Polarized high energy beams

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Success at RHIC is an essential step towards polarisation in HERA:

December 2001 "Injected polarisation maintained up to 100 GeV".

Contributers

DESY:

- D.P.Barber
- G. Hoffstätter
- M. Vogt

INR Troitsk:

- V. Balandin
- N. Golubeva

BINP, Novosibirsk:

- V. Ptitsin
- Yu. Shatunov

SPIN Collaboration, Ann Arbor

In contrast to electrons there is currently no convincing self–polarisation mechanism for protons! (or deuterons)

====> Obtain pre-polarised protons (deuterons) from a source and accelerate from low energy!!!

The steps:

- Polarised source.
- Accelerate to 39 GeV.
- Accelerate in HERA to high energy.
- Keep the polarisation at high energy ——**and what is the meaning of the "polarisation of a very high energy beam" anyway? ==>** the concept of the Invariant Spin Field: e.g. can have 100 percent polarisation at each point in phase space but small overall polarisation if the ISF has large divergence. See later transparency.

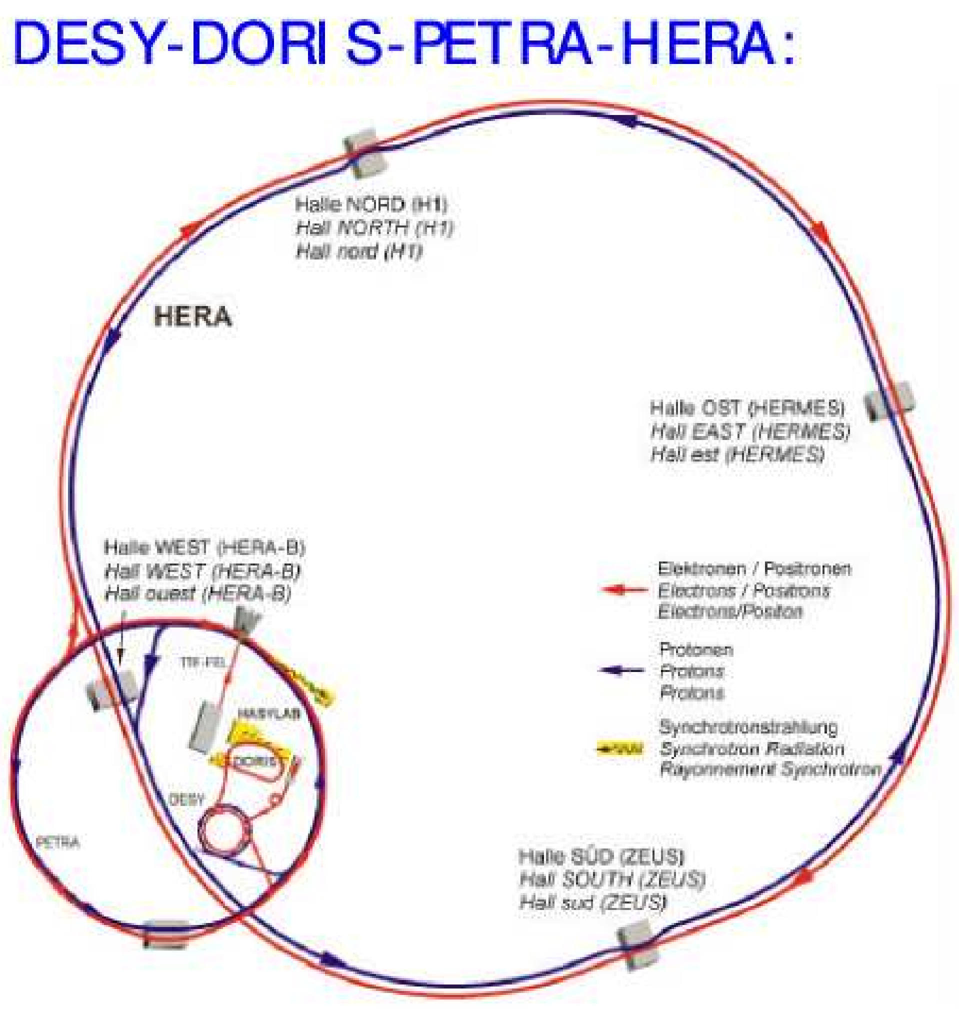
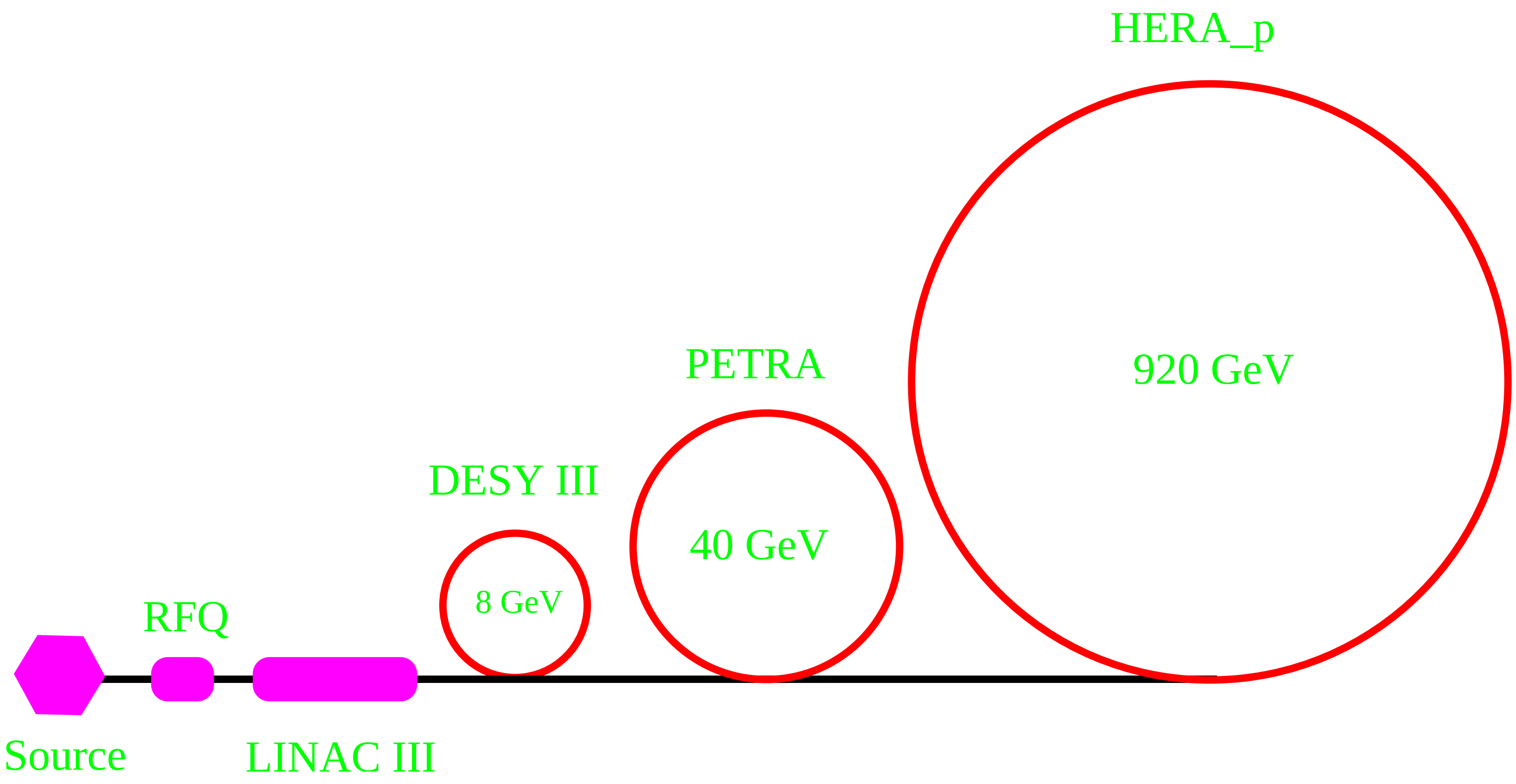


Figure 1: The DESY rings. Apologies for the low quality.

