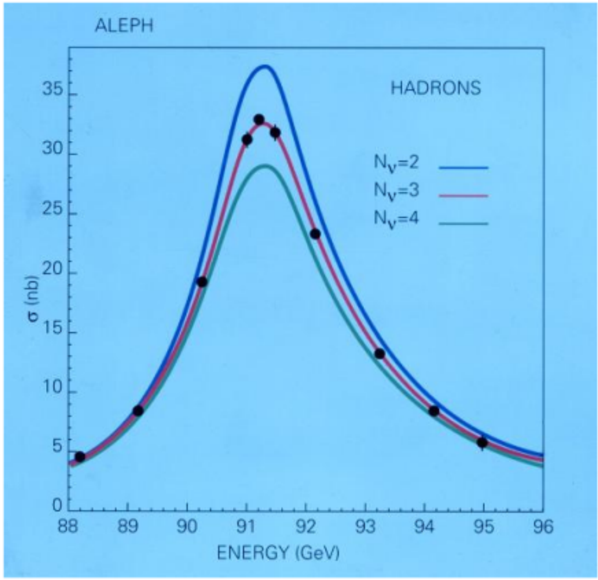




LINAC: Linear Accelerator
AGS: Alternating Gradient Synchrotron
RHIC: Relativistic Heavy Ion Collider

Example (3) Energy Calibration

- In electron-positron collisions the particles annihilate and all the energy in the center of mass system is available for the generation of elementary particles.
- Such particle generation if enhanced if there is a particle with rest mass equal to the collision energy.
- The energy of the colliding beams can be tuned to the rest mass of a known particle for studying its properties, or can be scanned for the research of unknown particles.



Center of Mass System (some special relativity)

- Two particles have equal rest mass m_0.

  Center of Mass Frame (CMF): Velocities are equal and opposite, total energy is E_{cm}.

$$P_1 = \left(E_{CM}/2c, p\right) \qquad P_2 = \left(E_{CM}/2c, -p\right)$$

Laboratory frame (LF):

$$\tilde{P}_1 = \left(E_1/2c, p_1\right) \qquad \tilde{P}_2 = \left(E_2/2c, p_2\right)$$

- The quantity $\left(P_1 + P_2\right)^2$ is invariant.
- In the CMF, we have $\left(P_1 + P_2\right)^2 = E_{CM}^2/c^2$
- While in the LF: $\left(\tilde{P}_1 + \tilde{P}_2\right)^2 = \tilde{P}_1^2 + \tilde{P}_1^2 + 2\tilde{P}_1\tilde{P}_2 = 2m_0^2c^2 + 2\tilde{P}_1\tilde{P}_2$
- And after some algebra we can obtain for relativistic particles:

$$E_{cm} \cong 2\sqrt{E_1 E_2}$$

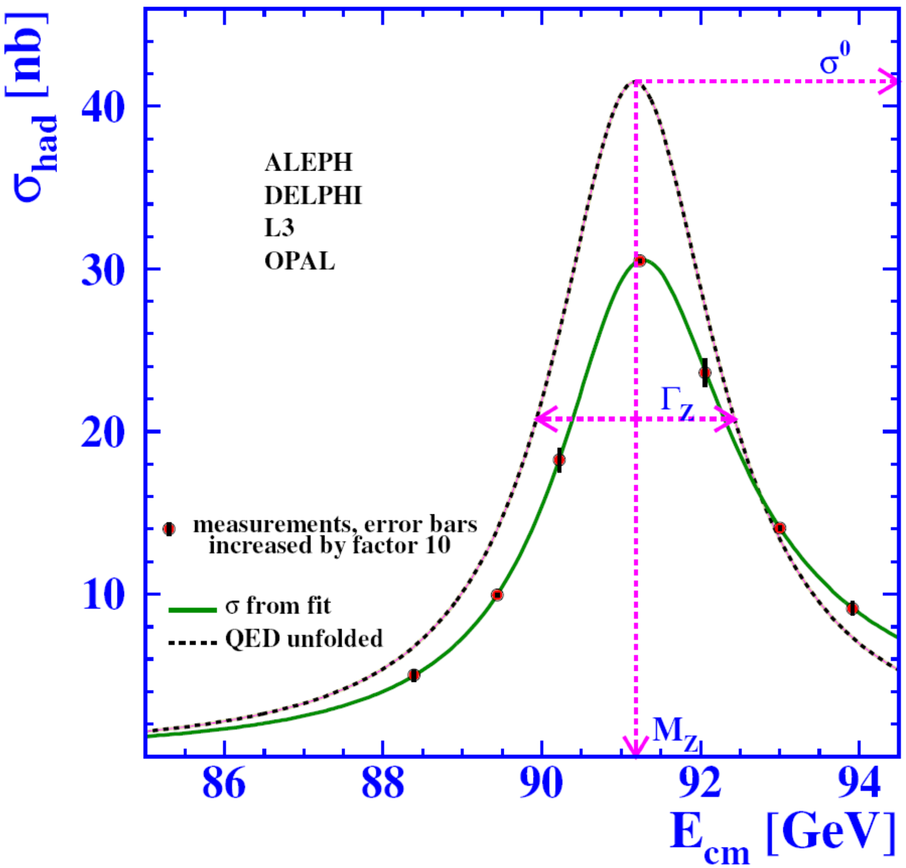
Example Results of Energy Calibration

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^{o}	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

