POLARIZED PROTON BEAMS[*]

T. Roser, Brookhaven National Laboratory, Upton, N.Y. 11973, USA

Abstract

The acceleration of polarized proton beams in circular accelerators is complicated by the presence of numerous depolarizing spin resonances. Careful and tedious minimization of polarization loss at each of these resonances allowed acceleration of polarized proton beams up to 22 GeV. It has been the hope that Siberian Snakes, which are local spin rotators inserted into ring accelerators, would eliminate these resonances and allow acceleration of polarized beams with the same ease and efficiency that is now routine for unpolarized beams. First tests at IUCF with a full Siberian Snake showed that the spin dynamics with a Snake can be understood in detail. We now have results of the first tests of a partial Siberian Snake at the AGS, accelerating polarized protons to an energy of about 25 GeV. These successful tests of storage and acceleration of polarized proton beams open up new possibilities such as stored polarized beams for internal target experiments and high energy polarized proton colliders.

I. INTRODUCTION

The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing resonances. During acceleration, a depolarizing 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 depolarizing 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_s, which is defined as the number of spin precessions per revolution. For an ideal planar accelerator, where orbiting particles experience only the vertical guide field, the spin tune is equal to $G\gamma$[1], where $G = 1.7928$ is the anomalous magnetic moment of the proton and γ is the relativistic Lorentz factor. The resonance condition for imperfection depolarizing resonances arise when $\nu_s = G\gamma = n$, where n is an integer. Imperfection resonances are therefore separated by only $523\,MeV$ energy steps. The condition for intrinsic resonances is $\nu_s = G\gamma = kP \pm \nu_y$, where k is an integer, ν_y is the vertical betatron tune and P is the superperiodicity. For the AGS, $P = 12$ and $\nu_y \approx 8.8$. For most of the time during the acceleration cycle, the precession direction, or stable spin direction, coincides with the main vertical magnetic field. Close to a resonance, 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, 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, ϵ is the resonance strength obtained from the spin rotation of the driving fields, 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. However, for a faster acceleration rate partial depolarization or partial spin flip will occur. 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]. At high energy, these traditional methods become difficult and tedious.

By introducing a 'Siberian Snake' [4], which is a $180°$ spin rotator of the spin about a horizontal axis, the stable spin direction remains 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.

Such a spin rotator can be constructed by using either solenoidal magnets or a sequence of interleaved horizontal and vertical dipole magnets producing only a local orbit distortion. Since the orbit distortion is inversely proportional to the momentum of the particle, such a dipole snake is particularly effective for high-energy accelerators, e.g. energies above about $30\,GeV$. For lower-energy synchrotrons, such as the Fermilab booster and the Brookhaven AGS with weaker depolarizing resonances, a partial snake[5], which rotates the spin by less than $180°$, is sufficient to keep the stable spin direction unperturbed at the imperfection resonances.

II. IUCF SIBERIAN SNAKE TESTS

The IUCF Cooler ring operates at a kinetic proton beam energy between $40\,MeV$ and $500\,MeV$, which spans two spin resonances: $G\gamma = 2$ and $G\gamma = 7 - \nu_y$. The low energy and the availability of long straight sections and also of polarized proton beam made this ring ideal for a first proof-of-principle test of Siberian Snakes. A solenoidal spin rotator was installed that was capable of rotating the spin by $180°$ around the beam direction and a internal target and a detector with full azimuthal coverage. Over the course of many detailed experiments it was clearly established that the spin dynamics and , in particular, the spin tune of a stored polarized beam can be manipulated using a local spin rotator. Most significantly the spin tune is indeed a half-integer with a full Siberian Snake as is shown in Fig. 1. To measure the spin tune an artificial spin resonance with adjustable driving field and frequency is used. Since the driving field for the ar-
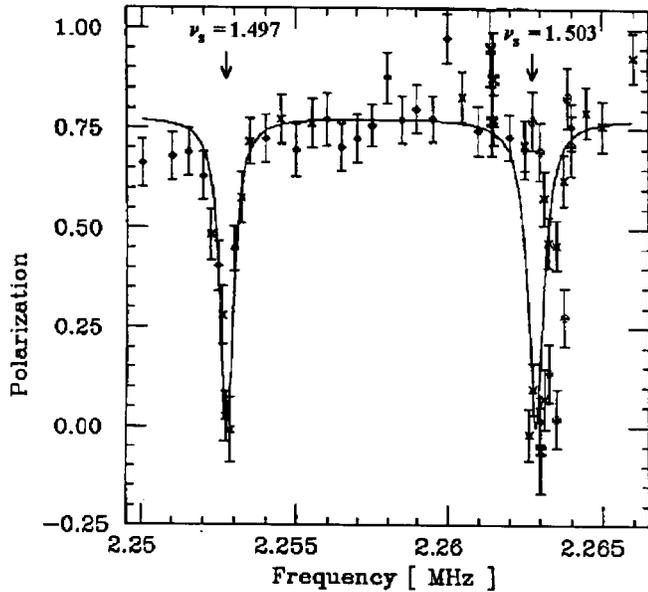
Figure. 1. Measured beam polarization vs. frequency of an artificial spin resonance. The depolarizing resonance indicates the spin tune v_s.

