Measuring the Proton Beam Polarization

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Abstract. Polarimeters are necessary tools for measuring and maintaining the beam polarization during the acceleration process. They serve, as well, as a yardstick for performing spin physics experiments. In this paper, I will describe the principles of measuring proton beam polarization and the techniques that are employed at various energies. I will use as a guide the design work for the Polarized Proton Project at the Relativistic Heavy Ion Collider (RHIC) which is under construction at Brookhaven National Laboratory.

INTRODUCTION

A polarimeter is a tool that measures the beam polarization, that being the degree of alignment of the spins of an ensemble of protons in a beam with respect to a specific direction. This is generally done by sampling the spin projection of a large number of particles in a scattering process that is sensitive to the spin direction.

Polarmeters are used at various stages in an accelerator primarily as diagnostic tools to maintain the polarization of the beam during acceleration, storage, and beam transport. Of course, the goal is the physics measurement and polarmeters are often employed as a first stage of an experiment to measure the polarization of the beam impinging on the target. This normalizes the final result and the error in the polarization measurement has a direct statistical impact on the data. While the accuracy from electron beam polarimeters is now well below 5%, this represents a lofty goal for proton beam polarimeters and is the desired goal for the polarized proton project at RHIC.

BEAM POLARIZATION

The degree of beam polarization along a certain direction is defined as:

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \tag{1}$$

where $N_\uparrow$ and $N_\downarrow$ are the number of protons with spins parallel and antiparallel to the desired direction. In an accelerator, the stable spin direction is usually transverse to the momentum vector and along the vertical. The task is to find proton-induced reactions that are sensitive to the spin alignment of the beam. This is often a nuclear reaction in a plane that is perpendicular to the beam polarization direction and is usually sensitive to the spin-spin or the spin-orbit interactions between the incoming proton beam particle and the target nuclei. The yield then depends on whether the beam is polarized up or down and is reflected in the number of scatters or events of particular interest measured in the apparatus.

Typically one tries to measure the number of events with the beam polarized up versus those with the beam polarized down, making sure that the experimental conditions remain unchanged. The resulting beam polarization is:

$$P = \frac{1}{A}\frac{n_\uparrow - n_\downarrow}{(n_\uparrow + n_\downarrow)} \tag{2}$$

where $n_\uparrow$ and $n_\downarrow$ refer to the number of scatters, properly normalized, with the beam polarization up and down respectively. A is a new term called the "analyzing power" of the reaction. This is a measure of the sensitivity of the reaction to the beam polarization, a number that varies between 0 and 100%. Of course the above equation assumes that one can flip the beam polarization without any other changes.

Similarly, an apparatus that can measure the number of scatters to beam-left, $n_{L,}$, and beam-right, n_R, simultaneously will determine the degree of up and down beam polarization independently and one substitutes n_L and n_R in the above equation. In general both methods are utilized and combined in order to reduce systematic errors and potential dependence on geometrical effects.

The associated statistical error in these measurements is a function of both the analyzing power A and the total number of events N (($n_\uparrow + n_\downarrow$) or ($n_\mathrm{L} + n_\mathrm{R}$) or the sum of all four terms if a combined measurement is performed):

$$\Delta P = \frac{1}{A}\frac{1}{\sqrt{N}}. \tag{3}$$

As an example, for a 5% statistical precision in the beam polarization measurement and using a reaction with an analyzing power of 10%, one needs 4×10^4 events. It is therefore important to utilize reactions with large analyzing power as well as large cross section. The latter is a measure of the frequency of the reaction given a certain number of protons impinging on a specific target. In the design of a polarimeter, the quantity to optimize is the product:

$$N \times A^2. \tag{4}$$

THE SALIENT FEATURES OF A POLARIMETER

In general a beam polarimeter should serve as the following:

- A polarization monitor capable of several samples over a reasonable period of time.
- A diagnostic tool that can be used on demand with a turn key operation.

- A tool for machine tuning with measurements and feedback provided within a few minutes.

The beam polarimeter should have:

- A large dynamic range for dealing with the acceleration cycle (e.g., at RHIC the range is from 25 GeV at injection to 250 GeV at top energy).
- A large analyzing power, high cross section and low background contamination to the physics process.
- A reasonable cost.

It is not always possible to combine all these features and certain compromises are sometimes necessary.

Proton Beam Polarimeter Reactions, the Empirical Way

Unlike electromagnetic reactions (see the presentation by C. Sinclair on electron beam polarimeters in these proceedings), the analyzing power and cross section of these proton-induced nuclear reactions are not precisely calculable, especially at high energies. Thus one reverts to experimental results. These measurements are generally done with polarized proton targets the polarization of which is well-measured using NMR techniques and Masers. Until recently, these targets were not pure hydrogen, thus the target material presents undesired background, especially in inclusive measurements. However, this is not an impediment for exclusive reactions such as p-p elastic scattering or p-carbon scattering when both outgoing particles are detected to provide good kinematic constraints.

