The HERA polarimeters – a review

CNFS workshop on

Beam Polarization and Polarimetry at EIC

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Stefan Schmitt, DESY

Outline

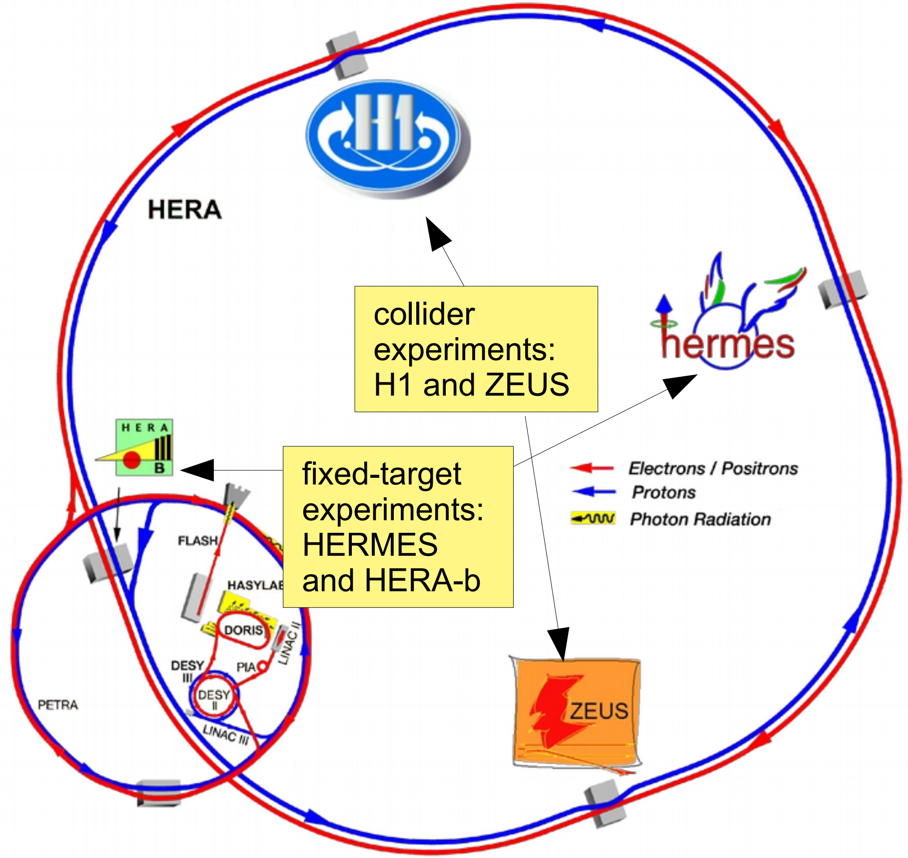
- Introduction
  - The HERA collider
  - Polarization at HERA
  - The HERA polarimeters
    - Transverse polarimeter (single photon mode)
    - Longitudinal polarimeter (multi-photon mode)
    - Cavity polarimeter (few photon mode)
  - Systematic limitations of the HERA polarimeters

Disclaimer:

this talk is on HERA polarimetry, but reflects my personal opinions only.
I have been working on with the POL2000 group in the years 2000-2007, mainly on the transverse polarimeter

The HERA collider

- Operated from 1992 to 2007
- Circumference 6.3 km
- Electrons or positrons colliding with protons
- Proton: 460-920 GeV, Leptons 27.6 GeV
- Peak luminosity ~7×10^{31} $cm^{-2}s^{-1}$
- Lepton beam polarization up to 40-60%

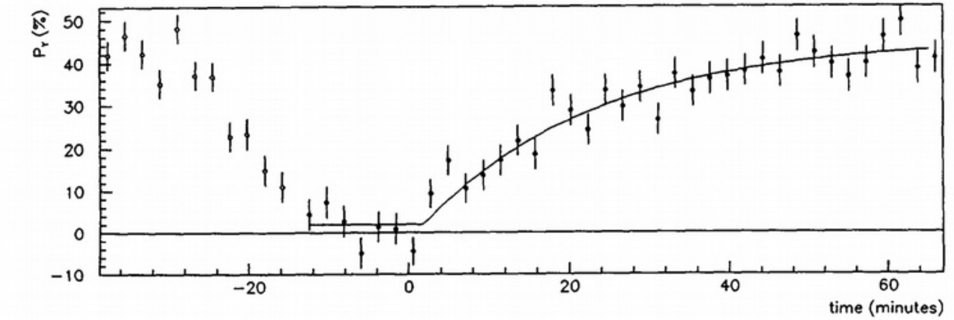


Beam polarization at HERA

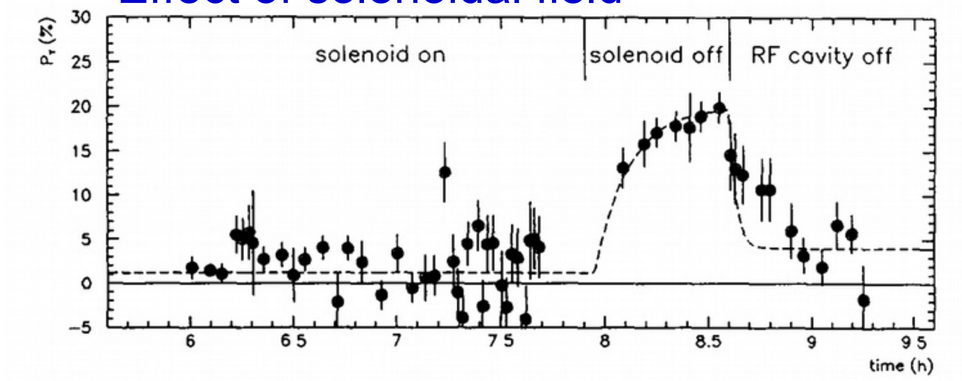
- Proton-beam: unpolarized
- Lepton beam: unpolarized at injection energy (12 GeV)
- Lepton beam acquires transverse polarization at collision energy (27.5 GeV): Sokolov-Ternov effect
- rise-time ~40 minutes

