CONF-951280--5   BNL-63478

ACCELERATION AND STORAGE OF POLARIZED PROTON BEAMS*

THOMAS ROSER

AGS Department,Brookhaven National Laboratory
Upton, NY 11973-5000, USA
E-mail: roser@bnl.gov

RECEIVED
OCT 30
OSTI

ABSTRACT

High energy polarized beam collisions will open up the unique physics opportunities of studying spin effects in hard processes. Proposals for polarized proton acceleration for several high energy colliders have been developed. A partial Siberian Snake in the AGS has recently been successfully tested and full Siberian Snakes, spin rotators, and polarimeters for RHIC are being developed to make the acceleration of polarized beams to $250\,GeV$ possible. This allows for the unique possibility of colliding two $250\,GeV$ polarized proton beams at luminosities of up to $2 \times 10^{32}\,cm^{-2}s^{-1}$.

1. Introduction

Polarized proton colliders will open up the completely unique physics opportunities of studying spin effects in hard processes at high luminosity, high energy proton-proton collisions. It will allow to study the spin structure of the proton, in particular the degree of polarization of the gluons and antiquarks, and also to verify the many well documented expectations of spin effects in perturbative QCD and parity violation in W and Z production.

Proton-proton collisions at high energies involve hard scattering of gluons and quarks. In this kinematic region factorization should hold and any asymmetry A measured for a high p_T reaction is a sum of corresponding asymmetries $\hat{a}$ at the parton level weighted by the actual degree of polarization of the initial partons given by the spin structure functions:

$$A = \sum_{subprocesses} \frac{\Delta a}{a} \times \frac{\Delta b}{b} \times \hat{a}\,(a + b \rightarrow c + d)$$

The subprocess asymmetries are predicted by the standard model and are often large. For example, $\hat{a}_{LL}$ in QCD is 50% or larger for most subprocesses and the parity violating $\hat{a}_L$ is unity in weak processes. By measuring different reactions and different types of asymmetries we can determine subprocess asymmetries, the spin structure functions of all partons, and also perform self consistency checks. This very ambitious program is greatly simplified by the fact that the spin structure functions of valence quarks are known from deep inelastic scattering measurements and that we can select reactions that are dominated by just one subprocess. A center-of-mass energy range of 200 to $500\,GeV$, as achievable in the Brookhaven Relativistic Heavy Ion Collider

(RHIC)[1], is ideal in the sense that it is high enough for perturbative QCD to be applicable and low enough so that the average x value is about 0.1 or larger which guarantees significant levels of polarization for the valence quarks.

2. Spin Dynamics and Siberian Snakes

To achieve high energy polarized proton collisions polarized beams first have to be accelerated which requires an understanding of the evolution of spin during acceleration and the tools to control it. 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[2],

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

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:

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

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 also called the spin tune ν_{sp}. At top RHIC energies this number reaches about 400. The Thomas-BMT equation also shows that at low energies ($\gamma \approx 1$) longitudinal fields $\overrightarrow{B_\parallel}$ can be quite effective in manipulating the spin motion, but at high energies transverse fields $\overrightarrow{B_\perp}$ 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 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_{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

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

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 $\nu_y \approx 8.8$. 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[3] 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[4]. At high energy, these traditional methods become difficult and tedious.

By introducing a 'Siberian Snake'[5], 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 Brookhaven AGS with weaker depolarizing resonances, a partial snake[6], which rotates the spin by less than $180°$, is sufficient to keep the stable spin direction unperturbed at the imperfection resonances.