The HERA Proton Chain



Key modern concepts for spin–orbit dynamics at very high energy:

- Resonance strengths
- Invariant spin field: stationary polarisation states
- Amplitude dependent spin tune (an equivalence class!)
- Limiting polarisation
- Dynamical polarisation
- Adiabatic invariance
- Spin–orbit Hamiltonians
- Stroboscopic averaging
- Perturbative versus non-perturbative concepts
- spin matching/snake matching
- Semi–classical Foldy–Wouthuysen
- Generalized Froisart–Stora behaviour
- Field symmetries — permitted resonances
- Topology, geometry
- etc, etc, etc.

Table 1: **The quest for high energy polarised protons**

Name	Energy
ZGS	12 GeV
KEK PS	12 GeV
AGS	26 GeV
IUCF	1 GeV
Saturn II	3 GeV
PSI cycl.	0.6 GeV
TRIUMF cycl.	0.5 GeV
LAMPF	0.8 GeV
RHIC	100 GeV
COSY	3.43 GeV

Table 2: **High energy accelerators whose polarised proton capability has been analysed**

Name	Energy
FNAL Main Injector	120 GeV
FNAL Tevatron	900 GeV
LISS	20 GeV
RHIC	250 GeV
HERA	920 GeV
EPIC	32 GeV
VLHC Booster	3000 GeV

Spin motion in electric and magnetic fields:

The T-BMT spin precession equation:

$$\frac{d\vec{S}}{ds} = \vec{\Omega} \times \vec{S}$$

$\vec{S}$: spin expectation value

$\vec{\Omega}$: depends on $\vec{B}, \vec{E}, \vec{\beta}, \gamma$

In transverse magnetic fields:

$$\Omega \ \propto \ (a + 1/\gamma) \cdot B$$

$a = (g - 2)/2$ where g is the relevant g factor.

$a = 1.793...$ for protons.

$a = -0.143$ for deuterons.

($a = 0.00115...$ for electrons.)

Then:

$$\delta\theta_{spin} = a\gamma \cdot \delta\theta_{orbit}$$

- $a\gamma$ is called the **“naive spin tune”**:

- It is a natural spin frequency of the system.

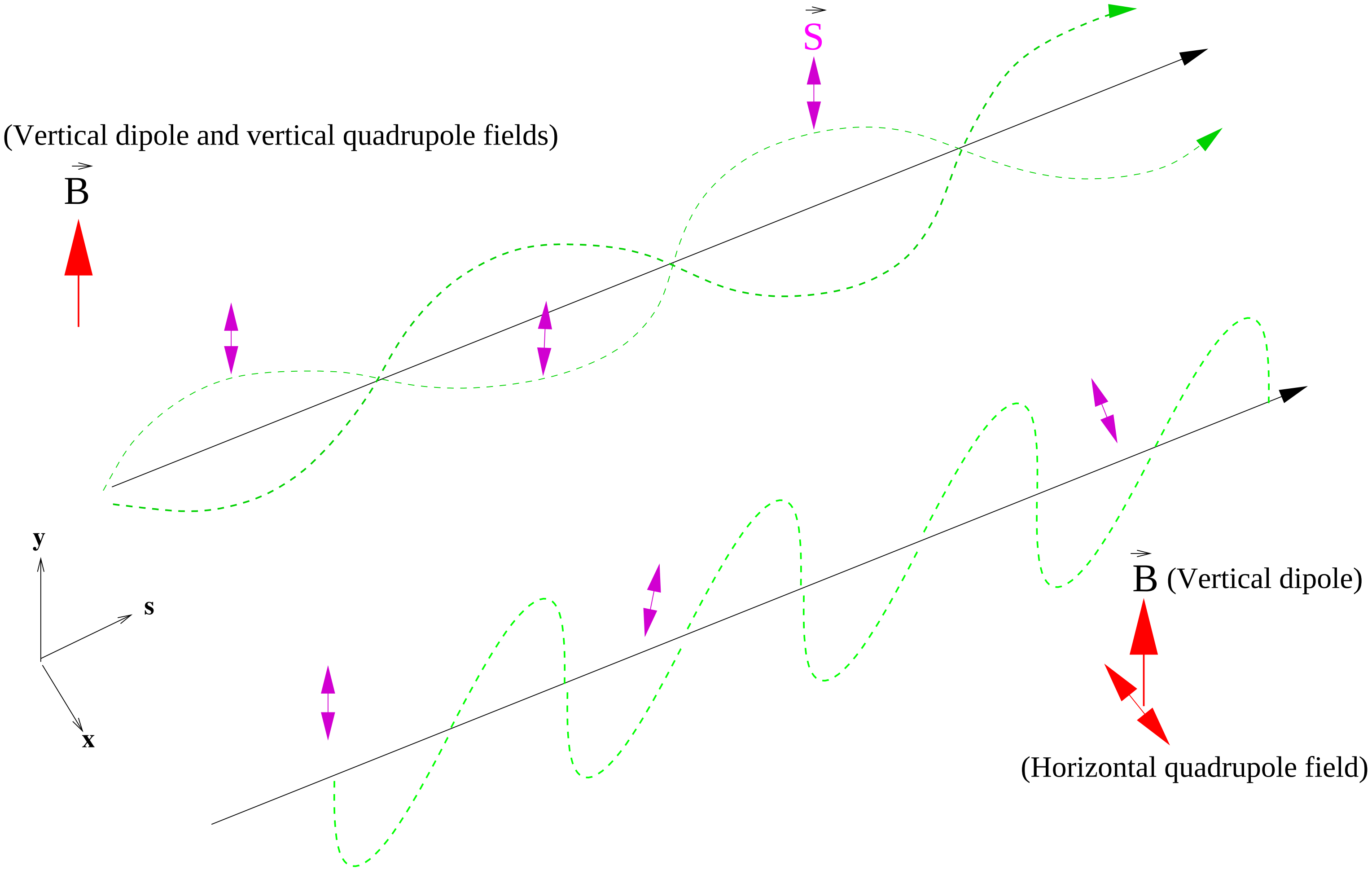
- At 27.5 GeV for electrons $a\gamma = 62.5$

- At 920 GeV for protons $a\gamma = 1759$–BIG!!

- ===> 1 mrad of orbit deviation causes $> \pi/2$
  of spin precession!!!!
  High fields=====> extreme sensitivity.

Combined effect of vertical dipole fields and horizontal quadrupole fields:

Non–commutation!



Spin–orbit resonance. c.f. NMR

- If the spin and orbit motion are in resonance:

  $\nu_{spin} = m + m_x \cdot Q_x + m_z \cdot Q_z + m_s \cdot Q_s$

- ====> **BIG** spin disturbance at fixed energy: potential DEPOLARISATION on crossing during acceleration.

- Two main groups of resonances:
  - Integer resonances due to motion along the **distorted** periodic orbit.
  - Synchro-beta ('intrinsic') resonances due to **synchro-beta oscillations** around the periodic orbit.

- $e^{\pm}$: $\Delta(a\gamma) = 1$ ==> $\Delta E \approx 440$ MeV.
- $p^{\pm}$: $\Delta(a\gamma) = 1$ ==> $\Delta E \approx 523$ MeV.
- $d^{\pm}$: $\Delta(a\gamma) = 1$ ==> $\Delta E \approx 13$ GeV .

- ====> For protons: several thousand resonances on the way to 920 GeV and many of them are killers!

A typical cure:

Include special magnetic field configurations so that the spin tune is no longer $a\gamma$, but fixed.

