Polarized Beams in Colliders

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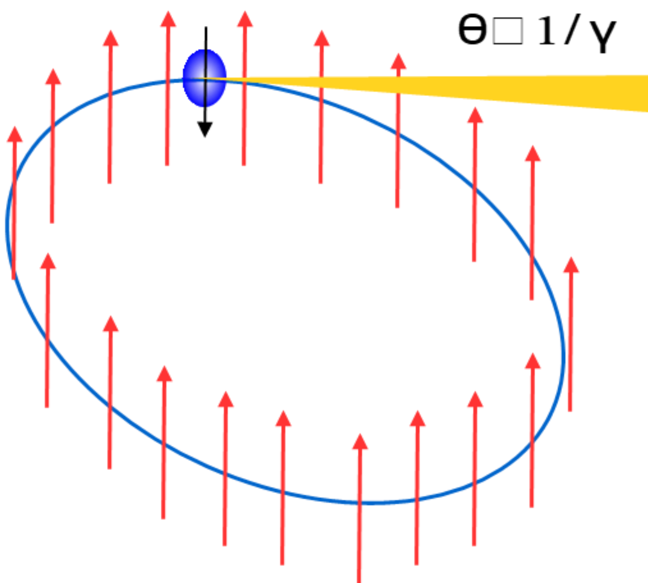
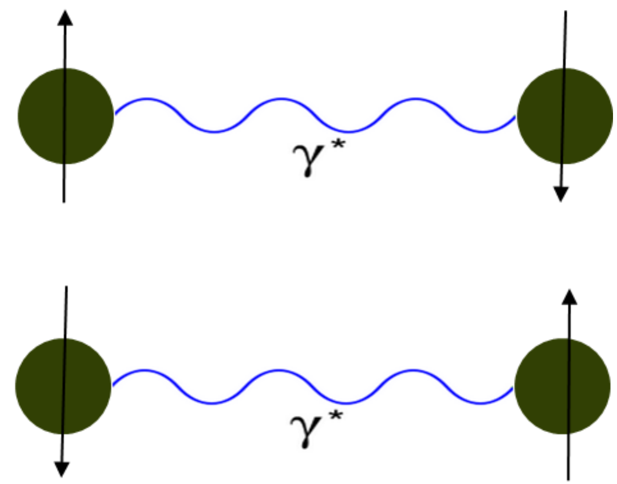
Colliders with polarized beams

- Polarized e+e- colliders
  - As early as early 70s like ACO, VEPP-2
  - Most are circular and the polarization was built up during the store time via Sokolov-Ternov effect (ST effect)





The difference of probability between the two scenarios allows the radiative polarization build up .

In a planar circular accelerator

- The ST induced radiative polarization buildup is given

$$P(t) = P_{ST}\left(1 - e^{-t/\tau_{ST}}\right),$$

where $P_{ST} = 8/5\sqrt{3} \approx 0.9237$

and $\boldsymbol{\tau_{ST}^{-1} = \frac{\frac{5\sqrt{3}}{8} c \lambda_e r_e \gamma^5}{\rho^3} = 3654 \frac{R/\rho}{B[T]^3 E[GeV]^2}}$ [sec^{-1}]

S. Mane et al, Spin-polarized charged particle bams

- For HERA, the estimated ST polarization buildup time for its 26.7 GeV electrons is about 43 mins

In a planar circular accelerator

- In reality, the emission of a photon can yield a sudden change of the particle's energy and induce a spin diffusion mechanism that leads to loss of polarization. The equilibrium polarization is the combination of the two effects

$$P_{eq} = \frac{8}{5\sqrt{3}} \frac{\left\langle |\rho^{-3}| \hat{b} \cdot \left[\hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma} \right] \right\rangle}{\left\langle |\rho^{-3}| \left[1 - \frac{2}{9} \left(\hat{\beta} \cdot \hat{n} \right)^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \right] \right\rangle}$$

and the subsequent polarization buildup time is

$$\tau_{eq}^{-1} = \tau_{ST}^{-1} + \tau_d^{-1}$$

with

$$\tau_d^{-1} = \tau_{ST}^{-1} \left[-\frac{2}{9} \left(\hat{\beta} \cdot \hat{n} \right)^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \right]$$

In a planar circular accelerator

- The radiative polarization buildup in HERA
  - **Best achieved polarization is around 75%**
  - **Polarization buildup time ~ 1.5 hours**

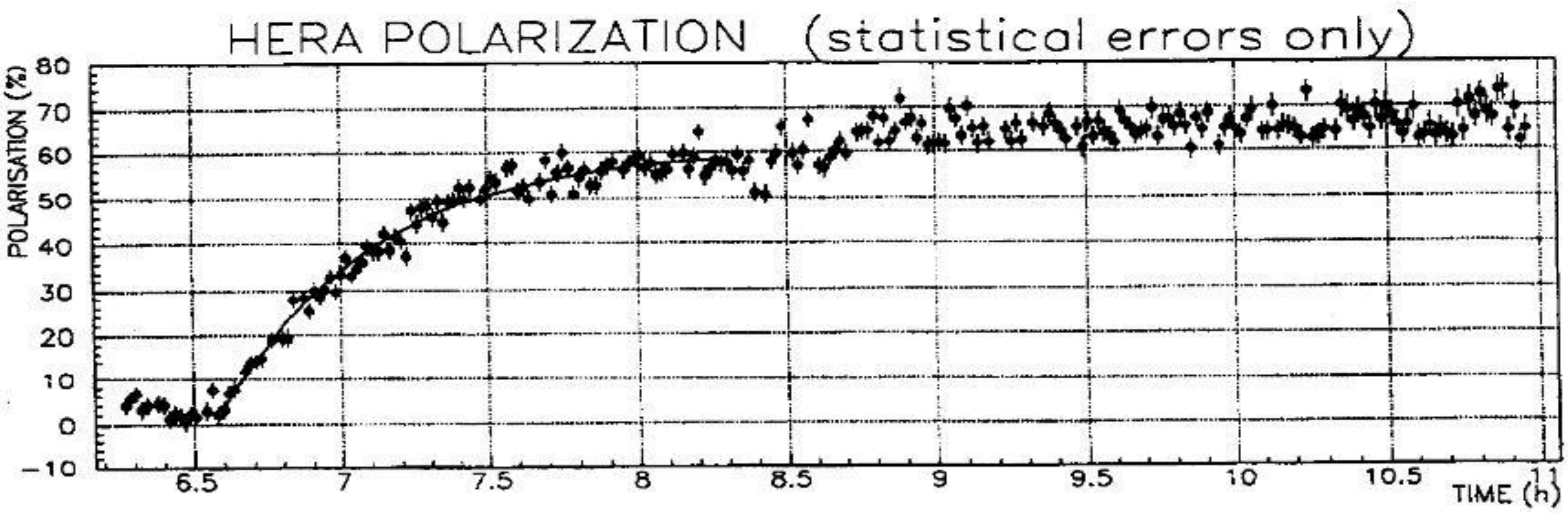


Fig. 19: Polarization P versus the time t in the storage ring HERA at 26.7 GeV.

J. Buon, J. P. Koutchouk, Polarization of Electron and Proton Beams

Spin Orbit Coupling

Thomas BMT Equation: (1927, 1959)

L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys, Rev. Lett. 2, 435 (1959)

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [(1 + G\gamma)\vec{B}_{\perp} + (1 + G)\vec{B}_{\parallel} + \left(G - \frac{\gamma}{\gamma^2 - 1}\right)\frac{\vec{E} \times \vec{\beta}}{c}]$$

$$\Rightarrow \quad \frac{d\vec{S}}{ds} = \boldsymbol{\Omega}(x, p_x, y, p_y, z, \delta)\hat{\boldsymbol{n}} \times \vec{\boldsymbol{S}}$$

- stable spin direction $\hat{n}$, an invariant direction that spin vector aligns to, when the particle returns to the same phase space

$$\hat{n}(I_z, \phi_z, \theta) = \hat{n}(I_z, \phi_z + 2\pi, \theta)$$

Here, I_z and ϕ_z are the 6-D phase-space coordinates $(x, p_x, y, p_y, z, \delta)$

- For particles on closed orbit, stable spin direction can be computed through one-turn spin transfer matrix. $\hat{n}$ is also know as $\hat{n}_0$

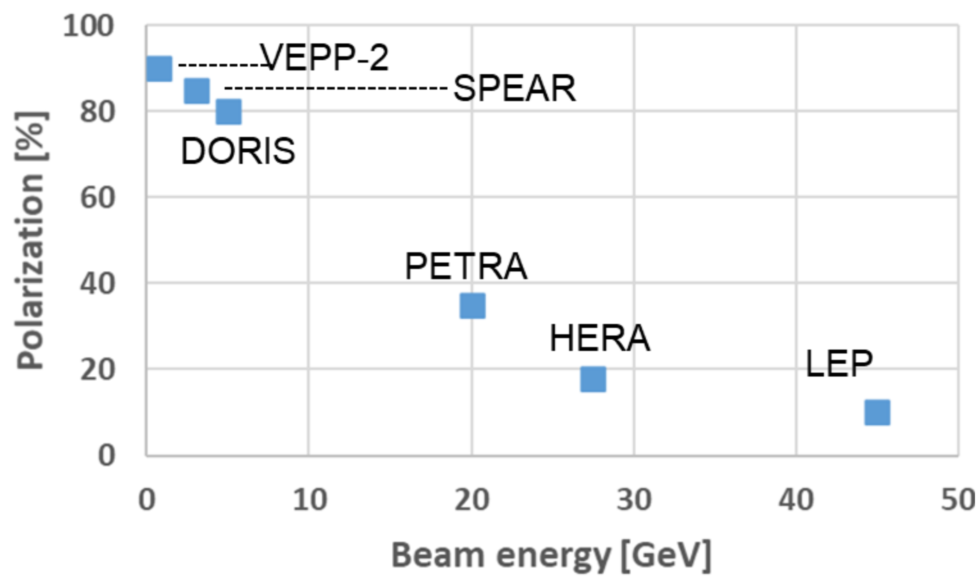
Depolarizing mechanism in a synchrotron

- For particles not on closed orbit, since the betatron tunes are typically non-integer, $\hat{n}$ can be significantly away from $\hat{n}_0$ when

$$Q_s = k + k_x Q_x + k_y Q_y + k_z Q_z$$

where k_x, k_y, k_z are horizontal, vertical and synchrotron tunes, respectively.

