POLARIZED PROTON BEAMS AT THE AGS*

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Abstract: In a major project modifying the Brookhaven AGS, polarized protons have been successfully accelerated to 22 GeV/c. A key element in this polarized proton project was the necessity of preserving the beam polarization during the acceleration process in which many depolarizing resonances had to be crossed. Two different procedures were used in the sequential tuning through the two types of resonances: rapid traversal of the 5 intrinsic resonances using 10 pulsed quadrupoles and experimentally correcting the horizontal imperfection fields for 35 imperfection resonances using 95 correction dipoles. These precedures were successful and 46% polarization was obtained at 22 GeV/c with an intensity of 2 × 10^{10} protons/pulse. An experimental program using the unique high energy polarized proton beam has begun with three independent experiments.

Introduction

The successful acceleration of a polarized beam to 12.75 GeV/c at the weak focusing Argonne ZGS[1] in the 1970's generated considerable interest in the possibility of a similar project at higher energies with a strong alternating gradient focusing accelerator. In 1977 a Workshop was organized at Ann Arbor by Krisch[2] to study this topic; the Workshop conclusion was that the techniques used at the ZGS could be expected to handle the stronger depolarizing resonances at a higher energy machine such as the Brookhaven AGS. A more detailed design study for an AGS polarized proton project was carried out the following summer at Brookhaven National Laboratory.[3,4] Department of Energy funding was received in 1980. This was a collaborative project: in addition to Brookhaven, participants were Argonne National Laboratory and Michigan, Rice, and Yale. The accelerator modifications[5] were installed and polarized protons accelerated successfully. As reported at the last Particle Accelerator Conference by Ratner et al.[6] 10^{10} protons per pulse were accelerated to 16.5 GeV/c with 40% polarization in summer 1984. In February 1986, 46% polarization was achieved at 22 GeV/c with an intensity of 2 × 10^{10} protons per pulse.[7,8] Three experimental programs have started up which utilize the polarized beam.

