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The Future of High Energy Polarized Proton Beams ¹

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Abstract. The acceleration and storage of high energy polarized proton beams has made tremendous progress over the last forty years challenging along the way the technologies, precision and the understanding of the beam dynamics of accelerators. This progress is most evident in that one can now contemplate high energy colliders with polarized beams and high luminosity at the same time. After a brief summary of the development and history of polarized proton beam acceleration the paper will focus on the highest energy polarized beams and the possibility of accelerating polarized beams to even higher energies in the future.

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SPIN DYNAMICS, RESONANCES AND SIBERIAN SNAKES

Accelerating polarized beams requires an understanding of both the orbital motion and spin motion. Whereas the effect of the spin on the orbit is negligible the effect of the orbit on the spin is usually very strong. The evolution of the spin direction of a beam of polarized protons in external magnetic fields such as exist in a circular accelerator is governed by the Thomas-BMT equation [1],

$$\frac{d\vec{P}}{dt} = - \left(\frac{e}{\gamma m} \right) \left[G\gamma\vec{B}_\perp + (1+G)\vec{B}_\parallel \right] \times \vec{P}$$

where the polarization vector P is expressed in the frame that moves with the particle. This simple precession equation is very similar to the Lorentz force equation which governs the evolution of the orbital motion in an external magnetic field:

$$\frac{d\vec{v}}{dt} = - \left(\frac{e}{\gamma m} \right) \left[\vec{B}_\perp \right] \times \vec{v}.$$

From comparing these two equations it can readily be seen that, in a pure vertical field, the spin rotates $G\gamma$ times faster than the orbital motion. Here $G = 1.7928$ is the anomalous magnetic moment of the proton and $\gamma = E/m$. In this case the factor $G\gamma$ then gives the number of full spin precessions for every full revolution, a number which is also called the spin tune ν_{sp} . At top RHIC energies this number reaches about 400. The

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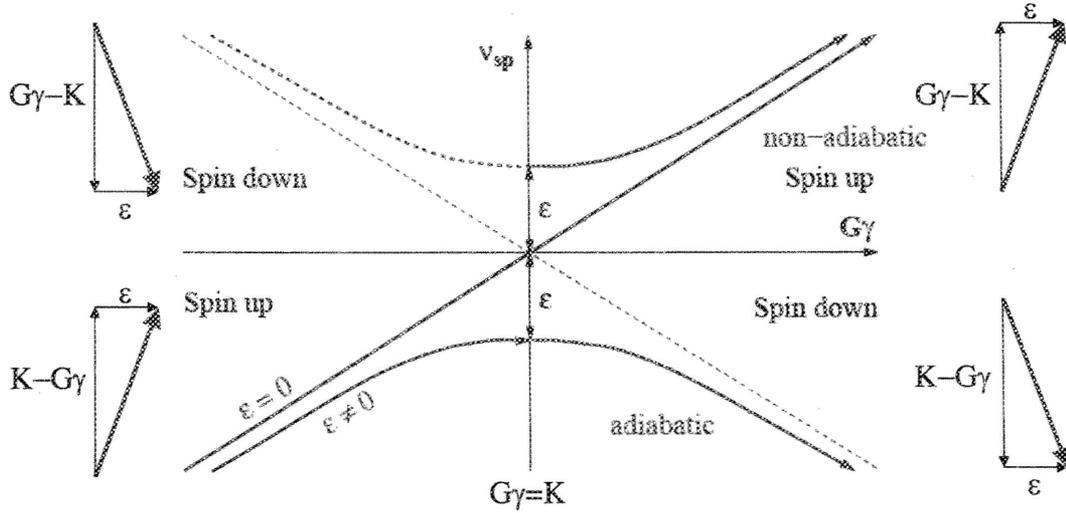


FIGURE 1. The evolution of the spin tune during the crossing of a resonance at $G/\gamma = K$ with strength ϵ .

Thomas-BMT equation also shows that at low energies ($\gamma \approx 1$) longitudinal fields \vec{B}_{\parallel} can be quite effective in manipulating the spin motion, but at high energies transverse fields \vec{B}_{\perp} need to be used to have any effect beyond the always present vertical holding field.

The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing spin resonances. During acceleration, a spin resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. There are two main types of spin resonances corresponding to the possible sources of such fields: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields.

