ZGS MACHINE EXPERIMENT REPORT

ADIABATIC CROSSING OF A DEPOLARIZING RESONANCE

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The aim was to test whether complete spin flip can be obtained with slow resonance crossing.

The procedure was to measure depolarization on the 8-ν resonance. The crossing speed ($\dot{\gamma}_{eff} = \dot{\gamma} + \dot{\nu}/G$) was varied by:

i) changing the acceleration ratio $\dot{B}$ and hence $\dot{\gamma}$,

ii) pulsing quadrupoles (such that $\dot{\nu}/G \approx - \dot{\gamma}$).

Partial reversal of the polarization from + 70% to at best - 20% was obtained. This is in qualitative agreement with recent theory which includes the beam momentum spread. More work is needed to scale these results to parameters of the CERN-PS.

I Introduction

Some theoretical models[2) 3) 4)] indicate that the beam polarization may simply change its sign (without changing its magnitude) when a depolarizing resonance is strong and/or crossed slowly enough. This kind of resonance crossing could provide a relatively simple technique[3)] for accelerating polarized beams in a strong focussing synchrotron where strong resonances must be crossed.

However, these models used several simplifying assumptions including a monoenergetic beam and a well isolated resonance. These restrictions are questionable because in synchrotrons like the PS and the ZGS the energy of each particle fluctuates around the average value due to synchrotron oscillations as shown in Figure 1. Moreover, the resonances are sometimes not well separated. Therefore, these assumptions were tested experimentally. It was felt that these experiments could give an interesting contribution to the physics of accelerating polarized beams with special importance to the CERN studies and to the ZGS operation.

II Experiments with Reduced $\dot{B}$

A typical B field cycle used in this type of experiment is shown in Figure 2. The beam was extracted with a Piccioni energy loss target and the polarization was measured at 4 GeV/c using the high rate polarimeter.[1)] This polarimeter was calibrated frequently against the more precise clean elastic polarimeter[1)] of the Michigan Group. The extracted beam intensity was typically 10^8 polarized protons per pulse (pppp) and about 15 min. runs were made with the fast polarimeter and one hour runs with the clean elastic polarimeter.

The $8-\nu$ resonance is crossed in the reduced $\dot{B}$ region just below the 4 GeV/c flattop as shown in Figure 2. The height of this ramp was $\Delta B \approx 100$ G independent of the value of $\dot{B}$. This ΔB was large enough to accommodate the width of the resonance including spreads and uncertainties in energy and ν value as discussed in Appendix 1. But ΔB was small enough to avoid slow passage through the nearby resonances shown in Figure 3.

The experiment consisted of measuring the loss in polarization as $\dot{B}$ was reduced and the dwell time on the resonance was thus increased. The results are summarized in Figure 4. Notice that the final polarization (P) has a broad minimum with $P \approx -20\%$ indicating that the spin only partially flipped. For fast crossing, the 70% polarization is maintained and for very slow crossing the final polarization seems to approach zero.

The shape of this curve might be explained by the influence of momentum spread[5] which makes each particle cross the resonance many times as it undergoes synchrotron oscillations. In fact, calculations made prior to the experiment which included synchrotron oscillations displayed the qualitative features of the data as shown in Figure 5. These calculations are discussed in Appendix 3.

The energy spread of the ZGS beam was estimated from the rf accelerating voltage at which some fraction of the beam was lost as discussed in Appendix 2. Probable values are $\Delta p/p = \pm 4 \times 10^{-4}$ at full rf (26 kV) and $\pm 3 \times 10^{-4}$ with the lowest practical voltage (10 kV).

Some data was taken with the rf reduced or with the beam size increased by misaligning the injection angle. In both cases spin reversal seemed to be a few percent higher. However, with the small changes in $\Delta p/p$ and beam size which could be obtained and the limited accuracy of the polarization measurement, no definite conclusions can be made.

III Measurements Using "Mistiming" of the ν Jump Quadrupoles

These were a repetition of an earlier experiment.[1] It had been observed that a partial reversal of P occurs when the ν jump quadrupoles at the 8-ν resonance were triggered too early. As shown in Figure 6, the resonance was then crossed on the trailing edge of the $\nu(+)$ waveform pulse rather than during the fast rise.

