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A PROPOSED TEST OF THE SPIN SPLITTER EFFECT IN HERA-p

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Abstract

A first proposal is presented on how to test and use the Stern-Gerlach-induced selfpolarization mechanism ("Spin-Splitter" effect) in HERA-p. The paper is divided into two parts. First it is shown that the polarization can be build up at the edges of the beam within a few minutes. The effect can be measured by a carbon fibre polarimeter. After the demonstration of the effect and after the basic measurements the knowledge of the induced particle and spin motions can be used to polarize the beam completly within a few minutes.

1 Introduction

The gradient fields in a storage ring (quadrupoles, sextupoles, endfields etc.) influence the trajectory of the particle via the spin of the proton (Stern-Gerlach effect). The use of the Stern-Gerlach effect for generating polarized (anti-)protons in a storage ring was discussed several years ago in various publications [1] [2] [3]. Up to now no serious efforts were undertaken in an accelerator to investigate this effect experimentally. There are two reasons for this:

I.) the effect is very small compared to other disturbances in a proton ring and the measurement seems to be very difficult;

II.) the interest in stored polarized (anti-)proton beams has so far been relatively limited: electron polarization had first priority.

As far as the second reason is concerned, the situation has recently undergone a change. Stored polarized electron beams and accelerated polarized electron beams up to 50 GeV with a high degree of polarization are now considered state of the art. Remedies exist, at least on paper, even against possible future difficulties (beam-beam depolarizing effect, depolarization in LEP II due to a high energy spread and depolarization due to wake-field effects in linear colliders) in the event that these effects could seriously limit the degree of polarization.

As a consequence, stored polarized proton beams moved into the center of interest. The standard technique (generating polarized protons at low energy and accelerating them through the various pre-accelerators to the maximum energy) is one possibility [4]. The pre-accelerators and the final storage ring have to be equipped with Siberian-Snakes and pulsed quadrupoles. However, this modification of existing accelerators is rather expensive. In addition, this technique cannot be applied to stored anti-proton beams since polarized anti-proton sources do not exist. Therefore, the question concerning a first quick test of the self-polarization of (anti-)proton beams becomes more and more important.

2 The strength of the Stern-Gerlach effect in HERA

In principle, all gradient fields in the direction of motion or perpendicular to the direction of motion of the particle generate Stern-Gerlach kicks: they can induce synchrotron or betatron oscillations, resp. Recently a general description on the effect for both longitudinal and transverse fields and arbitrary spin direction was published [7]. The results, independently reconfirmed by G. Hoffstaetter [5], are the following. A gradient field $G_{||}$ in the beam direction of a certain length l produces an energy spread in the beam:

$$\left(\frac{\Delta E}{E}\right)_{induced} = \mu \frac{G_{||}.l}{\beta^2 m_0 c^2} \tag{1}$$

μ is 8.8×10^{-14} MeV/T. A transverse spin and a transverse gradient produces a kick

$$\left(\frac{\Delta p}{p}\right)_{induced} = \mu \frac{G_{\perp}.l}{\beta^2 \gamma m_0 c^2} \tag{2}$$

$G_{\perp}$ is the transverse gradient.

In the very first publications of the spin splitter effect [1],[2] it was assumed that full polarization can only be obtained when particles with different spins are completely separated in space. The time in which this happens is in the order of hours under realistic assumptions. Considering this time as polarization time the effect was considered as too slow. Several effects could destroy the polarization build-up during this time: natural depolarization due to imperfections, intrabeam scattering, fluctuations of power supplies etc. This assumption (time needed for full separation = polarization time) was recently questioned by Y. Derbenev 6] in a remarkable talk at DESY on the spin-splitter effect.

His basic idea is the following: the spin splitter effect induces spin related particle oscillations (betatron or synchrotron oscillations). The phase of these induced motions is related to the spin direction. When a system exists which is able to detect the phase oscillations of the particle and amplify them via a feedback system the separation can be increased. Generalizing this idea nonlinear elements of any kind can be used to amplify the oscillations.

