Siberian Snakes and spin rotators in the acceleration and storage of high energy spin polarized beams *

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This article provides a pedagogical review of spin rotators and Siberian Snakes used in the manipulation and attainment of stored high energy spin polarized beams (SHESPB).

1. INTRODUCTION

Experimenters have long dreamt of access to SHESPB of electrons, positrons and protons to study the spin structure of nucleons and of the weak interaction etc, but with improvements in our understanding of spin–orbit dynamics and ability to control spin with "spin rotators" in the last decade, high energy stored longitudinally spin polarized $e^{\pm}$ beams can now be provided routinely. Moreover, with the availability of practical superconducting "Siberian Snake" magnets we are now on the verge of storing spin polarized proton beams of over 200GeV at RHIC. In this article I will restrict myself to high energy beams in storage rings and I will limit myself to a simple pedagogical discussion, aimed at non–experts, of the *raison d'etre* for, and basic aspects of, rotators and snakes and I will give examples. For the subtleties of spin–orbit dynamics I direct the reader to [1,2].

2. BASIC SPIN DYNAMICS

The goal is to obtain SHESPB with chosen polarization directions at the interaction points (IP's) of storage rings and since accelerators and storage rings rely on electric and magnetic fields to accelerate and guide particles, we begin by describing how these fields influence spin motion. The expectation value $\vec{S}$ of the spin in the centre of mass of an electron or proton moving in electric and magnetic fields precesses according to the T–BMT equation [3,4]. In a purely magnetic field with components $\vec{B}_{\|}$ and $\vec{B}_{\perp}$ parallel and perpendicular to the orbit this is $\frac{d\vec{S}}{ds} = \frac{e\vec{S}}{mc\beta\gamma} \times ((1+a)\vec{B}_{\|} + (1+a\gamma)\vec{B}_{\perp})$. The variable s is the distance around the ring and $a = (g-2)/2$ is the gyromagnetic anomaly; for electrons $a \approx 0.00116$ and for protons $a \approx 1.7928$. The other symbols have their usual meanings. This equation shows that for motion perpendicular to the field, the spin precesses w.r.t. the particle orbit at a rate $a\gamma$ faster than the corresponding rate of orbit deflection around the field. This relation is the key to the design of practical rotators at high energy and to understanding spin–orbit dynamics.

*Invited talk at the conference PANIC99, Uppsala, Sweden, June 1999.
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Electrons (or positrons) and protons become polarized in very different ways. Electrons become polarized *in situ* at the final energy by the Sokolov–Ternov effect (ST) [1], i.e. by the emission of spin–flip synchrotron radiation. There are also depolarization effects so that the attainable polarization is the result of a balance between the ST effect and depolarization [2]. The polarization can be particularly small near to the spin–orbit resonances to be explained below. Polarized protons must be injected prepolarized from a suitable source and then accelerated through the accelerator chain to high energy.

3. SPIN ROTATORS IN ELECTRON STORAGE RINGS

The polarization in an $e^{\pm}$ ring builds up to be aligned along the periodic solution to the T–BMT equation on the closed (i.e. periodic) orbit of the ring. This solution is denoted by $\hat{n}_0(s)$ and in a storage ring consisting only of horizontal bending magnets (with vertical fields), and various kinds of focussing and defocussing magnets, $\hat{n}_0$ is vertical; the periodic, i.e. stable solution is (obviously) simply parallel to the bending fields. It can also be shown [2] that the ST polarization is maximized and the depolarization minimized if $\hat{n}_0$ is vertical in as much of the ring as possible. However, high energy physics experiments usually require longitudinal polarization.

The solution to this dilemma is to install a magnet system called a "spin rotator" just before an IP, to rotate the polarization from the vertical to the longitudinal and to install an "anti–rotator" just after the IP to rotate the polarization back to the vertical. Thus $\hat{n}_0$ is longitudinal at the IP and vertical in the arc. The *value* of the polarization is the same all around the ring. Rotators can be viewed as devices for designing non–trivial s–dependence for $\hat{n}_0$.

At high energy the best way to rotate spins is to use a string of interleaved horizontal and vertical bending magnets as depicted in figure 1. This illustrates the spin motion in the spin rotators in use at HERA [5]. The total horizontal bend is about 27 mrad, replacing two bending magnets at the end of the arc. The vertical bends, with beam deflections of the order of 10 mrad, generate a closed vertical bump in the beam. Such small orbital deflections almost commute, with the result that the horizontal and vertical bends act almost independently on the orbit. However, the corresponding spin rotations w.r.t the orbit are, as we have seen, $a\gamma$ times larger. At 27.5 GeV in HERA, for example, $a\gamma \approx 62.5$. Therefore the spin rotations around the horizontal and vertical rotator fields do not commute and by careful design the polarization can be rotated from the vertical to the longitudinal with a minimum of orbit deflection. Furthermore the orbit deflections decrease with energy so that spin rotation in dipole rotators becomes easier at higher energy. The geometry and fields of the HERA rotators can be adjusted for running over a range of *fixed* energies.

The HERA rotators have been supplying up to 70 percent $e^{\pm}$ longitudinal polarization to the HERMES experiment since 1994 [6] and now that this has become routine, two more pairs of rotators will be installed for the H1 and ZEUS experiments in the year 2000.