3. Polarized Proton Acceleration at the AGS

Two polarized beam runs of experiment E-880 at the AGS have recently demon-
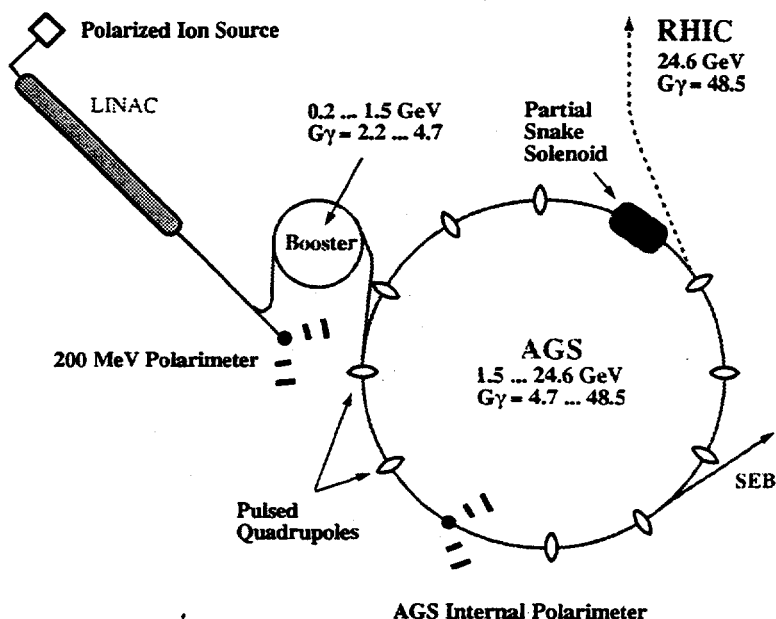
E880 Partial Snake Test at the AGS

Figure 1: Layout of the AGS accelerator complex showing the location of the Partial Siberian Snake, the pulsed quadrupoles, and the AGS internal polarimeter

strated the feasibility of polarized proton acceleration using a 5% partial Siberian Snake. Fig. 1 shows a layout of the AGS accelerator complex highlighting the necessary hardware for polarized beam acceleration in the AGS. It was shown that a 5% Snake is sufficient to avoid depolarization due to the imperfection resonances without using the harmonic correction method up to the required RHIC transfer energy of 25 GeV. Fig.2 shows the evolution of the beam polarization as the beam energy and therefore $G\gamma$ is increased[7]. As predicted the polarization reverses the sign whenever $G\gamma$ is equal to an integer.

Fig.3 shows the achieved polarization as a function of beam energy. 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 from most intrinsic resonances
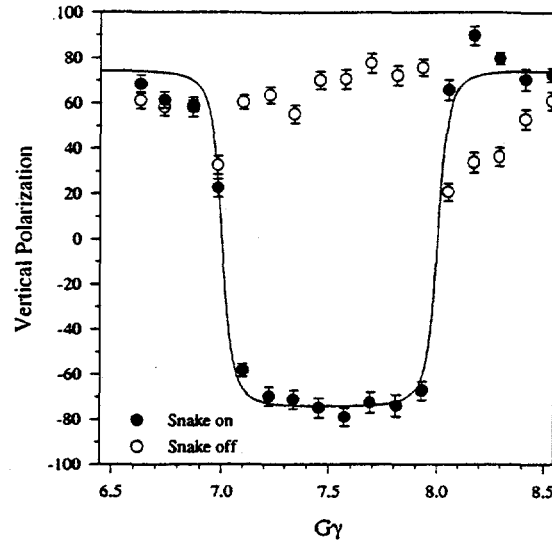
Figure 2: The measured vertical polarization as a function of $G\gamma$ for a 10% snake is shown with and without a snake. The solid line is the predicted energy dependence of the polarization.

___

was avoided with the tune jump quadrupoles. However, as can be seen, 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[8].

4. Polarized Proton Acceleration at RHIC

By using Siberian Snakes the stage is set for the acceleration of polarized proton beams to much higher energies. Polarized protons from the AGS are injected into the two RHIC rings to allow for up to $\sqrt{s} = 500\,GeV$ collisions with both beams polarized. Fig. 4 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. Each Snake or spin rotator consists of four $2.4\,m$ long, $4\,T$ helical dipole magnet modules each having a full 360 degree helical twist[9]. Using helical magnets minimizes orbit excursions within the extend of the Snake or spin rotator which is most important at injection energy. A prototype helical dipole magnet is now under construction at Brookhaven.
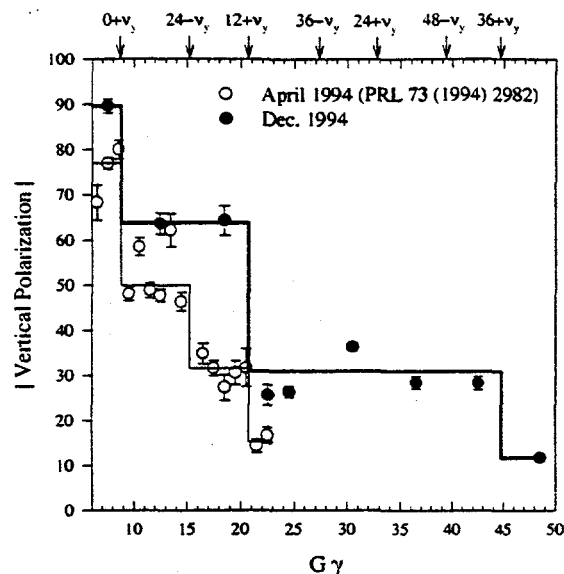
Figure 3: The measured absolute value of the vertical polarization is shown up to $G\gamma = 48.5$ which corresponds to an energy fo $25\,GeV$. The partial depolarization is due to intrinsic spin resonances at $G\gamma$ values indicated at the top of the figure. The results from the Dec. 1994 run are preliminary.

