

# Self Polarization in electron Storage Rings

## Contents

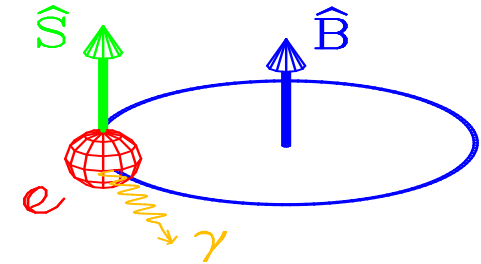
- Theoretical discovery of radiative polarization.
- Very first evidence of beam polarization.
- Later measurements at higher energy.
- HERA collider experience.
- Summary

Eliana GIANFELICE (Fermilab)  
Optics Tuning Workshop, June 27, 2023

## Radiative polarization

A small amount of the radiation emitted by a  $e^\pm$  moving in constant uniform magnetic field is accompanied by *spin flip*.

Slightly different probabilities  $\rightarrow$  *self polarization*!



- Equilibrium polarization

$$\vec{P}_{\text{ST}} = \hat{y} P_{\text{ST}} \quad |P_{\text{ST}}| = \frac{|n^+ - n^-|}{n^+ + n^-} = \frac{8}{5\sqrt{3}} = 92.4\%$$

$e^-$  polarization is anti-parallel to  $\vec{B}$ , while  $e^+$  polarization is parallel to  $\vec{B}$ .

- Build-up rate

$$\tau_{\text{ST}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar}{m_0} \frac{\gamma^5}{|\rho|^3} \rightarrow \tau_p^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar}{m_0 C} \oint \frac{ds}{|\rho|^3} \quad \text{for a ring including straight sections}$$

# Prediction of radiative polarization

A 1961 paper by Ternov, Loskutov and Korovina already predicts self-polarization.

SOVIET PHYSICS JETP

VOLUME 14, NUMBER 4

APRIL, 1962

## POSSIBILITY OF POLARIZING AN ELECTRON BEAM BY RELATIVISTIC RADIATION IN A MAGNETIC FIELD

I. M. TERNOV, Yu. M. LOSKUTOV, and L. I. KOROVINA

Moscow Power Institute

Submitted to JETP editor May 17, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1294-1295 (October, 1961)

Spin flip due to radiation produced by the motion of electrons in a uniform magnetic field is considered. It is shown that an initially unpolarized beam becomes partially polarized, with the magnetic moment primarily in the direction of the field.

The famous paper by Sokolov and Ternov about electrons moving in a homogeneous constant magnetic field appeared in 1963 in russian and in 1964 in english translation

Доклады Академии наук СССР  
1963. Том 153, № 5

ФИЗИКА

А. А. СОКОЛОВ, И. М. ТЕРНОВ

О ПОЛЯРИЗАЦИОННЫХ И СПИНОВЫХ ЭФФЕКТАХ  
В ТЕОРИИ СИНХРОТРОННОГО ИЗЛУЧЕНИЯ

(Представлено академиком Н. Н. Боголюбовым 4 VII 1963)

$$P_{\infty} = \frac{n_1 - n_2}{n_1 + n_2} = 92.4\%$$

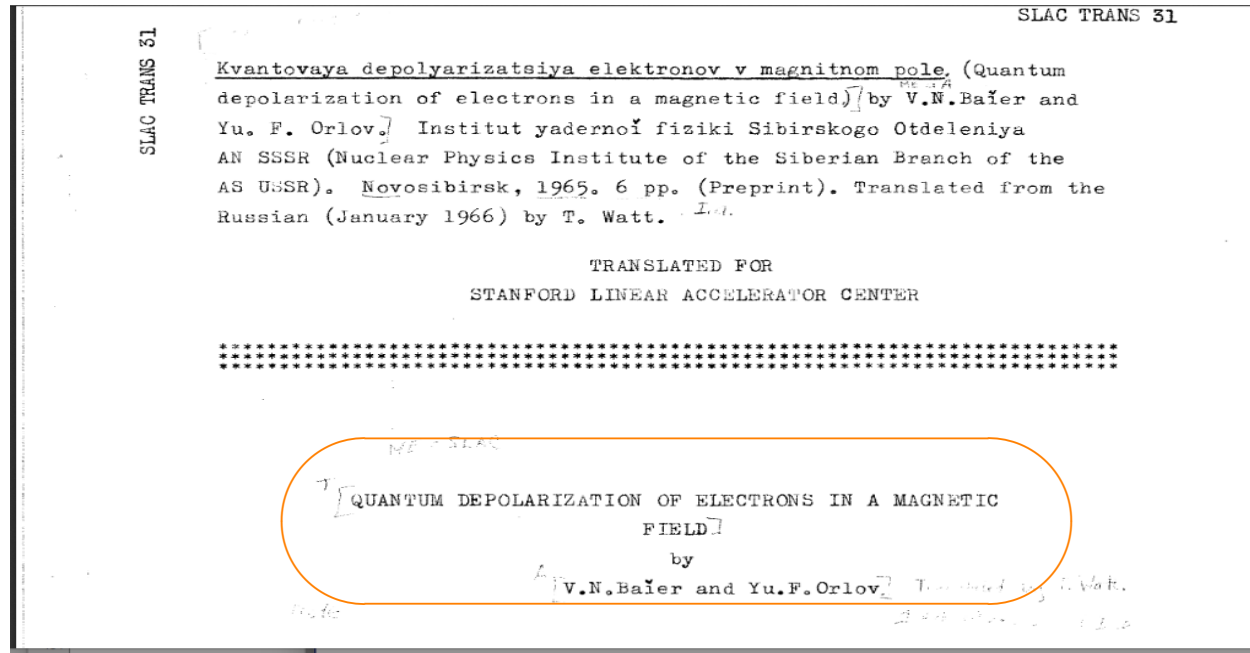
$$n_{1,2} = \frac{(15 \pm 8\sqrt{3})n_0 \mp (15(n_{20} - n_{10}) + 8\sqrt{3}n_0)e^{-t/\tau}}{30}. \quad (16)$$

Здесь верхние знаки относятся к  $n_1$ , а нижние к  $n_2$ , в начальный момент времени  $n_1 = n_{10}$  и  $n_2 = n_{20}$ .

Время жизни  $\tau$  равно

$$\tau = \left[ \frac{5\sqrt{3}}{8} \frac{\hbar}{m_0 c R} \left( \frac{E}{m_0 c^2} \right)^5 \frac{e_0^2}{m_0 c R^2} \right]^{-1} \quad (17)$$

$\Rightarrow e^{\pm}$ -beams polarization for free!



By applying Thomas-BMT equation to the spin of particles circulating in an *actual* storage ring, Baier and Orlov in their 1965 paper, pointed out the existence of *depolarising resonances* activated by the stochastic photon emissions and consequent trajectory perturbation (particularly important at high energy)

$$\nu_{spin} = m \pm m_x Q_x \pm m_y Q_y \pm m_s Q_s$$

Baier-Katkov-Strakhovenko (1970) generalized Sokolov-Ternov formulas to the case where the spin and motion direction are not everywhere perpendicular, however in absence of spin diffusion.

SOVIET PHYSICS JETP

VOLUME 31, NUMBER 5

NOVEMBER 1970

*KINETICS OF RADIATIVE POLARIZATION*

V. N. BAĬER, V. M. KATKOV, and V. M. STRAKHOVENKO

Novosibirsk State University

Submitted October 17, 1969

Zh. Eksp. Teor. Fiz. 58, 1695–1702 (May, 1970)

An equation describing the behavior of a spin in an external electromagnetic field is obtained in the quasiclassical approximation taking radiation effects into account. With the aid of this equation the process of radiative polarization is investigated.

$$\vec{P}_{\text{BKS}} = \hat{n}_0 P_{\text{BKS}} \quad \hat{n}_0(s) \equiv \text{periodic solution to T-BMT eq. on closed orbit}$$

$$P_{\text{BKS}} = P_{\text{ST}} \frac{\oint ds \hat{n}_0(s) \cdot \hat{b}(s) / |\rho|^3}{\oint ds [1 - \frac{2}{9} (\hat{n}_0(s) \cdot \hat{v}(s))^2] / |\rho|^3} \quad \hat{b} \equiv \hat{v} \times \dot{\hat{v}} / |\dot{\hat{v}}|$$

$$\tau_{\text{BKS}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m} \frac{1}{C} \oint ds [1 - \frac{2}{9} (\hat{n}_0 \cdot \hat{v})^2] / |\rho|^3$$

$\vec{P}_{\text{BKS}}$  and  $\tau_{\text{BKS}}$  are known for the unperturbed ring.

Spin diffusion included by Derbenev and Kondratenko (1973) in semi-classical approximation.

### Polarization kinetics of particles in storage rings

**Ya. S. Derbenev and A. M. Kondratenko**

*Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences*

(Submitted September 22, 1972)

Zh. Eksp. Teor. Fiz. **64**, 1918-1929 (June 1973)

A closed description of the radiative kinetics of the polarization of charged particles with arbitrary spin and magnetic moment is presented, and takes spin-orbit coupling into account. The analysis is based on an investigation of the dynamics of spin motion in inhomogeneous fields<sup>[8,10]</sup>. For ultrarelativistic electrons (positrons) the paper combines the results of a number of investigations<sup>[1-6]</sup> and contains some new effects due to spin-orbit coupling in an inhomogeneous field. The time constant and degree of equilibrium polarization of a beam in storage rings with arbitrary fields are found for nonresonant conditions. The method developed in the paper may also be applied when the perturbing electromagnetic field is related to an "external" source.

$$\vec{P}_{\text{DK}} = \hat{n}_0 \frac{8}{5\sqrt{3}} \frac{\oint ds < \frac{1}{|\rho|^3} \hat{b} \cdot (\hat{n} - \frac{\partial \hat{n}}{\partial \delta}) >}{\oint ds < \frac{1}{|\rho|^3} \left[ 1 - \frac{2}{9} (\hat{n} \cdot \hat{v})^2 + \frac{11}{18} \left( \frac{\partial \hat{n}}{\partial \delta} \right)^2 \right] >}$$

$\hat{b} \equiv \hat{v} \times \dot{\hat{v}}/|\dot{\hat{v}}|$

periodic solution  
to T-BMT eq. on c.o.

randomization of particle spin  
directions due to photon emission  
( $\delta \equiv \delta E/E$ )

Polarization rate

$$\tau_{\text{DK}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_0 C} \oint ds < \frac{1}{|\rho|^3} \left[ 1 - \frac{2}{9} (\hat{n} \cdot \hat{v})^2 + \frac{11}{18} \left( \frac{\partial \hat{n}}{\partial \delta} \right)^2 \right] >$$

These formulas involve *averaging over the beam distribution*.