This experiment consisted of measuring the final polarization while changing the length of the trailing edge and thus increasing the dwell time on the resonance. However, for each value of the trailing edge length we had to measure the polarization as a function of the B field at which the ν jump was triggered ("ν jump timing curve") to insure that the resonance curve was right on the trailing edge. Results for three different lengths of the slow decay are plotted in Figure 7. All these measurements are taken with the normal ZGS magnetic field cycle ($\dot{B} \approx 19$ kG/sec at the resonance).

In the earlier experiment, $\dot{B}$ was 15 kG/sec and spin reversal had been observed with 4.5 msec decay of the ν jump waveform. Thus, we now expected to find a similar spin reversal with about 3.5 msec decay time. However, the data shown in Figure 7 suggests a 5 msec decay time is optimal. Moreover, the detailed analysis given in Appendix 4 seems to indicate that the effective crossing speed ($\dot{\gamma} - \dot{\nu}/B$) was only reduced by a factor of about two whereas from Figure 3 one would need a factor of at least ten to have P reversal to - 20%.

A possible explanation is that in these experiments the quadrupole decay is not linear and that the crossing occurs on a steeper part of the trailing edge shown in Figure 7. In any case, the best P reversal that could be obtained was about - 20% in agreement with the measurements done by reducing $\dot{B}$.

A word of caution should be added: To do the measurement with the longer decays, capacitors were added to the ν jump quadrupole power supply. No spin reversal was found with slower decays. However, now even measurements with 5 msec decay no longer gave spin reversal. This again suggests sensitivity to the detailed shape of the decay. Thus, we may have missed the optimal conditions for spin reversal by not changing the shape and decay length in fine enough steps.

IV A Quick Look at an Imperfection Resonance

We decided to have a glance at the $\gamma G = 7$ imperfection resonance by centering the low B window around the corresponding energy. Only two measurements (both with a $\dot{B}$ of 1.2 kG/sec) were made. One with the ν jump working to rapidly pass the $\gamma G = 8-\nu$ resonance, the other with the ν jump off. In both cases polarization at 4 GeV/c was somewhat lower than with full $\dot{B}$ at $\gamma G = 7$. Unfortunately no time was available to make sure that depolarization was really caused by the $\gamma G = 7$ resonance. It is possible that with the $\dot{B}$ window rather close to $\gamma G = 8-\nu$, the tail of this strong intrinsic resonance may have been enhanced.

V Future Experiments

Theory suggests that imperfection resonances will be quite serious in the CERN PS. In the ZGS these resonances should be weaker. It is nevertheless somewhat puzzling[6)] that they seem to have no measurable effect at all on the ZGS polarization. Either theory is too pessimistic, or the magnets are very well aligned, or perhaps the depolarizing influence is masked by other effects.

We think that it is important to investigate this point further by redoing the experiment described above. Instead of $\gamma G = 7$, one would probably prefer another imperfection resonance far from any intrinsic resonances. Moreover, we might vary the strength of this resonance using a controlled orbit bump.

VI Conclusion

Energy spread and/or other influences prevent complete spin flip in the ZGS even when the strong $8-\nu$ resonance is crossed very slowly.

References

1. T. Khoe, et al., "Acceleration of Polarized Protons to 8.5 GeV/c," ANL Internal Report, to be published in Particle Accelerators.

2. L. Teng, "Depolarization of a Polarized Proton Beam in a Circular Accelerator," NAL Note FN 267 (1974). Abridged version in "Proc. Summer Study . . . ," ANL/HEP 70-02, p XIII.

3. J. Faure, et al., "Accelération de Protons Polarisès a SATURNE," Particle Accelerators, 3 (1972) p 225.

4. M. Froissart, R. Stora, "Depolarization d'un Faisceau de Protons Polarisés dans un Synchrotron," Nucl. Inst. Meth., 7 (1960) p 297.

5. D. Möhl, to be published.

6. PS Machine Studies Team, "Possibility of Acceleration of Polarized Particles in the CERN PS," MPS-DL Note 74-22 and ANL/HEP 75-02, p XIV.

