Synchrotron-sideband snake depolarizing resonances

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We recently created a snake depolarizing resonance using an rf solenoid magnet in a ring containing a nearly 100% Siberian snake. We found that the primary snake rf resonance also had two weaker synchrotron sidebands, which are second-order snake resonances; they were probably caused by the energy-dependent strength of the solenoid snake due to the Lorentz contraction of its longitudinal $\int B \cdot dl$. This was the first observation of an rf synchrotron-sideband depolarizing resonance in the presence of a nearly full Siberian snake. [S1098-4402(99)00044-0]

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In order to accelerate a polarized proton beam at very-high-energy facilities, such as RHIC [1], HERA [2], and Fermilab [3], one must overcome many first-order and higher-order spin depolarizing resonances. The Siberian snake technique was proposed to overcome all intrinsic and imperfection resonances [4]. Even with a full Siberian snake in a ring, an rf magnetic field from either a solenoid or dipole magnet can induce an rf depolarizing resonance [5], which is sometimes called a snake resonance, because it would not exist at its frequency without a Siberian snake. We recently used an rf solenoid magnet to induce an rf depolarizing resonance in a 104.1 MeV polarized proton beam stored in the Indiana University Cyclotron Facility (IUCF) Cooler Ring with a nearly full solenoidal Siberian snake; with this snake present we also found two second-order depolarizing rf resonances as sidebands of the primary snake resonance.

In circular accelerators or storage rings, each proton's spin precesses around the vertical fields of the ring's dipole magnets. The spin tune ν_s , which is the number of spin precessions during one turn around the ring, is proportional to the proton's energy

$$\nu_s = G\gamma, \quad (1)$$

where γ is the Lorentz energy factor and $G = 1.792847$ is the proton's anomalous magnetic moment. A Siberian snake forces the spin tune to be exactly a half-integer and suppresses most depolarizing resonances.

However, an rf-induced depolarizing resonance can still be created at a frequency

$$f = f_c(k \pm \nu_s) \pm lf_{\text{sync}}, \quad (2)$$

where f_c is the proton's circulation frequency, f_{sync} is the synchrotron frequency, while k and l are integers. Slowly sweeping the rf magnet's frequency through the resonance can flip each proton's spin [5–7].

The experimental apparatus used for this experiment including the IUCF Cooler Ring, the polarimeter, and the rf solenoid have been discussed before [5–19]; they are shown in Fig. 1. A new and more efficient superconducting snake solenoid, with 13 440 turns, was recently installed in the S section of the Cooler Ring. At its maximum current of 171 A, it has an $\int B \cdot dl$ of 2.9 T m [5]; for this experiment it operated near 1.7 T m.

With an approximately full Siberian snake in the ring, at 104.1 MeV the spin tune ν_s was very close to 0.5 but not exactly equal to $1/2$. Thus, from Eq. (2), there should be two closely spaced first-order ($l = 0$) rf depolarizing resonances centered around $1.5f_c = 2.2574$ MHz with frequencies

$$f_r^- = f_c(2 - \nu_s), \quad f_r^+ = f_c(1 + \nu_s). \quad (3)$$

We studied the higher frequency rf-induced snake resonance by operating the rf solenoid near $f_r^+ = 2272$ kHz; its voltage amplitude of 7 kV gave $\int B \cdot dl = 1.9$ T m. A 70% polarized proton beam was injected with horizontal polarization to match the stable spin direction with a full Siberian snake in the ring. The radial polarization was measured while varying the rf solenoid's frequency with its amplitude fixed; the measured radial polarization is plotted against the rf solenoid's frequency in Fig. 2. During the measurements, the snake solenoid had two liquid helium refills, which required turning it off; the

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FIG. 1. Layout of the IUCF Cooler Ring with the rf solenoid, the Siberian snake, and the polarimeter.

precision in resetting the solenoid's current was at best 0.01%. Even this very small variation, which slightly shifted the snake's strength, significantly changed the rf resonance's frequency. Therefore, for the two later data sets, each data point was shifted by +500 or -200 Hz in Fig. 2 to correct for the shift in the snake current; the horizontal bars on these data points show these two corrections to the measured frequencies [20].

The primary resonance's frequency and width were $f_r^+ = 2272.37 \pm 0.03$ kHz and $w^+ = 2.89 \pm 0.07$ kHz. The resonance is $\delta f = 15.02$ kHz away from $1.5f_c$, which indicates that the snake strength differed [5] from 100% by about

$$\Delta s = \frac{2 \cdot \delta f}{f_c} = \frac{2(15.02 \text{ kHz})}{1504.9 \text{ kHz}} = 1.996 \pm 0.004\%. \quad (4)$$

By comparison with another run [5], we determined that the snake was stronger than 100%; thus, the snake strength was $s = 1.01996 \pm 0.00004$.

The data in Fig. 2 show clear evidence for synchrotron sidebands around the rf-induced snake resonance near

$$f = f_r^+ \pm f_{\text{sync}}. \quad (5)$$

This is the first observation of a second-order rf depolarizing resonance in the presence of a nearly full Siberian snake. As expected [19], the frequencies $f_r^+ \pm f_{\text{sync}}$ lie near the outer edges of the two synchrotron sidebands, which are experimentally each centered at 3470 ± 50 Hz from the primary resonance. The widths of the upper and lower sidebands are 1030 ± 160 Hz and 1360 ± 220 Hz, respectively. Note that the minimum polarization in the

FIG. 2. The measured radial proton polarization at 104.1 MeV is plotted against the rf solenoid's frequency. The different symbols correspond to slightly different snake solenoid currents; the horizontal bars indicate the frequency's renormalization to a constant snake current [20]. The curve is a fit using a third-order Lorentzian for the primary resonance and two unequal second-order Lorentzians for the synchrotron sidebands.

sidebands is not zero; moreover, their depths are different. We earlier observed similar behavior of synchrotron-sideband resonances with no Siberian snake in the Cooler Ring [19].

A possible explanation [21] of these rather strong second-order sideband snake resonances involves the energy dependence of a solenoid's snake strength

$$s(\gamma) = \frac{\theta(\gamma)}{\pi} = \frac{(1 + G)e \int B \cdot dl}{\pi m_p c \beta \gamma}. \quad (6)$$

This energy-dependent Lorentz contraction of a longitudinal $\int B \cdot dl$, together with the energy-dependent synchrotron oscillations, would cause oscillations in the snake strength seen in each beam proton's rest frame. This could cause these second-order resonances to occur near $f_r^+ \pm f_{\text{sync}}$.

In summary, we used an rf solenoid to create a snake depolarizing resonance in the presence of a nearly full Siberian snake. We then found two second-order rf resonances near the primary rf resonance. These synchrotron-sideband snake resonances may be caused by the energy-dependent strength of the solenoid snake due to the Lorentz contraction of its longitudinal $\int B \cdot dl$ [21]. Fortunately, very high energy rings would probably use Siberian snakes constructed of transverse dipole

magnets whose $\int B \cdot dl$ is energy independent; then these synchrotron sidebands should not exist. Our future plans include developing a spin-flipping technique for an exactly 100% Siberian snake, increasing the spin-flip efficiency, and further studying higher-order snake resonances.

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