Measurement of Spin Motions in a Storage Ring Outside the Stable Polarization Direction

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Polarized, stored beams are becoming a more and more important tool in nuclear and high-energy physics. In order to measure the beam polarization in a storage ring the polarization vector of the stored beam has to aim, revolution for revolution, over a period of seconds to minutes, into the same, so-called "stable" direction. In this paper measurements at the Indiana University Cooler Ring are described in which, for the first time in a storage ring, oscillations around this stable direction have been measured. The existence and the dynamics of such oscillations are, for instance, important for a new proposed technique for polarizing stored hadron beams.

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The behavior of polarized beams was studied in both electron-positron storage rings [1,2] and proton storage rings [3]. The theoretical description of the polarization in these storage rings is mainly based on a formalism introduced by Derbenev and Kondratenko [4] and later by Chao [5]. The basic concept is the following: All the trajectories in a storage ring can be calculated relative to the closed orbit, a (fictive) trajectory, which repeats itself from one revolution to another. The behavior of the polarization can be calculated in a similar way. A polarization vector is found along this closed orbit which also repeats itself from one revolution to another. This vector is called the n axis.

The thinking in terms of an ever-recurring polarization direction is highly supported by the polarimetry used in storage rings. In order to measure polarization with sufficient accuracy, the measurements have to be performed over several minutes. Even the most sophisticated polarimeter [6] needs seconds to measure the polarization to an accuracy of 1%.

In this paper the first measurements of the stability of time-varying spin components are reported. The practical importance of an oscillating polarization is described elsewhere [7,8]. The measurements were performed at the Cooler Ring of the Indiana University Cyclotron Facility (IUCF) in Bloomington, Indiana. Recently a Siberian snake was installed in this ring for demonstration purposes [3]. The snake consists of a solenoid which rotates the polarization by 180° around the momentum axis and skew quadrupoles. The skew quadrupoles are located on each side of the solenoid. The authors of this paper used this snake, the existing polarized source, and the existing polarimeter [9] to measure time-dependent spin motions.

Particle and spin motion are related to each other. When the particle is deflected by an angle α around a certain axis its spin is rotated around this axis by an angle ψ:

$$\tfrac{1}{2}(g-2)\gamma\alpha = G\gamma\alpha = \psi\,, \tag{1}$$

where g is the proton g factor and γ the Lorentz factor. The numerical value of G is 1.7928. Equation (1) is a direct consequence of the well-known Bargmann-Michel-Telegdi (BMT) equation on the behavior of the spin $\mathbf{S}$ in a magnetic field [10]:

$$\frac{d\mathbf{S}}{dt} = \frac{e}{\gamma m}\mathbf{S}\times[(1+G\gamma)\mathbf{B}_\perp + (1+G)\mathbf{B}_\parallel]\,. \tag{2}$$

For the experiment an energy was chosen in which the spin performs two revolutions during one revolution of the beam: $G\gamma=2$. For a machine consisting only of bending magnets the energy corresponding to $G\gamma=2$ is 108.4 MeV. A more careful analysis [3,11] showed that the solenoid of the cooler also contributes to the spin tune and the correct energy for $G\gamma=2$ is 106.2 MeV. The solenoid of the Siberian Snake rotates the spin around the momentum axis by an angle of 180°. The required field strength for a 180° rotation can be derived from Eq. (2).

The n axis of a machine with a Siberian Snake can be derived from Fig. 1. Using the coordinate system defined in this figure, the n axis is

$$\mathbf{n} = (\sin[\psi(s)], \cos[\psi(s), 0])\,. \tag{3}$$

s is the path length of the trajectory and $\psi(s)$ is the spin

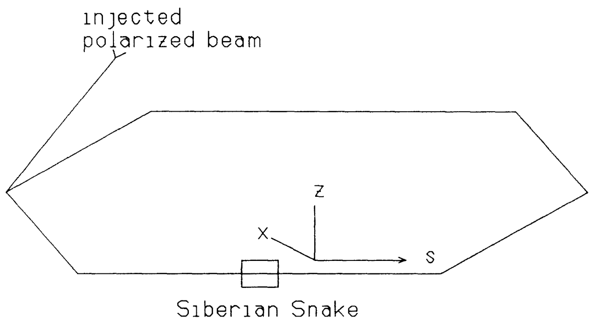

FIG. 1. The coordinate system. The IUCF cooler ring consists of six bending sections and six straight sections. The solenoid of the Siberian Snake is located together with the compensation quadrupoles in one of the straight sections. A spin manipulation system in the injector channel allows the injection of the beam in any polarization direction. For the experiment a polarization vector parallel to the vertical direction was chosen.

precession angle. The spin rotation only takes place in the bending magnets. The expression $\psi(s)$ describes the nonuniform spin advance in the machine.