For example at high energy:

Siberian Snakes: Rotate a spin by π, for all energies around some axis in the **horizontal** plane one or more times per turn—with tolerable orbit distortion ===>

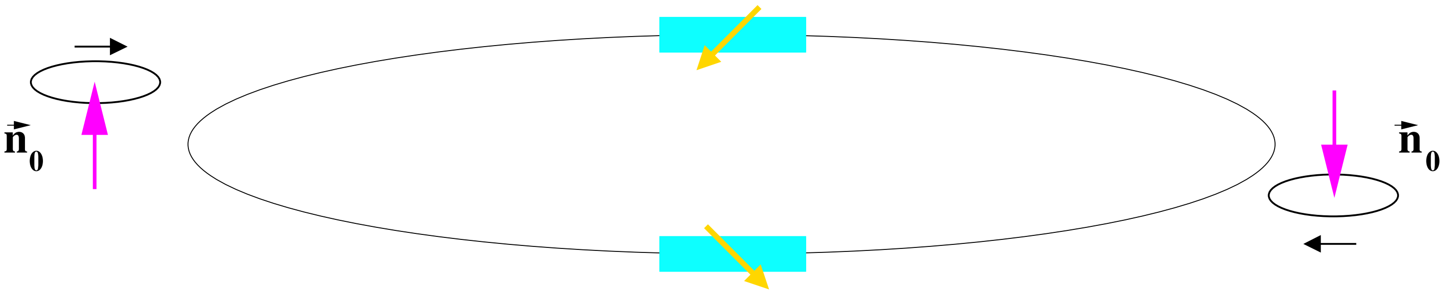
The new spin tune is independent of energy ==>
No resonance crossing!!! (almost)

Use interleaved sets of tilted or horizontal/vertical dipoles with fixed transverse fields. Exploit the non–commutation of large spin rotations: c.f. HERA spin rotators.

- Arrange for minimum orbit disturbance,
- but for maximum spin disturbance.

Siberian snakes for fixing the spin tune at 1/2 on the design orbit

Example with two snakes:



Energy independent spin tune at 1/2 on the design orbit:

Snake axes 90 degree apart

Ya.S. Derbenev, “Bending Snake”, Preprint: UM HE 97-07.

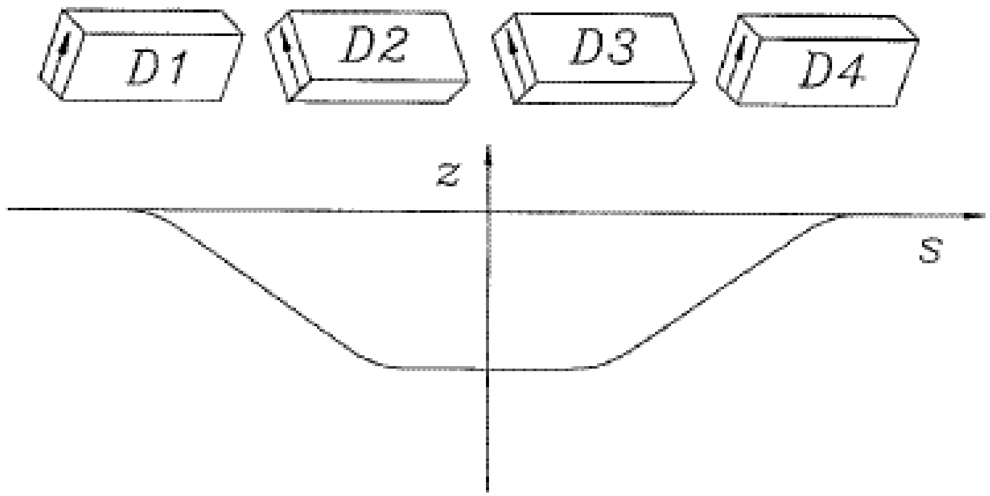


Figure 2: Bending snake with a radial spin rotation axis and a vertical orbit bump inside the snake.

V. Anferov: 8 dipole symmetric snake: May 99 DESY workshop.

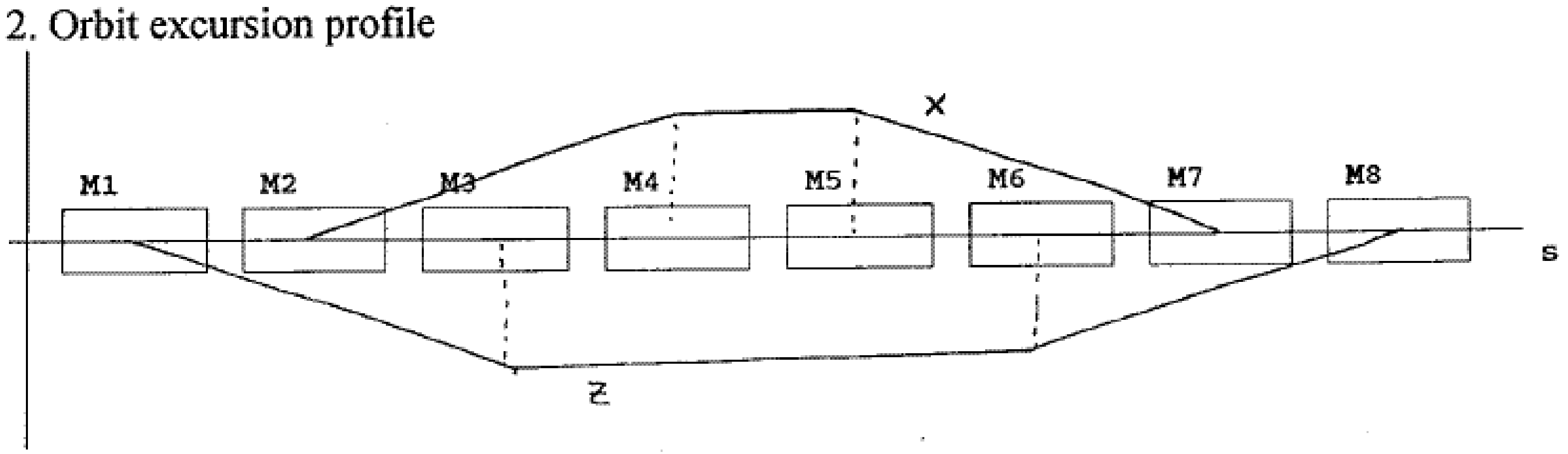


Figure 3: Radial axis, 90 degree spin rotation in each magnet, 20cm orbit excursion at 15.6 GeV.

Most compact form: the helical snakes of V. Ptitsin and Yu. Shatunov.
4 modules, super cond. 4 Tesla, each 2.4 m.