  (cf. duration of a fill: ~10 hours)
- Requirement: “flat” machine → compensating magnets for H1 & ZEUS solenoids

Polarization build-up τ=43 min, P_{max}=45%



Effect of solenoidal field



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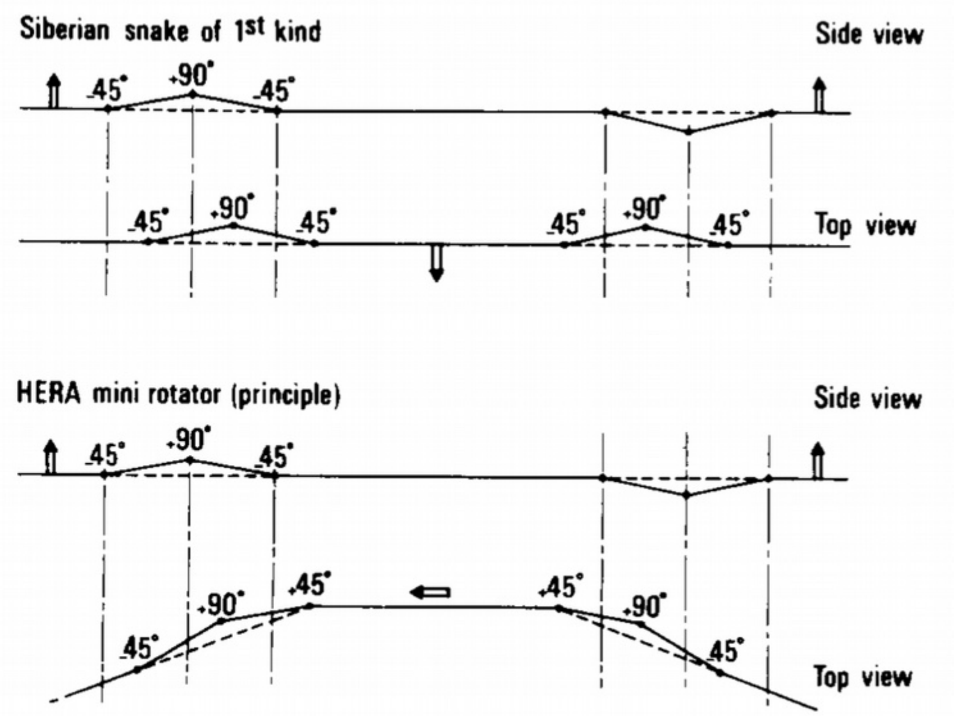
Longitudinal polarization for experiments

- First experiment making use of HERA beam polarisation: HERMES (start in 1995)
- Spin rotators: longitudinal polarization in the HERMES straight section, transverse polarization in the arcs
- Luminosity upgrade 2000-2002
  - Install spin-rotator pairs around H1 and ZEUS
  - Remove compensating coils



HERA mini rotator, similar to Siberian snake

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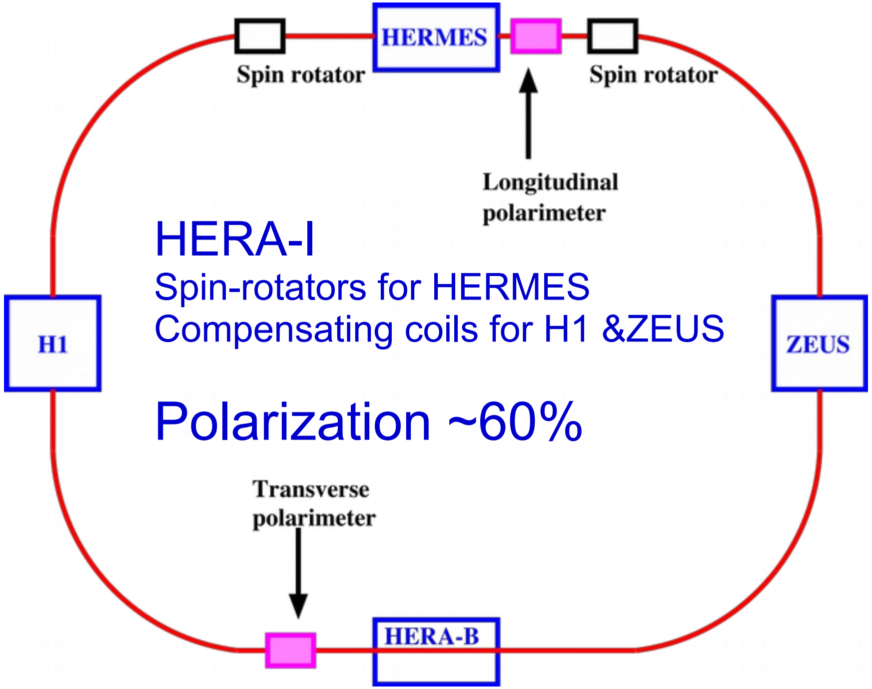
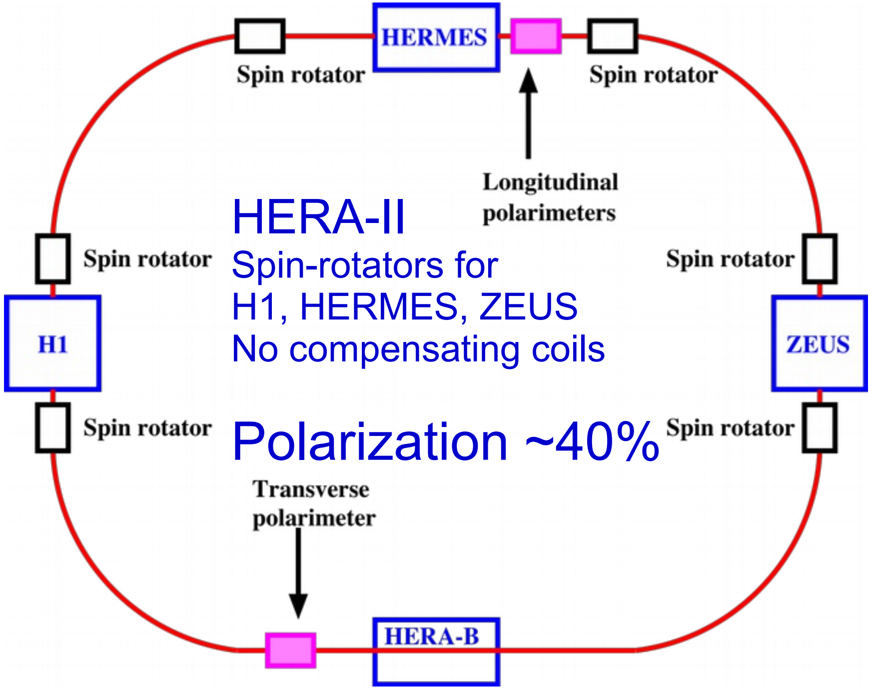
Polarisation during HERA operation



