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New DAQ System for the 200 MeV Polarimeter at BNL Linac

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A new data acquisition (DAQ) system for the 200 MeV proton-carbon polarimeter at the Brookhaven National Laboratory Linac was commissioned during the RHIC polarized proton Run 2024. The polarimeter measures the asymmetry of a vertically polarized 200 MeV proton beam scattering off a thin carbon target at scattering angles of 12° and 16.2°. For elastic scattering at 16.2°, the analyzing power approaches 100%, enabling precise absolute calibration of the beam polarization. To optimize the isolation of elastic events, a variable-thickness copper absorber is employed. The new DAQ system utilizes 14-bit, 200 MHz waveform digitizers (WFDs) to record full $\sim 300\,\mu$s signal waveforms from scintillator detectors during beam bunches. Comprehensive data analysis is performed between beam bunches, which typically repeat every 4.2 s, with processing completed in less than 50 ms. This dead-time-free operation ensures accurate control of systematic errors ($\lesssim 0.1\%$) in the measured elastic asymmetry for 16.2° scattering, resulting in a determination of the beam polarization with systematic uncertainties below 0.5%. For a combined analysis of elastic and inelastic events at 12° and 16.2°, the statistical accuracy of the measured beam polarization is approximately 0.5% for a one-hour measurement.

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1. Introduction

In the Relativistic Heavy Ion Collider (RHIC) Spin Program at Brookhaven National Laboratory (BNL), the polarized proton beam is produced using an optically pumped polarized H^- ion source (OPPIS) [1]. The beam is accelerated in a linear accelerator (Linac) to 200 MeV for strip-injection into the Booster, followed by further acceleration to 24.3 GeV in the AGS and finally to the RHIC injection energy. RHIC experiments typically utilize two polarized proton beam energies: 100 and 255 GeV.

Monitoring beam polarization during acceleration is critical for optimizing accelerator performance and minimizing depolarization. To achieve this, several polarimeters have been constructed to measure the polarization at various stages along the beam path. The 200 MeV polarimeter measures the beam polarization immediately after the Linac, prior to injection into the Booster. For this measurement, every second bunch is diverted to the carbon target, and the left/right asymmetry of scattered protons is determined using scintillator counters, as shown in Fig. 1.

The typical beam parameters during RHIC Run 24 are as follows: a beam energy of 200 MeV, a beam pulse (bunch) duration of 300 μs, a beam current of 350 μA ($\sim 6\times10^{11}$ protons per pulse), a bunch microstructure of 200 MHz, and a pulse repetition rate of 4.2 s. The proton spin orientation alternates with each beam pulse.

The original 200 MeV polarimeter design relied on inclusive pC scattering at a 12° angle. This polarimeter was calibrated to an absolute accuracy of ±5% in a dedicated experiment that compared its results with those of proton-deuteron elastic scattering [2].

To improve the accuracy of polarization measurements, a 16.2° elastic polarimeter was later developed [3]. This setup employs copper absorbers to isolate elastically scattered protons. The analyzing power of this polarimeter approaches unity, enabling absolute calibration of the 12° measurements.

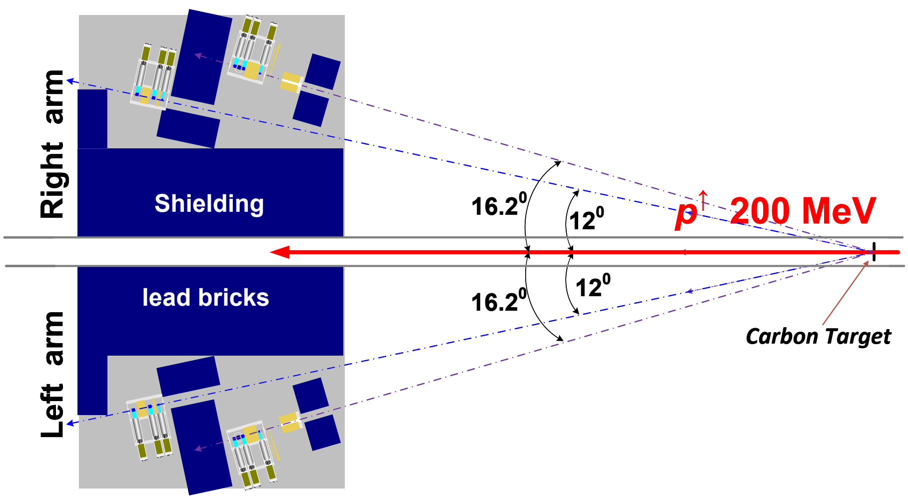

Figure 1: Layout of the 200 MeV polarimeter. Vertically polarized beam protons scatter off a thin carbon target, and the scattered protons are detected in left/right symmetric detectors. The inclusive 12° polarimeter and the elastic absolute 16.2° polarimeter are installed and aligned on a common table.