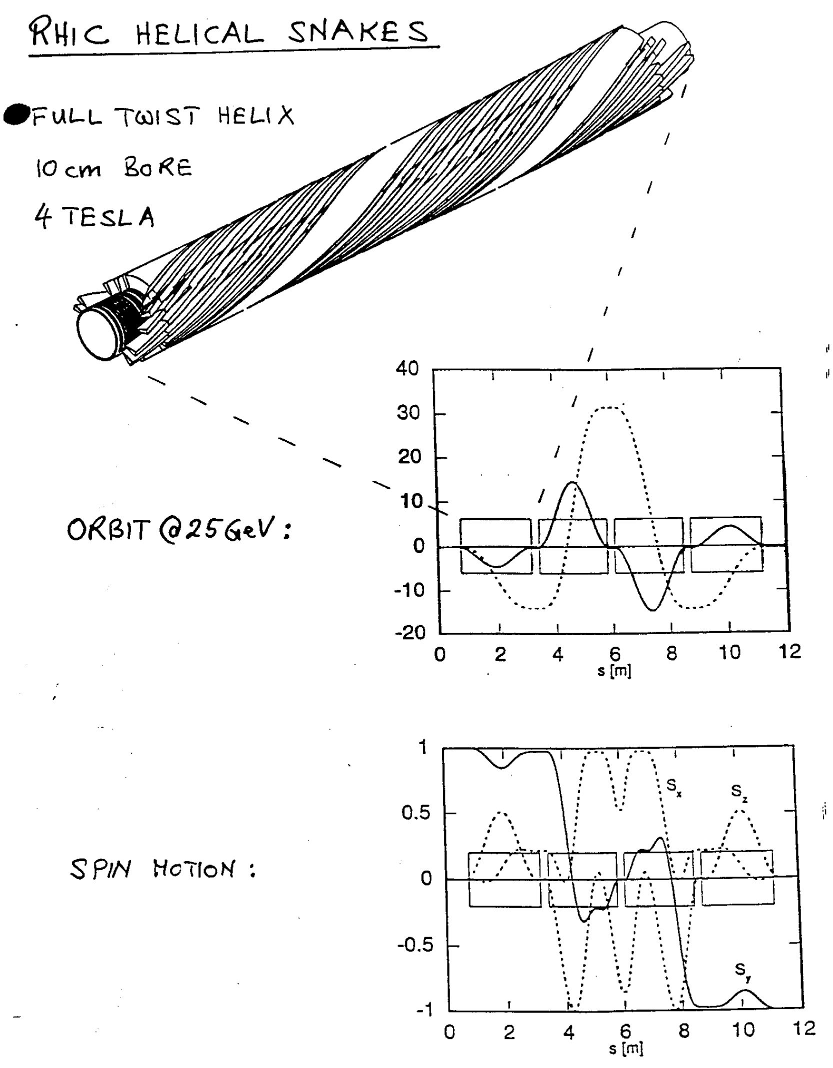


Figure 4: Rotators can be formed by choosing other combinations of the 4 modules Sketch from T. Roser, May 99 DESY Workshop.

RHIC SPIN Design Manual

38 *Chapter 4: Snakes and Spin Rotators in RHIC* **(July 1998)**

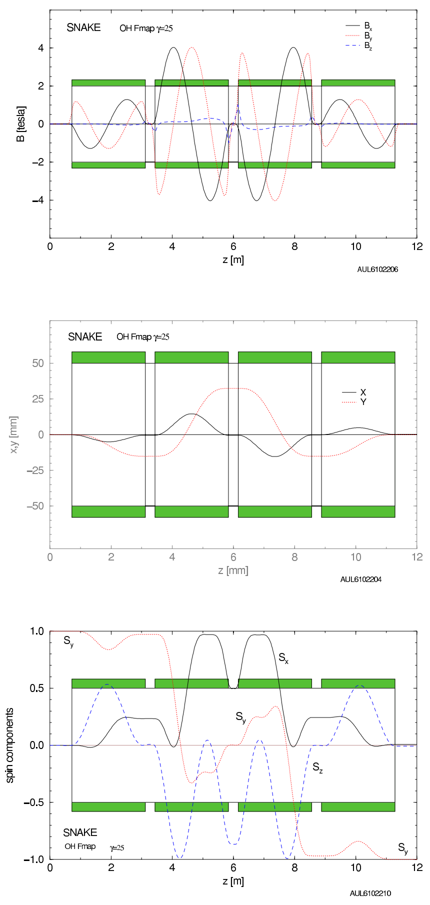
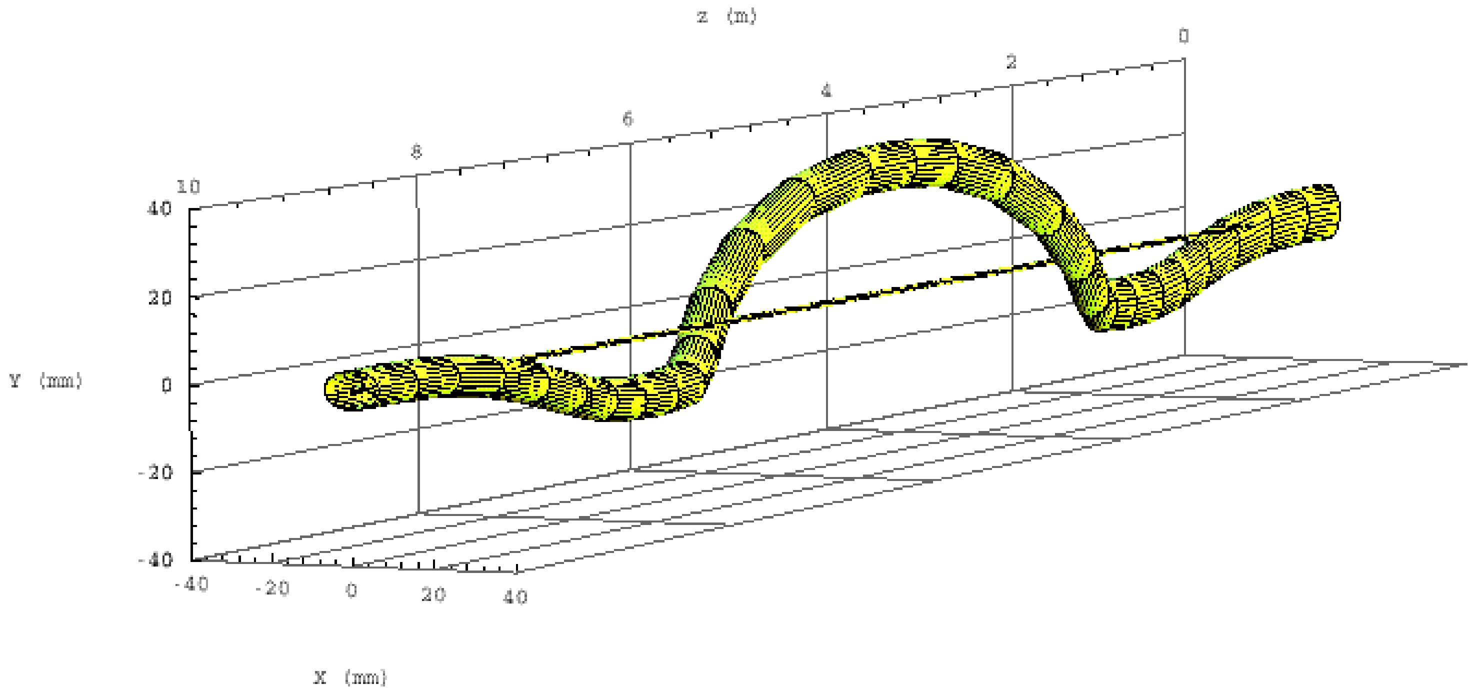
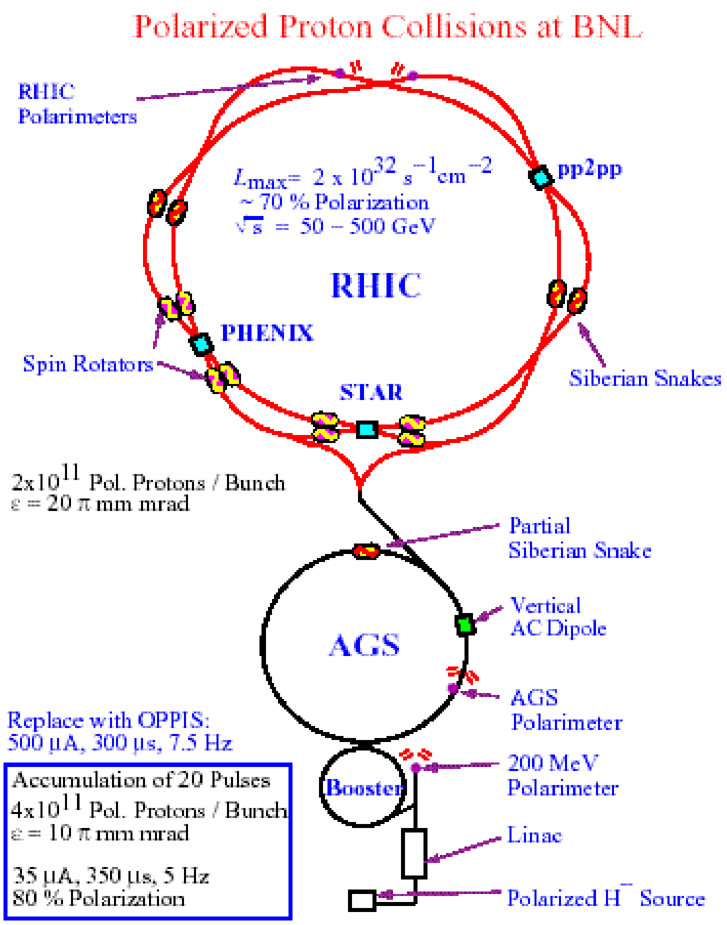