- $\hat{n}$  is a phase space dependent solution of T-BMT eq. satisfying the condition  $\hat{n}(\vec{u}; s) = \hat{n}(\vec{u}; s + C)$ .
- The term  $\partial \hat{n} / \partial \delta$  describes the variation of  $\hat{n}$  following a photon emission.

## Tools for radiative polarization computation

- By linearizing orbit and spin motion it is possible to calculate polarization “analytically” in terms of one turn maps. This formalism has been developed at the end of the 70s by A. Chao (SLIM) and K. Yokoya. A thick lenses version of SLIM is D. P. Barber SLICK.
  - Only linear resonances!
- The computation of Derbenev-Kondratenko expressions in the general case is tricky and codes attempting to evaluate them have limitations.
  - S. R. Mane wrote SMILE (middle 80s) handling fully 3D spin motion in *perturbation* theory. This approach required large computing time and had convergence problem at high energy.
  - SODOM by K. Yokoya (1992) computes Derbenev-Kondratenko  $\hat{n}$  and  $\partial\hat{n}/\partial\delta$  using Fourier expansions. It has similar issues as SMILE.

- Instead of trying to evaluate Derbenev-Kondratenko expression, a *statistical* approach is used in SITROS by J. Kewisch (1982). Orbital motion is up to 2d order and spin motion is not linearized. Initially fully polarized beam is tracked and stochastic photon emission takes place at user selected machine dipoles. As polarization evolves as

$$P(t) = P_{\infty}(1 - e^{-t/\tau_p}) + P(0)e^{-t/\tau_p}$$

with

$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\text{BKS}}} + \frac{1}{\tau_d} \quad \text{and} \quad P_{\infty} \simeq \frac{\tau_p}{\tau_{\text{BKS}}} P_{\text{BKS}}$$

SITROS evaluates  $\tau_p$  from  $P(t)$  and  $P_{\infty}$  from  $\frac{\tau_p}{\tau_{\text{BKS}}} P_{\text{BKS}}$

- More recently spin tracking and spin maps have been added to Bmad by D. Sagan.

## First measurements of radiative polarization

As reported by Belbeoch *et al.*, at 1968 USSR Nat. Conf. Part. Acc., the very first observation was in 1968 with a 536 MeV  $e^+$  beam at ACO (Anneau de Collisions d'Orsay), in operation as  $e^+/e^-$  collider from 1965 to 1973.

Available on-line

### STATUS REPORT ON ACO

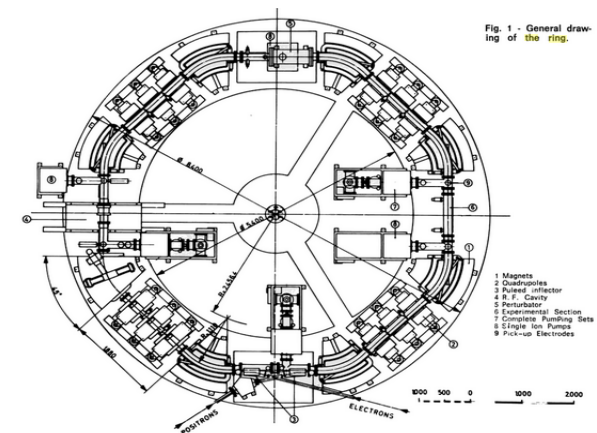
The Orsay Storage Ring Group<sup>†)</sup>

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Centre d'Orsay, Orsay, France.

(presented by D. Potaux)

(8th International Conference on  
High-Energy Accelerators,  
CERN, 1971)

Polarization measurement exploited the spin dependence of the Coulomb scattering cross section: smaller beam losses by increased polarization.



- Polarization was observed in 1972 also at VEPP-2.
- Polarization close to 92% (!) was later measured at
  - ACO (1973)
  - VEPP-2M (1976) at 500 MeV

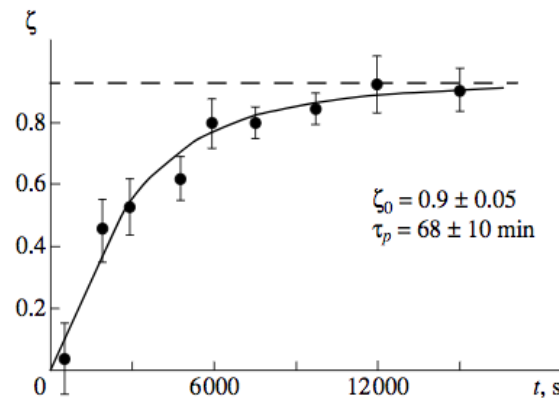


Fig. 3. The polarization buildup in VEPP-2M (1976).

(from Yu. M. Shatunov, *Polarized Beams at Storage Rings*, 2006)

Far from resonances, spin diffusion is negligible at low energy!

# Beam energy calibration

At VEPP-2M the method of beam energy measurement by *resonant depolarization* was first invented.

*Particle Accelerators*  
1980 Vol.10 pp.177-180  
0031-2460/80/1003-0177\$06.50/0

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Printed in the United States of America

(1980)

## ACCURATE CALIBRATION OF THE BEAM ENERGY IN A STORAGE RING BASED ON MEASUREMENT OF SPIN PRECESSION FREQUENCY OF POLARIZED PARTICLES\*

YA. S. DERBENEV, A. M. KONDRATENKO, S. I. SEREDNYAKOV, A. N. SKRINSKY,  
G. M. TUMAIKIN, and YU. M. SHATUNOV

*Institute of Nuclear Physics, Siberian Division USSR Academy of Sciences, Novosibirsk 90, USSR*

*(Received January 29, 1979)*

A method is described for measuring the particle energy in an electron-positron storage ring by means of resonance depolarization by a high frequency field. The measurement accuracy is discussed taking into account energy spread and synchrotron oscillations. It is found that in practice the limitation in accuracy is due to the irregular pulsations of the magnetic guide field. As a result, the electron beam energy in the storage ring VEPP-2M has been measured with an accuracy of  $\pm 2 \cdot 10^{-3}$ .

They used a *longitudinal* magnetic field for depolarizing the beam.

- Depolarization occurs when spin precession and field frequency are in resonance

$$\nu_{spin} = \frac{f_{exc}}{f_{rev}} + k$$

- $\nu_{spin} = a\gamma$  (in a planar ring, w/o solenoids)  $\rightarrow E_{beam} = \left[ k \pm \frac{f_{exc}}{f_{rev}} \right] \frac{E_0}{a}$

Later on polarization was observed at

- SPEAR (SLAC) where a Compton polarimeter was built for SPEAR2

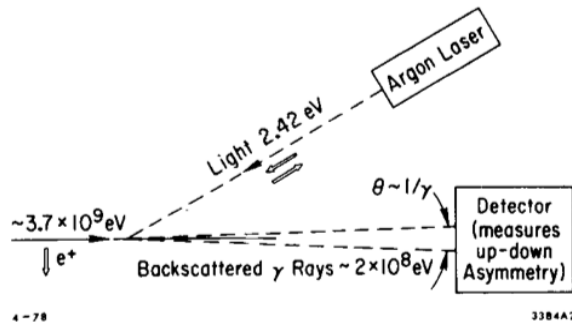
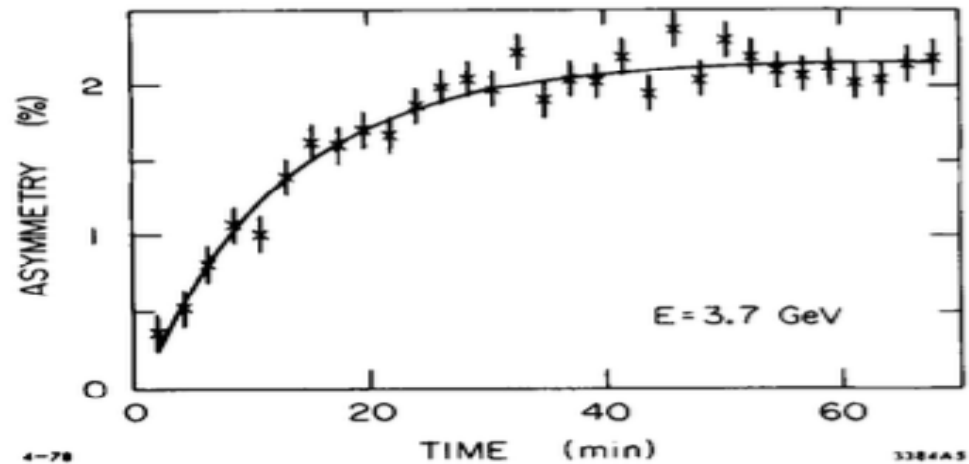


Fig. 4. Schematic diagram of SLAC-Wisconsin laser polarimeter.<sup>18</sup>



(R. F. Schwitters, *Experimental review of beam polarization in high energy  $e^+e^-$  storage rings*, 1979)

- DORIS II (beam energy calibration), PETRA (where “harmonic spin-matching” was invented), CESR, TRISTAN, LEP (beam energy calibration).

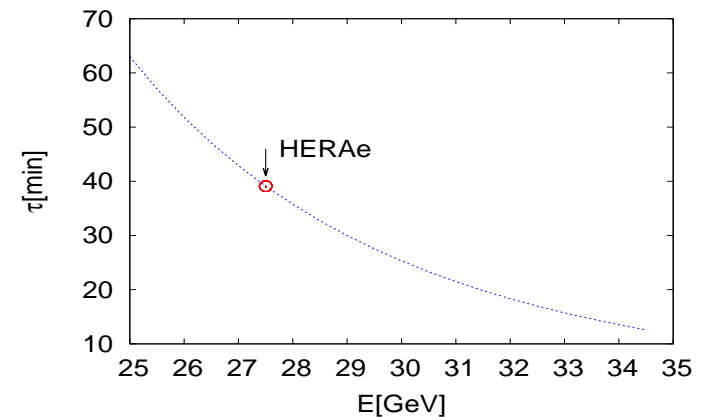
Polarization became ...*fashionable*!