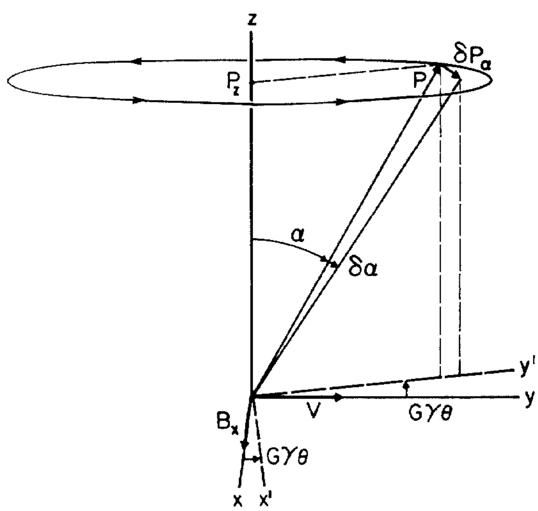

Fig. 1 Precession of the Polarization Vector

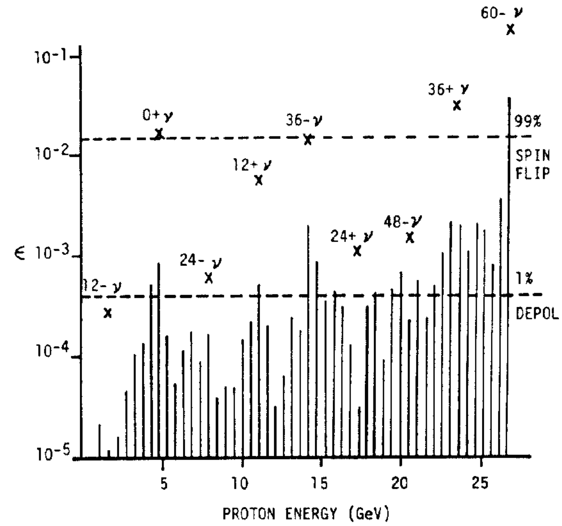

Fig. 2 AGS Resonance Strengths

Depolarizing Resonances

Depolarizaton of a vertically polarized beam will occur when a horizontal component of magnetic field experienced by the particle has the same periodicity as the spin precession, $G\gamma$ per revolution, where G = (g-2)/2 = 1.793 for a proton. This process is illustrated in Fig. 1. Imperfection fields from misalignments having periodicity k per revolution will cause depolarization when $G\gamma = k$, an integer. Particles undergoing vertical betatron oscillations, ν_z per revolution, moving in an alternating gradient magnetic field with periodicity nP, will experience a horizontal field periodicity $nP \pm \nu_z$ and a depolarizing resonance when $G\gamma = nP \pm \nu_z$; these are called intrinsic resonances because they are due to the inherent machine structure. There is also a variant type of imperfection resonance[9] with properties similar to the intrinsic resonances: an imperfection with periodicity k' will drive a vertical betatron oscillation creating a closed orbit distortion with periodicity k'; the particle will then experience fields with periodicity $nP \pm k'$, and will have a resonance there, from the same 'beat' phenomenon operating in the intrinsic resonance case. These imperfection beat resonances will be strongest when the driven betatron oscillation is largest, when k' is close to the free vertical betatron tune ν_z; if the driven and free betatron oscillations have comparable sizes, the associated depolarizing resonance strengths should also be comparable. These different types of resonances are illustrated in Fig. 2 which shows the results of a calculation of depolarizing resonance strengths for the AGS which was carried out by Courant and Ruth[10] in 1977. The imperfection resonances are largest when they are close to the intrinsic resonances, consistent with the imperfection beat resonance picture. The intrinsic resonance strengths we observed were consistent with the predictions; we had to rapidly traverse the five strongest up to 22 GeV/c. The imperfection resonance strengths, however, turned out to be larger than the estimates on the plot; all from $G\gamma$ = 7 to 41 had to be corrected. Those which were harmonics of the machine superperiodicity, $G\gamma$ = 12n, were particularly strong.

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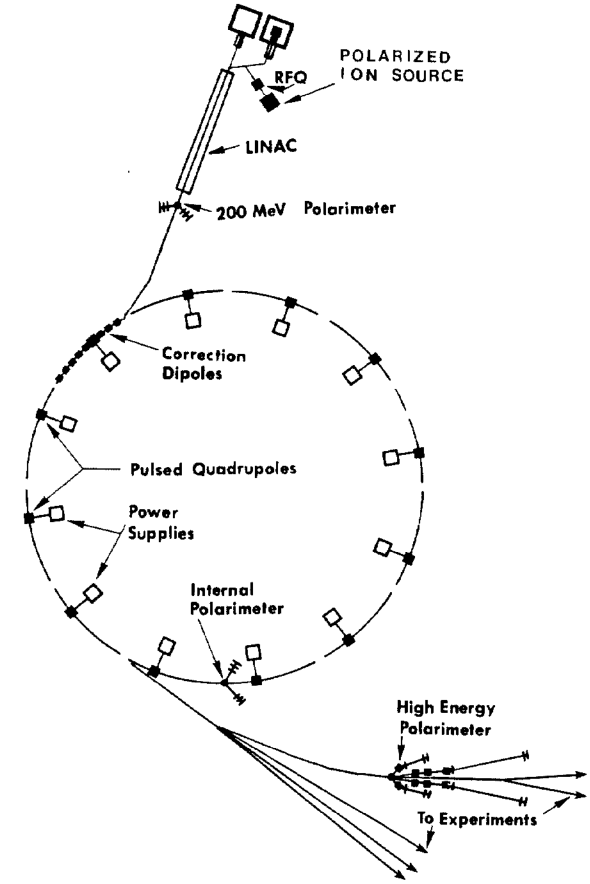

Fig. 3 AGS Layout for the Polarized Beam

AGS Polarized Beam Project

Modifications which have been made to the AGS to preserve and monitor the beam polarization are shown in Fig. 3. A ground level polarized ion source rather than one at 760 keV as used at the ZGS was possible through the use of a Radio Frequency Quadrupole. Three polarimeters were used: a low energy 200 MeV polarimeter following the Linac, an internal polarimeter which was a moving nylon thread swept into the beam, and a high energy polarimeter for the extracted beam. A set of 10 fast pulsed quadrupoles shifted the vertical betatron tune for rapid passage through the intrinsic resonances. A set of 95 correction dipoles, already in the machine