These methods have been applied at relatively low energies below beam momenta of 12 GeV/c with good results (3%–5%) and can in turn be used to measure the beam polarization to comparable statistical accuracy. This was done for the polarized proton project at the Argonne National Laboratory ZGS. At higher energies, the experiments are more difficult and the analyzing power becomes increasingly small, resulting in reduced accuracy.

At Brookhaven National Laboratory, an effort is underway to equip the RHIC with the capability to accelerate, store, and collide polarized proton beams at high luminosity. Polarimeters will be deployed to cover various energy ranges: 200 MeV, 4–24 GeV, and 24–250 GeV. I will discuss the choice of the physics processes and associated apparatus for each. But first, a few words about the RHIC project at BNL.

THE RELATIVISTIC HEAVY ION COLLIDER

The RHIC is a new project that is currently under construction at BNL with a target date of completion in June 1999. For heavy ions, the collider uses the Tandem-Booster-AGS as an injector to accelerate, store, and collide beams of various species from light ions to gold. The design luminosity for colliding gold beams is 2×10^{26} cm^{-2} sec^{-1}. The first round of experiments that are slated to receive beam include two large detectors, STAR and PHENIX, and two smaller detectors, BRAHMS and PHOBOS. The physics goal is to study a new state of matter under conditions of extreme temperature and pressure, the quark gluon plasma.

The polarized proton capability utilizes a polarized H^- source and the 200 MeV Linac-Booster as injectors to the AGS. The funding is provided in collaboration with the RIKEN, Japan, to equip the collider with the necessary hardware. This includes "Siberian Snakes," two in each ring, to preserve the beam polarization; two sets of spin rotators around the STAR and PHENIX experiments to orient the beam spins in the longitudinal or transverse directions depending on the physics demands; and beam polarimeters to tune the machine and measure the beam polarization during the 10-hour beam store. The goal is to study the contribution to the proton spin from the constituent quarks and gluons.

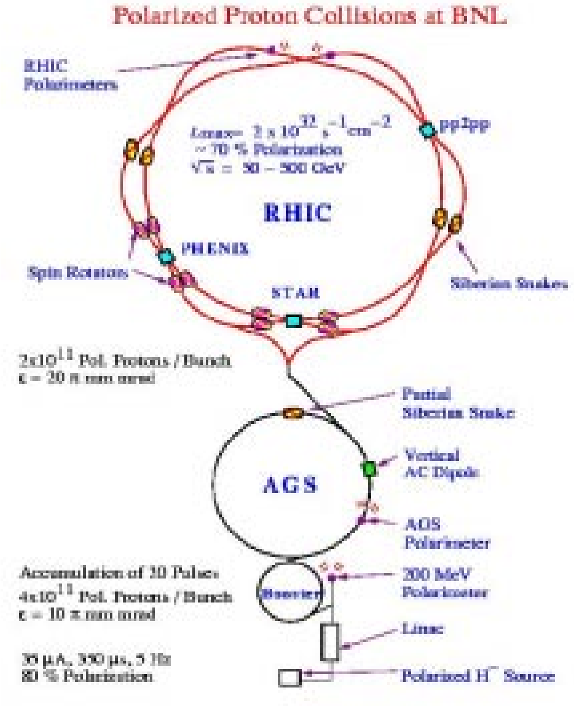

FIGURE 1. Polarized proton collisions at BNL.

The parameters that bear upon this discussion of polarimeters are the polarized beam intensities at the exit of the linac of 10–15 μA over a 300 μsec duration in the AGS, an approximately 2×10^{10} particle circulating beam, and a design goal of 2×10^{11} polarized protons per bunch in the RHIC, with a bunch spacing of approximately 100 nsec. A schematic of the complex is shown in Figure 1 in which the spin-related hardware and polarimeter locations are shown.

POLARIMETERS VERSUS ENERGY

The 200 MeV polarimeter

This polarimeter operates at the exit of the 200 MeV linear accelerator (1). At this energy, we have a large body of experimental data at our disposal. Experiments were carried out with polarized targets or using double scattering to infer the polarization of the outgoing particles. The cross sections are large and the analyzing power is appreciable, reaching unity in some cases (Figure 3). The task is easy and the apparatus is straightforward. The polarimeter of choice scatters polarized protons from a carbon target filament. The detectors are scintillators viewed by fast phototubes (Figure 2). The beam polarization is vertical and we measure the scattering in the horizontal plane. Two identical left/right spectrometers, subtending angles of 12 and 16 degrees in the laboratory frame on either side of the beam, measure the left/right scattering of the proton beam. A third spectrometer looks at 12 degrees in the vertical direction and serves two purposes: to measure any beam polarization component in the horizontal direction perpendicular to that plane, and to monitor intensity of the accumulated up versus down data. The polarization at the source is flipped on alternate pulses and the data of the two polarization states are accumulated simultaneously.

