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POLARIZED PROTONS IN HERA

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First a rough picture of the current situation of high energy accelerators with polarized beams is drawn. The process of creating polarized proton beams by a polarized source and subsequently accelerating them is described, the major problems are outlined and illustrated by examples from DESY accelerators. After polarized beams are accelerated to high energy, the polarization has to be stable for several hours in order to be useful for the experiments H1 and ZEUS. Furthermore the polarization in all parts of the beam has to be nearly parallel during all this time. The concept of the equilibrium spin distribution of an accelerator is introduced and results for HERA show how the polarization can be optimized by minimizing the opening angle of the spin distributing with a suitable choice of Siberian snakes. Finally results about the polarizations sensitivity to misalignments are shown and topics for future analysis are mentioned.

1 INTRODUCTION

Spin dependent synchrotron radiation causes an electron beam to automatically polarize itself anti-parallel to the magnetic dipole field if the beam is flat and disturbing effects of misalignments on the spin motion are compensated. However, the HERA electron ring is not flat. To the right and to the left of the HERMES experiment in the East hall, spin rotators consisting of vertical and horizontal bends have been installed, which deflect the beam and manipulate the spin motion in such a fashion that the polarization is parallel to the beam direction in the HERMES experiment, while it is vertical in the arcs. Installing the required vertical and horizontal bends in a high energy storage ring while maintaining the self polarizing mechanism of the electrons has not been achieved in any other laboratory and was only possible after spin matching of spin orbit motion[1]. Thus the attainment of longitudinally polarized electron or positron beams in HERA was and still is a unique achievement[2]. Table 1 illustrates the endeavor for polarized electrons in storage rings.

HERMES uses the polarized electron beam for interactions with polarized nuclei in a gas jet target. The center of mass energy of these collisions is approximately 7.2GeV. If one could store a polarized proton beam in HERA at 820GeV, one could analyze polarized *e*-*p* collisions with center of mass energies of up to 300GeV in H1 and ZEUS. Furthermore, collisions of the polarized protons with a polarized gas jet target would lead to polarized *pp* collisions at 39GeV. Particle physicists are still actively discussing which experiments could be performed with polarized protons and electrons at HERA energies.

At DESY a group of accelerator physicists, Desmond Barber, Klaus Heinemann, Georg Hoffstätter, Gerhard Ripken, Mathias Vogt, the guests Volodia Balandin, Yaroslav Derbenev, and Nina Golubeva, and a group of machine physicists lead by Alan Krisch, called the Spin Collaboration, are actively working on the question of if and how the polarized electron and positron beams at HERA can be complemented with a polarized proton beam.

However, the quest for polarized proton beams did not start with HERA. Table 2 lists some of the first accelerators which supplied polarized protons successfully. It is obvious from this table that the energy of polarized protons did not increase with the availability of bigger accelerators. This is due to the fact that, in contrast to high energy electrons, protons do not submit to a self polarization mechanism, since they do not emit sufficient synchrotron radiation by a big margin. Recently several laboratories have set out to close this gap between the energy of available unpolarized and polarized protons. Table 3 lists accelerators and the proton energies for which people are studying the possibility of accelerating polarized protons. For Fermilab[3], LISS[4], and RHIC[5] design reports for a polarized proton project have been published already. These documents are very useful, since they illustrate the state of thinking on proton polarization, give important references, and a glance at their cost estimates can give a feeling for the financial dimensions involved in such a project.

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TABLE 1: The quest for longitudinally polarized electrons in high energy storage rings.

Name	Year	Polarization	Energy
VEPP	1970	80%	0.65 GeV
ACO	1970	90%	0.53 GeV
VEPP–2M	1974	90%	0.65 GeV
VEPP–3	1976	80%	2 GeV
SPEAR	1975	90%	3.7 GeV
VEPP–4	1982	60%	5 GeV
CESR	1983	30%	5 GeV
DORIS	1983	80%	5 GeV
PETRA	1982	70%	16.5 GeV
LEP	1993	57%	47 GeV
HERA	1994	70%	27.5 GeV longitudinal $\Leftarrow$

TABLE 2: The quest for high energy polarized protons.

Accelerator	Energy
ZGS	12 GeV
KEK PS	12 GeV
AGS	22 GeV
IUCF	1 GeV
Saturn II	3 GeV
PSI Cyclotron	0.59 GeV
TRIUMF Cyclotron	0.5 MeV
LAMPF	0.8 MeV

TABLE 3: High energy accelerators whose polarized proton capability has been analyzed.

Accelerator	Energy
Fermilab Main Injector	120 GeV
Fermilab TEVATRON	900 GeV
LISS	20 GeV
RHIC	250 GeV
HERA	820 GeV

2 CREATION AND ACCELERATION OF POLARIZED PROTONS

Since the protons in HERA do not self polarize, methods for obtaining polarized proton beams will be completely different from the well established methods of obtaining polarized electron beams. Various ideas for creating a polarized high energy proton beam are being discussed:

- Resonance excitation by the Stern Gerlach Effect. This method has not been tested and requires very difficult phase space manipulations[6].
- Spin flipping by scattering the proton beam on a polarized electron beam. The polarization build up would be too slow[7].
- Spin filtering with a polarized target. This method has been tested and is understood for low energies[8]. For high energies the polarization build up would be too slow.
- Acceleration of polarized protons after creation in a polarized source. This method has been tested at several accelerators, some of which are mentioned in table 2.

We concentrate on the last possibility since all of these ideas except the last are currently either too difficult or not very promising. In this scenario one produces polarized protons in either a polarized atomic beam source (ABS)[9] or in an optically pumped ion source (OPIS)[10]. Up to 85% polarization for beam currents of up to 0.6mA and 1.6mA respectively has been achieved with these sources. Compared with the 60mA of DESY's current source this sounds rather limited. However experts think that in pulsed mode polarized beam currents of up to 20mA could be possible in OPIS sources[11]. If the transfer efficiency of DESY's low energy beam transport (LEBT) and of the radio frequency quadrupole (RFQ) can be improved, the current luminosity of HERA can be achieved with a 20mA source.

For polarization optimization, several polarimeters will have to be installed in the beamline. To measure the polarization at the source a Lyman-α polarimeter can be used. This does not disturb the beam[12]. After the RFQ at 750keV, another polarimeter would have to be installed[13]. This disturbs the beam and can therefore not be operated continuously. The transfer of polarized particles through LINAC III has to be optimized with yet another polarimeter which could be of the type used for the AGS LINAC[14].

Each of the following accelerator rings will need their own polarimeter. The polarimeter for DESY III could be similar to the AGS internal polarimeter[14]. Since polarization at DESY III momentum of up to 7.5GeV/c has been achieved at several labs, the technology of all the polarimeters mentioned so far is well understood. It is different with the polarimeters required for PETRA and HERA. Theoretical concepts for two kinds of appropriate high energy polarimeters have been developed, the Coulomb Nuclear Interference (CNI) polarimeter, and the Inclusive polarimeter[3]. Since the technology involved has not been tested, it seams advisable to plan an installation of both types of polarimeter in order to cross calibrate measurements.