Figure. 2. Final maesured polarization as a function of spin flips[6].

tificial spin resonance was in fact a oscillating horizontal field it simultaneously produced two resonances corresponding to the decomposition into two counter-rotating fields. By adjusting the current in the solenoid Snake the spin tune can easily be tuned to be exactly a half-integer. However, this adjustment is not critical as long as the betatron tune is chosen appropriately.

The ability to excite an artificial resonance is also very useful for experiments that use stored polarized proton beams with a long lifetime such as internal target experiments or colliding beam experiments. In these cases the artificial resonance can be used to reverse or flip the polarization of the stored beam periodically to minimize systematic errors of the experiments. The team at IUCF successfully used their artificial resonance driving field to demonstrate the feasibility of reversing the polarization multiple times without significant polarization loss[6]. Fig. 2 shows the result of repeated spin reversals of the stored polarized beam which was accomplished by slowly ramping the frequency of the artificial resonance through the resonance condition. In a ring with a Siberian Snake and therefore with a half-integer spin tune such a spin flipper resonance would need to be created with a true rotating field to generate only a single resonance. Designs for such devices that can be used in high energy accelerators would typically consist of orbit bumps that are excited at the spin precession frequency[7].

III. AGS PARTIAL SIBERIAN SNAKE TESTS

Two polarized beam test runs of experiment E-880 at the AGS have recently demonstrated the feasibility of polarized proton acceleration using a 5% partial Siberian Snake. During the first run[8] in April 1994 it was shown that a 5% Snake is sufficient to avoid depolarization due to the imperfection resonances without using the harmonic correction method. Fig. 4 shows the evolution of the beam polarization as the beam energy and therefore
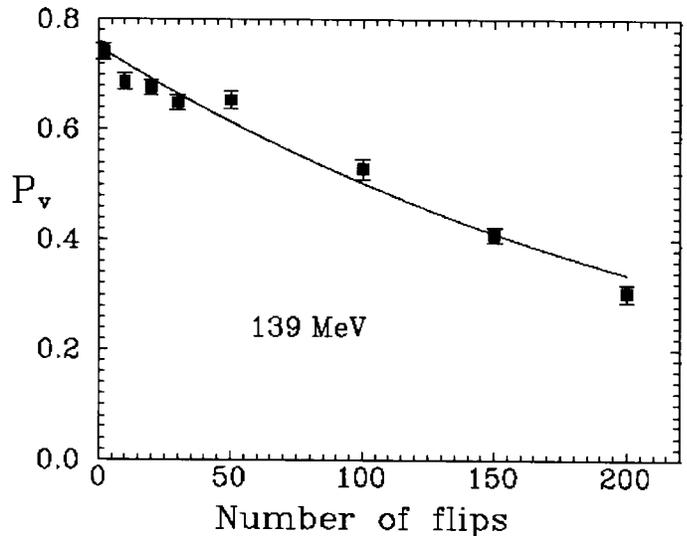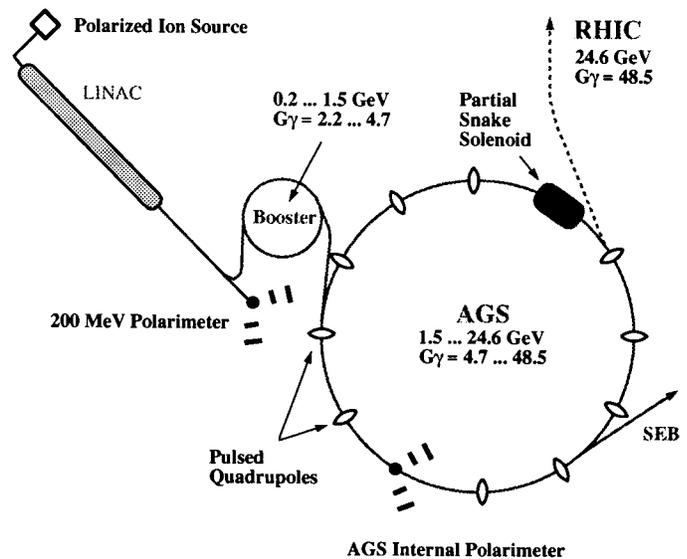

