Unexpectedly wide rf-induced synchrotron sideband depolarizing resonances

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(Received 11 May 1998)

Using an rf solenoid magnet, we studied the depolarization of a stored 104.1 MeV vertically polarized proton beam. The two primary rf depolarizing resonances were properly centered around the protons' circulation frequency f_c, at $f_c(3-\nu_s)$ and $f_c(\nu_s-1)$, where ν_s is the spin tune; moreover, each resonance was roughly consistent with the expected width of about 720 Hz. Each primary rf resonance had two synchrotron sideband resonances at the expected frequencies. The two ν_s-1 sidebands were deep dips while the two $3-\nu_s$ sidebands were very shallow; this was not expected. Moreover, all four sideband resonances were unexpectedly wider than the two primary resonances. [S1063-651X(98)12309-7]

PACS number(s): 29.27.Bd, 29.27.Hj, 41.75.Ak

Accelerating polarized protons to high energy requires overcoming many spin depolarizing resonances. Correcting each individual imperfection resonance and betatron-tune-jumping each intrinsic resonance successfully maintained the polarization at the zero gradient synchrotron (ZGS) [1], Saturne [2], KEK [3], and the alternate gradient synchrotron (AGS) [4]. However, this technique is limited to fairly low energies. Recent experiments [5–18] suggest that Siberian snakes [19] should overcome all depolarization effects and should allow polarized protons to be stored for many hours in high-energy storage rings; rf magnets could then be used to measure their spin precession frequency [9], or to reverse their spin direction [13]. Thus, it is quite important to study the detailed behavior of ''rf-induced'' depolarizing resonances.

In any ring, 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 each turn, is proportional to the proton's energy

$$\nu_s = G\gamma, \tag{1}$$

where γ is the Lorentz energy factor and $G = 1.792\,847$ is the proton's anomalous magnetic moment. This vertical spin precession can be perturbed by any horizontal magnetic fields in the ring. If this perturbation frequency is synchronized with the spin precession frequency, then the beam can be depolarized. If the spin tune is an integer, then the ring's horizontal imperfection fields can interact coherently with the proton's spin and cause an imperfection depolarizing resonance. Protons also encounter the horizontal fields in the ring's quadrupoles at the vertical betatron oscillation frequency; these fields can cause intrinsic depolarizing resonances. A horizontal rf field from either a solenoid or a dipole can cause ''rf-induced'' depolarizing resonances, which can be used to measure the spin tune of a stored polarized beam [9] or to flip its spin direction [13].

An rf magnet can depolarize the beam when its frequency is

$$f_r = f_c(k \pm \nu_s) + m f_{\text{sync}}, \tag{2}$$

where f_c is the proton's circulation frequency, k and m are integers, and f_{sync} is the bunched beam's synchrotron oscillation frequency. The primary rf resonances occur when

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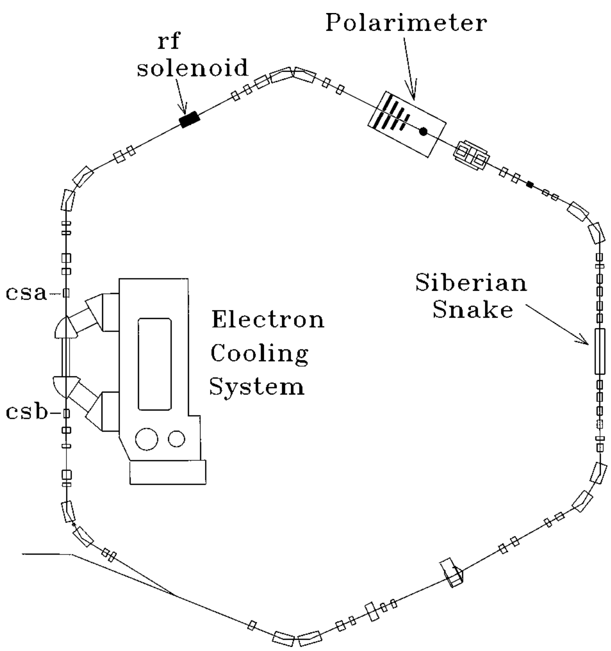

FIG. 1. Location of the rf solenoid and polarimeter in the IUCF Cooler Ring. The Siberian snake was not used.

m=0, while the ''synchrotron sideband'' rf resonances occur when $m=\pm1$. These rf sideband resonances had been observed [9] and were properly narrower than their primary resonance. However, we recently observed two primary rf resonances with unexpectedly wide and different synchrotron sidebands.

