Polarized Beams

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1. Introduction

2. Polarized ion sources
   short, no $\vec{e}$

3. Acceleration of pol. beams in circular machines

4. Buildup of polarization in storage rings

Lecture given at "Caucasian - German School and Workshop on Hadron Physics"
Tbilisi (Georgia) 30.8 - 2.9. 2004

1. Introduction

Polarization P: $P = \frac{N_{up} - N_{down}}{\text{"} + \text{"}}$ $(-1 \le P \le 1)$

(N_i = number of particles in a beam, a target etc)

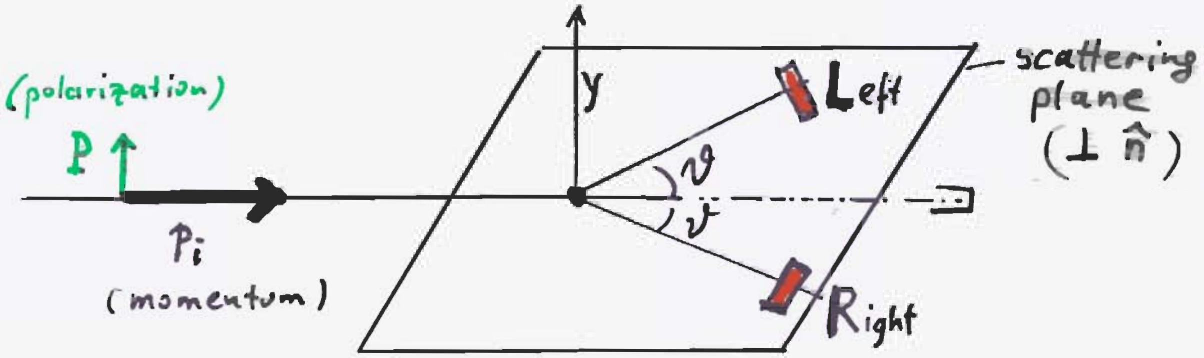
polarized

Scattering: $\vec{p} + A \rightarrow p + A$

or: $A(\vec{p}, p)A$ elastic

projectile polarized

detected, no pol. measurement



Scattering normal $\hat{n} = (\vec{p}_i \times \vec{p}_f) / |\vec{p}_i \times \vec{p}_f|$

For scattering to the Left: $\hat{n}$ up

" " " " Right: $\hat{n}$ down

LR asymmetry ε_{LR}: $$\boxed{\varepsilon = \frac{N_L - N_R}{N_L + N_R} = P_y A_y}$$

For parity-conserving forces (like strong interaction):

$$A_x = A_z = 0$$

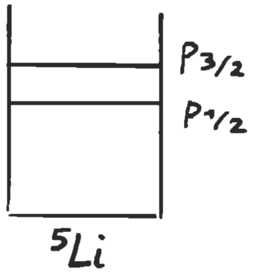
Elastic scattering, in cm system ($\vartheta_{lab} \to \vartheta_{cm}$):

Measure: 1) $A(\vec{p},p)A$ "vector analyzing power" A_y

2) $A(p,\vec{p})A$ "polarization" P'_y of outgoing proton

$\boxed{\text{TRI}: \quad P'_y = A_y}$ → method to produce and calibrate polarized proton beam by "Double Scattering": historically the 1st method.

M. Heusinkveld and G. Freier (1952): Determination of the sign of V_{ls} (in the shell model) in $p + {}^4He$ scattering!



I. First method to produce a polarized beam by

- a scattering process (not used anymore)

or - a reaction:

Parity not conserved in weak decays!

↷ $\pi^\pm \xrightarrow{\text{in flight}} \vec{\mu}^\pm\ (+\nu)$ (e.g. $E \simeq 100$ GeV)

Scattering exp. with HE pol. muons at CERN: COMPASS

↷ $\Lambda^0, \bar{\Lambda}^0 \xrightarrow{\text{in flight}} \vec{p}\,\pi^-, \ \vec{\bar{p}}\,\pi^+$

Exp. E 704 at Fermilab

ultra HE pol. nucleon beams (and antinucleon) disadvantage of polarized (tertiary) beams:

- low intensity
- pol. not switchable

2nd method:

II. Standard method for producing a polarized beam:

<u>Source for pol. ions</u> plus <u>accelerator</u>

(+ electrons, not discussed) — must conserve polarization to a high degree!

3rd method:

III. Production of polarization in a stored beam of <u>ions</u> or <u>electrons</u>

<u>ions</u>: spin filtering — polarized $\bar{p}$'s; lecture by F. Rathmann

<u>electrons</u>: Sokolov-Ternov effect — HERA-$\vec{e}$ ring (HERMES)

2. Sources of Polarized Protons

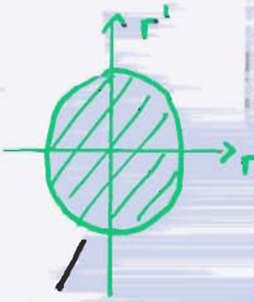
- Type of source related to accelerator

- Most efficient accel. for high energies: Synchrotron

  Modern synchrotrons also used as exp. storage ring:
  "storage ring accelerator"

  e.g. COSY RHIC* HERA* Tevatron* LEP/LHC*

  *) colliders



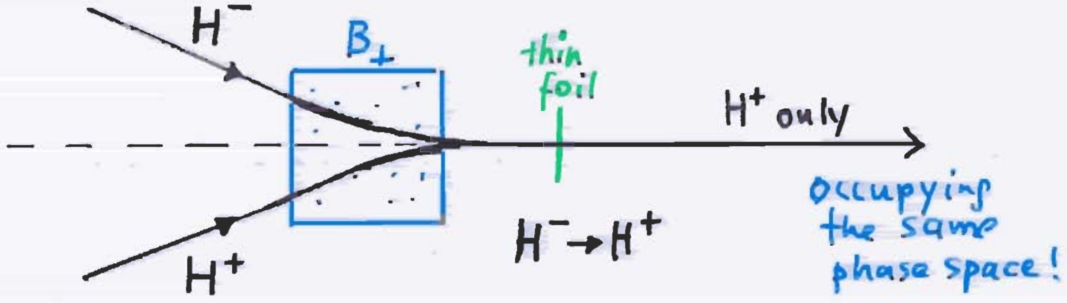
$\pi \cdot A =$

$= \pi \; r_{max} \cdot r'_{ma}$

[mm · mrad]

- Task: to fill the available phase space to the "space charge limit"!

- Best method: Stripping injection

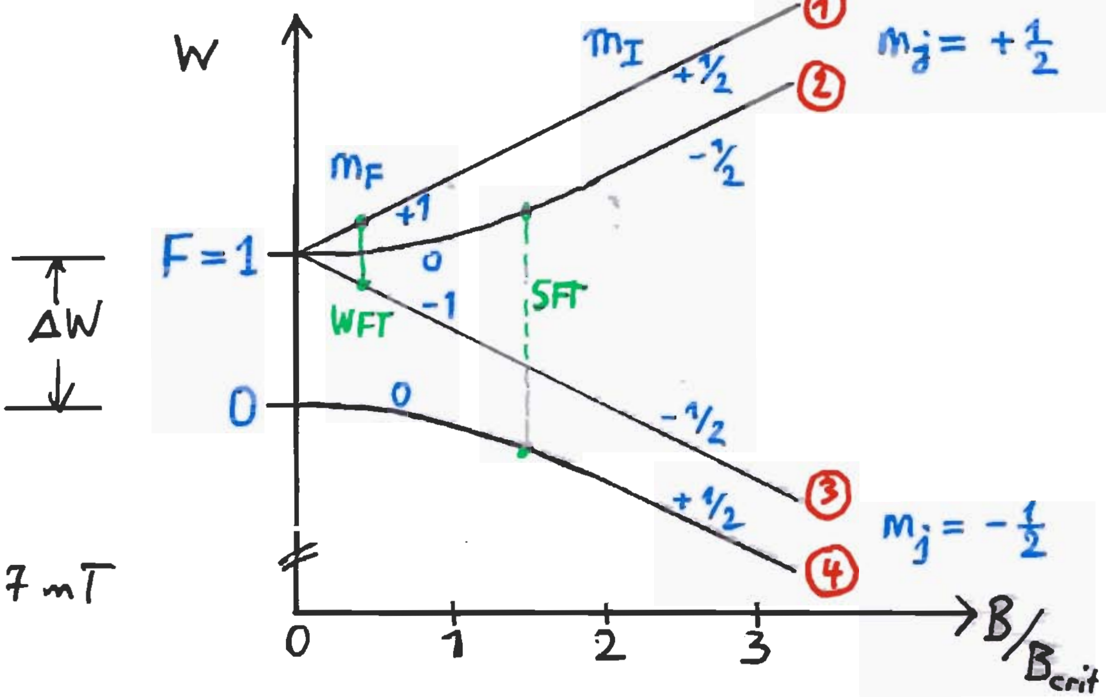


("violation" of Liouville theorem!)