APPENDIX 1

Required Width of the Low $\dot{B}$ Window

I Natural Width

Asymptotic conditions are reached when the normalized time distance from the resonance is $\tau \gg \left| \frac{K^2}{4} + \frac{\tau}{2} \right|$ (e. g., see reference 2) where $\tau = \sqrt{\omega_{rev} \dot{\gamma} G}\; t$ and K^2 is proportional to the square of the strength and inversely proportional to the crossing speed. Also from Froissart and Stora's formula, the asymptotic polarization is:

$$P = P_o \left(2e^{-\frac{\pi}{2}K^2} - 1 \right).$$

For ZGS parameters ($\omega_{rev} = 1.1 \times 10^7\ \mathrm{sec}^{-1}$, $\dot{\gamma} \simeq 0.67\ [\mathrm{kG}^{-1}]\ \dot{B}$) and $G = 1.79$, so one has

$$\tau \approx 3400\ \left[\mathrm{kG}^{-1/2}\ \mathrm{sec}^{-1/2}\right]\ \frac{\Delta B}{\sqrt{\dot{B}}}$$

where ΔB (in kG) is the field distance from the resonance ($\Delta B = \dot{B}\ t$). Also assuming $P/P_o = 0.7$ at normal $\dot{B}$ one has

$$\frac{K^2}{4} \approx 0.11\ (\mathrm{kG}^{1/2}\ \mathrm{sec}^{1/2})\ \frac{1}{\sqrt{\dot{B}}}$$

It is then easy to verify that a distance $\Delta B = \pm\ 0.01$ kG is largely sufficient to bracket the natural width of the resonance. These calculations assume constant crossing speed; with $\dot{\gamma}$ changing near the resonance, a larger width may be required.

II Energy Spread and Error

Let the spread be $\Delta p/p = \pm 5 \times 10^{-4}$, corresponding in the ZGS at 4 GeV/c to $\Delta B \simeq 1.6 \left(\frac{\mathrm{kG}}{\mathrm{GeV/c}}\right) \Delta p \approx \pm\ 3\mathrm{G}$.

Let the uncertainty in radial position, associated with energy uncertainty be $\Delta R = 5$ cm. $\frac{\Delta p}{p_o} = \gamma t^2 \frac{\Delta R}{R} \approx 10^{-3}$, ($R = 27$ m, $\gamma t^2 \simeq \nu_H^{\ 2} \approx 0.5$) which gives $\Delta B \approx \pm 6$ G.

III Tune Spread and Error

Let spread and error in the tune be $\Delta \nu = 10^{-2}$, then the corresponding resonance shift in the ZGS is $\Delta \gamma = \frac{\Delta \nu}{G} \simeq 5 \times 10^{-3}$ which gives $\Delta B = 7.5$ G.

IV Calibration of B Measurement

The "B clock" was recalibrated using the position of the $8-\nu$ resonance. We found that the resonance had moved by about 20 G from where it had been expected. Anticipating such an effect, we had chosen a window of ± 50 G. Due to the calibration error, the resonance is not exactly in the center of the window, but the remaining 30 G was adequate to cover effects I, II, and III. The window was, therefore, not readjusted.

APPENDIX 2

Measurements done by synchronizing a low rf voltage to the B window indicate that about 80% of the beam was contained in almost stationary buckets created by the 10 kV rf. We use this information to estimate the beam energy spread:

$$\left.\frac{\Delta p}{p}\right|_{\text{bucket}} = \pm \left(\frac{eU_{rf}\,\gamma}{2\pi h |\eta| m_p} \right)^{1/2} \frac{2}{\beta\gamma} \approx \pm\ 3 \times 10^{-4}$$

(U_{rf} = 10 kV, $\gamma \approx \beta\gamma \approx 4$, h = 8, $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \approx 2$, m_p = 938 MeV).
Hence with 10 kV, $\Delta p/p \approx \pm\ 3 \times 10^{-6}$. The energy spread with full rf voltage (26 kV) can be worked out using tables (e. g., F. Cole, P. Morton, UCID 10 130, 1964). One finds $\Delta p/p \approx 4 \times 10^{-4}$ fairly independent of $\dot{B}$.

This momentum spread is consistent with a spread of about ± 250 keV from the linac as was measured for operation with ordinary protons. In fact, scaling from 50 MeV to 3. 7 GeV/c, the corresponding $\Delta p/p$ agrees within less than 10%. The measurement is nevertheless rather crude as losses may have occurred due to other effects and the synchronization between low $\dot{B}$ and U_{rf} was not precise. Both effects appear to increase $\Delta p/p$.