## $e^\pm$ polarization at HERA

HERA was a 6.3 km  $p/e^\pm$  collider operating in Hamburg from 1992 to 2007.

The  $e^\pm$  ring was conceived from the beginning on for delivering beam longitudinal polarization using Sokolov-Ternov effect.

- Planar geometry;
- large number of BPMs and orbit correctors;
- spin rotators for longitudinal polarization:
  - large number of independently powered quadrupoles for spin matching.



## HERAe Mini-rotator

Several designs considered. Final choice: Steffen-Buon “mini-rotator”.

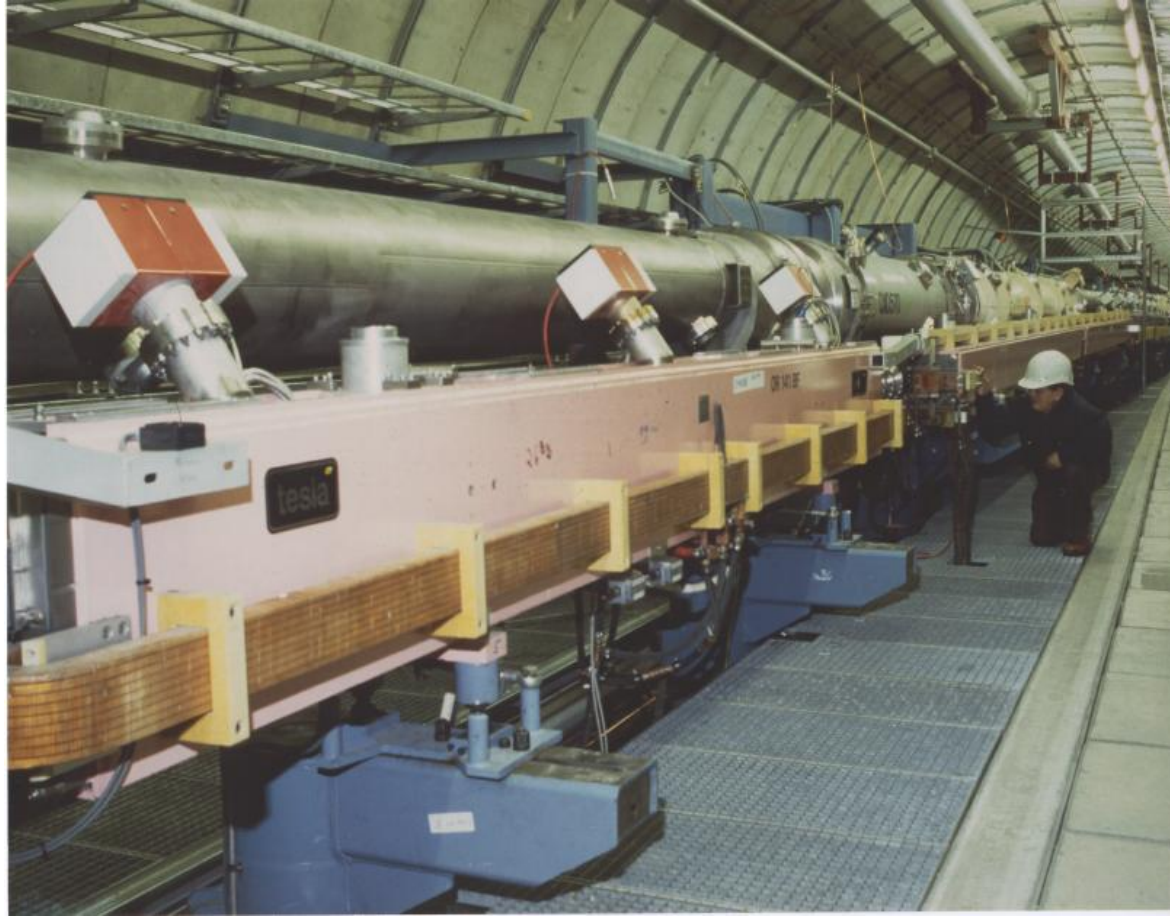
- Chain of interleaved horizontal and vertical bending magnets.
- Short enough ( $\simeq 56$  m): no quadrupoles needed!
- Spin helicity changed by flipping the sign of the vertical bending magnets:
  - magnets mounted on remotely controlled jacks for adjusting their elevation w/o entering the tunnel.
- Designed to operate between 26.8 and 35 GeV by changing the magnet settings:
  - energy changes larger than  $\pm 100$  MeV required a manual machine re-alignment.

Spin transparency for *linear* spin/orbit motion recovered by *spin matching*.

For the HERAe mini-rotator with

- $D_y \neq 0$  only at the rotators
- $\hat{n}_0$  non vertical only between the rotator pair

$\leadsto$  5 additional optics conditions (for symmetric IR and arcs).



HERAe Mini-rotator in place on the vertically movable jacks

## Spin diffusion due to random errors and counter-measures

In a real machine spin transparency is also randomly broken by magnet **misalignments**

- Quadrupoles
  - radial displacement: spin diffusion if  $\hat{n}_0$  is not vertical;
  - vertical displacement
    - \*  $D_y \neq 0$
    - \*  $\delta\hat{n}_0 \neq 0$
  - roll
    - \*  $D_y \neq 0$  if  $D_x \neq 0$
    - \* betatron motion coupling  $\leadsto \epsilon_y \neq 0$
- Horizontal bending magnets
  - roll  $\leadsto D_y \neq 0$  and  $\delta\hat{n}_0 \neq 0$

The most dangerous is the **vertical misalignment of quadrupoles**:

- at HERAe, usual closed orbit correction cured spurious vertical dispersion too;
- $\delta\hat{n}_0$  required special care!

Mais-Ripken formalism.

periodic spin basis

$$\delta \hat{n}_0 = \alpha \hat{m} + \beta \hat{l}$$

$$[\alpha - i\beta](s) = \frac{ie^{i[\psi(s) - \pi\nu_s]}}{2 \sin \pi\nu_s} \int_{s-C}^s ds' e^{-i\psi(s')} f(s') \quad f \equiv d_1 - id_2$$

$$\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = \mathbf{L} \left[ \mathbf{F} \vec{z} - \frac{1}{B\rho} \begin{pmatrix} \Delta B_\tau (1 + a) \\ \Delta B_x (1 + a\gamma) \\ \Delta B_z (1 + a\gamma) \end{pmatrix} \right]$$

- $\vec{z}$  is the 6-dimensional c.o.;
- $\Delta \vec{B}$  = extra fields along the design c.o.;
- $\mathbf{L} = 2 \times 3$  matrix of the components of the periodic spin basis vectors,  $\hat{m}$  and  $\hat{l}$ , in the orbital reference system;
- $\mathbf{F}$  is a  $3 \times 6$  (energy dependent) matrix containing the nominal fields.

$f(s)$  is periodic and can be expanded in a Fourier series

$$f_k = \frac{1}{C} \int_0^C ds f(s) e^{-i2\pi ks/C}$$

$\alpha$  and  $\beta$  in terms of the Fourier components of  $f$

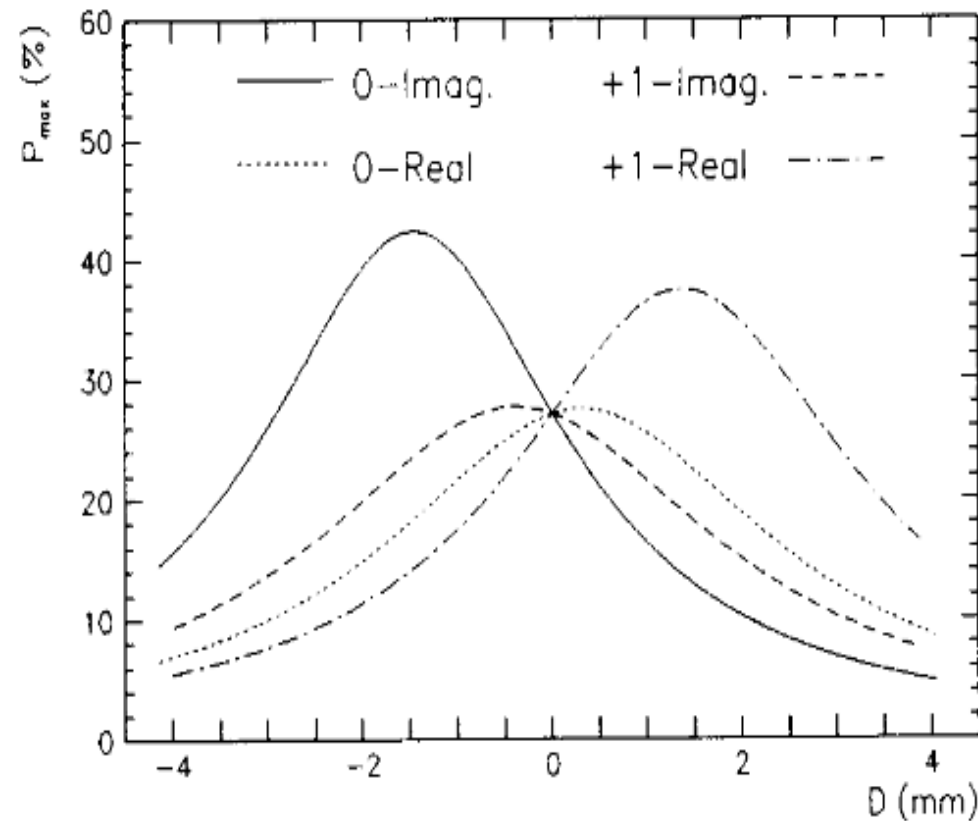
$$[\alpha - i\beta](s) = -i \frac{L}{2\pi} \sum_k \frac{f_k}{k - \nu_s} e^{i2\pi ks/C}$$

- $\delta\hat{n}_0$  increases linearly with energy ( $a\gamma$  factor is also embedded into  $\mathbf{F}$ );
- $\hat{n}_0$  tilt is more sensitive to the harmonics of the spin-orbit function  $f$  close to  $\nu_s$ .