Before polarization in DESY's high energy rings can be measured, care has to been taken that the polarization produced in the source is not lost during the acceleration and the beam transport process. To explain the problems involved, some concepts of polarization dynamics have to be introduced.

3 SPIN MOTION IN CIRCULAR ACCELERATORS

3.1 Basic facts

The equations of spin motion have some similarity to the Lorentz equation for particle motion through magnetic fields

$$\frac{d\vec{p}}{dt} = -(\frac{q}{m\gamma})\{ \quad \vec{B}_\perp \qquad\qquad \} \times \vec{p} \,, \tag{1}$$

$$\frac{d\vec{s}}{dt} = -(\frac{q}{m\gamma})\{a\gamma\vec{B}_\perp + (1+a)\vec{B}_\| \} \times \vec{s} \,. \tag{2}$$

Here $a = 1.79$ is the gyromagnetic anomaly of the proton. Several conclusions can immediately be drawn from these equations. If the orbit is deflected by an angle ϕ, then the spin is rotated by an angle $a\gamma\phi$. In a flat 820GeV ring, the one turn orbit deflection angle of 2π leads to 1567 spin rotations around the vertical direction. Whenever the energy is increased by 523MeV, the spin rotates once more. Therefore, a 1 mrad orbit kick at

HERA energy produces $\pi/2$ of spin rotation. The spin rotation in a dipole is proportional to the dipole field $B_\perp$ and a field integral of 2.74Tm always leads to a spin rotation of $\pi/2$. This is a rather remarkable fact, since it implies that the spin rotation in a bend does not change during the acceleration process if the bending field is not ramped. But of course the orbit deflection decreases.

3.2 Polarized particles on the closed orbit

When a particle moves along the closed orbit of a circular accelerator, its spin precesses around some rotation axis $\vec{n}_0$, which is vertical for a flat ring, and the total spin transport for one turn around the ring can be described by a rotation matrix $\underline{R}(\vec{e}_y,\phi)$ which rotates the spin around the vertical $\vec{e}_y$ axis by an angle ϕ. This angle divided by 2π is called the spin tune ν. Whenever this angle is closed to 2π, a case which is referred to as *imperfection resonance*, the rotation matrix gets close to the identity and the spin is hardly changed at all during one turn. When there are some misalignments, creating horizontal field components on the closed orbit, precession away from the vertical direction is produced. For small misalignments, the rotation around the horizontal might be very small. However, when the rotation angle ϕ is close to 2π, these small rotations will always dominate over the rotation $\underline{R}(\vec{e}_y,\phi)$. We are therefore faced with the fact that the precession direction for spins is vertical away from imperfection resonances and horizontal in their vicinity.

Since it is inadvisable to let misalignments dominate spin motion, imperfection resonances ought to be avoided. However, since the spin of a particle on the closed orbit in a flat ring rotates $a\gamma$ times around the precession direction $\vec{n}_0$, the spin tune $\nu = a\gamma/2\pi$ changes linearly with energy during acceleration and the crossing of imperfection resonances is unavoidable.

This fact is illustrated for DESY III in figure (1,left) where misalignments are included and the vertical component $n_{0,y}$ of the spin precession direction $\vec{n}_0$ is shown. Away from integer spin tunes $\vec{n}_0$ is vertical. But at integer spin tunes the precession direction is horizontal and it is vertical again for energies above the resonance. The spin tune is given by $a\gamma$ whenever the vertical component is 1. When it is close to 0, the spin tune is dominated by misalignments.

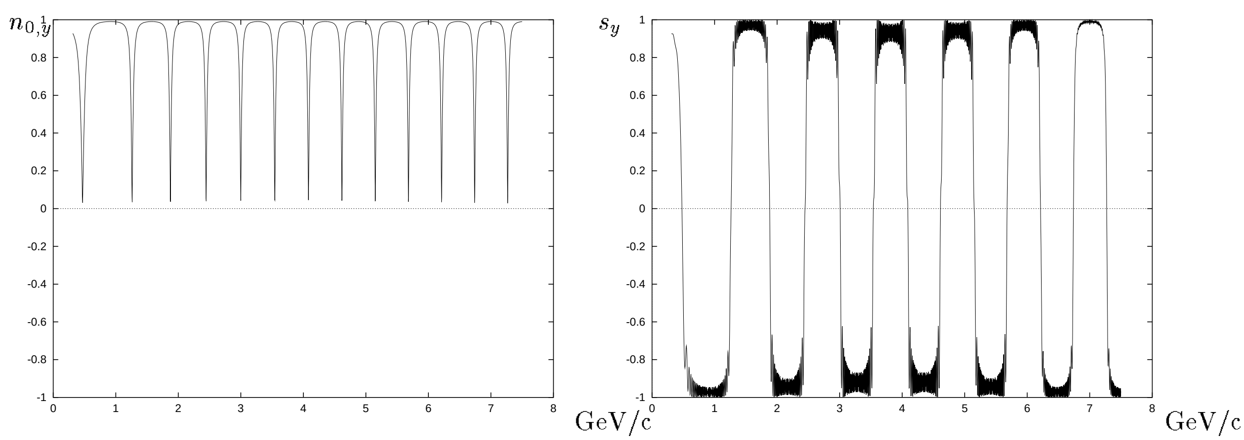

FIGURE 1: Left: The vertical component of the spin precession vector $\vec{n}_0$ for the closed orbit of DESY III with horizontal fields due to misalignments. Right: Spins on the closed orbit can only partially follow the change of the precession direction, resulting in depolarization.

Spins which are parallel or anti-parallel to the precession direction $\vec{n}_0$ will not have changed after one turn around the ring. Therefore one will always try to polarize particles in that direction. However, particles are accelerated and resonances are crossed while misalignments are present. Whenever the spin tune crosses a resonance the precession direction $\vec{n}_0$ at the corresponding energy suddenly flips from the vertical to the horizontal and back. During this time the spin can only partially follow the changes of $\vec{n}_0$ and will therefore end up rotated away form the vertical; an effect which obviously results in a loss of polarization as illustrated in figure (1,right). While the rotation vector for rotation angles $a\gamma$ always points vertically upwards away from imperfection resonances, spins which follow the precession vector change their sign when such a resonance is crossed.

Two limiting scenarios of resonance crossing can be thought of:

1. The misalignments are very small and the flip of the precession direction is so rapid that the spins hardly react and depolarization is very weak.
2. The misalignments are very strong and therefore the precession direction changes very slowly, since the precession around the horizontal fields of misaligned elements starts to dominate already far from an imperfection resonance. Then the spin can follow the slow change of the procession direction and depolarization again is very limited. In this case the spins slowly change their direction from up to down and vise versa.

The following two strategies can therefore be used to limit depolarization when imperfection resonances are crossed:

1. Careful correction of the closed orbit to limit horizontal field components.
2. Increasing the horizontal field components, for example by introducing a solenoid. A device which is deliberately used to increase the effect of imperfection resonances is referred to as partial Siberian snake.