The resonance conditions are usually expressed in terms of the spin tune ν_{sp} . For an ideal planar accelerator, where orbiting particles experience only the vertical guide field, the spin tune is equal to $G\gamma$, as stated earlier. The resonance condition for imperfection depolarizing resonances arise when $\nu_{sp} = G\gamma = n$, where n is an integer. Imperfection resonances are therefore separated by only 523 MeV energy steps. The condition for intrinsic resonances is $\nu_{sp} = G\gamma = kP \pm \nu_y$, where k is an integer, ν_y is the vertical betatron tune and P is the superperiodicity. For example at the AGS, $P = 12$ and $\nu_y \approx 8.8$.

Close to a spin resonance the spin tune deviates away from its value of $G\gamma$ of the ideal flat machine. For a resonance with strength ϵ , which is the total spin rotation due to the resonance driving fields, the new spin tune is given by the equation

$$\cos(\pi\nu_{sp}) = \cos(\pi G\gamma) \cos(\pi\epsilon).$$

Fig. 1 shows the solutions of this equation with and without a resonance. A similar calculation can be done for the effective precession direction or, as it is often called, the stable spin direction. The stable spin direction describes those polarization components

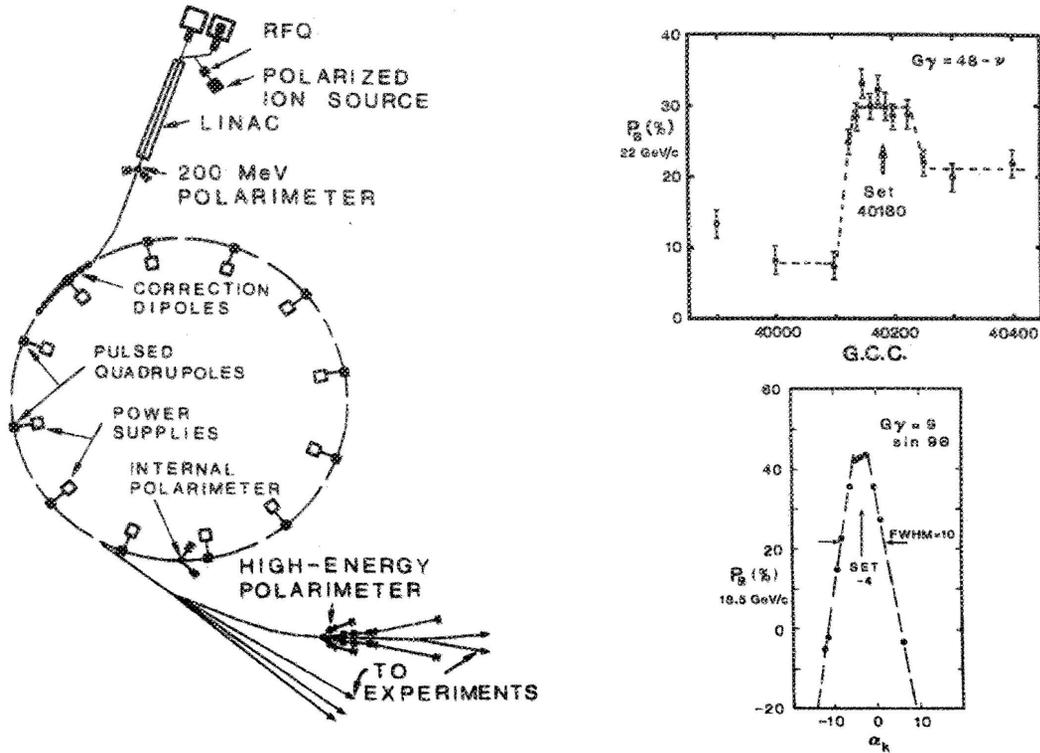


FIGURE 2.

that are repeated every turn. Note that both the stable spin direction and the spin tune are completely determined by the magnetic structure of the accelerator and the beam energy. The magnitude and sign of the beam polarization, however, depends on the beam polarization at injection and the history of the acceleration process.