Another idea can be added to this technique: in the separation process particles with different spin directions perform particle oscillations with different phases. The particles and therefore the spins see different fields. The spins move differently and this can be used to polarize the beam completely in a short time.

Summarizing these statements it is no longer assumed that a full separation of particles with different spins is required in order to obtain a high degree of polarization. In a few minutes the partial separation of particles with different spins can be used to polarize the beam completely.

3 The time scale in which the polarization takes place

The general statement given in the last chapter will be explained in the following in more detail. In a first example the HERA quadrupoles could be used as the gradient fields driving the spin-splitter effect. In order to do so the machine has to operate on a horizontal spin resonance.

$$a.\gamma = n \pm Q_x \tag{3}$$

Q_x is the horizontal tune of the accelerator. This resonance is not depolarizing when the machine is carefully adjusted. Vertical spin resonances cannot be used since they are depolarizing. In the following it is assumed that ways are found to allow the kicks to add up over many revolutions.

HERA has 224 quadrupoles, the gradient at 820 GeV/c is 91.18 T/m and the length of each quadrupole is 1.861 m. The induced kick is according to formula (1)

$$4,1 \times 10^{-15}\ rad/revolution$$

or

$$7 \times 10^{-7} rad/hour$$

The induced Stern-Gerlach kicks change the beam emittance ϵ

$$\sigma' + (\Delta\sigma')_{induced} = \sqrt{(\epsilon_0 + (\Delta\epsilon)_{induced})\beta} \tag{4}$$

β is the betafunction. The change in beam size is

$$(\Delta\sigma)_{induced} = \beta(\Delta\sigma')_{induced} \tag{5}$$

The separation of the particles with the different spin directions is shown in fig. 1.

The separation shows first at the edges of the beam. This allows to measure the effect during the build-up time. The arrangement how to measure the effect is shown in fig. 2 [8]. A carbon fiber is moved toward the beam from one side and the particles at the edges of the beam undergo scattering. A detector measures the asymmetries of the scattered particles and therefore the degree of polarization like in any standard polarimeter.

The detector has to be gated with the betatron frequency. The resolution of the position of the carbon wire could be 1μm. Following formula 3 and assuming a betafunction of 100 m a visible measuring effect could be obtained after less than one minute. As a result HERMES-B could have polarized beams under the conditions that the machine is correctly tuned and the detector is gated with the betatron frequency after a build-up time of minutes.

The longitudinal Stern-Gerlach effect is much stronger according to equation (2) but has the disadvantage that additional elements have to be installed: there are no longitudinal separating fields except the fringe fields of the bending magnets.

Conte, Penzo and Pusterla [7] have proposed to use the magnetic gradient in a TE cavity to polarize the beam. The induced energy spread can be calcuated from equation (1).

The proposed layout is shown in fig. 3.

In the proposal the spin direction is vertical in the arcs. The separating cavity is placed between 2 spin rotators. The spin rotators can also be used for the experiment.

In the following the separation time will be estimated. Assuming that it is possible to install somewhere in the acccelerator a section with a dispersion of 10 m. The energy spread in HERA at 820 GeV is about 5×10^{-5}. Recently it was claimed that it is possible to build TE cavities with a gradient of 100 T/m [9]. The cross section of the beam is $5 \times 10^{-5} \times 10$ m or 500 μm. A 2m long TE "linac" is required to separate the tails within 5 minutes.

Summarizing these statements: it seems to be possible to separate the spins at the edges of the beams within minutes and it also seems to be very simple to measure this separation by using HERA-B type scattering wires and by gating the detector with the beam frequencies (betatron- or synchrotron frequency). After the first test strategies have to found to polarize the beam completely.

4 Obtaining beams with a high degree of polarization with the test facility

Despite the fact that the separation at the edges of the beam might occur in a few minutes full separation requires hours. The separaration might be destroyed in this time by other competing effects like intrabeam scattering, fluctuation in the power supplies etc.

Recently Ya. Derbenev [6] questioned the need of full separation in order to fully polarize the beam. With this statement he brought the spin splitter from a theoretical concept close to a practical design. The concept Derbenev presented will be published by the author in a separate paper. Here only the basic idea is explained. more from a pedagogical point of view than from a fundamental point of view.

