The HERA transverse polarimeter

The HERA TPOL

Stefan Schmitt, DESY

Outline

- Introduction
  - The HERA collider
  - Polarization at HERA and HERA polarimetry
  - The HERA Transverse Polarimeter (TPOL)
  - Systematic limitations of the HERA polarimeters

Disclaimer:

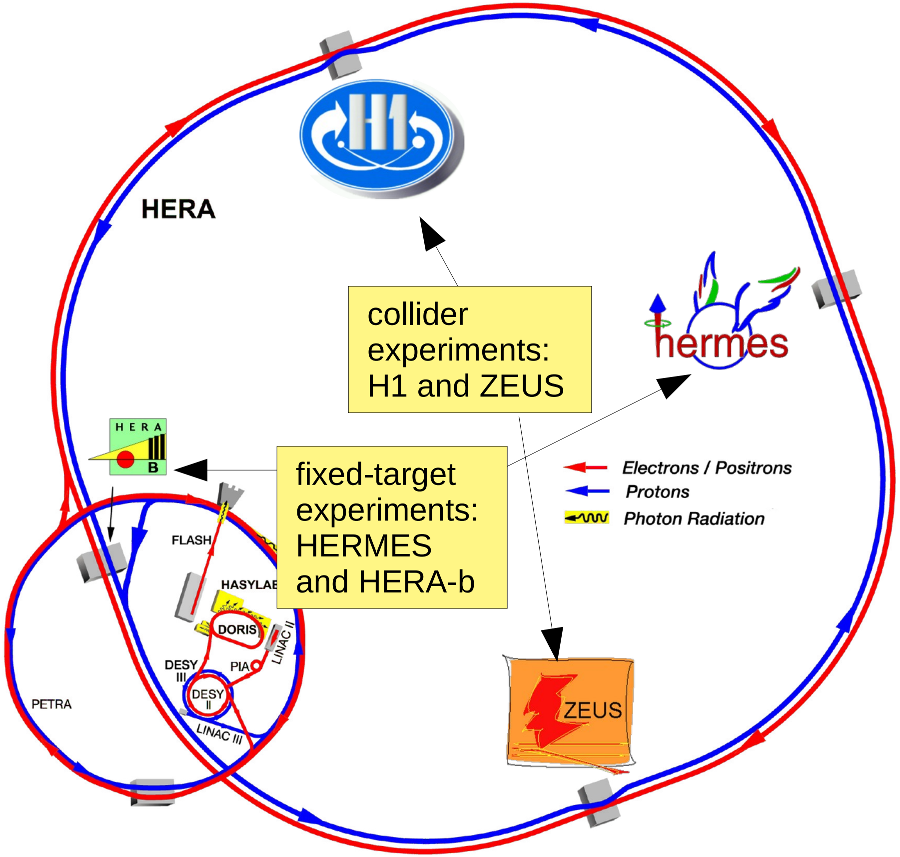
this talk is on HERA polarimetry, but reflects my personal opinions only. I have been working on with the POL2000 group in the years 2000-2007, mainly on the transverse polarimeter

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 above 60% achieved


Straight section


Curved section

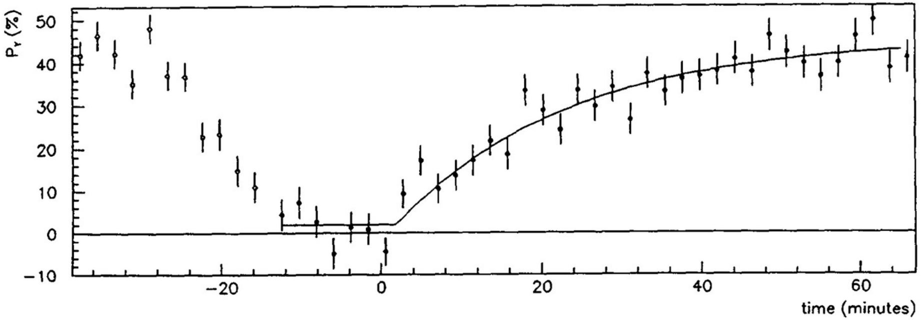


Beam polarization at HERA

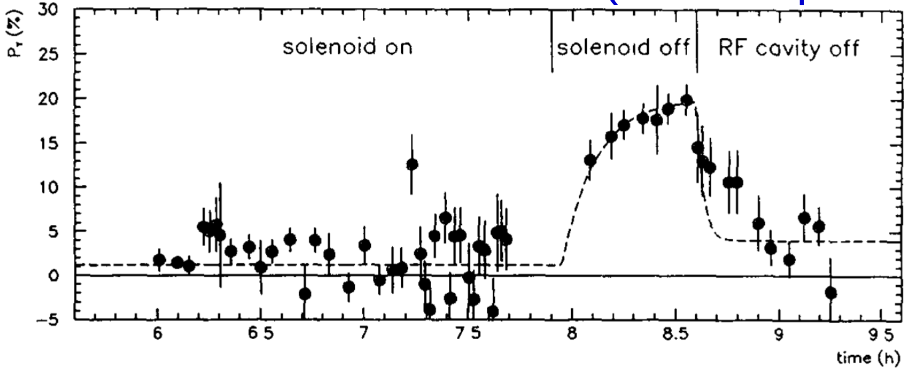
- Proton-beam: unpolarized
- Lepton beam: unpolarized at injection energy (12 GeV)
- Lepton beam acquired transverse polarization at collision energy (27.5 GeV): Sokolov-Ternov effect
- Rise-time at HERA ~40 minutes