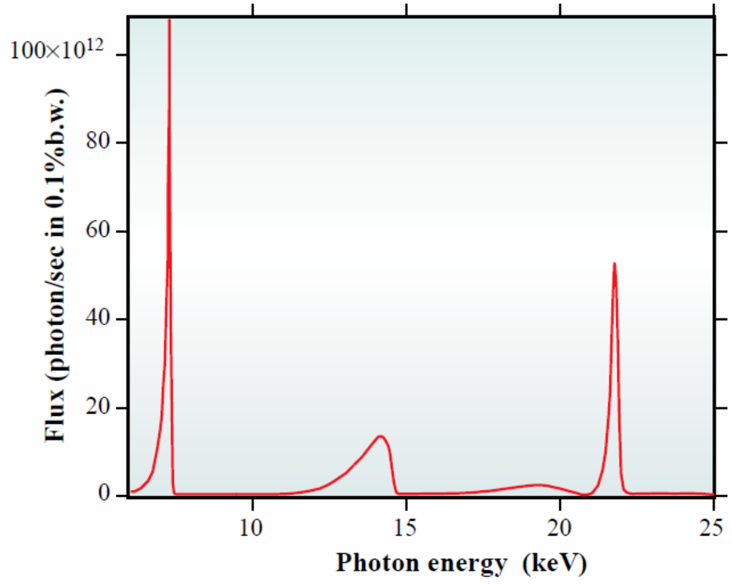
- Using resonant depolarization allows an ultra high precision measurement of the beam energy
- Many applications: precise determination of particle masses, ...

Main Physics Result (LEP)



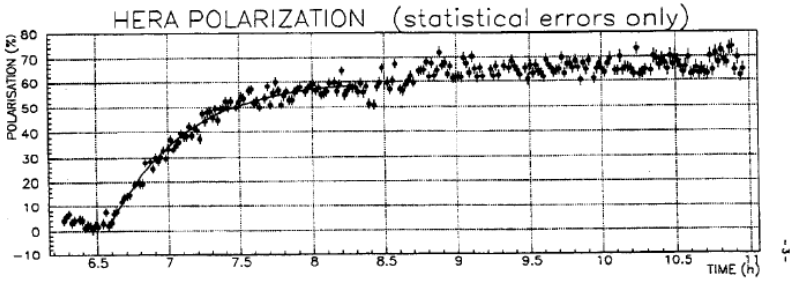
- Using resonant depolarization allows an ultra high precision measurement of the beam energy
- Another application: resonance linewidths. Example of LEP: Precision measurement of Z_0 width allowed conclusion that only 3 lepton families with light neutrinos exist.

Other Applications of Energy Calibration



- 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.

Sokolov-Ternov Effects



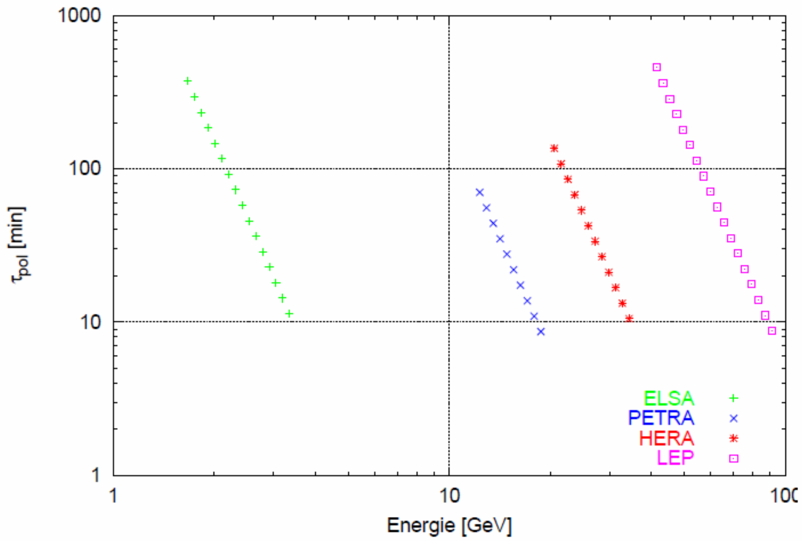
	VEPP[10]	VEPP2-M[11]	ACO[8,9]	BESSY[44]	SPEAR[45]	VEPP4[46]
E(GeV)	0.640	0.625	0.536	0.800	3.70	5.0
τ_p(min)	50	70	160	150	15	40
P(%)	52	90	90	>75	>70	80
	DORIS II[47]	CESR[48]	PETRA[49]	HERA[19]	TRISTAN[50]	LEP[51]
E(GeV)	5.0	4.7	16.5	26.7	29	46.5
τ_p(min)	4	300	18	40	2	300
P(%)	80	30*	80**	70**	75**	57**