HERA-I
Spin-rotators for HERMES
Compensating coils for H1 &ZEUS

Polarization ~60%



HERA-II
Spin-rotators for
H1, HERMES, ZEUS
No compensating coils

Polarization ~40%

Luminosity upgrade for H1 and ZEUS ↔ down-grade for HERA beam polarisation

Losses from extra spin rotators and beam-beam effects (different polarization for colliding and non-colliding bunches)

Polarimetry requirements at HERA

- Machine setup for tuning beam energy and “harmonic bumps”, to maximize polarization
  - Resonably fast
  - Absolute scale uncertainty is less important (5-10%)

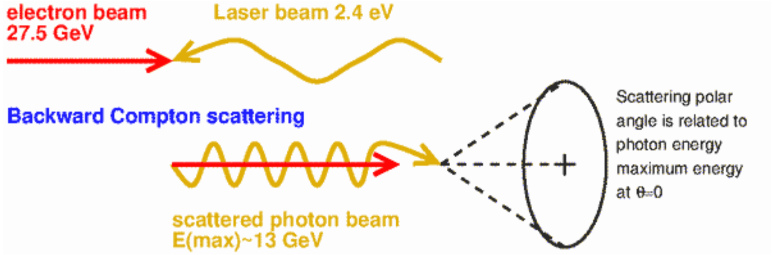
- Experiments
  - Fast and reliable monitoring of polarization during data taking
  - Colliding bunches (H1,ZEUS) and all bunches (HERMES)
  - Absolute scale uncertainty better than 2%

- Transverse polarimeter (HERA-I design)

- Longitudinal polarimeter near HERMES
- Transverse polarimeter HERA-II upgrade and offline analysis
- LPOL cavity polarimeter

Polarimetry at HERA

- Make use of backward Compton scattering off a laser beam



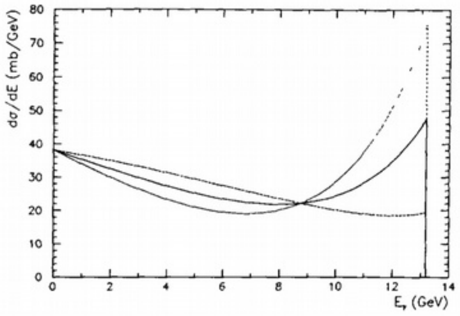
- Laser helicity is flipped regularly
- Polarization is proportional to the difference between cross section data with opposite laser helicity

- Compton scattering cross section

$$\frac{d\sigma}{d\Omega} \sim \Sigma_0 + S_3 \left(P_Y \Sigma_{2Y} \sin\phi + P_Z \Sigma_{2Z} \right)$$

S_3 laser beam helicity
P_Y transverse beam polarization
P_Z longitudinal beam polarization
$\Sigma_0, \Sigma_{2Y}, \Sigma_{2Z}$ photon energy dependent terms