  (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%



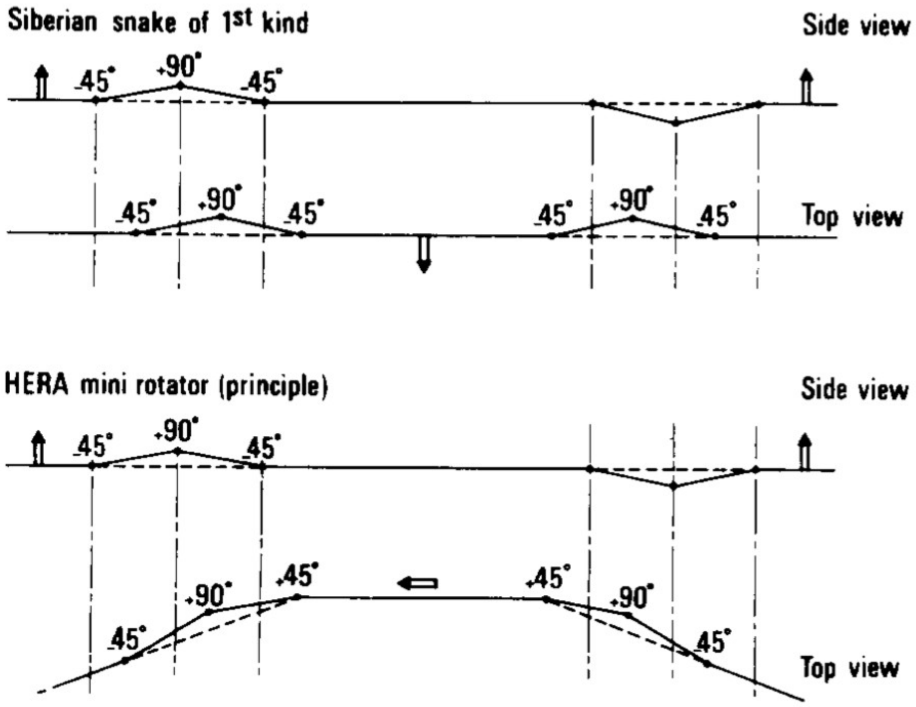
Effect of solenoidal field (w/o compensator)



NIM A329 (1993) 79

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



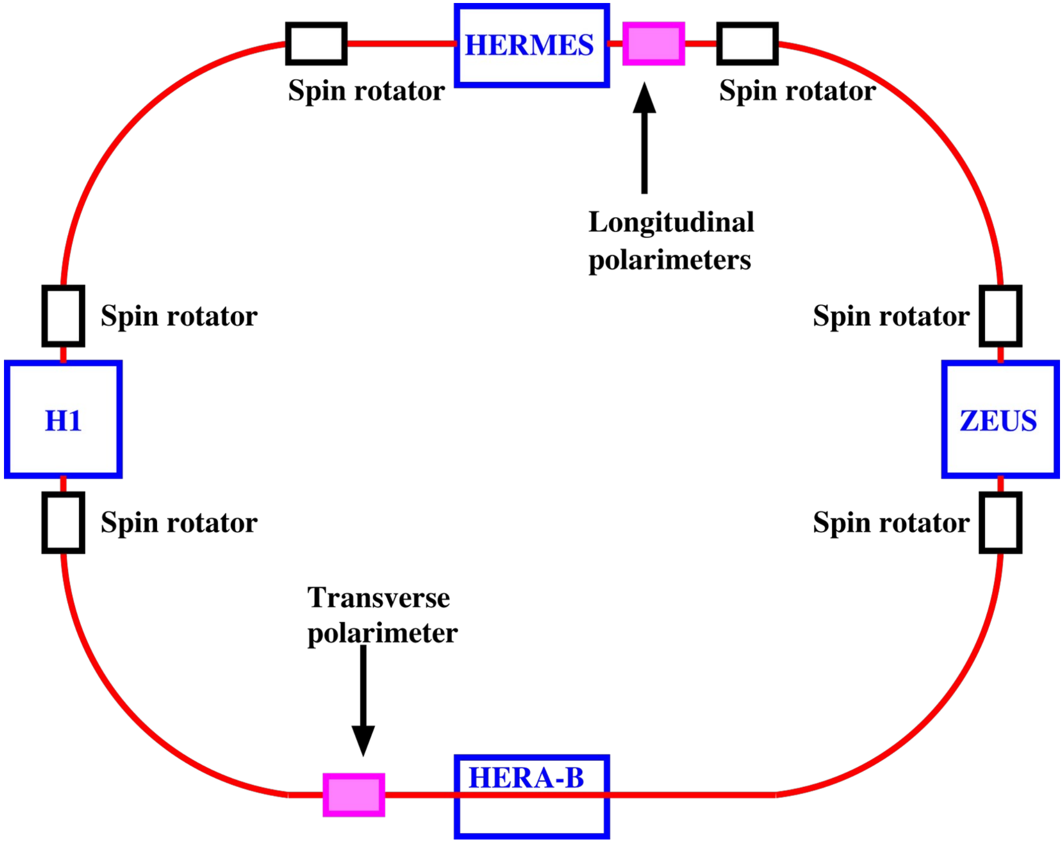
HERA mini rotator, similar to Siberian snake

NIM A245 (1986) 248

The Polarimeters at HERA

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

HERA-I phase (1992-2000): no spin-rotators for H1 and ZEUS



Polarimetry requirements at HERA

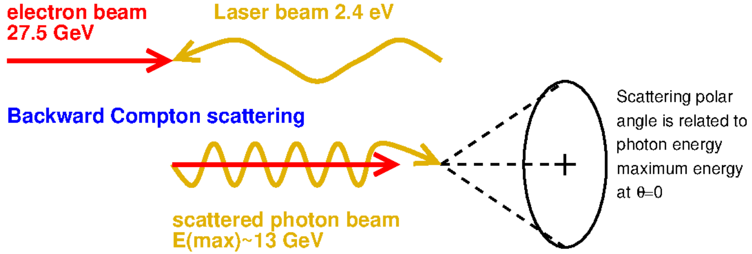
- Machine setup for tuning beam energy and "harmonic bumps", to maximize polarization
  - Resonably fast feedback
  - Absolute scale uncertainty is less important (5-10%)
- Transverse polarimeter (HERA-I design)

- 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-II design) and offline analysis

Not covered in this talk, see backup slides {
- Longitudinal polarimeter near HERMES
- 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 differences between cross section data with opposite laser helicity