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

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

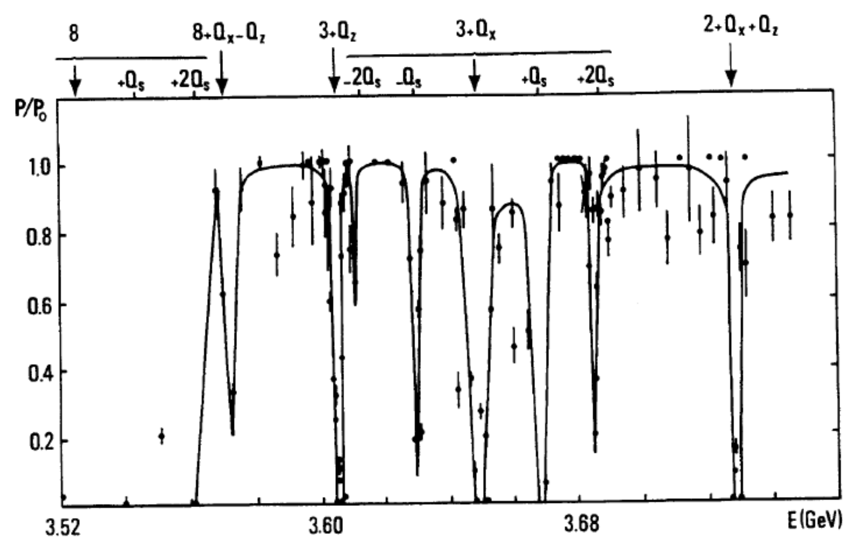
- has been observed at most lepton storage rings that have looked for the effect.

Typical Polarization Buildup Times



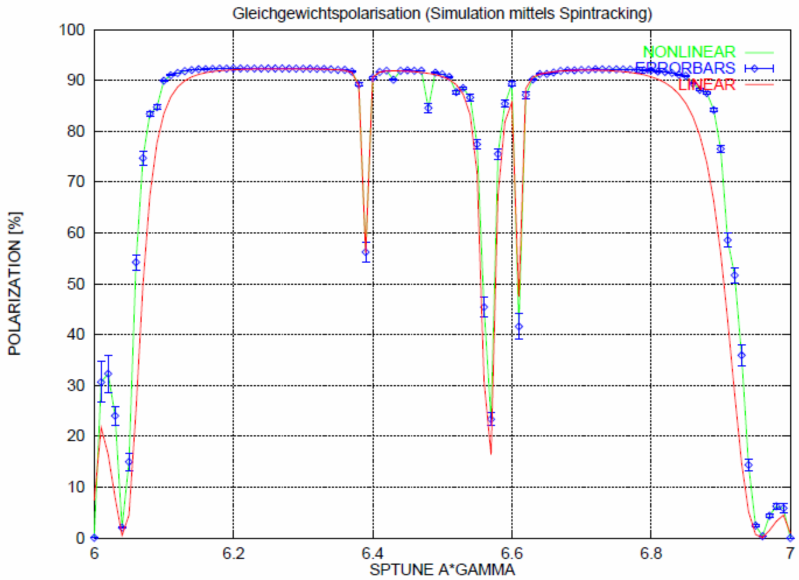
- Even though the polarization buildup time for a given ring strongly depends on the beam energy, it has about the same order of magnitude for most lepton storage rings.
- Reason is that it also scales with the bending radius and machines with higher energy typically have to have much larger bending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

Equilibrium Polarization and Depolarizing Resonances



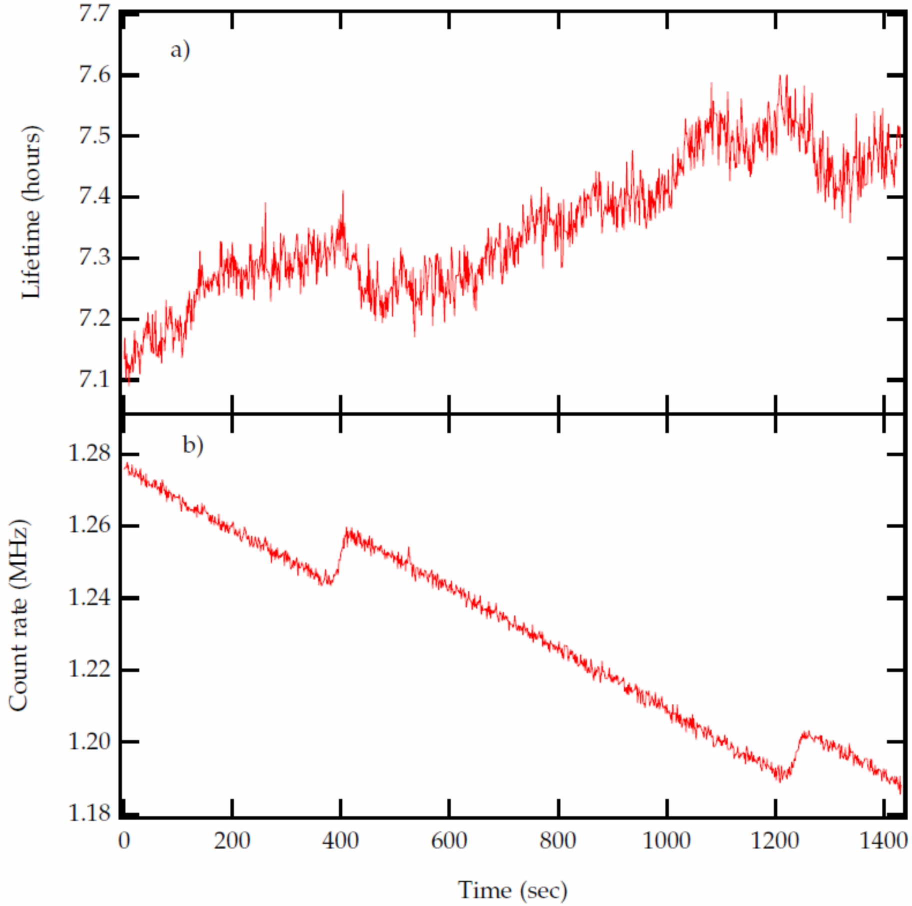
- Equilibrium of self polarization and resonances depends on energy.
- Resonance strength increases with energy.
- Imperfection resonance strength scales with the closed orbit error
- Intrinsic resonance strengths scales with the vertical emittance

