POLARIZATION REVERSAL AND LUMINOSITY GAIN BY SPIN REVERSAL OF STORED PROTON BEAMS

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In conventional polarized beam experiments, the projectile is incident upon a target external to the accelerator. In this case, the direction of the polarization vector of the beam can be reversed at the polarized ion source without any loss in luminosity. In the Cooler, however, the polarization of the stored beam has been given by the polarization direction during injection. Reversal of the polarization requires dumping the beam and waiting until the ring is filled again with protons of the opposite spin. Refilling the ring periodically in order to invert the spin results in a loss in time-averaged luminosity.

Considerably increased luminosity results if it is possible to flip the spin of the stored beam without discarding the stored particles. Here we describe the successful operation of a spin flipper of high flip efficiency in the Cooler. While successful tests of the spin flipper have been reported previously,[1] the emphasis here is on improvements that lead to very reliable and robust operation during long data-taking runs, as well as the associated increase in time-averaged luminosity.

When a depolarizing resonance is crossed, the polarization direction of the stored beam is either conserved or reversed, depending on whether the crossing occurs rapidly or slowly.[2] In a storage ring, a depolarizing resonance occurs when the spin tune is such that non-vertical magnetic field components are encountered in phase on subsequent revolutions. In other words, small rotations of the polarization vector of the stored beam add up during many turns around the ring.

It has been shown that a depolarizing resonance can be introduced by an RF solenoid whose magnetic field oscillates along the beam axis.[3] A depolarizing resonance is introduced if the frequency of the oscillating longitudinal field, f_{sol}, is given by

$$f_{sol} = f_{circ} \cdot (\nu_{spin} \pm N),\qquad(1)$$

where f_{circ} is the circulation frequency of the stored beam, and ν_{spin} is the spin tune. The integer N may be chosen such that f_{sol} lies in the frequency range of the solenoid. If the field in the ring is purely vertical, the spin tune equals $G\gamma$ where $G=1.783$ is the anomalous magnetic moment of the proton and γ is the usual relativistic factor.

For the measurements reported here the solenoid is part of an LC circuit where C, a high voltage capacitor, is adjustable such that (for a given frequency) the circuit is driven in resonance and thus the amplitude of the magnetic field is maximized. Spin flip is achieved

if the solenoid frequency is ramped adiabatically across the resonance frequency given by Eq. 1. The LC-resonant circuit is tuned to the frequency in the middle of the band across which the frequency is swept.

In the presence of a bunching RF cavity, the momenta of the particles in the ring are modulated due to synchrotron oscillations about the momentum of the ideal particle. Depolarizing sidebands to the resonance frequency occur at $\pm f_{sync}$ where f_{sync} is the synchrotron frequency of the stored particle[4]

$$f_{sync} = f_{circ} \cdot \sqrt{\frac{h \cdot e \cdot V \cdot \eta}{2\pi \cdot \beta^2 \cdot E}} .$$
(2)

Here h is the harmonic number, V the cavity voltage, and E the energy of the beam. The dispersion in revolution frequency, η, is given by $\eta = |1/\gamma_{tr}^2 - 1/\gamma^2|$, where γ is the usual relativistic parameter, and γ_{tr} is the transition energy in units of the rest energy of the stored particles. For the Cooler we have $\gamma_{tr} = 4.85$.

In order to be useful for nuclear physics experiments, a device is needed that operates reproducibly and reliably, and that does not require time-consuming preparatory measurements. Initial tests of the RF solenoid as a spin-flipping device have been performed at a beam energy of 139 MeV.[1] In these tests, a crossing of the sidebands was avoided by restricting the frequency ramp to a narrow range on either side of the resonance. With increasing beam energy this mode of operation becomes more and more difficult because the synchrotron frequency scales with the inverse square root of the energy of the stored beam. In principle, the sidebands can be moved away from the main resonance by increasing the cavity voltage and harmonic number. However, as the beam energy increases, this eventually requires cavity voltages beyond the specification of a given device (2 kV maximum in our case). The test at 139 MeV was performed with a cavity voltage of 1200 V and $h=9$. In addition, main resonance and synchrotron sidebands have a finite width. For the test at 139 MeV a careful optimization procedure was necessary to place the endpoints of the frequency range between the tails of main resonance and the two sidebands. In this mode the flipper has been demonstrated to work with a high efficiency. However, a mode of operation that is not limited to low energies, and that lets the experimenter chose the cavity voltage and harmonic number is desirable.