The spin tune and stable spin direction calculations apply only to a time-independent static situation or if parameters are changed adiabatically. Far from the resonance the stable spin direction coincides with the main vertical magnetic field. Close to the resonance at $G/\gamma = K$, the stable spin direction is perturbed away from the vertical direction by the resonance driving fields. When a polarized beam is accelerated through an isolated resonance at arbitrary speed, the final polarization can be calculated analytically [2] and is given by

$$P_f/P_i = 2e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1,$$

where P_i and P_f are the polarizations before and after the resonance crossing, respectively, and α is the change of the spin tune per radian of the orbit angle. When the beam is slowly ($\alpha \ll |\epsilon|^2$) accelerated through the resonance, the spin vector will adiabatically follow the stable spin direction resulting in spin flip as is indicated in Fig. 1. However, for a faster acceleration rate partial depolarization or partial spin flip will occur.

POLARIZED PROTON ACCELERATION FROM ZGS TO RHIC

Traditionally, the intrinsic resonances are overcome by using a betatron tune jump, which effectively makes α large, and the imperfection resonances are overcome with the harmonic corrections of the vertical orbit to reduce the resonance strength ϵ [3]. Both of these methods aim at making the resonance crossing non-adiabatic. They were used very successfully for the first two efforts to accelerate polarized proton beams to high energy. At the ANL ZGS polarized protons were accelerated to 12 GeV/c with a maximum polarization of 70%. Later, polarized protons were accelerated at the strong focussing BNL AGS to 22 GeV/c. The intrinsic resonance strengths at the strong focusing AGS were much stronger than at the ZGS requiring stronger and faster pulsed quadrupoles. Fig. 2 shows the layout used at the AGS as well as tuning curves used to adjust the timing of the pulsed quadrupoles and the strengths of the correction dipoles. The resonance correction techniques require very accurate adjustments at every resonance crossing, which becomes very difficult and time consuming.

New techniques to cross both imperfection and intrinsic resonances adiabatically have been developed. The correction dipoles used to correct the imperfection resonance strength to zero were replaced by a localized spin rotator or 'partial Siberian snake' which makes all the imperfection resonance strengths large and causes complete adiabatic spin flip at every imperfection resonance [4]. The tune jump quadrupoles were initially replaced by a single rf dipole magnet, which increased the strength of the intrinsic resonances by driving large coherent betatron oscillations[5].

More recently two strong partial Siberian snakes were installed in the AGS that can overcome both imperfection and intrinsic resonances. With strong enough partial snakes a gap between the spin tune and an integer opens up that becomes large enough to place the fractional part of the betatron tune and therefore the intrinsic resonance inside this gap. Fig. 4 shows the measured asymmetry during acceleration in the AGS showing adiabatic spin flip at every integer of Gy.

At higher energies a 'full Siberian snake' [6], which is a 180° spin rotator of the spin about a horizontal axis, will keep the stable spin direction unperturbed at all times as long as the spin rotation from the Siberian snake is much larger than the spin rotation due to the resonance driving fields. Therefore the beam polarization is preserved during acceleration. An alternative way to describe the effect of the Siberian snake comes from the observation that the spin tune with the snake is a half-integer and energy independent. Therefore, neither imperfection nor intrinsic resonance conditions can ever be met as long as the betatron tune is different from a half-integer.

Fig. 3 shows the lay-out of the Brookhaven accelerator complex highlighting the components required for polarized beam acceleration in the AGS and RHIC. The new 'Optically Pumped Polarized Ion Source'[7] is producing 10^{12} polarized protons per pulse. A single source pulse is captured into a single bunch, which is ample beam intensity to reach the nominal RHIC bunch intensity of 2×10^{11} polarized protons.

In the AGS two partial Siberian snakes are installed. One of them is an iron-based helical dipole[8] that rotates the spin by 11° . The other is a superconducting helical dipole that can reach a 3 Tesla field and a spin rotation of up to 45° . Both helical dipoles have the same design with a variable pitch along the length of the magnet to minimize orbit excursions and also to fit into the 3 m available straight sections in the AGS. With