Results can also be understood in numerical simulations



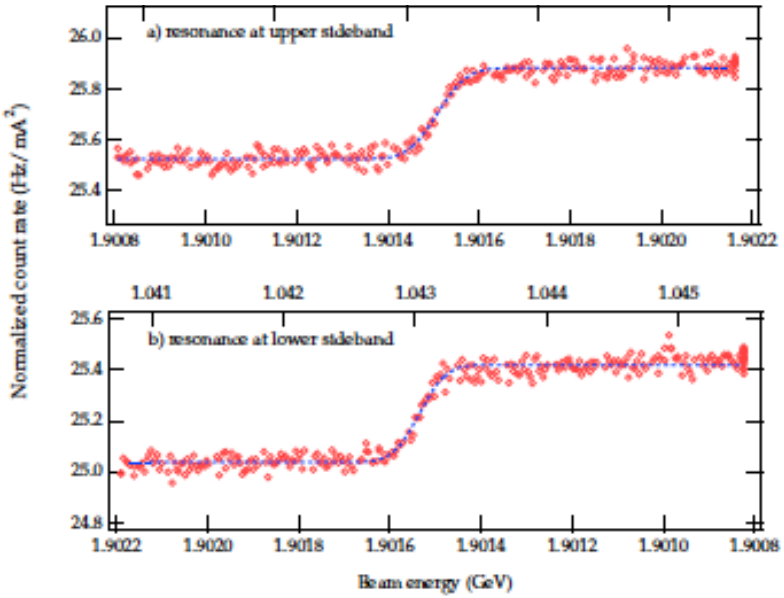
- Using spin tracking codes, one can calculate the equilibrium between polarizing and depolarizing effects.
- Using the simulations, one can optimize the correction techniques (orbit correction, harmonic spin matching, coupling correction, ...)
- Correction is much faster, if one has a good model of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

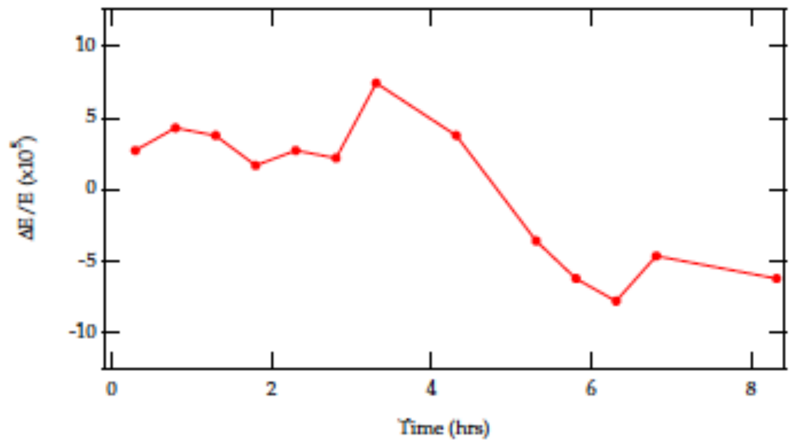
Example: ALS – Touschek Lifetime as Polarimeter



