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Overcoming Intrinsic Spin Resonances with an RF Dipole*

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A coherent spin resonance excited by an RF dipole was used to overcome depolarization due to intrinsic spin resonances at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. Full spin flip of a polarized proton beam, without emittance growth, was observed at $G\gamma = 12 + \nu_z$ and $36 - \nu_z$ by adiabatically exciting a vertical coherent betatron oscillation using a single RF dipole magnet. The interference pattern observed between the intrinsic spin resonance and the coherent spin resonance agrees well with multi-particle spin simulations based on a simple two-resonance model. The interference pattern can be used for beam diagnostics.

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In a planar synchrotron, the vertical magnetic guide field causes the polarization vector of a polarized proton beam to precess about the vertical axis $G\gamma$ turns per revolution, where $G = (g-2)/2 = 1.7928474$ is the proton anomalous magnetic g-factor, and γ is the relativistic Lorentz factor. Thus $G\gamma$ is called the spin tune of polarized protons in the synchrotron. On the other hand, horizontal magnetic fields such as those from a tilted dipole magnet, and vertical orbital motion through quadrupoles, can alter the polarization vector away from the vertical direction. When a spin resonance condition is encountered, this effect adds coherently and causes depolarization. Important spin resonances are classified as imperfection resonances resulting from vertical closed orbit errors or intrinsic resonances resulting from vertical betatron motion [1].

In medium or low energy accelerators, imperfection resonances can be corrected by using harmonic orbit correctors [2], or by using a partial Siberian snake [3–5]. A 5% partial snake has been successfully implemented at the AGS to overcome the imperfection resonances that occur at $G\gamma =$ integers. However, the strength of the 5% partial snake is too weak to overcome the intrinsic spin resonances at $G\gamma = kP \pm m\nu_z$, where k and m are integers, $P = 12$ is the superperiodicity, and $\nu_z \approx 8.70$ is the vertical betatron tune for the AGS.

During acceleration of polarized protons in the AGS up to 25 GeV/c, 7 intrinsic spin resonances at $0 + \nu_z, 24 - \nu_z, 12 + \nu_z, 36 - \nu_z, 24 + \nu_z, 48 - \nu_z$ and $36 + \nu_z$ are encountered. The resonance strength ϵ_k is defined as the Fourier amplitude of the spin perturbing field. When a polarized beam is uniformly accelerated through such an isolated spin resonance, the final polarization P_f is related to the initial polarization P_i by the Froissart-Stora formula [6]

$$P_f = \left(2e^{-\pi|\epsilon_K|^2/2\alpha} - 1\right) P_i, \tag{1}$$

where α is the resonance crossing rate given by

$$\alpha = \frac{d(G\gamma - kP \mp m\nu_z)}{d\theta}, \tag{2}$$

and θ is the orbital angle in the synchrotron. At the nominal fast acceleration rate at the AGS, four strong spin resonances at $0 + \nu_z, 12 + \nu_z$, $36 - \nu_z$ and $36 + \nu_z$ are most harmful ones to the beam polarization.

Since the intrinsic spin resonance strength is proportional to the betatron amplitude, the final polarization is an ensemble average of the Froissart-Stora formula over the betatron amplitude of the beam particles. Assuming a Gaussian beam distribution, the final polarization becomes

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$$\langle P_f \rangle = \left(\frac{1-\pi|\epsilon_{\rm rms}|^2/\alpha}{1+\pi|\epsilon_{\rm rms}|^2/\alpha} \right) \langle P_i \rangle, \tag{3}$$

where $\epsilon_{\rm rms}$ is the spin resonance strength corresponding to an rms emittance [1]. It is difficult to achieve a full spin flip for all particles since the strength of the beam core is small. Furthermore, the spin flip method is not applicable to many weak spin resonances driven by horizontal and vertical coupling, synchrotron motion, field gradient errors and other sources.