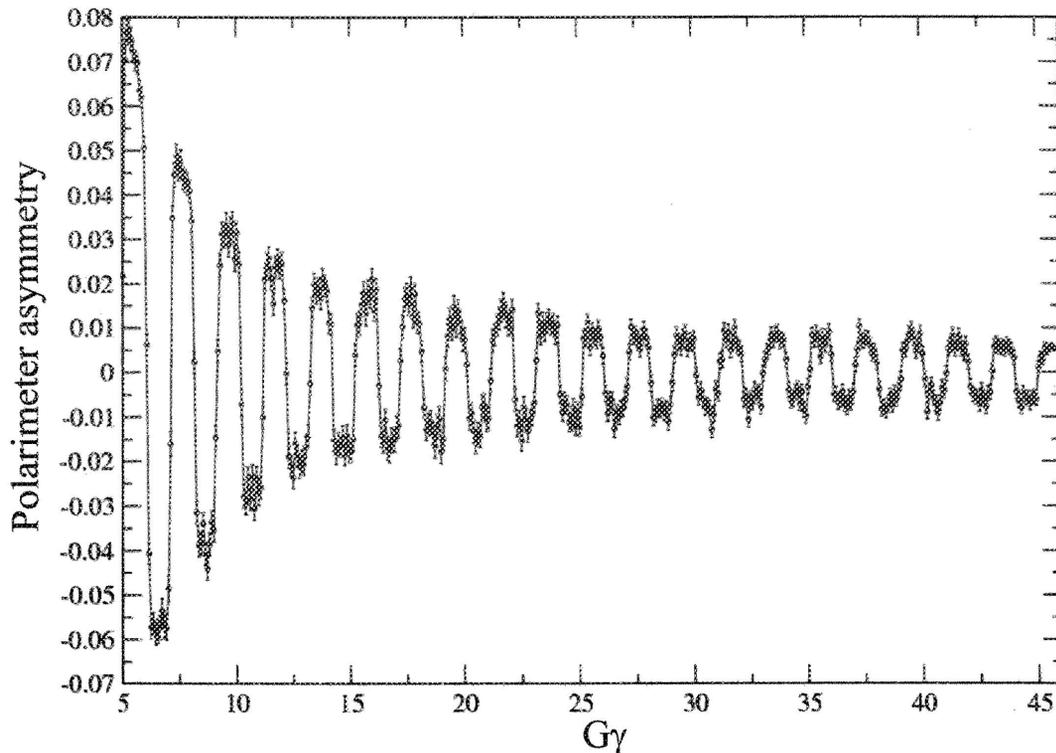


FIGURE 3. Left-right asymmetry measured by the AGS polarimeter during the the acceleration cycle. Note that the asymmetry flips sign at every interger value of $G\gamma$. The drop of the magnitude of the asymmetry during acceleration is mainly due to the decreasing analyzing power of the analyzing reaction of small-angle proton-carbon scattering.

the two partial snakes strategically placed with one third of the AGS ring between them all vertical spin resonances can be avoided up to the required RHIC transfer energy of about 25 GeV as long as the vertical betatron tune is placed at 8.98, very close to an integer[9]. This was achieved reliably over the whole acceleration cycle. With a 80% polarization from the source 65% polarization was reached at AGS extraction. The remaining polarization loss in the AGS might come from weak spin resonances driven by the horizontal motion of the beam. They could be overcome by moving also the horizontal betatron tune close to an integer.

The full Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC each consist of four 2.4 m long, 4 T helical dipole magnet modules each having a full 360° helical twist. The 9 cm diameter bore of the helical magnets can accommodate 3 cm orbit excursions at injection. The super-conducting helical dipoles for both the RHIC snakes and spin-rotators and the superconducting AGS partial snake were constructed at BNL using thin cable placed into helical grooves that have been milled into a thick-walled aluminum cylinder[10].

Fig. 5 shows circulating beam current, luminosity and measured circulating beam polarization of a typical store during the 2006 run[12]. A peak luminosity of about about