- 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

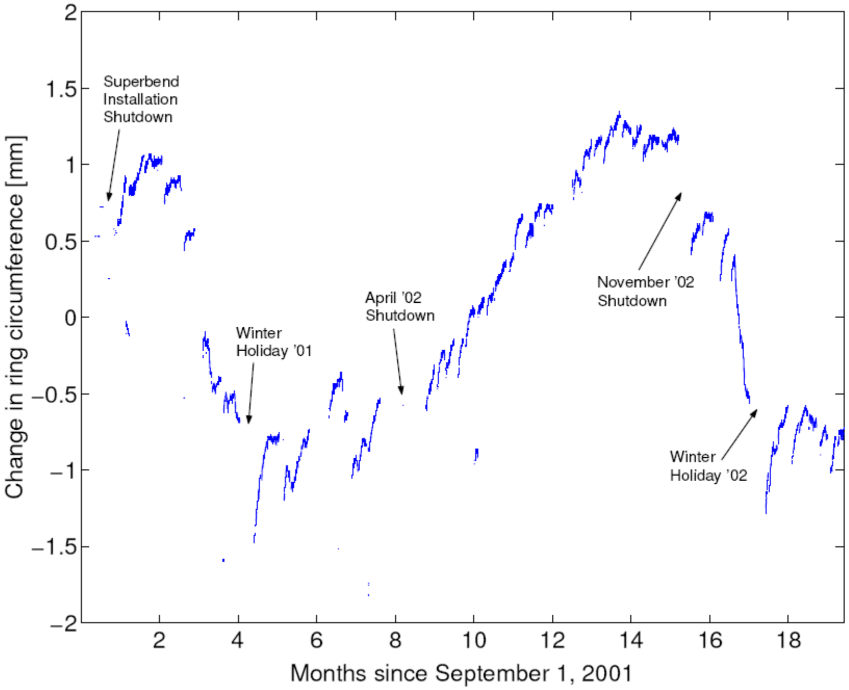
Energy Stability





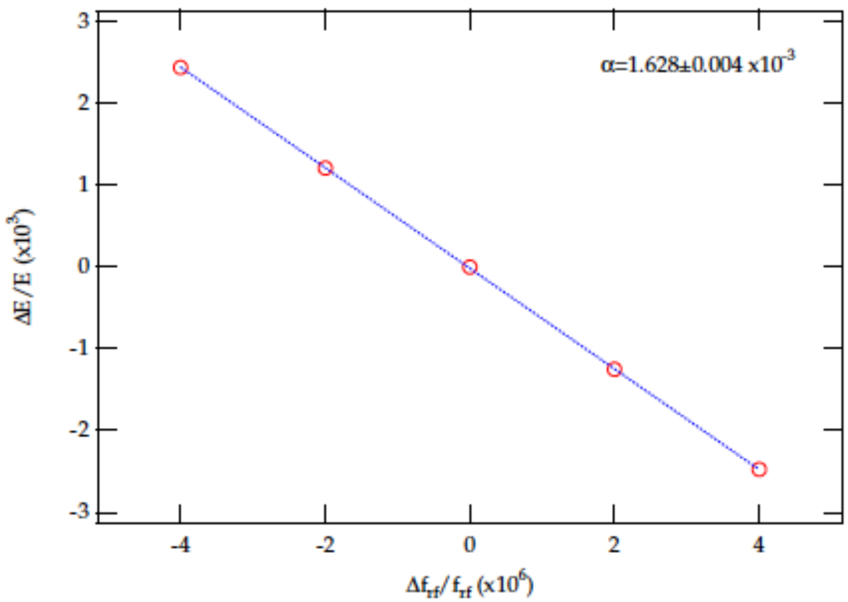
- ❑ partial depolarization allows better accuracy in sweeping measurements
- ❑ energy stable to a about $\pm 1 \cdot 10^{-4}$ within a week without rf-frequency feedback - much better with ...

Effects that Change the Energy



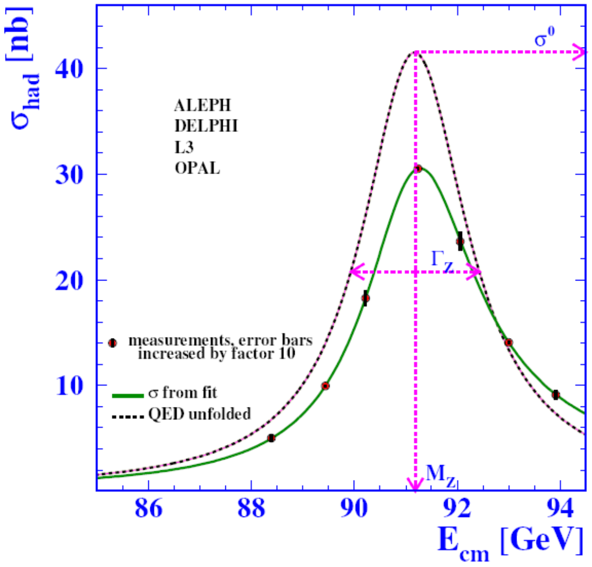
- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation,)
- RF keeps frequency fixed - beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies of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

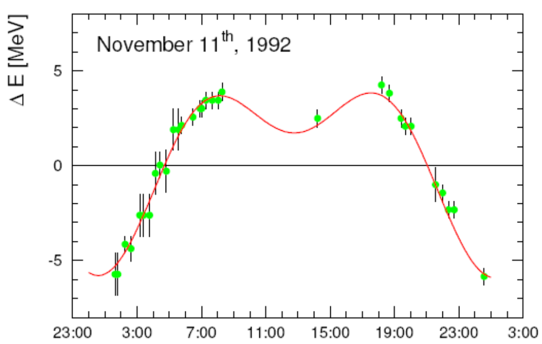
Application: Momentum Compaction Factor Measurement