- These resonances contribute to the depolarization time and result to much less equilibrium polarization



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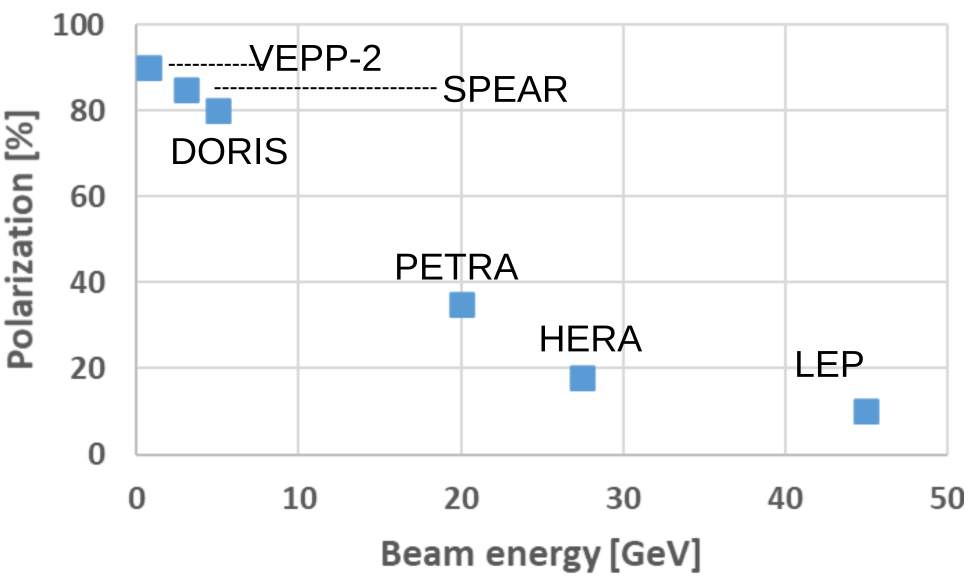
- These resonances contribute to the depolarization time and result to much less equilibrium polarization

- Sources of these resonances
  - Miss-alignment of quadrupole
  - Devices that deviate $\hat{n}$ from $\hat{n}_0$
  - Other high order fields



Overcome depolarizing mechanism

- In general, the effect of these resonances grows with energy. For planar electron storage rings, a simply scaling law*

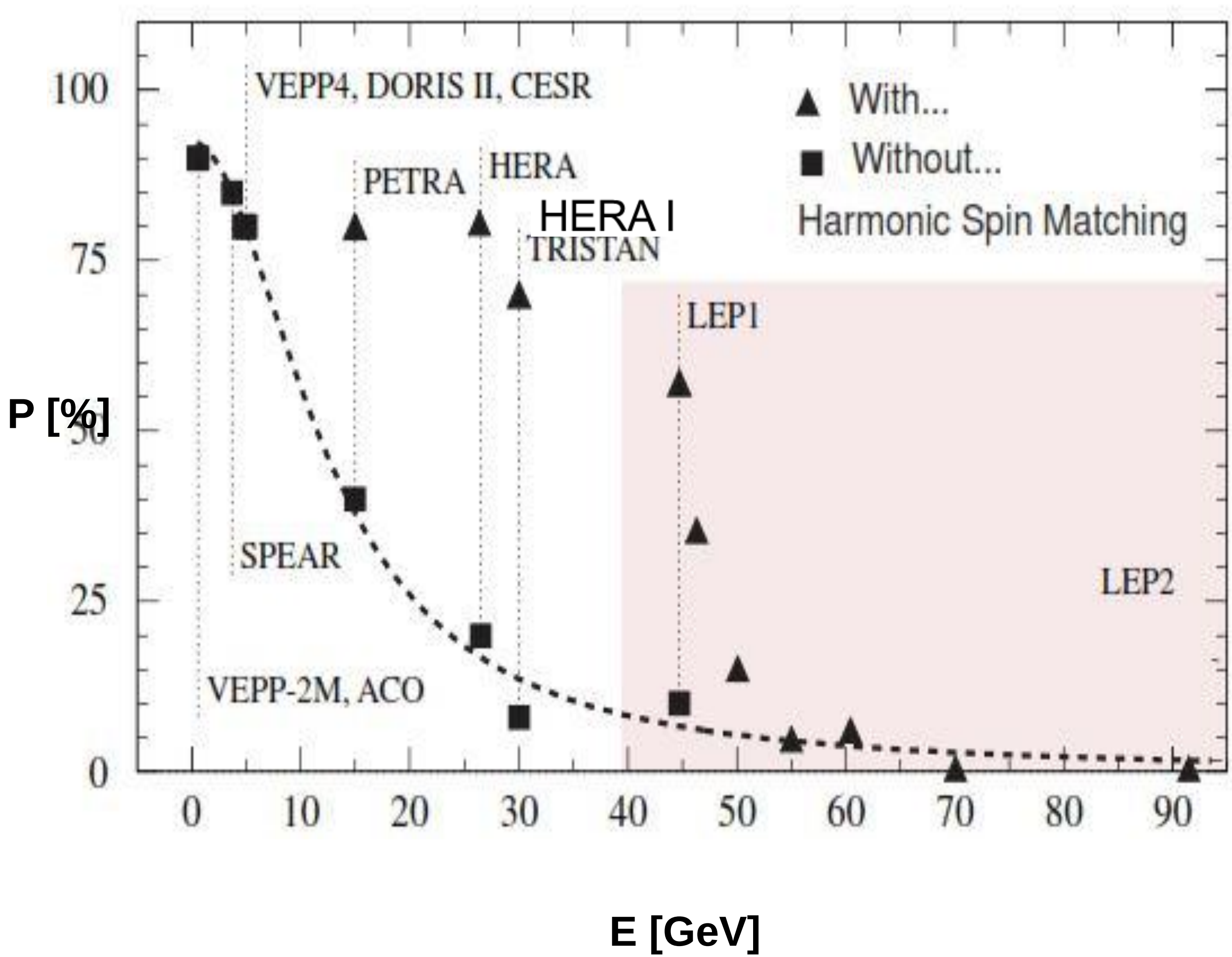
$$p_{eq} \approx \frac{92.4\%}{1+\alpha^2 E^2}$$

Where α is the lattice related factor

- To overcome these resonances in a storage ring, it is critical to either break the resonance condition such as utilizing Siberian snakes, or adapt the lattice optics to minimize the spin orbit coupling strength $\left|\gamma \frac{\partial \hat{n}}{\partial \gamma}\right|^2 \sim (1+G\gamma)^2 \sum_k |c_k|^2/(G\gamma - k)^2$ via spin matching
  - Strong spin matching: full spin transparent at all harmonics
    - Practically very difficult
  - Harmonic spin matching: minimize the driving term at the nearby harmonics
    - Has been implemented in various rings

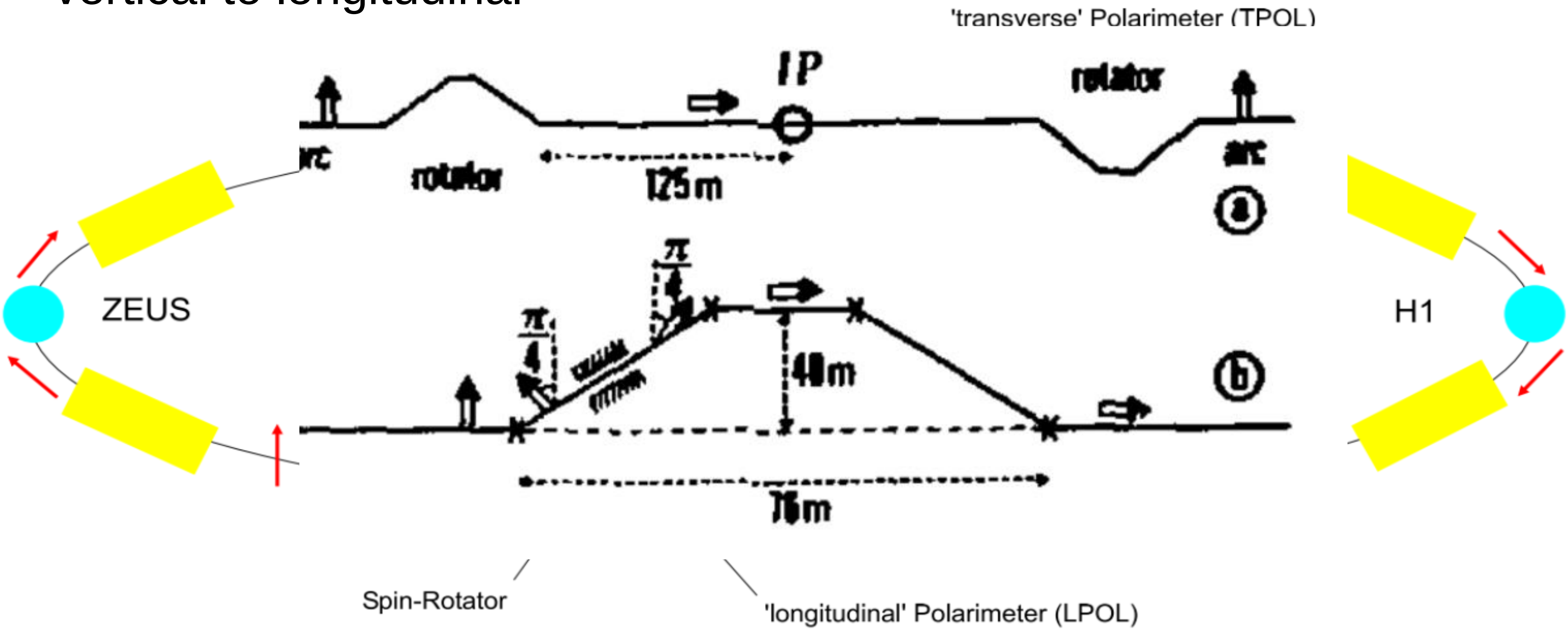
* S R Mane, Yu M Shatunov and K Yokoya, *Spin-polarized charged particle beams in high-energy accelerators*, Rep. Prog. Phys. 68 (2005) 1997–2265