→ **Requirement: intense $\vec{H}^-$ sources**

First step: Atomic Beam Source (ABS)

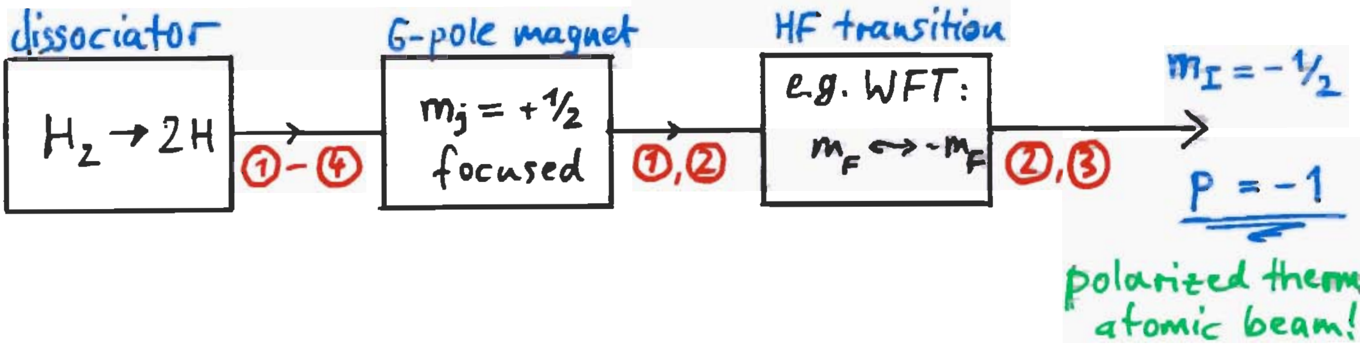
Hyperfine structure of the Hydrogen atom:



$\frac{\Delta W}{h} = 1420\,\text{MHz}$

$B_{crit} = 50.7\,\text{mT}$

ABS:

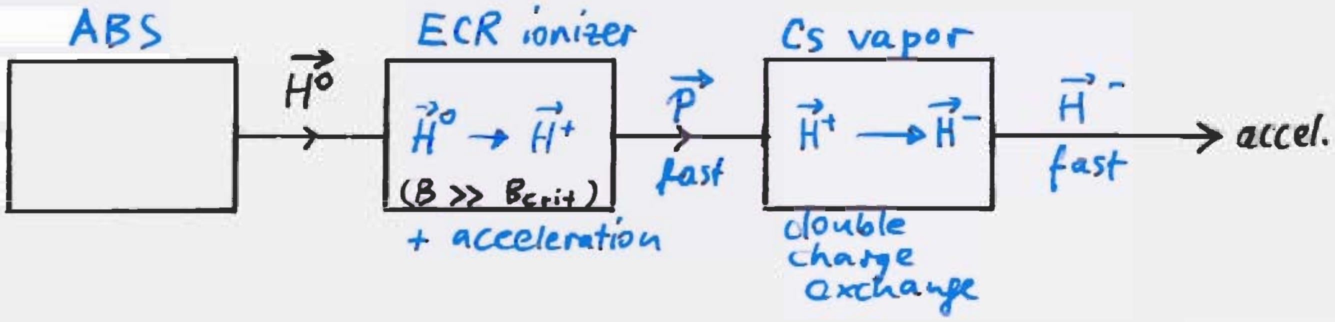


Modern sources:

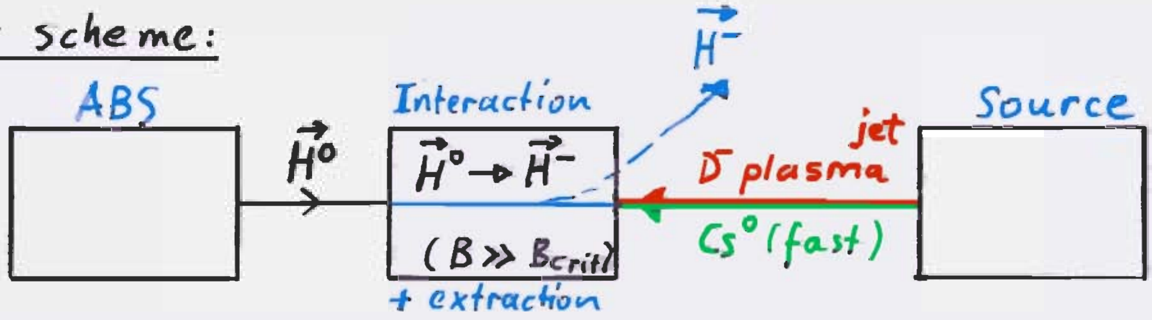
- dissociator with cooled nozzle (100K)
- high-speed pumping system (turbomolec. pumps)
- Sextupole magnets with high tip field
  e.g. permanent magnets: $B_0 > 1.5\,\text{T}$
- HF transitions with 100% efficiency

Ionizer

From thermal pol. atoms ($\vec{H}^0$) to ions ($\vec{H}^-$):



Other scheme:



→ Colliding beam source

- Fast Cs^0 beam : COSY / FZ Jülich
- Slow D^- plasma jet : IUCF / Indiana
  (pulsed)

Other schemes based on optical pumping with pulsed high-power lasers (OPPIS)

- TRIUMF / Vancouver
- RHIC injector / BNL

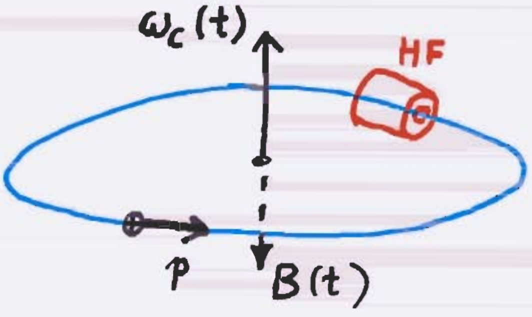
Peak currents in the mA range!

3. Acceleration of Polarized Protons in a Circular Machine: Synchrotron

- Protons on circular orbit with R = const. and homogeneous B-Field $B(t)$

$$\boxed{\vec{\omega}_{cycl.} = -\frac{q\,\vec{B}(t)}{m}}$$

with $q = +e$,
$m = \gamma\, m_0$

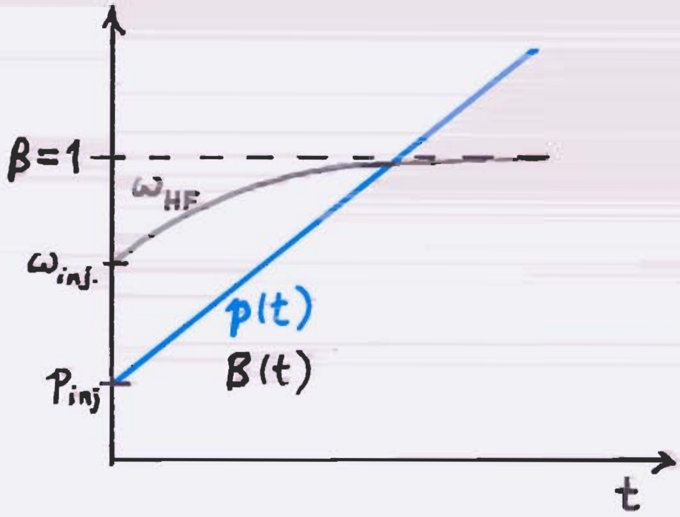


$$\boxed{|\vec{p}| = q\,B\,R}$$ (momentum)

- Synchroneous acceleration

$$\boxed{\omega_{HF} = n\,\omega_c(t)}$$

harmonic number



- Focusing elements (quadr. m.) required for stable motion near design orbit (here: circle).
  → betatron oscillations in the x (hor.) and y (vert.) direction

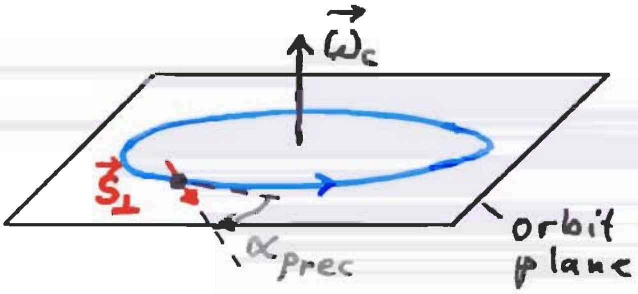
Number of betatron oscill. per turn:

$$\left|\begin{array}{ll} Q_x & \text{hor.} \\ Q_y & \text{vert.} \end{array}\right\}\text{"betatron tune"}$$

Q_x, Q_y must not be integer! Otherwise excitation of orbit resonances → beam lost!