- 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

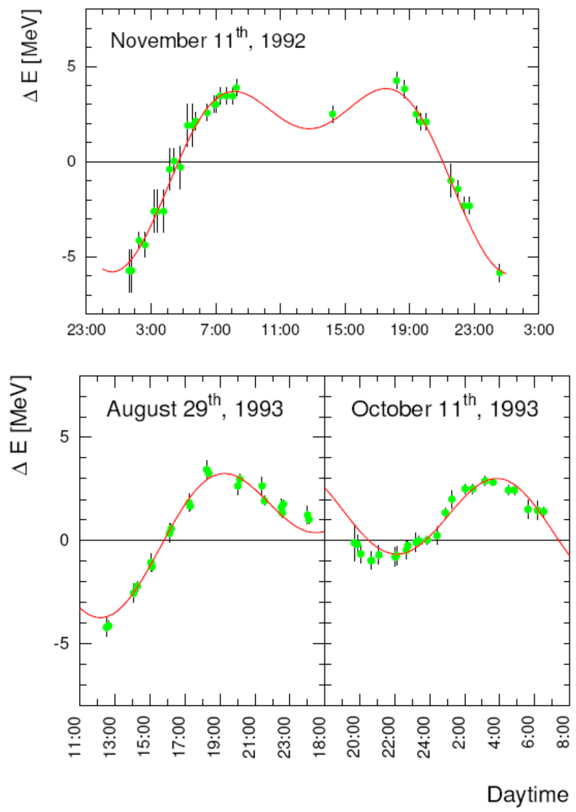
Back to LEP – Other Effects





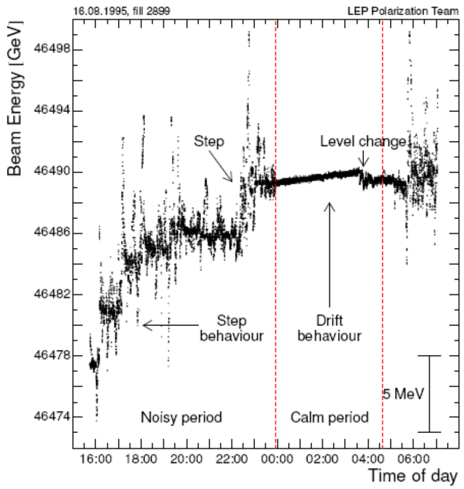
- Many electroweak precision measurements
- Precise energy calibration essential
- Found many interesting effects: Tides, Lake Geneva, TGV, ...