The experimental apparatus shown in Fig. 1, including the IUCF Cooler Ring, the polarimeter, and the rf solenoid, have been discussed before [5–17]. We operated the rf solenoid near 1.5 MHz at a voltage amplitude of 6 kV, which corresponds to an $\int B\,dl$ of about 1.3×10^{-3} T m. At 104.1 MeV, the resulting rf depolarizing resonance strength ϵ, which is the rf-induced spin precession per radian around the ring, was about 3.5×10^{-4}. Note that the rf solenoid also generates rf electric fields; however, its $\int E\,dl$ is only about 10% of the rf acceleration cavity's $\int E\,dl$.

At 104.1 MeV, the first-order spin tune $G\gamma$ is equal to 1.9918. This proximity to 2 causes two closely spaced rf resonances centered around the Cooler Ring's circulation frequency of $f_c=1.504\,90$ MHz at frequencies of

$$f_{3-\nu_s}=f_c(3-\nu_s),$$
$$f_{\nu_s-1}=f_c(\nu_s-1). \tag{3}$$

Due to the type-3 snake, caused by the Cooler Ring's electron cooling system [8,20,21], the spin tune was increased from its $G\gamma$ value of 1.9918 by about 0.003. This ν_s shift moved each resonance about 4.5 kHz closer to f_c.

The 104.1 MeV vertically polarized proton beam was first accumulated and cooled while bunched at the 1.504 90 MHz first harmonic. The acceleration cavity was then turned off, allowing the bunch structure to ''smear out'' longitudinally. Then, a second rf acceleration cavity, operating at 1.5 kV, rebunched the beam at the sixth harmonic frequency of 9 029 469±60 Hz. The rf solenoid was next turned on at some fixed frequency; then the polarization was measured during about 16 runs with alternating spin states to reduce the systematic error. In each run, the polarization was measured for about 20 sec during each 30 sec long flattop; the total statistical error was about 2.5% from the 16 runs in each data point.

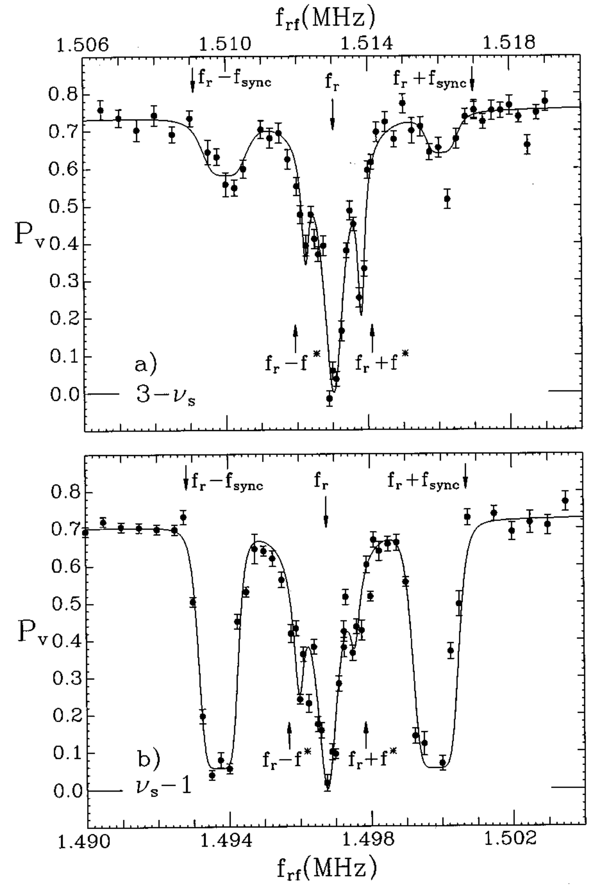

FIG. 2. The measured vertical proton polarization at 104.1 MeV is plotted against the rf solenoid frequency. The beam circulation frequency was $f_c=1.5049$ MHz and the rf solenoid voltage was 6 kV. (a) shows the $3-\nu_s$ resonance with its center at 1.513 03 MHz; (b) shows the ν_s-1 resonance with its center at 1.496 77 MHz. The curves contain Lorentzian fits to the primary resonances and higher-order Lorentzian fits to the sidebands. The horizontal parts of the curves both have the same small slope to best fit the data. All six rf resonance frequencies are indicated by the upper arrows. The very narrow resonances, indicated by the lower arrows, are probably due to additional weak rf beam structure with $f^*=1080$ Hz.