Alternatively, if the beam is kicked to induce a coherent betatron oscillation so that the betatron oscillation amplitudes of all particles are large, a full spin flip can be attained [7,8]. However, as a non-adiabatic process this method causes an emittance growth. To eliminate the problem of the emittance growth, a coherent betatron motion can be adiabatically excited and maintained by an RF dipole (See reference [9], in which RF dipole was referred as AC dipole due to lower frequency). Essentially, the RF dipole field and the focusing potential of the accelerator form a potential well that preserves the emittance of the beam. Such a controlled coherent betatron oscillation can be obtained by using an RF dipole magnet operating at a frequency close to a betatron sideband. This paper reports the results from recent polarized proton beam experiment at the AGS in July 1997, where an RF dipole was used to induce coherent betatron oscillations for achieving a full spin flip during the acceleration of polarized beam, when an intrinsic spin resonance was encountered.

In the linear approximation, the amplitude of the coherent betatron motion is given by

$$Z_{\rm coh} = \frac{\Theta}{4\pi\delta}\beta_z, \tag{4}$$

where Θ is the maximum beam deflection angle from the RF dipole, β_z is the vertical betatron function at the RF dipole, and δ is the difference between the RF dipole tune and the tune of the nearest betatron sideband. Equation (4) shows that the beam is unstable at $\delta = 0$.

Since the betatron coordinate can be expressed as the linear combination of the vertical intrinsic and induced coherent betatron motion [9], the polarized protons experience not only the intrinsic spin resonance, but also a coherent spin resonance at the RF dipole frequency. The resulting polarization, in the limiting case with $\delta = 0$, is given by

$$\langle \frac{P_f}{P_i} \rangle = \frac{2}{1+\pi|\epsilon_{\rm rms}|^2/\alpha} \exp\left\{ -\frac{(Z_{\rm coh}^2\hat{\beta}_z/2\beta_z\sigma_z^2)(\pi|\epsilon_{\rm rms}|^2/\alpha)}{1+\pi|\epsilon_{\rm rms}|^2/\alpha} \right\} - 1, \tag{5}$$

and in the case with $\delta \gg$ the intrinsic spin resonance strength, by

$$\langle \frac{P_f}{P_i} \rangle = \frac{1-\pi|\epsilon_{\rm rms}|^2/\alpha}{1+\pi|\epsilon_{\rm rms}|^2/\alpha} \left(2\exp\left\{ -\frac{Z_{\rm coh}^2\hat{\beta}_z}{\beta_z\sigma_z^2}\frac{\pi|\epsilon_{\rm rms}|^2}{2\alpha} \right\} - 1 \right). \tag{6}$$

Here $\hat{\beta}_z$ is the maximum vertical betatron function in the accelerator, and σ_z is the rms beam size. The more interesting and relevant situation lies between these two cases producing rich interference patterns [10]. A multi-particle simulation based on a two spin resonance model was developed to numerically analyze this situation.

In the AGS polarized beam experiments, polarized beam from an atomic H^- source was accelerated up to 200 MeV through the LINAC and strip injected into the Booster. At the end of the LINAC, the beam polarization was measured by a 200 MeV polarimeter. In the Booster, the polarized beam was accelerated to 1.56 GeV or $G\gamma = 4.7$, just below the Booster vertical betatron tune set at 4.9 to avoid an intrinsic spin resonance. The imperfection resonance at $G\gamma = 4$ was corrected by harmonic orbit correction dipole magnets . The polarized beam was injected into the AGS at $G\gamma = 4.7$, where the polarization was about 0.77±0.05, and the polarized beam intensity was about 5×10^9 polarized protons per pulse [5].

In the AGS, the polarization of the circulating beam was measured with the AGS internal polarimeter, which measures the left-right asymmetry of p-p elastic scattering off a nylon fishline ($C_6H_{11}NO$) target. The background from the quasi-elastic scattering was estimated by measuring the asymmetry from a carbon fiber target, and was subtracted from the asymmetry measurement with nylon target to get the pure asymmetry of p-p elastic scattering. The beam polarization was calculated from the measured asymmetry normalized by the effective analyzing power for the nylon target, which was obtained from the analyzing power for the p-p elastic scattering data [11]. The beam emittance was measured by an ionization profile monitor (IPM) [12] as a function of time during the AGS cycle of 2.5 s. However, the IPM wasn't available during the most time of the experiment.