- Compton scattering cross section

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

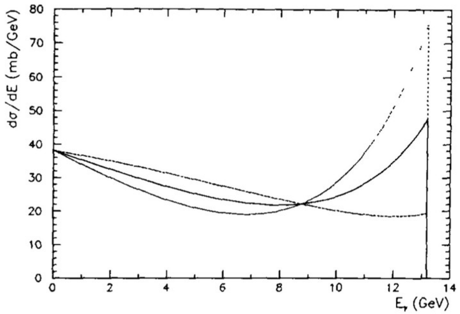
S_3 laser beam helicity

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 longitudinal beam polarisation $S_3P_Z=\{-1,0,+1\}$

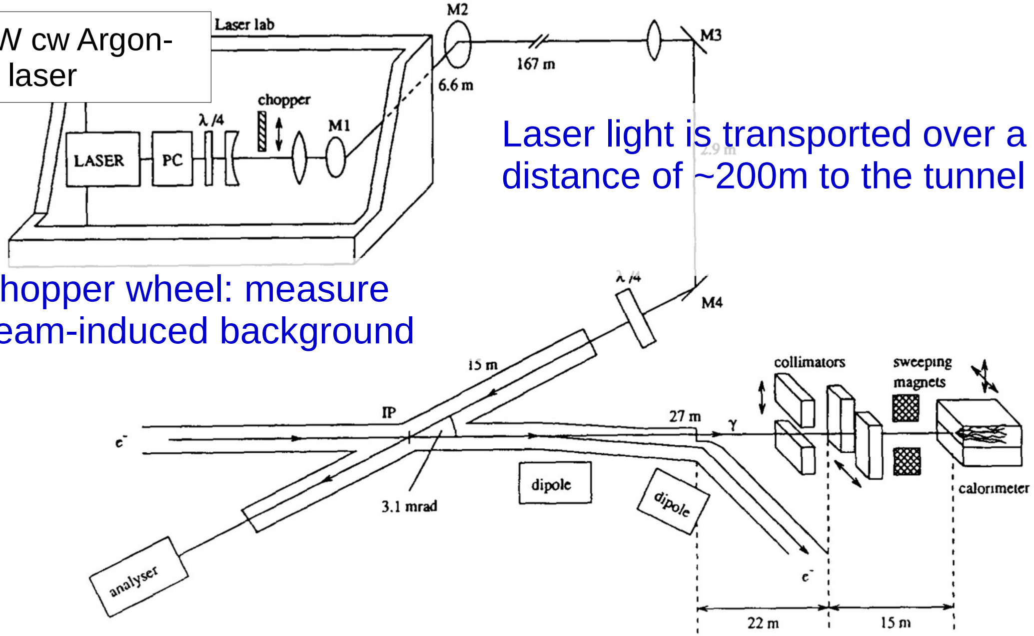


NIM A329 (1993) 79

Transverse polarimeter (TPOL) 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 (lead housing)
- Laser beam-dump with optical diagnostics (measure residual linear light polarization)

10W cw Argon-ion laser



Laser light is transported over a distance of ~200m to the tunnel

Chopper wheel: measure beam-induced background

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

NIM A329 (1993) 79

The photon calorimeter

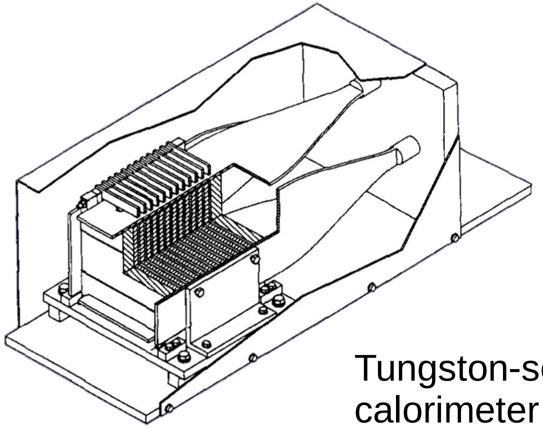
- Transverse beam polarisation causes spatial asymmetry in cross section (up-donw asymmetry)
- Calorimeter is split into two optically isolated halves
- Shower-sharing between up and down depends on vertical impact point (non-linear transformation)
- Left and right channels for calibration and trigger

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

S_3 laser beam helicity

P_Y transverse beam polarization

Σ_0, Σ_{2Y} photon energy dependent terms



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

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

η corresponds to $\sin\phi$

Tungston-scintillator sampling calorimeter $12 \times 1.6\ X_0$

Two optically isolated halves, read-out on four sides

Transverse polarimeter online data analysis

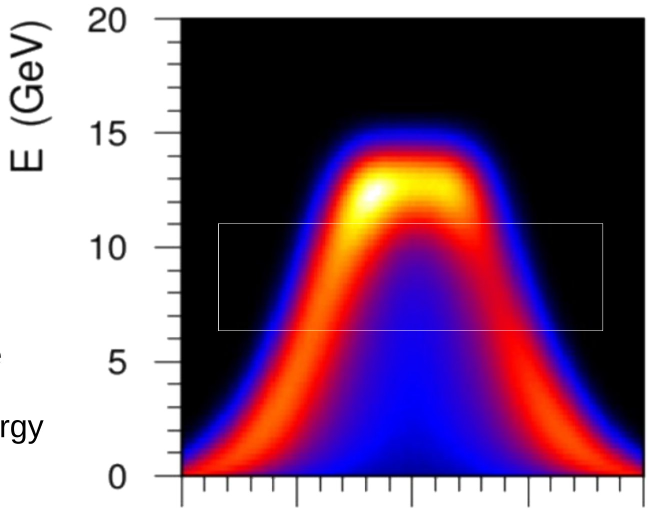
$$E = E_{up} + E_{down}$$

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

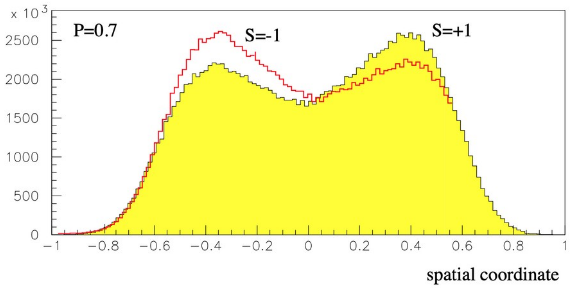
- Polarization measurement:
  - In selected energy window: get mean of up/down asymmetry for both laser helicity states (S_3=L,R)
  - Difference of means is proportional to polarization