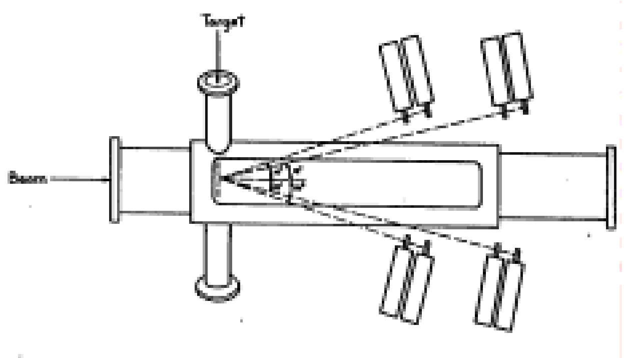

FIGURE 2. The 200 MeV polarimeter.

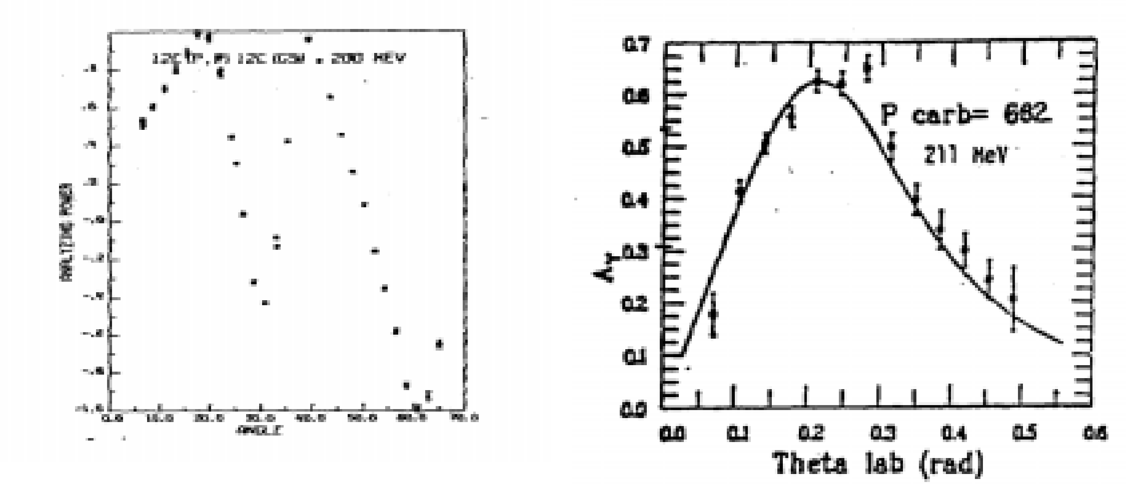

FIGURE 3. The analyzing power versus scattering angle in p-carbon elastic and inclusive production at 200 and 211 MeV, respectively.

The initial intention was to select the elastic scatters by inserting absorbers to uniquely define the scattered proton energies and angles. Later we settled on the inclusive measurement, at the expense of lower analyzing power (62% at 12° and 51% at 16°) but higher cross section. A 2% statistical measurement is achieved in about 2–3 minutes. The polarimeter was calibrated using the polarized beam at IUCF.

The AGS polarimeter

The polarimeter in the AGS (2) operates between the booster injection energy of a few GeV to the extraction energy at 24 GeV. The peak in the analyzing power in p-p elastic scattering at low four-momentum transfer values of 0.1–0.3 GeV^2/c^2 is utilized. As mentioned earlier, this has been measured precisely using polarized proton targets to better than 5% up to energies of 12 GeV. Beyond that, the cross sections are lower and the data get worse. The available measurements (Figure 5) were fitted and parameterized (3). Thus the asymmetry is known to about 10% and falls off with increasing beam energy as (~1/P). At the AGS energy the analyzing power ranges between 5 and 2%.

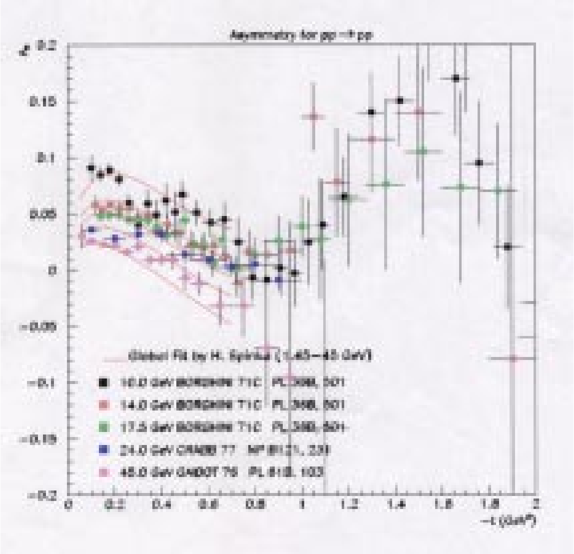

FIGURE 4. The analyzing power in p-p elastic scattering.