Example: scattered photon energy for S_3P_Z={−1,0,+1}



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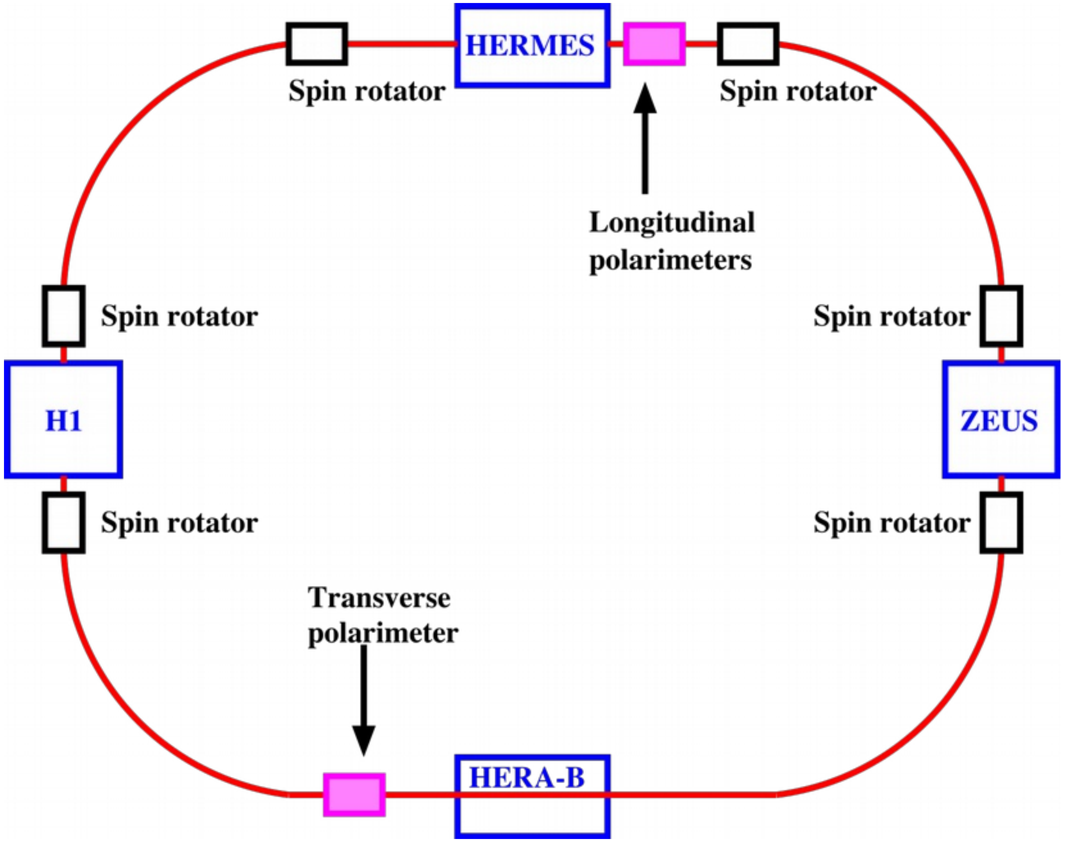
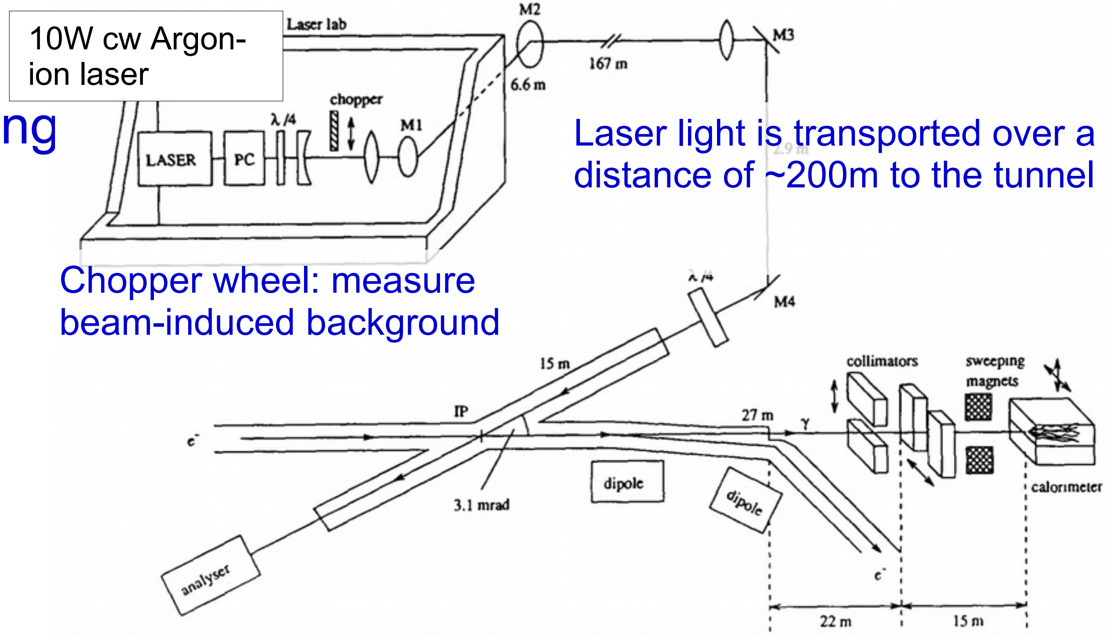
The Polarimeters at HERA

- Three HERA polarimeters
  - Transverse polarimeter (TPOL) 1992-2007
  - Longitudinal polarimeter (LPOL) 1995-2007
  - LPOL Cavity polarimeter operation 2006-2007



Transverse polarimeter setup

- Continuous-wave laser: single photon mode (Compton scattering probability per bunch <1%)
- Vertical crossing angle 3.1mrad
- Electron and photon beams are separated by dipoles
- Photon calorimeter is 65 meter away from interaction point
- Laser beam-dump with optical diagnostics (measure residual linear light polarization)



Electron beam Twiss parameters at IP are chosen to give small vertical beam size of photon beam at calorimeter $\sigma_y \sim 0.5$ mm, $\sigma_x \sim 2$ mm