Spin Precession on Circular Orbits

$\vec{S}_\perp$ = spin component ⊥ to $\vec{\omega}_c$ (in the orbit plane!)



$$\alpha_{prec.} = \sphericalangle\left(\underset{\text{momentum } \vec{p}}{\text{tangent}}, \vec{S}_\perp\right)$$

$$\boxed{\omega_p = |\vec{\omega}_p| = \dot{\alpha}_p = \gamma\ a\ \omega_c}$$

Lorentz factor   anomaly: $\frac{g-2}{2} = a \quad (\equiv G)$

Note: a is $\ll 1$ for true Dirac particle, like e, μ, ...
($a_{exp.} \neq 0$ explained by QED)

Reminder: Proton has spin comp. $S_z = \pm \frac{1}{2}\hbar$
and magnetic moment $\mu_z = \pm \frac{1}{2} g_p \underbrace{\frac{e\hbar}{2m_p}}_{\mu_N}$

with $g_p \simeq 5.586$ non-Dirac particle, → internal structure

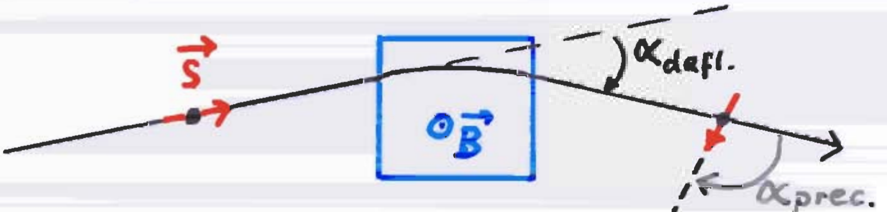
⇝ $a_p \simeq 1.793$

- Non-relativistic ($\gamma = 1$): $\boxed{\omega_{prec.} = 1.793\ \omega_{cycl.}}$

[Note: ω_p defined in a frame rotating with ω_c]

⇝ The hor. spin component $\vec{S}_\perp$ precesses 1.793 × per turn! (→ "spin tune" ν_s)

- Effect of dipole magnet:



$$\boxed{\alpha_p = 1.793 \cdot \alpha_d}$$

(spin precession on circular orbits, ctd.)

- relativistic beams: $$\boxed{\omega_p = \gamma \cdot \overset{a_p}{1.793} \cdot \omega_c}$$

$\gamma(t)$, increases during acceleration ("ramping")

spin tune $$\boxed{\nu_s = \frac{\omega_p}{\omega_c} = \gamma \cdot a_p}$$

* COSY: $\gamma_{max}(T = 2.5\,\text{GeV}) = 3.67 \rightarrow \nu_s^{max} = 6.58$

* RHIC: $\gamma_{max}(E = 250\,\text{GeV}) = 267 \rightarrow \nu_s^{max} = 479$

- Effect of dipole magnet:

$$\underline{\alpha_p = \gamma \cdot 1.793 \cdot \alpha_d = \nu_s \cdot \alpha_d}$$

At RHIC ($E_{max} = 250\,\text{GeV}$): $\alpha_p = \underline{479} \cdot \alpha_d$!

- During ramping (= acceleration phase):

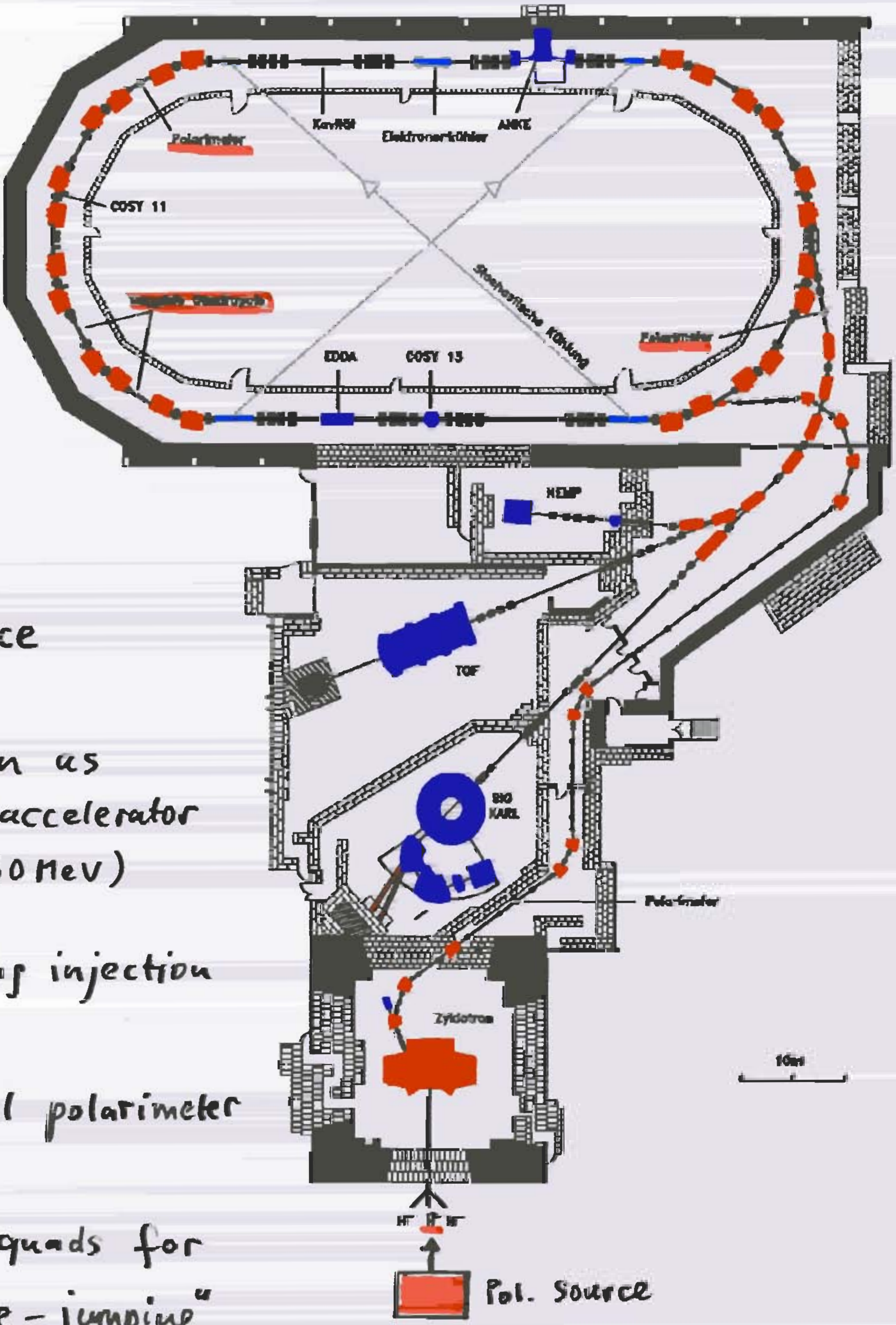
ν_s increases with time and crosses integer values!

$$\nu_s = n \in \mathbb{N} \rightarrow \text{resonant depolarization!}$$

If $\nu_s = n$, then at a certain orbit position z_0 the hor. component $\vec{S}_\perp$ has always (i.e. after 1 turn, 2 turns, ..., many turns) the same direction → kicks on $\vec{S}$ by field errors add up coherently → resonant depolarization!

$$\boxed{\nu_s = n}$$ "imperfection resonance"

Cooler Synchrotron COSY (FZ Jülich)