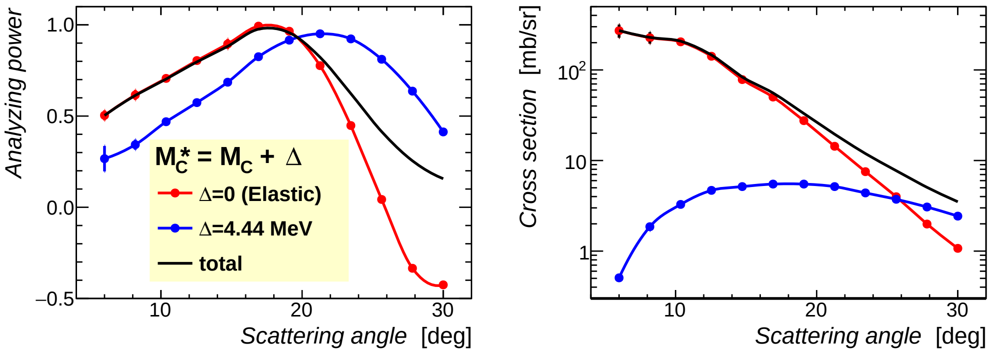

Figure 2: Analyzing power [5] (left) and cross-section [6] (right) for 200 MeV proton scattering on a carbon target. The red curves correspond to elastic scattering, while the blue curves represent inelastic scattering with $\Delta = 4.4$ MeV.

The original data acquisition (DAQ) system for absolute polarization measurements [4] relied on counting scattered proton signals using scalers. Recently, the DAQ system was upgraded to incorporate a waveform digitizer (WFD) readout, enabling precise elastic event identification and a more detailed systematic error analysis for absolute polarization measurements.

The WFD-based DAQ system was successfully commissioned during RHIC Run 24. This paper examines the systematic errors associated with beam polarization measurements using the upgraded DAQ system. Preliminary results indicate that the systematic errors are expected to remain below $\delta P/P \lesssim 0.5\%$.

2. Analyzing Power of 200 MeV Proton-Carbon Scattering

For scattering processes with the spin structure $\frac{1}{2} + 0 \rightarrow \frac{1}{2} + 0$, it has been demonstrated [7] that the analyzing power can reach exactly unity for specific combinations of beam energy T and scattering angle θ. One such case, $p + {}^{12}\text{C}$ scattering at $T_0 = 189 \pm 2$ MeV and $\theta_0^{\text{lab}} = 17.3° \pm 0.3°$, has been extensively studied at IUCF [5]. Near this maximum, the analyzing power can be approximated as [8]:

$$A_N(T, \theta) = 1 - \alpha\,(T - T_0)^2 - \beta\,(T - T_0)\,(\theta - \theta_0) - \gamma\,(\theta - \theta_0)^2\,. \tag{1}$$

Using the values of α, β, and γ from Ref. [8], the analyzing power for a 200 MeV beam reaches its maximum value at a scattering angle of $\theta = 16.2°$:

$$A_N\,(200\text{ MeV}, 16.2°) = (99.35 \pm 0.15)\,\%. \tag{2}$$

It is notable that at this maximum, A_N exhibits weak sensitivity to detector misalignment or variations in θ, minimizing systematic uncertainties arising from angular positioning.

In this context, background events, particularly inelastic scattering ($\Delta > 0$),

$$p + C \rightarrow p + C^*, \qquad \Delta = M_{C^*} - M_C, \tag{3}$$

become the primary limiting factor for such an absolute polarimeter. A comparison of analyzing powers and cross-sections for elastic and inelastic scattering with $\Delta = 4.44$ MeV is shown in Fig. 2.