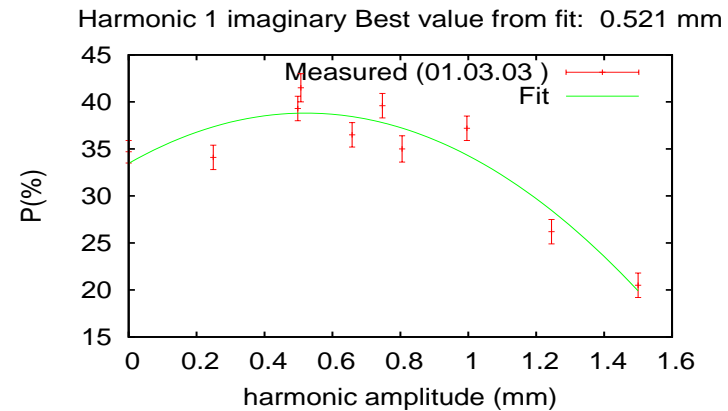
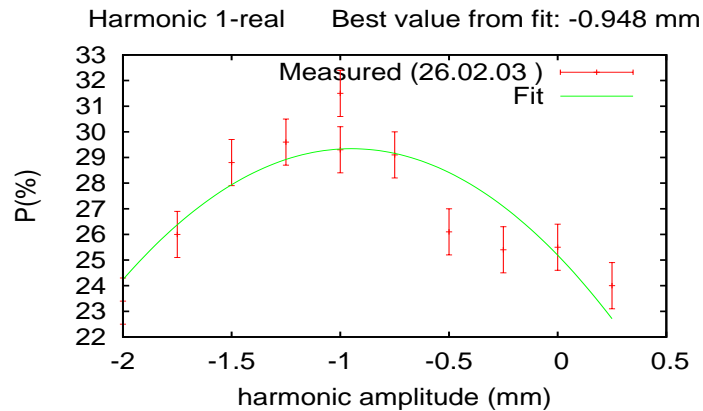
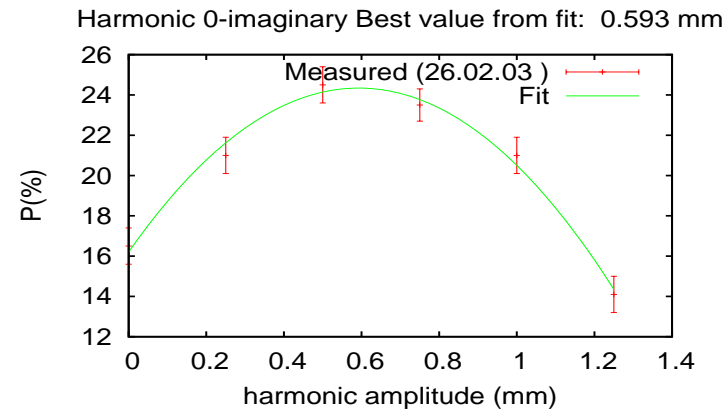
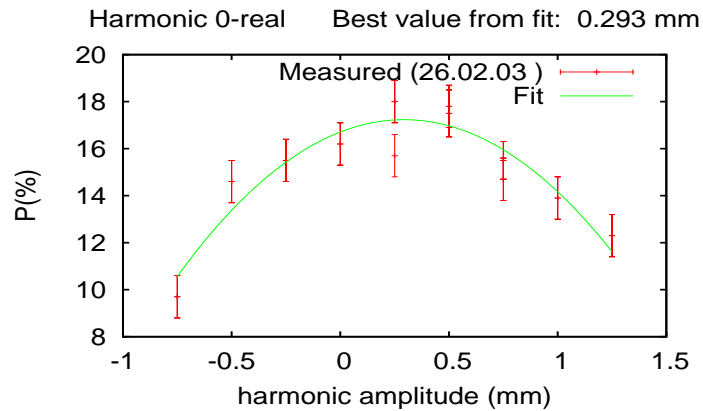
The correction consists in compensating these harmonics by powering some of the usual correction coils. In practice using *closed orbit bumps* in the arc cells allows to correct  $\delta\hat{n}_0$  w/o perturbing the orbit everywhere  $\leadsto$  harmonic bumps

Correction done **empirically** by scanning the most important harmonic components.

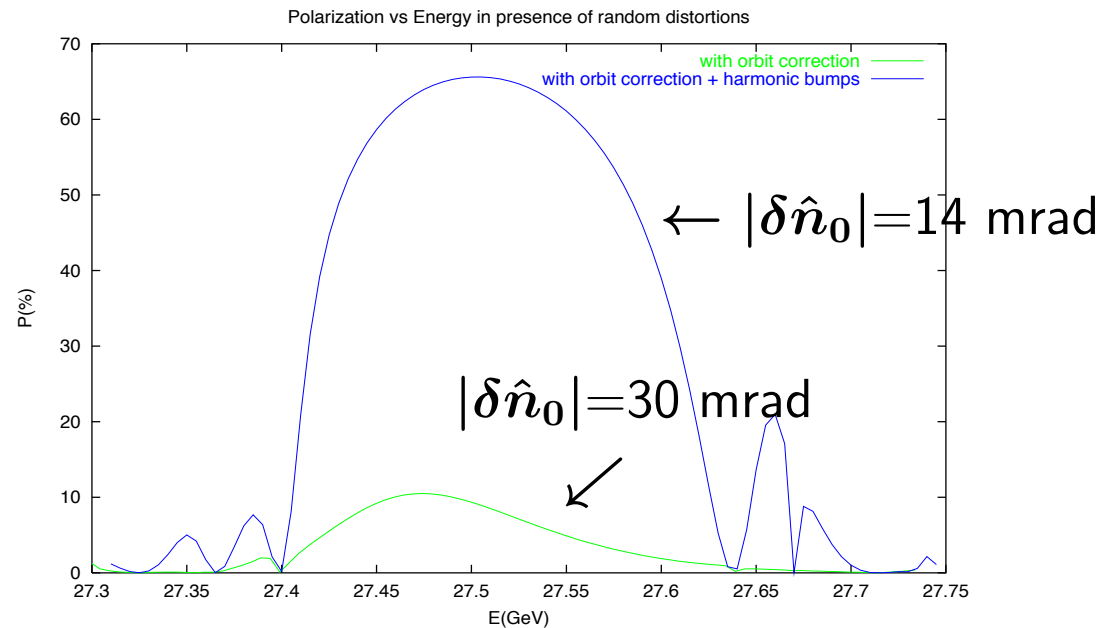
Expected effect on polarization of harmonic bumps scans:



...and *real life*:



Expected effect of harmonic bumps on HERAe polarization  
(simulation with  $\delta Q_{rms}^y = 0.3$  mm):



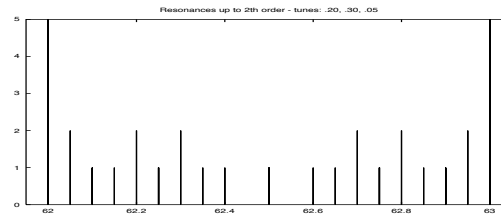
# Beam parameters choice

Spin diffusion is larger when the spin-orbit resonance conditions are met

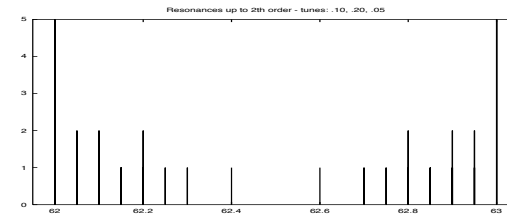
$$\nu_s = m \pm m_x Q_x \pm m_y Q_y \pm m_s Q_s$$

→ Small fractional parts of betatron tunes are convenient.

Resonances  
position

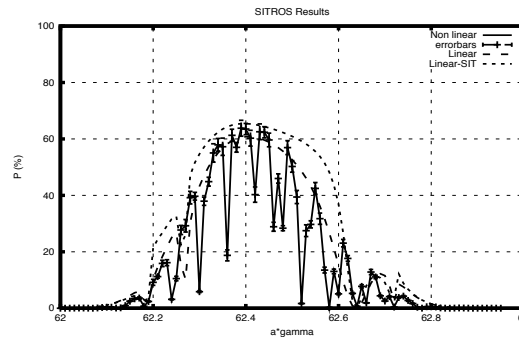


$$q_x=0.2 \quad q_y=0.3$$

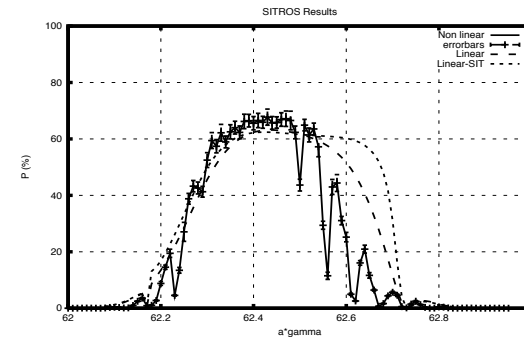


$$q_x=0.1 \quad q_y=0.2$$

SITROS  
simulations



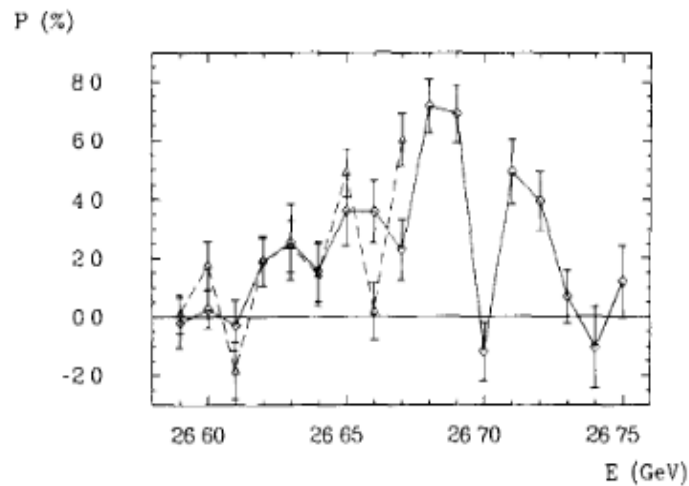
$$q_x=0.2 \quad q_y=0.3$$



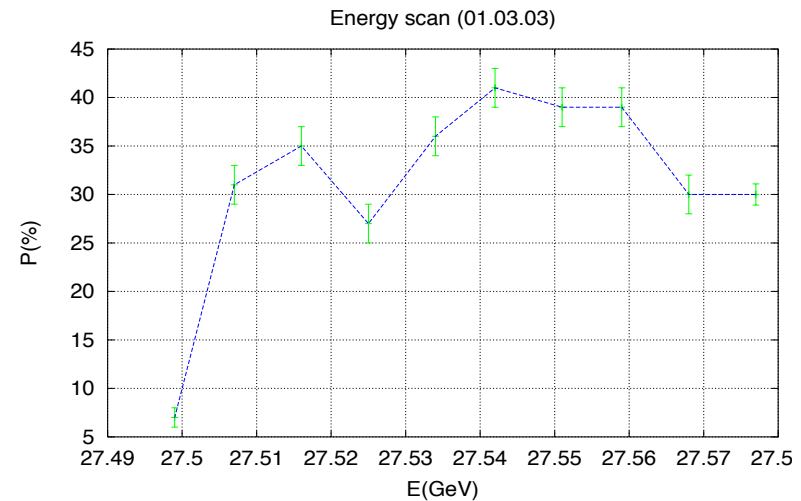
$$q_x=0.1 \quad q_y=0.2$$

- Same order resonances are not equally strong
- Beam energy not exactly known

→ **Beam energy scan** allows finding best spot for polarization.



