Phenomena Associated with the Acceleration of Polarized Protons in Circular Accelerators*

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ABSTRACT

A series of machine studies has been done with the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory in order to better understand the phenomena associated with the acceleration of polarized protons and to determine the feasibility of acceleration to energies higher than the 12 GeV/c available at the ZGS. We also investigated the question of how long polarized protons can remain in storage rings without losing excessive polarization.

The three topics investigated were:

1. The adiabatic crossing of an intrinsic depolarizing resonance.
2. The depolarization due to imperfection resonances.
3. The survival time of polarization on a long flattop.

This paper is a preliminary report of these three investigations.

ADIABATIC CROSSING OF AN INTRINSIC DEPOLARIZING RESONANCE

The purpose of this test was to determine whether the beam polarization would simply change sign without changing its magnitude when a very strong depolarizing resonance was crossed slowly enough. This was predicted by some theoretical models.1)2)3) Such a spin flip could provide a relatively simple technique2) for crossing the strong depolarizing resonances in strong focussing accelerators. This would be much easier than the quadrupole

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produced tune shift technique used in the weak focussing ZGS, where these resonances are not so strong.

Since all models use simplifying assumptions, which are questionable in real machines, experimental tests were deemed necessary. In particular, the energy of each particle fluctuates around the average value due to synchrotron oscillations and is not constant as assumed in the models. (Fig. 1)

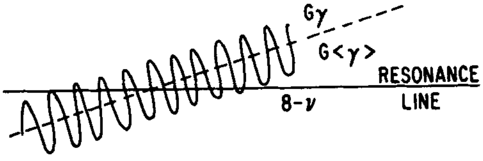

Fig. 1 Schematic representation of synchrotron oscillations

The intrinsic resonances occur at $G\gamma = k \pm \nu_y$, where k is a harmonic number associated with the machine geometry and ν_y is the vertical tune. Depolarization occurs for each k when γ passes through the value satisfying this equation. Thus as γ is increased during the acceleration cycle several such depolarizing resonances will occur.

The experimental technique was to study the $8 - \nu_y$ resonance by varying the crossing speed which is given by $\dot{\gamma}_{eff} = \dot{\gamma} + \dot{\nu}/G$. This was done by changing the acceleration ratio $\dot{B}$ and hence $\dot{\gamma}$ or by pulsing the tune shift quadrupoles such that $\dot{\nu}/G \approx -\dot{\gamma}$. The field cycle used for the experiments with reduced $\dot{B}$ is shown in Fig. 2. The beam was extracted at 4 GeV/c with an energy loss target and the polarization measured. The $8 - \nu_y$ resonance was crossed in the reduced $\dot{B}$ region just below the 4 GeV/c flattop. The height of the low $\dot{B}$ ramp was about 100 G independent of $\dot{B}$, which was large enough to accommodate the width of the resonance including uncertainties in energy and ν values. The loss in polarization was measured as $\dot{B}$ was reduced thus increasing the dwell time on the resonance. The results are summarized in Fig. 3. 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 the curve might be due to the beam's momentum spread. Calculations, made prior to the experiment and including synchrotron oscillations, displayed the qualitative features of the data as shown in Fig. 4.

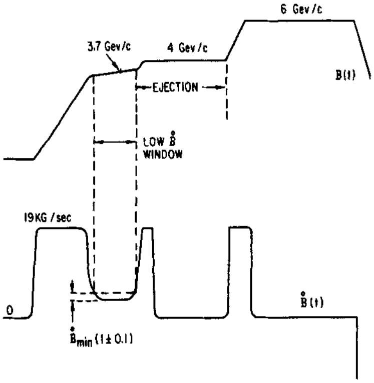

Fig. 2 Low $\dot{B}$ field cycle

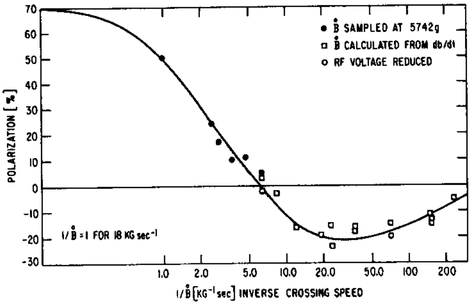

Fig. 3 Loss of polarization as a function of dwell time on the resonance

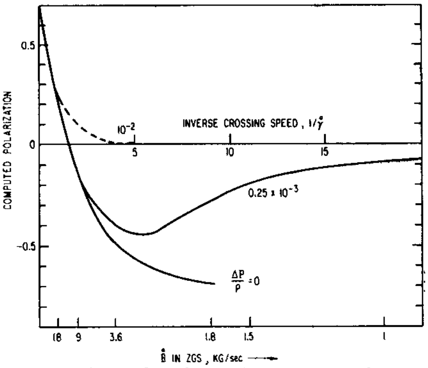

Fig. 4 Calculated curves for various momentum spreads.