Since the closed orbit is not very well controlled in DESY III, a solenoid partial Siberian snake can therefore probably not be avoided. A third possibility comes to mind, namely to avoid the crossing of resonances completely by using sufficiently non–flat rings. There the spin rotation angle is not $a\gamma$ and does not have to become a multiple of 2π at any energy. Devices which achieve that goal by producing non–integer spin tunes which are independent of energy are called full Siberian snakes. They have to create sufficient disturbance of spin motion and this can only be done with sufficient orbit distortion. For momenta below about 8GeV/c, the required orbit distortions seem unacceptable[3].

3.3 Polarized particles with betatron amplitudes

Particles which are not on the closed orbit are exposed to fields which fluctuate with the orbital tunes. These periodic field variations lead to depolarization whenever the spin tune ν is in resonance with the orbital tunes ν_x, ν_y, ν_s

$$\nu = nN_{sym} + i\nu_x + j\nu_y + k\nu_s \quad , \quad n, N_{sym}, i, j, k \in \mathbb{N} \ . \tag{3}$$

The number of these resonances is reduced by the number N_{sym} of super periods in a ring. These resonances are called intrinsic resonances, and if $|i| + |j| + |k| = 1$ one refers to a first order intrinsic resonance. The depolarizing effect of these resonances was experimentally verified in the AGS and other accelerators. It is the dominant reason for depolarization after solenoids are introduced to eliminate the effect of imperfection resonances. Figure (2) is taken from a talk give by T. Roser[15] and shows how the polarization was only reduced at imperfection resonances after a solenoid acting as partial Siberian snake effectively avoided the imperfection resonances at the AGS.

During acceleration in DESY III only two strong intrinsic first order resonances are crossed. These are the $\nu - \nu_y$ resonance at 1.58GeV/c and the $\nu + \nu_y$ resonance at 6.48GeV/c. When these resonances are crossed fast enough, depolarizing effects can be limited. Since the ramping speed cannot be increased by a sufficient amount, special quadrupoles are inserted which temporarily and very quickly change the orbit tunes, leading to a crossing of the resonances in a few micro seconds[16]. One can also think of devices which temporarily cause a rapid change of spin tune, but such devices have not been tested so far.

The depolarizing process at integer spin tunes has been explained by the fact that the direction of the periodic spin $\vec{n}_0$ on the closed orbit becomes dominated by misalignments at imperfection resonances. The depolarizing effect at intrinsic resonances can be understood in similar terms. Spins on the closed orbit do not change their direction from turn to turn if they are parallel to $\vec{n}_0$, since $\vec{n}_0$ is the rotation axis of the spin transport matrix $\underline{R}(\vec{n}_0, 2\pi\nu)$ for the closed orbit. Similarly one can ask if the whole distribution of spin directions in phase space can be invariant from turn to turn. For particles which are not on the closed orbit, the spin transport is described by the rotation $\underline{A}(\vec{z})$ which is a function of the particle's phase space point $\vec{z}$.

Invariance of the spin distribution $\vec{n}(\vec{z})$ does not require that spins do not change from turn to turn, but rather that a spin in direction $\vec{n}(\vec{z}_i)$ at an initial phase space point $\vec{z}_i$ gets transported via $\underline{A}(\vec{z}_i)$ to a spin direction which agrees with $\vec{n}(\vec{z}_f)$ at the final phase space point $\vec{z}_f$ after one turn around the ring.

$$\vec{n}(\vec{z}_f) = \underline{A}(\vec{z}_i)\vec{n}(\vec{z}_i) \ . \tag{4}$$

Such an invariant spin field $\vec{n}(\vec{z})$ in phase space is called the Derbenev–Kondratenko $\vec{n}$-axis[17] or the equilibrium spin distribution.

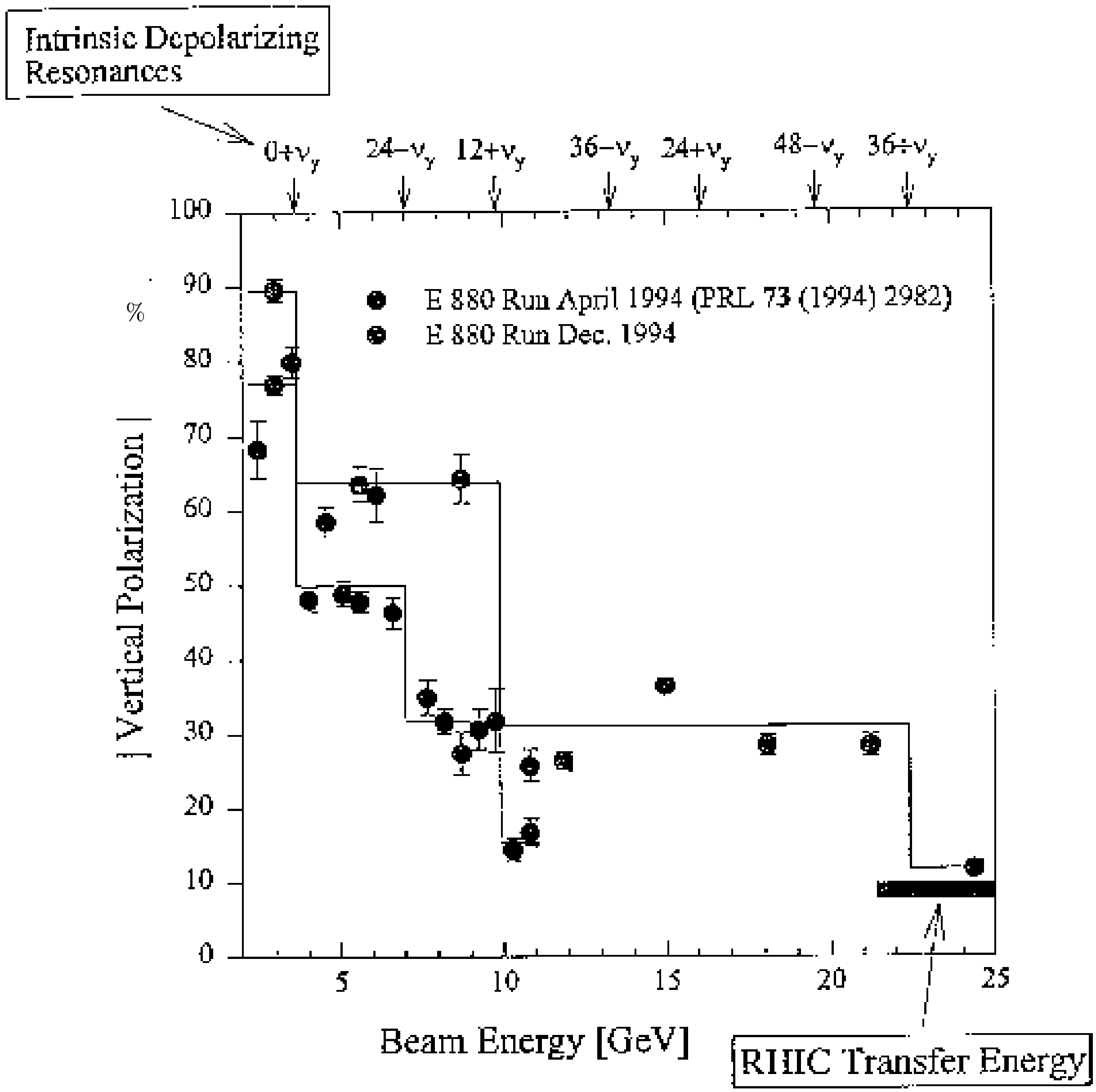

FIGURE 2: Depolarization during acceleration in the AGS. A solenoid was used to avoid the *imperfection resonances*; only the *intrinsic resonances* cause depolarization.