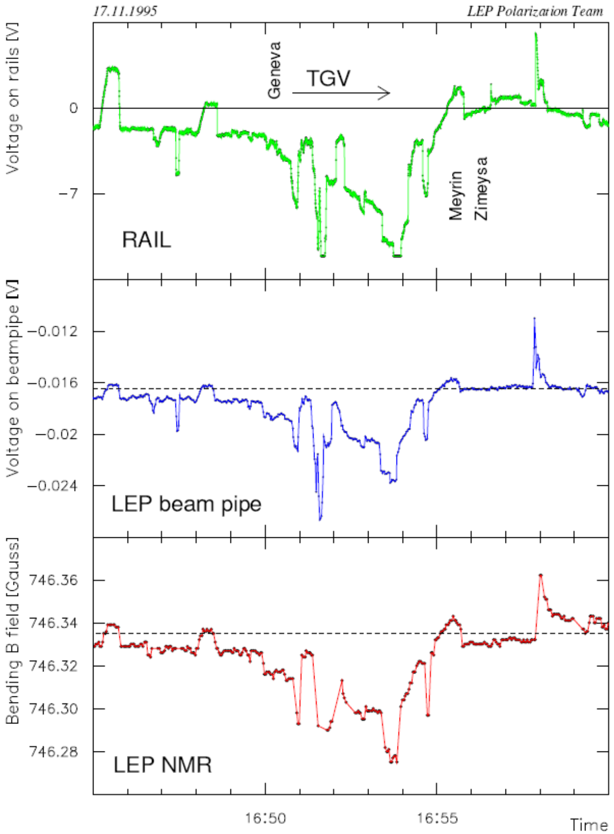
Tides at LEP



- 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

The TGV …

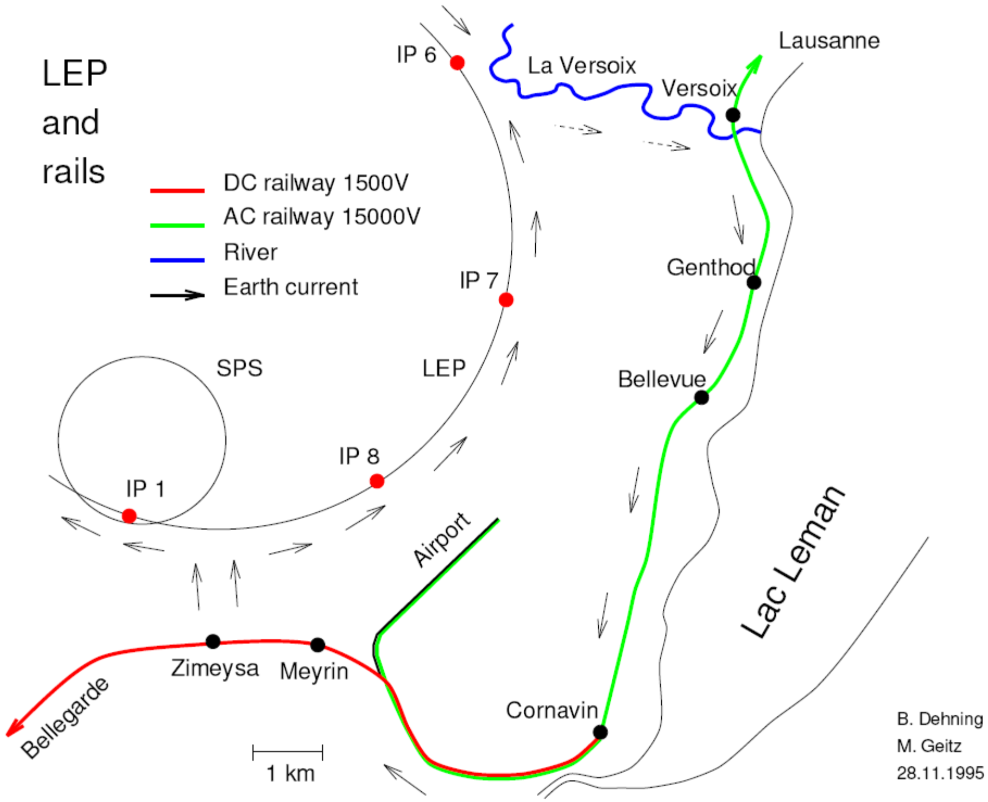




- Large noise in magnetic dipole field found
- Stopped overnight
- Intensive search - accidental discovery (on French holiday)
- Return currents of TGV