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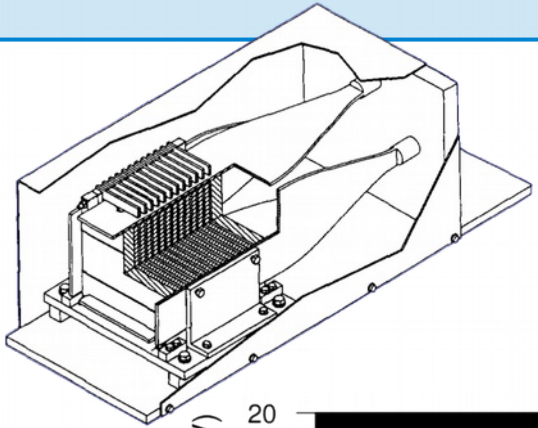
Transverse polarimeter online data analysis

- Calorimeter is split into two optically isolated halves
- Shower-sharing between up and down depends on vertical impact point (non-linear transformation)
- Polarization measurement:
  - In selected energy window: get mean of up/down asymmetry for both laser helicity states (S_3=L,R)
  - Difference of means is proportional to polarization

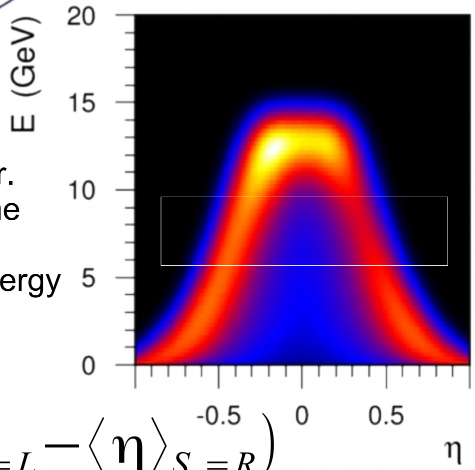


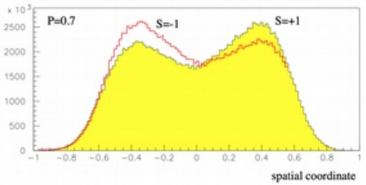
Tungsten-scintillator sampling calorimeter 12ό1.6 X_0
Two optically isolated halves, read-out on four sides
(Left and right channels for calibration and trigger)

$$E = E_{\text{up}} + E_{\text{down}}$$

$$\eta = \frac{E_{\text{up}} - E_{\text{down}}}{E_{\text{up}} + E_{\text{down}}}$$

Predicted signal in calorimeter. White frame indicates approx. energy window





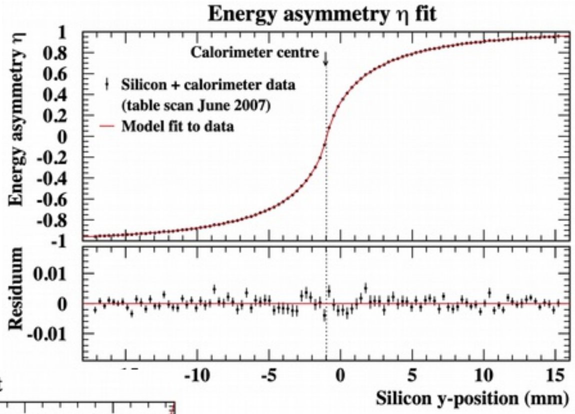
Energy asymmetry η for two helicities

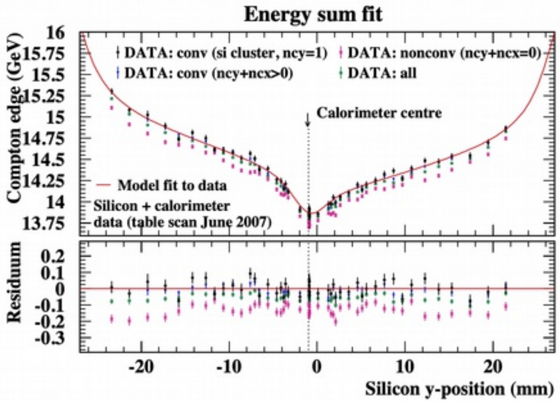
$$P = \text{AP} \times \left(\langle \eta \rangle_{S_3=L} - \langle \eta \rangle_{S_3=R} \right)$$

TPOL offline analysis

- Original analyzing power was based on simulations → polarization scale accurate to 8% NIM A329 (1993), 79
- Non-linear transformation: corrections from beam emittance, IP position, ...
- HERA-II upgrade: converter plate and silicon-strip detector→in situ calibration
- HERA-II offline-analysis based on in-situ measurement of η-y transformation and energy response
- Also takes into account further corrections: beam size, IP pos, ...

In situ energy-asymmetry response as a function of vertical position





In situ energy response as a function of vertical positioncc

HERA-II TPOL scale uncertainty 1.9%

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Longitudinal polarimeter

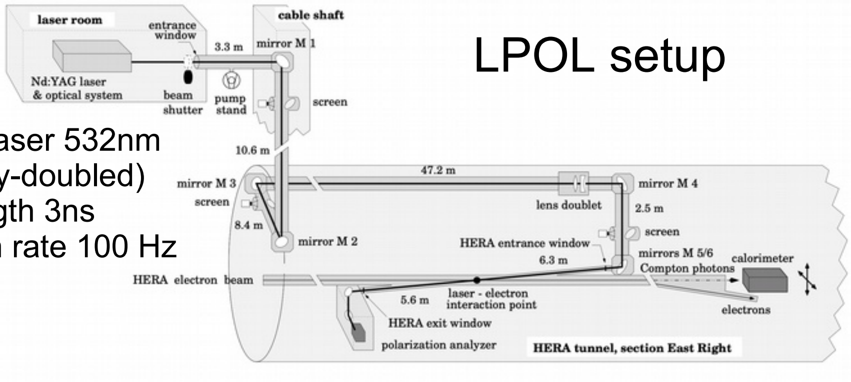
- HERMES physics operation: need better polarimeter with precision 1-2%