The polarization state of a particle beam is therefore not invariant when all particles are completely polarized parallel to each other, but rather when each particle is polarized parallel to $\vec{n}(\vec{z})$ at its phase space point $\vec{z}$.

When the fields in a ring change during the ramp, this equilibrium direction will also change. In particular it can be illustrated why depolarization occurs at intrinsic resonances $\nu = \nu_y$. If the spin vectors are expressed in terms of a coordinate system which rotates by 2π during a betatron period of vertical motion, then the spins rotate by $2\pi(\nu - \nu_y)$ during one turn around the ring rather than by $2\pi\nu$. At $\nu = \nu_y$ the spin does not change at all with respect to the rotated coordinate system and any spin distribution would lead to equilibrium. At these resonances therefore, misalignments dominate over the effect of the accelerators design fields. Away from intrinsic resonances this means that an accelerator's $\vec{n}(\vec{z})$ is associated with its design fields while it is dominated by misalignments close to these resonances. When the energy of an accelerator changes, the corresponding $\vec{n}(\vec{z})$ changes. If spins can not follow this change, the polarization is reduced.

4 THE NECESSITY OF SIBERIAN SNAKES

At high energy the energy spread and the synchrotron motion causes additional problems. In HERA a 1σ energy spread of $\Delta_p/p = 1.6 \cdot 10^{-4}$ creates an associated spin tune spread of about $\Delta\nu = 0.25$. It is therefore apparent that the spin tune can easily cross integer values or a first order intrinsic resonance during one synchrotron period. The depolarizing effect of periodically crossing of resonances during synchrotron motion is illustrated in figure (3) which is discussed in more detail in[18]. When the spin tune's dependence on the energy deviation is eliminated, the depolarizing effect disappears. At high energy it is therefore essential to make the spin tune independent of energy deviations.

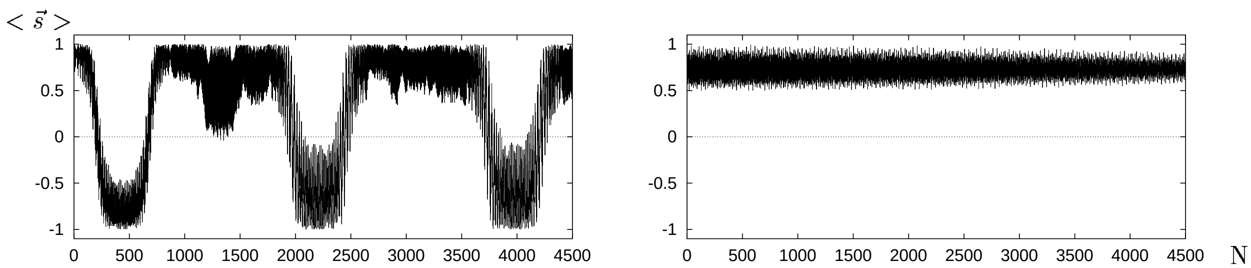

FIGURE 3: Left: Depolarizing effect of periodic crossing of the $\nu + \nu_y$ resonance (after 400, 2000, and 3600 turns) and the $\nu - \nu_y$ resonance (after 1200 and 2800 turns) in HERA at 820GeV. One synchrotron periods takes 1600 turns. Right: Without synchrotron motion no depolarization is observed.

Furthermore, the great number of spin rotations at 820GeV implies that 1567 imperfection resonances have to be crossed during acceleration. Each resonance crossing, even if it is handled very well, adds to a grand total depolarization. At energies above DESY III, it therefore becomes necessary to avoid imperfection resonances completely by making the spin tune independent of energy.

Both jobs can be achieved with Siberian snakes[19], making the spin tune independent of machine energy as well as independent of energy fluctuations during a synchrotron period. Siberian snakes are combinations of magnets which rotate the spin by π around some fixed axis, independently of energy, while having limited influence on the particle motion. This is possible, since the spin rotation is proportional to the magnetic field and independent of energy. A suitable insertion of Siberian snakes causes the spin tune to become $\nu = 1/2$ for all energies. The Siberian snakes which have been suggested for RHIC consist of four 2.4m long helical dipole magnets, which create an orbit distortion of 3cm at 25GeV. The orbit and spin motion are shown in figure (4), which is also taken from a talk given by T. Roser[19].

The increase of orbit distortion with decreasing energy is the reason why Siberian snakes can only be used at rather high energies. For example a snake which creates an orbit distortion of 15cm has been proposed[3] for an 8GeV/c ring. Similar devices would become necessary if one would implement Siberian snakes in PETRA at the low energy end. A better possibility might be to install magnets which acts as a partial Siberian snake compensating imperfection resonances for particles with momenta from 7.5GeV/c to about 20GeV/c. The field would be ramped with particle momentum up to about 20GeV/c where the magnet would have sufficient

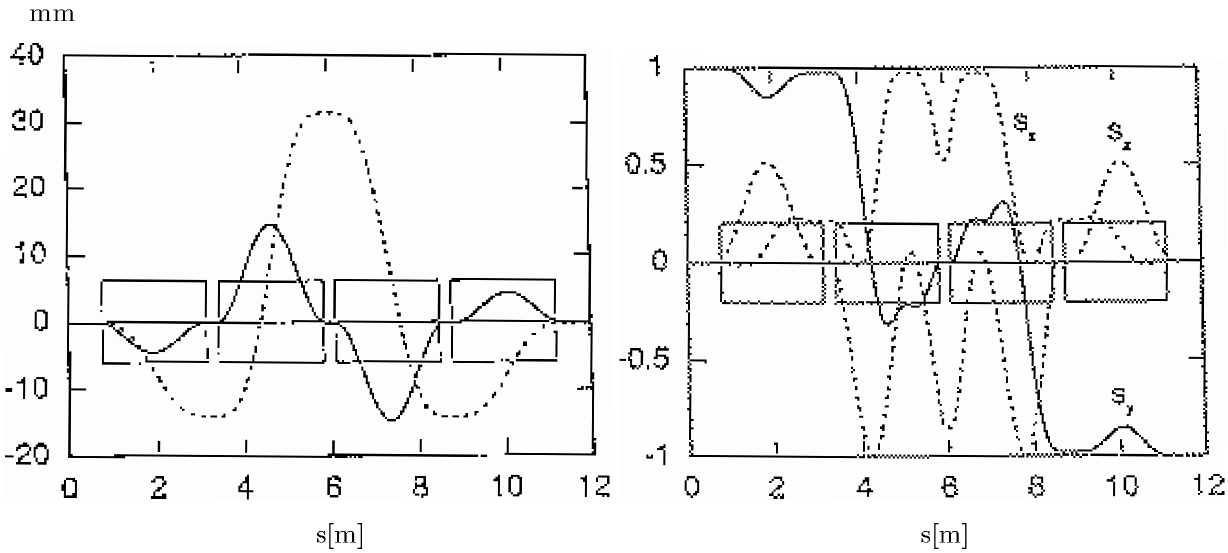

FIGURE 4: Orbit and spin motion in a helical snake designed for RHIC.

strength to act as a full Siberian snake. Subsequently the field strength would stay constant up to 40GeV/c. In PETRA there would be sufficient space for two Siberian snakes, presumably in the East and the West straight section.