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

  - Analyzing power depends on beam parameters and calorimeter properties



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



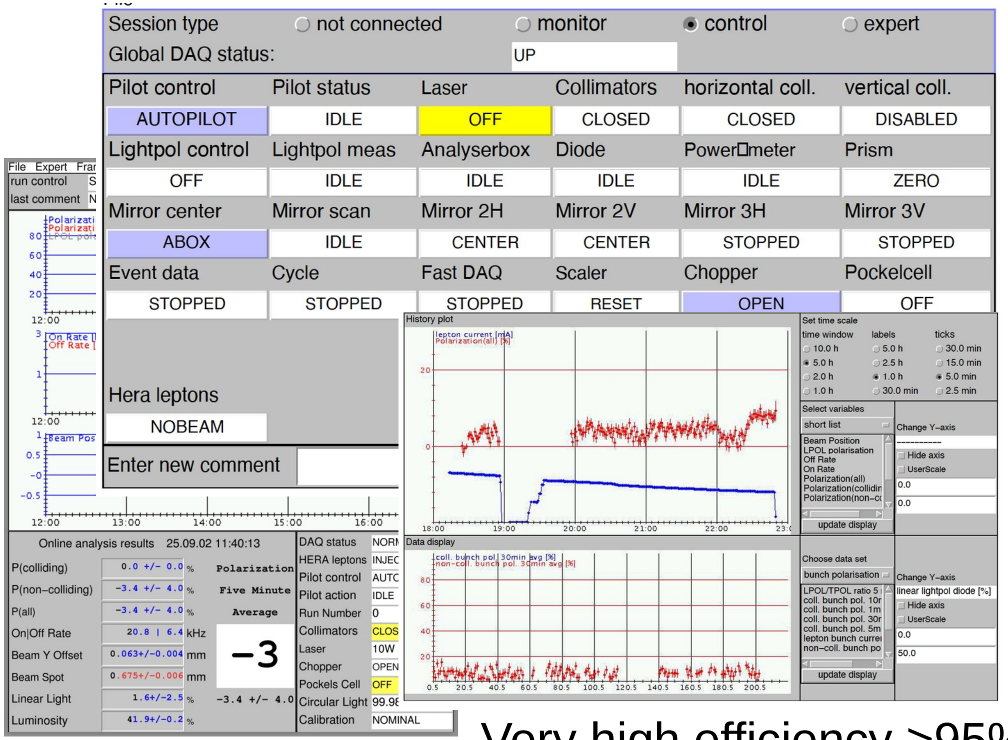
Energy asymmetry η for two helicities

Stat.precision: ~1% per minute (all bunches averaged)

Operation of transverse polarimeter

- Between fills: center laser on analyzer box, measure residual linear light polarisation of L and R helicity states
- Injection and ramp: keep collimator closed, protect calorimeter
- At collision energy:
  - Adjust mirrors to maximize Compton rate (luminosity)
  - Adjust calorimeter position to have beam in its center
  - Adjust HV for calorimeter calibration
  - Measure polarisation
- **Autonomous operation (autopilot)**

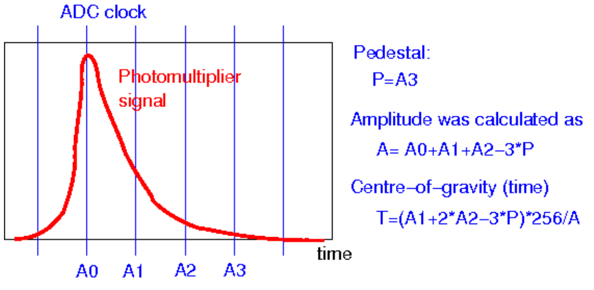
User interface: auto-pilot, main window, details

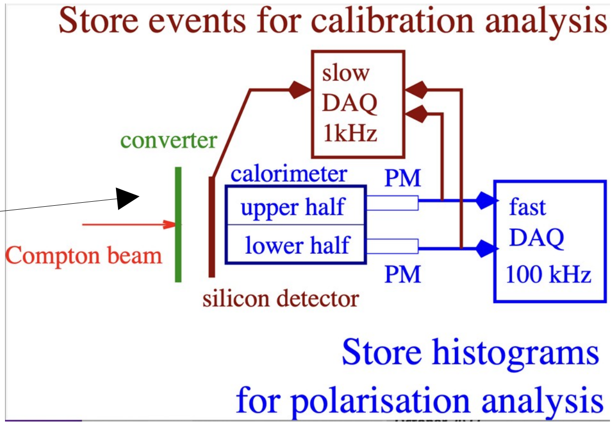


Very high efficiency >95%

Detector upgrade in 2000-2002

- Spin rotators for HERMES, H1 and ZEUS: have to measure both polarisation of colliding bunches and all bunches
- DAQ upgrade: electronics from H1 luminosity system. Sampling ADC with two independent pipelines
- Digitisation at 40 MHz, readout by dedicated 20 MHz bus (fast DAQ branch) or by VME
- Per-pulse pedestal subtraction
- Detector upgrade: silicon-strip sensor
- Goal: in-situ calibration of energy-asymmetry response

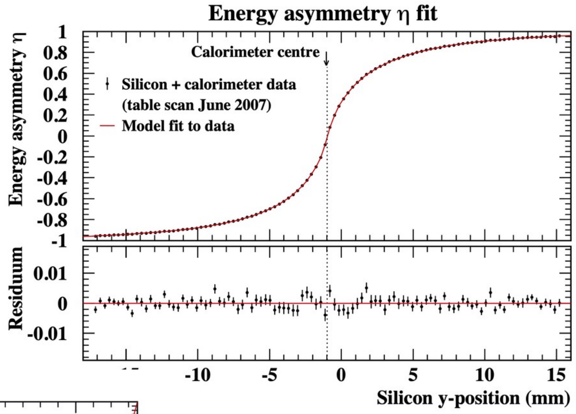


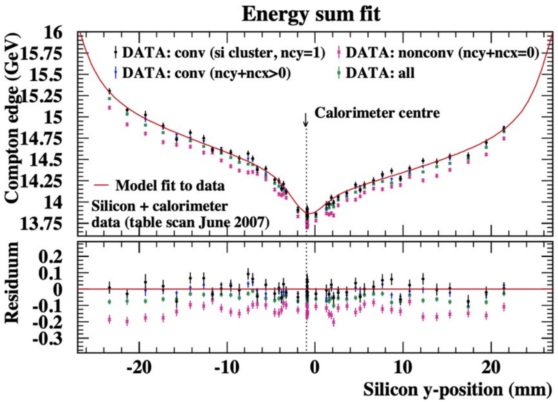


TPOL offline analysis

- 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
- New offline-analysis based on in-situ measurement of η-y transformation and energy response
- Offline Analysis power takes into account all known corrections, e.g.: η-y transformation, beam size and position

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





In situ energy response as a function of vertical position.