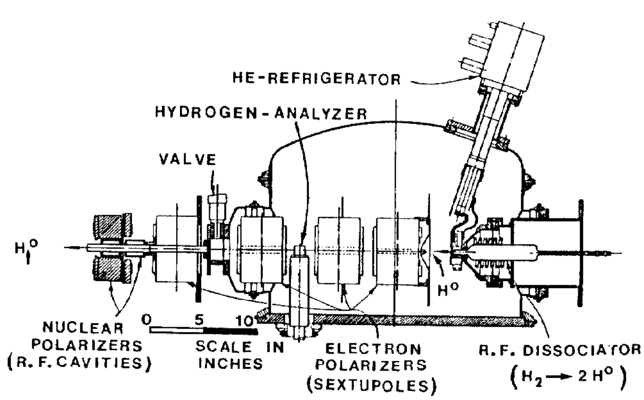

Fig. 4 Polarized Atomic Hydrogen Source

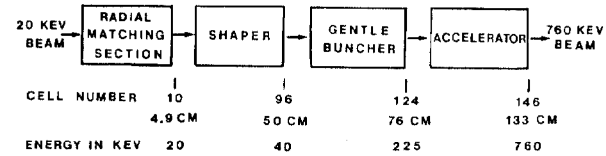

Fig. 5 RFQ Block Diagram

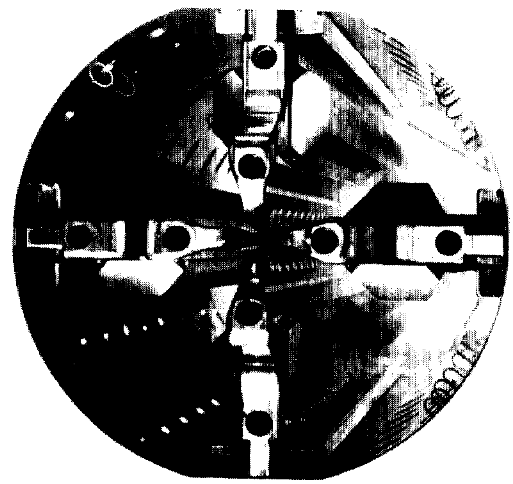

Fig. 6 RFQ Photo

for steering at injection, were pulsed on at the imperfection resonances to cancel the appropriate harmonic of the imperfection fields.

A schematic of the polarized atomic hydrogen source is shown in Fig. 4. The electrons in the neutral hydrogen atoms are polarized using the Stern-Gerlach effect, and the protons by a subsequent RF transition. In a following stage charge exchange with neutral cesium atoms produces a 20 keV negative hydrogen ion beam of approximately 25 μa and 75% polarization. This beam is accelerated to 760 keV by the RFQ, as indicated on Fig. 5. An end-on photo of the RFQ is shown in Fig. 6.

The approach used for rapid traversal of an intrinsic resonance $G\gamma = nP \pm \nu_z$ is presented in Fig. 7. For normal accelerator operation the resonance is crossed by the increasing particle energy, with the relevant crossing time in the millisecond range. When the pulsed quadrupoles are fired the vertical betatron tune is shifted downward and the resonance is crossed in under 2 μs, which is expected to produce reasonably small polarization

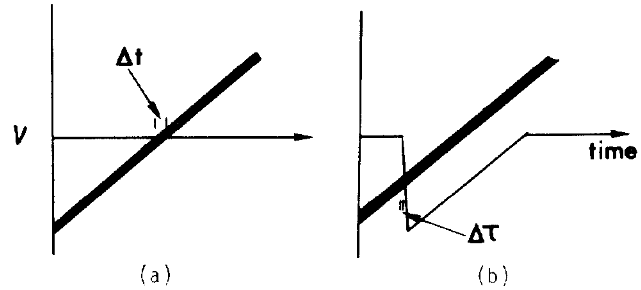

Fig. 7 (a) Normal Resonance Crossing
(b) Rapid Tune Shift Crossing

losses for all intrinsic resonances except at the highest energy resonance, where $G\gamma = 60 - \nu_z$, driven by the basic quadrupole structure of the machine. A section of a pulsed quadrupole is shown in Fig. 8. The ferrite pole faces and the conductors have hyperbolic