In the AGS, the 5% partial Siberian Snake was ramped to produce a full spin flip at every integer $G\gamma$ [5]. The present experiment employed an RF dipole to overcome the intrinsic spin resonances at $0+\nu_z$, $12+\nu_z$, and $36-\nu_z$.

A ferrite dipole magnet was tuned with a parallel capacitor to about 108 kHz that coincided with a sideband of the vertical betatron tune. The vertical betatron function at the RF dipole location was about $\beta_z = 16.6$ m. The maximum strength was about 2×10^{-3} T-m. Between the $0 + \nu_z$ resonance and $36 + \nu_z$ resonance, the revolution frequency changes from about 363.8 kHz to 371.5 kHz. The AGS horizontal and vertical betatron tunes were set at 8.85 and 8.7, respectively. At each of the three strong intrinsic spin resonances, the RF dipole was linearly ramped up to its full amplitude in 1000 revolutions before the intrinsic spin resonance was encountered, and was kept at this amplitude level for 1000 revolutions during which the spin resonance was crossed. It was immediately ramped back to zero in another 1000 revolutions. The acceleration rate was $\alpha = 4.8 \times 10^{-5}$. In order to keep a fixed modulation tune, the frequency of the RF dipole excitation was phase locked to the AGS RF frequency.

The polarization was measured at a fixed energy flat-top above each intrinsic resonance. The measurement flat-tops were set at $G\gamma = 13.5, 24.5$, and 30.5, respectively. The parameters varied in the experiment were the RF dipole field strength and the separation of the modulation tune from the vertical intrinsic betatron tune. Since the RF dipole is a narrow band magnet tuned at 108kHz, the RF dipole modulation tune was fixed and the vertical betatron tune was varied to obtain different tune separation.

Figure 1 shows the measured polarization at the three flat-tops vs. the RF dipole strength. The overall systematic scale error of the beam polarization measurement was estimated to be 0.10 [5], and the statistical error was about ± 0.03. The lines shown on the figure correspond to results obtained from numerical spin simulations of a two spin resonance model. The spin vector of each particle was tracked by multiplying its turn by turn transform matrix. The beam polarization was then obtained from the spin ensemble average of a Gaussian beam distribution. A scaling factor was introduced to convert the simulation results to the corresponding asymmetry measured by the polarimeter. This factor is a combination of the initial polarization and the effective analyzing power.

The simulations for the $12 + \nu_z$ and $36 - \nu_z$ resonances were done with the measured betatron tune. On the other hand. since the betatron tune at the $0 + \nu_z$ resonance was not measured accurately enough during the experiment setup, the tune separation δ at the $0 + \nu_z$ resonance was obtained by fitting it to the data. The best fit corresponded to a tune separation of $\delta = 0.0063 \pm 0.0014$. The beam emittance used in the numerical simulations was obtained from the measured depolarization with RF dipole off at $G\gamma = 13.5, 24.5$ and 30.5, which based on Eq. 3, indicates that the normalized 95% beam emittance was about $36 \pm 13\pi$mm-mrad for the $0 + \nu_z$ resonance and $26 \pm 4\pi$mm-mrad for the $12 + \nu_z$ and $36 - \nu_z$ resonances. This is also consistent with beam profile measurements made with the AGS ionization profile monitor (IPM). However, the IPM measurements were not very reliable due to the low beam intensity. The lower beam emittance for the $12 + \nu_z$ and $36 - \nu_z$ resonances was attributed to a more careful machine tuning later in the experiment.

