First Observation of Kinetic Build-up of Longitudinal Electron Polarization


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We report the first measurement of the build-up of longitudinal electron polarization in a storage ring by non-spin-flip emission of synchrotron radiation. Such self-polarization can occur in a ring equipped with a solenoidal magnet in a Siberian Snake configuration. Unpolarized electrons of 0.72 GeV were injected into the Amsterdam Pulse Stretcher ring and the degree of longitudinal polarization was measured as a function of time using a Compton laser backscattering polarimeter. The growth of the polarization was described by an asymptotic polarization of 0.13 ± 0.03 and a time constant of 89 ± 23 min, in approximate agreement with a predicted asymptotic polarization of 0.063 and time constant of 107 min.

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Stored beams of longitudinally polarized electrons have become an important tool for probing the electromagnetic properties of nucleons and nuclei [1-6]. Such beams have been obtained either by waiting for unpolarized electrons in the storage ring to build up transverse polarization via the Sokolov-Ternov effect [7] and then using spin manipulators to rotate the spin into the longitudinal direction [8, 9] or by injecting polarized electrons into a storage ring equipped with a solenoidal magnet in a Siberian Snake configuration [10]. A third method, known as kinetic self-polarization, was proposed by Y.S. Derbenev and A.M. Kondratenko in 1976 [11]. While the Sokolov-Ternov effect relies on the difference in spin-flip emission of photons to build up polarization parallel to the magnetic field in the region of radiation, the predicted kinetic self-polarization arises from the non-spin-flip emission of photons. In a storage ring with a solenoidal Siberian Snake, this results in the spontaneous development of polarization along an axis lying in the horizontal plane and parallel to the momentum of the electron beam on the side of the ring opposite the solenoidal magnet. We demonstrated this effect for the first time at the Amsterdam Pulse Stretcher and Storage Ring (AmPS) at NIKHEF.

An accurate description of electron beam behavior in storage rings is obtained with semi-classical models with quantum effects included in the description of synchrotron radiation emission. The intensities of synchrotron radiation associated with the various quantum transitions are given by [12]

\[ W^{\pm \pm} = W_{cl} \left[ 1 - \xi \left( \frac{55}{24} \sqrt{3} \pm 1 \right) + \xi^2 \left( 20 \pm \frac{245}{48} \sqrt{3} \right) \right] \]

\[ W^{\pm \mp} = W_{cl} \left[ \xi^2 \left( \frac{4}{3} \pm \frac{35}{48} \sqrt{3} \right) \right], \]

up to second order in \( \xi = (3/2) (\lambda_c/\rho) \gamma^2 \), where \( \lambda_c \) is the reduced Compton wavelength of the electron, \( \rho \) the magnetic bending radius, and \( \gamma \) the Lorentz factor. Further, \( W_{cl} = (2/3) (\alpha \lambda_c/\rho^2) mc^2 \gamma^4 \) is the classical radiation intensity, with \( c \) the speed of light, \( \alpha \) fine structure constant, and \( m \) the mass of the electron. The \( \pm \) index specifies the initial spin state being parallel (+) or antiparallel (−) to the magnetic field direction. The arrows indicate the relative direction of the spin in the initial and final states. The Sokolov-Ternov effect, which arises from the spin-flip term \( W^{\pm \pm} \), has been routinely used in high-energy electron/positron storage rings [9] such as the 27.5 GeV HERA ring at DESY and the 47 GeV LEP ring at CERN. The non-spin flip term \( W^{\pm \mp} \) results from the dependence of synchrotron-radiation intensity on the spin state and the energy dependence of the precession axis [12]. No polarization specifically associated with the \( W^{\pm \mp} \) term had been observed previously.

