SPIN-SPLITTER STUDIES: POLARIZATION STABILITY MEASUREMENTS AT IUCF

N. Akchurin, A. Bravar, J. McPherson, F. Olchowski, and Y. Onel
University of Iowa, Iowa City, Iowa 52242

L. Badano and M. Conte
Dipartimento di Fisica dell'Universita' di Genova, INFN Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

A. Penzo and A. Bravar
INFN Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy

J. Hall
University of New Mexico, Albuquerque, New Mexico

A. Pisent
INFN-LNL, Via Romea 4, 35020 Legnaro (PD), Italy

M. Pusterla
Dipartimento di Fisica dell'Universita' di Padova, INFN Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy

T. Rinckel
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

R. Rossmanith
CEBAF, Newport News, Virginia 23606

A self-polarization mechanism for stored (anti)-protons and ions based on the Stern-Gerlach effect in gradient fields has been proposed. The aim of the ongoing measurements at the Indiana University Cyclotron Facility (IUCF) is to verify experimentally the various assumptions on which this effect is based. The final goal is to demonstrate this new polarization effect, which could be a potential tool to produce polarized stored hadron beams both in the low-energy range and at SSC and LHC energies.

The Concept of the Spin Splitter

The Spin-Splitter concept was proposed some time ago[1,2,3] as a novel method for obtaining *in-situ* polarization of stored beams. This is particularly important for those cases where the use of beams from polarized sources is either impossible or impractical, as, for example, in the case of accumulated antiprotons. With this method a macroscopic separation of opposite spin-states of circulating (anti)protons could be obtained. The separation is caused by repetitive Stern-Gerlach kicks in an inhomogeneous magnetic field; particles with opposite spins are deflected in opposite directions. In the original Stern-Gerlach experiment the effect was detected in a single pass. For a beam circulating in a storage ring, it is necessary to implement a constructive mechanism that allows the kicks to add up turn after turn.

In its basic configuration the Spin Splitter consists of a strong quadrupole doublet with a solenoid in between that rotates the spin 180°. Due to the quadrupole gradient the (anti)protons experience a small kick in a direction that depends upon the sign of $\vec{S}$, and because of the 180° rotation the kick of the second quadrupole adds in the same direction. Furthermore, the solenoid also acts as a siberian snake, with a very beneficial influence on the spin dynamics in the ring. A major opportunity for achieving an appreciable spin separation with the Spin-Splitter is indeed related to the long term stability of the polarization in the presence of a (partial) siberian snake.

The spin motion in a ring, described by the BMT equation, corresponds for each revolution to a rotation relative to an axis $\vec{n}(s)$ with frequency ν_s (spin-tune). The component of the spin along $\vec{n}$ is stable, while for the two components transverse to $\vec{n}$ the depolarization rate is related to the magnitude and distribution of the spin-tune spread $\Delta\nu_s$. If the machine is planar, the magnetic field $\vec{B}$ is always vertical, $\vec{n}$ coincides with the direction of $\vec{B}$ and the spin tune is $\nu_s = a\gamma$ ($a = 1.793$ is the proton anomalous magnetic moment). In the general case one has to compose the spin rotations due to the single elements of the machine and, in particular, when there is a siberian snake in the ring, $\vec{n}$ is longitudinal at the point opposite to the rotator and the spin tune is half-integer. In the presence of the Spin-Splitter configuration, if the polarization is kept in the direction of $\vec{n}$ the kick repeats at the same azimuth turn after turn. Thus the effect would add up only when the betatron tune is an integer (and the machine unstable).

The way to overcome this problem is to have the component of the polarization $\vec{P}$ that is transverse to the motion at the azimuth of the Spin-Splitter rotating an angle λ turn after turn. The condition for a coherent addition of the kicks becomes:

$$\lambda = 2\pi\Delta Q_H \quad \text{or} \quad \lambda = 2\pi\Delta Q_V \tag{1}$$

where ΔQ_H and ΔQ_V are the distances of the two betatron tunes from the nearest integer or half-integer.