Calorimeter response is neither uniform nor symmetric along y

HERA-II TPOL scale uncertainty 1.9%

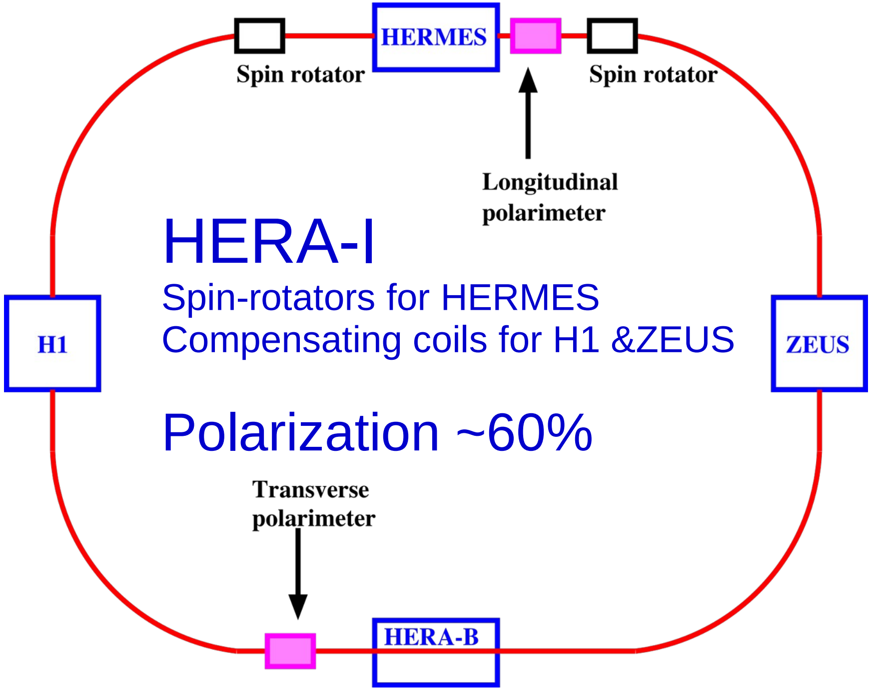
hep/ex 1201.2894

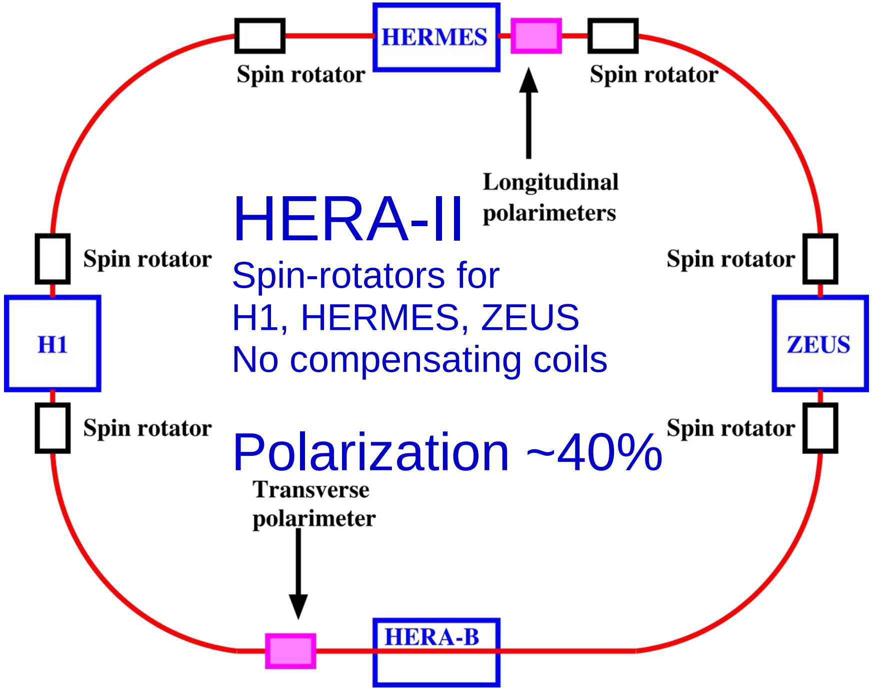
Summary

- HERA: lepton beam polarisation above 60% for HERA-I (above 40% for HERA-II) achieved using the Sokolov-Ternov effect
- First polarimeter in operation: transverse polarimeter (TPOL)
- CW Argon laser with 10W gave Compton interaction rate up to 50 kHz (0.5% of the 10 MHz bunch-crossing rate)
- Simple calorimeter design with two optically separated halves and four channels → build for reliability, not for precision
- Very robust design, fully autonomous operation
- Absolute scale precision below 2% reached only after adding converter plate and silicon detector for HERA-II operation [plus years of analysis]