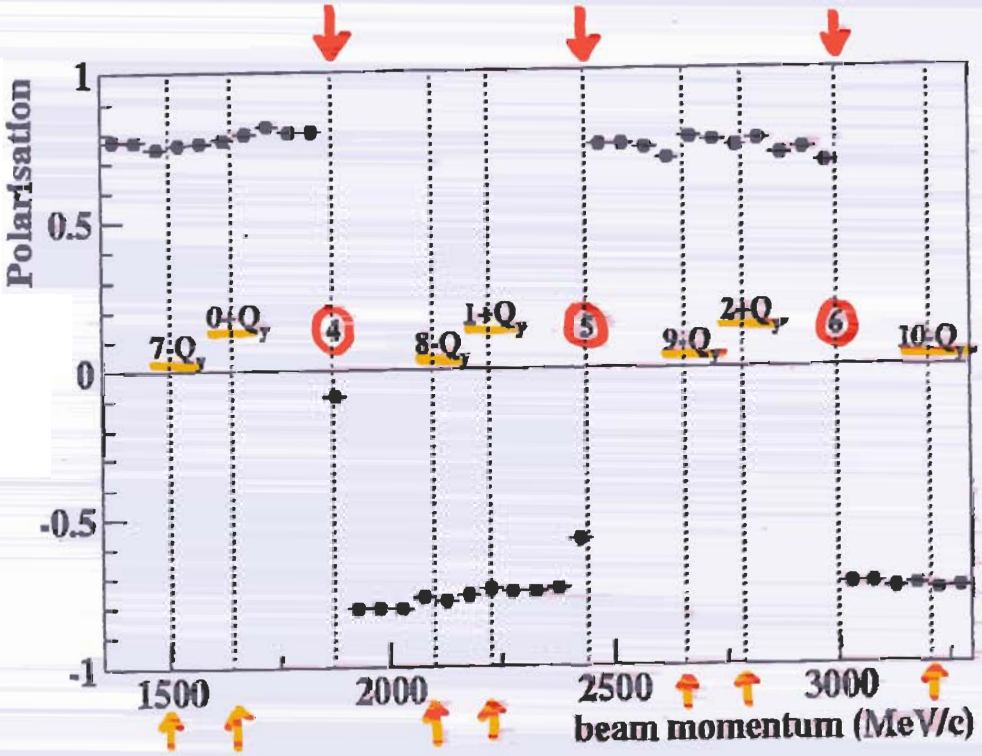
- $\vec{H}^-$ source
- Cyclotron as pre-accelerator (30 MeV)
- Stripping injection
- Internal polarimeter
- Pulsed quads for "tune-jumping" ("intrinsic resonances")

Acceleration of Polarized Protons by COSY

A. Lehrach, R. Maier, D. Prasuhn, et al.

- Imperfection resonances ($\gamma a = n$):

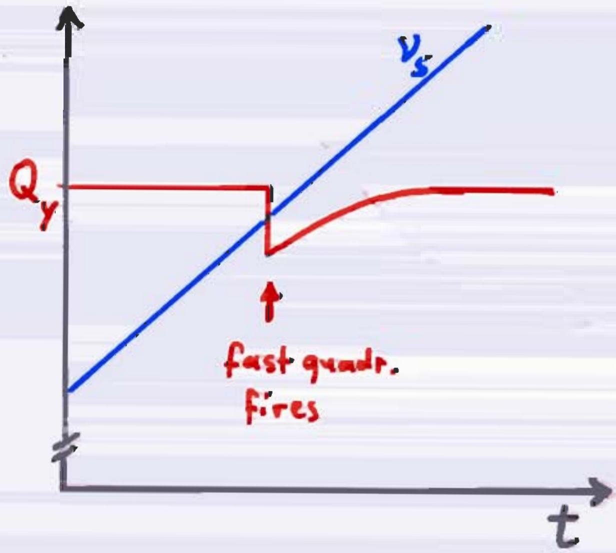
Proper spin-flip induced with enhanced resonance strength (correction dipoles).



- Intrinsic resonances (e.g. $\gamma a = Q_y$):

Fast crossing by tune-jumping:

↝ negligible polarization loss!



Example : Depolarizing Resonances in COSY

imperfection resonances

$$\gamma a = n$$

intrinsic resonances

$$\gamma a = k_1 + k_2 Q_y$$

$$Q_y^{COSY} \simeq \frac{11}{3}$$

Momentum MeV/c	Kinetic energy MeV	Imperfection resonance $\gamma \cdot G = \ldots$	Intrinsic resonance $\gamma \cdot G = \ldots \pm Q_y$	
463.9	108.4	2		
781.2	282.7		6-	$6 - Q_y$
1033.3	457.5		-1+	$-1 + Q_y$
1258.8	631.7	3		
1470.4	806.0		7-	$7 - Q_y$
1674.1	980.8		0+	Q_y
1871.3	1155.1	4		
2064.4	1329.4		8-	$8 - Q_y$
2255.0	1504.1		1+	$1 + Q_y$
2442.7	1678.4	5		
2628.5	1852.7		9-	$9 - Q_y$
2813.4	2027.5		2+	$2 + Q_y$
2996.6	2201.8	6		
3178.7	2376.0		10-	$10 - Q_y$
3360.6	2550.8		3+	$3 + Q_y$

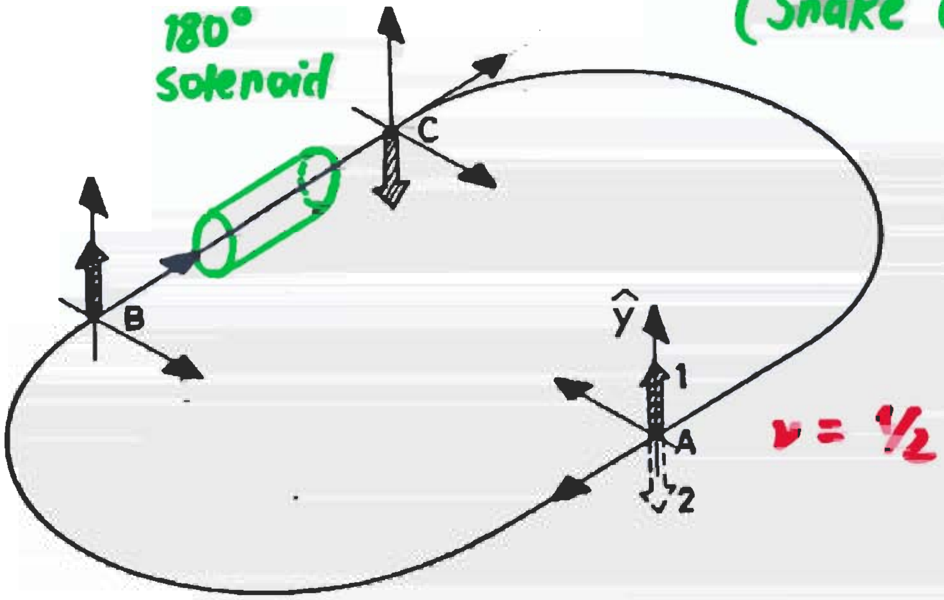
↑ same energies for all proton rings!

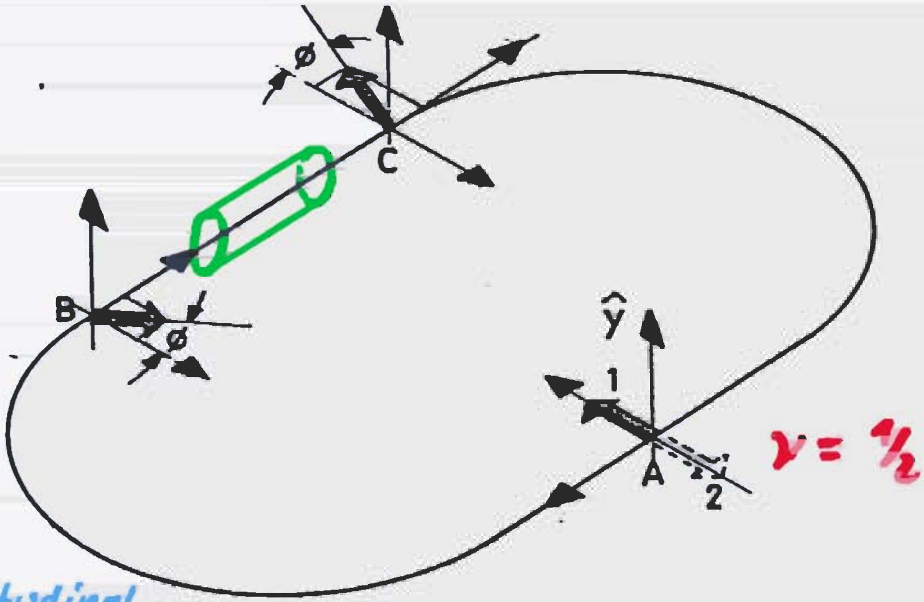
↑ depend on vertical tune, i.e. machine optics.