APPENDIX 3

Synchrotron Oscillations

Due to the action of the rf, the energy of a particle varies as: $\gamma = \gamma_o + \dot{\gamma}\, t + \Delta\gamma \cos(\omega_s t + \alpha)$. (Phase α and amplitude $\Delta\gamma$ are different for different particles.) These oscillations sweep a particle repetitively through a resonance when $\dot{\gamma} << \omega_s \Delta\gamma$. The depolarization curves in Figure 4 have been computed taking this effect into account. A Gaussian amplitude distribution $\left[N\ (\Delta\gamma) \right]$ and a uniform distribution of phases α were assumed. The strength of the resonance was assumed to be the same for all particles ("hollow beam approximation") and adjusted such that with the normal ZGS $\dot{B}$ ($\dot{\gamma} = 1$ in the normalized units of Figure 1) the polarization drops from 70% to 20%. The synchrotron oscillation frequency was assumed to be $\omega_s \approx 2400\ \text{sec}^{-1}$. The measurement showed a drop of polarization from 70% to 45% at full voltage and thus an ω_s of 3000 sec^{-1} to 4000 sec^{-1} is expected. These differences as well as the hollow beam approximation make a quantitive comparison between Figures 4 and 5 difficult.

APPENDIX 4

The ν Jump

As pointed out in reference 4, the width of the plateau of the ν jump timing curve in Figure 7 is a measure of the size of the jump. In fact, neglecting energy and ν spreads we have $\Delta\nu \simeq G\ \Delta\gamma$. For the ZGS; $\Delta\gamma = 0.67\ (kG^{-1})\ \Delta B$. From Figure 7 one obtains a plateau width of $\Delta B \approx 55G$ which gives $\Delta\nu \approx 0.065$.

We note in passing that Figure 18 of reference 4 suggests that $\Delta B \approx 45$ G giving $\Delta\nu \approx 0.055$. This difference may partly explain why this time a longer decay was needed to obtain spin flip.

However, for the 5 msec decay length the average $d\nu/dt$ is $\dot{\nu} = -0.065/5\ \text{msec} \approx -13\ \text{sec}^{-1}$. Whereas $G\dot{\gamma} \approx 1.2\ (kG^{-1})\ \dot{B} \approx 23\ \text{sec}^{-1}$. Hence for a purely linear decay there is not perfect cancellation beween $\dot{\nu}$ and $G\dot{\gamma}$.