1991 very first energy scan

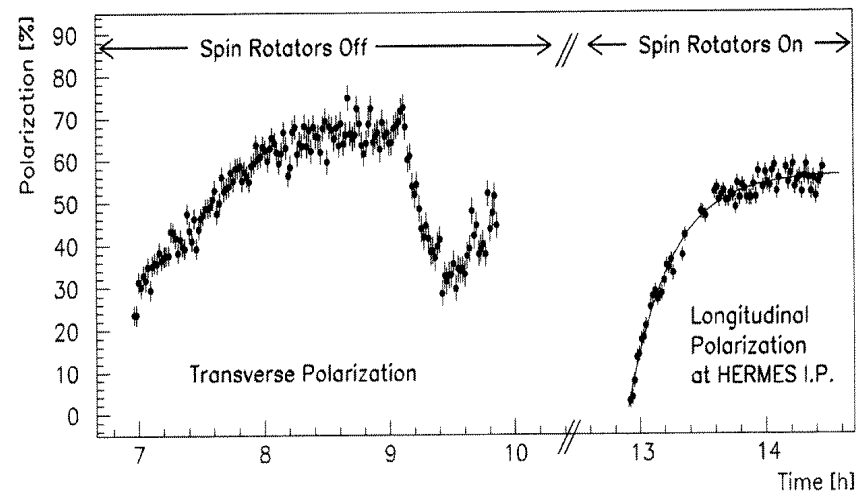


A 2003 scan with 3 rotators pairs

## HERAe polarization milestones

- November 1991: first observation of **transverse** electron beam polarization,  **$\simeq 10\%$** , at 26.66 GeV w/o dedicated optimizations.
- 1992:  **$\simeq 18\%$**  after some magnet re-alignments.
- June 1992: **60%** after **dedicated machine tuning**.
  - Installation of a spin rotator pair around IP East for HERMES.

- May 4, 1994: **Rotators turned on**, polarization reached **65%** after some re-tuning!



First time achievement of longitudinal polarization in a high energy storage ring!



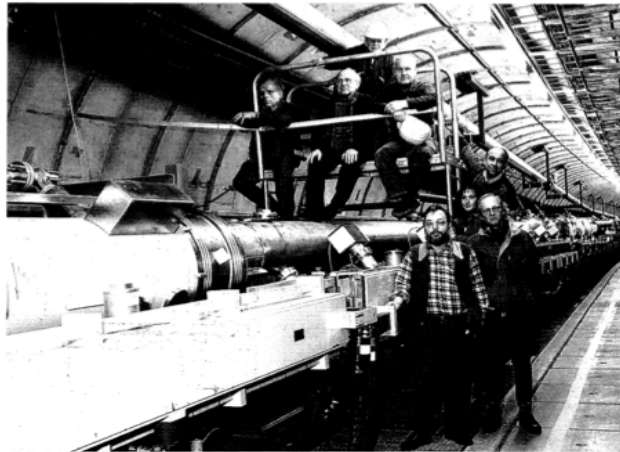
## DESY TELEGRAMM

vom Mai 1994

HERA ist einmalig !

# Nouvelles des Laboratoires

L'équipe du rotateur de spin au collisionneur électron-proton HERA de DESY. Les aimants rotateurs de spin spéciaux pour l'anneau d'électrons sont visibles sur la droite.



## DESY Succès de la polarisation longitudinale des électrons

Le 4 mai l'anneau d'électrons de 6,3 km du collisionneur électron-proton HERA à DESY, Hambourg, a maintenu en circulation un faisceau d'électrons longitudinalement polarisés c'est-à-dire dont les électrons individuels, comparables à de petites toupies, avaient leurs spins alignés sur la direction de leur mouvement et de même sens ou de sens contraire.

La polarisation longitudinale de ces électrons rend l'asymétrie gauche-droite inhérente aux interactions faibles plus faciles à observer et ouvre la porte à de nouvelles mesures de précision.

C'est la première fois qu'un tel faisceau d'électrons de haute énergie a été produit: normalement les faisceaux d'électrons sont polarisés transversalement, c'est-à-dire avec leurs

spins orientés perpendiculairement à la direction du mouvement.

Des aimants rotateurs de spin spéciaux sont utilisés pour ces manipulations; ils ont été installés dans l'anneau HERA l'hiver dernier après avoir été mis au point sous la direction du regretté Klaus Steffen en collaboration avec Jean Buon de Saclay.

Ces aimants communiquent une série d'impulsions horizontales et verticales qui renversent les spins mais ensemble ne produisent aucune déflexion nette de l'orbite des électrons.

De nombreux sceptiques avaient pensé que cette polarisation serait difficile sinon impossible à obtenir du fait de la sensibilité potentielle de ces exercices délicats à de petites perturbations du faisceau. La première session a produit un degré de polarisation de 55%.

Les aimants rotateurs de spin font pivoter la polarisation naturelle transversale (verticale) des électrons: dans le mouvement circulaire de ces derniers, leur spin, comme l'aiguille d'une boussole, tend à s'aligner sur le champ magnétique de l'anneau de stockage. Cependant même cette polarisation naturelle est à la merci des résonances dépolarisantes qui ont tendance à

déranger les spins. La disponibilité d'électrons polarisés longitudinalement est comme un lever de rideau pour l'expérience HERMES (décembre 1993, page 19) utilisant une cible interne dans le faisceau d'électrons d'HERA pour étudier le rôle du spin du quark dans celui des nucléons. HERMES doit commencer à saisir des données l'an prochain.

Des aimants rotateurs de spin supplémentaires seront installés dans le faisceau d'électrons d'HERA de sorte que les grandes expériences ZEUS et H1 pourront aussi bénéficier de la polarisation.

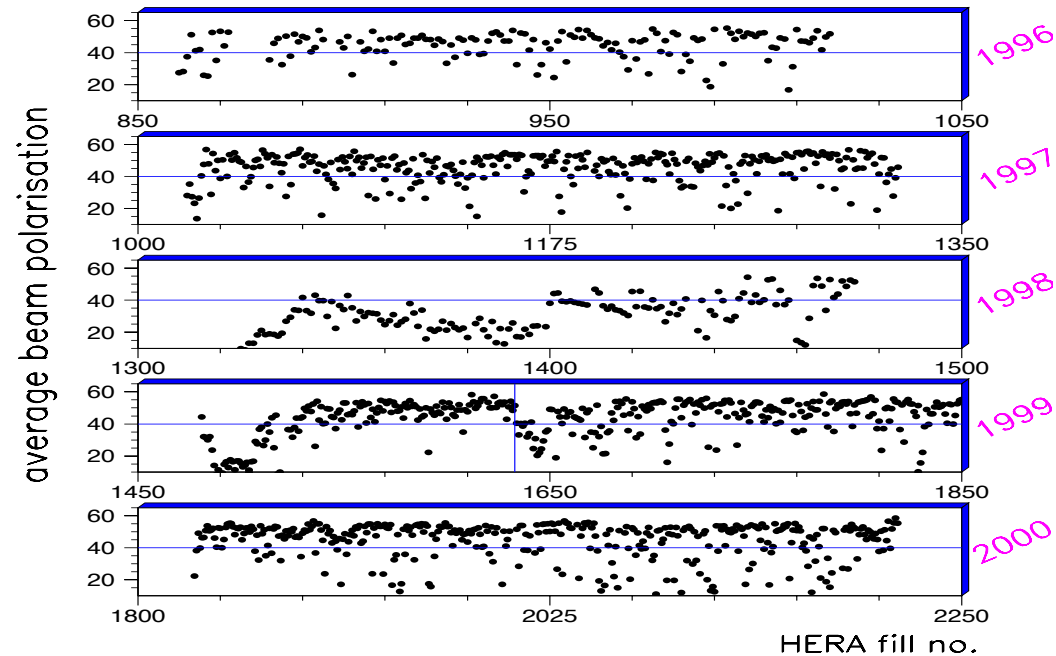
## Noyaux magiques Etain-100 étincelant

De même que le tableau périodique des éléments chimiques reflète le remplissage des couches successives d'électrons orbitaux, les nombres dits magiques de la physique nucléaire correspondent à des couches fermées de 2, 8, 20, 28, 50, 82, 126, ... neutrons et/ou protons. Plus fortement liés que les autres noyaux, ils sont les analogues nucléaires des gaz inertes. Les noyaux "doublement magiques" possèdent des couches fermées de neutrons aussi bien que de protons. Les exemples présents dans la nature sont l'hélium-4 (2 protons et 2 neutrons), l'oxygène-16 (8 et 8), le calcium-40 (20 et 20) et le calcium-48 (20 et 28). L'étain radioactif-132 (50+82) a été largement étudié.

Dans cette liste les noyaux "recherchés" comprennent l'oxygène 28 (8 et 20), le nickel 78 (28 et 50) et l'étain-100 (50 et 50). Ce dernier vient d'être observé dans des études sur ions lourds au laboratoire français GANIL, Caen, et au laboratoire allemand GSI, Darmstadt. Bien que ces observations confirment comme prévu la stabilité de l'étain-100, il faudra attendre de disposer d'intensités plus élevées pour en étudier réellement les propriétés physiques.