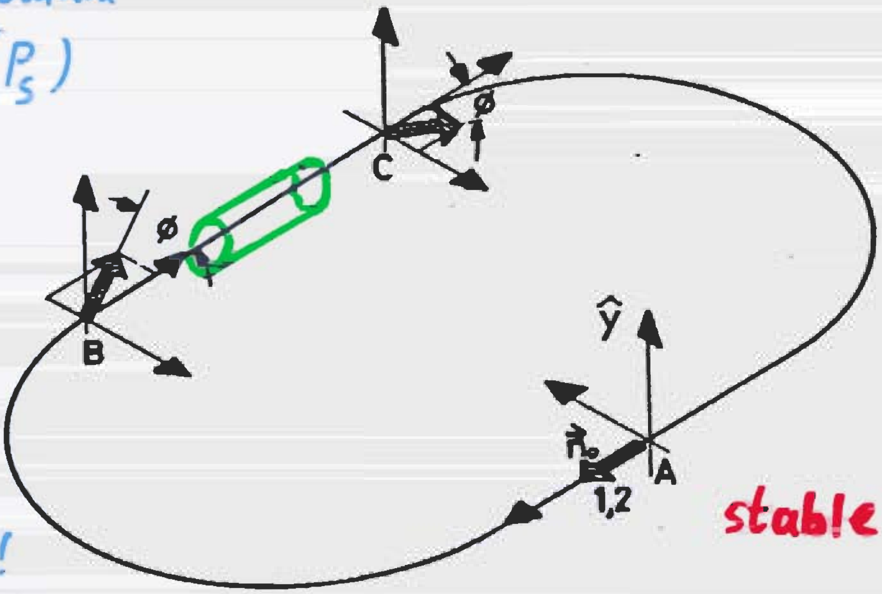
↷ six imperfection and ten intrinsic resonances in COSY !

Spin motion with 180° solenoid

(Snake of 1st Kind)







Result:

1. Stable longitudinal polarization (P_s)
2. Spin comp. transverse to $\hat{s}$ have spin tune 1/2

→ No resonant depolarization!

Siberian Snakes

Derbenev
+ Kondratenko
(1972)

Pioneering work at VEPP-4 (Novosibirsk)

- Full snake :

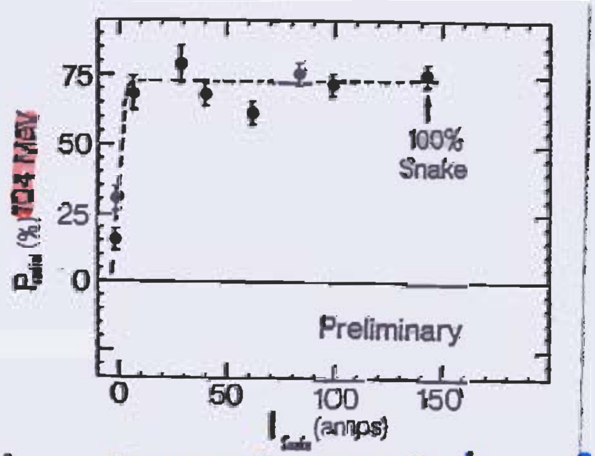
$$\boxed{\alpha_{\parallel} = 180^\circ}$$

→ low γ : solenoid
high γ : set of dipoles
(BNL : helical dipoles!)

- Partial snake: $\alpha_{\parallel} = \frac{180^\circ}{n}$ $(n = 2, 3, \ldots)$

applied at AGS / BNL (no space for full snake...)

Siberian Snakes provide a global cure of imperfection r., and (in first order) also for intrinsic resonances!

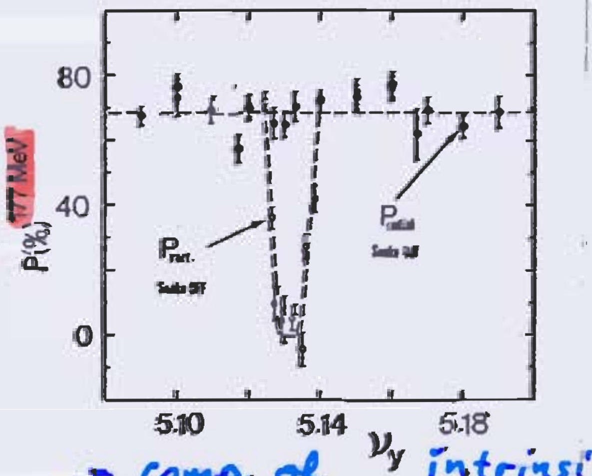


- Comp. of $\gamma a = 2$ imperfect. resonance

- Systematic studies performed at IUCF Cooler ring by A. Krisch, T. Roser, R. Pollock et al

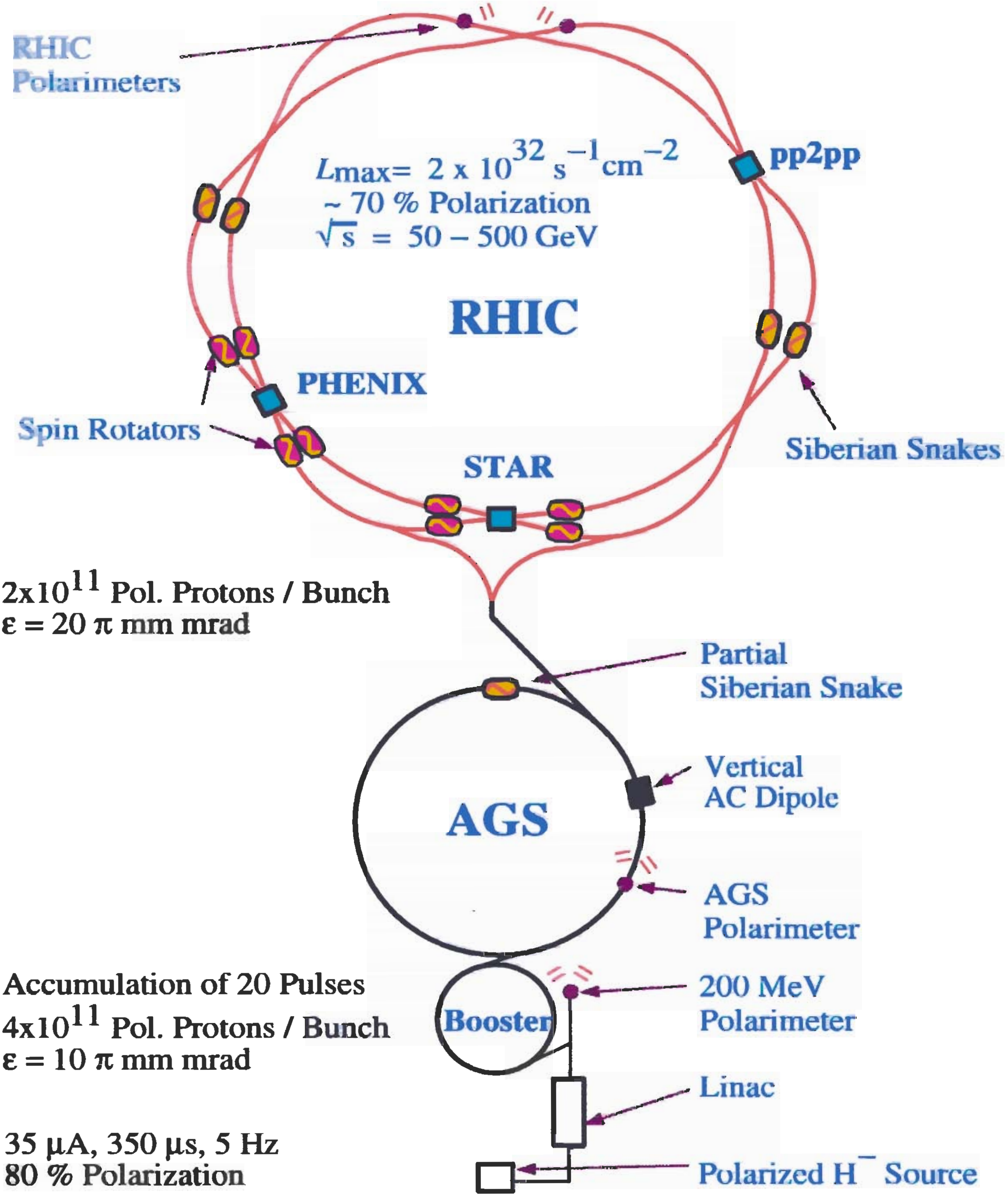
→ many new discoveries and theor. explanations; new "spin tools" developed.

- Applied at RHIC !



- comp. of intrinsic resonance $\gamma a = Q_y - 3$

Polarized Proton Collisions at BNL



RHIC Polarimeters

Lmax= 2 x 10^{32} $s^{-1}$$cm^{-2}$
~ 70 % Polarization
$\sqrt{s}$ = 50 – 500 GeV

pp2pp

RHIC

PHENIX

Spin Rotators

STAR

Siberian Snakes

$2\text{x}10^{11}$ Pol. Protons / Bunch
ε = 20 π mm mrad

Partial Siberian Snake

Vertical AC Dipole

AGS

AGS Polarimeter

Accumulation of 20 Pulses
$4\text{x}10^{11}$ Pol. Protons / Bunch
ε = 10 π mm mrad

Booster

200 MeV Polarimeter

Linac

35 µA, 350 µs, 5 Hz
80 % Polarization

Polarized H^{-} Source

4. Self-Polarization in Storage Rings

Two cases relevant for experiments:

A. Polarized stored antiprotons ($\bar{p}, \uparrow$)

$\bar{p}$s are expensive → most efficient use very important : storage ring!