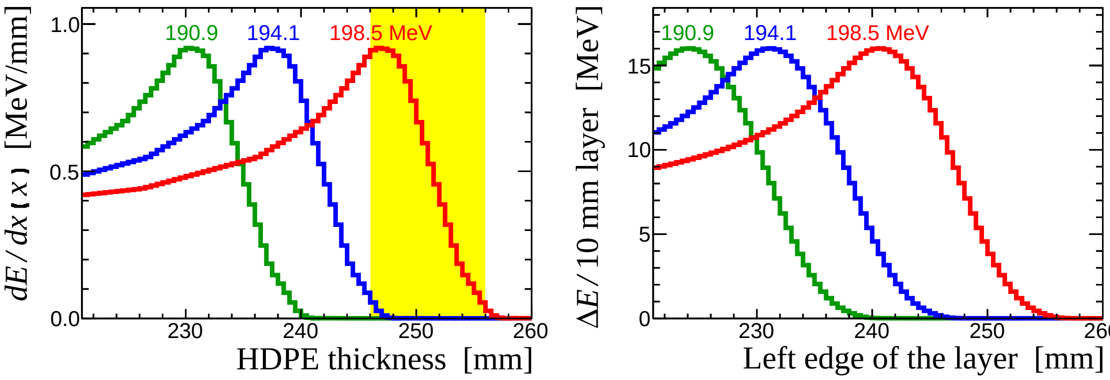

Figure 3: Bragg peaks in high-density polyethylene (HDPE) for proton energies of 198.5, 194.1, and 190.9 MeV, corresponding to elastic and inelastic ($\Delta = 4.44$ MeV, $\Delta = 7.65$ MeV) scattering at 16.2° of a 200 MeV proton beam on a carbon target. The curves are derived from NSRL measurements with a 205 MeV proton beam [9]. Peak positions are adjusted according to the stopping range for the specified energies [10]. Left: energy loss rate as a function of proton path in HDPE. The shaded area indicates a 10 mm layer that can be used to isolate elastic protons. Right: deposited energies in a 10 mm layer as a function of the layer position.

For scattering on carbon with excitation energies of 0 (elastic), 4.44, or 7.65 MeV, the corresponding scattered proton energies at 16.2° are 198.5, 194.1, or 190.9 MeV, respectively. Although the energy differences between elastic and inelastic protons are small, they allow reliable isolation of elastic events when a suitable absorber is employed, as illustrated in Fig. 3.

3. The 200 MeV Polarimeter

The 200 MeV polarimeter (Fig. 1) consists of a 12° relative inclusive polarimeter and a 16.2° absolute elastic polarimeter. In the measurements discussed, the polarized beam was scattered off a carbon target with a width of 2 mm and a thickness of 0.1 mm. The transverse beam size at the target location was 2.3 mm (rms).

3.1 The Inclusive 12° Polarimeter

In its original configuration, the 12° polarimeter utilized the known analyzing power of 62% for inclusive scattering of vertically polarized protons on a carbon target. No absorbers were employed to suppress inelastic background events. Scattered protons were identified in each arm by signal coincidences in a telescope consisting of two scintillator counters. During Run 24, a third scintillator counter was added to each arm, with a 20 mm copper absorber placed in front of it. While the previous setup remained operational for standard measurements, the third scintillator (positioned after the absorber) facilitated experimental evaluation of the potential benefits of background suppression for the 12° inclusive polarimeter.

The primary purpose of this polarimeter is to provide high-statistics polarization measurements, enhancing the statistical precision of the beam polarization determination. The polarization values

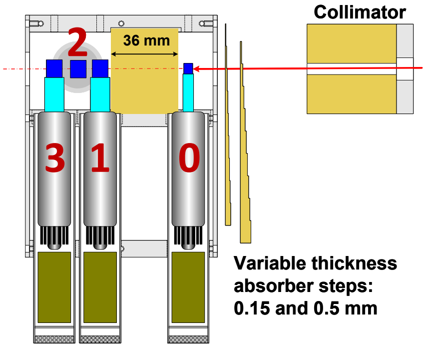

Figure 4: The 16° polarimeter (one arm).

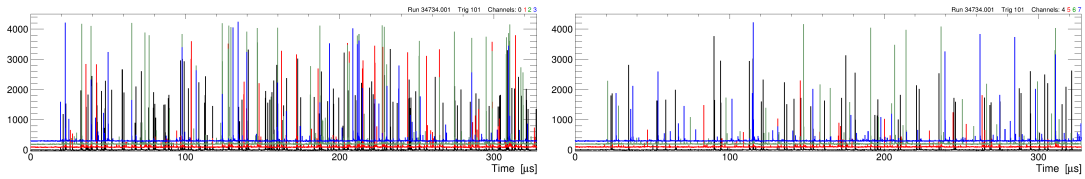

Figure 5: Typical bunch waveforms in the left and right arms of the 16.2° polarimeter. The signals from the scintillators in each arm are distinguished by color, with baseline shifts of 100 units for clarity.

measured with the 12° polarimeter are calibrated using concurrent results from the 16.2° polarimeter for improved accuracy.