In the measurements using the pulsed quadrupoles we triggered the pulse early so that the resonance was crossed on the trailing edge of the $\nu(+)$ waveform rather than during the fast rise. This is shown in Fig. 5. Results for 3 different trailing edge lengths are shown in Fig. 6. The normal $\dot{B} \approx 19$ kG/sec was used. The maximum reversed polarization was about - 20% as in the low $\dot{B}$ case. It appears that energy spread and possibly other influences prevent complete spin flip in the ZGS even when the strong $8 - \nu_y$ resonance is crossed very slowly. Thus it is unlikely that 100% spin flip can be achieved in any machine. Probably strong focussing accelerators will have to use tune-jump quadrupoles to maintain polarization.

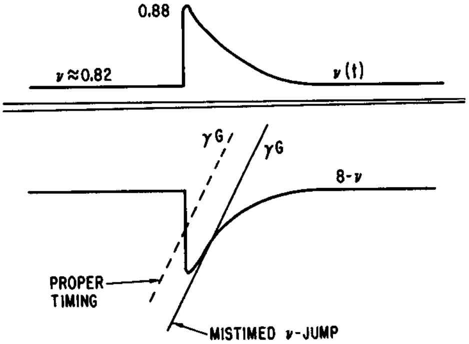

Fig. 5 Quadrupoles timing wave form

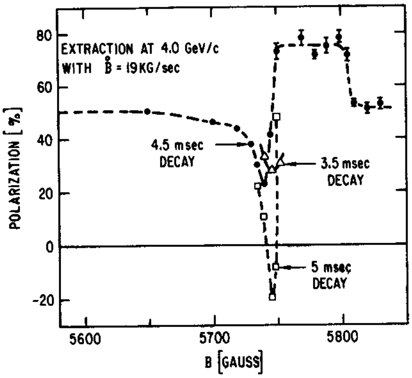

Fig. 6 Polarization as a function of quadrupole timing

DEPOLARIZATION PRODUCED BY IMPERFECTION RESONANCES

The imperfection resonances characterized by γG = integer are a somewhat controversial subject and had never been detected previous to this experiment. Some theoretical models[4)] indicated that they did not exist at all, whereas others suggested that they may be very serious in strong focussing synchrotrons. The imperfections in synchrotrons cause vertical orbit distortions which might cause depolarization when $G\gamma$ = integer is passed during the acceleration cycle.

We studied these by again reducing the $\dot{B}$ of the ZGS in the neighborhood of the resonance which increased the dwell time. We then produced vertical orbit bumps by pulsing pole face windings in Octant III of the ZGS. The ZGS magnetic field cycle is shown in Fig. 7. A reduced $\dot{B}$ window was centered at the position of the $\gamma G = 6$ or $\gamma G = 7$ resonance. Most measurements were done at $\gamma G = 6$ since it is most isolated from neighboring intrinsic resonances. The orbit distortion produced is shown in Fig. 8 and the sensitivity of orbit distortion to PFW current in Fig. 9.