B. Polarized stored electrons / positrons

stored $\vec{e}$ of high current allow to use pol. gas targets ($\vec{H}, \vec{D}$) → - pure
- high av. polarization

(A) • Several methods for $\bar{p}^{\uparrow}$ production discussed
e.g. Workshop Bodega Bay 1985
AIP Conf. Proc. 145

• Two methods were studied theor. and/or experimentally:

* "Spin Splitter": Stern-Gerlach force on $\vec{\mu}_{\bar{p}}$ by gradient fields → coherent SG kicks!

→ no experimental demonstration yet

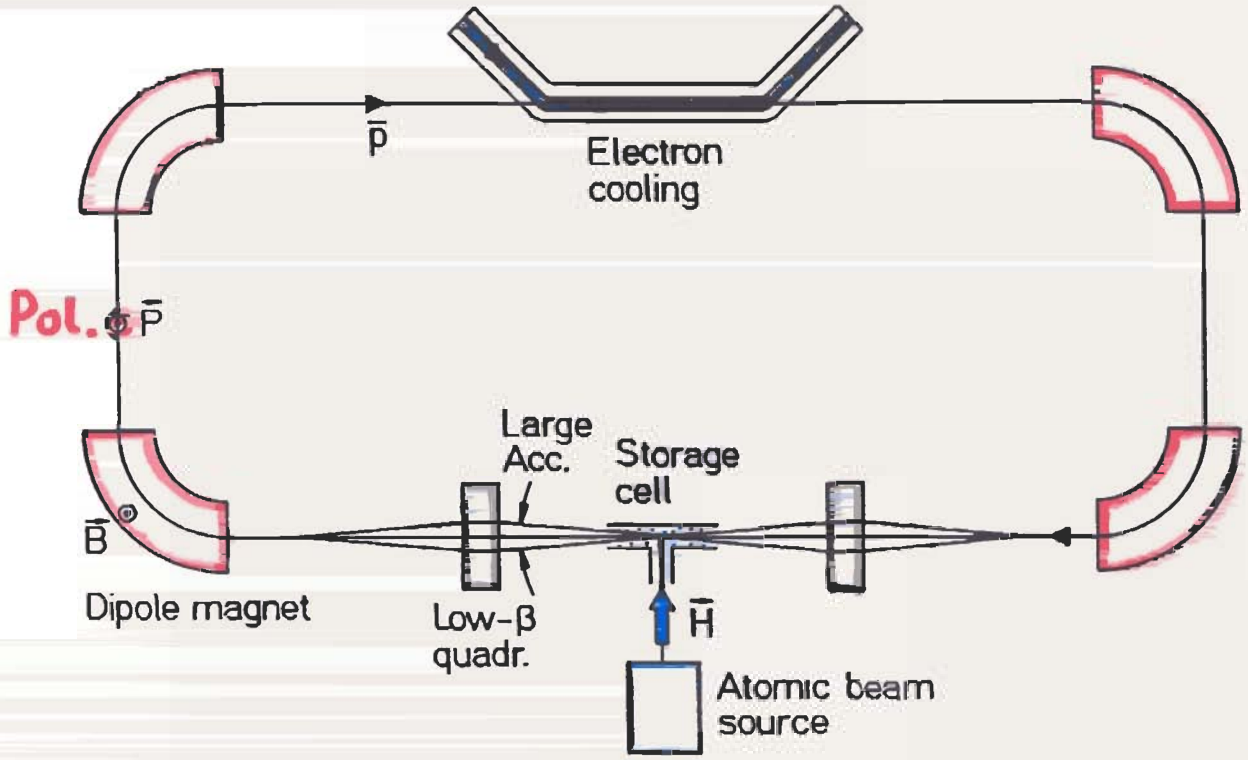
* "Spin Filter": Spin-dependent attenuation of $\bar{p}$ beam → build-up of polarization!

→ experimental demonstration with p at TSR / Heidelberg (1992)

How to polarize stored antiprotons?

Workshop Bodega Bay, 4/85 (Chamberlain, Jackson, Jeffries, Krisch, v.d. Meer, Yokosawa, ...) → Filter method is the most promising method to polarize stored antiprotons.

Csonka, NIM 63 (1968) 247; Kilian + Möhl, 2nd LEAR worksh. Erice 1982



Requirements:

- Internal $\vec{H}$ target – high density
- Large acceptance – $\theta_{acc.} \gtrsim 15$ mrad
- Continuous cooling – Ecool
- Long polarization life time – hours

Spin filter method

For P_{Beam} and P_{Target} vertical:

$$\rightarrow \quad \boxed{\sigma_{tot} = \sigma_0 + \underbrace{\sigma_1 \cdot P_B \cdot P_T}_{\text{Spin-dependent}}}$$

Assume $P_T = 1$. The unpol. $\bar{p}$ beam has 50% $\bar{p}$s with $\underbrace{m = +1/2}_{P_B = +1}$, 50% with $\underbrace{m = -1/2}_{P_B = -1}$.

$$m(\bar{p}) = +1/2 : \quad \sigma^{+}_{tot} = \sigma_0 + \sigma_1$$

$$\text{"} \quad -1/2 : \quad \sigma^{-}_{tot} = \sigma_0 - \sigma_1$$

↷ **Intensity** $I(t) \simeq e^{-t/\tau_0}$

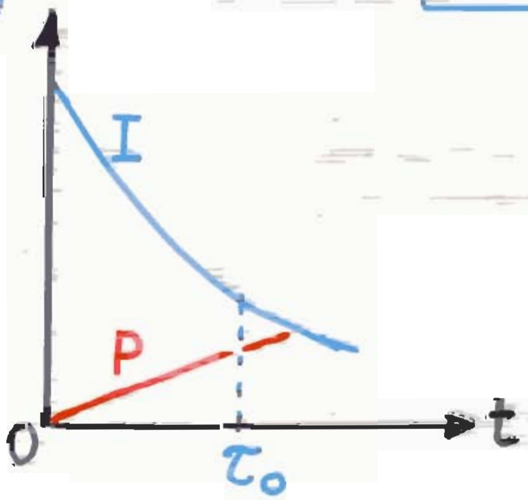
Polarization $P(t) = \tanh t/\tau_1$

Beam life time

$$\boxed{\tau_0 = \frac{1}{\sigma_0 \cdot n \cdot f_{rev}}}$$

Polarization build-up time

$$\boxed{\tau_1 = \frac{1}{\sigma_1 \cdot \underset{\text{target density}}{n} \cdot \underset{\text{revolution frequency}}{f_{rev}}}}$$

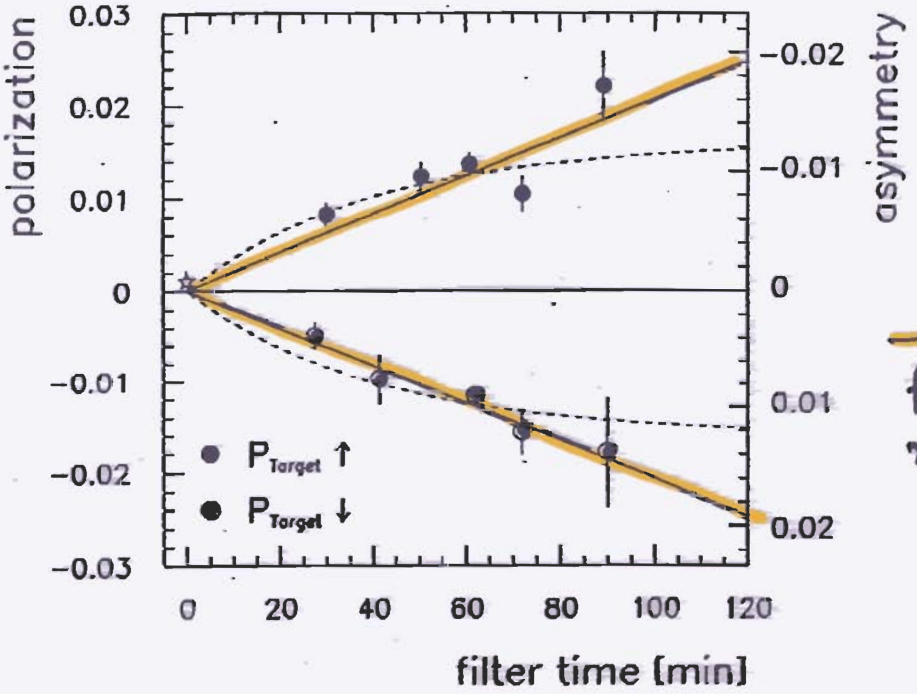


Pol. Build-Up as Function of time

F. Rathmann et al , PRL 71 (1993) 1379

Effective beam life time $\tau_{eff} = 30$ min

→ losses due to single-scattering Coulomb losses



fit with no depol.

