RF INDUCED DEPOLARIZING RESONANCES, SPIN FLIP, AND PARTIAL SIBERIAN SNAKES†

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We have made detailed studies[1–4] of the Siberian snake concept[5] for overcoming depolarizing resonances in proton accelerators. These Cooler Ring experiments may eventually allow the acceleration of polarized protons to TeV energies[6] at facilities such as the SSC and the Fermilab Tevatron. A 25 kV rf solenoid magnet was recently constructed and installed in the Cooler Ring; this allowed us to produce an "rf induced" depolarizing resonance. This new capability allowed us to obtain a great deal of interesting data on spin-polarized beams and depolarizing resonances during CE-20 runs in June, October, and November 1991 and March 1992. Some highlights are:

1. In the June run we found very narrow unexpected structure with a width of a few Hz as shown in Fig. 1. This same behavior occurred again in the October run; it was partially but not completely reproducible.
2. We studied this unexpected behavior by varying the rf voltage and the rf on-time. It now appears that we were observing "free spin precession" which stopped at the exact instant the rf solenoid was turned off. This precession was directly seen when we varied the rf on-time in very fine steps and saw the spin direction change smoothly

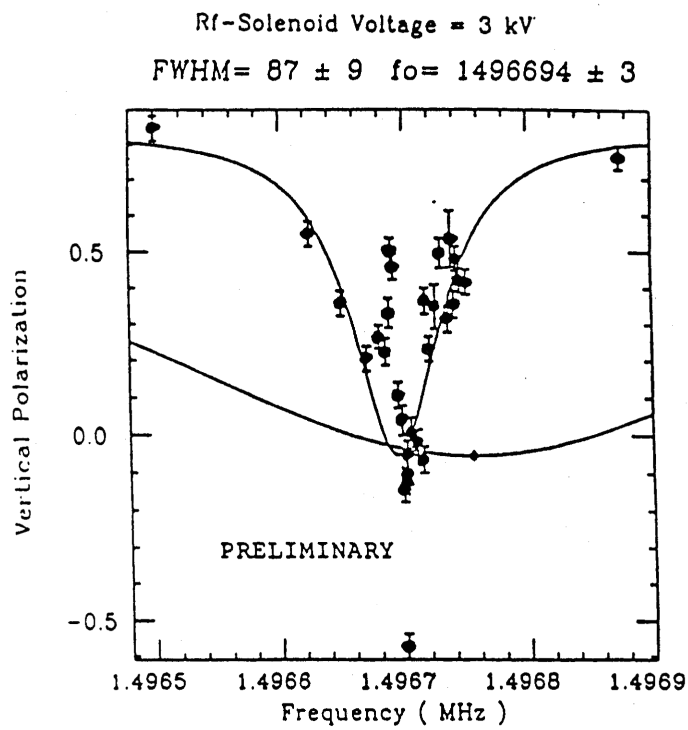

Figure 1. The measured vertical beam polarization at 104 MeV is plotted against the frequency in the rf solenoid magnet. The dip of width 87 Hz is due to a weak (3 kV) rf induced resonance. The very narrow structure is due to free spin precession associated with tiny variations in the fixed 150 msec rf-on time. The broad curve fits the data with a strong (25 kV) rf induced resonance.

from up to down. The free spin precession is especially clear in Fig. 2, where we made the oscillation structure wider by reducing the rf on-time to 10.3 msec. In Fig. 1, the rf on-time was 150 msec; this made the oscillations only a few Hz wide and thus difficult to reproduce.

3. The originally planned spin tune measurements were then made while keeping the rf on during the polarization measurements. The spin tune is the number of spin precessions during one turn around the Cooler Ring. Since the spin precessed many times during each measurement, we now measured the time averaged polarization. We obtained the spin tune with excellent precision from the measured position of the central dip shown in Fig. 3. Also notice the two sideband synchrotron depolarizing resonances due to the synchrotron oscillations caused by the Cooler Ring's acceleration cavity.
4. Using the recently repaired superconducting solenoid Siberian snake, we searched for a first order snake resonance. This snake resonance occurred just as expected near