C'est le laboratoire Bévalac à Berkeley qui a lancé la production de noyaux exotiques par fragmentation de

After delivering high longitudinal polarization in routine operation



(E. Aschenauer courtesy)

2 more pairs of spin rotators installed for H1 and ZEUS during the 2000/2001 shut down for the machine luminosity upgrade, while the compensating solenoids were removed because of lack of space!

# February 2003: First polarization with 3 rotators pairs!

Wed Feb 26 12:00 2003  
Polarisation [%]

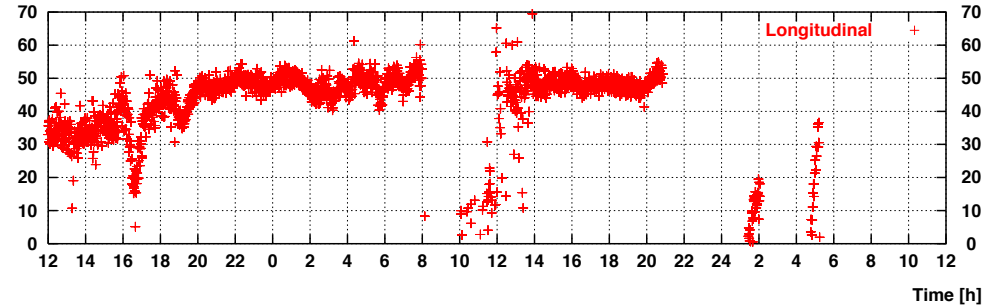
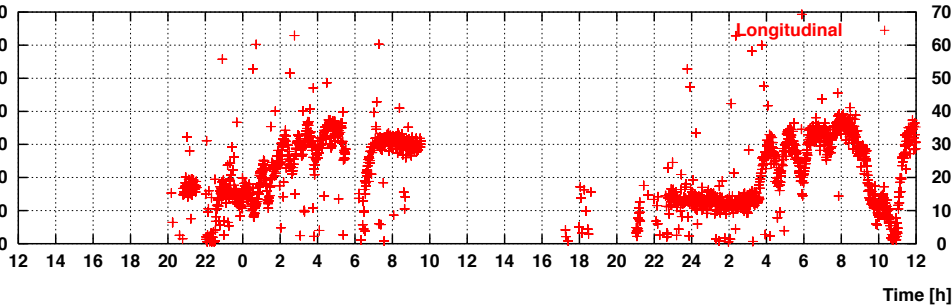
HERA-e Polarisation

Fri Feb 28 12:00 2003

Sat Mar 01 12:00 2003  
Polarisation [%]

HERA-e Polarisation

Mon Mar 03 12:00 2003



<- tuning  
(solenoids off) ->

<- tuning  
(solenoids on) ->

<-further optimisations-> <-luminosity->

Achieved peak polarization in 2004:



## DESY TELEGRAMM

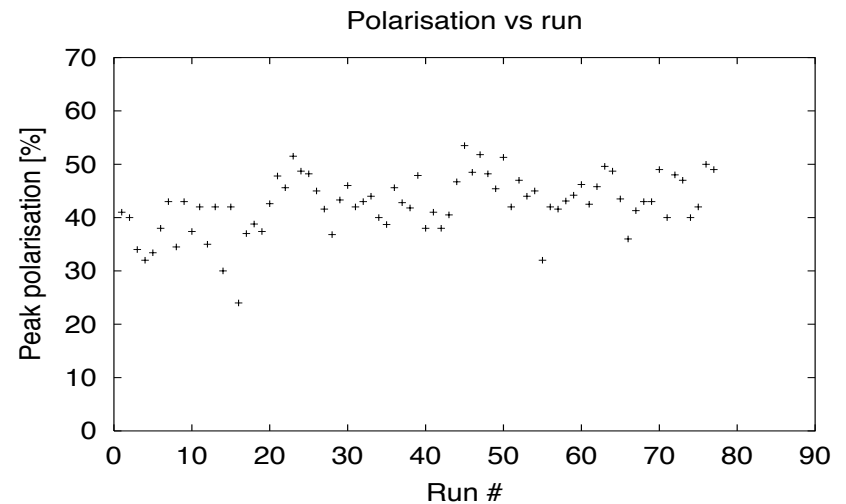
vom 3. März 2003

**Alle drei HERA-Rotatoren in Betrieb: 50% Polarisation!**

Großer Erfolg für HERA II kurz vor Beginn des Shutdowns

**All Three HERA Rotators Running: 50% Polarization!**

Great success for HERA II shortly before shutdown



Finding a trade-off between luminosity and polarization wasn't easy!



Figure1: Bryan Montague's cartoon from the 1980 Spin Symposium in Lausanne

- Extra non-linear lens ( $\rightarrow$  tune shift and spread)
- Emittance increase
- Stochastic kicks

## Summary

We have reviewed the milestones of Radiative Polarization in storage rings:

- Prediction by Sokolov-Ternov (1963), after 1961 Korovina et al. paper.
- Very first observations at ACO (1968) and VEPP-2 by exploiting loss rate dependence on polarization.
  - Large polarization was observed at low energy, w/o special corrections.
  - In PETRA at 15 GeV dedicated orbit correction was successfully experimented.
- Use of beam polarization for precise energy calibration at VEPP-2M, DORIS II, LEP1.
- The unique experience of the HERA  $p/e^\pm$  collider where longitudinal lepton beam polarization was an integral part of the physics program.
  - Now the adventure continues in the US with the EIC design pursued by BNL and JLab!

THANKS!

BACK UP SLIDES

Polarization measurement exploited the spin dependence of Coulomb scattering cross-section.

The counting rate  $\dot{n}$  is proportional to the square of the current, to the inverse of the volume of the bunch ( $V = \Delta X \times \Delta Z \times \Delta \ell$ ) and to the cross section for Coulomb scattering within the bunch, integrated over the acceptance of the system :

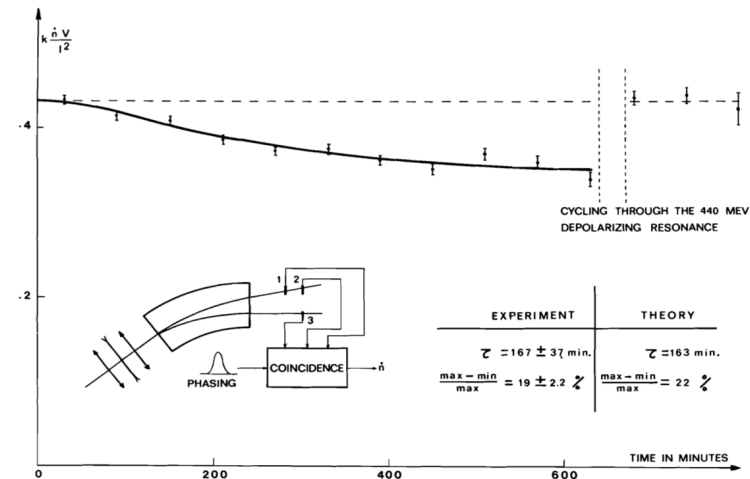
$$\dot{n} = k \frac{I^2}{\Delta X \times \Delta Z \times \Delta \ell} \times \sigma$$

If polarization occurs the normalized counting rate  $Y$

$$Y = \dot{n} \frac{\Delta X \Delta Z \Delta \ell}{I^2}$$

should exhibit a typical variation with time of the form :

$$Y = a - b \left(1 - e^{-t/\tau}\right)^2 .$$



536 MeV positrons

## More about $\delta\hat{n}_0$ correction

Writing explicitly  $\mathbf{F}$  and assuming for simplicity that there are no solenoids or skew quadrupoles:

$$\begin{pmatrix} \mathbf{F}\vec{z}_1 \\ \mathbf{F}\vec{z}_2 \\ \mathbf{F}\vec{z}_3 \end{pmatrix} = \begin{pmatrix} a\gamma[\frac{x'}{\rho_y} + \frac{y'}{\rho_x}] - (1+a)\frac{e}{p}\Delta B_s \\ (1+a\gamma)[(\frac{1}{\rho_y^2} - g)y - \frac{e}{p}\Delta B_x] \\ -(1+a\gamma)[(\frac{1}{\rho_x^2} + g)x + \frac{e}{p}\Delta B_y] \end{pmatrix} = \begin{pmatrix} a\gamma[\frac{x'}{\rho_y} + \frac{y'}{\rho_x}] \\ -(1+a\gamma)y'' \\ (1+a\gamma)x'' \end{pmatrix}$$

The  $2 \times 3$  matrix  $\mathbf{L}$  contains the components of the *periodic* spin basis:

$$\mathbf{L} = \begin{pmatrix} \ell_s & \ell_x & \ell_y \\ -m_s & -m_x & -m_y \end{pmatrix}$$

Therefore

$$\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = \begin{pmatrix} a\gamma\ell_s[x'/\rho_y + y'/\rho_x] + (1+a\gamma)[- \ell_x y'' + \ell_y x''] \\ -a\gamma m_s[x'/\rho_y + y'/\rho_x] + (1+a\gamma)[m_x y'' - m_y x''] \end{pmatrix}$$

$\delta\hat{n}_0$  is known if the horizontal and vertical closed orbit are known.

For establishing a relationship with R. Schmidt for PETRA expressions we shall neglect the small terms  $y'/\rho_x$  and  $x'/\rho_y$ , use the non-periodic spin basis and assume the ring is nominally planar ( $\ell_y = m_y=0$ )

$$\alpha - i\beta = -i \frac{1 + a\gamma}{2 \sin \pi \nu_s} e^{-i\pi \nu_s} \int_{s-C}^s ds' (-\ell_x^0 y'' + i m_x^0 y'')$$

As the spin basis components advance only in the bending magnets while  $y''$  changes only at the quadrupoles, one can chop the integral in a sum

$$\alpha - i\beta = -i \frac{1 + a\gamma}{2 \sin \pi \nu_s} e^{-i\pi \nu_s} \sum_{j=1}^N [\sin(\nu_s \phi_j^b) \Delta y'_j + i \cos(\nu_s \phi_j^b) \Delta y'_j]$$

$\phi_j^b \equiv$  cumulative bending angle at  $s_j$ .