For the sake of simplicity in the following the cavity solution is chosen. This is purely arbitrary and the ideas can be applied in a analogue way to the transverse case. Particles with opposite spin directions perform synchrotron oscillations with opposite phases. Since these oscillations are induced by the cavity the phase of the oscillations is well known. As a result each particle performs two sorts of synchrotron oscillations: a coherent, induced one (due to its polarization) and an incoherent, natural one with arbitrary phase and amplitude:

$$\Delta E = \pm\Delta E_{induced} sin(\omega_s t) + \Delta E_{natural} sin(\omega_s t + \phi) \qquad (6)$$

ϕ and $E_{natural}$ have arbitrary values. The plus or minus sign depends on the spin of the particle. Since the phase of the induced oscillations is known, these oscillations can be amplified with a feedback system. A detector mesasures the quadrupole oscillations of the beam and compares the detected signal with a signal deduced from the excitation. The phase correct signal is amplified and the oscillations are enhanced by this special feedback system.

Such a system does not allow to obtain beams with 100 % polarization but with a high degree of polarization.

This basic idea can be modified in many ways. In the above given example the induced synchrotron oscillation is the vehicle which is used to increase the separation. For symmetry reasons it must be also possible to use the spin motion as the separation vehicle. This is shown as an example in the following.

In a first step it is assumed that the beam consists of only two particles without natural synchrotron oscillations. Before the spin separating cavity is switched on they are supposed to have the same energy and $E_{natural}$ (equation(6)) is zero. After the cavity is switched on and the splitting commerces the two particles perform synchrotron oscillations with opposite phases.

After a while the splitting is stopped and the spin is quickly rotated in the ring into the horizontal direction by a beam bump similar to the concept used for polarization handling in the SLC arcs at SLAC [10]. Now the spins of the particles perform oscillations with different speed. The number of spin revolutions per particle revolution is

$$G(\gamma + \Delta\gamma) = n_1$$

and

$$G(\gamma - \Delta\gamma) = n_2 \tag{7}$$

Since the synchrotron oscillations have opposite phases there exist in general moments where both spins are either left or right of the x axis. And since the phase of the excitation is known it is easy to polarize such a beam by applying a weak field similar to a depolarizer. The field with the correct frequency lifts both spins into the positive vertical direction and polarizes the beam.

In the next degree of complication it is assumed that $E_{natural}$ is no longer zero. In this case the simple picture is no longer valid, especially in the case when $E_{natural}$ is significantly larger than the amplitude of the induced synchrotron oscillations.

A simple computer simulation shows that applying a field with the correct frequency and the right phase with the "de"polarizer magnet the beam can be polarized as before. A computer simulation of the vertical polarization growth shows for HERA a build-up of polarization even when the induced synchrotron oscillation have 1/100 of the amplitude of the natural oscillations. The build-up time is significantly delayed by the natural oscillations and therefore, as in the case before, the total polarization will be less than 100%.

This is in principle the same idea as before but with the exception that the spin is now directly affected and not via the synchrotron oscillations.

In principle numerous of such effects are thinkable and it will be a matter of detailed computer simulations to select the best technique for the experiment.

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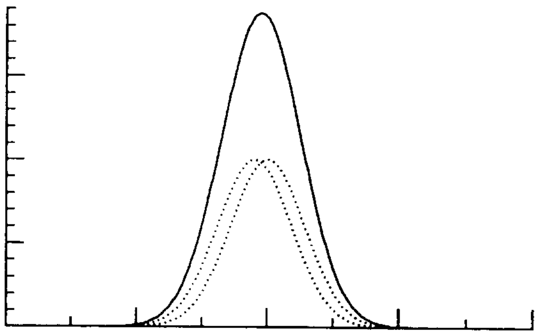

Figure 1: *Example of spin separation in the tails of a Gaussian beam. The dotted lines represent the distribution of the two spin directions, the solid line the sum of the two distributions. The separation effect first shows up in the tails of the beam.*