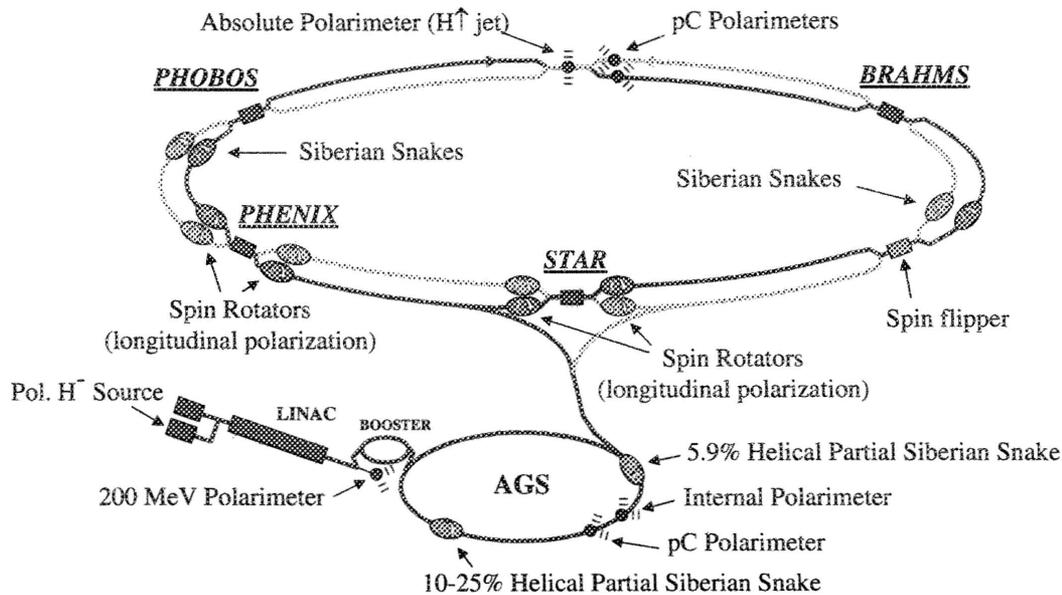


FIGURE 4. The RHIC accelerator complex with the elements required for the acceleration and collision of polarized protons highlighted.

$35 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ was reached. The beam polarization of up to 65% was calibrated at 100 GeV with the absolute polarimeter mentioned above. To preserve beam polarization in RHIC during acceleration and storage the vertical betatron tune had to be controlled to better than 0.005 and the orbit had to be corrected to better than 1 mm rms to avoid depolarizing “snake” resonances[13].

More than 20 years after Y. Derbenev and A. Kodratenko[6] made their proposal to use local spin rotators to stabilize polarized beams in high energy rings, it has now been demonstrated that their concept is working flawlessly even in the presence of strong spin resonances at high energy.

A first successful test of polarization survival during acceleration to 250 GeV crossing three very strong spin resonances was performed[14]. A polarization of 45% was measured at 250 GeV using the pC polarimeter calibrated at 100 GeV. It is not expected that the calibration would change significantly between these two energies, but a more accurate polarization will have to await a calibration measurement with the polarized gas jet performed at 250 GeV. Nevertheless, this preliminary result bodes well for a successful operation of RHIC with polarized 250 GeV proton beams producing collisions at $\sqrt{s} = 500 \text{ GeV}$ with a planned luminosity of up to $1.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