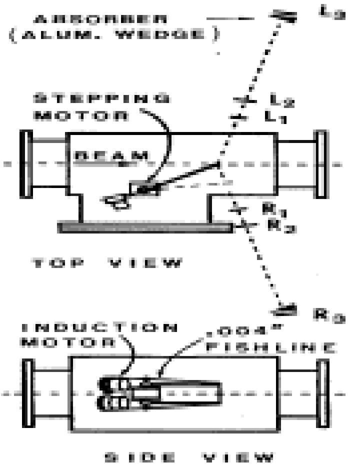

FIGURE 5. A schematic of the AGS polarimeter.

A typical p-p elastic polarimeter has two arms to simultaneously measure the forward scattered and recoil protons. However, the physical constraints in the AGS, the vacuum pipe and the 10 ft long straight sections, do not permit the placement of the forward arms that subtend a few degrees from the beam line. The measurement is done with the recoil proton at kinetic energy of approximately 500 MeV and scattering angle of approximately 76 degrees with respect to the beam direction (Figure 5). Time-of-flight, energy-range, and energy-angle correlation is utilized to select the p-p elastic scattering reaction from the multitude of inelastic scatters. The detectors are scintillation counters viewed by extremely fast phototubes. Similar to the 200 MeV polarimeter, this allows for relatively fast retrieval of the data with minimal on-line computer processing time. It is a counting experiment of the data that passed the trigger cuts.

The environment in the AGS is extremely harsh. The counting rates are high, necessitating debunching the beam during the polarization measurement. Pileup leads to accidental rates of the order of 10–20% depending on the energy. A nylon fish line target is used which is spooled at a rate of 100 cm/sec and flipped in and out of the beam in order to avoid damage due to heating or localized radiation. This requires a complicated computer controlled target mechanism. The loss of a target results in several hours downtime. A 1% statistical measurement takes from 5 minutes at low energy to 20 minutes at the higher energies. A second carbon target is periodically substituted for the fish line in order to measure and subtract the carbon contamination in the fish line. This apparatus serves as a relative polarimeter to tune the 50 imperfection and four intrinsic and depolarizing resonances in the AGS. For physics experiments using extracted AGS beams, this polarimeter is then calibrated against a separate external polarimeter that measures the fully constrained p-p elastic scattering process using a polarized proton target. Those in turn calibrate simple local polarimeters in each experiment.

Polarimeters at high energies (RHIC)

As the beam energy increases, the reach of the AGS-type polarimeter becomes increasingly difficult. Thus one has to revert to different reactions.

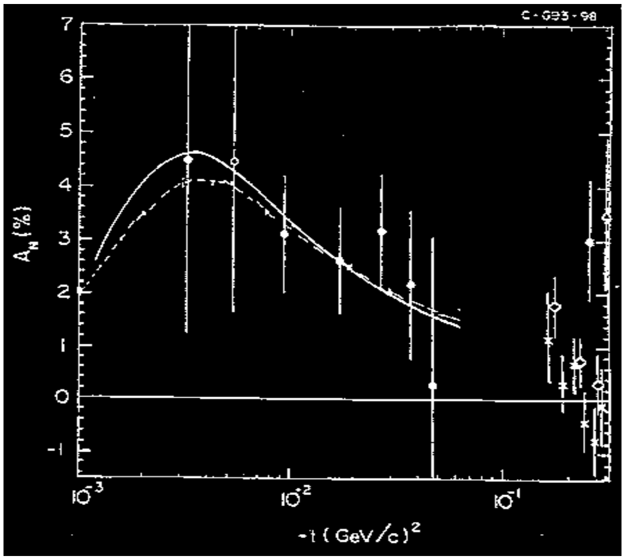

FIGURE 6. The CNI asymmetry in p-p elastic scattering.

An interesting possibility is to utilize the analyzing power in the Coulomb nuclear interference (CNI) region ($10^{-3} < t < 10^{-2}$) in p-p elastic scattering which arises primarily from the interference between the real electromagnetic helicity-flip amplitude and the imaginary hadronic helicity-nonflip amplitude. Unlike the previous process, this is calculable and the analyzing power is a respectable 5%, which appears to be energy independent. However, the hadronic interaction need not conserve helicity in the small t region and the inclusion of the single-flip hadronic amplitude may be relevant. The associated uncertainties with the latter render this measurement less certain. The precision of experimental data is good to approximately 15% (Figure 6).

Other calculable reactions are in the domain of proton-electron elastic scattering with both the proton and electron beams polarized. Polarimeters based on these processes, while experimentally challenging, may be quite feasible.