Observed: $\dot{P}_{exp.} = 1.3\ \% / hour$

Expected: $\dot{P}_{theor.} = 2.5\ \% / hour$

from known pp-interaction

Found later (Horowitz + Meyer, PRL 72 (1994) 3981):

Destructive effect from $\vec{e}p$ interaction;
$\vec{H}$ target had high electron pol., too.

→ Effect can be employed to polarize $\bar{p}$s !

(see lecture F. Rathmann)

(B) Polarized Stored Electrons/Positrons

- Sokolov + Ternov (1964): Prediction of build-up of polarization in HE electron storage rings!
- First observations: ACO/Orsay 1968 + 71
  VEPP-2/Novosibirsk 1971

p. 417

- Qualitative arguments (J.D. Jackson, Rev. Mod. Phys. 48 (76)):
  - Deflecting field $B_\perp$ tranformed into electron rest frame : $B'_\perp = \gamma \cdot B_\perp$

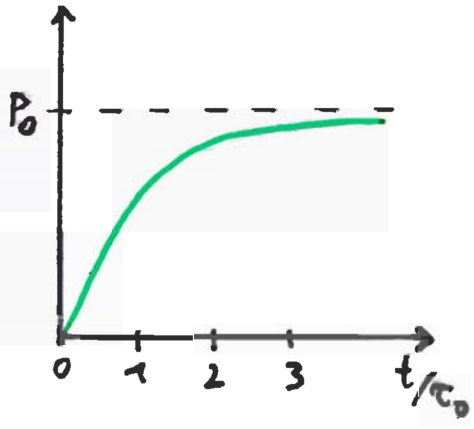
    HERA: $\left.\begin{array}{l} B_{\mathrm{Dipole}} = 0.15\ \mathrm{T} \\ \gamma = 53\,800 \end{array}\right\} \rightarrow B'_\perp \approx 8000\ \mathrm{T}$
  - State of lowest energy $B'_\perp \uparrow \uparrow \vec{\mu}_e \, \downarrow \vec{S}_e$ $(\vec{\mu} \uparrow\uparrow \vec{B})$ populated by M1-transitions:
    → slow build-up of polarization!

- Quantitive (depol. neglected):

radiative polarisation
$$\boxed{P(t) = P_0\,(1 - e^{-t/\tau})}$$

with $P_0 = \frac{8}{5\sqrt{3}} = 0.924$

$$\tau_0 = 98.7\,\mathrm{s}\ \frac{(\rho/m)^3}{(E/\mathrm{GeV})^5} \cdot \frac{R}{\rho}$$



Here: $2\pi R = C$ (circumference incl. straights)
ρ = bending radius in the dipoles

HERA: $C = 6336\ \mathrm{m} \rightarrow \left.\begin{array}{l} R = 1008\ \mathrm{m} \\ \rho = 608\ \text{"} \\ E = 27.5\ \mathrm{GeV} \end{array}\right\} \tau_0 = 39\ \mathrm{min}$

- Depolarization included → τ_{exp} and P_{max} reduced.

HERA e-p Collider

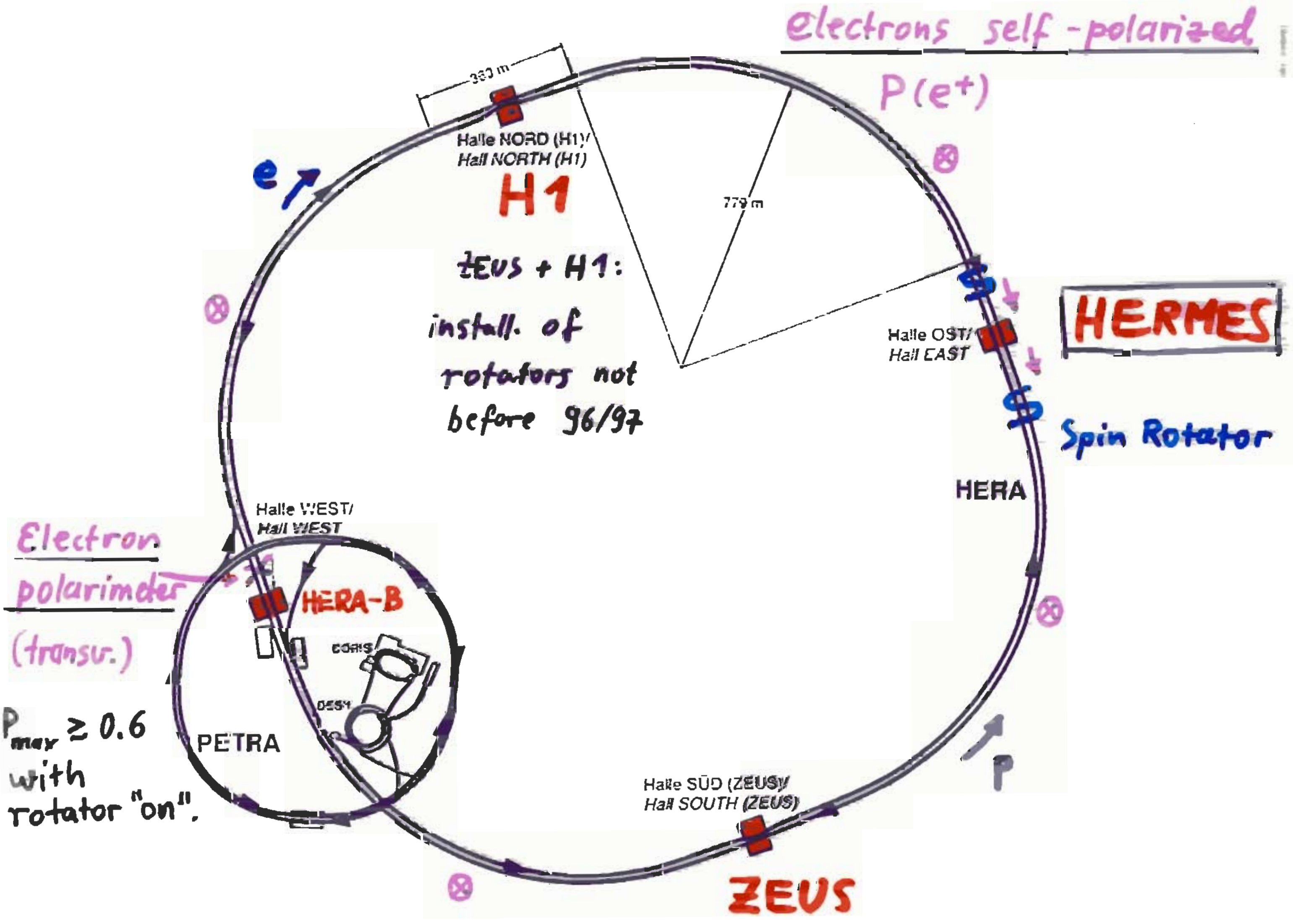
$E_e = 27.55$ GeV $\nu_s = 62.5$ $E_p = 820$ GeV

Substantial increase in E requires big investment into SC cavities!

$I_e^{design} = 58$ mA in ~210 bunches, $f_B = 10.47$ MHz ≙ 96 ns

present: $I^{max} = 40$ mA ; $\tau(e^+) \sim 6-8$ h.

$\sigma_{hor} \sim 0.3$ mm and $\sigma_{vert} \simeq 0.1$ mm at IP



ZEUS + H1: install. of rotators not before 96/97

$P_{max} \geq 0.6$ with rotator "on".

HERMES runs in parallel to ZEUS + H1: no strong interference! (Background, beam life time: $\Delta\tau_{max}^{gas} \simeq 45$ h at present)

→ high gain in int. luminosity, compared with dedicated running!