Achieved Performance of Polarized e Beams



HERA polarization

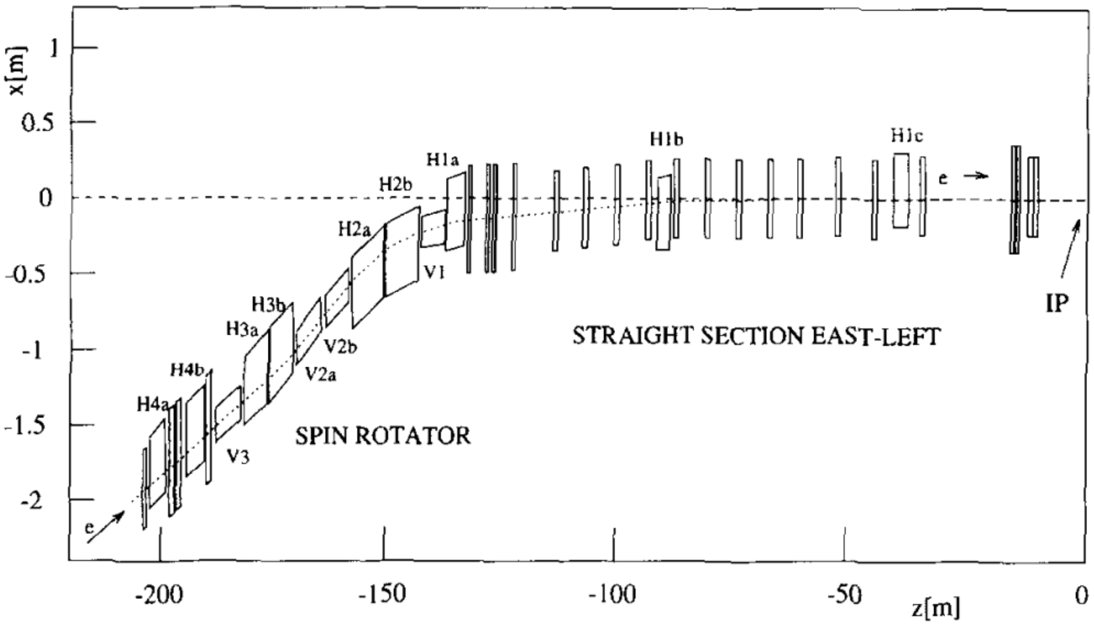
- HERA was the 1st high energy collider, that employed local spin rotators to provide longitudinally polarized electron
- A spin rotator consists of a sequence of horizontal and vertical orbit correctors that interleaves with each other to precess spin vector from vertical to longitudinal



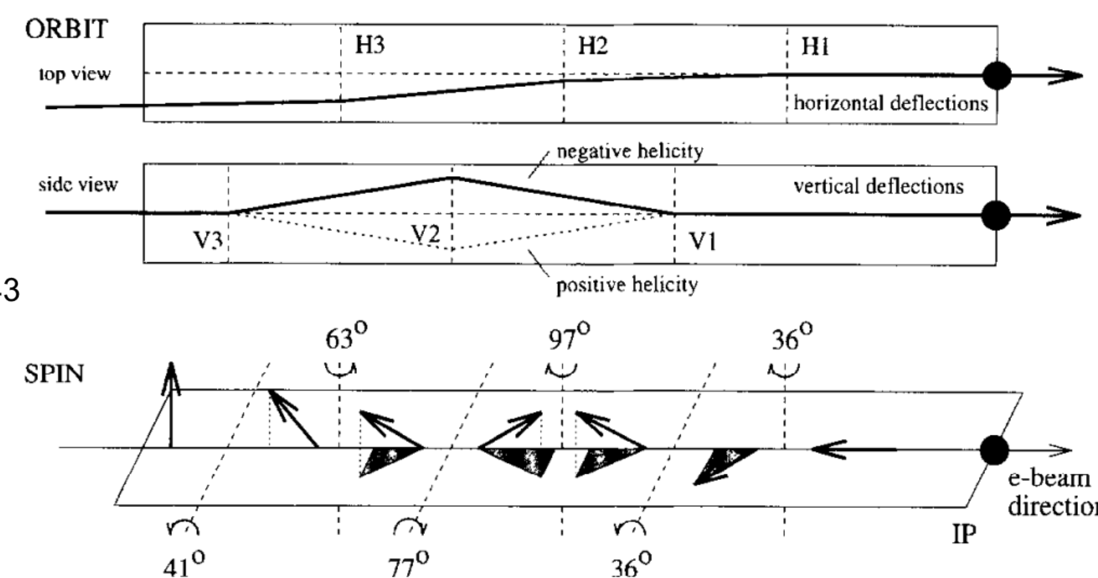
HERA polarization

- A spin rotator induces large orbital excursions in both planes and tilts the $\hat{n}$ away from vertical

HERA polarization



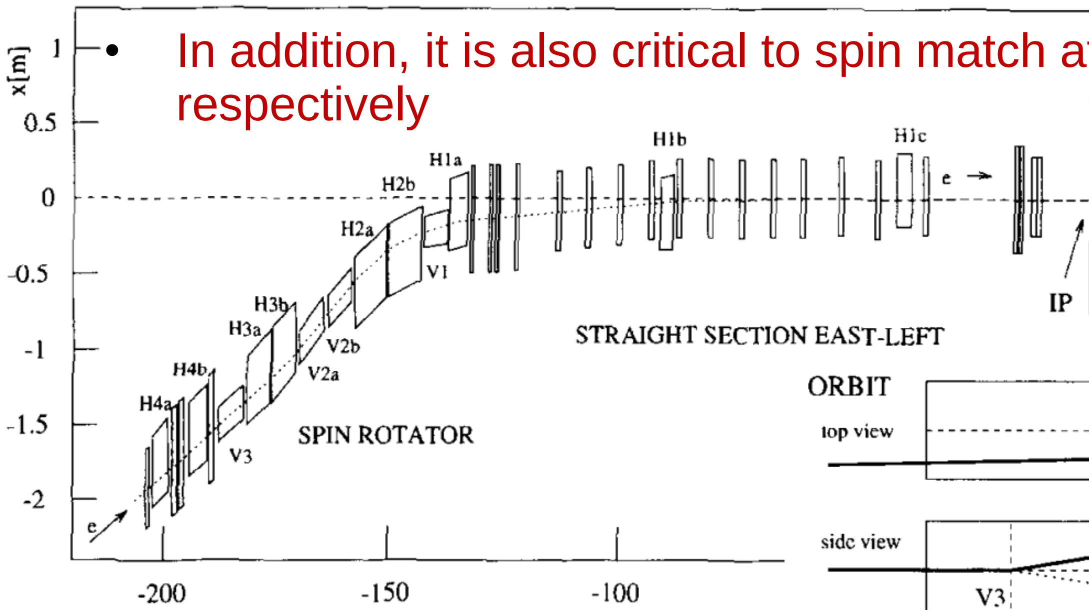
Vertical orbital bump ~ 20mm



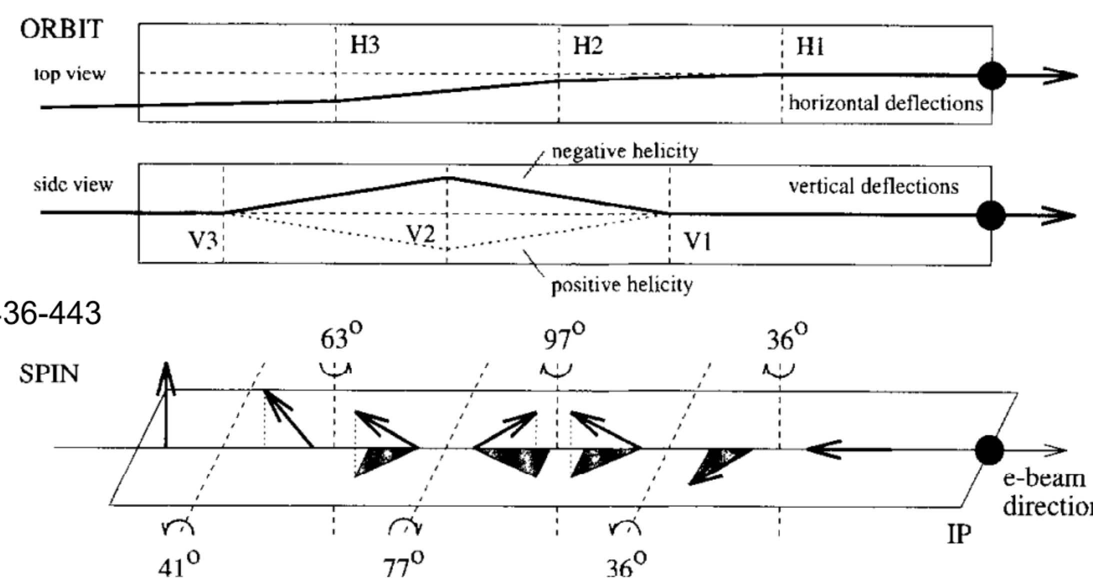
D.P. Barber et al. /Physics Letters B 343 (1995) 436-443

HERA polarization

- A spin rotator induces large orbital excursions in both planes and tilts the $\hat{n}$ away from vertical
  - Spin matching to make the section between spin rotators spin transparent to the 1st order
  - In addition, it is also critical to spin match at the entrance and exit of the rotator, respectively



