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SELF-POLARIZATION OF PROTONS IN STORAGE RINGS

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ABSTRACT

It is shown that stored proton or heavy ion beams can be polarized by spatially separating particles with opposite spin directions. The separation is done by the quadrupole fields with the help of the bending magnets in between. Although the separation of one quadrupole is weak, it is shown that under certain circumstances the effect adds up over many quadrupoles and revolutions. This method can replace the existing technique for obtaining polarized proton or heavy ion beams, where low energy polarized beams are first generated by a source, and then accelerated through numerous depolarizing resonances up to the final energy. Although the method is not limited to large machines, it works best with rings having large diameter, low vertical emittance and superconducting quadrupoles with strong gradient.

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1. INTRODUCTION

During the last years the polarization has been used in various electron-positron storage rings for a variety of fascinating experiments: the determination of the half integer spin of the quark [1] and the precise measurement of the rest masses of the J/ψ - and the ϵ family [2]. All these measurements were based on the Sokolov-Ternov effect [3]: the stored electron (or positron) beam becomes polarized by the emission of photons. In practice various depolarizing effects [4] destroy the polarization. These effects are caused by the interaction of the spin with the different magnetic fields along the particle trajectory. Extended studies on this effect (called in several papers "spin orbit coupling") have given a deep insight into the mechanism. Manipulating the polarization by manipulating the particle trajectories is now a standard tool in electron-positron storage rings for obtaining polarized beams [5].

Extended studies on the possibility of obtaining stored polarized proton or ion beams have been performed [6]. Since there is no self-polarization mechanism known up to now, the polarized protons have to be generated by a polarized source and accelerated to the energy at which the beam is stored. The acceleration of polarized protons has been studied in three synchrotrons: ZGS in Argonne [7], SATURNE in Saclay [8] and recently AGS in Brookhaven [9]. Crossing of various spin resonances during acceleration leads to depolarization. The higher the final energy, the higher the number of the crossed depolarizing resonances and the lower the degree of polarization after the acceleration. Nevertheless, there is hope that the installation of the so-called Siberian Snakes, invented by Derbenev and Kondratenko [10], can drastically reduce the depolarizing effects.

In this paper a different approach for obtaining stored polarized proton beams is presented. The unpolarized beam is polarized only at the energy of storage. This self-polarization is based on the Stern-Gerlach effect: in an inhomogeneous magnetic field the spins of particles, aligned parallel or antiparallel to the field, are deflected in opposite directions and become spatially separated. A conventional storage ring has magnets with inhomogeneous fields: quadrupoles. Considering one single quadrupole, particles with different spin directions are deflected by different angles in the quadrupole field. Since this deflection angle is extremely weak a quadrupole with opposite polarity, following the first one, would exactly cancel the effect of the first. Fortunately, there are bending magnets in between the quadrupoles (in the arc). The bending magnets rotate the spin and under certain conditions they rotate the spin in such a way, that the kicks obtained in the quadrupoles add up, following the sign of the

betatron motion. The spin precession has to fulfill the condition: $((g-2)/2)\gamma = (2n+1)Q_y$, where $g = 2.79$ is the proton g -factor and Q_y the vertical Q -value. When the kicks add over many quadrupoles and further over many revolutions, the vertical separation of the particles with different spin directions will become macroscopic. One polarization direction can now be dumped or flipped and the beam becomes polarized with spin in the horizontal plane. The method bears some resemblance with double resonance methods in solids, where one resonance is used for driving or detecting another. Here the spin resonance is being used for driving the vertical betatron resonance; their coupling is through the very weak force on the magnetic dipole $\mu = g\mu_N$ ($\mu_N = eh/2m_p c$ is the nuclear magneton) of the proton: $\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}) \approx (\vec{\mu} \cdot \nabla)\vec{B}$. Because the damping of the betatron motion is very small (the main contribution being synchrotron radiation), a weak force can be sufficient for the buildup of spatial separation for the beam components of opposite polarization.

Although this seems to be straightforward for a monoenergetic beam, it has to be proved that the method is also practicable with real beams consisting of particles with different energies. This will be shown in the present paper.

2. SEPARATION OF PARTICLES WITH DIFFERENT SPIN DIRECTIONS

The field of a quadrupole can be described in first order by the following equations:

$$\begin{aligned} B_x &= -by \\ B_y &= bx \end{aligned}$$

The coordinate system is explained in Fig. 1. The force on the magnetic dipole is [11]

$$\vec{F}_\mu = \nabla(\vec{\mu} \cdot \vec{B}) = b\nabla(-\mu_x y + \mu_y x) = b(\hat{i}\mu_y - \hat{j}\mu_x)$$

and the additional deflections of the particle in the x - z and y - z planes are, respectively,

$$\begin{aligned} x' &= -b\mu_y \Delta L/E \\ y' &= b\mu_x \Delta L/E \end{aligned}$$

where μ_x and μ_y are the projections of the magnetic moment along the x

and y directions, ΔL is the length of the quadrupole and E is the beam energy. We note that when the spin points in the direction of the beam, there is no deflection; when it points along x the particle is deflected vertically, and when it points up the deflection is horizontal. The radial field gradient b is positive for quadrupoles focusing in the vertical plane and negative for those focusing in the horizontal plane.