  (TPOL precision ~8% at the time)
- Measure longitudinal polarization between spin rotators
- Pulsed laser, multi-photon mode

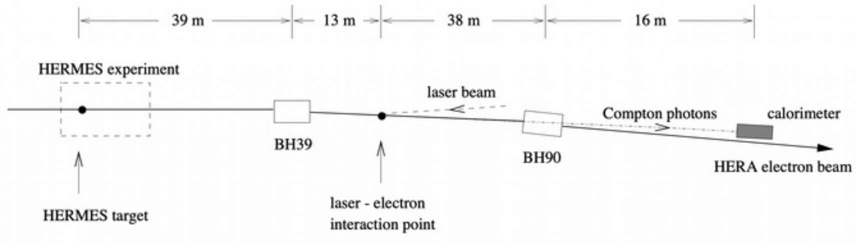
  Per shot, the total energy of ~1000 photons is measured in a crystal calorimeter
- Asymmetry between two laser helicity states → beam polarization

LPOL setup

Nd:YAG laser 532nm (frequency-doubled)
Pulse length 3ns
Repetition rate 100 Hz



Interaction region
Compared to TPOL, less space for calorimeter



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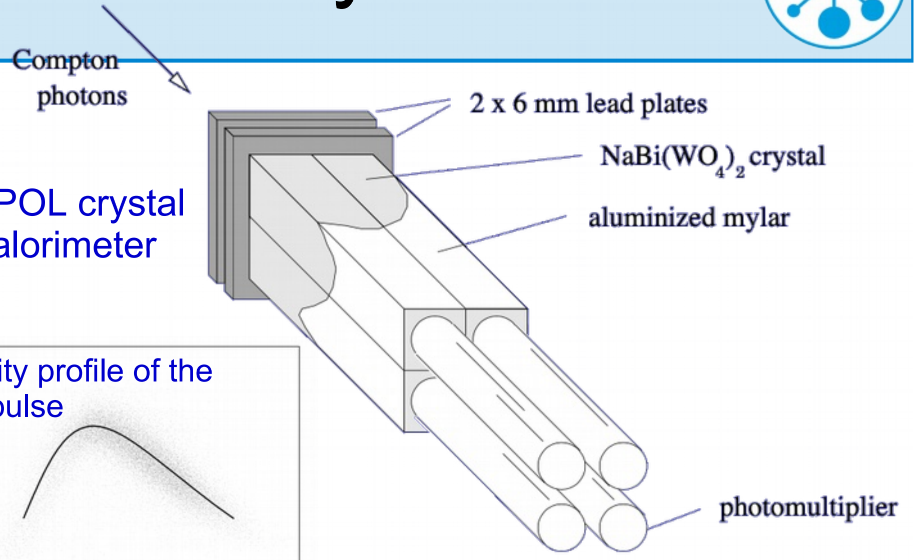
Longitudinal polarimeter analysis

- Energy asymmetry is fairly robust against systematic effects, analyzing power is known analytically
- Experimental difficulties
  - Pedestal from synchroton radiation
    → data with non-charged laser
  - Timing and intensity jitter

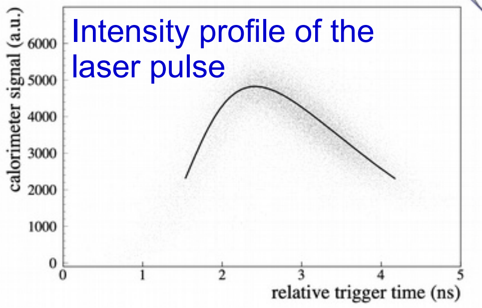
    → fixed energy 100mJ per shot

    → correction based on laser timing
  - Calorimeter linearity

    → crystal calorimeter, test beam



LPOL crystal calorimeter



Intensity profile of the laser pulse

$$P = \mathrm{AP} \times \frac{I_{1/2} - I_{3/2}}{I_{1/2} + I_{3/2}}$$

I : timing-corrected energy

$1/2,\ 3/2$: laser helicity states

$\mathrm{AP} = 0.1838$ for the HERA setup

Result: HERA-II LPOL scale uncertainty 2%

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How to improve the statistical precision

- CW laser, single photon mode
  - Measurement of cross section → precision offline analysis possible
  - Statistically limited by low counting rate
- Pulsed laser, multi-photon mode
  - Measurement of energy-integrated cross sections only
  - Statistically limited (repetition rate)
  - Systematically limited by calorimeter linearity

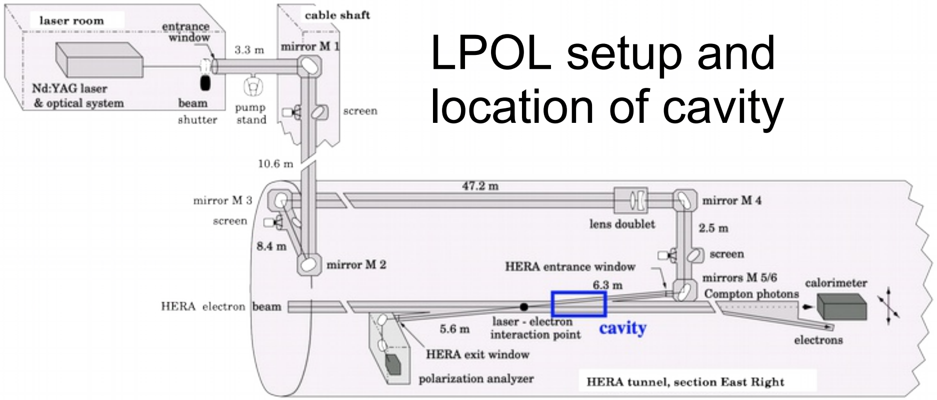
- Possible improvements
  - CW laser with Fabry-Perot cavity → higher interaction rate. Simple detector is sufficient to resolve the energy spectrum in few-photon mode