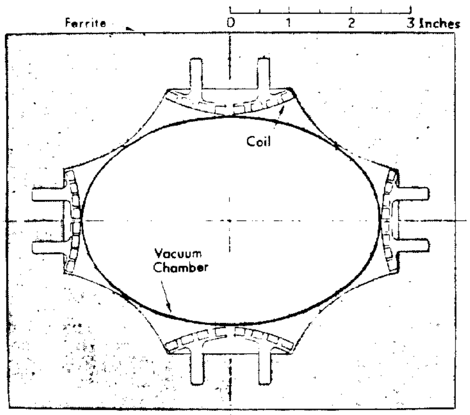

Fig. 8 Ferrite Pulsed Quadrupole

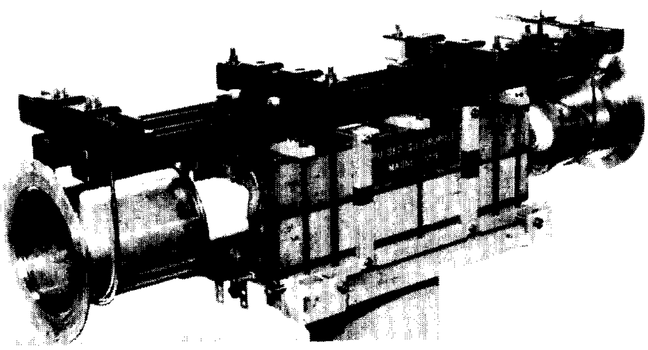

Fig. 9 Pulsed Quad Photo

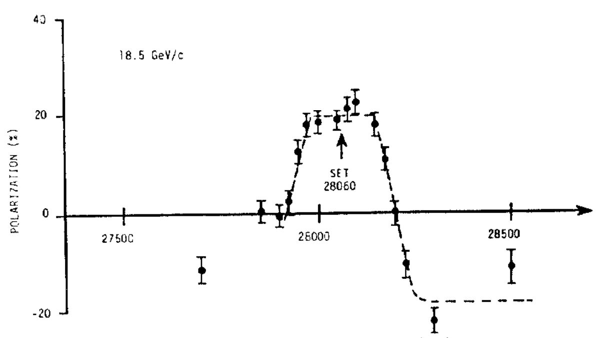

Fig. 10 Firing Time---Polarization Curve for Intrinsic $G\gamma = 36 - \nu_z$ Resonance

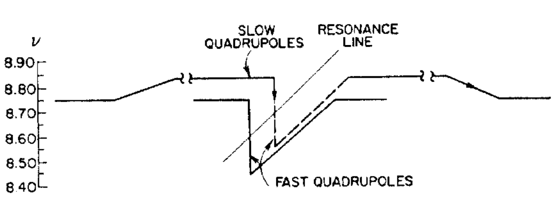

Fig. 11 Tune Shift Using Slow Quads

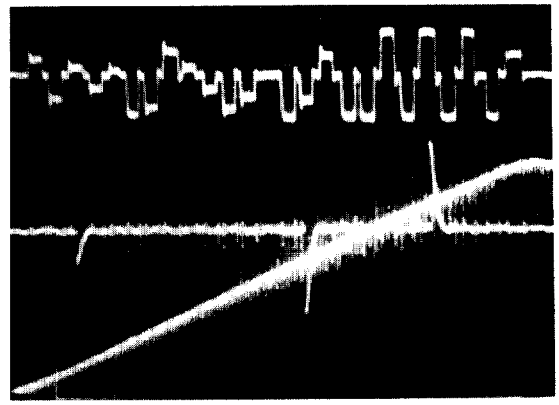

Fig. 12 (Top) Pulsed Dipole Current
(Center) Pulsed Quad
(Bottom) Magnetic Guide Field

contours. The ferrite was obtained from a spare RF cavity from the ZGS. Figure 9 is a photo of a pulsed quadrupole. Measurements of the resulting polarization after crossing the intrinsic resonance, $G\gamma = 36 - \nu_z$, as the pulsed quadrupoles firing time is varied, are presented in Fig. 10. If the firing time is early or late, the resonance crossing is at the standard slow rate, and the moderately strong resonance partially flips the spins. Curves of this type were made during the polarized beam commissioning period to determine the proper firing time, which was then fixed. As indicated earlier it was necessary to fast tune jump five significant intrinsic resonances to get to 22 GeV/c. Some slower pulsed quadrupoles were available to position the vertical tune for the most effective resonance crossing, as indicated on Fig. 11. In Fig. 12 a photo of scope traces over the acceleration cycle shows, in the bottom trace, the magnetic guide field which is proportional to the particle momentum, in the central trace the firing times and currents in the pulsed quadrupoles, and in the top trace the current being pulsed through one of the correction dipoles.