4.1 The number of snakes required

A simple rule of thumb is often used to decide how many snakes are needed: the Siberian snakes have to dominate the spin motion. The spin motion on the closed orbit is described by the spin tune ν and the precession direction $\vec{n}_0$. Particles with betatron amplitude experience additional precession around a direction perpendicular to $\vec{n}_0$. The resonance width[20, 18] ϵ is a measure for that precession and is shown for HERA in figure (5). One chooses the number of snakes, which has to be even, sufficiently larger than 5ϵ[21]. This would lead to four Siberian Snakes in HERA, each of which would be superconducting and below 10m long. From tracking analysis[18] it has become clear that four snakes are not necessarily better than two snakes for the non–flat HERA ring. However, that analysis did not include misalignments.

To summarize, there are around 10000 spin tunes which satisfy equation (3) for imperfection and first order intrinsic resonances when particles are accelerated up to 820GeV. By the introduction of partial Siberian snakes, the depolarizing effect of imperfection resonances is avoided. Full Siberian snakes additionally avoid intrinsic resonances. Assuming there were two Siberian snakes in PETRA and four Siberian snakes in HERA, then all intrinsic resonances above 20GeV/c would be avoided. The number of resonances is further reduced by mid plane symmetry and by the fact that DESY has eight fold symmetry. If the fourfold symmetry of PETRA can be restored for the proton line, for example by changing the bypass region, then only 16 resonances have to be crossed, 2 in DESY III and 14 in PETRA.

5 MAINTAINING POLARIZATION AT HIGH ENERGY

When a polarized beam has been accelerated to high energy in HERA, it still has to be stored over several hours with limited depolarization. During all this time the degree of polarization at every point in phase space has to be high and furthermore the polarization direction at every point in phase space has to be close to parallel to the averaged polarization direction.

The first question posed was therefore: "How does the equilibrium polarization distribution in phase space look at high energy[7]?" When spins at different phase space points in the beam point in significantly different directions, three problems occur. This divergence of the polarization direction not only diminishes the average polarization available to the particle physics experiments, it also makes the polarization involved in each collision analyzed in a detector strongly dependent on the phase space position of the interacting particle.

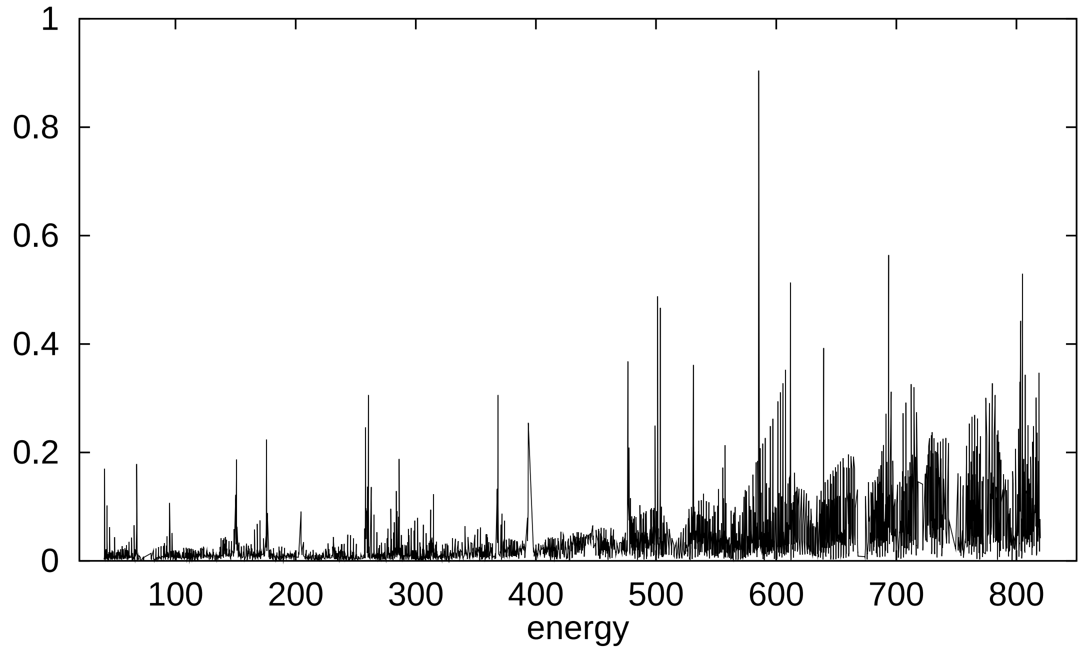

FIGURE 5: Spin resonance strength for HERA.

Furthermore polarimeters which measure the polarization of particles in the tails do not yield accurate values for the average polarization of the beam.

5.1 The equilibrium spin phase space distribution

Knowledge about the equilibrium phase space distribution of spins $\vec{n}(\vec{z})$ is hard to compute but important in many circumstances. It was already explained in section 3.2 that spins of particles on the closed orbit precess around the closed orbit spin $\vec{n}_0$. When this precession direction changes, the spins follow this change when it is slow enough. Otherwise depolarization occurs. A similar effect is relevant when the equilibrium spin distribution changes its direction during the ramp, an effect that cannot even be avoided with Siberian snakes. When higher order resonances are crossed during acceleration, the equilibrium direction of spins at different points in the beam diverge and becomes parallel again as illustrated in figure (6,top left). When this change in direction is fast enough, the spins do not react strongly. If it is slow enough, the spins follow the equilibrium direction adiabatically. When the ramping speed is chosen between these limits, depolarization takes place, as shown in figure (6,top right). These two pictures were presented by T. Roser[15]. Such an effect not only occurs during ramping but also due to the energy change associated with synchrotron motion. In figure (6,bottom) it is shown that the strength of this effect depends on the orbit tunes. It can be seen that resonances up to 20^{th} order are relevant. This figure is taken from a conceptual design report for RHIC[5]. These and several other effects can be understood in terms of the equilibrium spin distribution $\vec{n}(\vec{z})$.

The simplest[22] well established way to approximate the equilibrium spin distribution is a linear approximation in spin and orbit variables used in the program SLIM. When the average opening angle of the equilibrium spin distribution over the beam is computed, opening angles of order 1rad can be observed as shown in figure (7)[23]. The situation is even worse near first order resonances.