    Next slides
  - Pulsed laser and detector with many channels, measurement of the electrons using a dipole magnet, etc

    (Not realized at HERA)

HERA LPOL Fabry-Perot polarimeter

- Added Fabry-Perot cavity in the electron beam-line near the original LPOL IP
- Cavity is driven by 0.7W Nd:YAG laser (1064 nm), effective power in cavity ~3000 KW. Optical table in the tunnel.
- Use sampling calorimeter from original LPOL setup to detect photons
- Read out and histogram calorimeter data at the HERA bunch crossing rate of 10.4 MHz → quite difficult (FPGA and CPU limitations 20 years ago)



LPOL setup and location of cavity

Cavity and optical table in HERA tunnel

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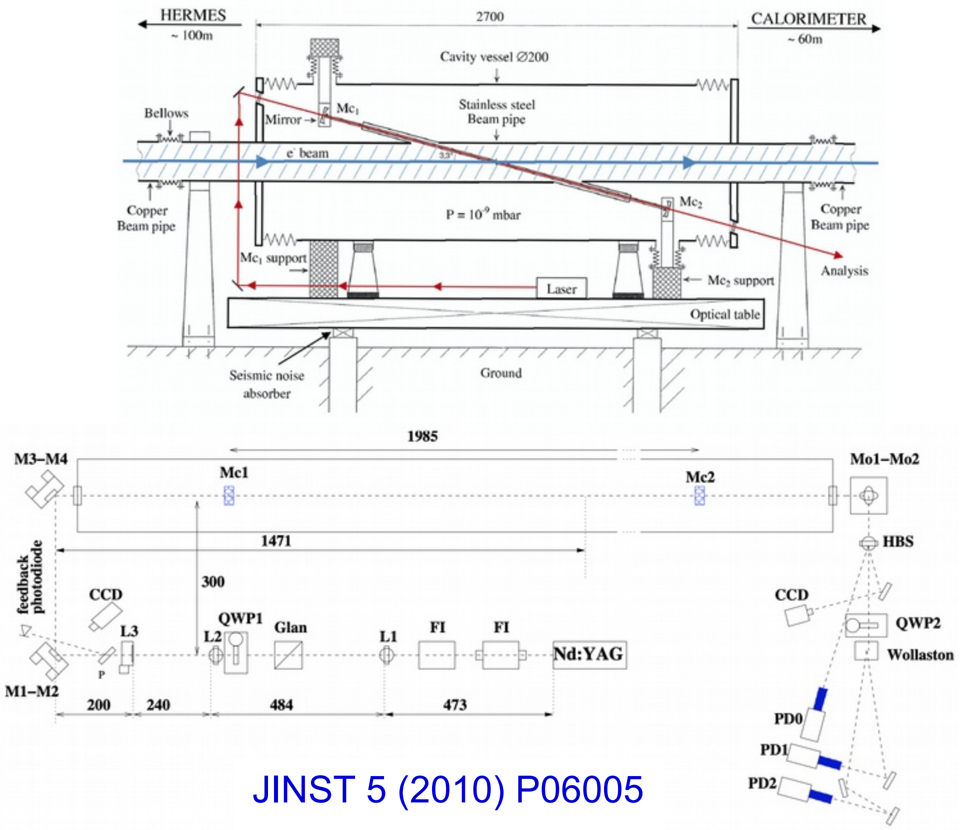
Fabry-Perot optical setup

- Two high-reflectiveness mirrors (R>0.999)
- Optical components mounted on optical table. Mechanically decoupled from HERA vacuum vessel using a system of bellows
- Laser is frequency-locked to a cavity resonance using an active feedback system
- Laser helicity is selected using a rotating quarter-wave plate
- Light polarization is measured behind the second cavity mirror



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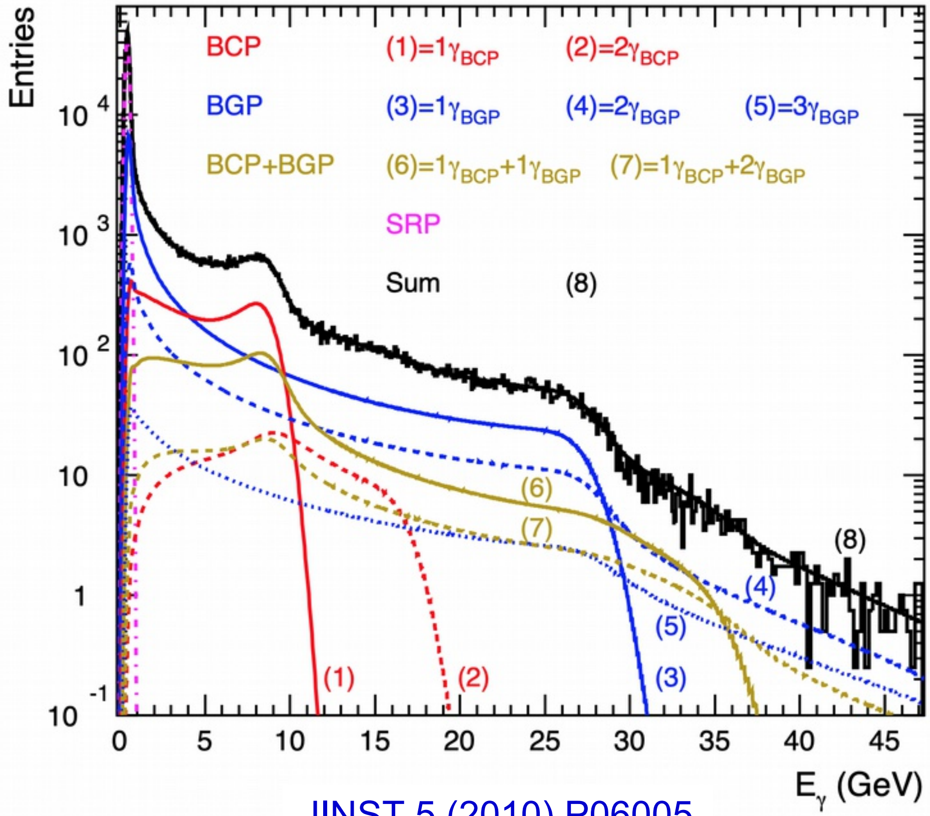
LPOL Cavity analysis