Figure. 3. Layout of the AGS accelerator complex showing the location of the Partial Siberian Snake, the pulsed quadrupoles, and the AGS internal polarimeter

$G\gamma$ is increased. As predicted the polarization reverses the sign whenever $G\gamma$ is equal to an integer.

Fig. 5 shows the achieved polarization as a function of beam energy. It shows that no polarization was lost at the imperfection resonances. The only polarization loss occurred at the location of the intrinsic resonances for which the pulsed quadrupoles are required for the tune jump method. During the first run the pulsed quadrupoles were not available. During the second run in December 1994 it was shown that it is possible to use the tune jump method in the presence of the partial Snake. A new record energy for accelerated polarized beam of $25\,GeV$ was reached with about 12% beam polarization left. Again no polarization was lost due to the imperfection resonances and depolarization
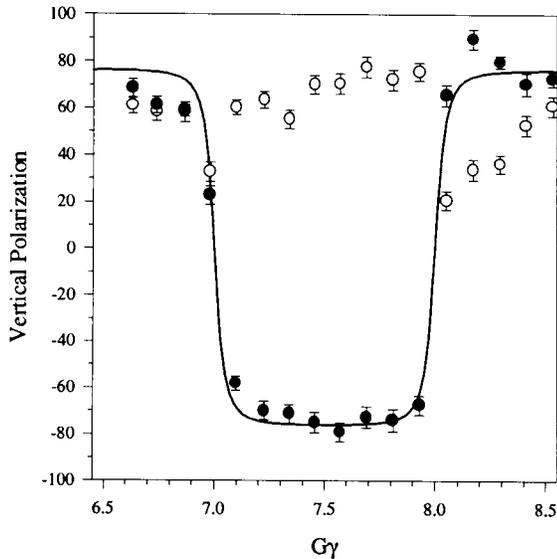
Figure. 4. The measured vertical polarization as a function of the spin tune $G\gamma$ for a 10% snake is shown with and without a snake. Note here that partial depolarization at $G\gamma = 8$ is avoided by using a 10% snake. The solid line is the predicted energy dependence of the polarization.

Figure. 5. The measured absolute value of the vertical polarization at $G\gamma = n + \frac{1}{2}$ up to $G\gamma = 48.5$ which corresponds to an energy fo $25\,GeV$. The partial depolarization is due to intrinsic spin resonances at $G\gamma$ values indicated at the top of the figure. The results from the Dec. 1994 run are preliminary.

from most intrinsic resonances was avoided with the tune jump quadrupoles. However, as can be seen from Fig. 5, significant amount of polarization was lost at $G\gamma = 0 + \nu_y$, $12 + \nu_y$ and $G\gamma = 36 + \nu_y$. The first two of these three resonances were successfully crossed previously and it will require further study to explain the unexpected polarization loss. The strength of the tune jump quadrupoles is not sufficient to jump the last resonance. We attempted to induce spin flip at this resonance but were only partially successful. During the next study run the method of inducing spin flip at intrinsic resonances will be further investigated[9].

IV. TOWARDS A POLARIZED PROTON COLLIDER

With the successful tests of Siberian Snakes the stage is set for the acceleration of polarized proton beams to much higher energies to be used in collider experiments to explore spin effects at the highest energies attainable. Two efforts are presently underway to develope Snakes designs for high energy accelerators. In the first project polarized protons from the Brookhaven AGS will be injected into the two RHIC rings to allow for up to $\sqrt{s} = 500\,GeV$ collisions with both beams polarized[10]. Fig. 6 shows the lay-out of the Brookhaven accelerator complex highlighting the components required for polarized beam acceleration.