In between the quadrupoles there are bending magnets (Fig.2) with homogenous field. The motion of the spin in a homogenous field is described by the BMT (Bargmann-Michel-Telegdi)-equation [12]:

$$d\vec{s}/dt = (q/m\gamma)\vec{s} \times ((1+a)\vec{B}_{||} + (1+a\gamma)\vec{B}_{\perp}) \quad (1)$$

here $\vec{s}$ is a unity vector describing the spin direction in the laboratory frame, q is the charge of the particle, m is the rest mass, $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz-factor and $a = (g-2)/2$. $\vec{B}_{||}$ and $\vec{B}_{\perp}$ are laboratory frame fields parallel and perpendicular to the motion of the particle. The required integrated field strength for a 90° spin rotation for protons is 2.7 T·m (this is not too different from electrons : 2.3 T·m). This statement is valid independent of the energy of the particle in the relativistic limit.

The spin motion from one quadrupole to the next is shown in Fig. 3. It is assumed for a moment that the integrated field strength of one bending magnet is 5.4 T·m. In this case the spin precesses 180° around the vertical y-axis. Therefore both the gradient of the quadrupole and the x-component of the spin have different signs from one quadrupole to the next: the separation from one quadrupole to the next between the two possible spin directions becomes stronger. The y-component of the spin does not change sign from one quadrupole to the next, but the corresponding gradient does: the particles with opposite vertical spin directions are not separated.

We summarize these statements: under the assumed conditions particles with opposite horizontal spins become vertically separated.

This formula will be illustrated in the following for a magnet design discussed for the SSC [13] :

Field-gradient 105 T/m

Magnetic length of the quadrupole 5 m

For 1 TeV we have $x' = 4.6 \cdot 10^{-17}$ rad per magnet. In the following a ring with 100 km circumference and 1000 quadrupoles is considered. When the deflection of each quadrupole adds to the previous deflections, the total deflection per revolution is $4.6 \cdot 10^{-14}$ rad. The beam cycles $3 \cdot 10^3$ times per second in the assumed machine with a circumference of 100 km. After one second the separation of the two spins will be $7.2 \cdot 10^{-5}$ mm. The separation

of the two polarization directions will become 1 mm after approximately 3.85 hours.

The general formula for the build-up of the separation is

$$dx/dt = n \cdot (\Delta L) \cdot \mu b L f / (4EQ_y), \quad (2)$$

where x is the separation, n the number of quadrupoles, μ is the magnetic moment, $b = \partial B / \partial r$ the radial gradient in the quadrupole, ΔL the length of the quadrupole, L the circumference of the machine, f the cycling frequency, E the energy and Q_y the vertical Q-value.

When the gradient scales with energy (which is in general the case) the separation time is a machine constant.

In order to obtain a short build up time the vertical emittance and therefore the vertical beam height must be small. The polarization time can also be increased by installing alternating gradient fields in the bending magnets. The magnitude of the additional gradient fields can be easily derived from formula (2). The required gradient for speeding up the polarization build up by a factor of 2 is 6.5 T/m distributed all over the ring, when it is assumed that 80 km of the circumference are filled with 5 T bending magnets.

Finally, two questions have to be answered:

- a) The spin precession of a proton in a superconductive storage ring is violent. In a 5 T bending magnet the spin precesses approximately 180° around the vertical axis in one meter. What happens when the spin precession in one bending deviates from $(2n+1)\pi$?
- b) The beam consists of particles with slightly different energies and therefore slightly different spin precession angles. The deviations in the precession angle add over many bending magnets and revolutions and the net polarizing effect of the whole beam is therefore small. How can the spin coherence be maintained?

Both problems can be solved in a similar way. This is shown in the following.

When the spin precession in one bending magnet deviates from $(2n+1)\pi$ (n any integer) the procedure sketched in Fig. 4 can be applied. It is assumed that the spin points in the first quadrupole into the correct direction (A). After passing the bending magnet it is assumed that the spin has rotated by $(2n+1)\pi - \Delta$ and points exactly into direction (B). When a vertical field of 5.4 T·m is applied, the spin is rotated by 180° around the horizontal x-axis and points now in direction C. The field of 5.4 T·m causes a beam deflection of 1.5 mrad (beam energy 1 TeV). The induced vertical closed orbit distortion after a 1m long magnet (180°

precession) is 1.5 mm. After the next precession by $(2n+1)\pi - \Delta$ the spin aims exactly into the original direction A. The closed orbit can now be backbent without influencing the spin (spin and field are parallel and according to the BMT-equation the influence is zero). It is evident that instead of vertical deflecting magnets also closed orbit distortions can be used. The vertical deflecting field is produced by the closed orbit deviation in the quadrupole.