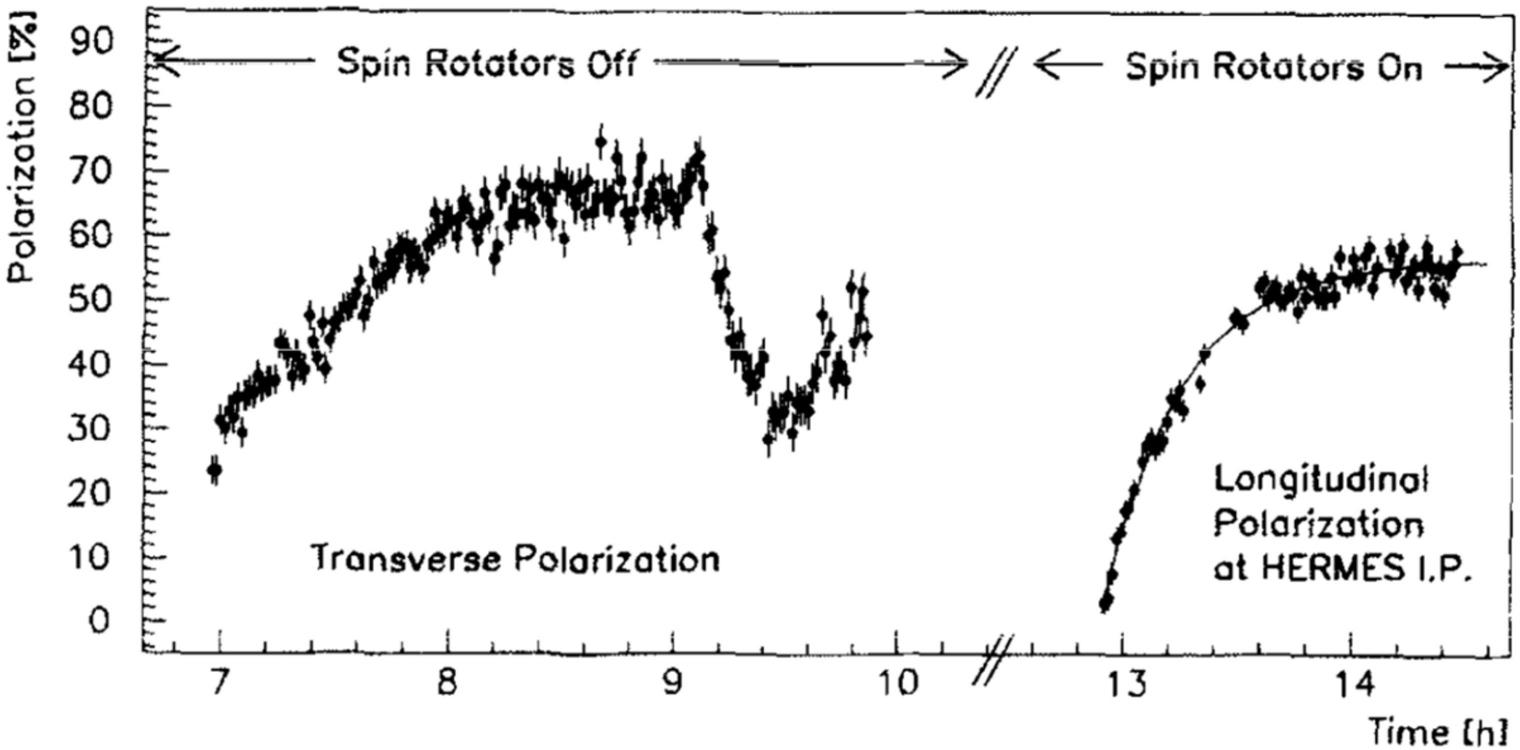
Vertical orbital bump ~ 20mm



D.P. Barber et al. /Physics Letters B 343 (1995) 436-443

HERA polarization

- With the HEAR mini-rotator



- Polarization was later-on improved to 65% after a dedicated spin-match optics was implemented

D.P. Barber et al. /Physics Letters B 343 (1995) 436-443

HERA polarization

- With 3 pairs of rotators

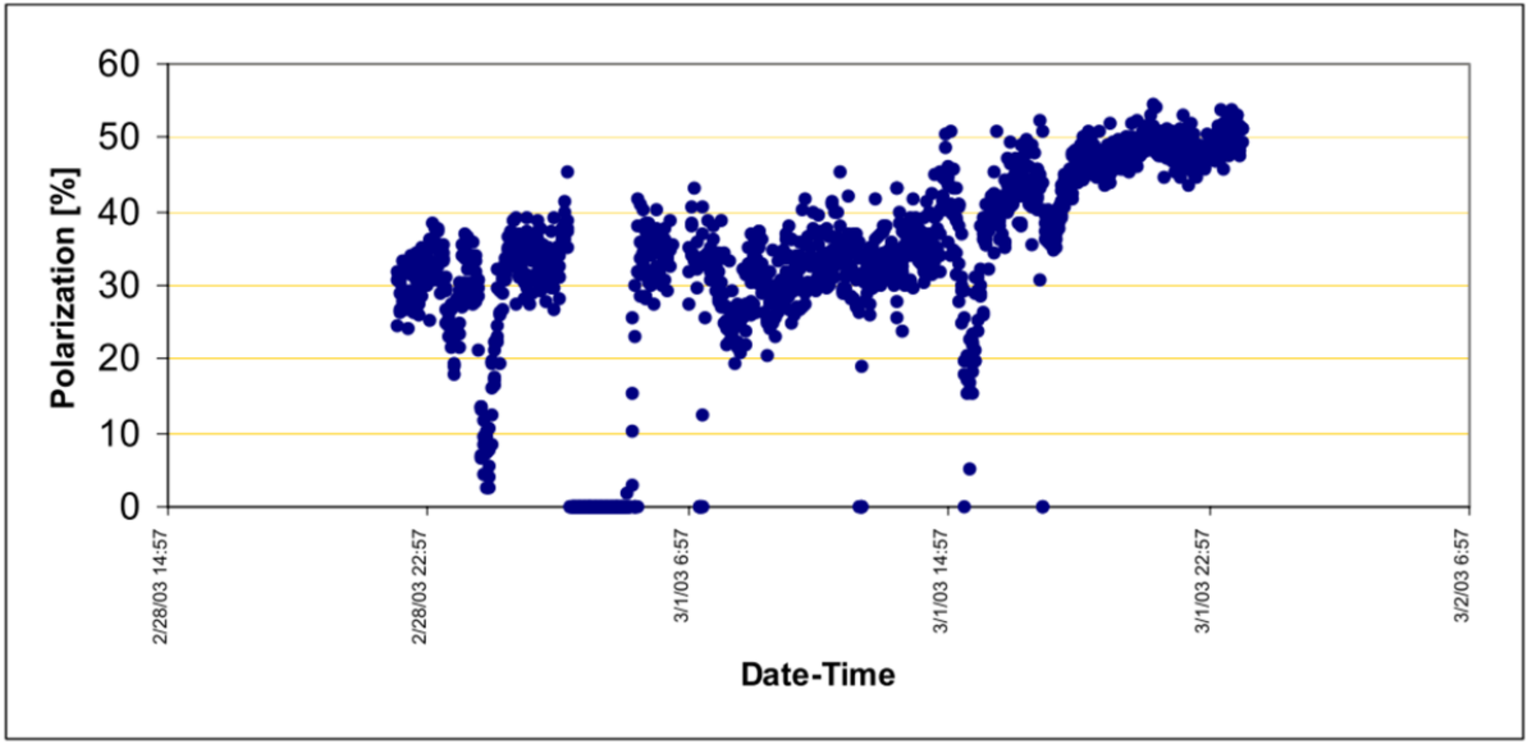


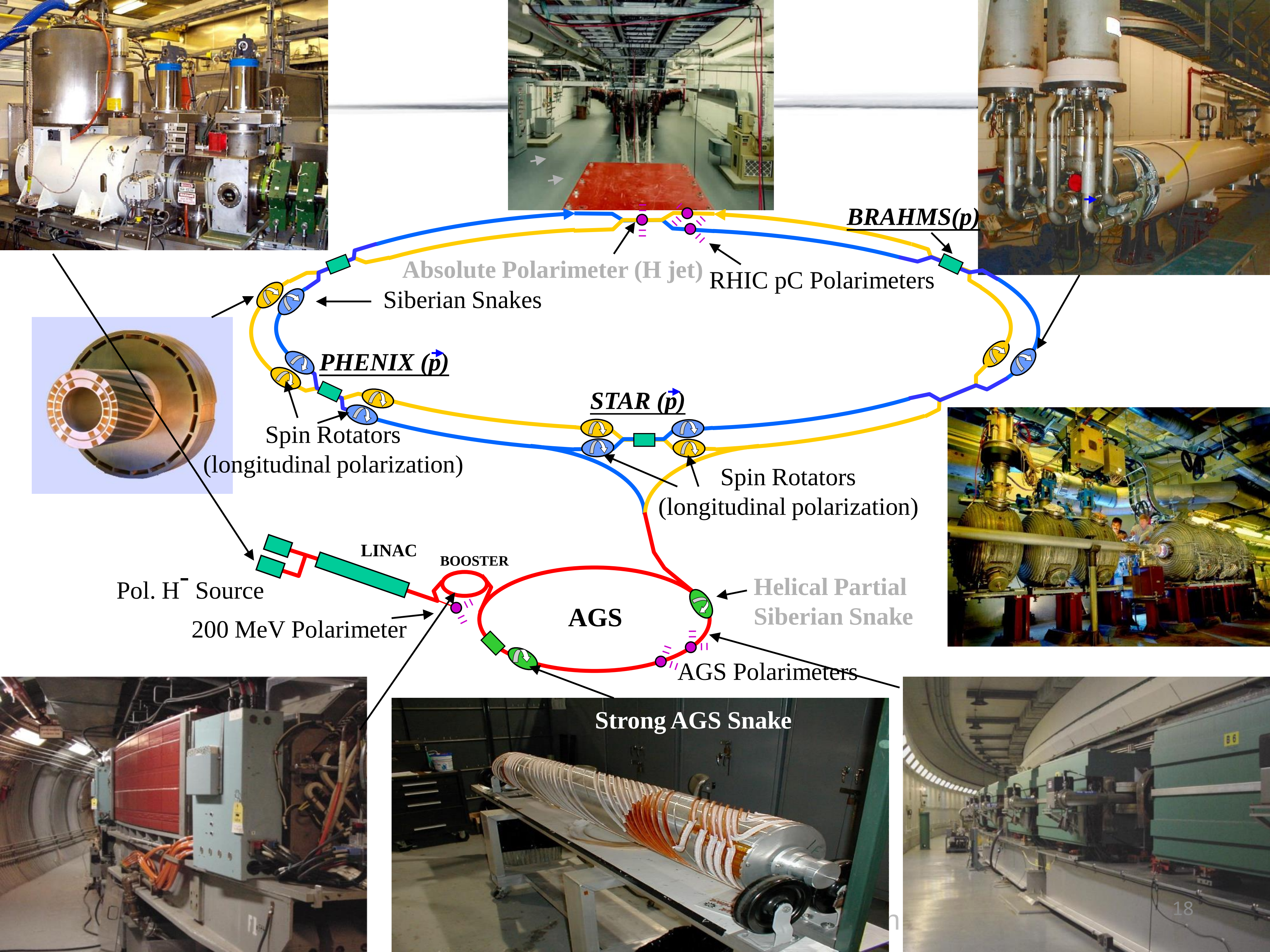
Figure 1: Polarization optimizations with 3 pairs of spin rotators in HERA-e on the 1st of March 2003. A polarization of 54% was ultimately obtained.