Backup slides

Achieved Polarisation during HERA operation



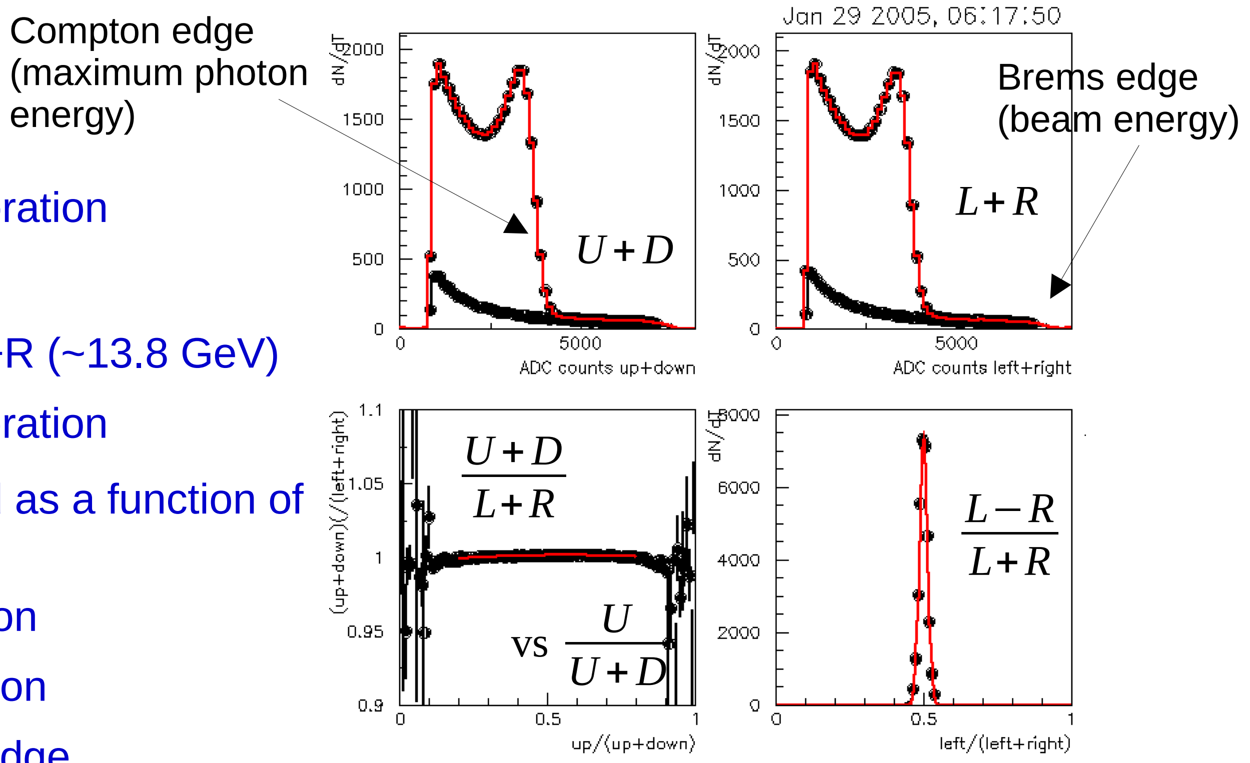


Luminosity upgrade for H1 and ZEUS ↔ down-grade for HERA beam polarisation

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

Transverse calorimeter online calibration

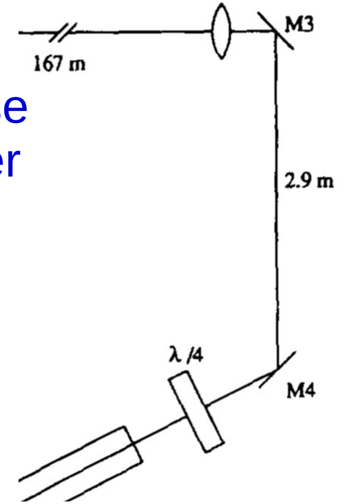
- Average over both helicities
- Subtract laser-off background
- Left (L) and Right (R) channel calibration
  - Make sure L/(L+R) is at 0.5
  - Compton edge at expected L+R (~13.8 GeV)
- Up (U) and Down (D) channel calibration
  - Ratio (U+D)/(L+R) is analyzed as a function of x=U/(U+D)
  - Extrapolate to x=0: D calibration
  - Extrapolate to x=1: U callibration
  - Cross-check: U+D Compton edge



Operational difficulties (selection)

- Main weakness: transport system of laser light over 200 metres
- Limited diagnostics and slow mirror controllers – difficulties to steer the laser into the tunnel after long shutdowns
- Longer-term: somewhat limited laser stability, rather high cost (maintenance contract with company)
- Residual linear light polarisation: difficult to adjust optics (could have profited from 2nd Pockel's cell)

- Over longer periods: damage on Mirror M4 (close to beam). Not clear whether it was from radiation or because of the (more focussed) laser beam
- Potential weakness: laser steered to electron beam, could not monitor light polarisation in that position.
- Exit window → true laser polarisation inside vaccum not known



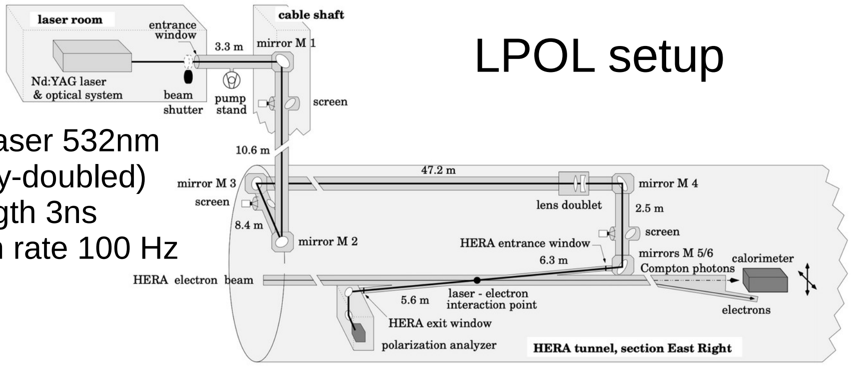
Longitudinal polarimeter

- 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

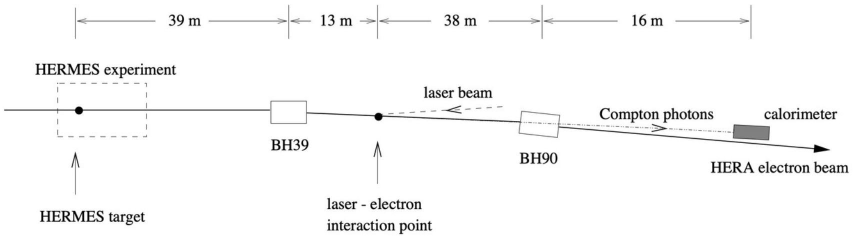
  Per shot, the total energy of ~1000 photons is measured in a crystal calorimeter
- Asymmetry between two laser helicity states → beam polarization