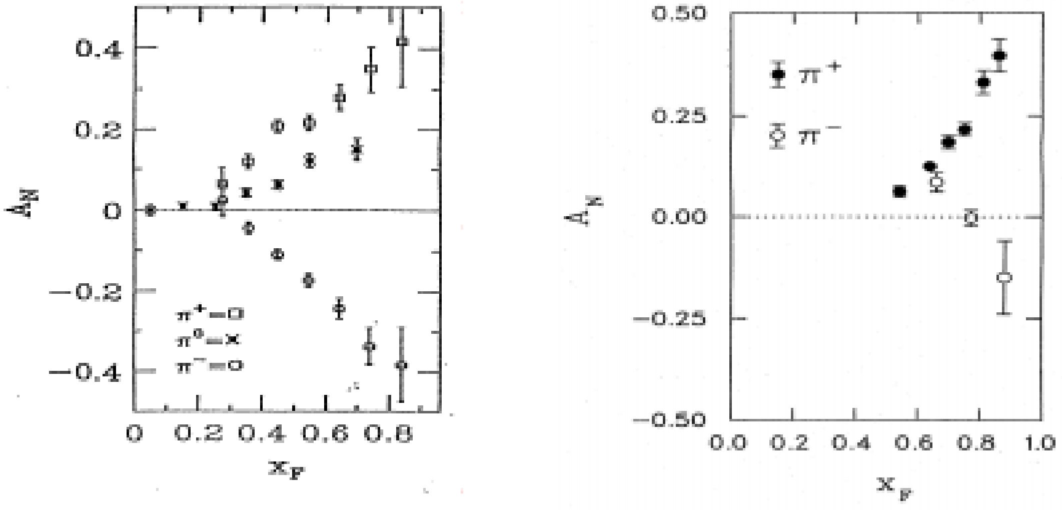

FIGURE 7. Asymmetries in pion production measured at Fermilab and the ZGS.

Experiments using polarized proton beam scattering from unpolarized hydrogen targets, carried out at 12 GeV/c at the ZGS (4) and at 200 GeV/c at Fermilab (5), observed large left-right asymmetries reaching over 30% in the inclusive production of pions (Figure 7). The copious production of pions and the associated large analyzing power seem to be ideally suited for the polarimeter application. The data and associated systematics provide a 10% absolute measurement which may be good for beam commissioning and the early physics results.

In what follows, I will sketch in some detail the steps in the design of this pion polarimeter for RHIC including the conditions that dictated the choice of parameters.

1. From the Fermilab data, one can parameterize both the A and the cross section data in terms of the kinematic variable x_f (~ the ratio between the scattered pion momentum to the beam momentum) and then optimize the value A^2N in order to determine the ideal conditions. For $p_t > 0.7$ GeV/c this resulted in $x_f \sim 0.5$ and a respective analyzing power of 15%.
2. Choose an acceptable transverse momentum of the outgoing pion ($p_t = 0.8$ GeV/c), which determines the scattering angle, the geometry, and the production cross section. The scattering angle ranges from 64 mrad to 6.4 mrad as the energy is raised from 25 to 250 GeV.

3. The cross section also grows linearly with energy requiring an apparatus with variable acceptance. Having defined this, one then proceeds to calculate the time required for one measurement with a specified precision. For a 7% statistical measurement that is comparable to the experimental data at 15% analyzing power one requires 10^4 scattered pions in the detector.
4. The required accuracy in the measurement of the scattered pion momentum of ~1% sets the need on the magnet rigidity ~8 T-m. This and the desire to measure the left and right scattering dictates that the magnets and detectors fit within a 1-meter lateral dimension between the two RHIC beam pipes. This led to an ingenious 4 magnet toroidal, 30-meter design that satisfied these requirements. A $\pm 7^{\circ}$ wedge gap increased radially outwards which provided the variable acceptance. The magnets were independently powered to accommodate the continuous energy range. The magnet excitations for various beam energies are shown in the table below. The polarimeter layout is in Figure 8.