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.

Two types of polarimeters are required for RHIC. First an absolute polarimeter is needed to provide the necessary calibration to compare results obtained at RHIC with other experiments, particularly with deep inelastic lepton scattering results. Very few other spin experiments have been performed in this energy region, which makes it necessary to rely on processes that can reliably be calculated. The most promising process at the moment is proton-proton elastic scattering in the Coulomb-Nuclear interference region. A separate collider experiments is planned to do this rather difficult measurement. Secondly, two relative polarimeters are required that are capable of measuring the polarization of the circulating beam in each ring independently at various stages during the acceleration cycles. These polarimeters utilize the asymmetries in inclusive π^- production. The polarimeter consists of a $5\,\mu m$ diameter carbon fiber fixed target and magnetic spectrometers.
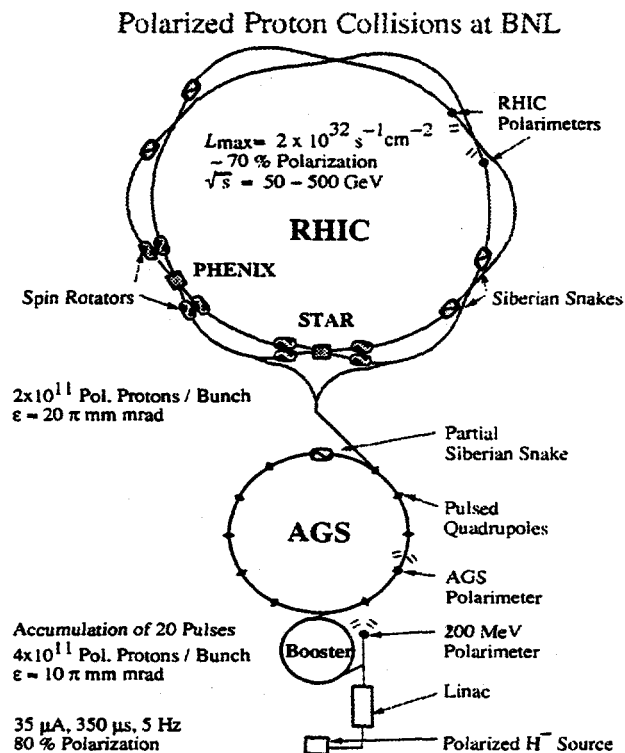
Polarized Proton Collisions at BNL

Figure 4: 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.

5. Polarization Sign Reversals

Since the proposed asymmetry measurements are high precision measurements, frequent polarization sign reversal is imperative to avoid systematic errors. Possible sources for systematic errors are luminosity variations, crossing angle variations, and detector efficiency variations. Each bunch can be filled independently, so the "pattern" of polarization direction for the 120 bunch positions in each ring can be arranged in an optimal way. At each intersection region the same pairs of bunches interact, but there are different pairs at each intersection. It is typically desirable to
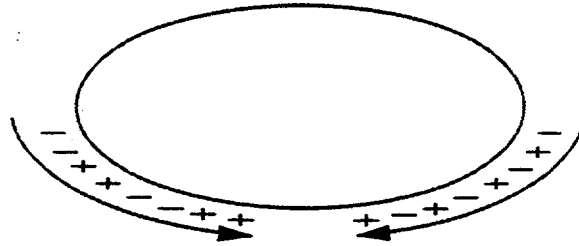
Figure 5: The pattern of the polarization signs of the bunches in the two counter-rotating beams in RHIC

---

collide equal numbers of $(++, +-, -+, --)$ bunches at each experiment, where $+-$ represents a bunch in one beam with polarization up colliding with a bunch in the other beam with polarization down.