There are basically two means to implement the scheme with a spin rotation angle λ:
(a) by placing[3,4,5] the polarization in the direction orthogonal to $\vec{n}$, for instance at $a\gamma = 2$, and choosing $\nu_s = 1/2 + \lambda/2$;
(b) by introducing a time dependent field, such as an RF-rotator, which adiabatically rotates $\vec{n}$ an amount λ on each turn.

Results from the 1990-91 Runs

Our measurements were performed using the IUCF Cooler with polarized proton beams, the CE-15 Siberian Snake Solenoid[6] and the CE-01 polarimeter.[7] During our shifts the machine team optimized the betatron tunes Q_H and Q_V by correcting the closed orbit and by adjusting the electron cooling elements. We were able to use a stored current of 20 μA. The beam lifetime was 20 minutes with cooling on and 3.5 minutes without cooling.

A) Polarization lifetime measurements

Measurements have been performed at 108 MeV ($a\gamma = 2$) with $\vec{n}$ longitudinal at the snake, which was operated with either full field or partial field (25%). Multiturn injection succeeded in storing a high intensity (up to 20 μA) beam of polarized protons in order to measure with the CE-01 polarimeter the polarization of a single filling with sufficient accuracy. The polarization of the protons injected in the Cooler ring was measured by the BL3 polarimeter and was always found to be close to 75%.

During the first run we performed the following set of measurements:

i) vertical polarization injected, snake off: P_V=0.15, P_H=0.08;

ii) vertical polarization injected, snake on (25%): P_V=0.09, $P_H = -0.07$;

iii) radial polarization injected, snake on (25%): P_V=0.05, P_H=0.69.

All these measurements were made immediately after injection. The accuracy was about ±0.05 for both components of the polarization. The solenoid was not compensated by skew quadrupoles during this run. The result in iii) is consistent with a full conservation of the polarization since, between the snake and the polarimeter, the spin performed a precession of 240°.

We then repeated these measurements, waiting up to 15 minutes after a filling time of 10 minutes:

iv) radial polarization injected, snake on (25%): $P_V = -0.04, P_H$=0.68;

v) vertical polarization injected, snake on (25%): $P_V = -0.08, P_H = 0.07$;

vi) radial polarization injected, snake on (25%) during filling, then slowly switched off: P_V=0.53, P_H=0.48;

vii) radial polarization injected, snake off: P_V=0.13, P_H=0.25.

With the snake at full strength, the polarization stability along the $\vec{n}$-axis was measured also, giving $P_V = 0.07$ and $P_H = 0.71$ with horizontal injected polarization (0.78). The radial component P_H was practically the same after 15 minutes of storage, plus 10 minutes of stacking.

These measurements with partial and full (compensated) snake confirm that the results of CE-15 on the preservation of polarization across a depolarizing resonance are valid over expanded times and show that *spin motion stability is at least as good as beam lifetime.*

B) Stability of non-equilibrium polarization components

When the spins of the circulating particles are injected orthogonal to $\vec{n}$, they will oscillate around this axis and the polarization direction of the stored beam, changing from revolution to revolution. In order to avoid a mixing of particles with opposite polarization, new particles must be injected only when their spins are parallel to the stored particles. A system to suppress fillings when the two polarizations are not parallel was necessary for this purpose. For the same reason the polarimeter had to be gated with the revolution frequency in order to measure non-zero polarization. These *stroboscopic* injection and measurement gating systems were implemented and tested.

We injected vertically polarized beam orthogonal to $\vec{n}$ and, as obtained in the previous run with partial snake, we found negligible polarization when we did not use the synchronizing systems for injection and the polarimeter. When these systems were switched on, we could measure $P_V = 0.36 \pm 0.10$ and $P_H = 0.05 \pm 0.08$, after 10 and 20 minutes of storage time without appreciable changes. The error in the last measurement is considerably larger than for the other results, i.e. ± 0.05, as the useful statistics correspond in this case to a fraction of the previous one, due to the gating procedure.