In order to eliminate the requirement to locate precisely the endpoints of the solenoid frequency ramp between the synchrotron sidebands, we attempted to ramp the solenoid frequency through both sidebands and the main resonance. For this and all following measurements, the solenoid frequency was ramped linearly from $f_{sol}=2.2743$ MHz to $f_{sol}=2.2943$ MHz and back to $f_{sol}=2.2743$ MHz for two subsequent polarization reversals. The duration of one frequency ramp was 500 ms. At the endpoints of the frequency ramp the voltage across the solenoid was 5 kV peak-to-peak. Since the tuning capacitor was fixed, the voltage across the solenoid followed the resonance curve for each frequency ramp. It reached a maximum value of 12 kV peak-to-peak on resonance.

All beam polarization measurements reported here have been obtained using the CE35 storage-cell target.[5] The beam energy was 200 MeV and the target gas was either polarized hydrogen atoms from an atomic beam source[6] or unpolarized hydrogen bled into the target cell through a teflon tube.

Figure 1. Polarization flipping by crossing an induced depolarizing resonance. The fraction of polarization of a 200 MeV beam remaining after multiple flips is shown. The solid symbols were obtained when, during flipping, the beam was debunched by shorting out the ring RF cavity. The efficiency is 0.984±0.004. The open symbols illustrate the same measurement with a bunched beam, corresponding to an efficiency of 0.83±0.03. The efficiencies were obtained from fits to the data, shown as solid lines.
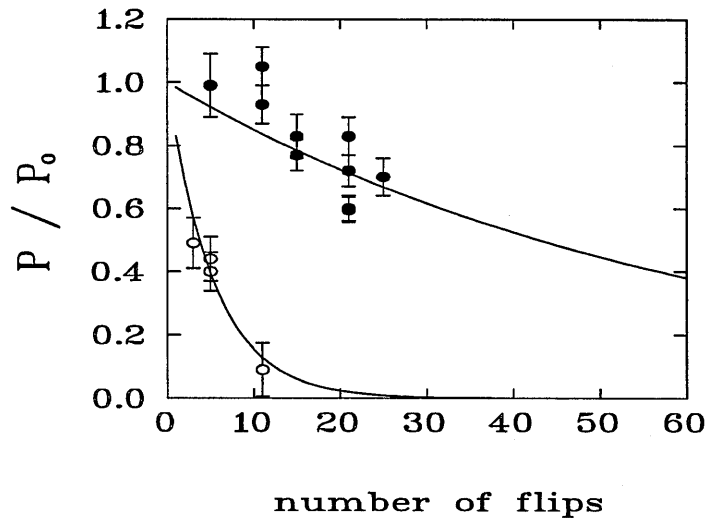
Let us define the spin-flip efficiency ξ to be the ratio of the magnitude of the beam polarization after a frequency ramp divided by the magnitude of the beam polarization before the frequency ramp. Because the loss of polarization in a single flip is small, ξ was measured by flipping the polarization many times before measuring the remaining polarization.

The data in Fig. 1 (open circles) show clearly that passing through the sidebands results in a low overall spin-flip efficiency. Since the sidebands are depolarizing resonances themselves, one passage corresponds to *three* reversals of the beam polarization, each individual reversal with a spinflip efficiency less than one.

Shorting the RF cavity removes the time structure of the stored beam and should therefore result in a resonance without the sidebands. With the sidebands removed, it should then be possible to flip the polarization with higher efficiency by ramping the frequency across the main resonance alone using the same wide frequency range. In a second measurement we therefore shorted out the cavity prior to the frequency ramp. After the frequency ramp was complete, the RF cavity was turned back on and the beam was rebunched. We allowed 5 s for debunching and 5 s for rebunching after the flip. By observing the time structure of the beam on an electrostatic pickup signal, we verified that 5 s is sufficient for the beam to lose its time structure completely. As can be seen from Fig. 1 (solid dots), the spin flip efficiency ξ is greatly increased. From the data one obtains a value of ξ=0.984±0.004 for the remaining fraction of the initial polarization after one flip.