One solution which would satisfy all the intersections is to load one ring with $(++--++--++--,$ etc.$)$, and load the other ring with $(+-+-+-+-+-+-,$ etc.$)$. Each experiment has 30 complete sets of $(++, +-, -+, --)$. This is illustrated in Figure 5.

Although this will greatly reduce systematic errors it is still true that one pair of bunches would always cross with the same combination of polarization signs during the whole lifetime of the stored beams which is at least several hours. To eliminate the possibility of systematic errors from this situation we are planning to install a spin flipper in each ring which is capable of reversing the polarization sign of all bunches. A spin flipper typically consists of horizontal DC dipole magnets interleaved with high frequency vertical dipole magnets[10]. Exciting the vertical magnets with about $40\,kHz$ AC current would drive an artificial spin resonance which can be used to adiabatically reverse the polarization direction. This concept has successfully been tested at the Indiana University Cyclotron Facility (IUCF)[11].We estimate that complete spin reversal would take less than one second. The same device will be used to accurately measure the spin tune by measuring the spin reversal efficiency as a function of the frequency of the spin flipper excitation. This is instrumental to adjust the spin tune to 0.500.

In most cases a simple oscillating driving field is very effective in driving an artificial resonance since the oscillating field can be thought of as the sum of two counter-rotating fields, only one of which is in resonance with the beam precession frequency. However, with a Snake the spin tune is a half-integer and therefore the two counter-rotating fields are both in resonance and interfere so that effectively only half of the beam around the ring circumference sees a driving field. By designing a true rotating field the beam polarization can be fully flipped even with a half-integer spin tune. A

straight-forward extension of the scheme described above makes this possible.

6. Conclusions

With all the recent advances in the understanding of spin dynamics and the development of techniques for spin manipulation, polarized beam operation could become more of an integral part of future high energy accelerators. In particular, polarized proton beam capabilities are being developed for RHIC and it is anticipated that all the necessary hardware for polarized proton acceleration will be in place for the expected turn-on of RHIC in 1999.

7. References

1. Proposal on Spin Physics Using the RHIC Polarized Collider (R5), submitted to the BNL PAC August 1992; update September 1993.
2. L.H. Thomas, Phil. Mag. **3**, 1 (1927); V. Bargmann, L. Michel, V.L. Telegdi, Phys. Rev. Lett. **2**, 435 (1959).
3. M. Froissart and R. Stora, Nucl. Instr. Meth., **1**, 297 (1960).
4. T. Khoe et al., Part. Accel. **6**, 213 (1975); J.L. Laclare et al., J. Phys. (Paris), Colloq. **46**, C2-499 (1985); H. Sato et al., Nucl. Inst. Meth., Phys. Res. Sec A272, 617 (1988); F.Z. Khiari, et al., Phys. Rev. D39, 45 (1989).
5. Ya.S. Derbenev et al., Part. Accel. **8**, 115 (1978).
6. T. Roser, AIP Conf. Proc. No. 187, ed. K.J. Heller p.1442 (AIP, New York, 1988).
7. H.Huang et al., Phys. Rev. Lett. **73**, 2982 (1994)
8. T. Roser, in Proc. of the 10th Int. Symp. on High Energy Spin Physics, Nagoya, Japan, p. 429 (1992).
9. V.I.Ptitsin and Yu.M.Shatunov, Helical Spin Rotators and Snakes, Proc. 3. Workshop on Siberian Snakes and Spin Rotators (A.Luccio and T.Roser Eds.) Upton, NY, Sept. 12-13,1994, BNL-52453, p.15
10. T.Roser, Spin Rotators and Split Siberian Snakes, NIM A342 (1994) 343.
11. D.D. Caussyn et al.,Phys. Rev. Lett. **73**, 2857 (1994)
12. 'Acceleration of Polarized Protons to 1 TeV in the Fermilab Tevatron', University of Michigan Report, August 1994.
13. D.P. Barber, Possibilities for polarized protons at HERA, Workshop on the Prospects of Spin physics at HERA, DESY-Zeuthen, August 1995, to be published