At energies of just a few GeV, $a\gamma$ is small so that dipole rotators must cause large orbit distortion in order to produce enough spin rotation. It is then better to use combinations of solenoids and dipoles as described in [7]. Since the rate of spin precession in solenoids decreases with energy this kind of rotator is usually inappropriate at high energy.

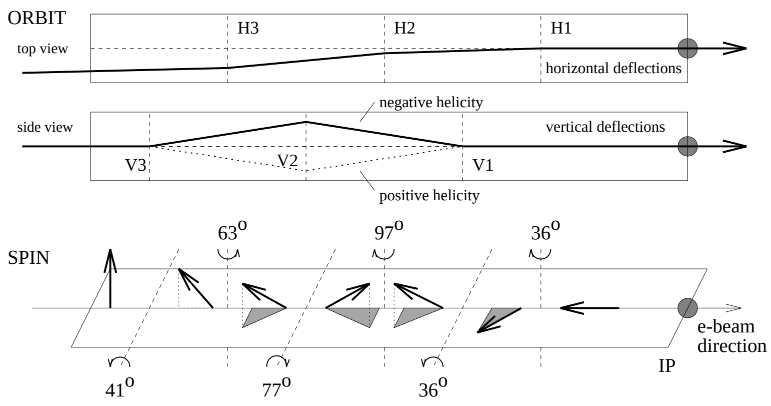

Figure 1. The orbit and spin motion in a HERA spin rotator at 27.5 GeV [6].

4. SIBERIAN SNAKES IN PROTON RINGS

So far, for brevity, we have ignored the effect on spins of the radial fields in the quadrupoles experienced by the spins as they execute vertical betatron motion and/or if there is vertical closed orbit distortion. These fields tend to tilt spins from the (stable) vertical direction and for particles circulating for many turns the total disturbance to a spin can grow to become very big if there is coherence between the natural spin precession around $\hat{n}_0$ (i.e. around the vertical in a simple ring without vertical bends) and the oscillatory motion in the beam characterised by the spin-orbit resonance condition: $\nu_{spin} = m + m_x\, Q_x + m_z\, Q_z + m_s\, Q_s$ where the m's are integers, the Q's are respectively the horizontal, vertical and longitudinal tunes (frequencies) of the orbital oscillations and the "spin tune" ν_{spin} is the number of precessions around $\hat{n}_0$ for one turn around the ring. In a simple machine without vertical bends $\nu_{spin} = a\gamma$ and this increases by unity for every 523 MeV (440 MeV) increase in energy for protons (electrons). Therefore by accelerating protons from the source to the final energy of typically hundreds of GeV, the beam crosses hundreds or even thousands of spin–orbit resonances and each resonance crossing can potentially destroy the polarization. This effect will be especially strong in the fields used at high energy: at hundreds of GeV, $a\gamma$ is in the hundreds. Then a 1 mrad change in the direction of a particle can lead to tens of degrees of spin rotation.

Depolarization at resonances can in principle be largely controlled by installing Siberian Snakes. These are special spin rotators designed to rotate spins through 180 degrees, independently of energy, around an angle in the horizontal plane. So snakes flip vertical polarization from up to down and *vice versa.* They are so named because the concept originated at the Institute of Nuclear Physics in Novosibirsk with Derbenev and Kondratenko [8], and because the particle orbits inside snakes tend to be snake–like. With a suitable distribution of snakes in the ring, the number of spin precessions around $\hat{n}_0$ is a half integer independently of energy so that resonance crossing during acceleration is avoided and there is a much better chance to preserve the polarization. From another point of view, the action of a snake is analogous to that of a spin flipping magnetic field used in a nuclear magnetic resonance set–up to cause "spin–echo" whereby disturbances to spins can be made to cancel. An instructive sketch of spin motion in the presence of snakes can be found in [9].

In contrast to rotators in $e^{\pm}$ rings running at fixed energies, snakes must provide a rotation of 180 degrees over a large energy range during acceleration. Moreover, during acceleration it is impractical to change their geometry or fields. Thus at the lowest energy (at injection) of the storage ring the orbit distortion can be very large and inconvenient so that a key aspect of snake design is the minimization of orbit distortion. This, in turn, favours short magnets with very high fields. Snakes can be formed out of strings of dipoles, by elaborating on the rotator concept discussed above [10] but perhaps the most elegant and compact solution involves the superconducting helical (i.e. twisted) dipoles to be used at RHIC [11,12].

The efficacy of snakes has been demonstrated experimentally at very low energy at the IUCF [13] but so far there has been no experimental demonstration at very high energy. However, spin–orbit tracking simulations indicate that with careful choice of number and layout, snakes should perform as advertised [14,11]. Snakes are also essential for stabilizing spin motion at the top (collision) energy [14]. Of course, proton rings also need normal rotators at the IP's. They would be turned on adiabatically at the top energy.

In conclusion, exciting times lay ahead. Longitudinal $e^{\pm}$ polarization will be provided for three experiments in HERA and there is every likelyhood that high energy proton polarization will be attained at RHIC in the next few years. Perhaps one day we will even have both polarized $e^{\pm}$ *and* protons at HERA [14].

ACKNOWLEDGEMENT

I thank M. Berglund for carefully reading the manuscript.

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