Expanding  $y'$  in a Fourier series with  $\phi_j^b$  as parameter, one finds that the important harmonics are those close to  $\nu_s$ .

In practice, it seems difficult to extract such harmonics from the BPMs readings. However, at LEP those harmonics were extracted from the BPMs reading and a “deterministic” correction applied.

## Rotator spin matching

A flat machine is *spin transparent*. The presence of rotators breaks the transparency:

- $\hat{n}_0 \neq \hat{y}$  between rotator pairs leads to spin diffusion in the involved quadrupoles;
- vertical dispersion introduced by vertical bending magnets or by solenoids (through coupling) leads to a finite vertical beam dimension  $\leadsto$  spin diffusion in the quadrupoles of the *whole* ring.

Spin transparency for *linear* spin/orbit motion may be recovered by *spin matching*.

It consists in designing the focusing structure so that the spin direction does not depend on the particle orbital coordinates.

For the HERAe mini-rotator with

- $D_y \neq 0$  only at the rotators
- $\hat{n}_0$  non vertical only between the rotator pair

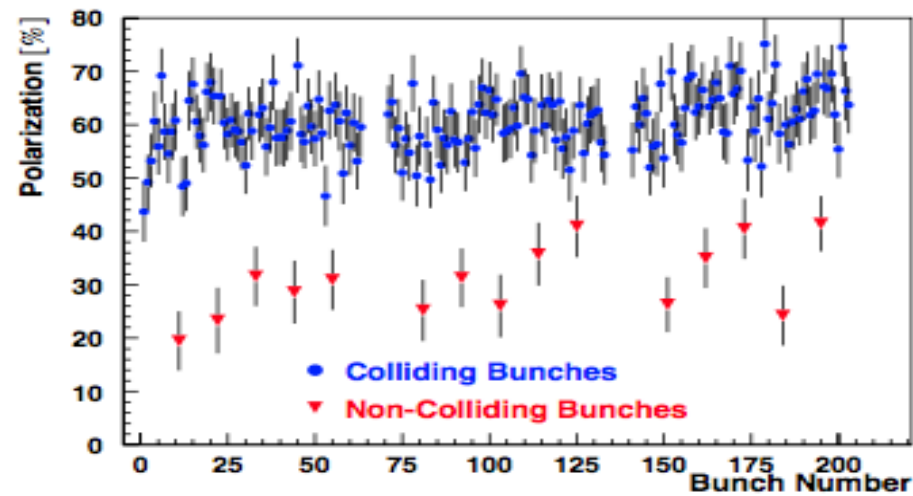
for symmetric focusing around IP (before upgrade) and arc center  $\leadsto$  5 additional optics conditions .

## Reliability: sharpen your weapons!

- Limited polarization tuning possibility during luminosity operation: keeping (vertical) closed orbit below 1 mm rms value w/o affecting the luminosity  $\leadsto$  “lumicor”.
- Meticulous book keeping
  - record of golden orbit;
  - tracking of beam energy changes due to different horizontal corrector settings;
  - run-to-run tracking of harmonic bump settings;
  - analysis of harmonic content of changed vertical corrector settings.

## Beam-beam effects on HERAe Polarization

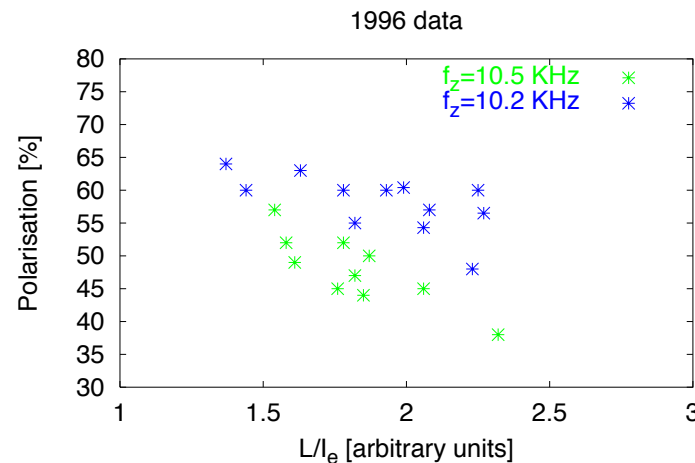
- Extra non-linear lens ( $\rightarrow$  tune shift and spread)
- Emittance increase
- Stochastic kicks



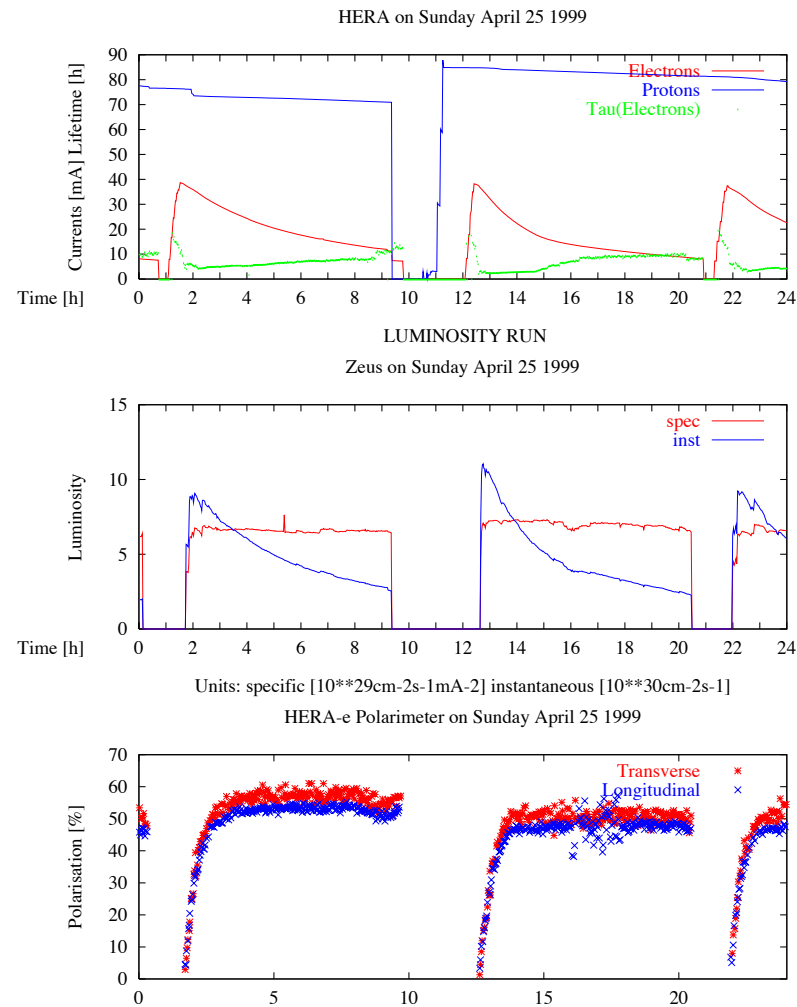
1996: First hints of beam-beam effects on HERAe polarization when

- $\beta_z^p = 0.7 \text{ m} \rightarrow 0.5 \text{ m}$
- $I_p \simeq 70 \text{ mA}$ .

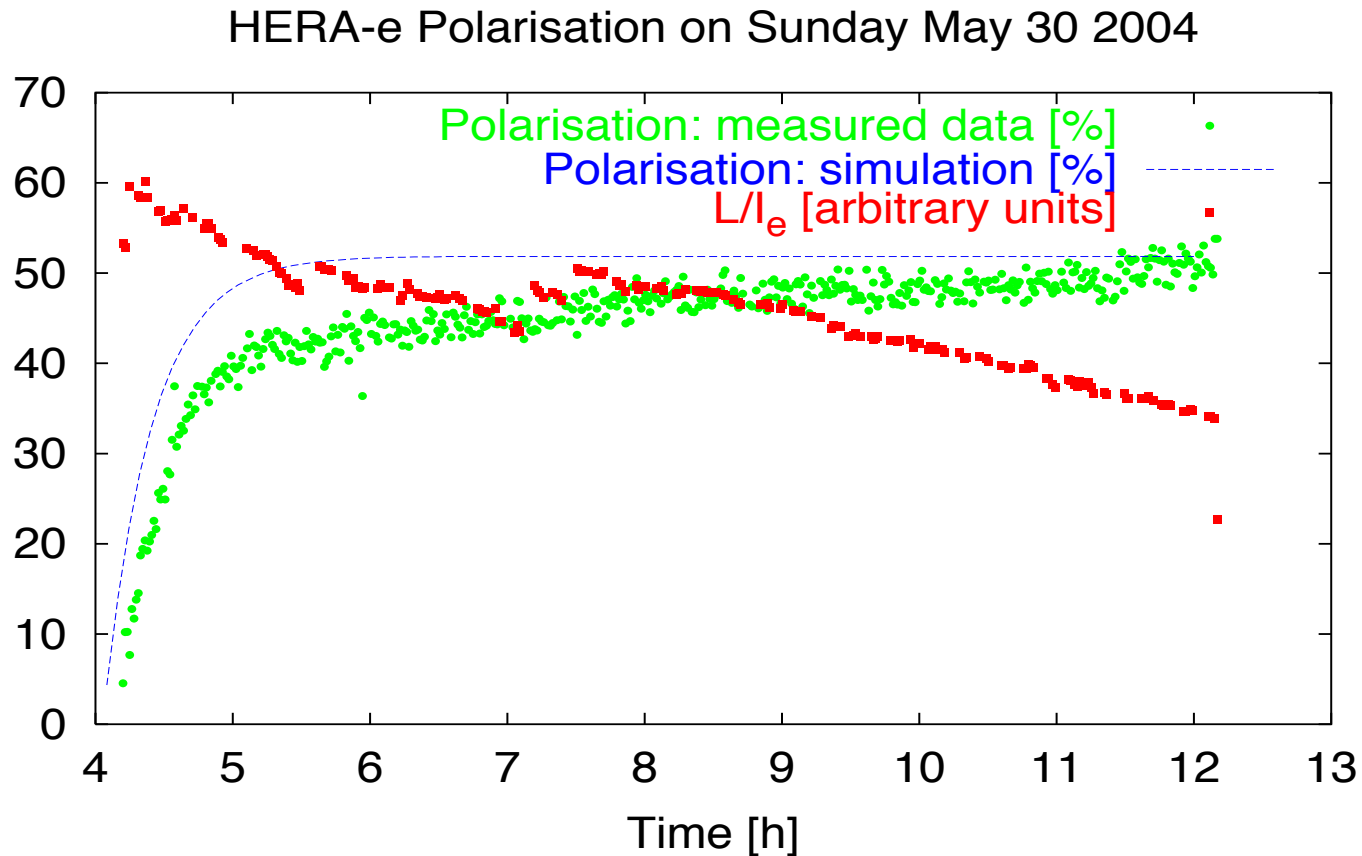
A  $Q_y$  change by  $-6 \times 10^{-3}$  allowed to recover polarization!