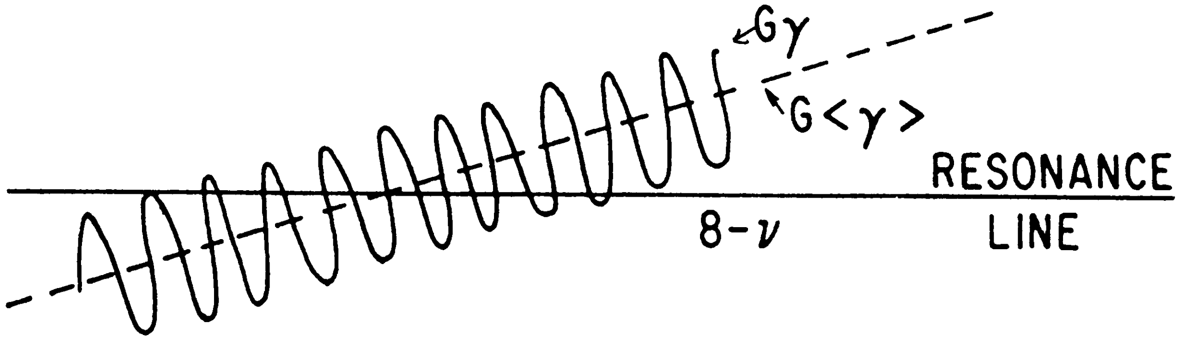

Figure 1 Resonance Crossing for a Particle that Performs Energy Oscillations

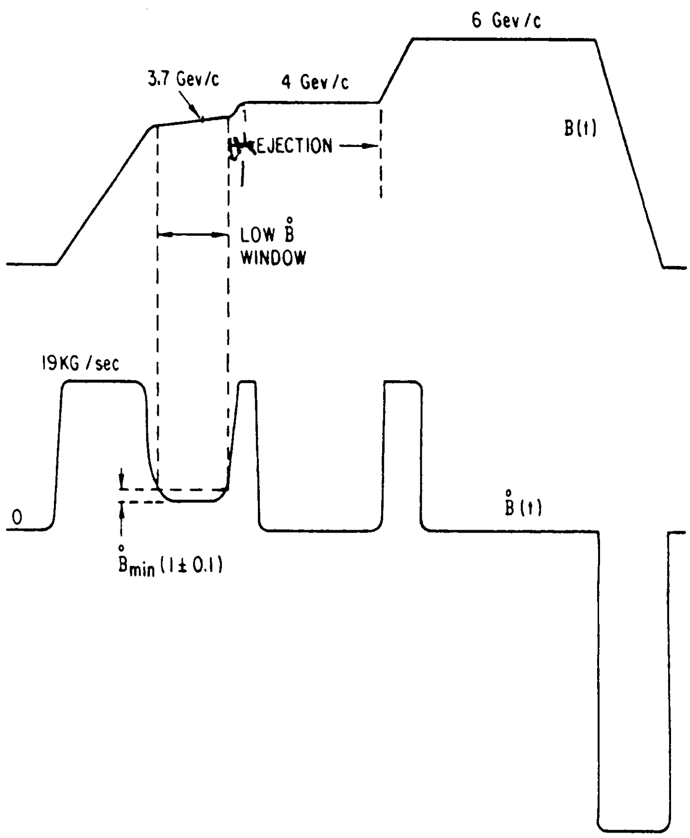

Figure 2 Magnetic Cycle used in the Experiments