Such a system also would cure the problem b). This can be shown by assuming that the spin in Fig. 4 belongs to the energy-deviating particle and that the particle with the correct energy precesses exactly by $(2n+1)\pi$.

Several of such systems must be installed along the circumference of the ring. Clearly such a system makes it easy to follow the terrain without influencing the degree of polarization.

3. SUMMARY

In an ultrahigh energy storage ring the protons can become polarized due to the well-known Stern-Gerlach effect. The polarization time can be less than one hour when beams with small vertical emittances are stored. The high magnetic field strength of superconducting magnets, and the fast precession rate of the proton magnetic moments make it relatively easy to handle the spins for obtaining a high degree of polarization.

The spin rotation devices causing vertical deflections can be swept with energy, because exact 180° rotations are required only at the final energy of storage. The beam can therefore stay in the centre of the vacuum pipe throughout the acceleration cycle. Furthermore, the vertical bends and the machine lattice can be designed in many different ways, allowing to adopt the machine to the terrain.

In $p\bar{p}$ machines both beams will become polarized. The vertical steering of bunches by fast kickers would allow to choose collisions in pure spin states with spin parallel or antiparallel to each other. By placing dipole magnets symmetrically around intersection points, the spins can be chosen to be in longitudinal or transverse horizontal position at the intersection. These will allow the fast reversal of the spin directions and therefore elimination of slow drifts in the machine and experiment.

In pp colliders with separate rings, it may be possible to choose the spin alignment at the intersections totally independently.

As already mentioned in the introduction the two spin directions, vertically separated in the beam, can be aligned parallel in different ways even without dumping the beam asymmetrically. One possibility is shortly

sketched in Fig. 5. The device consists of one short horizontal bending magnet rotating the spin by 90° and a set of vertical focusing magnets. The spins are rotated into the same (vertical) direction by pulsing the device during one turn of the machine (or for each individual bunch).

How much of the horizontal polarization can be converted into vertical single polarization will depend on the extent of vertical separation, and on the vertical emittance of the beam halves.

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REFERENCES

1. R. F. Schwitters et al., Phys. Rev. Lett. **35** (1975) 1320.
2. B. Gittelmann, Proc. Int. Symp. on Lepton and Photon Interactions at High Energies, Cornell 1983, p. 275.
3. A.A. Sokolov and I. M. Ternov, Sov. Phys. Dokl. **8** (1964) 1203.
4. R. Rossmanith and R. Schmidt, DESY 82-105, and Nucl. Instr. Meth., in print.
5. H. D. Bremer et al., DESY 82-026.
6. For an overview see e.g. A. D. Krisch and A. J. Salthouse, Editors, Higher Energy Polarized Protons Beams, Ann Arbor 1977, AIP Conf. Proc. No 42 (AIP, New York 1976).
7. T. Khoe et al., Particle Acc. **6** (1975) 213.
8. E. Gyorud et al., Proc. Int. Symp. on High Energy Spin Physics 1982, AIP Conf Proc. No 95 (AIP, New York 1983).
9. A. D. Krisch, Proc. Conf. on High Energy Spin Physics 1984 in Marseille, in print.
10. Ya. S. Derbenev and A. Kondratenko, Proc. High Energy Physics

with polarized beams and targets, Argonne 1978, AIP Conf. Proc. No. 51 (AIP, New York 1979) p. 292.

11. e. g. R. Leighton, Principles of modern Physics (McGraw Hill Book Company, New York 1959).
12. V. Bargmann, L. Michel and V. L. Telegdi, Phys. Rev. Lett. 2 (1959) 435.
13. Report on a workshop on Accelerator Issues for a Superconducting Super Collider, Ann Arbor, Michigan (1984).

FIGURE CAPTIONS

Fig. 1 : Coordinate system used in this work.

Fig. 2 : Vertically and horizontally focusing quadrupole magnets with a dipole magnet in between.

Fig. 3 : Spin motion in the magnets of Fig. 2.

Fig. 4 : Vertical bend spin rotator for the correction of dephasing of spins due to energy spread. This device can be thought as a snake without beam returning to the original axis; it makes the spins to echo back to same phase in analogy with spin echo in the NMR of condensed matter.

Fig. 5 : Spin rotation in a pulsed long quadrupole. The vertically separated beam components have their spins rotating in opposite directions. For a well separated beam the transfer to vertical single polarization can be nearly complete.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5