Georg Hoffstaetter et al, Experiences with the HERA beams, ICFA Newsletter May 2003

Colliders with polarized beams

- Polarized hadron colliders:
  - RHIC@BNL: polarized protons

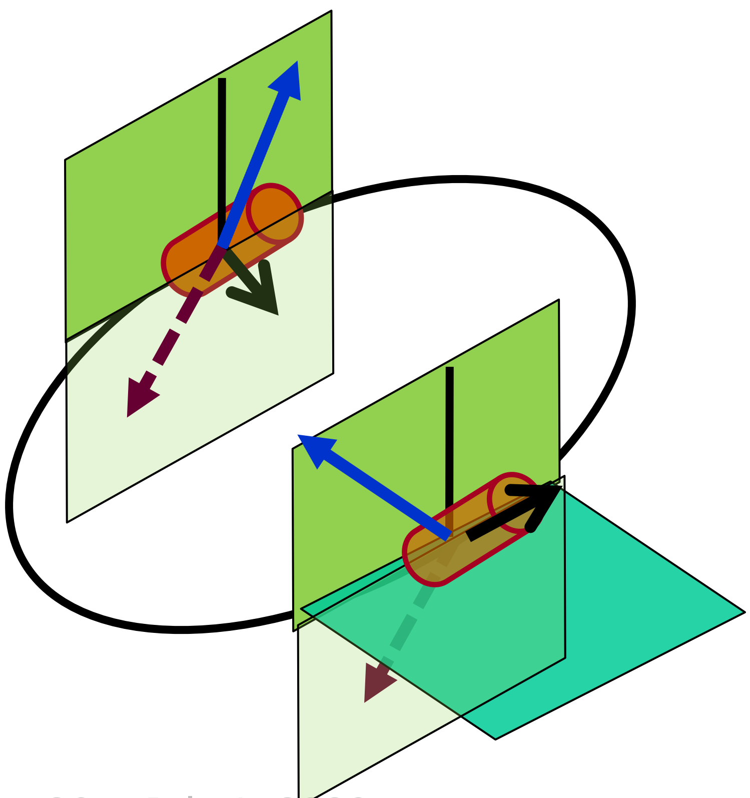
- Unlike the e+e- colliders, polarized beam starts from the source, and polarization need to survive through acceleration chain
  - Polarized ion source
  - Pre-Injector: LINAC, booster
  - Injector
  - Collider

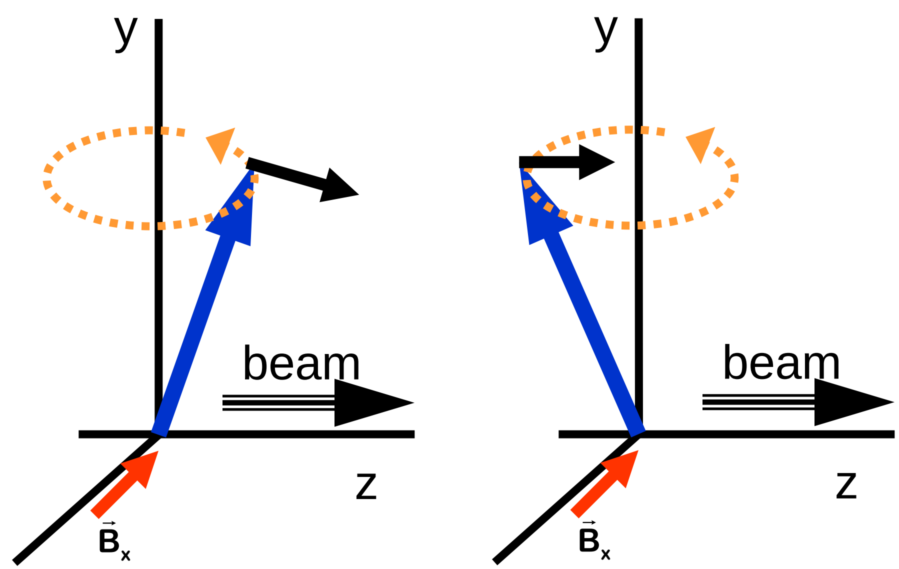


BRAHMS(p)
Absolute Polarimeter (H jet)
RHIC pC Polarimeters
Siberian Snakes
PHENIX (p)
STAR (p)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
LINAC
BOOSTER
Pol. H⁻ Source
200 MeV Polarimeter
AGS
Helical Partial
Siberian Snake
AGS Polarimeters
Strong AGS Snake

Principle of full Siberian snake

- Use one or a group of snakes to make the spin tune to be at ½
- Break the coherent build-up of the perturbations on the spin vector





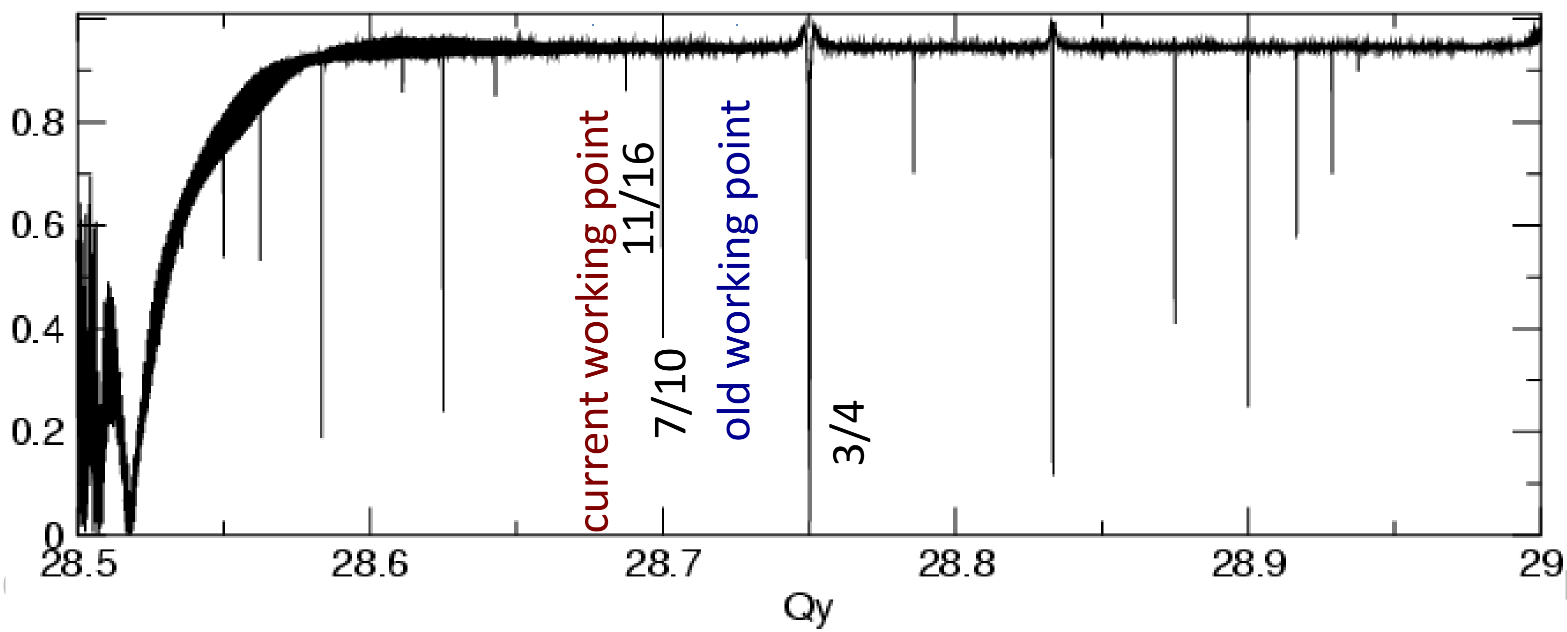
Snake Depolarization Resonance

- S. Y. Lee, Tepikian, Phys. Rev. Lett. 56 (1986) 1635
- S. R. Mane, NIM in Phys. Res. A. 587 (2008) 188-212