Of particular interest is the design of the Siberian Snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC. Proposed by V. Ptitsin and Yu. Shatunov from BINP[11], it is based on helical dipole magnet modules each having a full 360 degree helical twist. Using helical magnets minimizes orbit excursions within the extend of the Snake or spin rotator[12] which is most important at injection energy. Fig.
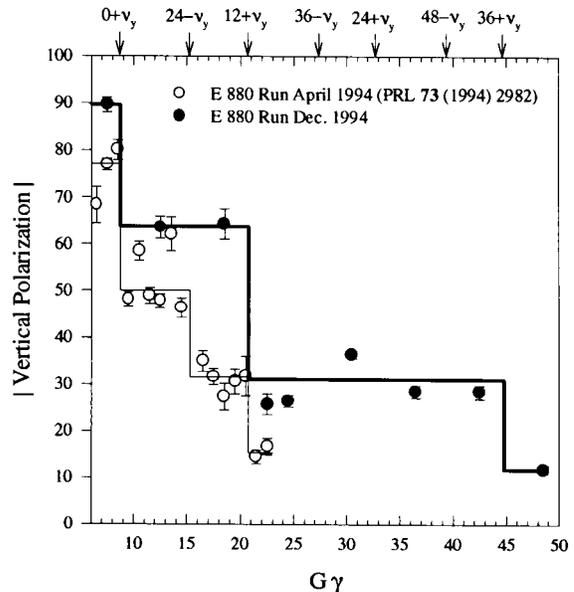
7 shows the aluminum former for the prototype helical dipole magnet now under construction at Brookhaven. The construction of a large bore high field helical dipole presents a formidable challenge for present superconducting magnet technology.

The second project consists of accelerating polarized protons in the Tevatron replacing some of the Tevatron dipole magnets with higher filed magnets to gain space to install the six required Siberian Snakes[13]. The project focuses on single spin collider experiments since at this time it is not feasible to polarize anti-protons, although the results discussed in the following section could open up the possibility of polarized anti-protons in the future.

With one or two Snakes all depolarizing resonances should be avoided since the spin tune is a half-integer independent of energy. However, if the spin disturbance from small horizontal fields is adding up sufficiently between the Snakes depolarization can still occur. This is most pronounced when the spin rotation from all the focusing fields add up coherently which is the case at the strongest intrinsic resonances. At RHIC two Snakes can still cope with the strongest intrinsic resonance whereas at the Tevatron six Snakes will be needed. At the energies of these strongest intrinsic resonances the betatron tune has to be adjusted very carefully to avoid the accumulation of the spin rotation of the focusing fields over more than one turn which would occur for a fractional part of the betatron tune of $\Delta\nu_y = (\frac{1}{2} \pm k)/n$, where both k and n are integers. These so called 'Snake resonances' conditions[14] are now energy independent and are the same as the location of the stop-band resonances. Therefore, with Siberian Snakes orbit and polarization stability conditions coincide.
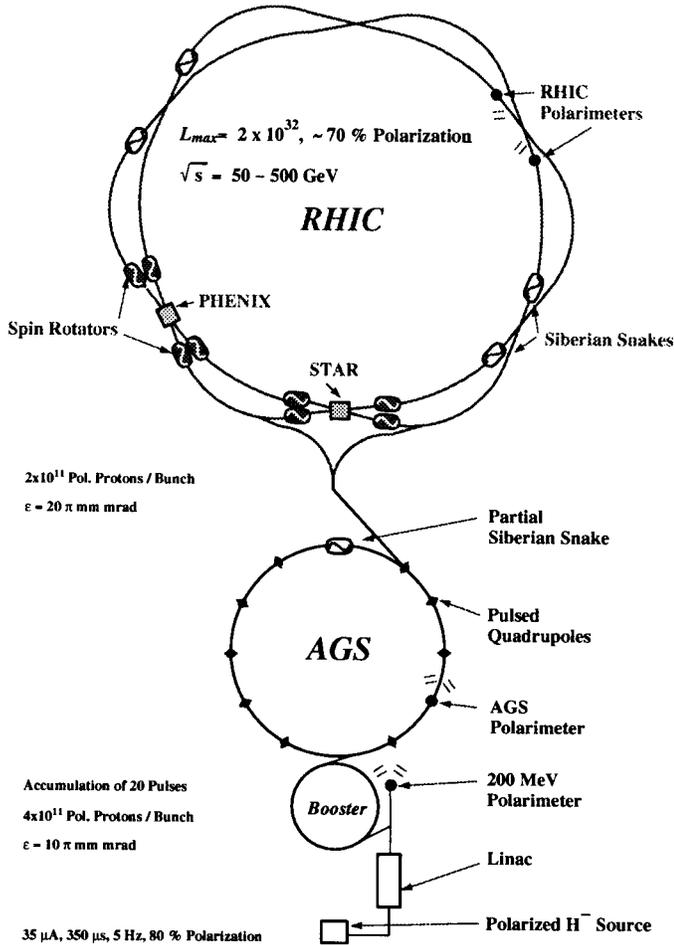
Figure. 6. The Brookhaven hadron facility complex, which includes the AGS Booster, the AGS, and RHIC. The RHIC spin project will install two snakes per ring with four spin rotators per detector for achieving helicity-spin experiments.