Nevertheless, even in these two very pessimistic pictures it becomes apparent that Siberian snakes help to keep the spin distribution more parallel. Since these rather simple linear calculations already draw attention to a problem with which high energy accelerators have to deal, we analyzed the problem with more advanced methods. Perturbative normal form transformations[24] were applied to carry the computation of the equilibrium spin distribution to higher orders by an implementation in the program COSY INFINITY. This method was used to find optimal snake combinations via the following automated sorting algorithm.

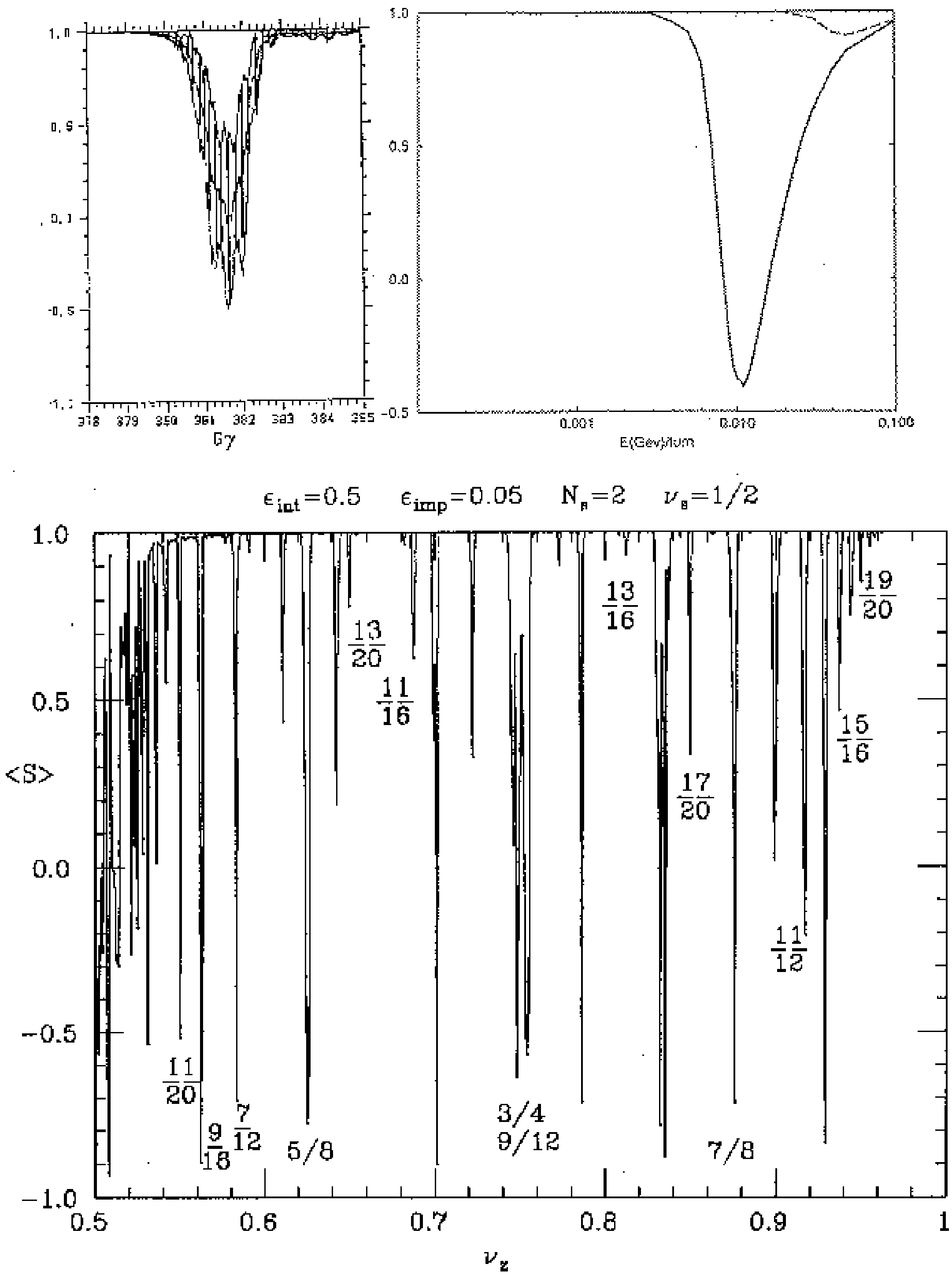

FIGURE 6: Top left: Fluctuating average polarization when ramping through higher order resonances, since the equilibrium spin distribution opens and closes again. Top right: Polarization loss at certain ramping speeds for a model ring. Bottom: Vertical component of the polarization after acceleration through a strong intrinsic resonance and a moderate imperfection resonance shown as a function of the fractional vertical betatron tune ν_z.

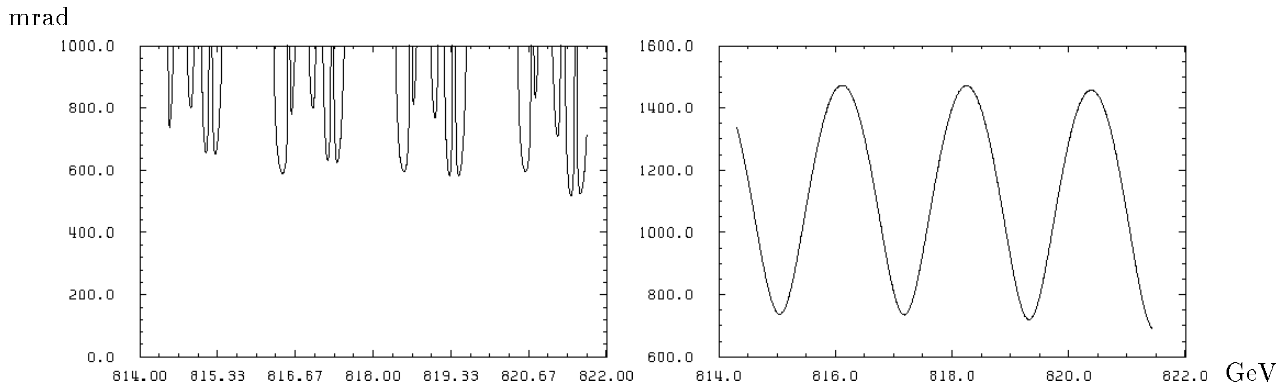

FIGURE 7: Opening angle of the equilibrium spin distribution as computed with SLIM. Left: HERA. Right: HERA with four Siberian snake.

4 snakes	$[<\phi>_{min}, <\phi>_{max}]$	
{ijkl}	for flat HERA	for HERA (5th order)
{2313}	[0.05 , 0.40]	[0.43 (+0.04) , 0.60 (+0.04)]
{2333}	[0.05 , 0.30]	[0.26 (+0.04) , 0.43 (+0.04)]
{3121}	[0.05 , 0.75]	[0.20 (+0.05) , 0.60 (+0.05)]
{3222}	[0.03 , 0.35]	[0.20 (+0.06) , 0.36 (+0.06)]
{3323}	[0.08 , 0.75]	[0.46 (+0.03) , 0.70 (+0.03)]

TABLE 4: The spread of the average opening angle $<\phi>$ in rad for beam energies between 815GeV and 816GeV as calculated with first order spin orbit motion. In parentheses we indicate the corrections obtained from fifth order calculations. The five cases shown refer to the five snake combinations which passed the automated filtering algorithm. The coding $\{ijkl\}$ with $i,j,k,l \in 1,2,3$ describes the direction of the rotation axes of the snakes for the East, South, West, and North straight section. 1: radial snake, 2: vertical snake, 3: longitudinal snake. Flat HERA refers to a model where all vertical bends are removed.