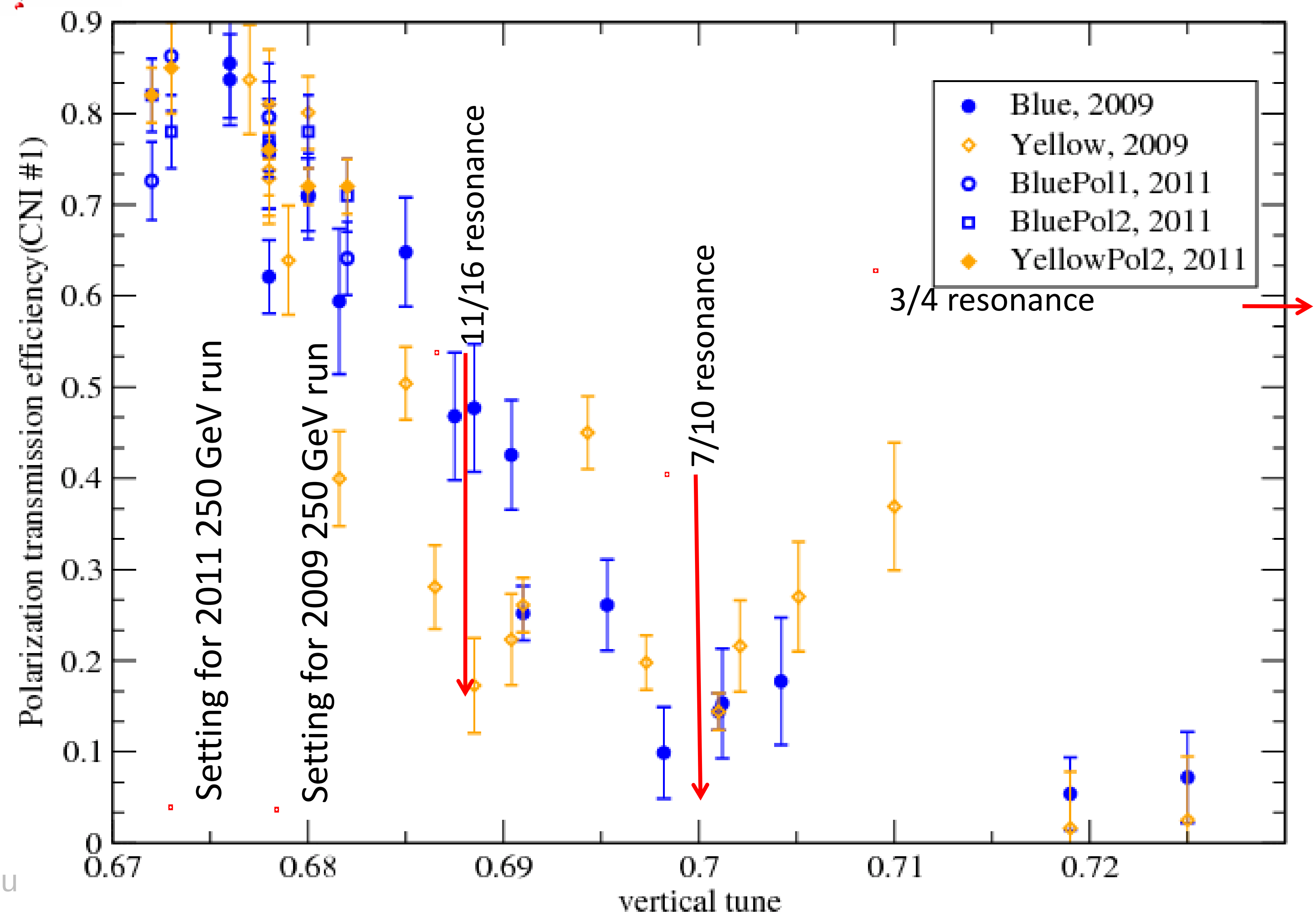
- **Condition**

$$mQ_y = Q_s + k$$

- **even order resonance**
  - Disappears in the two snake case if the closed orbit is perfect
- **odd order resonance**
  - Driven by the intrinsic spin resonances



Snake resonance observed in RHIC



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How to avoid a snake resonance?

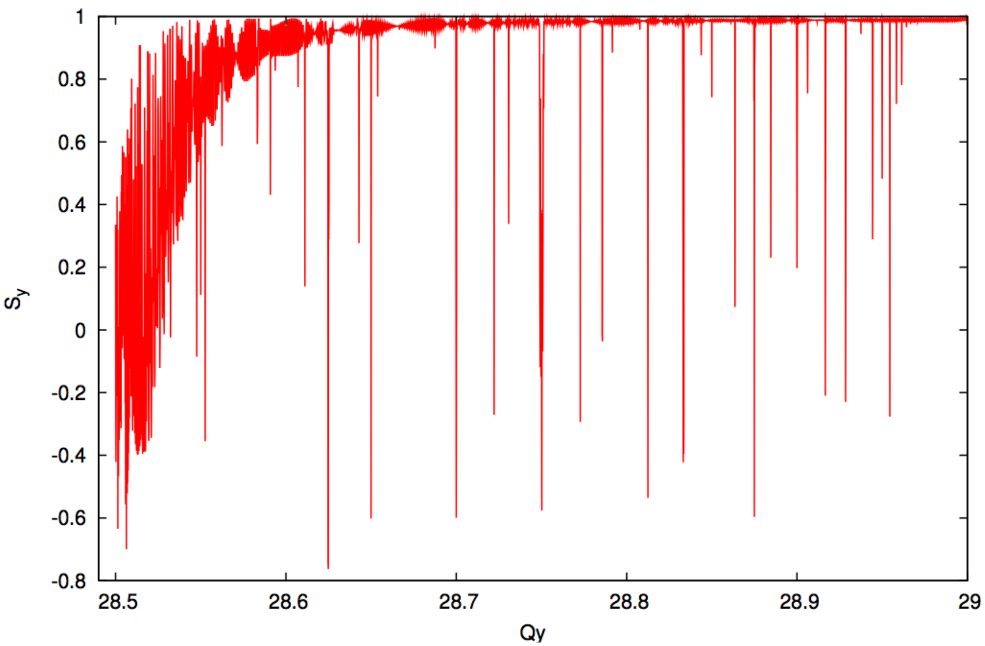
- Adequate number of snakes

$$N_{snk} > 4\left|\epsilon_{k,\max}\right| \qquad Q_s = \sum_{k=1}^{N_{snk}} (-1)^k \phi_k$$

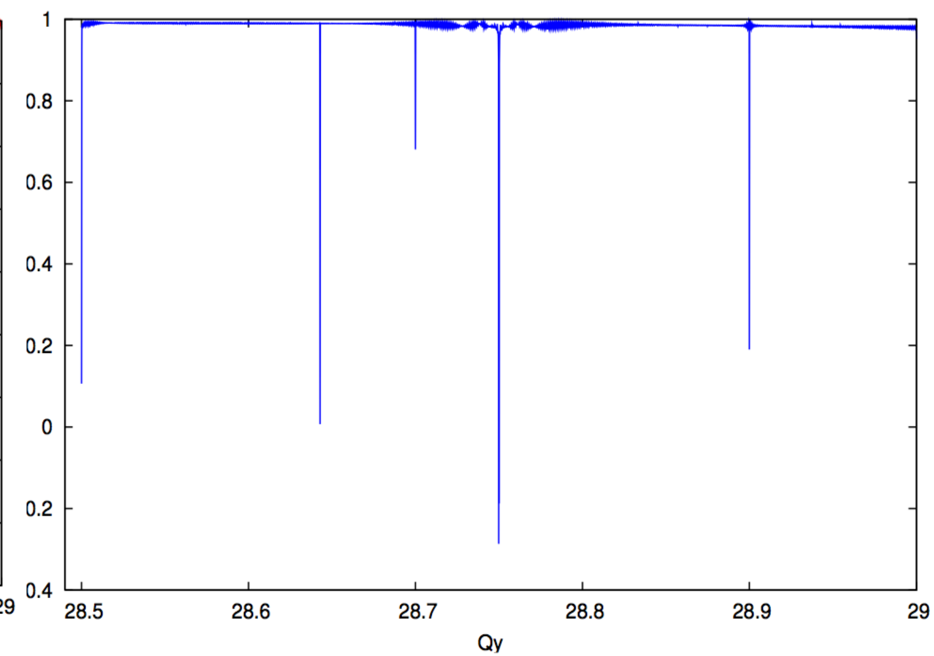
ϕ_k is the snake axis relative to the beam direction

- Minimize number of snake resonances to gain more tune spaces for operations

He-3 with dual snake



He-3 with six-snake



Avoid polarization losses due to snake resonance

- Adequate number of snakes

$$N_{snk} > 4|\epsilon_{k,\max}| \qquad Q_s = \sum_{k=1}^{N_{snk}} (-1)^k \phi_k$$

ϕ_k is the snake axis relative to the beam direction

- Keep spin tune as close to 0.5 as possible
  - **Source of spin tune deviation**
    - Snake configuration
    - Local orbit at snakes as well as other spin rotators. For RHIC,

angle between two snake axes

$$\Delta Q_s = \frac{|\Delta\phi|}{\pi} + (1+G\gamma)\frac{\Delta\theta}{\pi}$$

H orbital angle between two snakes

  - **Source of spin tune spread**
    - momentum dependence due to local orbit at snakes
      - equalize the dispersion primes at both snakes
    - betatron amplitude dependence

How to avoid a snake resonance?