After having established that the flipper can be used as a reliable and easily tunable device if the bunching RF cavity is shorted, the spin flipper is now used routinely by the CE35 collaboration. During a week of running the reproducibility and the long-term performance of the flipper was studied. The spin-flip efficiency was found to be constant within the error of the measurement.
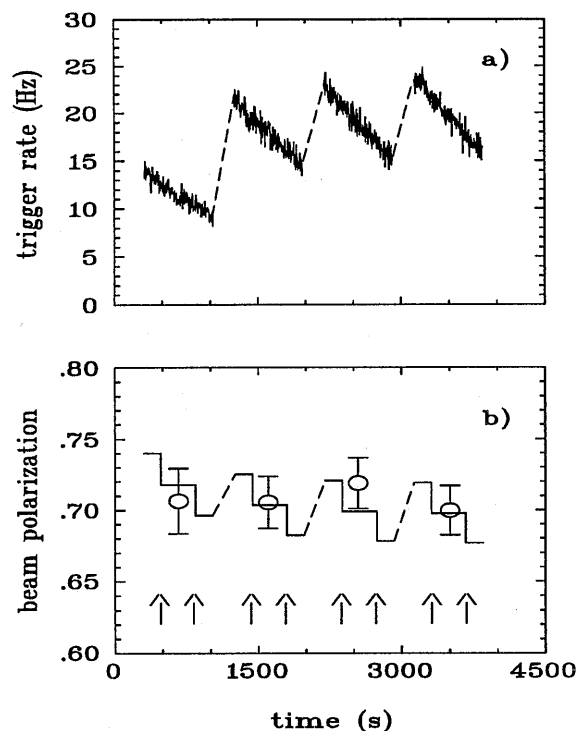
Figure 2. a) Trigger rate in the CE35 detector as a function of time for four subsequent cycles. Beam left at the end of a cycle remains in the ring. The dashed line indicates the filling of the ring during which time the rate is not measured. b) Beam polarization as a function of time. The circles correspond to the measured beam polarization averaged over one cycle. The line represents the expected polarization as a function of time due to filling of the ring (dashed) and flipping the spin of the stored beam (arrows); see text for details.

Using the flipper has enabled us to establish a new mode for experiments with stored, polarized beams. Previously, the beam had been injected in one of two spin states, then —if required by the experiment— accelerated. After data taking, the beam was dumped to empty the ring before accepting freshly injected beam in the opposite spin state. Now with the flipper, the ring is always filled with beam in the same spin state. The new mode of running consists of injection, data taking, spin flip of the stored beam, data taking, another spin flip, data taking and finally injection of more beam in the same spin state *without* dumping the beam prior to injection.

If the beam were dumped at the end of each cycle, the event rate would be the same for every cycle. If the beam is not dumped at the end of a cycle —typically every few hundred seconds— the luminosity increases in subsequent cycles. This increase is illustrated in Fig. 2a where the trigger rate in the CE35 detector is plotted as a function of cycle time for a sequence of four cycles. For polarization experiments, however, one has to consider the figure of merit LP^2 where L is the luminosity and P is the beam polarization. The data points in Fig. 2b represent the measured beam polarization for each cycle as a function of cycle number. The data points were obtained using the cross ratio method[7] for every cycle. The cross ratio was calculated using software time gates before and after the two spin flips to obtain count rates in spin state 1 and another software time gate between the two spin flips to obtain count rates in spin state 2. Thus, the data points represent the average polarization during each cycle. It can be seen from Fig. 2a and 2b that the gain in luminosity is greater than the loss in P^2, resulting in a net gain in the figure of merit.

In Fig. 2b we also show the calculated beam polarization as a function of time. Input into the calculation is the measured spin-flip efficiency. A parameterization of the measured

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increase in beam current during injection as a function of time also enters the calculation. The measured polarization agrees within error bars with the expected polarization.

In summary, the spin flipper has been demonstrated to be a reliable device. If it is used to reverse the polarization of the stored beam, an increase in the average luminosity and the overall figure of merit is achieved, since it is no longer necessary to empty the ring prior to injection.

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TOWARDS LONGITUDINAL BEAM POLARIZATION IN THE COOLER

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Certain experiments with polarized beam on a polarized target require that both beam and target are polarized in the longitudinal direction. The Wisconsin/IUCF hydrogen