1. Find all snake combinations for a flat ring which lead to a spin tune of $\nu = 1/2$.
2. Compute the spin tune on the closed orbit for the non–flat HERA ring and filter on small spin tune fluctuations away from $\nu = 1/2$.
3. Compute 1st order opening angle for the non–flat HERA proton ring and filter on small opening angle of the equilibrium spin distribution.
4. Compute the opening angle by 3rd and 5th order normal form theory for the snake combinations which are left after all these filters.

To obtain the results depicted in table 4 we neglected longitudinal phase space motion and performed this analysis for all possible combinations of four Siberian snakes, one in each straight section, with rotation angles of π and rotation axes either longitudinal, radial or vertical. Several conclusions can be drawn from these calculations. First of all, our initial worries about big opening angles are in general justified, however, special snake combinations can be found where these opening angles are small. These angles can be computed realistically by high order normal form theory, since the normal form expansion converges. And finally, for the cases of small opening angles, which we found by the filtering technique, the straight forward linear SLIM formalism leads to a good approximation of the spread in polarization direction. This is an important point, since now it is possible to apply the same linear spin matching techniques[1] for optimizing the equilibrium distribution which were so valuable to electron polarization in HERA.

Figure (8) shows how spin matching of the HERA electron ring was used to minimize the opening angle of the equilibrium distribution[23]. Without these techniques, the electron beam would most likely not be polarized today. The same method and the experience collected at DESY with electrons now turns out to be useful for polarized protons.

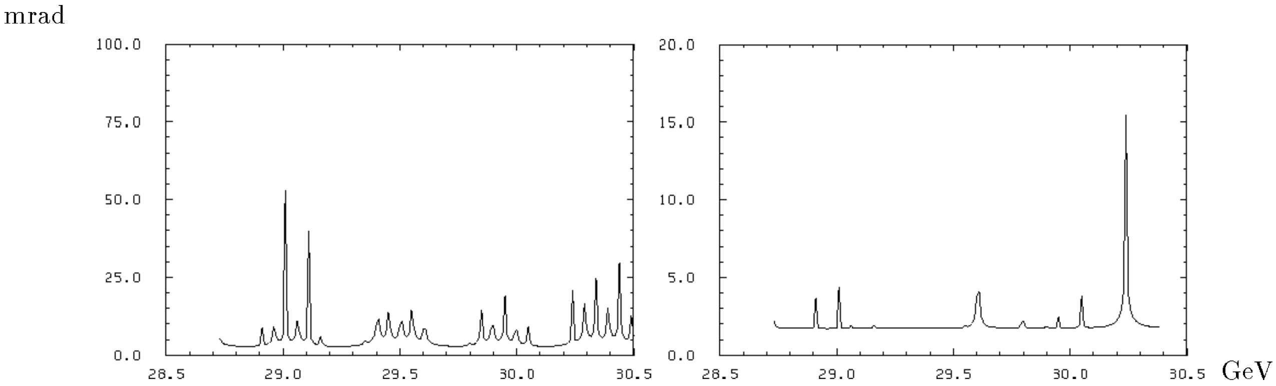

FIGURE 8: Opening angle of the equilibrium spin distribution computed by SLIM for the HERA electron ring. Left: without, Right: with spin matching.

5.2 Divergence of the spin phase space distribution

In order to analyze in detail how the beam optics influences the stable spin direction, the method of stroboscopic averaging has been introduced[25]. The previously mentioned normal form method does not converge close to resonances and for large phase space amplitudes. Stroboscopic averaging is non–perturbative and can therefore also be applied close to resonances, it only uses tracking data and can therefore easily be added to every spin tracking code. Furthermore it converges rapidly. With this method the fluctuation of the equilibrium spin direction over one vertical phase space ellipse was computed. Particles at different points of this ellipse have different equilibrium polarization directions which can be depicted as points on a unit sphere. The resulting closed curve on the unit sphere was projected on the horizontal plain and depicted in figure (9). The variation of the opening angle with vertical phase space amplitude computed by stroboscopic averaging is also depicted in figure (9,bottom right). It is planned to apply this innovative method to analyze and understand the optical reasons for big opening angles. Such an understanding is obviously essential in order to design optical devices which compensate destructive effects on the spin distribution.

6 THE SENSITIVITY OF POLARIZATION TO MISALIGNMENTS

The sensitivity of the average polarization of a proton beam to misalignments of beamline elements has been analyzed by N. Golubeva and V. Balandin. Figure (10,middle) shows the closed orbit deviation produced by a random set of misalignments. The drop of average polarization can be seen when comparing the top figure, showing beam transport without misalignments, with the bottom figure for beam transport through a misaligned HERA ring at 820GeV. In both cases 2 snakes (radial in the East and longitudinal in the West straight section) were incorporated. For both curves an initially completely polarized beam was assumed. This result is quite promising, since here the polarization does not drop by a frightening amount when quite realistic closed orbit deviations are present. However, the displayed figure does not include any closed orbit correction and therefore the simulated misalignments were much smaller than actual element misalignments in HERA. A closer analysis with various schemes for closed orbit corrections are necessary.

7 FURTHER QUESTIONS TO BE STUDIED

Several questions could be very important and I therefore want to mention the following list of topics that will have to be studied in the near future:

- How does a low energy chain ($\leq$ 20GeV) compare in detail to previous successful projects?
- Design of partial snake which can be ramped to a full snake for PETRA.
- How can the vertical bends in HERA (5.74 mrad) be compensated for spin motion and rotator action?
- Can we improve the symmetry of HERA-p?