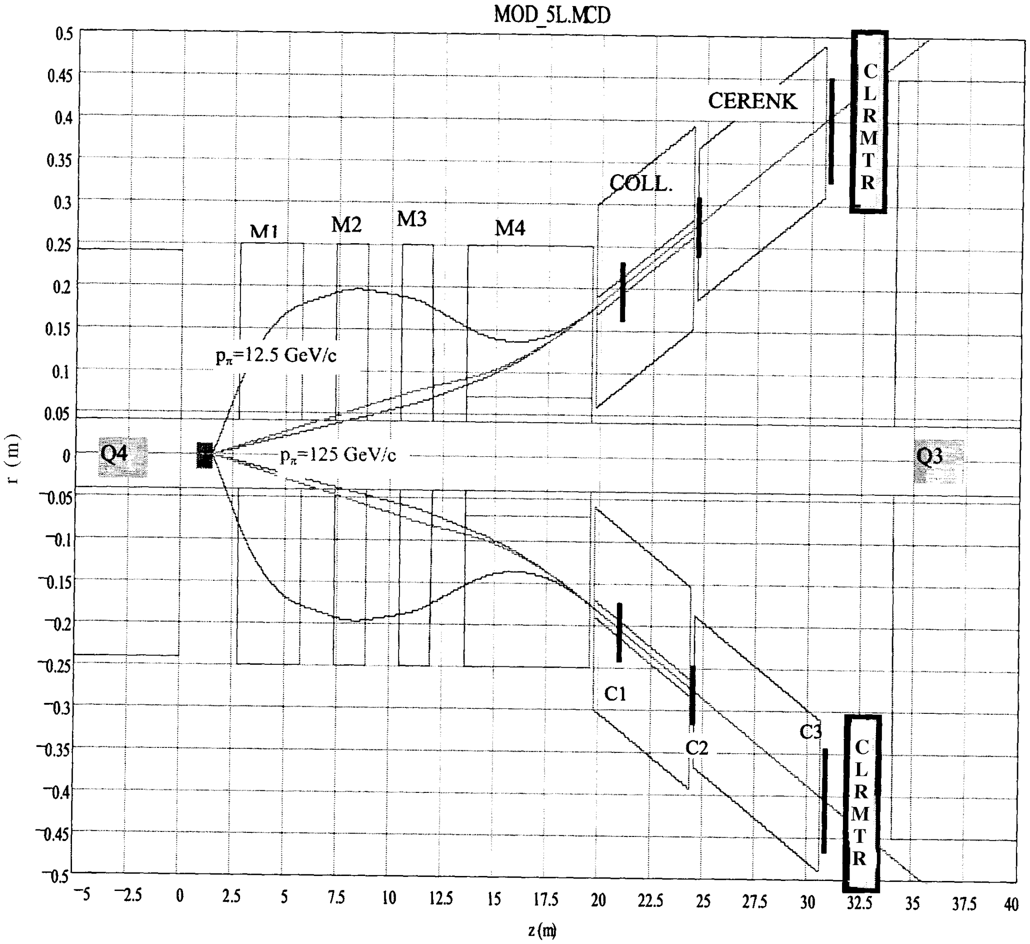

FIGURE 8. A schematic layout of the RHIC polarimeter and detectors.

TABLE 1. Polarimeter Element Lengths and Magnet Excitations

	TARGET	M1	M2	M3	M4	COLL	CRNKV
Length (M)	0	3	1.5	1.5	6	4.6	6
Position (m)	1.5	2.75	7.35	10.45	13.55	19.75	24.55
23 GeV/c		–1	–1	–0.859	+0.3743		
100 GeV/c		0.2	–1	–0.9576	+0.7706		
200 GeV/c		0	0	–0.305	+0.945		
250 GeV/c		0	0	+0.95	+0.95		

5. The carbon target heating was calculated, taking into account the beam intensity per bunch and the number of bunches in each ring (Figure 9):

$$T_{equ.} = \left(\frac{\varepsilon_h f_r N_p \frac{dE}{dx} \rho d}{8\pi \sigma_x \sigma_y \varepsilon_{rad} \sigma_{SB}} + T_0^4 \right)^{1/4} \qquad (4)$$

where N_p = number of protons per fill, ε_{rad}= 0.8 (emissivity), f_r = 78 kHz (RHIC beam rev. freq.), σ_{SB}= Boltzmann const, dE/dx = 1.78 MeV/gm·cm^2 (energy loss), ε_h= 0.3 (heating efficiency), $\sigma_{x,y}(p)$= rms beam width at momentum p, and ρ =1.75 gm/cm^3.