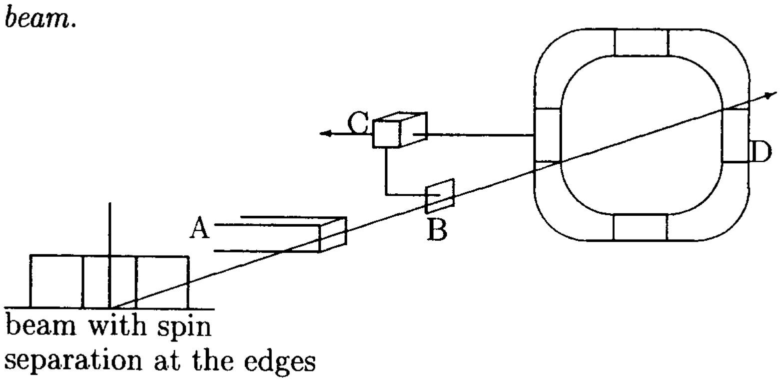

Figure 2: *Measurement of the spin separation at the edges of the beam. A carbon target is moved from one side into the beam and the fully polarized particles at the edges are scattered. The distribution of the scattered particles is measured by the detector D. B is a pick-up station for the betatron oscillation. The detected raw-signal is gated with the betatron frequency by C.*

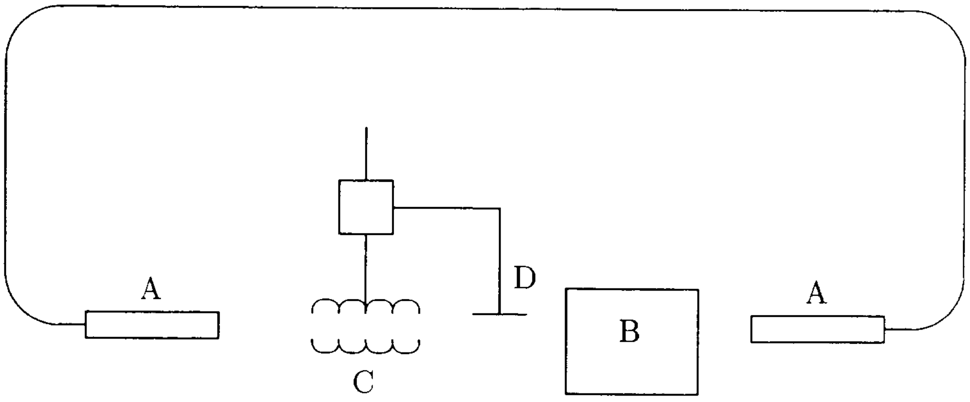

Figure 3: *The proposed test with a TE cavity. The beam has vertical polarization in the arcs. In the polarizer region the spin is rotated into the longitudinal direction by spin rotators (A). The TE cavity C is used to induce spin dependent synchrotron oscillations. D is a synchrotron frequency pick-up. B is a high energy detector. The spin rotators can be used both for the polarizer and for the experiment.*

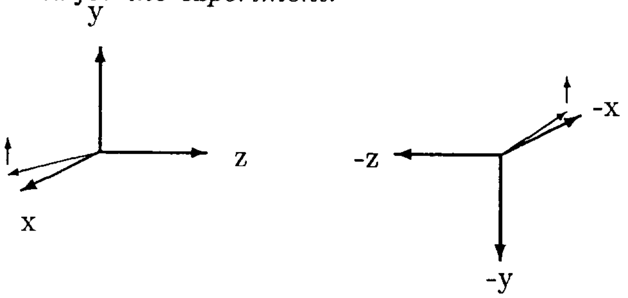

Figure 4: *The beam is moving into the positive z-direction. Particles with spins aiming into the positive y axis are rotated in the arc into the horizontal x axis. At the same time particles with spins aiming into the negative y axis are rotated into the negative x axis. The spin of both particles oscillate around the x-axis. Opposite spin directions correspond at any time to opposite energy deviations. A weak RF field in the direction of the x axis moves both spins towards the positive y axis. The beam becomes vertically polarized.*