- Measured energy spectrum receives contributions from
  - Compton scattering (BCP)
  - Bremsstrahlung (BGP)
  - Synchrotron radiation (SRP)
- For a given events there are contributions from 1,2,3,... superimposed photons
- Analytic fit extracts relative size of these components, calorimeter properties, beam polarization, etc



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LPOL cavity results

- LPOL cavity was commissioned rather late → not used for regular operation, only in dedicated runs

  However, results were very good

  - Fast and accurate measurement (every 20 s for groups of bunches)
  - Statistical accuracy for a single bunch: 2% per minute
  - Systematic scale uncertainty 0.9%

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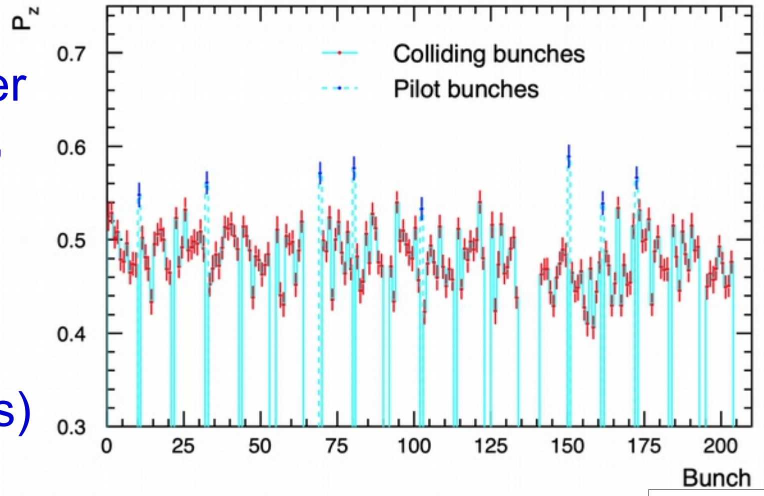
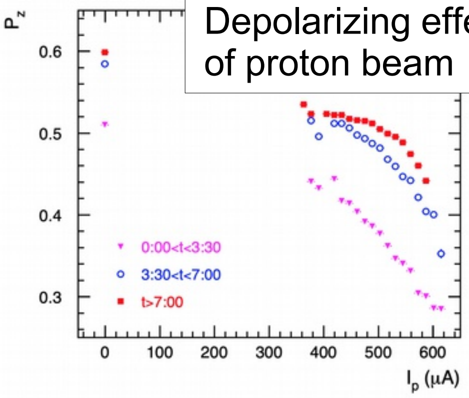


Per-bunch polarization: colliding and non-colliding bunches have different polarization (different depolarizing effects)

Correlation of bunch polarization with proton-bunch current:

Strongest correlation early in the fill (small p-beam emittance)



Depolarizing effect of proton beam

Summary

- Lepton-beam polarization and polarimetry at HERA: the result of constant work from machine physicists and experimentalists
- Sokolov-Ternov effect provided transverse polarization
- Limited by depolarizing effects (Spin-rotators, etc)
- Polarimetry
  - Transverse polarimeter: spatial asymmetry in single-photon mode [2%]
  - Longitudinal polarimeter: integral energy asymmetry multi-photon mode [2%]
  - Fabry-Perot cavity: energy spectra in few photon mode [<1%]

Backup slides

Accelerators for particle physics at DESY

- DESY was founded in 1959
- German national laboratory for particle physics, accelerators, synchrotron sources
- Accelerators for particle physics
  - DESY 1964-1978 [6 GeV]
    Since 1978: used as pre-accelerator only
  - DORIS 1974-1992 [e^+e^- $\sqrt{s}$=12 GeV]
    1992-2012: used as synchrotron source
  - PETRA 1978-1986 [e^+e^- $\sqrt{s}$=45 GeV]
    1990-2007: pre-accelerator, since 2009 synchrotron source
  - **HERA 1992-2007 [$e^{\pm}p$ $\sqrt{s}$=320 GeV]**
- DESY accelerators in 2020

  → photon science

~5 miles to city center

HERA compared to other colliders

- HERA at construction time: energy frontier (E_p~Tevatron, E_e~ ½ LEP)

  Detectors were designed for discoveries, not so much for precision

- EIC compared to HERA:
  - Reduced center-of-mass energy ×0.3
  - Much higher luminosity ×100
  - Better lepton polarisation
  - Target polarisation
  - Heavy targets
  - Much improved detectors: tracking, acceptance, particle identification, forward detectors, ...