The TGV: explanation

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

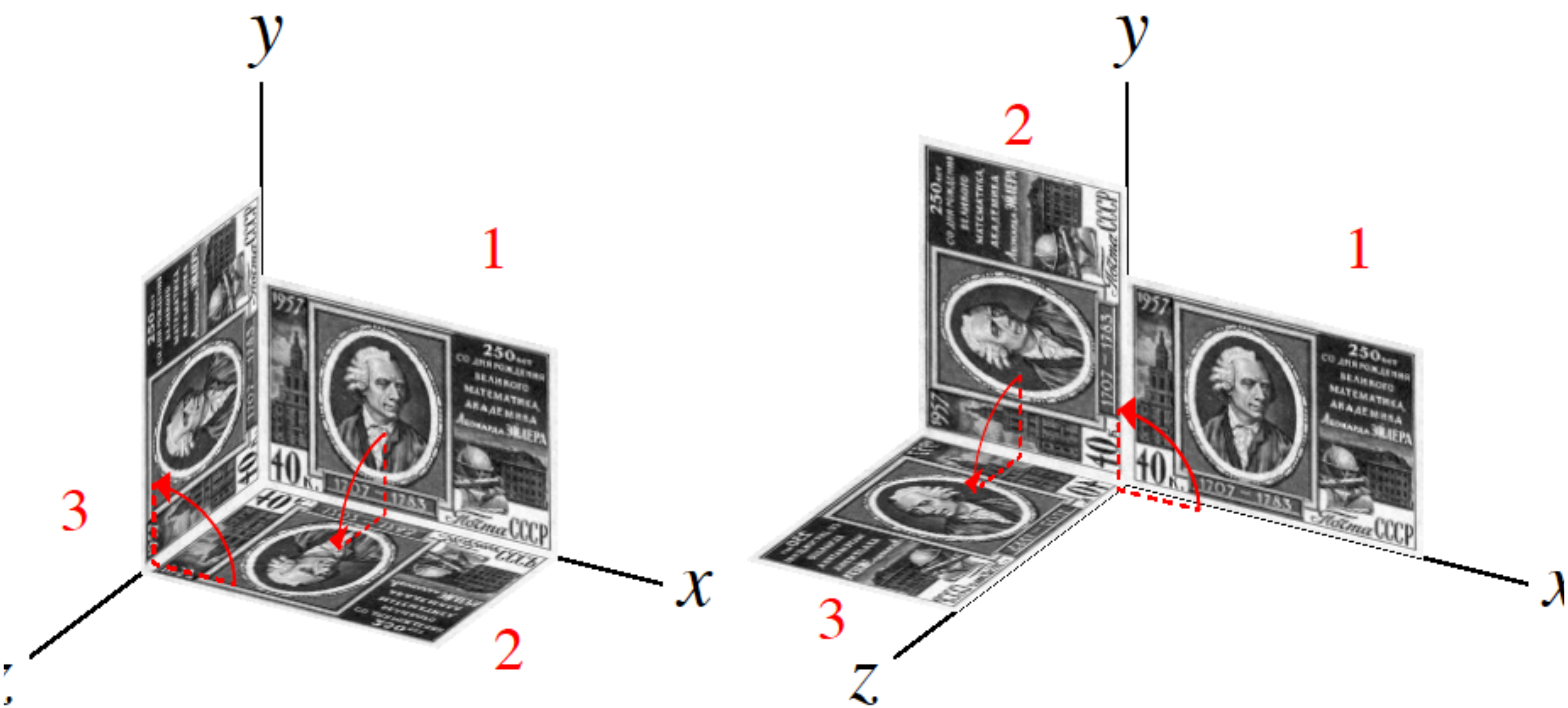


Summary

- Spin is a fundamental property of elementary particles
- Guiding fields in accelerators act on spin (precession)
- Polarization is important in many particle/nuclear physics experiments
- Generating polarized beams and preserving their polarization is difficult
  - Many effects depend on particle type, beam energy, … - No universal solution exists
- Energy calibration using polarized beams enables high accuracy beam energy determination (as well as lattice measurements – momentum compaction factor, …)
  - Typically uses self-polarized beam (by Sokolov-Ternov effect).

Backup Slides

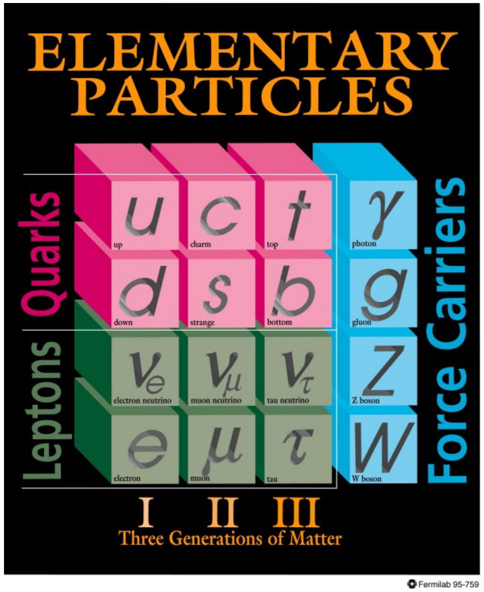
Rotations usually do not commute



$R_z(90°)\, R_x(-90°)$ $R_x(-90°)\, R_z(90°)$

Energy frontier: Particle Physics

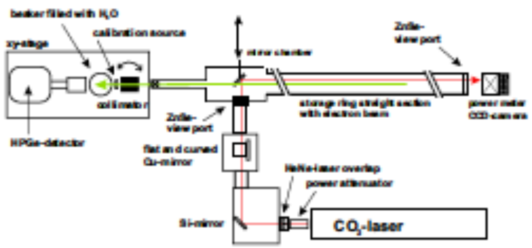
- For very long time particle physics has been driving accelerator development – higher and higher energies, while simultaneously higher luminosity
- Reasons:
  - Resolution
  - Particle production thresholds
- Particles once thought of as elementary have been shown to be composites …

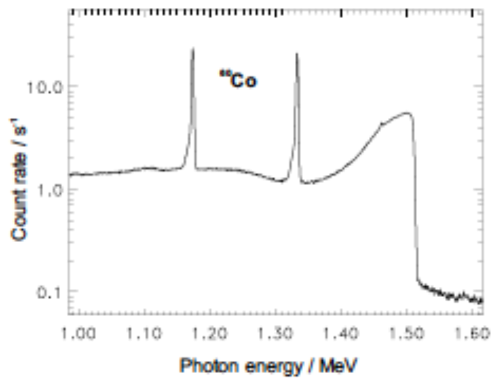


$$\lambda = \frac{h}{p}, \text{de Broglie wavelength}$$

$$E = mc^2, \text{Energy} - \text{mass relation (Einstein)}$$

Other Energy Measurement Techniques

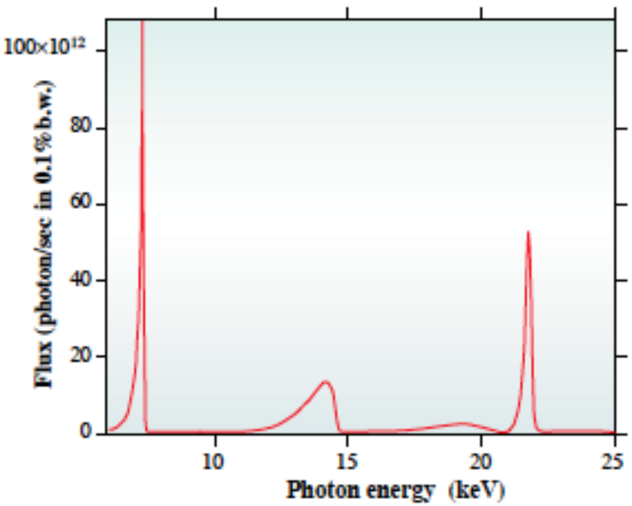




- ❑ Measuring energy spectrum of compton backscattered (laser) photons
- ❑ high energy edge is well defined (laser photon energy + γ^2 Lorentz boost)
- ❑ Addition of line spectrum from radioactive decay allows easy online calibration
- ❑ Advantage is relatively fast measurement - No polarizatiob necessary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

Substantial progress by quantifying effects of energy spread, emittance, detector acceptance, … - now resolution almost comparable to depolarization

Further Techniques



- 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