Larger the luminosity, smaller the polarization!



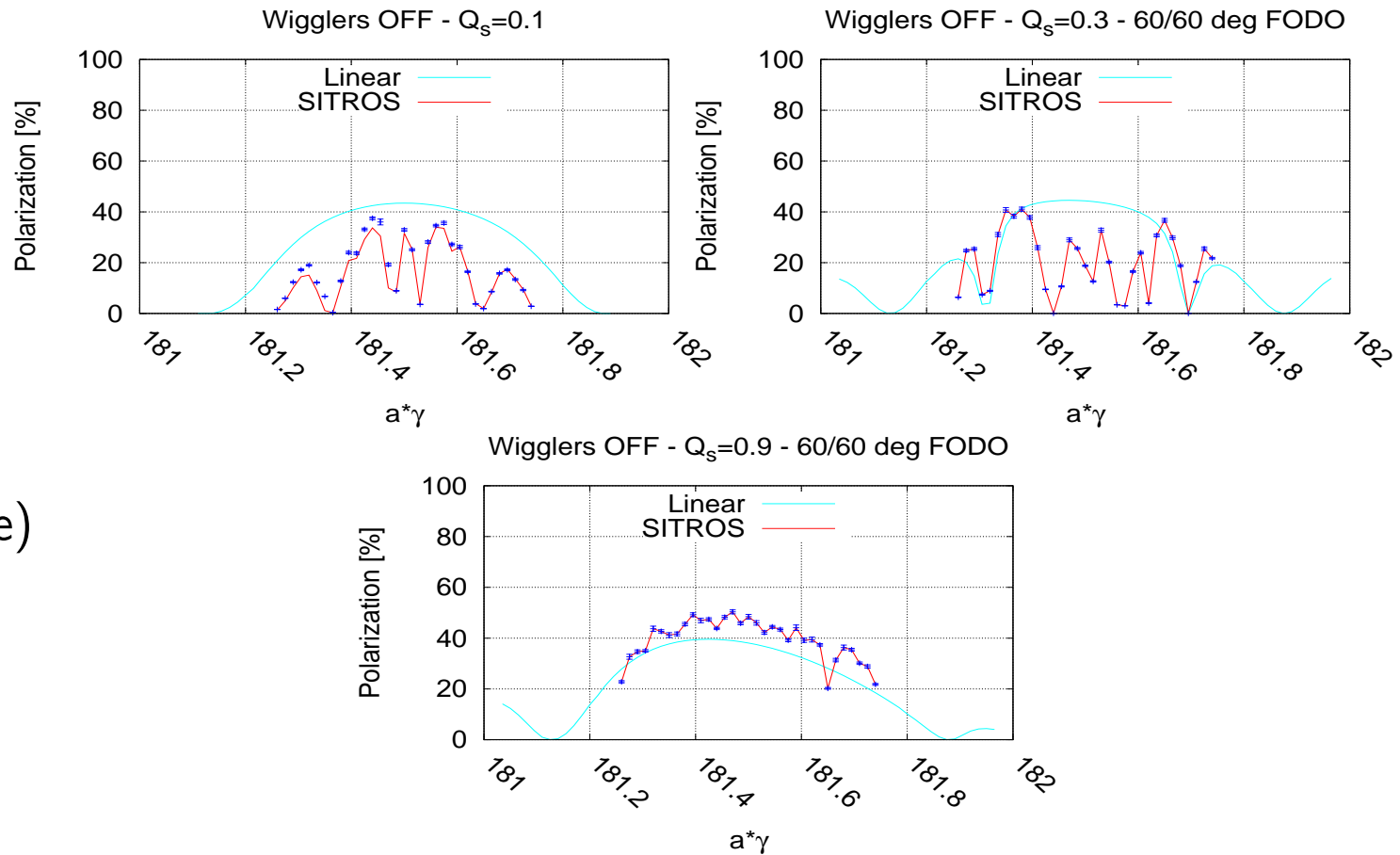
Hints of beam-beam effect on polarization: polarization grows more slowly than expected from Sokolov-Ternov effect:



# Importance of synchrotron tune

Energy spread enhancement of synchrotron side bands

$$\xi = \left( \frac{a\gamma}{Q_s} \frac{\sigma_E}{E} \right)^2$$



## Rotator spin matching

A flat machine is *spin transparent*. The presence of rotators breaks the transparency.

- Vertical dispersion introduced by vertical bending magnets or by solenoids (through coupling) leads to a finite vertical beam dimension  $\leadsto$  spin diffusion in the whole ring quadrupoles
- $\hat{n}_0 \neq \hat{y}$  between rotator pairs leads to spin diffusion in the involved quadrupoles

Spin transparency may be recovered by *spin matching*: it consists in designing the focusing structure (quadrupoles) so that globally the spin direction does not depend on the orbital coordinates.

$G_{2 \times 6}$  matrix relating spin orientation wrt  $\hat{n}_0$  to the 6 orbital coordinates

$$\begin{pmatrix} \Delta\alpha \\ \Delta\beta \end{pmatrix} = G \vec{y}$$

In a flat machine:

$$G_x \equiv \underline{0} \quad G_s \equiv \underline{0} \quad G_y \neq \underline{0} \quad \text{but} \quad y = 0$$

With rotators

$$y \neq 0$$

and

$G_x$  and  $G_s \neq 0$  between rotator pairs

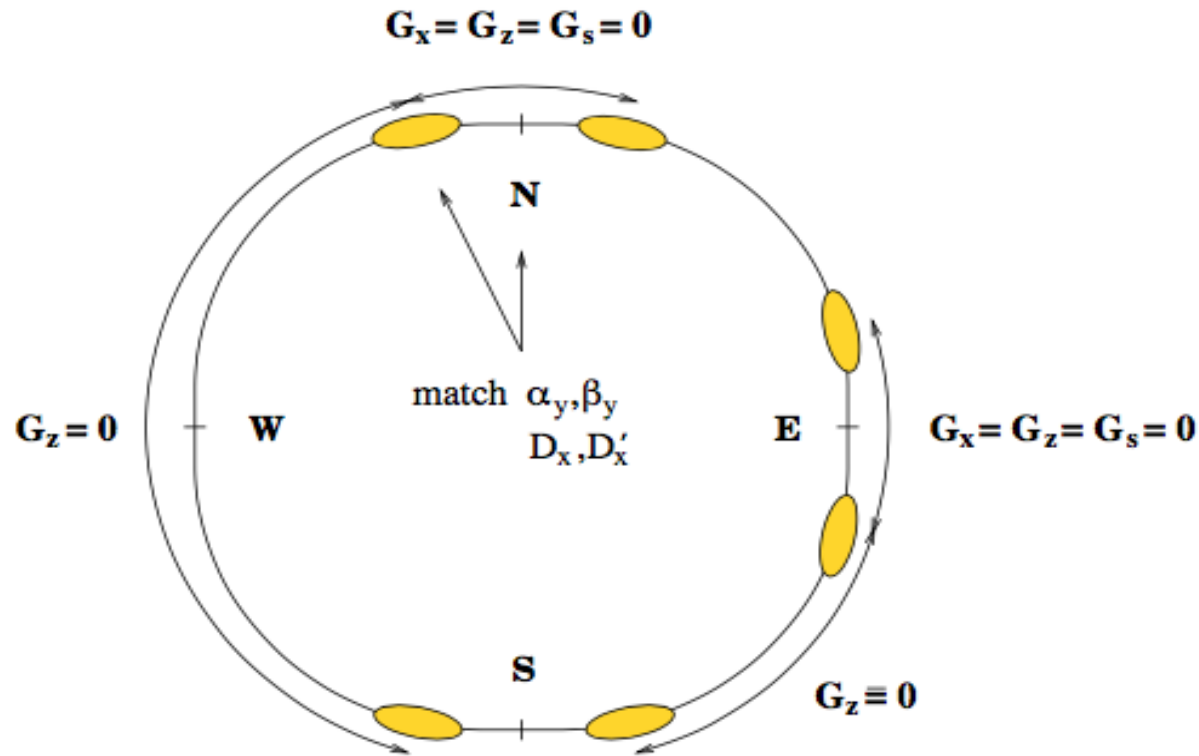


Figure 6.7: Spin matching conditions in the HERA upgrade lattice. The shaded ellipses represent the rotators.

(from M. Berglund PhD Thesis)

In terms of Twiss functions the conditions for spin transparency are

$$\Delta_{\pm x} = \Delta_{\pm y} = \Delta_{\pm s} = 0$$

$$\Delta_{\pm x, \pm y}(s) = (a\gamma + 1) \frac{e^{\mp i\mu_{x,y}}}{e^{2i\pi(\nu \pm Q_{x,y})} - 1} \frac{[-D \pm i(\alpha D + \beta D')]_{x,z}}{\sqrt{\beta_{x,y}}} J_{\pm x, \pm y}(s)$$

$$\Delta_{\pm s} = (a\gamma + 1) \frac{e^{\pm i\mu_s}}{e^{2i\pi(\nu \pm Q_s)} - 1} J_s$$

with

$$J_{\pm x, \pm y} = \int_s^{s+L} ds' (\hat{m}_0 + i\hat{l}_0) \cdot \begin{Bmatrix} \hat{y} \sqrt{\beta_x} \\ \hat{x} \sqrt{\beta_y} \end{Bmatrix} K e^{\pm i\mu_{x,y}}$$

$$J_s = \int_s^{s+L} ds' (\hat{m}_0 + i\hat{l}_0) \cdot (\hat{y} D_x + \hat{x} D_y) K$$