Since the spin resonance at $12 + \nu_z$ was relatively weak compared with the other three resonances, it is easier for the RF-induced spin resonance to dominate, giving a smooth dependence of the measured polarization on the RF dipole field strength shown in the middle plot of Fig. 1. On the other hand, since the intrinsic spin resonances at $0 + \nu_z$ and $36 - \nu_z$ were strong enough to partially flip the spin, they strongly interfered with the coherent spin resonance induced by the RF dipole. In agreement with the numerical simulation, the upper and lower plots of Fig. 1 show complicated interference patterns when the tune separation is large. Nevertheless, a full spin flip can eventually be obtained when the strength of the RF-induced spin resonance becomes strong enough.

Since the vertical betatron tune, in this experiment, was not set as its optimal value at the $0 + \nu_z$ resonance for the polarization measurement at higher energy flat-tops, there was a 15% $\sim$ 20% polarization loss. This was reflected in a lower polarization value at the higher energies for the $12 + \nu_z$ and $36 - \nu_z$ spin resonances. This polarization loss at the $0 + \nu_z$ resonance can be avoided in the future by carefully measuring the betatron tune and by properly setting the vertical betatron tune and the RF dipole field strength amplitude.

Figure 2 shows the measured beam polarization for the $12 + \nu_z$ intrinsic resonance as a function of the tune separation at a fixed RF dipole field strength of 1.85×10^{-3} T-m. The solid line shows the result of a multi-particle numerical simulation. When the RF dipole modulation tune is near the intrinsic betatron tune, the polarization reaches a plateau of full spin flip.

In conclusion, we have studied the method of employing an RF dipole field to overcome strong intrinsic spin resonances. We found that there was a strong interference between the intrinsic spin resonance and the RF-induced spin resonance. The interference pattern depended upon their tune separation, relative phase, and relative strength. The experimental data were found to agree well with multi-particle numerical spin simulations. The data showed that a full spin flip can be achieved, and depolarization due to the intrinsic spin resonance can be avoided by the coherent betatron motion induced by an RF dipole.

In general, the application of such a method requires a small beam emittance, because the corresponding intrinsic spin resonance would be weaker and therefore it would be easier for the coherent spin resonance to dominate and reach full spin flip. At the same time, the tune spread of the beam should also be minimized in order to ease the beam aperture requirement. In the future, we plan to study the effects of the chromaticity correction and the effect of the nonlinear betatron detuning on the polarization.

I. ACKNOWLEDGMENTS

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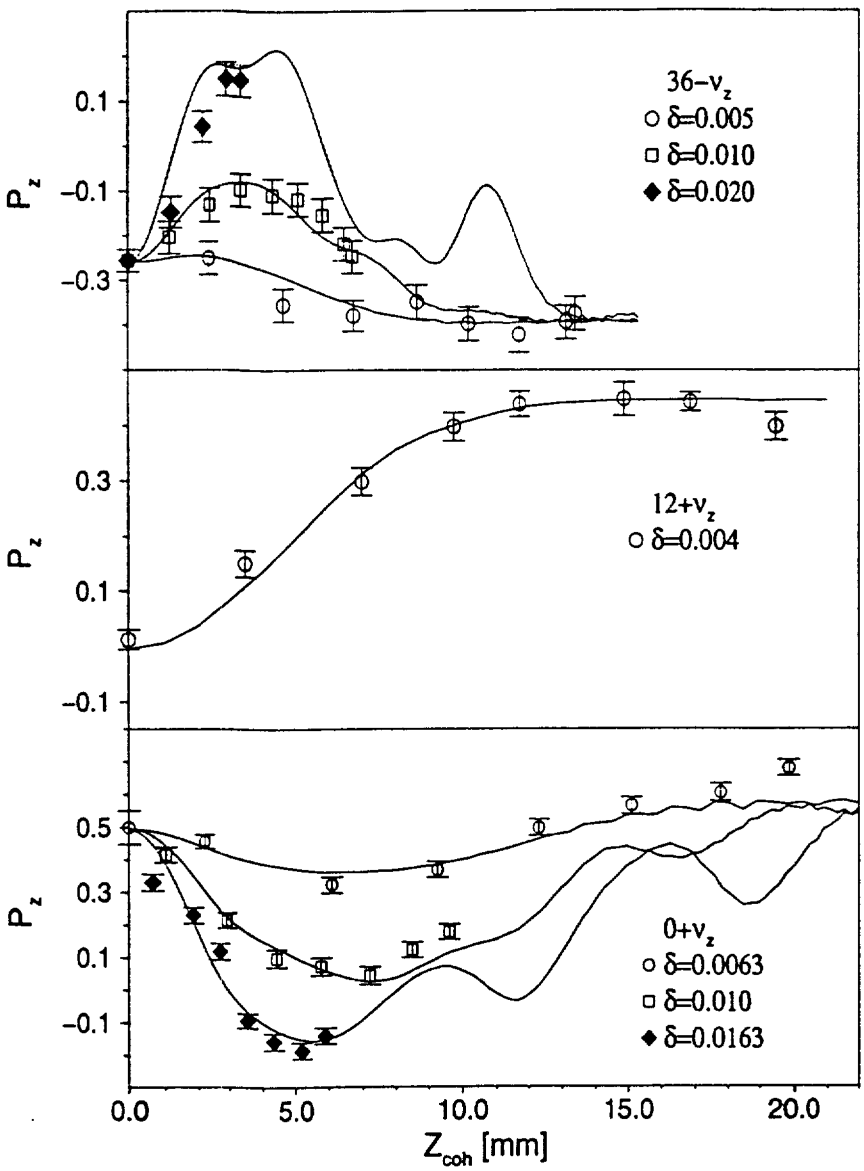