The internal polarimeter was used to provide a fairly rapid scan of proton-nylon scattering asymmetry as a function of momentum, which highlighted possible polarization loss points, as shown on Fig. 13. The asymmetry drop in the neighborhood of $36 - \nu_z$ appears at least partly due to an interaction between

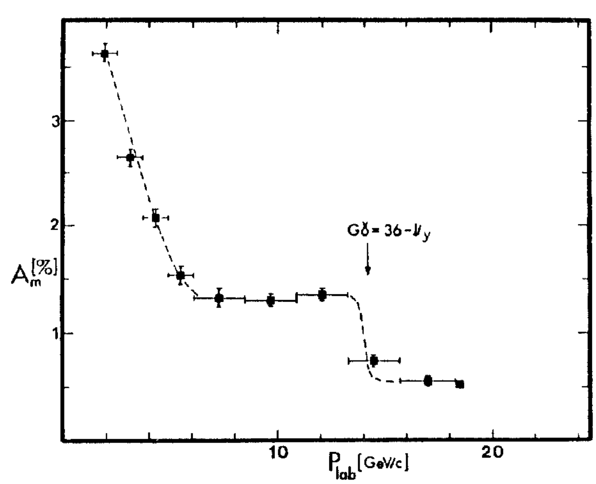

Fig. 13 Polarization Energy Scan

the 36 - ν_z and 36 - 9 = 27 resonances: shifting ν_z, separating the intrinsic resonance further from the imperfection resonance, increased the beam polarization appreciably, allowing us to reach 46% polarization at 22 GeV/c.

Imperfection Resonance Studies

The correction dipole currents necessary to cancel the effect of the perturbing imperfection fields at an imperfection resonance $G\gamma = k$ (or $G\gamma = nP \pm k'$) were determined experimentally, by measuring the polarization following the resonance, while varying the strength of $\sin(k\theta)$ or $\cos(k\theta)$ currents applied to the 95 dipoles around the machine. Figure 14 shows the results of a set of measurements taken in our 1984 run. The imperfection fields are corrected when both components are maximum. The top four plots illustrate the imperfection beat resonances $G\gamma = nP + k'$, with $nP = 0$. The widths of these response curves clearly narrow as the harmonic $k' = k$ of the applied correction current approaches the vertical tune