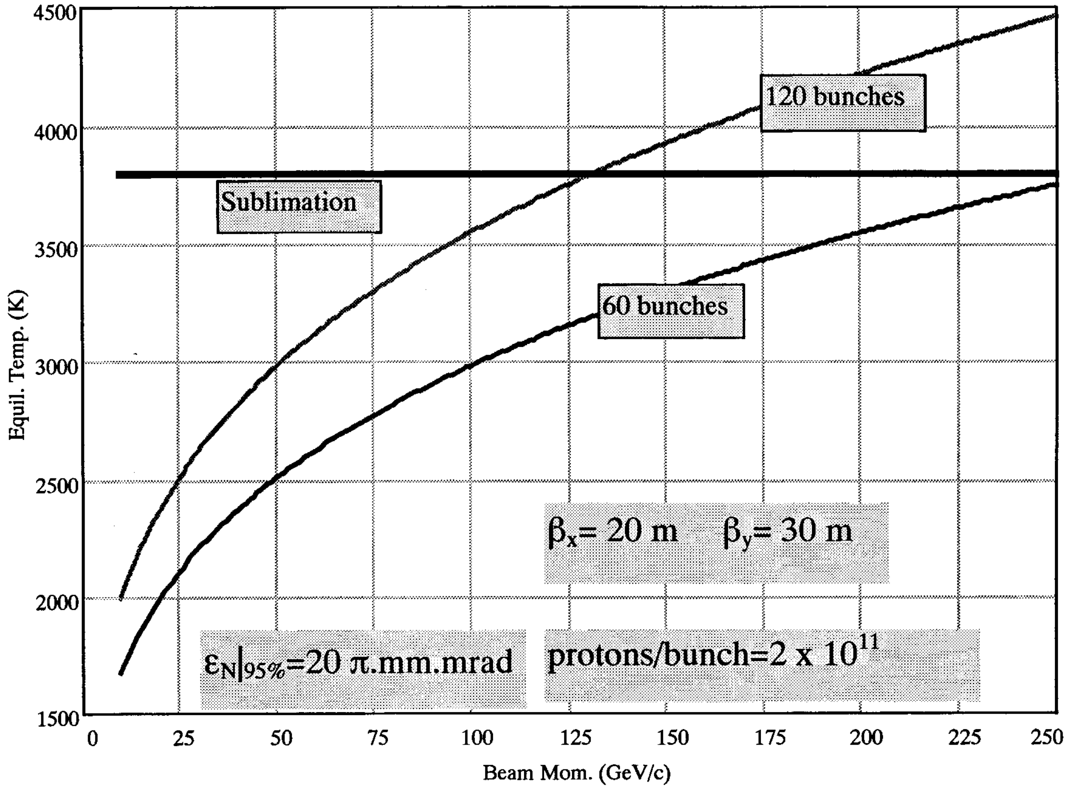

FIGURE 9. Heating of a 5-micron target in the RHIC polarimeter.

The 5-micron-thick target reaches the sublimation temperature at 125 GeV. This necessitates flipping the target in and out of the beam to allow cooling. A lighter filament, 20 μgm/cm^2, has been developed at the Indiana University Cyclotron Facility and is being regularly used as a target. Calculations indicate that it can survive beam heating at all energies (Figure 10). Calculations of the expected pion production rates for these two fiber configurations are shown in Table 2. The rates are quite reasonable even in the lighter target. One also needs to calculate the survival time for such a thin ribbon due to knock-out of its atoms. This appears to be a few hours of continuous beam bombardment. Thus the target design will allow for multiple ribbon configuration. The emittance growth in the worst case with a 5-micron target at 25 GeV energy is approximately 1 π·mm·mrad, which is acceptable.

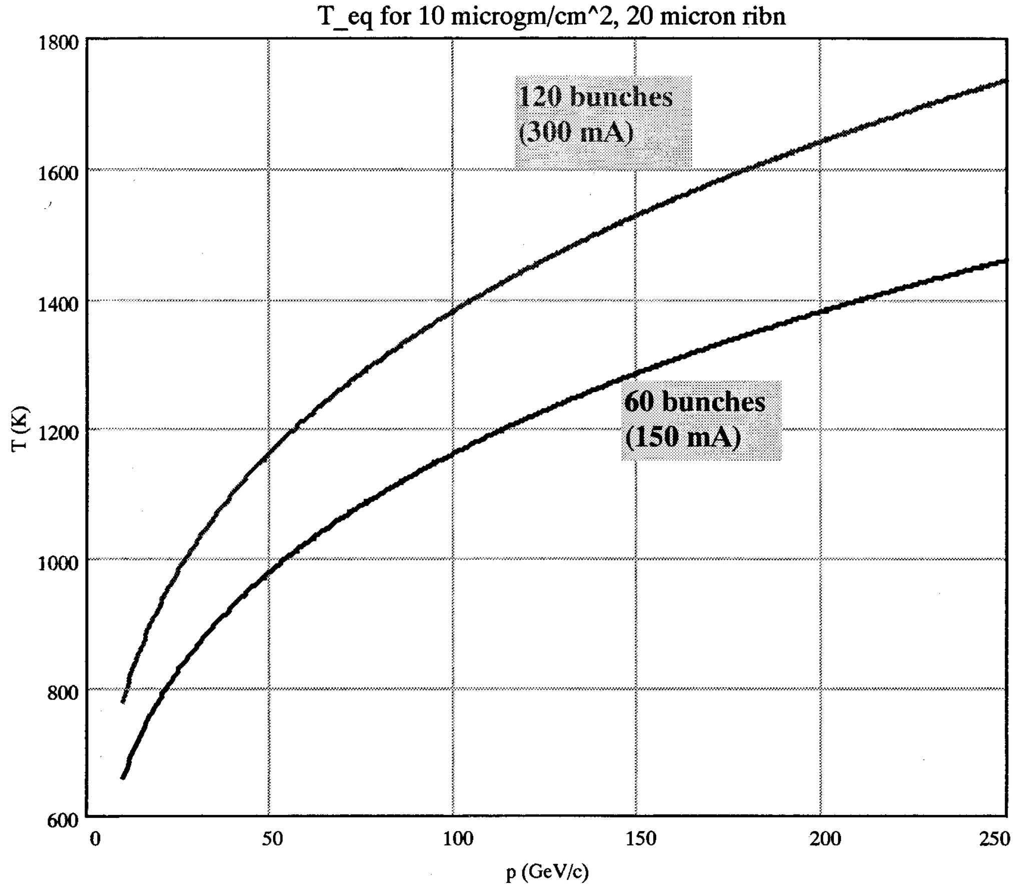

FIGURE 10. The expected heating of the ribbon target.