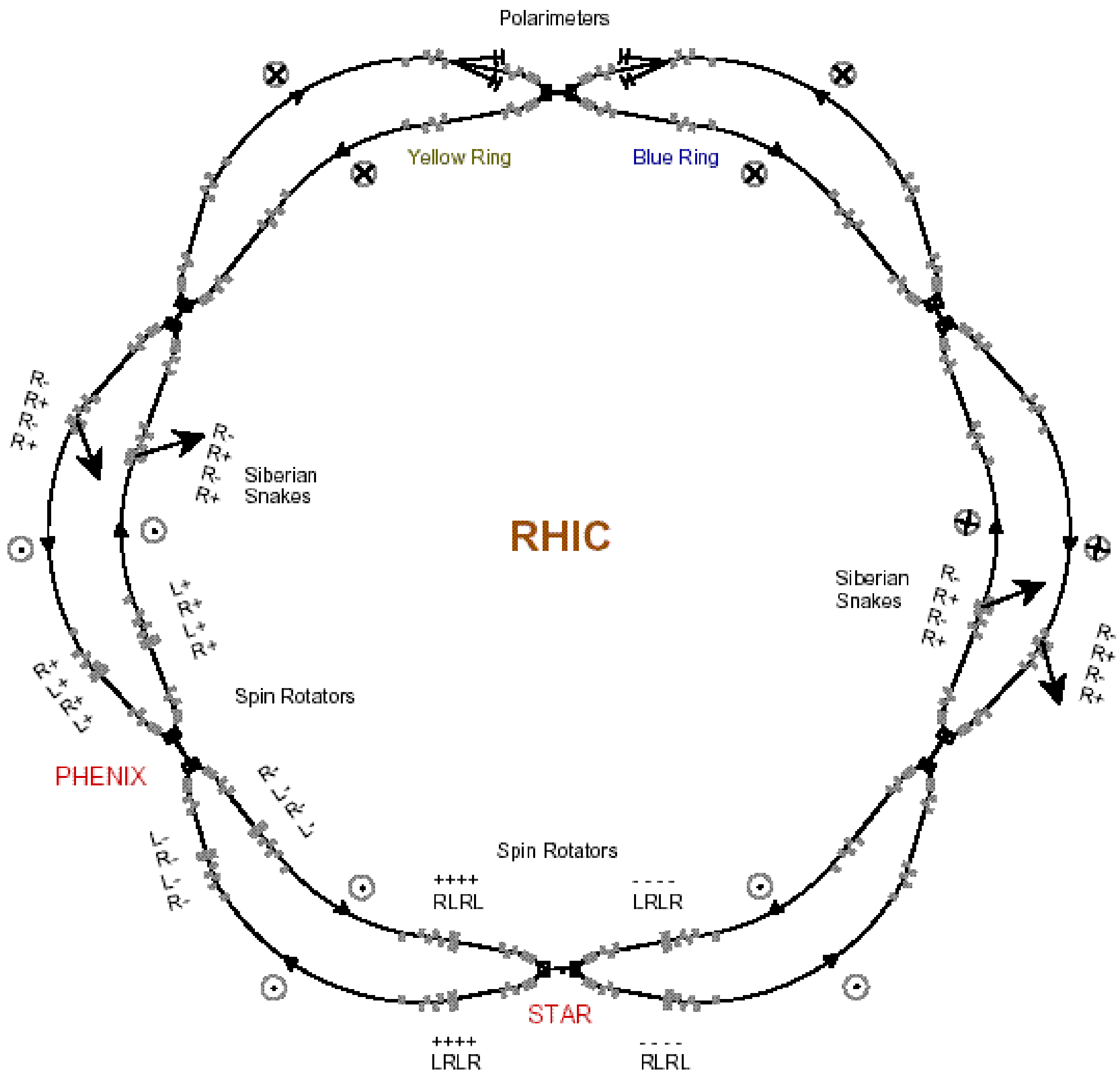
Figure 4.1: Field, orbit, and spin tracking through the four helical magnets of a Siberian Snake at $\gamma = 25$. The spin tracking shows the reversal of the vertical polarization.

The snake–like orbit in a RHIC snake



Winding the coil on a RHIC helical snake module


Polarized Proton Collisions at BNL
RHIC Polarimeters
L_{max}= 2 x 10^{32} $s^{-1}cm^{-2}$
~ 70 % Polarization
$\sqrt{s}$ = 50 – 500 GeV
RHIC
pp2pp
PHENIX
Spin Rotators
STAR
Siberian Snakes
$2x10^{11}$ Pol. Protons / Bunch
ε = 20 π mm mrad
Partial Siberian Snake
AGS
Vertical AC Dipole
AGS Polarimeter
Replace with OPPIS:
500 µA, 300 µs, 7.5 Hz
Accumulation of 20 Pulses
$4x10^{11}$ Pol. Protons / Bunch
ε = 10 π mm mrad
35 µA, 350 µs, 5 Hz
80 % Polarization
Booster
200 MeV Polarimeter
Linac
Polarized H^- Source



Rotators = Hor field (at ends), + = radially "out," - = radially "in"
Snakes = Ver field (at ends), + = "up," - = "down"

The RHIC snakes are installed and

WORKING IN RHIC UP TO 100 GeV!!!

Further tricks:

- “Filtering” (G. Hoffstaetter) to select snake layouts:
  - number and position
  - snake axes.

  Don’t trust folklore or rules of thumb! E.g. 8 poorly selected snakes can be worse than 4 well selected snakes.

- Optimize the orbital tunes: understand “spin tune” properly.

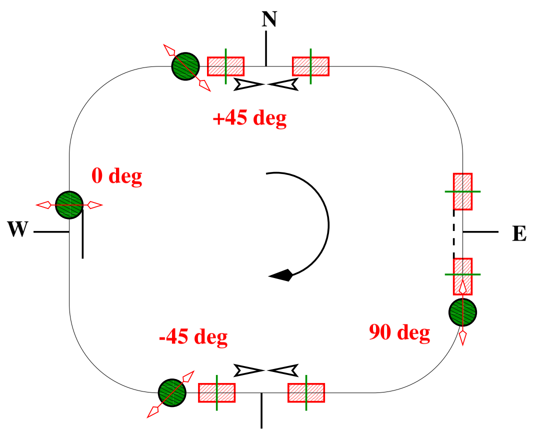
========>

“Filtered” 4 and 8 snake schemes.