A beam polarized along the z axis is injected into the storage ring. The beam is cooled by an electron beam and stored for about 10 s. After this time, the beam is directed towards the target of the polarimeter [9]. The target is a 4.5-mm-thick graphite slab. The transverse tail of the bunch is scattered. During the next revolutions the center of the beam is brought gradually closer to the target until the whole beam intercepts with the target (Fig. 2). Afterwards a new beam is injected and the measurement is repeated.

According to Eq. (3) the n axis of the ring with the Snake is in the horizontal plane. The polarization of the injected vertically polarized beam oscillates, therefore, around the n axis:

$$\mathbf{S}=(0,0,(-1)^m)\,, \tag{4}$$

where m is the number of revolutions. For a moment energy oscillations are neglected.

A standard polarimeter integrating over many revolutions would find that the beam is unpolarized: In the time average the vertical spin direction cancels. In order to measure this time-varying polarization the polarimeter has to be gated in such a way that data are taken only every second revolution (Fig. 2). The gate is opened every second revolution for half a revolution. If there is no depolarization, the polarimeter should measure a vertical polarization.

Synchrotron oscillations modify this result significantly. Synchrotron oscillations are energy oscillations around the nominal energy:

$$\left(\frac{\Delta\gamma}{\gamma}\right)=\left(\frac{\Delta\gamma}{\gamma}\right)_0 \sin(\omega_s t+\delta)\,, \tag{5}$$

where ω_s is the synchrotron frequency. Although the en-

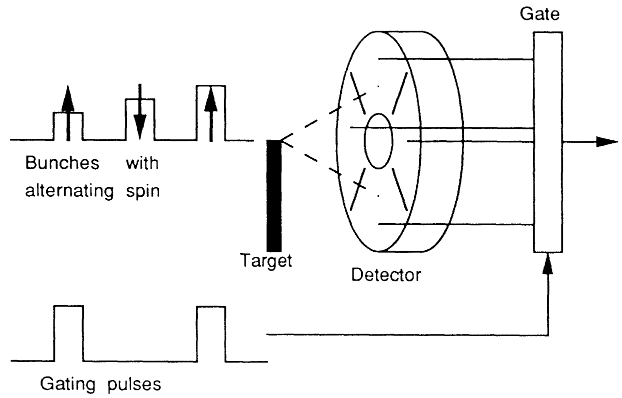

FIG. 2. The polarimeter. The beam is directed to a carbon target and the asymmetry in the distribution of the scattered particles is measured [9]. The polarimeter is gated in such a way that data are taken every second revolution. The polarimeter can measure both the horizontal and the vertical polarization.

ergy deviations are small, these oscillations change the measurement in two ways: (a) $G\gamma$ is not for all particles 2 but $2+G\Delta\gamma(t)$. This time-dependent spin tune changes Eq. (4) into a time-dependent equation with spin components in all three directions. (b) The spin rotation in the solenoid is no longer 180°. Particles with higher (lower) energies than the nominal energy are rotated less (more) than 180° according to Eq. (2).

It can be shown that effect (b) changes the results of the measurements significantly. Figure 3 tries to explain why. As a result of the energy oscillations the spin deviates from the vertical axis by

$$u=\sum_n \sin[2\pi n+A\sin(2n\omega_s t_0+\delta)] \tag{6}$$

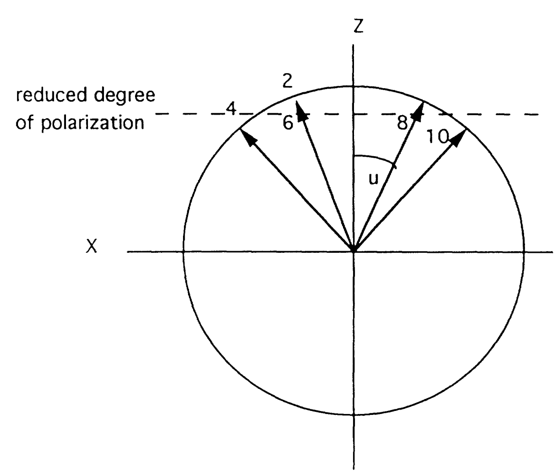

FIG. 3. Schematic description of the effect of synchrotron oscillations on the result of the measurement. The spin rotation angle in the solenoid depends on the energy of the particle. The numbers describe the number of revolutions of the particle after the measurement has started.