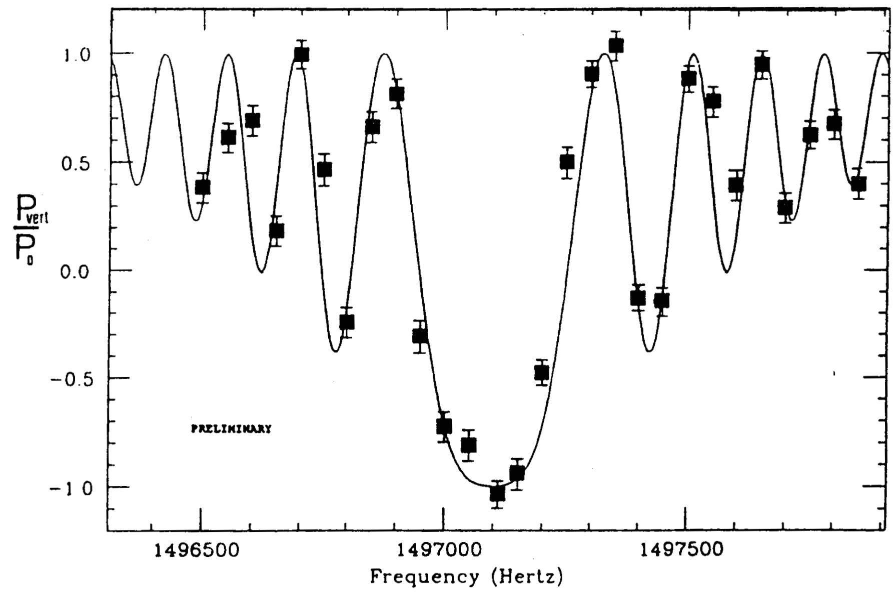

Figure 2. The normalized measured vertical beam polarization at 104 MeV is plotted against the frequency for a short well-stabilized rf on-time of 10.3 msec. The data fit fairly well the calculated "free spin precession" curve.

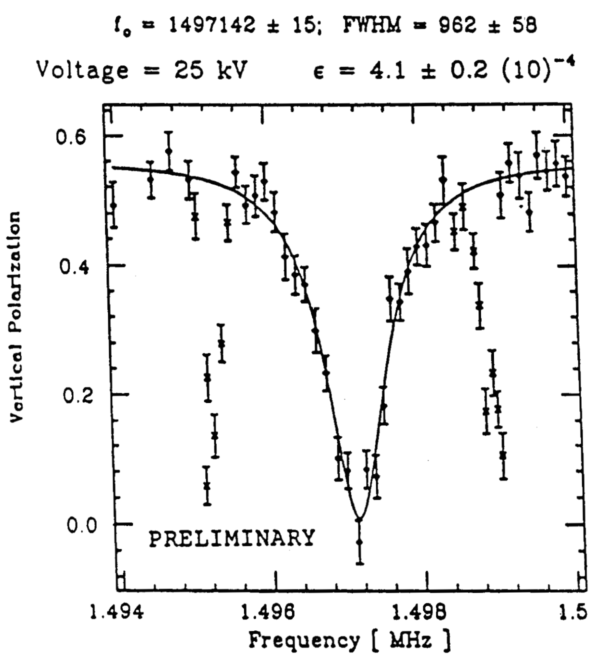

Figure 3. The measured vertical beam polarization at 104 MeV is plotted against the frequency in the rf solenoid. The 962 Hz wide dip is due to a strong (25 kV) rf induced resonance. The rf was now on continuously eliminating the narrow structure due to free spin precession. The two narrow sideband dips are synchrotron depolarizing resonances.

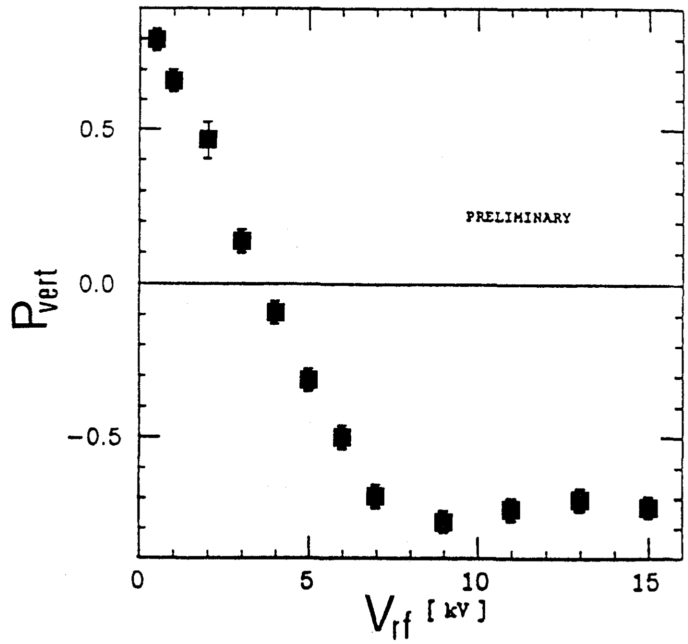

Figure 4. The measured vertical beam polarization at 104 MeV is plotted against the voltage in the rf solenoid, while the frequency was ramped from 1.509 to 1.507 MHz during 30 msec. Note that full spin-flip occurs for voltages greater than 7 kV.

$$f_{rf} \sim (1 + \frac{1}{2})\, f_{revolution} \sim 2.26\ MHz.$$

There were now no synchrotron sideband resonances because this snake resonance does not depend on the protons' energy, which varies during synchrotron oscillations. However the resonance appeared as two symmetric dips on either side of $(1+\frac{1}{2})f_{revolution}$; this splitting occurred because the superconducting solenoid is not precisely enough calibrated to rotate the spin by exactly 180°. The frequency shift of about 10 kHz corresponds to a solenoid miscalibration of about 0.2%. We also found that during 8 hours the dips shifted by about 1 kHz showing that the solenoid was only stable to about 0.04%; the solenoid stability was recently improved.