LPOL setup



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

Interaction region
Compared to TPOL, less space for calorimeter

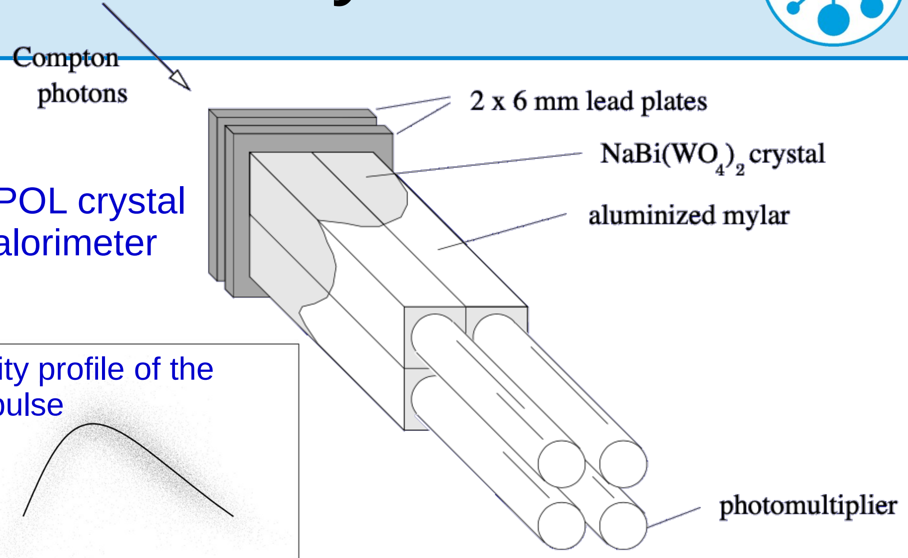


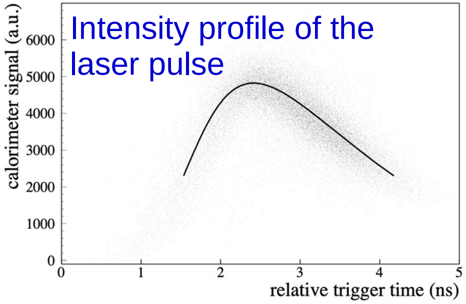
NIM A479 (2002) 334

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





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

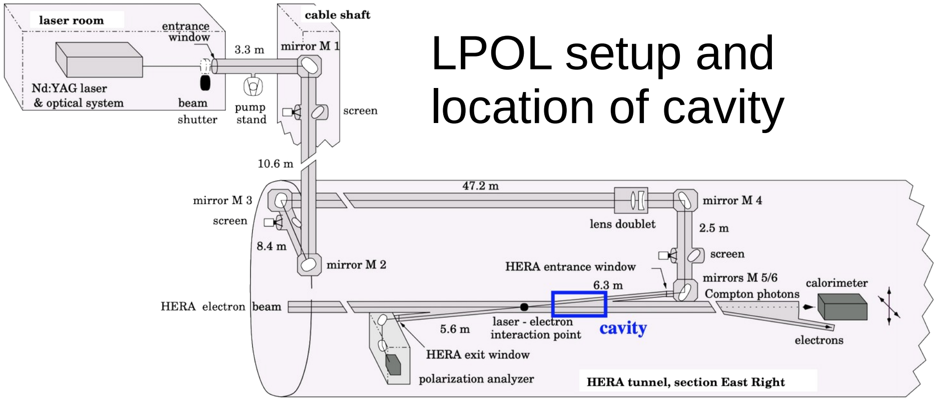
I : timing-corrected energy
$1/2,\ 3/2$: laser helicity states
$AP = 0.1838$ for the HERA setup

Result: HERA-II LPOL scale uncertainty 2%

hep/ex 1201.2894

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)