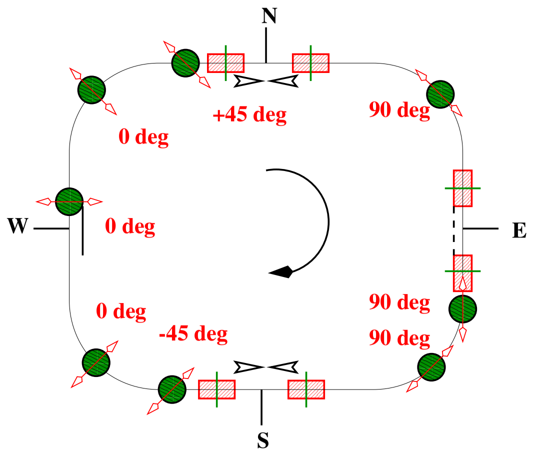
Numerical and theoretical spin stability studies for HERA-p / WS may 99 9

Siberian Snake schemes

Scheme 3e1b



Scheme 33e111b3

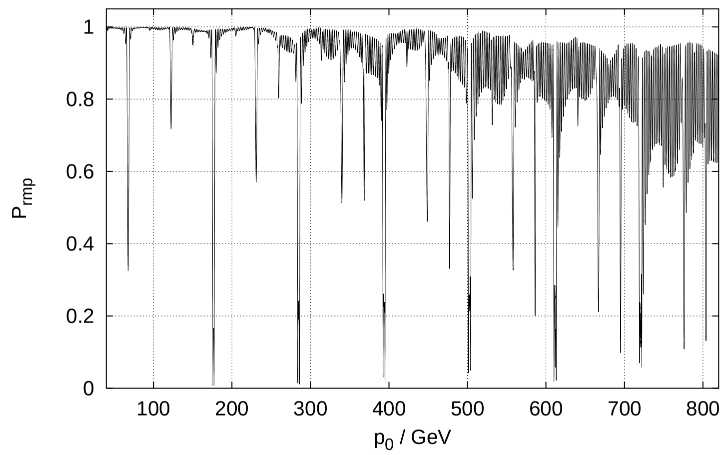


M. Vogt Thesis: DESY–THESIS–2000–054, www.desy.de/~mpybar.

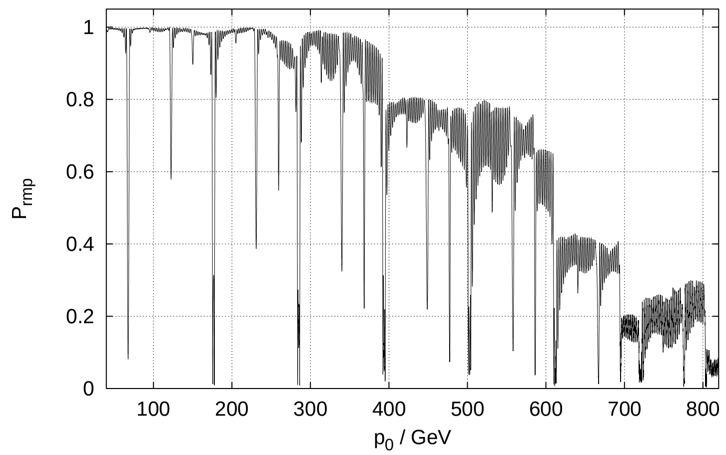
New RAMP tunes ($Q_y = .286$) / filtered (4+6) scheme

acceleration

Ramp : 10 X Speed / ensemble 2*2*2 / torus 2.0-2.0-2.0



Ramp : 200 keV p.t. / ensemble 1*3*3 / torus 2.5-2.5-2.5



Balandin and Golubeva, 1999, 4 snakes and flattening snakes.

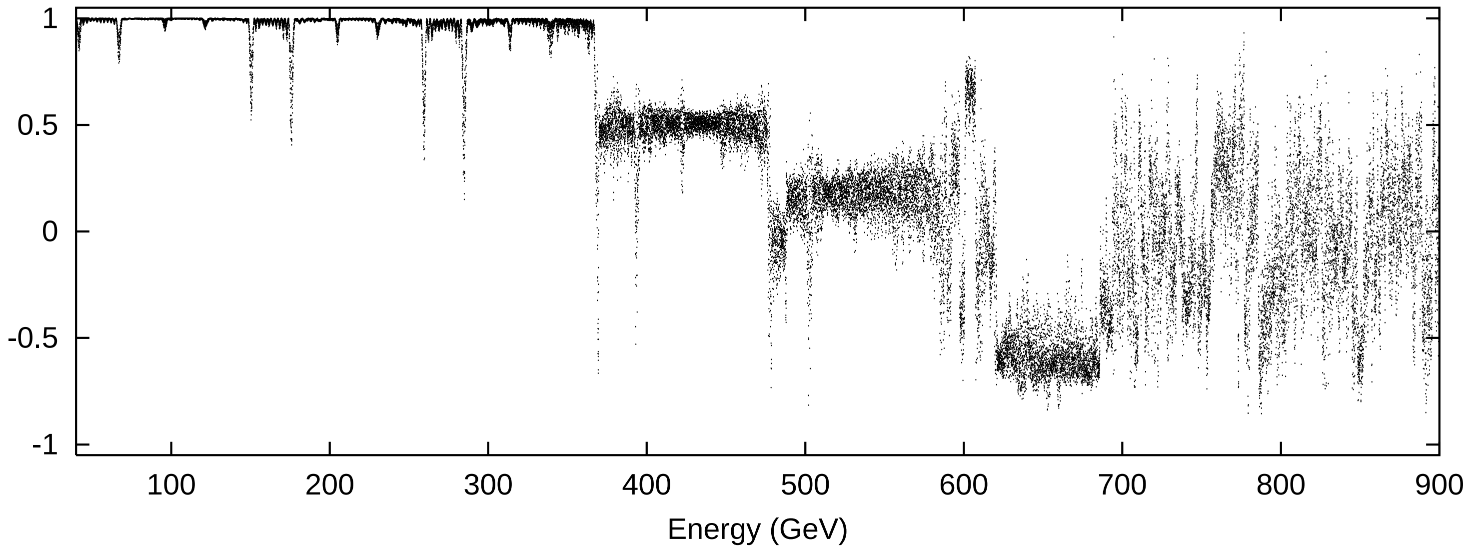


Figure 5: Emittances: $\varepsilon_x = \varepsilon_z = 0.0$, $\varepsilon_y = 4 \cdot 10^{-6}\, m \cdot rad.$ $x_{rms} = y_{rms} = 0.5$ mm.

Special aspects of HERA:

(1) No simple symmetry (not 4 and not 6)

(2) Vertical bends (interleaved with horizontal bends) ==> "flattening snakes".

(3) Very high energy.

(4) Much longer than other rings.

(5) Not much space for snakes, 8 snakes difficult.

But: 2 and 5 and perhaps the optic get better with just ONE EXPERIMENT.

In low energy rings without full snakes:

The Froissart–Stora formula for crossing resonances

$$\frac{P_{\text{final}}}{P_{\text{initial}}} = 2\ e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1$$

- ϵ is the "resonance strength", a measure of the dominant spin perturbation at resonance (Fourier component),

- α expresses the rate of resonance crossing.

Very fast resonance crossing: Small $\frac{|\epsilon|^2}{2\alpha}$: polarisation preserved.

Very slow resonance crossing: Large $\frac{|\epsilon|^2}{2\alpha}$: adiabatic invariance ===> full spin flip without polarisation loss.

In low energy rings at a few GeV:

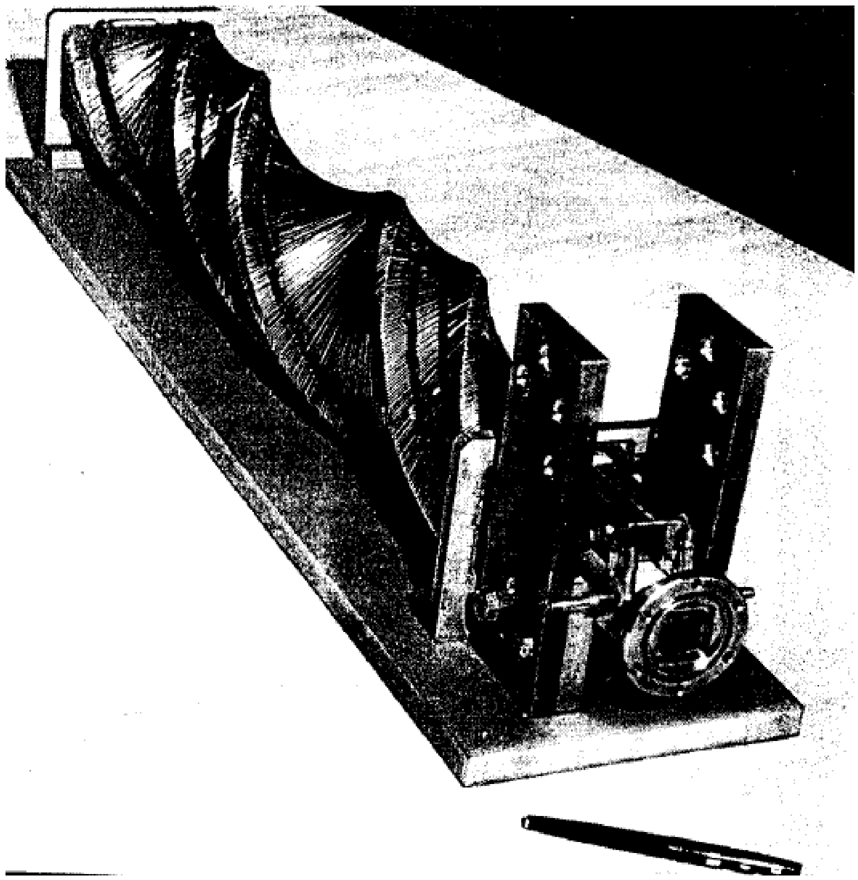
- Full dipole snakes cause too much orbit distortion.
  Full solenoid snakes need impractically high time varying fields.
  So use Partial snakes:
  These rotate spins by a small fraction of π and represent a deliberate well understood large imperfection which dominates other imperfections and ensures full spin flip without loss of polarisation when crossing integer resonances during acceleration: use, e.g. a solenoid or helical dipole.

- Betatron tune jumping, to ensure polarisation preservation by fast resonance crossing.

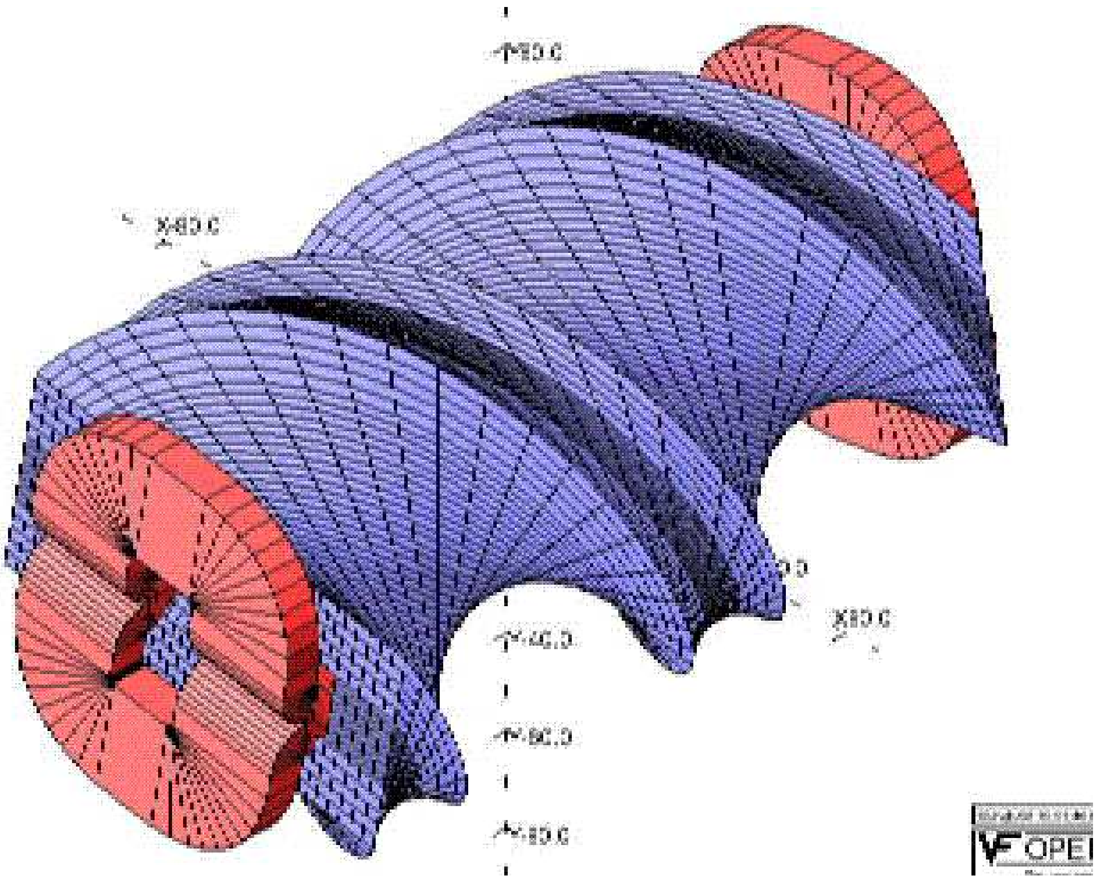
- Coherent excitation of vertical betatron motion to increase the resonance strength of (vertical) intrinsic resonances and ensure full spin flip without loss of polarisation at all orbit amplitudes when crossing these resonances.

Tested at AGS and COSY ===> DESY III (and PETRA?)

T. Roser et al: helical dipole partial snake.



T. Roser et al, RHIC SPIN Note 1998.



The acceleration chain: minimum modifications for polarisation

- The source: **optically pumped H^-.** 80 percent, 20 mA
- **New radio frequency quadrupole to 750 KeV.**
- Proton linac to 50 MeV.
- Transfer line to DESY III: **snakelike spin direction tuner**.
- DESY III: stripping foil injection, $50MeV \to 7.5GeV$:
  partial snake and pulsed quadrupoles RF coherent vertical excitation.
- Transfer line DESY III to PETRA II: **snakelike spin direction tuner**.
- PETRA II: $7.5GeV \to 39GeV$: **two Siberian Snakes.**
- Transfer line PETRA II to HERA: **snakelike spin direction tuner**.
- HERA: **at least 4 Siberian Snakes and also spin rotators.**
  Integrate the rotators into the vertical bends?
- **POLARIMETERS!!!!!!**
- **Spin flipper?.**

The luminosity—the source:

- Currently the best polarised H^- sources give about 1.5 mA D.C.
- The experts (Zelensky BNL) promise 80 percent polarisation with a 20 mA pulsed source.
- They need support to prove it.

  Then if beam losses in the RFQ and the.... can be cured there is a good chance that there will be no loss of luminosity.

C.D.P. Levy and A. N. Zelensky: in Acceleration of Polarized Protons to 920 GeV at HERA: The SPIN Collaboration and the DESY Polarization Team, UM-HE-99-05 University of Michigan (1999)

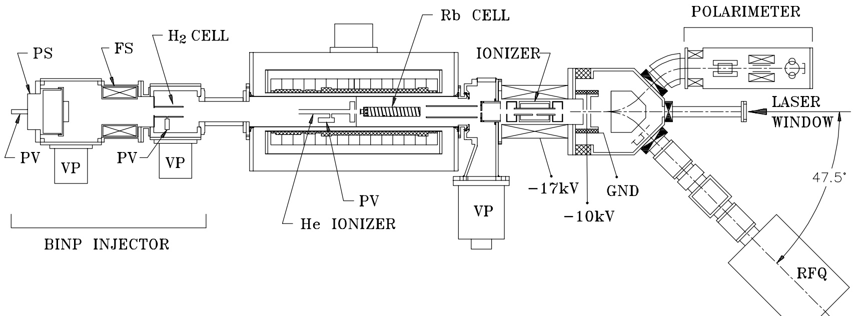


Figure 2.1: Proposed pulsed OPPIS, configured for 21 keV beam energy at injection to an RFQ: PS – plasmatron proton source; PV – pulsed valve; VP – vacuum pump; FS – focusing solenoid; GND – ground. The 47.5^o magnetic bend preserves longitudinal polarization.