- Adequate number of snakes

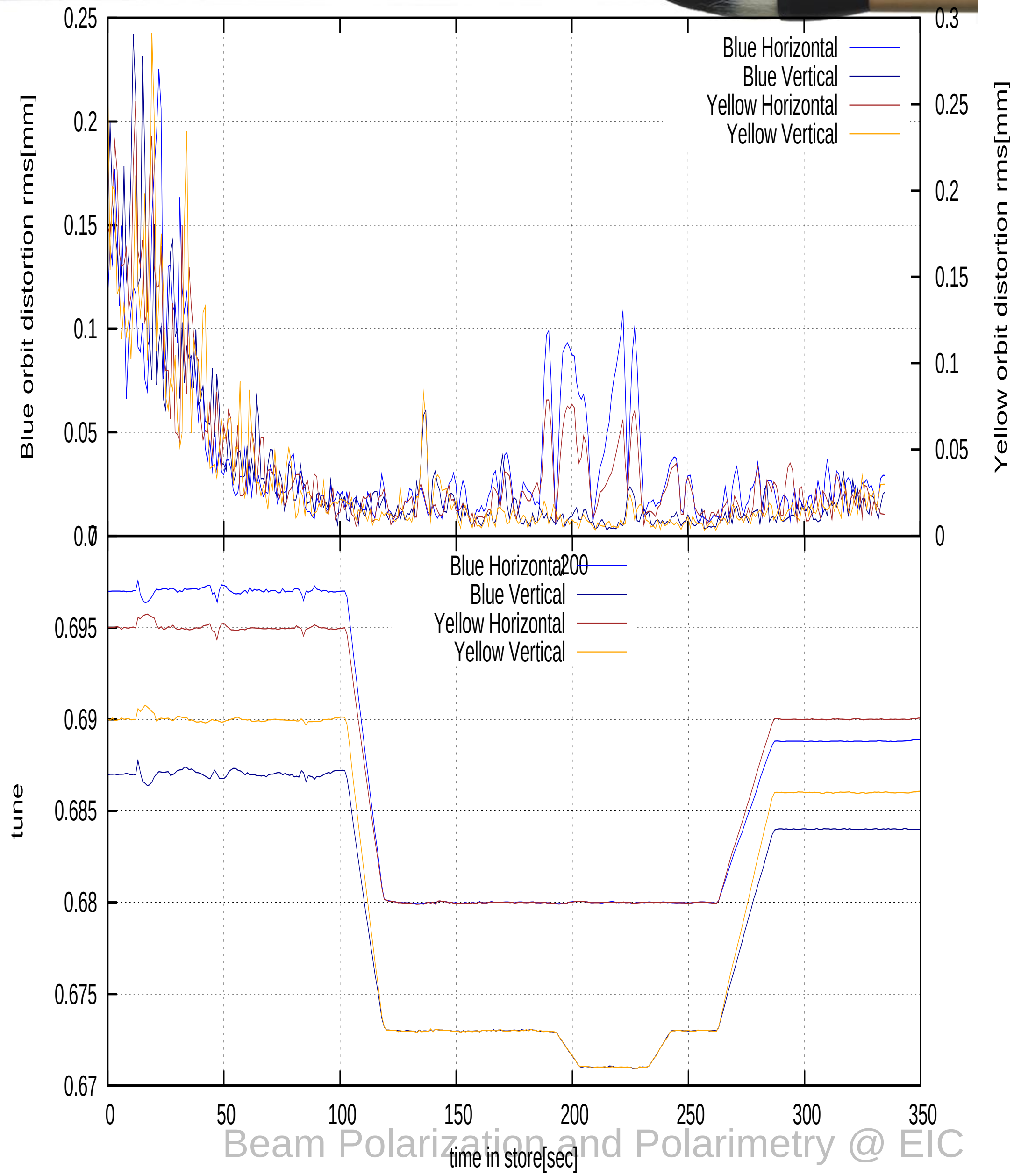
- Keep spin tune as close to 0.5 as possible

- Precise control of the vertical closed orbit

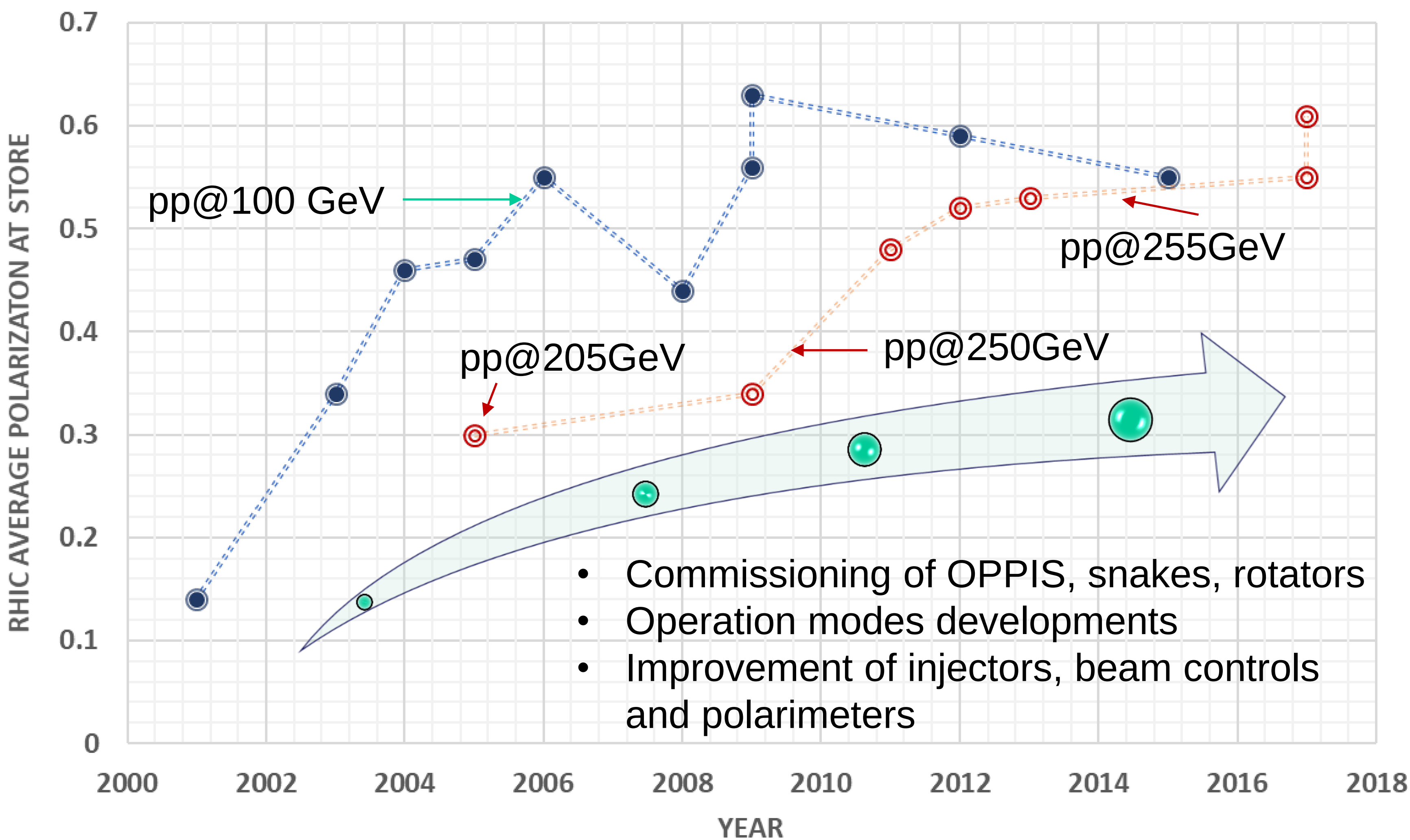
- Precise optics control
  - Choice of working point to avoid snake resonances
  - Minimize the linear coupling to avoid the resonance due to horizontal betatron oscillation

Precise Beam Control

- Tune/coupling feedback system: acceleration close to 2/3 orbital resonance
- Orbit feedback system: rms orbit distortion less than 0.1mm