We searched for the rf resonances by measuring the vertical polarization while varying the rf solenoid's frequency from 1.490 to 1.520 MHz; the vertical polarization is plotted against the solenoid's frequency in Fig. 2. Note the two primary rf resonances located near 1.497 and 1.513 MHz; each is about 8 kHz from the measured circulation frequency of 1 504 900±10 Hz, and each has a pair of synchrotron sideband resonances. All four rf synchrotron sideband resonances are surprisingly wide; this is especially clear for the two wide and deep lower-frequency sidebands in Fig. 2(b).

Also note that the upper and lower primary resonances each have a second pair of very narrow sideband resonances that are located partway up each slope. These narrow dips near $f_r\pm f^*$ were apparently caused by a very weak har-

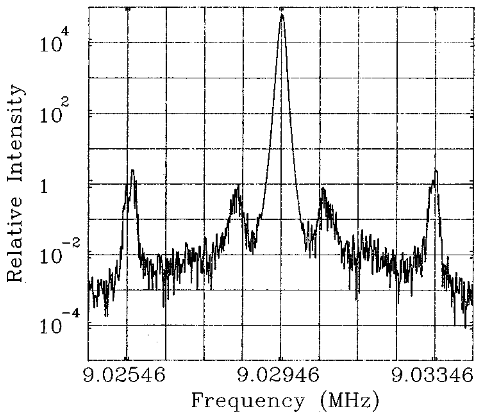

FIG. 3. The rf spectrum of the Cooler Ring measured with a spectrum analyzer. The central peak corresponds to the sixth harmonic of the circulation frequency. Note that, in addition to the primary synchrotron sidebands at $f_{\rm sync} = \pm 3940$ Hz, there are weak sidebands at $f^* = \pm 1080$ Hz caused by a weak first harmonic in the acceleration cavity.

monic of the acceleration frequency and were later found at $f^* = \pm 1080$ Hz in the Cooler Ring's measured rf spectrum, which is shown in Fig. 3. The frequencies $f_r \pm f^*$ are indicated by the lower arrows in Fig. 2.

The higher frequency $f_c(3-\nu_s)$ resonance region is shown in Fig. 2(a). The primary rf resonance's central frequency of $f_{3-\nu_s} = 1\,513\,030 \pm 11$ Hz is indicated by an arrow labeled f_r; its width is 722 ± 20 Hz FWHM. This frequency corresponds to a spin tune of $\nu_s = 1.994\,59 \pm 0.000\,01$. Since $G\gamma = 1.9918$ at 104.1 MeV, this ν_s value implies that the Cooler Ring's type-3 snake [20,21] increased the spin tune by about 0.0028. The expected frequencies of

TABLE I. Parameters and fits for the depolarizing resonance data shown in Figs. 2, 4, and 5.

Energy (MeV)	$V_{\rm rf}$ (kV)	Resonance	Frequency (Hz)	Width (Hz)	Min. Pol.
		$3-\nu_s$	$1\,513\,030 \pm 11$	722 ± 20	0%
104.1	6	$3-\nu_s+\nu_{\rm sync}$	$1\,516\,090 \pm 13$	940 ± 90	61%
Fig. 2(a)		$3-\nu_s-\nu_{\rm sync}$	$1\,509\,970 \pm 13$	1330 ± 130	56%
		ν_s-1	$1\,496\,770 \pm 11$	753 ± 27	0%
104.1	6	$\nu_s-1+\nu_{\rm sync}$	$1\,499\,830 \pm 13$	1330 ± 30	6%
Fig. 2(b)		$\nu_s-1-\nu_{\rm sync}$	$1\,493\,710 \pm 13$	1150 ± 20	5%
		ν_s-1	$1\,800\,230 \pm 15$	240 ± 15	0%
139	3	$\nu_s-1+\nu_{\rm sync}$	$1\,803\,520 \pm 20$	1070 ± 90	50%
Fig. 4(a)		$\nu_s-1-\nu_{\rm sync}$			
		ν_s-1	$1\,800\,233 \pm 13$	460 ± 10	0%
139	6	$\nu_s-1+\nu_{\rm sync}$	$1\,803\,525 \pm 15$	1080 ± 16	20%
Fig. 4(b)		$\nu_s-1-\nu_{\rm sync}$	$1\,796\,990 \pm 15$	1060 ± 15	26%
		ν_s-1	$1\,497\,149 \pm 10$	1020 ± 90	0%
104.1	14.5 [a]	$\nu_s-1+\nu_{\rm sync}$	$1\,498\,950 \pm 12$	280 ± 50	12%
Fig. 5		$\nu_s-1-\nu_{\rm sync}$	$1\,495\,261 \pm 12$	280 ± 50	12%