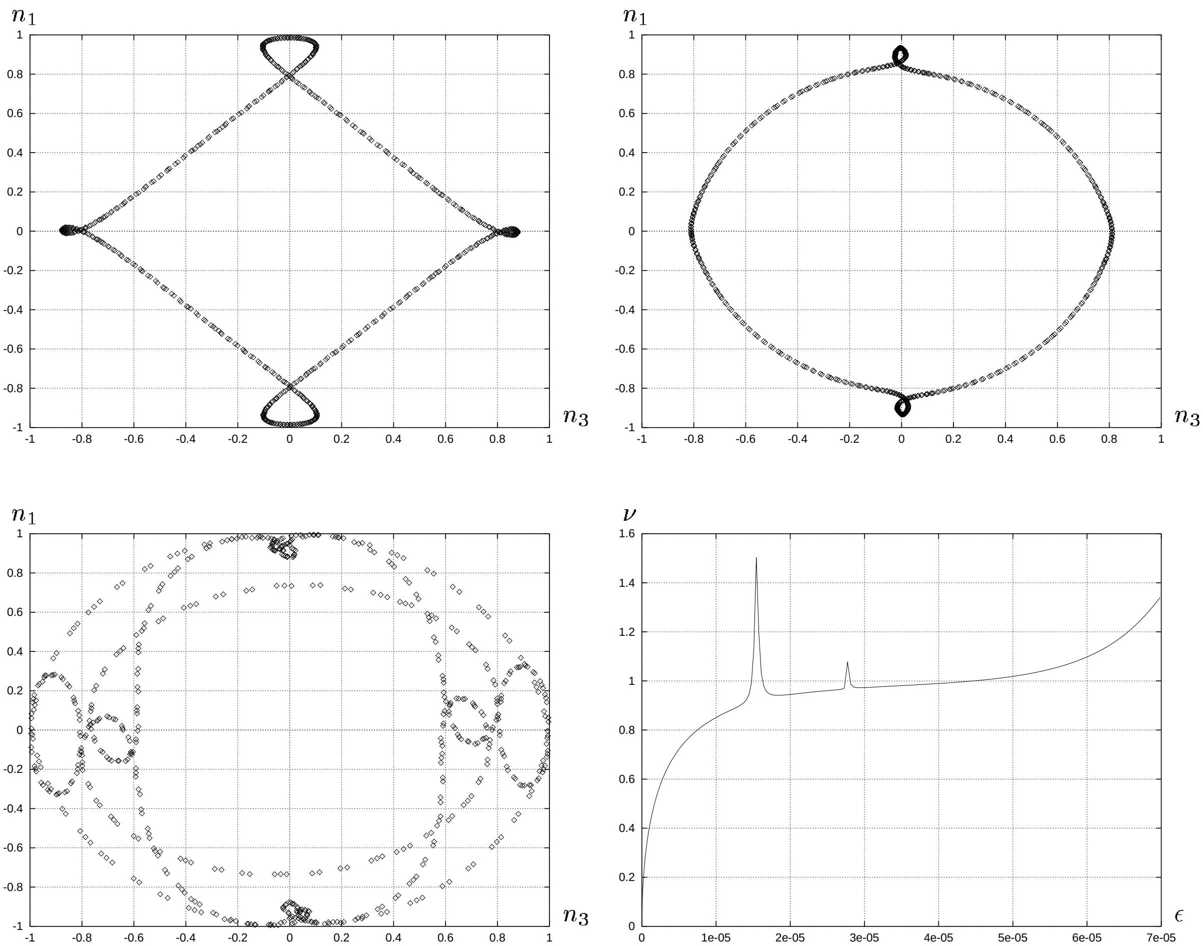

FIGURE 9: The equilibrium spin direction projected on the horizontal plane for particles with a normalized vertical emittance of 16, 36, and 64 πmm mrad from top left to bottom left. Bottom right: Average opening angle of the equilibrium phase space distribution as a function of vertical emittance in πmm mrad.

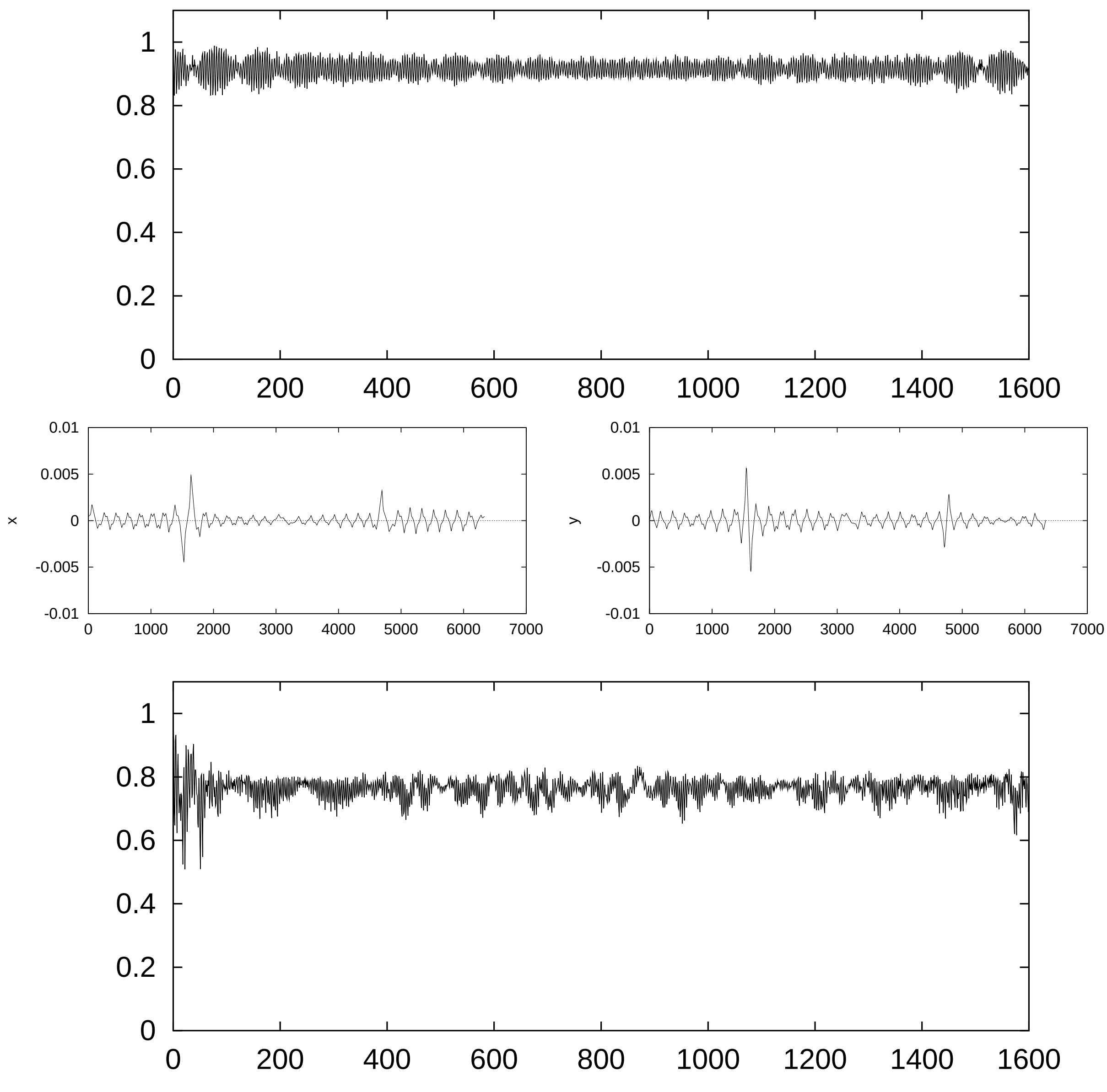

FIGURE 10: Top: Transport of an initially completely polarized beam. Middle: The closed orbit deviation produced by random misalignments. Bottom: The resulting loss in polarization.

- Judge the influence of nonlinear fields at low energy (40GeV).
- Further study of snake placement.
- Simulate acceleration in HERA.
- Further study of the destructive effects of misalignments?
- How destructive is the beam–beam–effect, can spin–beam–beam matching be applied?
- How does the diffusion of the beam influence spin diffusion?

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