The time dependence of the polarization \( (P) \) can be calculated from Eq. (1) by integrating over an ensemble of electrons and the synchrotron photon energy. The motion of the electrons in the ensemble is determined by the lattice of the storage ring. The general solution for polarization by synchrotron radiation of an initially
unpolarized electron beam then becomes [13]
\[
P = P_\infty \left(1 - e^{-t/\tau_p}\right),
\]
with \( t \) the time. The asymptotic polarization \( (P_\infty) \) and the polarization time \( (\tau_p) \) are given by
\[
P_\infty = \frac{8}{5\sqrt{3}} \frac{\alpha_-}{\alpha_+} \quad \text{and} \quad \tau_p^{-1} = \frac{5\sqrt{3}e^2\hbar\gamma^5}{8m^2c^3}\alpha_+.
\]
Here, \( e \) denotes the charge of the electron, while \( \hbar \) represents the reduced Planck’s constant. The parameters \( \alpha_- \) and \( \alpha_+ \) depend on the lattice of the storage ring, and are given by
\[
\alpha_- = \left\langle \frac{1}{|\mathbf{p}|} \mathbf{b} \cdot [\mathbf{n} - \mathbf{d}] \right\rangle,
\]
\[
\alpha_+ = \left\langle \frac{1}{|\mathbf{p}|} [1 - \frac{2}{3}(\mathbf{n} \cdot \mathbf{v})^2 + \frac{1}{15}\mathbf{d}^2] \right\rangle,
\]
where \( \mathbf{n} \) is the equilibrium spin direction at a given point in the ring, \( \mathbf{v} \) is a unit vector in the direction of the electron velocity, \( \mathbf{b} \) is a unit vector the direction of the magnetic field, and the brackets \( \langle \ldots \rangle \) indicate an average around the ring. The spin-orbit coupling function \( \mathbf{d} \) can be expressed as \( \mathbf{d}_1 + \mathbf{d}_2 \), where \( \mathbf{d}_1 = \gamma \partial \mathbf{n}/\partial \gamma \) represents the direct dependence of the vector \( \mathbf{n} \) on the particle energy \( E \), while \( d_2 \) results from the change of betatron amplitudes resulting from the emission of a photon.

In a storage ring with magnetic fields restricted to the vertical direction, \( \mathbf{n} \) is everywhere vertical, independent of energy. Thus, \( \gamma \partial \mathbf{n}/\partial \gamma \) is zero and \( \mathbf{d} \) is small except near resonances. In that case the radiative polarization arises from the term proportional to \( \mathbf{b} \cdot \mathbf{n} \) in Eq. (4). This is known as the Sokolov-Ternov effect.

In the case of a ring with a solenoidal Siberian Snake configuration, longitudinal polarization is preserved by precessing the spin of passing electrons exactly through \( \pi \) (at the nominal energy) with respect to the electrons’ direction of motion, as illustrated in Fig. 1. Outside the solenoid, \( \mathbf{n} \) lies in the ring plane and therefore \( \mathbf{b} \cdot \mathbf{n} = 0 \). For energies slightly different from the nominal, the precession generated by the solenoid differs from \( \pi \) and \( \mathbf{n} \) acquires a small vertical component. However, for reasonable energy spreads the term \( \mathbf{b} \cdot \mathbf{n} \) remains extremely small and, for a given electron, oscillates about zero as the electron’s energy oscillates about the nominal energy. On the other hand, the energy dependence of \( \mathbf{n} \) becomes finite and is described by a vector with a vertical component
\[
\mathbf{b} \cdot \mathbf{d}_1 = \mathbf{b} \cdot \gamma \frac{\partial \mathbf{n}}{\partial \gamma} = \pm \frac{\pi}{2} \sin(2\varphi),
\]
where \( 2\varphi \) is the precession angle of the spin as the electron goes from the solenoid to the point diametrically opposite to it, the internal target point in our case. The kinetic polarization build-up in a ring with a solenoidal Siberian Snake configuration arises from the fact that in the dipoles \( \mathbf{b} \) points vertically, i.e. \( \mathbf{b} \cdot \mathbf{d}_1 \neq 0 \).

Figure 1 presents a schematic outline of the AmPS storage ring and illustrates the behavior of the equilibrium spin direction \( \mathbf{n} \) around the storage ring, corresponding to the case with a Siberian Snake configuration. The snake is located on the opposite side of the storage ring from the NIKHEF internal target facility. The Siberian Snake consists of two super-conducting solenoids and five quadrupole magnets and is capable of providing a field integral of up to 10.5 Tm. The spin rotation in the snake for ultra-relativistic electrons is given by
\[
\varphi = \frac{e}{2E_e} \int \mathbf{B} \cdot d\mathbf{l},
\]
with \( e \) the elementary charge. The quadrupoles are designed to make the system an optically transparent addition to the ring lattice.