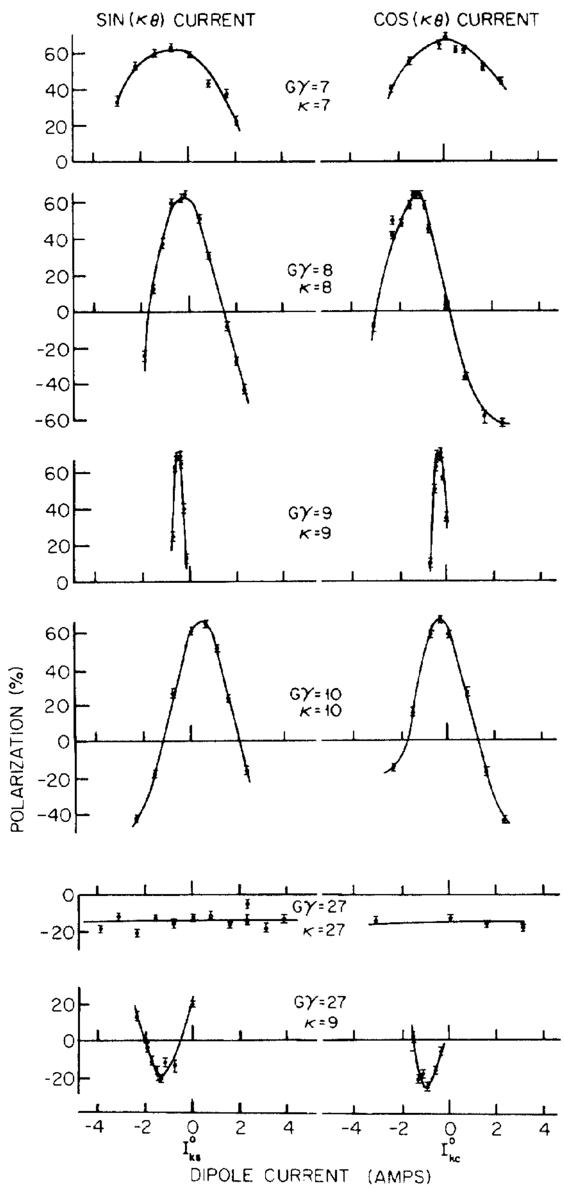

Fig. 14 Polarization Response to Dipole Currents

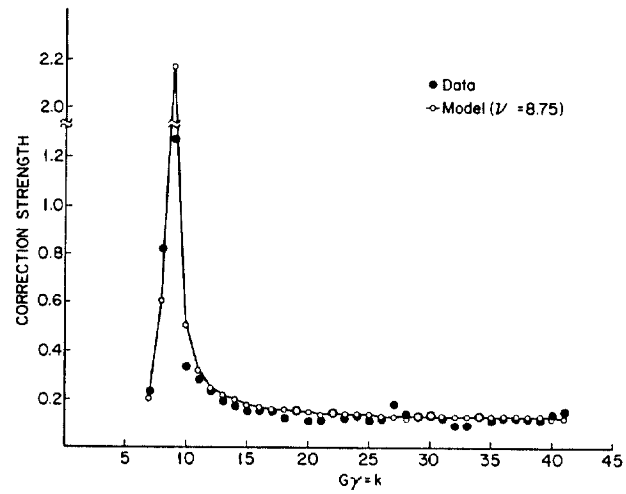

Fig. 15 Correction Strengths of the Directly Driven Imperfection Resonances

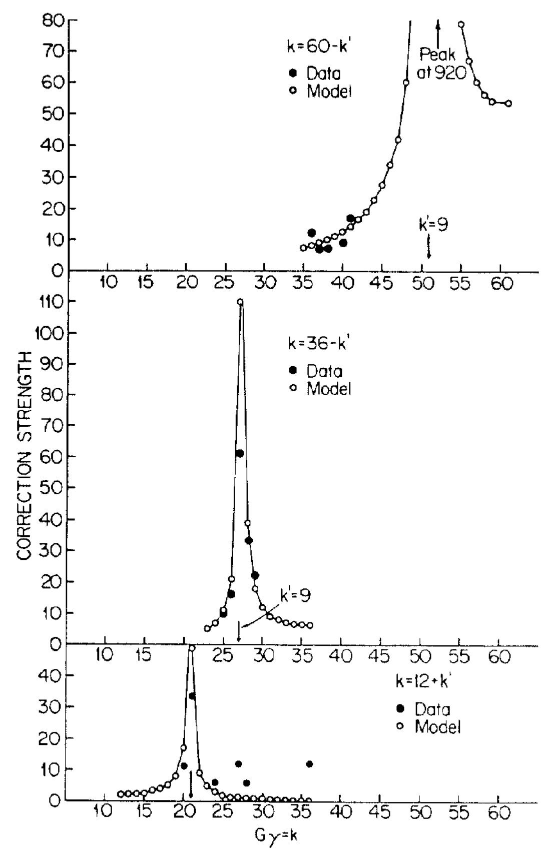

Fig. 16 Correction Strengths of the Imperfection Beat Resonances (×100)

ν_z = 8.75, smaller currents being required to achieve a given depolarization. The driven vertical betatron oscillations are larger and the protons sample larger fields from the quadrupoles when the periodicity of the applied driving perturbation is close to the free vertical betatron periodicity. The bottom two plots show the response at $G\gamma$ = 27. No effect was observed for the direct drive k = 27, but treating it as an imperfection beat resonance, $G\gamma = 36 - 9 = 27$, and applying the harmonic $k' = 9$ generated a strong response.