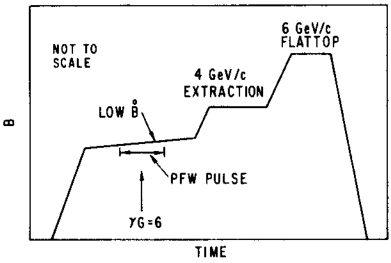

Fig. 7 ZGS field cycle for imperfection resonances

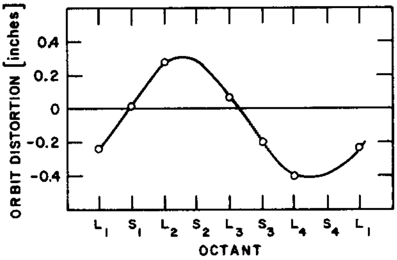

Fig. 8 PFW orbit distortion

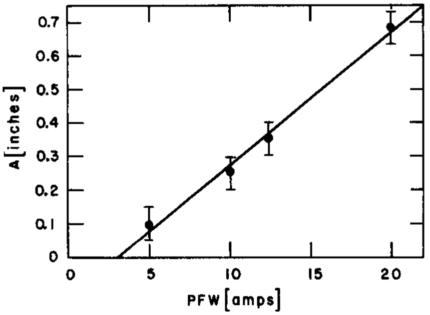

Fig. 9 Orbit distortion as a function of PFW current

The PFW excitation current was a square wave pulse whose length could be varied from 30 msec to 1 sec. The polarization was measured for different crossing speeds, pulse lengths, pulse positions, and pulse magnitudes. The polarization as a function of PFW current is shown in Figs. 10, 11, 12, for $\gamma G = 6$, and in Fig. 13 for $\gamma G = 7$. The $\dot{B}$ window with $\dot{B}$ = 200 g/sec has a length ΔB = 100 G and thus a length $\Delta T \approx 0.5$ sec; similarly when $\dot{B}$ = 100 g/sec ΔB = 100 g, and when $\dot{B}$ = 50 g/sec ΔB = 40 g. A PFW current of 2A is required to make the polarization equal to the injected beam polarization. This indicates that there is a 6th harmonic ZGS orbit distortion which is exactly compensated by 2A. For large currents the polarization decreases and eventually changes sign. The degree of spin flip depends on the magnitude and length of the magnetic pulse and on the value of $\dot{B}$.