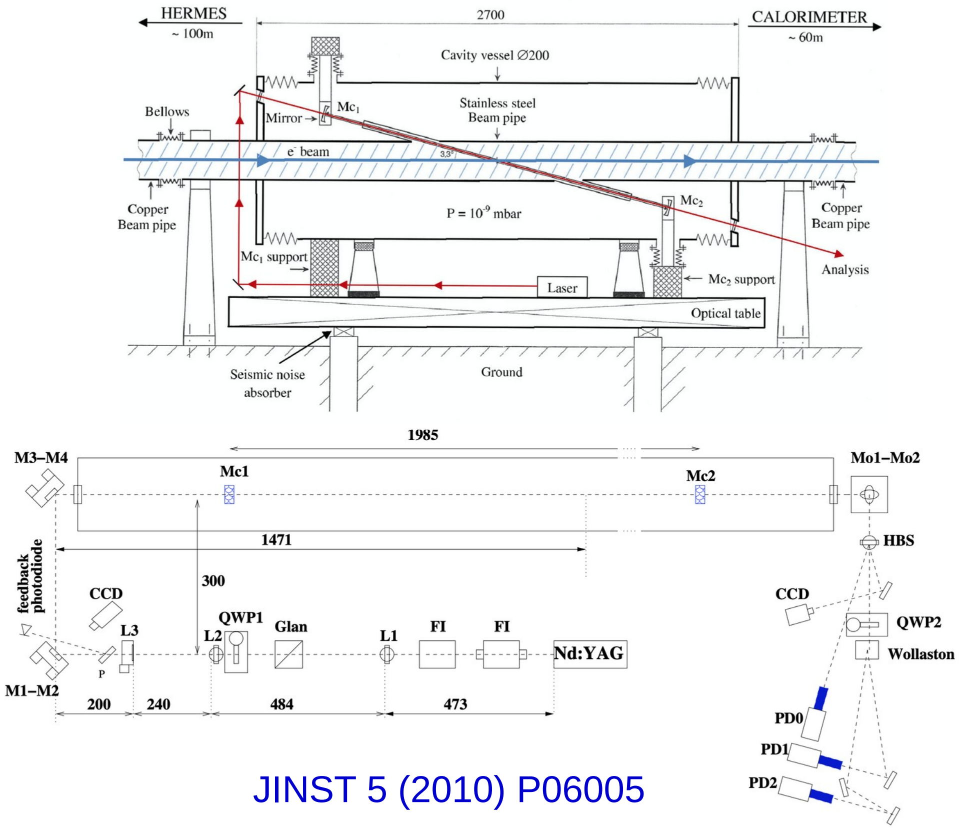
LPOL setup and location of cavity

Cavity and optical table in HERA tunnel

JINST 5 (2010) P06005

Fabry-Perot optical setup

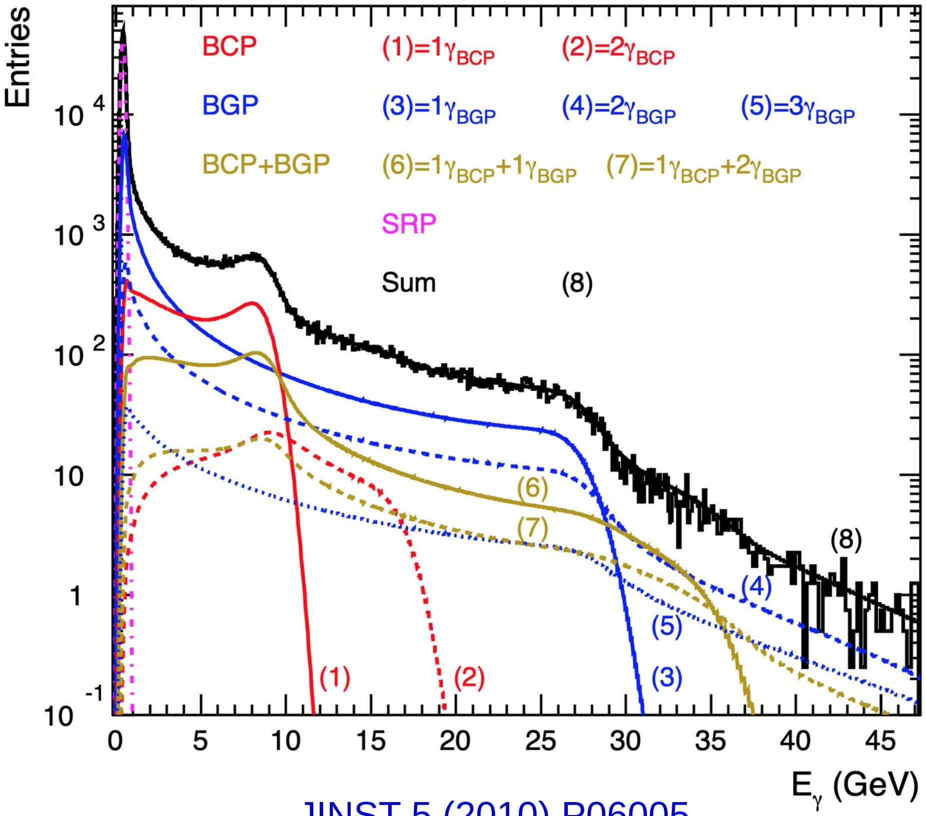
- Two high-reflectiveness mirrors (R>0.999)
- Optical components mounted on optical table. Mechanically decoupled from HERA vacuum vessel using a system of bellows
- Laser is frequency-locked to a cavity resonance using an active feedback system
- Laser helicity is selected using a rotating quarter-wave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



JINST 5 (2010) P06005

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



JINST 5 (2010) P06005

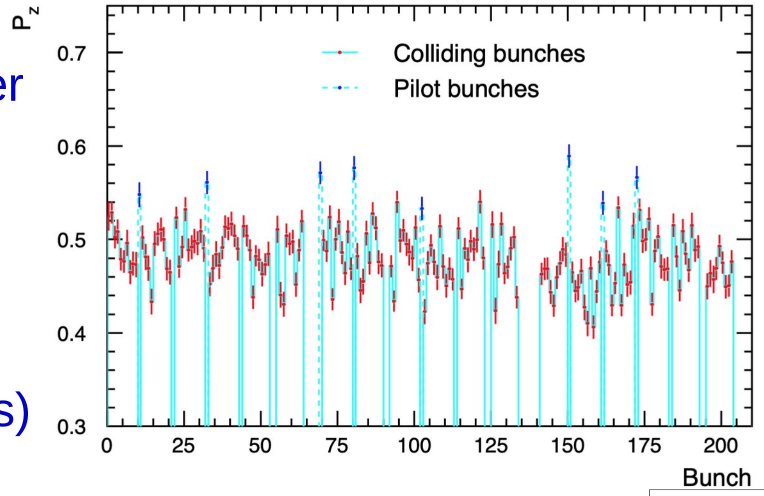
LPOL cavity results

- 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%

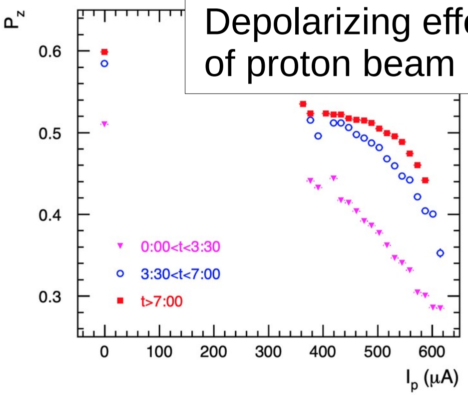
JINST 5 (2010) P06005



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

Sokolov-Ternov Effect: risetime

- Build-up of polarisation in a flat machine (only Dipoles)
- Rise-time depends on circumference, energy, magnetic field strength along the ring
- Exact formula can be found in

  NIM A329 (1993), 79

$$\tau \approx 10^5 h \frac{C(C-S)^2}{E^5}$$

C : circumference [km]
S : straight sections [km]
E : energy [GeV]

My personal estimates … add a big grain of salt...

	Circumference	Energy	Risetime
HERA	6.3 km	27.5 GeV	~1/2 hour
LEP	27 km	45 GeV	~10 hours
FCC	90 km	45 GeV	~400 hours
FCC	90 km	150 GeV	~1 hour