[a]The data in Fig. 5 were taken with a different rf solenoid.

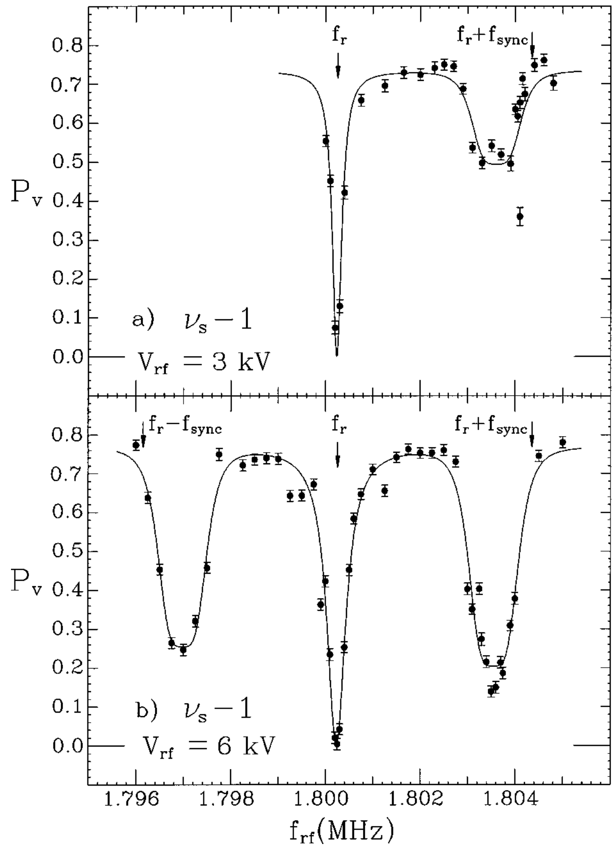

FIG. 4. The measured vertical proton polarization at 139 MeV is plotted against the rf solenoid frequency at values above the beam circulation frequency of 1.6973 MHz [22]. The rf solenoid was set at 3 kV for (a) and at 6 kV for (b). The curves contain Lorentzian fits to the primary resonances and higher-order Lorentzian fits to the sidebands. The resonance frequencies are indicated by the arrows.

the synchrotron sidebands, $f_{3-\nu_s} \pm f_{\rm sync}$, are also indicated by arrows in Fig. 2(a); the synchrotron frequency was measured using the Cooler Ring's spectrum analyzer to be $f_{\rm sync} = 3.94 \pm 0.01$ kHz. Note that these frequencies correspond to the outer limit of each sideband resonance. Both sidebands are much shallower than the main resonance; the sidebands' widths have large uncertainties, as indicated in Table I.

The lower frequency $f_c(\nu_s-1)$ resonance region is shown in Fig. 2(b). The primary rf resonance's central frequency of $f_{\nu_s-1} = 1\,496\,770 \pm 11$ Hz is indicated by an arrow labeled f_r; its width is 753 ± 27 Hz FWHM. This frequency corresponds to $\nu_s = 1.994\,59 \pm 0.000\,01$, which agrees *exactly* with the spin tune obtained just above for the $3-\nu_s$ resonance. The expected synchrotron sidebands' positions are also indicated by arrows. Note that these synchrotron sideband resonances are more than 1 kHz wide. The positions and widths of all three resonances are listed in Table I.