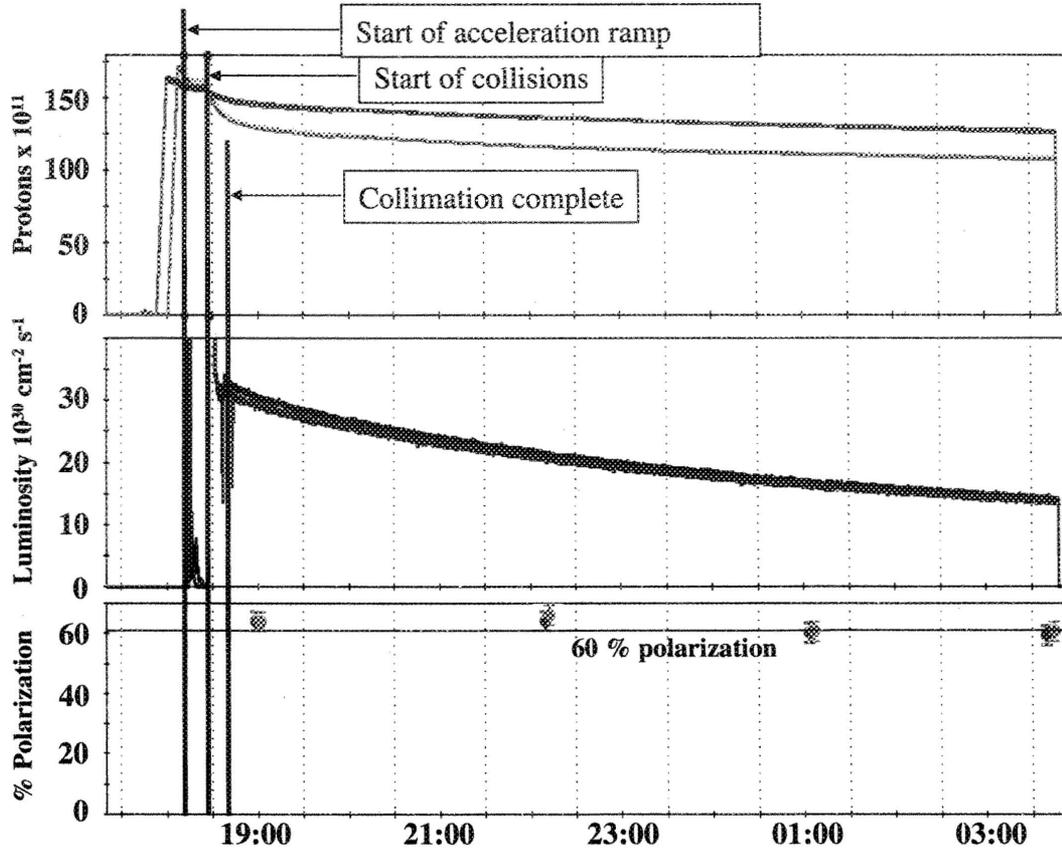


FIGURE 5. Circulating beam in the blue and yellow ring, luminosity at PHENIX (black) and STAR (red), as well as the measured circulating beam polarization in the blue and yellow RHIC ring (blue(dark) and yellow(light) lines and symbols, respectively) for one typical store.

ACCELERATING POLARIZED PROTONS TO HIGH ENERGY

POLARIMETRY, SPIN MANIPULATION AND FLIPPING

In addition to maintaining polarization, the accurate measurement of the beam polarization is of great importance. Very small angle elastic scattering in the Coulomb-Nuclear interference region offers the possibility for an analyzing reaction with a high figure-of-merit, which is not expected to be strongly energy dependent[11]. For polarized beam commissioning in the AGS and RHIC an ultra-thin carbon ribbon is used as an internal target, and the recoil carbon nuclei are detected to measure both vertical and radial polarization components. The detection of the recoil carbon with silicon detectors using both energy and time-of-flight information shows excellent particle identification. It was demonstrated that this polarimeter can be used to monitor polarization of high energy proton beams in an almost non-destructive manner and that the carbon fiber target could be scanned through the circulating beam to measure polarization profiles. A polarized atomic hydrogen jet was also installed as an internal target for small angle proton-proton

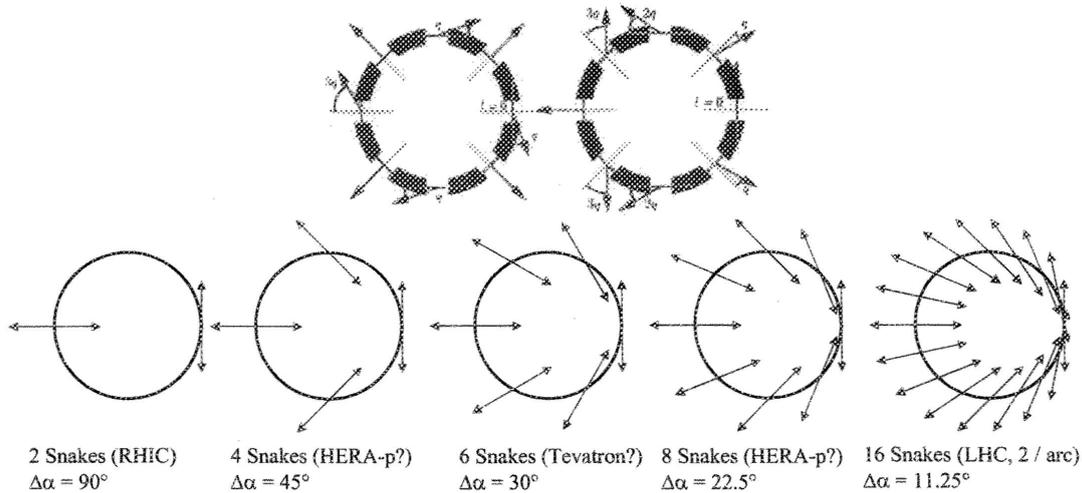


FIGURE 6.

scattering, which allows the absolute calibration of the beam polarization to better than 5 %.