5. During the November 1991 run we successfully flipped the spin of the stored polarized beam by ramping the rf solenoid frequency through the resonant frequency. The spin-flip can be clearly seen in Fig. 4. This spin-flip capability will be most useful for experiments using stored polarized proton beams in the Cooler Ring. By rapidly flipping the spin direction, experimenters can strongly discriminate against most systematic errors.
6. During the November 1991 run we also observed the first clear evidence for interference between overlapping depolarizing resonances. We first adjusted the rf solenoid frequency to move the "rf induced" resonance close to the $G\gamma = 2$ imperfection reso-

nance. We then varied the strength of the imperfection resonance and produced the sharp destructive interference shown in Fig. 5.

7. During the March 1992 run we used a partial Siberian snake to shift the frequency of the "rf induced" depolarizing resonance. The resonant frequency obeyed the prediction of a quadratic variation with snake strength as shown in Fig. 6.

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g. Also at Los Alamos.

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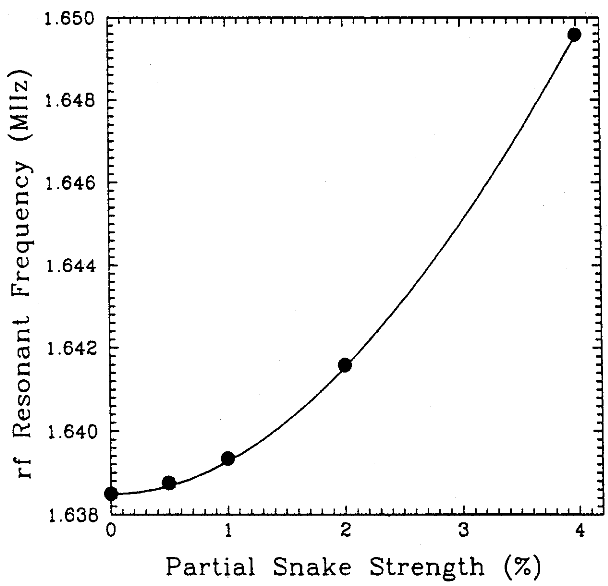

Figure 5. The interference between the $G\gamma = 2$ imperfection depolarizing resonance and the rf induced resonance is shown. The radial polarization at 106.4 MeV is plotted against the strength of the $G\gamma = 2$ resonance which is proportional to the current in the correction solenoid. Note the sharp destructive interference when the rf solenoid is on.

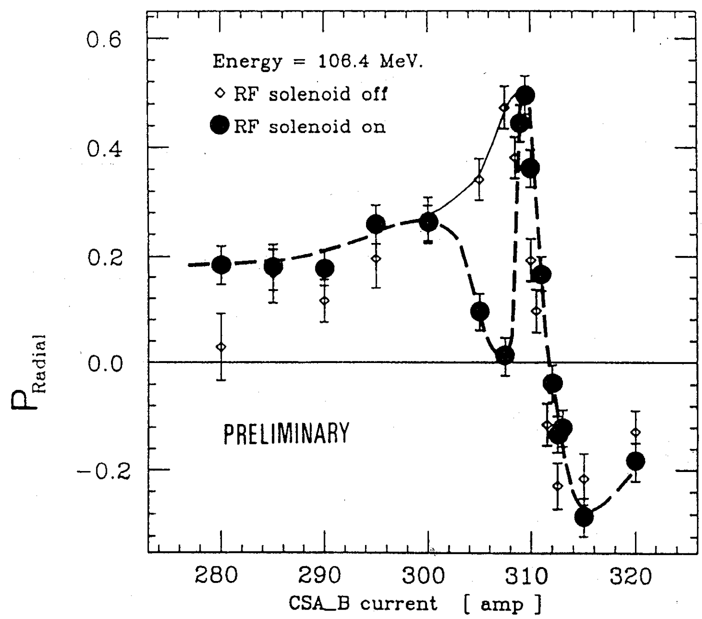

Figure 6. The measured frequency of the "rf induced" depolarizing resonance is plotted against the strength of a partial Siberian snake. The curve is the predicted quadratic behavior.