TABLE 2. Comparison of Expected Rates in theKinematic Range: x_F=0.5, p_T=0.8 GeV/c, δx_F = +/–0.05

Target	P_{beam}(GeV/c)	Luminosity (cm^{-2}s^{-1})	V (m/s)	Nπ/bunch	τ_{meas} (sec)	T_{max} (K)
5 μm fiber	250	3.9×10^{36}	4.5	4×10^{-2}	60	1700
	25	1.2×10^{36}	1.4	2×10^{-3}	130	1700
10 μg/cm^2, 20 μm wide ribbon	250	1.8×10^{35}	0	2×10^{-3}	0.8	1740
	25	5.6×10^{34}	0	6×10^{-5}	1.8	1000

From these simulations, it appears that the ribbon would reduce the rates per bunch crossing to quite comfortable levels. If technically feasible, a 10 μgm/cm^2, 20 μm-wide ribbon target would allow π^+ measurement with the present collimator arrangement.

6. The use of the carbon target presents another dilemma. Does the production from a nuclear target dilute the observed asymmetry from hydrogen? Is the asymmetry large enough at lower energies? The available negative pion data at lower energy is not similar to that at higher energy. The above questions led us to carry out a special measurement of the pion asymmetry, using the AGS polarized proton beam on a carbon target at 22 GeV. The preliminary results, shown in Figure 11, are quite promising. The numbers should be scaled (divided) by the average beam polarization, measured to be approximately 30% over the run. Thus it appears that using negative pion production is a strong possibility. This simplifies the polarimeter as no particle identification (Cerenkov counter) is needed with negative pions. The expected background is negligible.

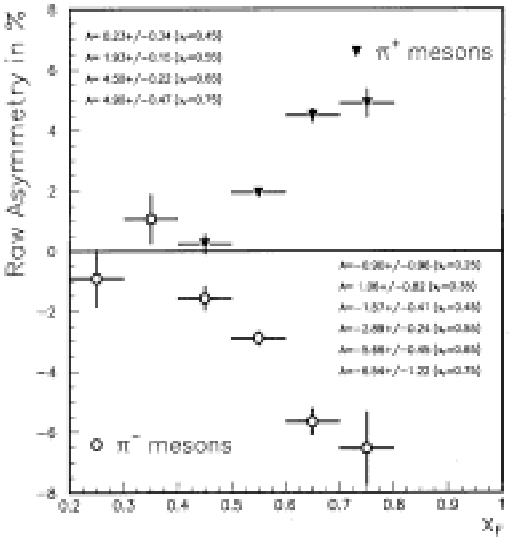

FIGURE 11. Preliminary results from AGS experiment E925 on asymmetries in charged pion production from a 22 GeV polarized proton beam on a carbon target.

7. This being the case, we turn our attention to computer simulations to determine the expected counting rate of charged particles from all sources (real pion scatters, scattering from the vacuum pipe, scattering from the magnet pole faces, neutral particle conversion, etc.) in the detectors. Ideally, and to avoid confusion, one would like no more than one particle in the detector per bunch crossing. This also determines the granularity of the detectors and the type that can be used.
8. Finally, the data acquisition and trigger systems have to be chosen to make sure a) that the correct scattering process is accepted, b) there is minimum dead time resulting after a trigger is accepted, and c) the data is processed and accumulated in a pipeline within the time spacing between bunches.

REALITY CHECK

The estimated cost of the above design for two polarimeters was approximately $1.5M. The current fiscal status of the project mandated a rethinking and simplifying of this concept. We are in the process of designing a single arm inclusive pion polarimeter for one ring using five existing conventional dipoles and scintillation detector hodoscopes from the E925 experiment at the AGS. This will serve during the beam commissioning phase, which we hope to carry out during the first year of RHIC running in FY 2000. The polarimeter described above is capable of measuring the absolute beam polarization to 10%. This is acceptable for Day-1 physics since luminosity will take some time to reach the design value. Currently we are also testing other polarimeter concepts such as p-carbon scattering in the CNI region. Should this prove viable, the detector is quite cheap can be easily configured to look at the same target of the pion polarimeter.

Beyond Day-1 and in order to reach the desired absolute polarization measurement of 5%, we need to calibrate these polarimeters using a polarized hydrogen jet target. The polarization of these jets can indeed be measured to the 5% accuracy.

ACKNOWLEDGMENTS

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