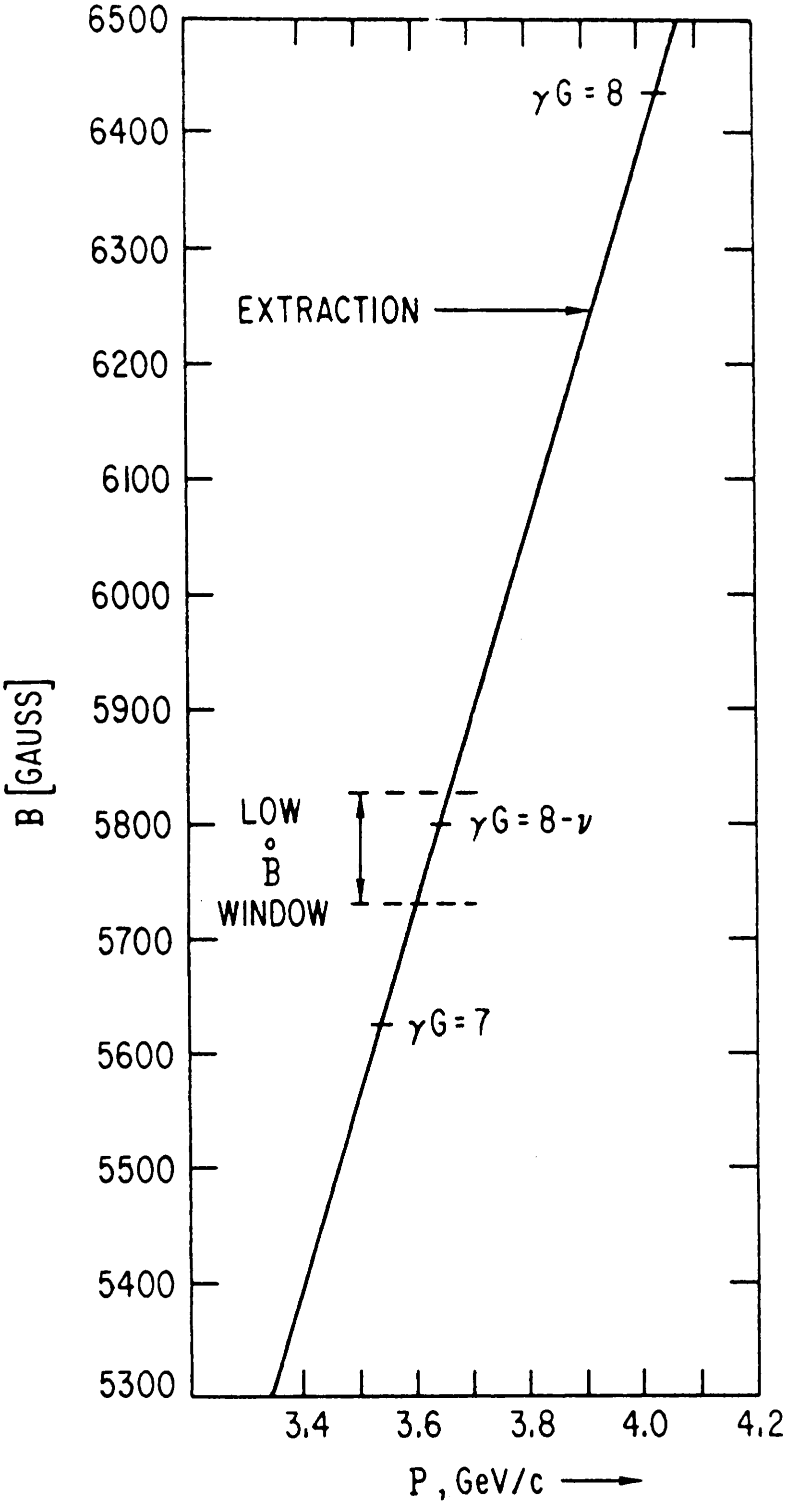

Figure 3 Plot of Field vs. Momentum Showing Location of Resonances

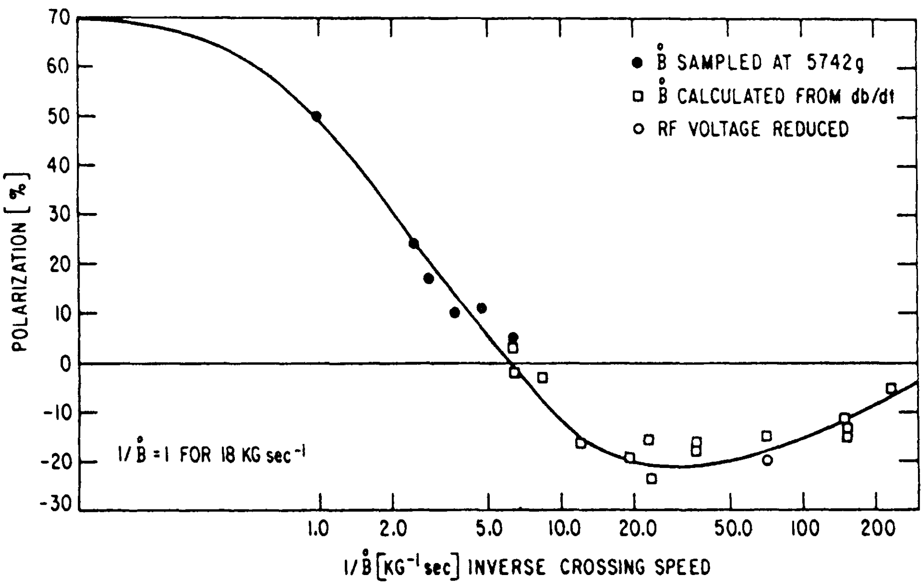

Figure 4 Loss in Polarization as a Function of Dwell Time (inverse crossing speed)