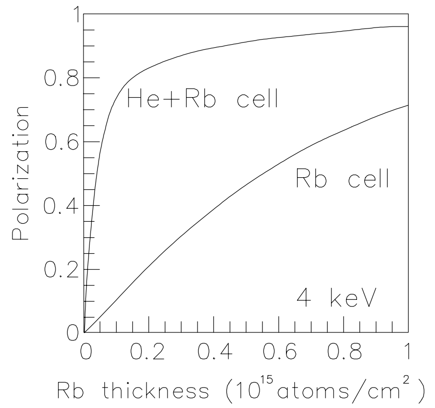


Figure 2.2: Hydrogen electronic polarization as a function of Rb vapor thickness, at a beam energy of 4 keV. Top line – combined charge- and spin-exchange polarization; bottom line – spin-exchange polarization only.

Things needing urgent attention: work with the SPRINT algorithm to define the criteria for maintaining high energy polarisation.

LOTS of long term spin orbit tracking studying perturbations wrt "stationary states".

- Understand the effects of misalignments. Find cures.
- Find space for practical optimized snake schemes.
- Handle the vertical bends, rotators: $\vec{P}_0$ vertical in arcs
- What is the maximum allowed emittance?
- Keep a watch on the upgrades.
- Beam-beam effect.
- Noise in power supplies.
- Optical non-linearities.
- Intrabeam scattering.
- Electron/positron injection.
- Optical coupling.
- Optimised optic.
- Study the efficacy of the snakes for controlling the spin 'equilibrium' during the adiabatic acceleration.

etc.
etc.
etc.

Deuterons:

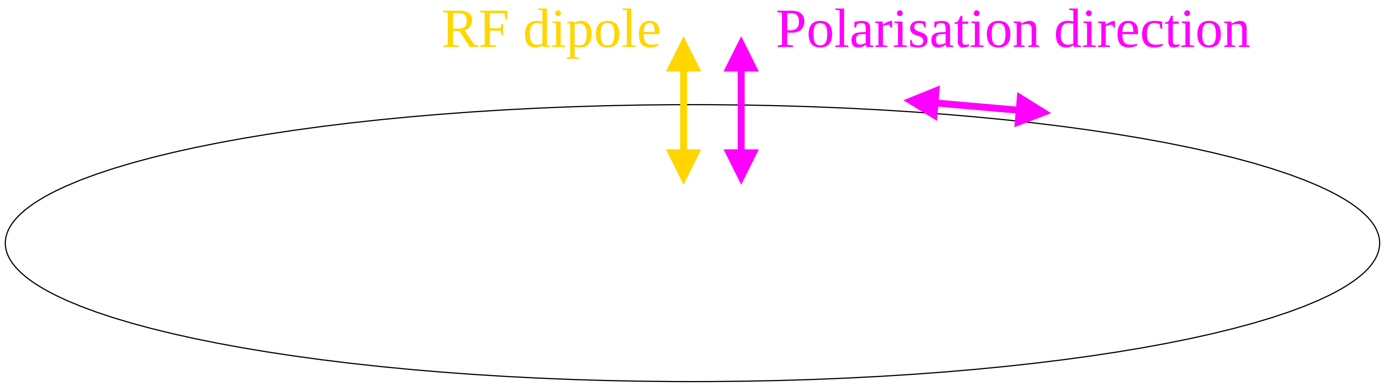
- Charge = 1 unit ===> top momentum (energy) same as for protons.
- $a_p/m_p \approx 25 a_d/m_d$ ===>
- Resonance strengths $\times$ 25 smaller.
- Resonance scale: 13.1 GeV instead of 0.523 GeV.
- At first order the "spin cone" is $\times$ 25 narrower.

===> HERA for deuterons looks like PETRA for protons

BUT:

- Spin rotators need enormous field integrals! Impossible
- To overcome the integer resonances use the vertical bends as partial snakes? Direction of $\vec{n}_0$ vs. energy?
- Instead of rotators: resonant driving of spin with horizontal RF fields.
  - Derbenev, Anferov, Skrinsky: **suggestion!!!!**, embryonic.
  - Spin tune $= 1/2$.
  - Lock polarisation direction onto RF field at one point in the ring.
  - Polarisation flips from turn to turn
  - Run on a high harmonic to hit all bunches.
  - etc.

Horizontal RF field to trap spin in a RF resonance.



Key modern concepts for spin–orbit dynamics at very high energy:

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- Generalized Froisart–Stora behaviour
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- etc, etc, etc.

MANY FASCINATING PROBLEMS FOR PHYSICISTS AND MATHEMATICIANS

The Invariant Spin Field $\hat{n}$

At very high energy for protons $\delta\theta^{ave}_{n,n_0}$ can be very large:

- If $\vec{P}(\vec{u};s) = 1 \cdot \vec{n}(\vec{u};s)$
  i.e. 100 % polarisation at each phase space point, then:
- With $\delta\theta^{ave}_{n,n_0} \approx 60^\circ$ ===>
- $< \vec{P}(\vec{u}:s) >_{phasespace} \approx 50\%$!!!

===> Knowledge of $\vec{n}$ gives us the upper limit on the phase space averaged polarisation of the beam.

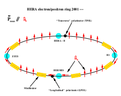
If $\vec{n} \perp \vec{n}_0$ at the edge of the beam, polarimetry by scattering off fibres becomes tricky.

The edges of the beam are likely to be ‘exotic’ and in a poorly known spin state.

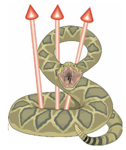
For much more enlightenment:

- www.desy.de/~mpybar
- www.desy.de/~hoff
- www.desy.de/heraspin

Doktorarbeiten und Diplomarbeiten bei DESY



Ultra–relativistic spin dynamics in the HERA storage rings at DESY



The Deutsches Elektronen-Synchrotron laboratory (DESY) in Hamburg is a leading centre for the production and use of ultra–relativistic spin–polarized electron and positron beams in high energy particle physics and for the theory of ultra–relativistic spin motion in accelerators. An impression of the topics under study can be found at:

http://www.desy.de/~mpybar/
http://www.desy.de/heraspin/
http://www-mpy.desy.de/proton_pol/
http://www-mpy.desy.de/proton_pol/desypolpapers.html

General information about DESY and its accelerators can be found at:

http://www.desy.de/html/home/index.html
http://www.desy.de/html/home/fastnavigator.html
http://www-mpy.desy.de/desy-acc.html

Among our immediate interests are:

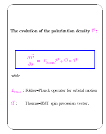
- The depolarizing effects of the beam–beam interaction in the electron/positron ($e^{\pm}$) ring at HERA.
- Proton spin dynamics at up to 920 GeV in the HERA proton ring.
- General theoretical and mathematical matters associated with efficient descriptions of deterministic and stochastic spin motion.

We are looking for diploma and doctoral students to join us in this exciting work. Our projects will be mainly of interest to physicists but mathematicians are also strongly invited to contact us.

The person(s) joining us should:

- be prepared to quickly obtain a solid knowledge and understanding of spin polarization in accelerators,
- be prepared to quickly become expert with large scale numerical calculations and in interpretation of the results in terms of physical concepts, and/or contribute to the mathematical aspects of our work,
- be prepared to work cooperatively in a small team.

Our projects provide an opportunity for making a significant contribution to our understanding of spin dynamics at the international level and to the long term performance of HERA; for becoming skilled in large scale numerical computation on modern processors; and for correlating interesting mathematical concepts with the results of numerical calculations.



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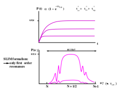
G.H. Hoffstätter: (Tel: 040-8998-3430, e-mail: hoff@mail.desy.de)

at DESY.



Summary

- It's difficult but well worth investing effort!

- Feasibility, ideas, theories, conjectures etc. must be checked with massive amounts of spin–orbit tracking simulation: SPRINT.

- We need HELP! experienced scientists and students.

- Success at RHIC is pivotal:
  December 2001 Polarisation at 100 GeV.