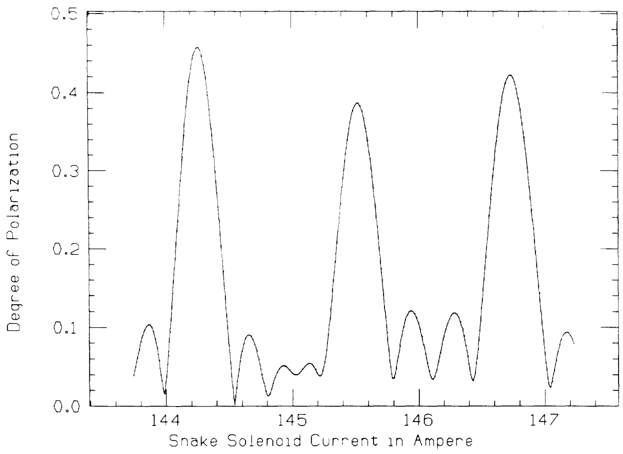

FIG. 4. Simulation of the measurement. The injected beam is 80% vertically polarized. The polarimeter measures the transverse component of the polarization. The polarimeter is gated so that data are taken only every second revolution of the beam. The two peaks centered around the main peak are caused by synchrotron oscillations. The central peak is at the position where the spin of a particle with the nominal energy is rotated by 180°. For the simulation it was assumed that the energy oscillations have a maximum relative width of 1.3×10^{-2}. With this assumption all three peaks have nearly the same height of 40%.

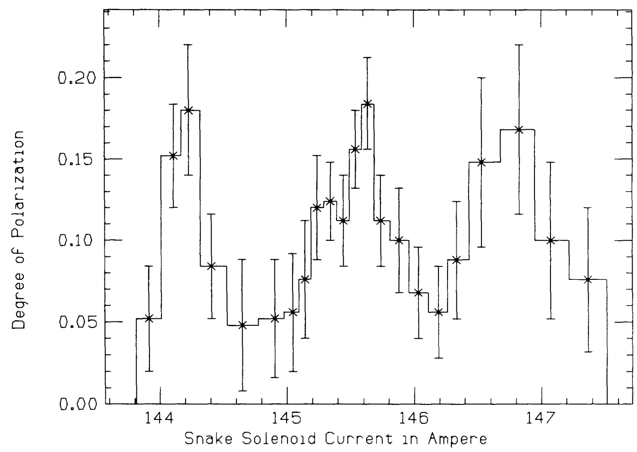

FIG. 5. The result of the measurements. The three peaks are separated by the amount predicted in Fig. 4. The absolute height is smaller by a factor of 2 compared to the calculations. This deviation has to be investigated in more detail in the near future.

when the polarimeter only takes data every second revolution. t_0 is the revolution time, and A is a measure for the magnitude of the energy deviations. As a result the energy oscillations reduce the degree of the measurable polarization. The degree of reduction depends on the magnitudes of A and ω_s. The degree of the measurable polarization increases with ω_s.

In the following the rotation angle of the solenoid is changed from 180° to $180°+\beta/2$. For the same measurement as before, Eq. (6) has to be rewritten in the following way:

$$u=\sum_n \sin[2\pi n+n\beta+A\sin(2n\omega_s t_0+\delta)] . \qquad (7)$$

In this equation two terms now depend on n. These two terms can interfere. When the solenoid current is changed from 180° in steps, one would expect that with a gated polarimeter polarization is measured not only at 180° solenoid rotation but also at other rotation angles.

Equation (7) can be solved analytically or by a simple numerical program. Figure 4 shows the expected results of the measurement obtained with a numerical program. The polarization is plotted as a function of the current through the snake solenoid. 145.5 A corresponds to a spin rotation of 180°. A lower current means less than 180° rotation and a higher current more than 180° rotation. It was assumed that the original polarization of the injected beam was 80% parallel to the vertical direction (as in the experiment). The distance between the center frequency and the two sidebands corresponds to a synchrotron tune of $Q_s=0.004$ (at which the machine operates). The ratio of the height between the central peak and the two side peaks depends on A [defined in Eqs. (6) and (7)].

Figure 5 shows the results of the measurements. The position of the side peaks relative to the main peak is in excellent agreement with the simple assumptions developed in Eqs. (6) and (7). The maximum polarization is lower by a factor of 2 compared to the simulations. This deviation has to be the subject for further investigations.

In summary, it was demonstrated for the first time that oscillations of the polarization around the stable direction exist and can be measured. In addition, the results of the measurements can be explained in a simple way.

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