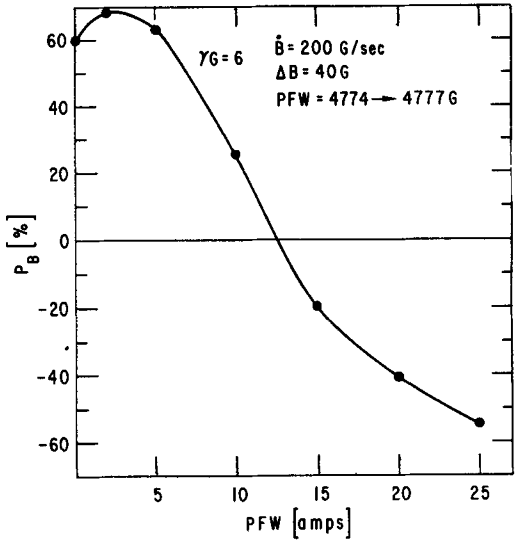

Fig. 10 Polarization at $\dot{B}$ = 200 g/sec, YG = 6

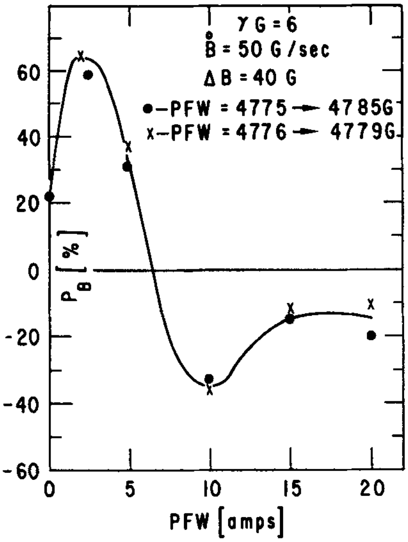

Fig. 11 Polarization at $\dot{B}$ = 50 g/sec, YG = 6

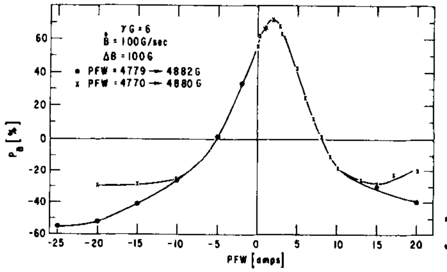

Fig. 12 Polarization at $\dot{B}$ = 100 g/sec, GY = 6

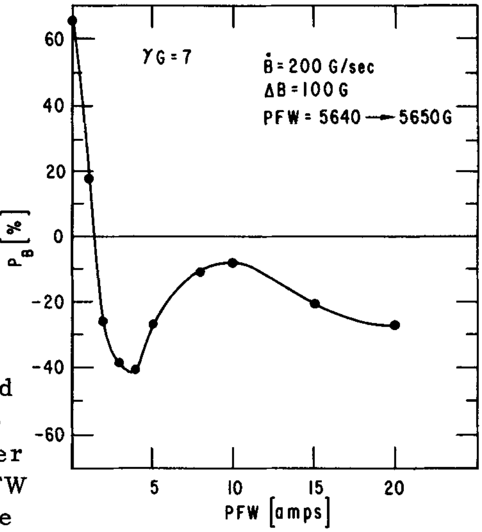

Fig. 13 Polarization at $\dot{B}$ 200 g/sec, YG = 7

Comparison between Fig. 10 and 13 suggests that the γG = 7 resonance is about 10 times stronger then the γG = 6 for the same PFW bump. This is probably because our pulsed orbit distortion has a strong first harmonic while the focussing fields have an 8-fold periodicity. The combination of $\cos 8\theta$ and $\cos\theta$ terms leads to strong 7th and 9th harmonics. Without a PFW pulse, the depolarization due to YG = 7 is relatively weak which suggests that there is normally little 7th harmonic perturbation in the ZGS. The measured depolarizations agree, within about a factor of 2, with simple theoretical predictions.[5)] Additional measurements of higher harmonics have been made at the normal $\dot{B}$(18 kG/sec); we see small effects which might give a total depolarizations of up to 5%. The 12 GeV/c polarization is somewhat lower than would be expected from the depolarization of the intrinsic resonances only.

We thus see that even in the weak focussing ZGS, imperfection resonances exist and may have some deleterious effect on polarization. The simple theory predicts tolerable orbit distortion for the ZGS of

$$Z_k \leq \frac{3.5\ \text{mm}}{k^2\ (1 + k)} \qquad (1)$$

and for the strong focussing CERN PS of

$$Z_k \leq \frac{40\ \text{mm}}{k^2\ (1 + k)} \qquad (2)$$

This apparent factor of 12 less sensitivity in the PS may be misleading. The expection value of Z_k for a given magnet misalignment is proportional to $\sqrt{\frac{n}{m}\ \frac{R}{P}}$ (n is field gradient, m the number of magnets), and this factor is 85 times larger in the PS then in the ZGS. Thus in the PS the depolarization from these resonances may be 10 times larger than in the ZGS (~ 50-60% between 6 GeV/c and 12 GeV/c). The PS would then require a very sophisticated correction system for vertical orbit distortions.

POLARIZATION SURVIVAL TIME

In view of both the effects of intrinsic and imperfection resonances it is highly probable that to achieve higher energies than 12 GeV/c, we will have to use colliding beam devices. We have performed the following experiment on the ZGS, to determine survival time and the effects of resonance tails.

The polarized beam was accelerated to 3.25 GeV/c which is as far as possible from any known resonance, and allowed to circulate on a 21 sec flat top. The ZGS repetition rate was 22.62 sec. We used an operational sequence of two pulses extracted at the beginning of flat-top and the next six pulses at the end of flat-top. The spin was flipped on alternate pulses, so that this sequence gave one measurement of "early" polarization and three of "late" polarization. This gave about the same number of events for measuring both "early" and "late", since the factor of three compensated for the beam loss and reduced extraction efficiency due to vacuum scattering beam growth during the 21 sec flat-top. A preliminary analysis of the data indicates about a ±1/2% systematic error. No effect can be seen at this level. The statistical accuracy was about 0. 1%. This upper limit corresponds to a rate of depolarization of 0. 025%/sec and would give a loss of polarization of 45% in a half hour run. Since this is an upper limit, it is a rather encouraging result which indicates that non-resonant depolarization may not make storage rings impossible.

We next moved the flat-top field closer to the resonance ($G\gamma = 6$) and we were able to map its extent. This is shown in Fig. 14. The estimated width of the resonance is $\Delta B_{FWHM} <$ 10 G and $\frac{\Delta B}{B} = \frac{\Delta\gamma}{\gamma} \approx 2 \times 10^{-3}$.

Note that the resonance effect drops 3 orders of magnitude in 30 G. Since the storage field is 400 G away, the effect of the resonance on storage is negligable. Further experiments will be done to try to improve the upper limits quoted here.