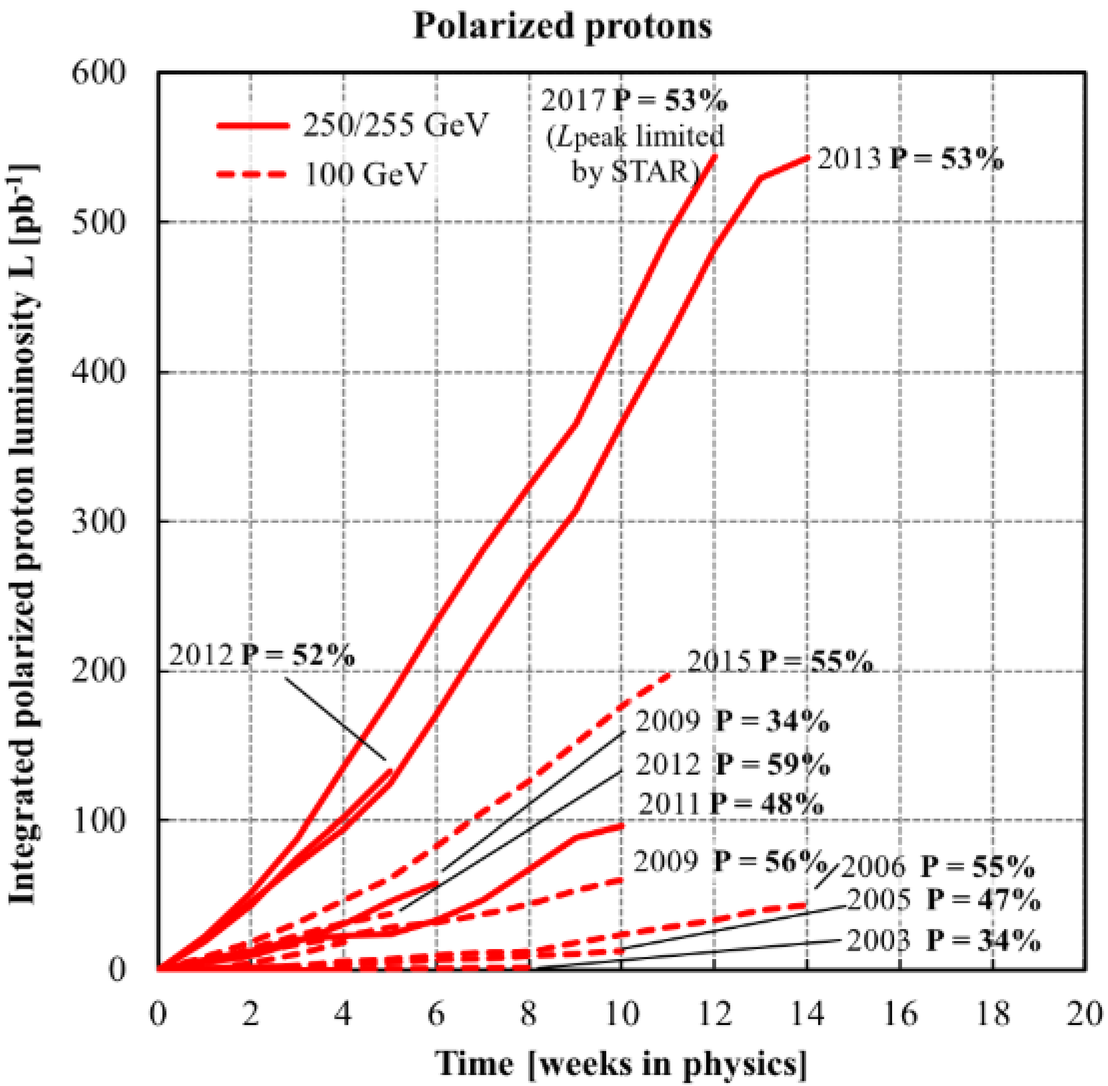


RHIC Polarization Performance



- Commissioning of OPPIS, snakes, rotators
- Operation modes developments
- Improvement of injectors, beam controls and polarimeters

RHIC, the world's 1st high energy pp collider



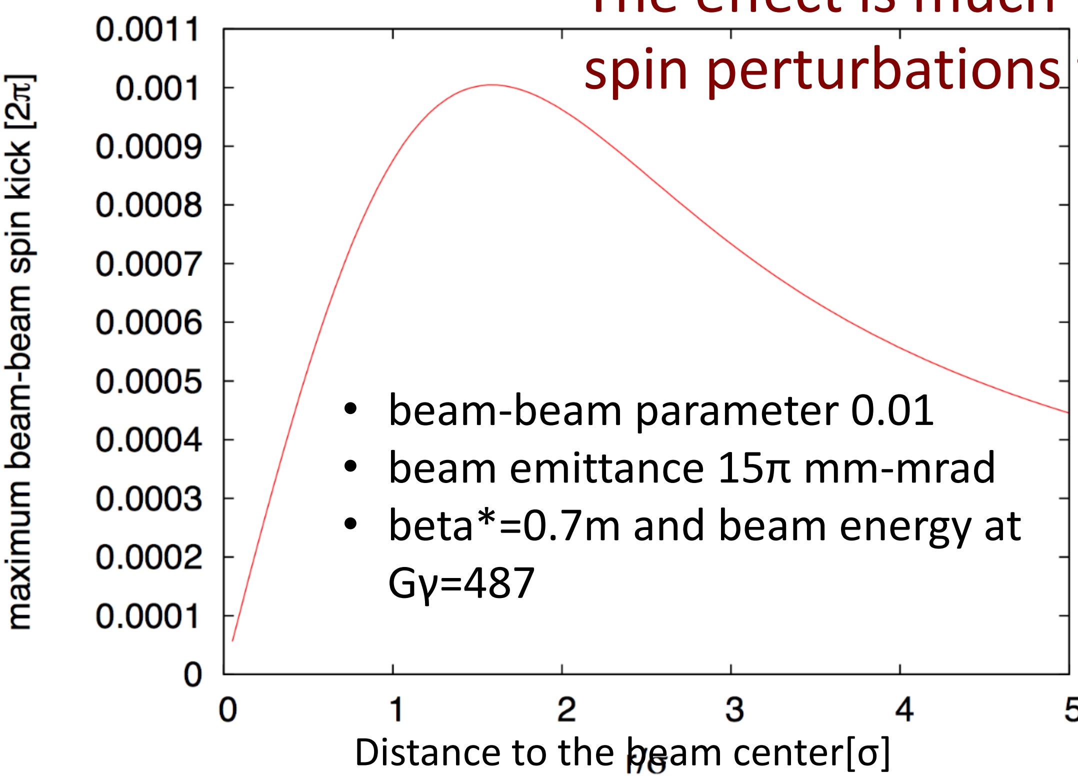
https://www.agsrhichome.bnl.gov/RHIC/Runs/

Beam-beam Effect on Polarization

- Beam-Beam force on spin motion
  - For a Gaussian round beam, particle from the other beam sees

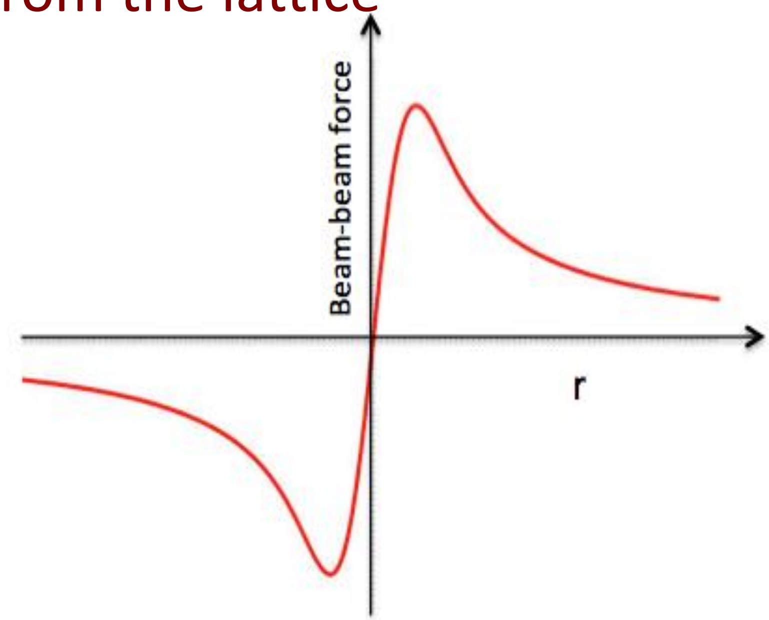
$$\vec{E} = \frac{qN}{2\pi\varepsilon_0 l r}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]\hat{r} \qquad \vec{B} = \frac{1}{c}\vec{\beta}\times\vec{E}$$

The effect is much weaker than the spin perturbations from the lattice



- beam-beam parameter 0.01
- beam emittance 15π mm-mrad
- beta*=0.7m and beam energy at Gγ=487

Distance to the beam center[σ]

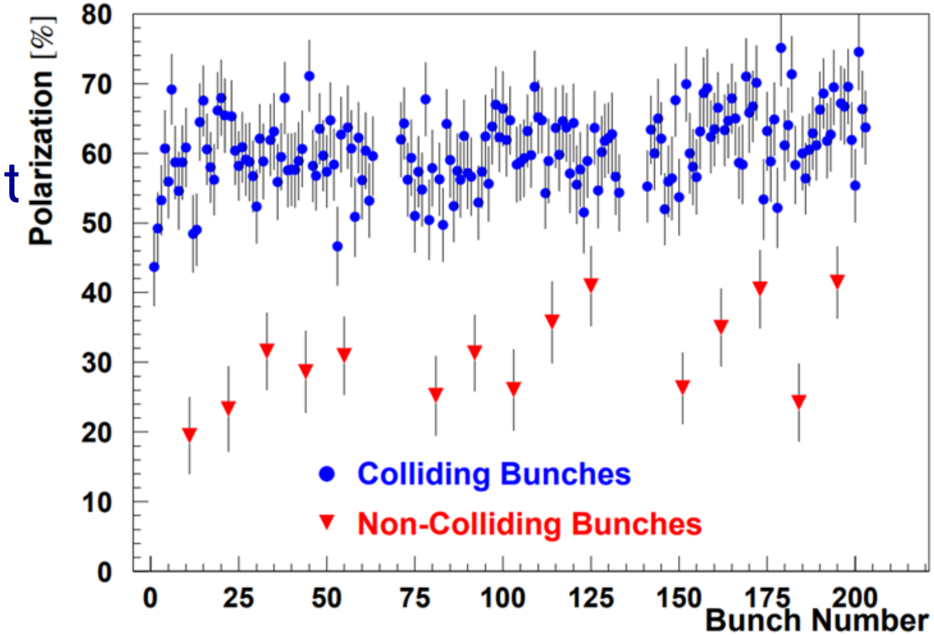


Polarization Performance and Beam-beam

- Beam-Beam induces tune shift of $x = \frac{N r_0 b^*}{4 p g s^2}$, as well as incoherent tune spread

- Both HERA and LEP observed the beam-beam effect on the electron beam polarization

- RHIC has observed very mild t during store



polarization of positrons colliding/not colliding with protons at HERA.

D.P. BARBER, arXiv:physics/9901040v1

Summary

- Polarized beams have been successfully used for exploring high energy particle and nuclear physics
- The upcoming EIC, as well as future high energy collider proposals (FCC-ee, ILC, CEPC, etc) requires
  - High luminosity with high polarized lepton and hadron beams
  - Polarized beams at very high energy
- The challenges ahead
  - Novel techniques in overcoming depolarizing effects
    - Existing spin orbit tracking and simulation codes, i.e. SLIM, SITROS, SLICKTRACK, PTC@Bmad, zgoubi etc met challenges in balancing computation power and accuracy
    - Innovative spin orbit tracking and simulation such as the latest discovery of a complete system of spin-orbit stochastic ODEs by K. Heinemann et al
      - More robust and fast spin matching algorithms
  - Novel techniques in spin manipulation

Look forward to polarized EIC!!!

- Highly polarized beams
  - Proton 80%
  - Electron 85%
  - Polarized Helium

- High luminosity
  - $1.3 \times 10^{34}\ cm^{-2}s^{-1}$