If one assumes an isomagnetic ring and ignores the finite energy spread of the beam as well as the changes in the betatron amplitude accompanying the emission of synchrotron radiation (\( d_\beta = 0 \)), it is straightforward to calculate the asymptotic polarization, \( P_\infty \), and the polarization time, \( \tau_p \), from Eqs. (3) and (4). The results of such a calculation are represented by the dashed curves in Figs. 2 and 3. While polarization times are long at low energies, sizable polarizations are predicted except for energies near the resonant energies of 0.44 and 0.88 GeV, corresponding to \( \varphi = \pi/2 \) and \( \pi \). We also performed
a full calculation using the ASPIRRIN [14] simulation code. This code treats the electron motion classically using a complete second-order description of the AmPS storage ring lattice. Ideal magnets with random strength and positioning errors are assumed. The emission of synchrotron radiation is treated quantum mechanically using first order perturbation theory. The results are represented by the solid curves in Figs. 2 and 3. The predicted asymptotic polarizations are generally lower than the results assuming $d_{3} = 0$, especially at higher energies. Furthermore, the zero crossings are shifted to higher energies. A second full calculation, performed using the SLIM [15] simulation code, yielded identical results [16].

Our measurement of kinetic self-polarization was performed by injecting 200 mA of unpolarized, 0.72 GeV electrons into the AmPS storage ring and measuring the polarization as a function of time. The lifetime of the beam in the storage ring was over 3000 s. Thus, the beam could be stored as long as 4 hrs while still retaining enough current to perform the polarization measurements. The measurements of the beam polarization were performed with a Compton backscattering polarimeter [17]. The principal elements of the polarimeter are an argon-ion laser and a CsI detector. Circularly polarized light from the 10 W Ar-ion laser is directed by a series of mirrors through a vacuum window into the AmPS storage ring. Photons which Compton scatter from the electrons circulating in the ring are detected with the CsI crystal. Using a Pockels cell to flip the helicity of the laser light at a rate of 75 Hz, the count rate asymmetry, $A_{exp}(E_{\gamma})$, in the energy spectra of the scattered photons is determined via,

$$A_{exp}(E_{\gamma}) = \frac{N_{L} - N_{R}}{N_{L} + N_{R}} = \Delta S_{3} P_{z} \cos(\alpha) A_{3z}^{exp},$$  \tag{7}

where $N_{L}$ and $N_{R}$ are the normalized count rates for left- and right-handed polarized light, $\alpha$ is the spin precession angle at the interaction region, $\Delta S_{3}$ is the average circular polarization of the left and right handed laser light, and the experimental spin correlation function $A_{3z}^{exp}$ is obtained with Monte Carlo simulations using the exact energy response formulas for Compton scattering. The longitudinal polarization of the electron beam, $P_{z}$, is determined by taking $P_{z}$ to be a free parameter and fitting the measured asymmetry with Eq. (7). This polarimeter has been used to determine the beam polarization during a number of internal target measurements [4–6, 18, 19].

The results of the measurements of the polarization as a function of time are shown in Fig. 4. The data were fit using Eq. 2 with the depolarization time constrained by the previously measured value of 83±25 min [20]. The fit yielded an asymptotic polarization of $P_{\infty} = 0.13 \pm 0.031$ and a polarization time constant of $\tau_{p} = 89 \pm 23$ min. These values are close to the predictions of ASPIRRIN which gave an asymptotic polarization of $P_{\infty} = 0.063$ and a polarization time constant $\tau_{p} = 107$ min.
FIG. 4: Longitudinal polarization of 0.72 GeV electrons in the AmPS storage ring. The dotted curve represents the best fit to the data. The dashed curve, $d_3 = 0$, is the result of a calculation assuming no energy spread in the beam and no changes in betatron amplitudes accompanying the emission of synchrotron radiation. The solid curve represents the result of a full calculation using the ASPIRRIN code.

In summary, the build-up of longitudinal polarization of an electron beam via the process of kinetic self-polarization has been observed for the first time. Recent calculations [21] have indicated that if an asymmetric wiggler is inserted into a medium energy storage ring, then this mechanism can generate high degrees of polarization on a time scale short compared to the lifetime of the stored beam. Our confirmation of the prediction of kinetic self polarization establishes that it is possible and practical to construct medium energy storage rings in which positrons become longitudinally polarized. Also, kinetic polarization has been predicted to play a significant role in high energy storage rings where spin rotators are used. At HERA for example, the effect of this mechanism on the asymptotic polarization is estimated to be as large as several percent per spin rotator [16]. A direct observation of kinetic polarization lends credence to these predictions.

Further investigations into this process have been proposed for the MIT-Bates storage ring in which a Siberian Snake was recently commissioned [22].

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