Artificially driven spin resonances can be used to control the polarization of the stored proton beam. Typically a horizontal magnetic dipole field that is modulated at or close to the spin tune frequency is used. These devices are called either rf or ac dipoles depending on the frequency of modulation. As described above an rf dipole was used in the AGS to overcome intrinsic resonances. By ramping the drive frequency through the resonance condition a full spin flip can be achieved [15]. For RHIC with a spin tune of 0.5 the two resonances that a simple rf dipole produces interfere during the resonance crossing and prevent a full spin flip. A new device that consists of two ac dipoles with a spin rotator in between can avoid this problem by producing only a single resonance by properly adjusting the relative amplitude and phase of the ac dipole excitations[16]. Fig. ?? shows the magnet arrangement and the tracking results with a single ac dipole and two ac dipoles. Full spin flip can only be achieved with two ac dipoles.

This device can also be used to measure the spin tune. By adiabatically exciting the spin flipper at a drive tune close to the spin tune the beam polarization will be tilted away from the otherwise stable vertical direction. If the strength of the spin flipper is larger than the spin tune spread the whole beam polarization will tilt in the same way and can be measured with the polarimeter. The ratio of the vertical and horizontal polarization component is then proportional to the difference between the drive tune and the spin tune.

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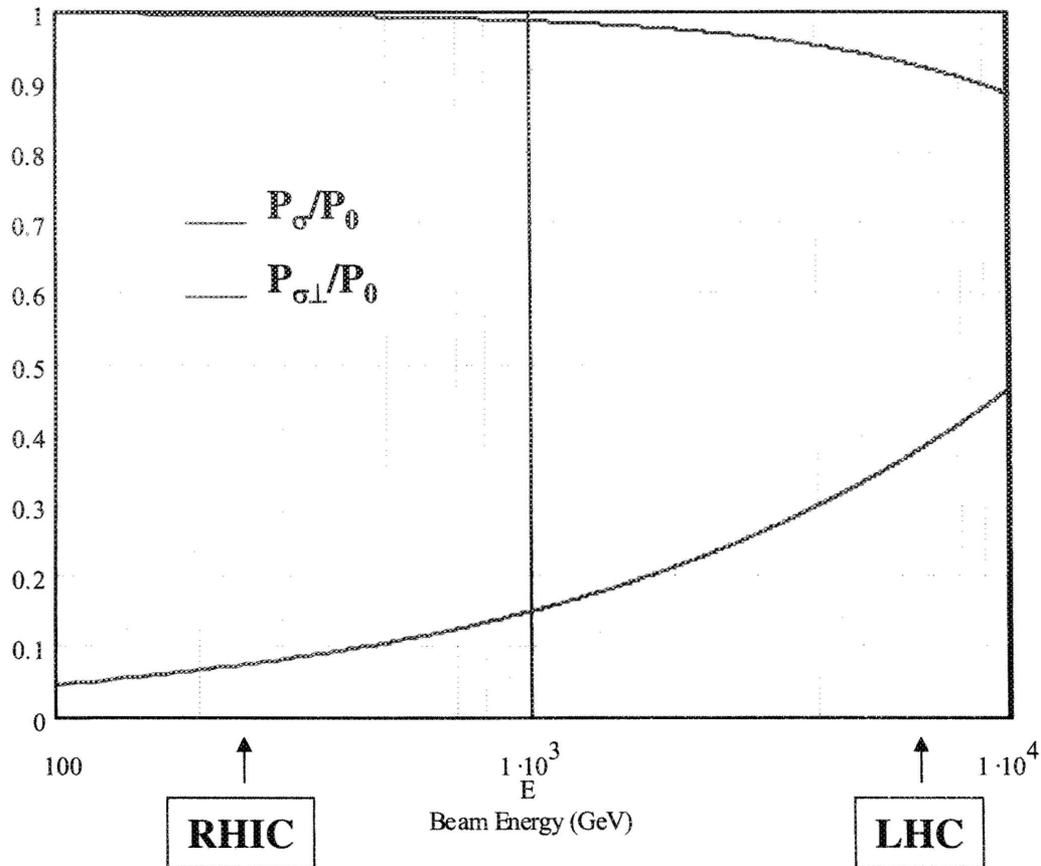


FIGURE 7.

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