A systematic study[8] was made of imperfection resonance data from the 1986 commissioning run. A plot of the correction strengths, the inverse of the measured response curve widths at half maximum and proportional to the depolarizing strength for a given driving current, is shown in Fig. 15 for the direct drive harmonics $k = G\gamma$. The solid line is the result of a simple driven harmonic oscillator model using the smooth approximation,[9] which agrees well with the data. The resonance behavior near the vertical tune is dramatically evident. Far from ν_z the perturbing fields that are effective are just those that are directly applied, with no amplification from the quadrupoles. Similar plots for three imperfection beat resonances, $G\gamma = nP \pm k'$, are presented on Fig. 16. The model calculation here is an extension of that used for the case $nP = 0$, with the depolarizing strengths for the $nP \neq 0$ gradient harmonics obtained from the Courant and Ruth computer calculation[10] for the intrinsic resonances, under the assumption that for a given intrinsic resonance, a close-by imperfection resonance with an equal vertical betatron amplitude will have equal strength. The $36 - k'$ plot clearly exhibits the resonance behavior expected by the model. We are possibly seeing the beginning of the large $60 - k'$ set which will peak at $G\gamma = 60 - 9 = 51$. As indicated before, the nearby $60 - \nu_z$ intrinsic resonance is too strong for fast traversal. The tail of the $12 + k'$ curve does not go all the way to zero as the model predicts. A couple of the points on the tail are possibly generated by other beat resonances.

Future Developments

There are tenative plans for a polarized beam physics run at the AGS this fall, hopefully with at least the polarization and intensity levels achieved in 1986. With further polarized beam studies it should be possible to reach the original design goal of 50% polarization at 26 GeV/c. With further polarized source development and the addition of the Booster to the AGS the polarized beam intensity should increase dramatically, possibly a couple of orders of magnitude over the present 2×10^{10} level.

In addition to the ZGS and AGS, polarized beams have been accelerated at Saclay[11] and KEK[12] using the approaches discussed above as well as full spin flipping with the very strong resonances. Because of the increasing strength and number of resonances with energy, higher energy polarized beams in possible future accelerators such as RHIC or the SSC will require use of the Siberian Snake[13] scheme. Experimental tests of this method are now being considered.

Acknowledgements

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References

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1. T. Khoe et al., Particle Accelerators 6, 213 (1975).
2. Higher Energy Polarized Protons Beams (Ann Arbor, 1977), A.D. Krisch and A.J. Salthouse Eds., AIP Conference Proceedings No. 42.
3. B. Cork, E.D. Courant, D.G. Crabb, A. Feltman, A.D. Krisch, E.F. Parker, R.D. Ruth and K.M. Terwilliger, "Preliminary Design Study for the Acceleration of Polarized Protons in the Brookhaven AGS", unpublished report, October, 1978.
4. D.G. Crabb et al., IEEE Trans. on Nuc. Sci. NS-26, 3203 (1979).
5. K.M. Terwilliger et al., IEEE Trans. on Nuc. Sci. NS-28, 2031 (1981).
6. L.G. Ratner et al., IEEE Trans. Nuc. Sci. NS-32, 1656 (1985).
7. G.R. Court et al., Phys. Rev. Lett. 57, 507 (1986).
8. F.Z. Khiari Ph.D. Thesis, University of Michigan (1987). This work contains many details of the AGS Polarized Beam Project.
9. K.M. Terwilliger et al., IEEE Trans. on Nuc. Sci., NS-32, 2635 (1985).
10. E.D. Courant, Ref. 2, p. 94.
    E.D. Courant and R.D. Ruth, BNL Report 51270 (1980).
11. E. Grorud et al., in High Energy Spin Physics-82, Brookhaven National Laboratory, G.M. Bunce, Ed. (AIP, New York, 1983) p. 407.
    T. Aniel et al., in High Energy Spin Physics, Marseille, 1984, J. Soffer, Ed. Journal de Physique Colloque C2, Sup. No. 2, Tome 46, p. C2-499 (1985).
12. M. Kihara et al., in Proc. 13th Int. Conf. on High Energy Accelerators, Novosibirsk (1986).
13. Ya.S. Derbenev and A.M. Kondratenko, Proc. 10th Int. Conf. on High Energy Accelerators, Protvino, Vol. 2, 70 (1977).