Figure. 7. Aluminum former for the helical dipol magnet prototype under construction at BNL
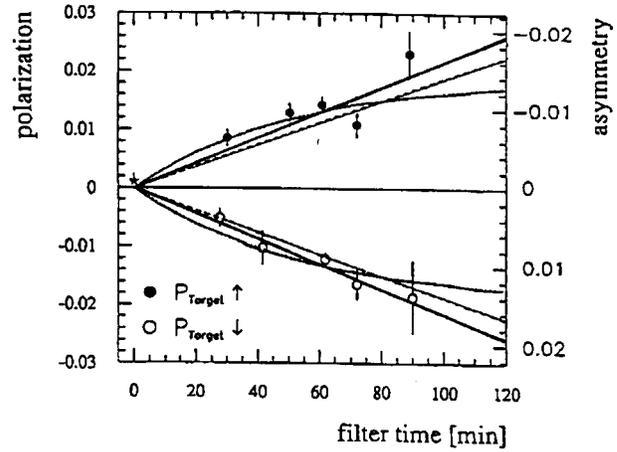
Figure. 8. Polarization build-up measurements at the Heidelberg Test Storage Ring.

V. POLARIZATION BUILD-UP IN STORAGE RINGS

Several people have proposed schemes to build-up the polarization of a stored beam using the fact that a small spin effect can lead to a sizable polarization if it accumulates over many million revolutions. In fact, high levels of electron polarization are being achieved routinely using the very small spin flip probability during the emission of synchrotron radiation. The motivation for such schemes is two-fold: by polarizing the beam after acceleration the depolarization from passing through the many spin resonances can be avoided and, maybe more importantly, such a scheme could also be used to produce a polarized anti-proton beam. Now, for the first time, a positive result was achieved at the Test Storage Ring in Heidelberg[15]. A polarized internal hydrogen gas target was inserted and the polarization of the circulating proton beam started to build-up reaching a maximum value of about 2% after about 90 minutes. This result is shown in Fig. 8. The beam polarization was measured before and after
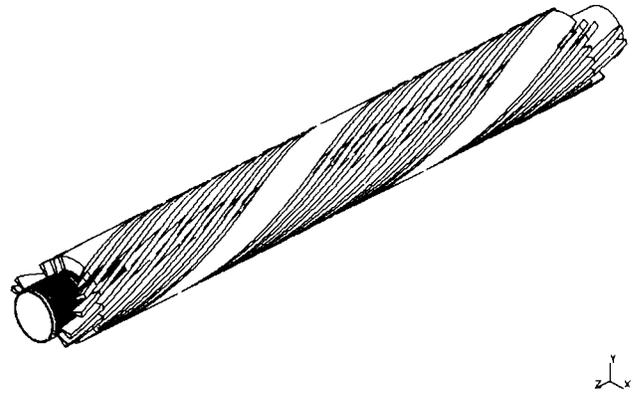
the build-up process using proton-alpha scattering as analyzing reaction. Three different processes contribute to the polarization build-up. The first process is spin dependent beam loss due to proton-proton scattering out of the storage ring acceptance. The remaining two effects are due to polarization transfer from either the proton or the electron to the beam proton. The polarization transfer from the electron has the opposite sign of the other two effects. The combination of all three effects is in very good agreement with the measured result.

There is no data available on the nuclear spin dependent effects between anti-proton and protons. However, the polarization transfer from polarized electrons to anti-protons can be calculated[16]. For the first time, we seem to have a realistic scheme to produce polarized anti-proton beams.

VI. CONCLUSIONS

Over the last years several new tools have become available for the acceleration and manipulation of polarized proton beams. The Siberian Snake concept has been proven to be correct and the first partial Snake has been used in a high energy accelerator. Artificial spin resonances have been used extensively as diagnostic

tools and also for spin flipping. And, in the more distant future, it might even be possible to create polarized anti-proton beams for use in high energy accelerators. With all these advances, polarized beam operation should become more of an integral part of future high energy proton accelerators.

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