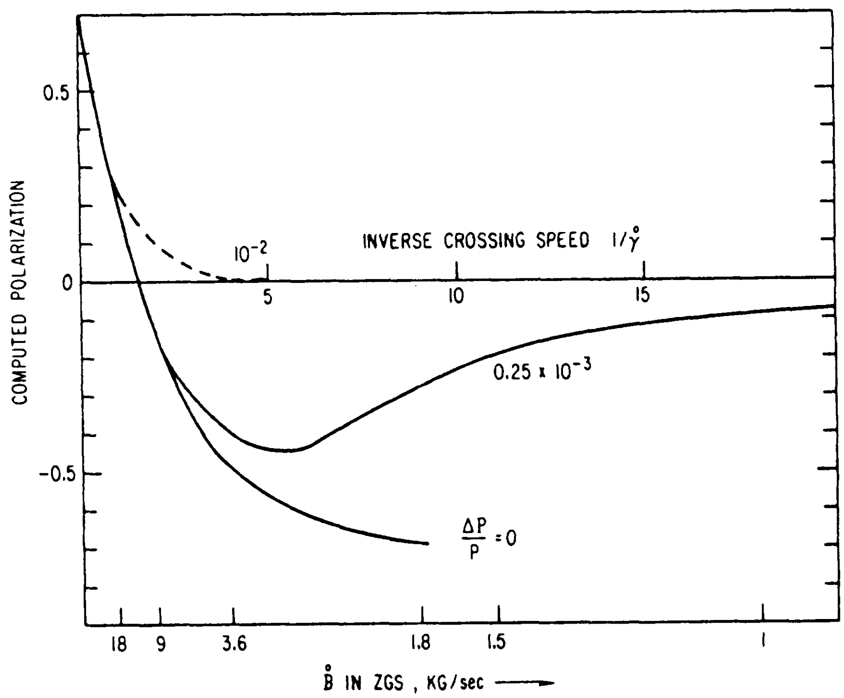

Figure 5 Computed Polarization vs. Crossing Speed

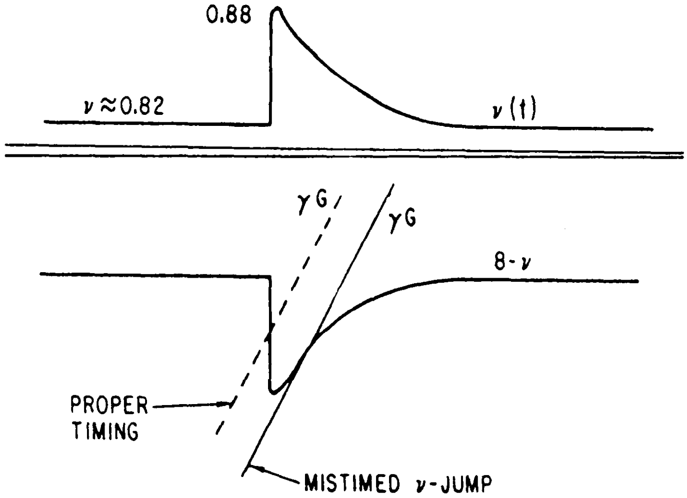

Figure 6 Plot Showing Relationship of Quadrupole Timing Pulse and Resonance Line

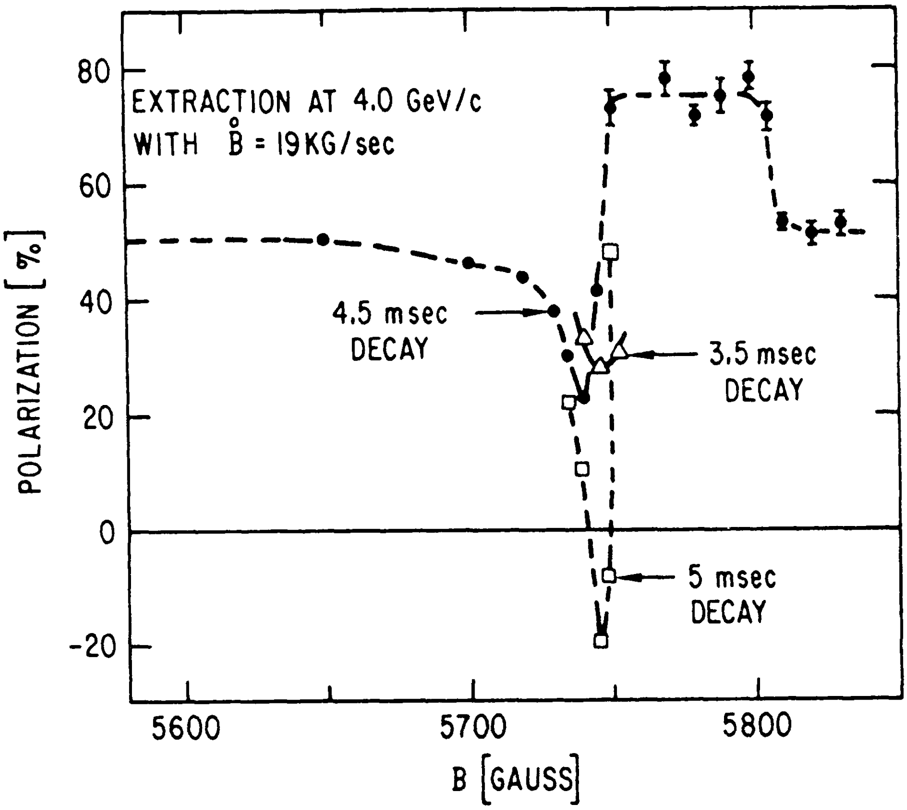

Figure 7 Polarization as a Function of Quadrupole Pulse Turn-on Time