We earlier observed similar wide synchrotron sidebands while studying only the $f_c(\nu_s-1)$ resonance at 139 MeV; these previously unpublished data are shown in Fig. 4. The experimental procedure was similar to the 104.1 MeV procedure, except that the 139 MeV beam was bunched on the ninth harmonic with the acceleration cavity at 1.2 kV; this made the synchrotron frequency 4.1 kHz. Figure 4(a) shows 139 MeV data with the rf solenoid voltage amplitude at 3

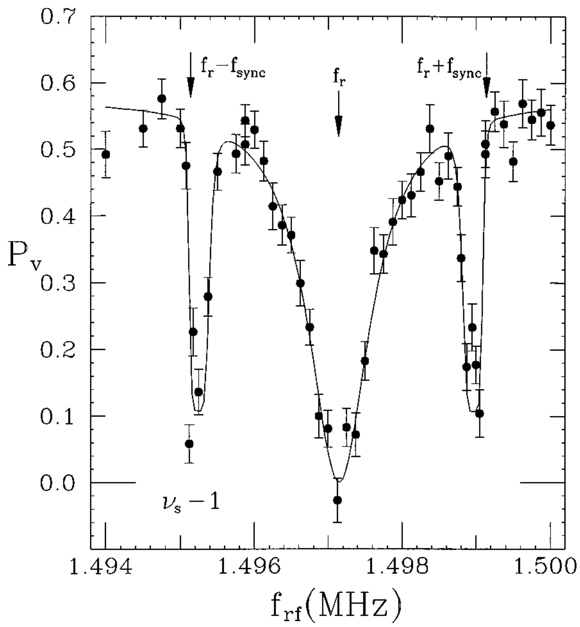

FIG. 5. The measured [23,24] vertical proton polarization at 104.1 MeV is plotted against the rf solenoid frequency; the Cooler Ring operated using single turn injection [25]. The curve contains a Lorentzian fit to the primary resonance and higher-order Lorentzian fits to the sidebands. The resonance frequencies are indicated by the arrows.

kV, while Fig. 4(b) shows similar data with the rf solenoid at 6 kV. The resonance frequencies f_{ν_s-1} and $f_{\nu_s-1} \pm f_{\text{sync}}$ are indicated by arrows and listed in Table I. The primary rf resonance had a FWHM of 460 ± 10 Hz at 6 kV, while its synchrotron sidebands were both about 1 kHz wide. Note that the $f_{\nu_s-1} + f_{\text{sync}}$ sideband was equally wide at 3 and 6 kV, but it was much deeper at 6 kV [22].

During the early operation of the Cooler Ring, our group found much narrower synchrotron sideband resonances; the 104.1 MeV data on the $\nu_s - 1$ resonance, which are shown in Fig. 5, only appeared in an internal report [23] and a thesis [24]. The sideband resonances in these 1991 data had widths of about 280 ± 50 Hz FWHM; these widths were about four times narrower than the recent data in Figs. 2 and 4, as listed in Table I. One possible reason for this difference is that the 1991 data were taken with single turn injection, while the later data in Figs. 2 and 4 were taken using multiturn injection with rf stacking [25]. Perhaps this stacking injection caused the broadening of the sideband resonances; note that at high intensity the Cooler Ring was found to have a large synchrotron frequency spread [26].

In summary, we found that the $f_c(\nu_s - 1)$ rf depolarizing resonance has very wide and deep synchrotron sideband resonances, while the nearby $f_c(3 - \nu_s)$ resonance's sidebands are certainly shallow and also seem very wide. We do not yet understand why these two equally strong primary rf resonances should have such different synchrotron sidebands or why these sidebands are much wider than with single turn injection; we plan to study this further. Understanding the behavior of such sideband depolarizing resonances is quite important since their primary rf resonances may be needed to flip the spin of stored high-energy polarized proton beams.

We would like to thank J. M. Cameron and the entire Indiana University Cyclotron Facility staff for the successful operation of the Cooler Ring. We are grateful to R. Baiod, A. Barkan, A. W. Chao, J. Duryea, M. Ellison, S. Hiramatsu, F. Z. Khiari, A. Koulsha, W. Lehrer, H.-O. Meyer, D. I. Patalakha, R. E. Pollock, T. Roser, H. Sato, D. Shoumkin, T. Toyama, B. S. van Guilder, and U. Wienands for their help with earlier parts of this experiment. This research was supported by grants from the U.S. Department of Energy and the U.S. National Science Foundation.

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