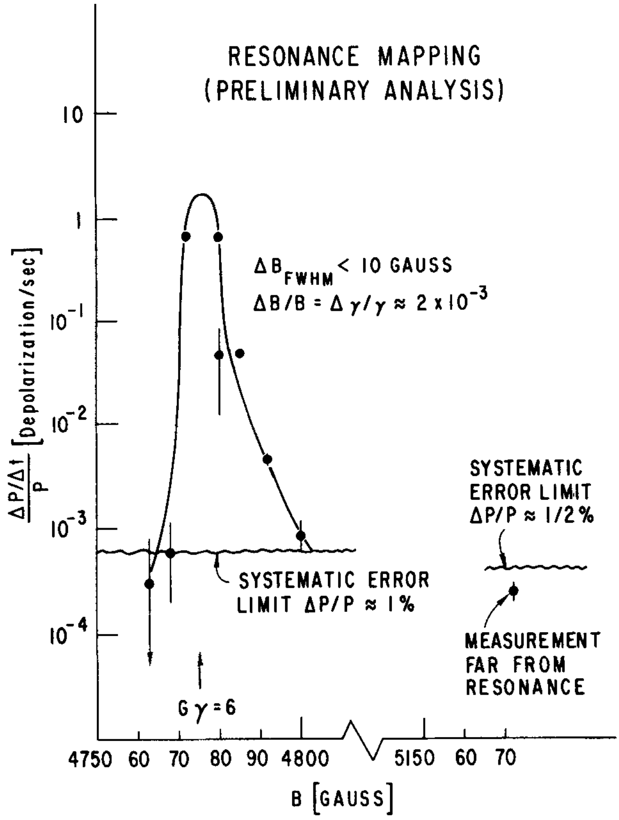

Fig. 14 Resonance Mapping

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DISCUSSION

Courant: (Brookhaven) The depolarization during the flattop would tend to be enhanced by the fact that your beam is growing due to gas scattering because that increases the effect of the depolarizing field, so if you had a really good vacuum would you expect the lifetime of the polarization to be better than you observed?

Ratner: Well, there is the possibility of another effect. When the beam grows you also are probably throwing away those parts of the beam with the large vertical betatron amplitudes, which would have the least polarization. The reason we limited ourselves to this 20 second flattop was essentially [because of] gas scattering. We did run a 50 second flattop, but we were not able to get sufficient statistics because of beam loss and poor extraction efficiency. But certainly with another order of magnitude in the vacuum system, this experiment could be done at the level that would really be [a] positive factor.

Nagle: (LASL) I'd just like to offer a comment. I think it's been just one more very nice, very intriguing development in what has been overall a very satisfying and very delightful development in accelerator physics.

Ratner: Thank you.

Cork: (LBL) Did you have in mind the intersecting storage rings [to be] weak focussing?

Ratner: It's not clear what one would do at that stage. If one is talking storage rings, I think one would seriously investigate the difficulties in weak and strong. However, I would think that a non-accelerating, strong focussing storage ring would probably be far enough away from (one could design it presumably far enough away from) resonances so that one could store a beam. However, I think that both options would have to be investigated if one were going to do this.

Chamberlain: (U.C., Berkeley) Could you give a little more definite idea as to how you see the maintainance of polarization in the strong focussing accelerators? I understand you to say that you thought it unlikely that the adiabatic passage with polarization reversal would work. How does that leave the prospects, in your opinion?

Ratner: I think the prospects are reasonable. The tune-shifting quadrupole correction for the intrinsic resonances should work in a strong-focussing machine. The resonances are somewhat stronger; it probably would take more field gradient than we use here, but we use 50 gauss per inch, so it's certainly no problem.

Teng:(Fermilab) Actually the imperfections could be corrected out; it's only a factor of ten.

Ratner: It's a question of sensitivity. You have to have corrections. Well, I think perhaps Dieter Möhl will talk a little more about it, but the thing is that you need more sensitivity than any measuring system can presently attain. Probably the polarized beam itself would be your best diagnostic for corrections. Well we corrected for the $\gamma G = 6$ by less than a tenth of an inch and this becomes even more severe in AG machines. One has to be correcting on the order of tenths of millimeters, I believe, to get to 12 GeV. If you're talking about going to 24, I think it becomes an order of magnitude worse than that. You must remember that there are two of these [resonances] every GeV, so you're going to wind up with a huge number to correct, which is one of the reasons I think it's going to be very difficult to go much above 12. I think Dieter Möhl will have a lot more to say about that than I do.