These results were presented at the Bonn Spin Conference[8] and at the Polarized Collider Workshop.[9]

During the stacking, the beam is debunched, implying that particles with different energies perform a different number of revolutions until bunching occurs again. Therefore we cannot expect full conservation of the polarization. In order to stack protons with their polarization perpendicular to the $\vec{n}$-axis at the siberian snake and avoid this drawback, we checked a possible method which consists of stacking the beam with polarization parallel to $\vec{n}$ and then rotating the spins to the desired angle by means of the RF-solenoid of Experiment CE-20. We found that this procedure is in principle viable but limited by the accuracy of the current setting of the snake solenoid. For the following runs the power supply of the snake was changed in order to give more precise readings of the current. For the time being, in order to avoid the problem of matching the spins of injected and circulating protons, and spin migration during stacking, protons were injected in a single turn with spin either vertical or horizontal. We varied the current in the solenoid in order to scan an interval of precession angles around 180°.

Vertical injected polarization: We injected the beam with the polarization pointing in the vertical direction in order to be orthogonal to the stable solution $\vec{n}$ at the siberian snake solenoid. As this implies continuous spin flipping, the polarimeter was gated in such a way as to take data only every second revolution. Values of the transverse polarization, $\mathrm{P}_{\perp} = \sqrt{\mathrm{P}_{\mathrm{H}}^2 + \mathrm{P}_{\mathrm{V}}^2}$, at the polarimeter were typically less than 0.1 and independent of the snake solenoid current.

Horizontally injected polarization: Protons were injected with their spins lying in the horizontal plane, having activated the solenoid in the beam transfer line. Due to the spin precession related to $a\gamma = 2$, these spins are again orthogonal (*sidewise* this time) to the stable solution $\vec{n}$ at the siberian snake solenoid. Again, the values of the transverse polarization were about 0.1 and independent of snake solenoid current.

In these runs the polarization was fully transverse to $\vec{n}$, either horizontal or vertical at injection. In both cases $\vec{P_0}$ precesses around $\vec{n}$ all along the ring, and in particular around the longitudinal direction at the snake; therefore, the largest $P_{\perp} = \sqrt{P_H^2 + P_V^2}$ detectable at the polarimeter can vary, from P_0=0.750 to P_0=0.375, even when we assume full conservation of the transverse polarization components: the measured values will actually depend upon the fluctuations of the various machine parameters.

To take into account at least the principal effects, in particular the energy spread and fluctuations to the beam, we proceeded to describe our measurements by means of a computer simulation. It is assumed in this calculation that the synchrotron oscillations have a maximum width of 0.013 and a tune $\mathrm{Q}_s = 0.004$. Typical values of $\mathrm{P}_{\perp}$ are less than 0.1, but three peaks appear between snake solenoid currents of 144 and 147 A. The two side peaks are explained as synchrotron-frequency sidebands due to the interference of two effects:

1) because of the energy dependence of the spin precession, protons with different energies (momentum spread) undergo spin rotations in the solenoid slightly different from

180°. As a consequence, if we start with a vertical polarization of the beam the spin is not completely vertical in the ring, but oscillates around the vertical direction;

2) this fact triggers a second effect, the resulting horizontal component of the polarization oscillates with the synchrotron frequency. Hence the horizontal spin-tune oscillates around its nominal value of 1/2, giving rise to the sidebands.

Our simulation assumes that a current of 145.5 A corresponds to 180° precession of the spin in the snake solenoid, and that the synchrotron oscillations have $Q_s = 0.004$ with an energy spread of 1.3×10^{-2}. A scan in fine steps measured such a peak at $I_{snake} = 145.5$ A with a peak value of $P_{\perp} \approx 0.3$.

We would like to complete these measurements in 1992, both to improve the statistical significance of our results and to perform additional cross checks by varying some of the most crucial parameters.

For the time being we can conclude that we have found significant indications that components transverse to $\vec{n}$ survive across a depolarizing resonance with a snake for sufficiently long time to conduct these studies.

These data have been presented at the 1992 Adriatico Conference[10] and at EPAC92[11] and have been submitted for publication to Physical Review Letters.

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