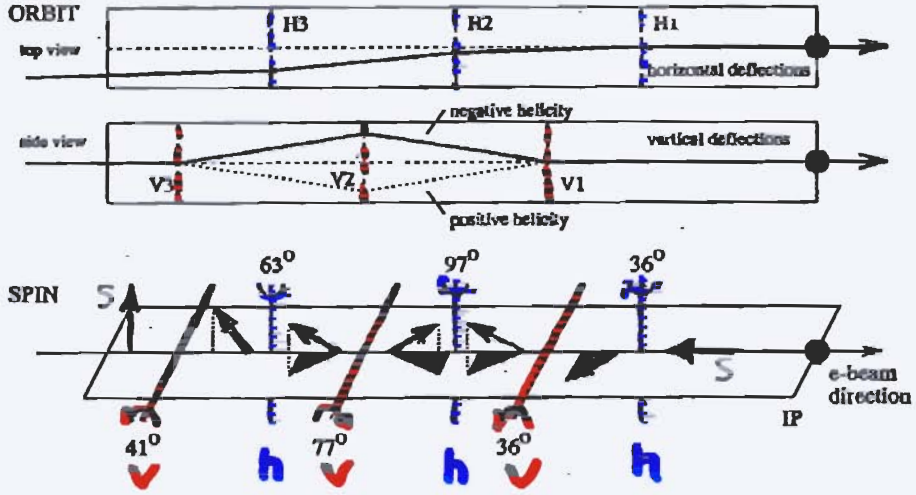
Spin Rotator

K. Steffen
J. Buon

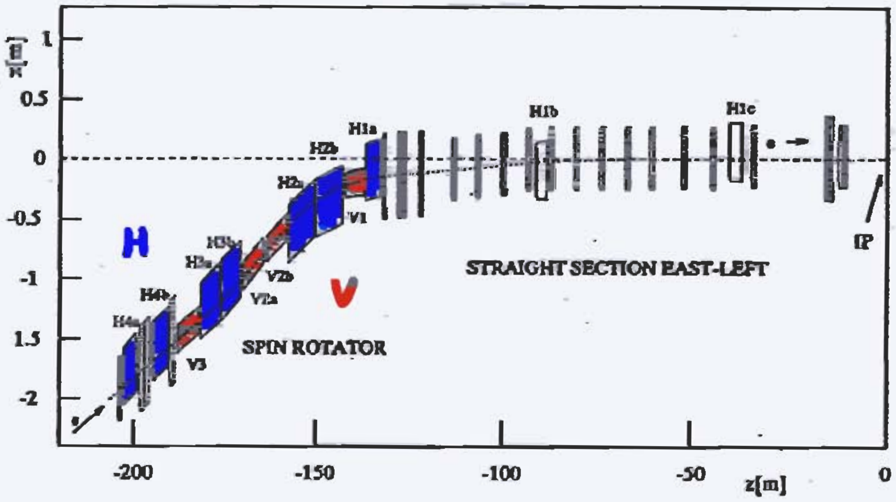
orbit deflections

- horizontal
- vertical

spin pression

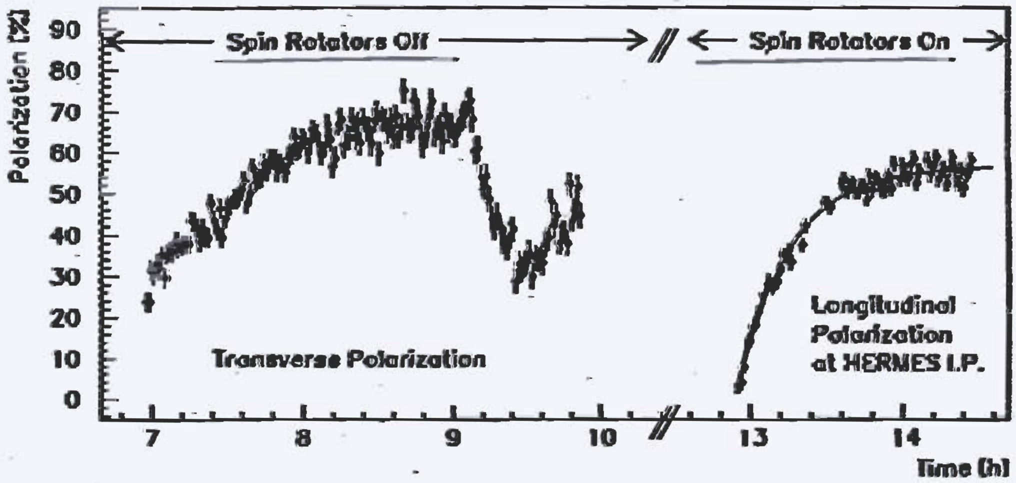


Mini-Rotators (L ≈ 80 m only)



Orbit excursions of up to ±20cm for the two spin directions ±½ : magnets are moved transv.!

First achievement of long. electron pol. in a HE electron storage ring



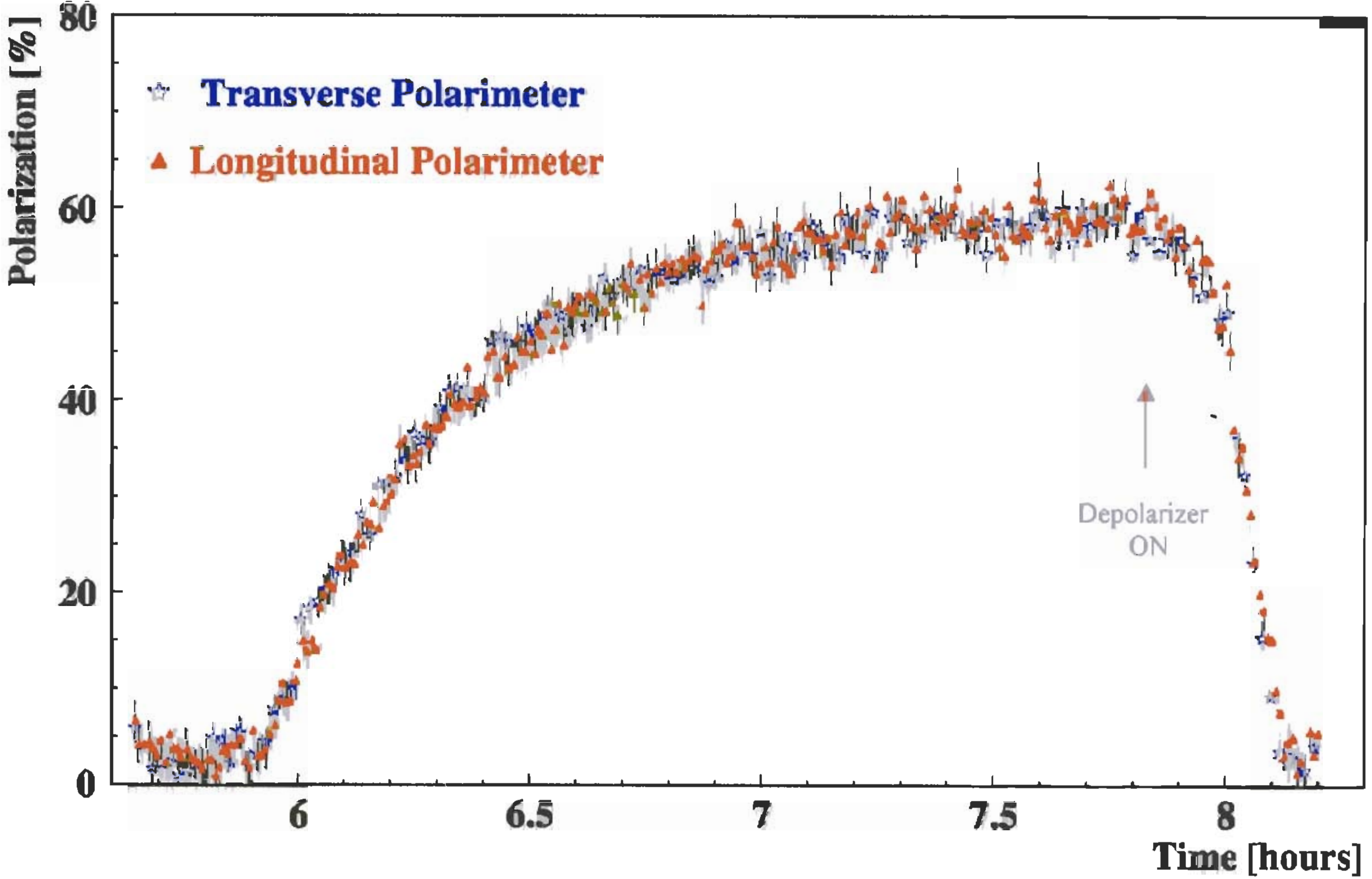
D.P. Barber et al, NIM (1994)

4.5.1994

Transverse polarization detected via backscattering of polarized laser photons (Now: TPol , LPol)

Polarization of stored 27.5GeV electrons in HERA measured by the TPol and LPol

Comparison of rise time curves



SUMMARY

- Polarized beams play important rôle in nuclear and particle physics.

- Two alternatives:
  - pol. source and acceleration of polarized ions:
    - * most flexible
    - * crossing of resonances involved! (in circular machines)
  - buildup of polarization in stored beams:
    - * less flexible (no rapid switching)
    - * avoids resonance crossing

- Several examples → powerful tools exist for next generation of hadron physics experiments!