FIG. 1. The measured proton polarization vs. the coherent betatron oscillation amplitude (in mm) for different tune separations at spin depolarizing resonances $0 + \nu_z$ (bottom plot), $12 + \nu_z$ (middle plot), and $36 - \nu_z$ (upper plot). P_z stands for the vertical polarization, while Z_{coh} stands for the vertical coherent oscillation amplitude. The error bars show only the statistical errors. The resonance strength of the coherent spin resonance due to the RF dipole is proportional to the coherent betatron amplitude. The lines are the results of multi-particle spin simulations based on a model with two overlapping spin resonances.

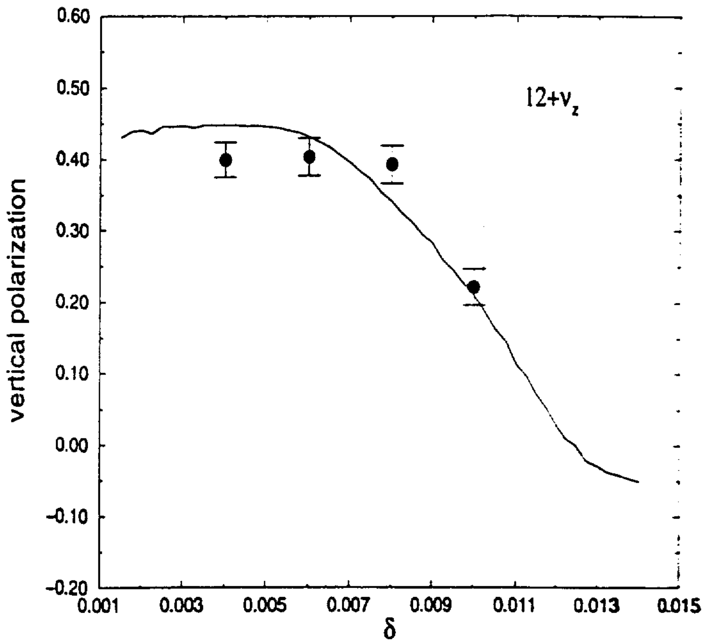

FIG. 2. The measured proton beam polarization, at the spin resonance $12 + \nu_z$, vs. the tune separation with a fixed RF dipole field strength of 1.85×10^{-3} T-m. The line shows the results of multi-particle spin simulations with a normalized 95% beam emittance of 26 π-mm-mrad, and an initial polarization of 0.45.