3.2 The Absolute Elastic 16.2° Polarimeter

The 16.2° polarimeter employs four scintillator counter telescopes in each arm, as illustrated in Fig. 4. The dimensions of the scintillator counters are $6\times6\times4\,\text{mm}^3$ for scintillator 0 and $10\times10\times9.5\,\text{mm}^3$ for scintillators 1–3. Signal readout is performed using Hamamatsu H6524 photomultiplier tubes (PMTs).

A fixed 36 mm copper absorber is installed between scintillators 0 and 1, while two variable-thickness absorbers, adjustable in steps of 0.15 and 0.5 mm, are positioned in front of scintillator 0 for fine-tuning.

To isolate elastic scattering events, coincidences across all four scintillators are required. To improve statistics, events that do not meet the elastic criteria were processed with a simplified event selection based on cuts applied to the first two scintillators only. Polarization measurements obtained from these events are referred to as those of the *inelastic 16.2° polarimeter*. Naturally, results from the inelastic 16.2° polarimeter must be calibrated using measurements from the elastic configuration.

3.3 The DAQ System

During RHIC Run 24, a new waveform digitizer (WFD)-based data acquisition (DAQ) system was commissioned. Signals from all PMTs were independently counted using both the scalers and

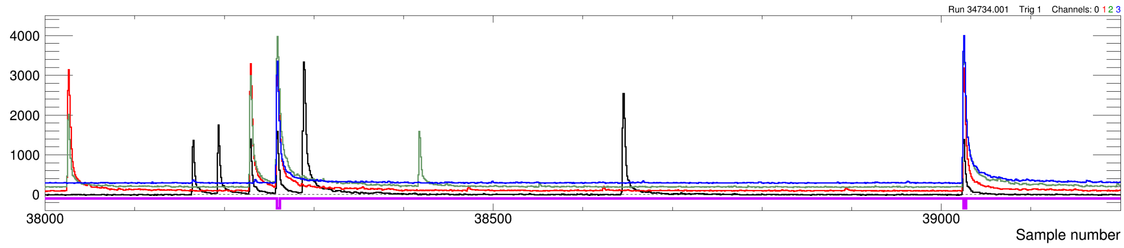

Figure 6: Illustration of signal coincidences in the scintillator counters of one arm. Coincidences across all four scintillators are shown in the violet histogram.

the WFD (after splitting), allowing the new DAQ system to be commissioned alongside the regular operation of the 200 MeV polarimeter.

The new DAQ system utilizes a VME-based 250 MHz, 14-bit WFD (SIS 3316) for data readout. The WFD is clocked by the 200 MHz Linac frequency, ensuring synchronization of the elastic signal phases with the WFD sampling. The full waveform of each scintillator, comprising 35,534 samples over 327 μs, is recorded for all 14 scintillators in every bunch.

An example of the recorded bunch waveforms from the 16.2° channels is shown in Fig. 5. A more detailed view, illustrating elastic signal coincidences across all four scintillators, is presented in Fig. 6.

Online data monitoring is performed using a single-board computer in the VME crate. Comprehensive processing of the data from a single bunch takes approximately 50 ms, enabling real-time data analysis.

4. Determination of the Spin Asymmetry

For a vertically polarized proton beam, the spin asymmetry is calculated as [11]

$$a = A_N P_{\text{beam}} = \frac{\sqrt{N_L^+ N_R^-} - \sqrt{N_L^- N_R^+}}{\sqrt{N_L^+ N_R^-} + \sqrt{N_L^- N_R^+}}, \tag{4}$$

where $N^{\pm}_{L,R}$ denotes the number of events detected in the left/right (LR) symmetric detectors, depending on the beam polarization sign (±). Since the analyzing power for elastic pC scattering of 200 MeV protons at a 16.2° angle is well established [see Eq. (2)], the beam polarization can be directly derived from the measured asymmetry using the elastic 16.2° polarimeter.

However, background events, particularly those from inelastic scattering, can significantly distort the analyzing power and compromise the polarization measurement. Therefore, it is essential to rigorously exclude background events from the analysis.

A typical signal amplitude distribution in the 16.2° detectors is shown in Fig. 7. Vertical dashed lines represent the event selection cuts. Each histogram includes only events that meet the selection criteria in all other scintillators. For scintillators 0–2, which are traversed by the selected elastic protons, the amplitude distributions exhibit Gaussian-like shapes with negligible background. As shown below, the background contribution to the scintillator 3 histogram is also

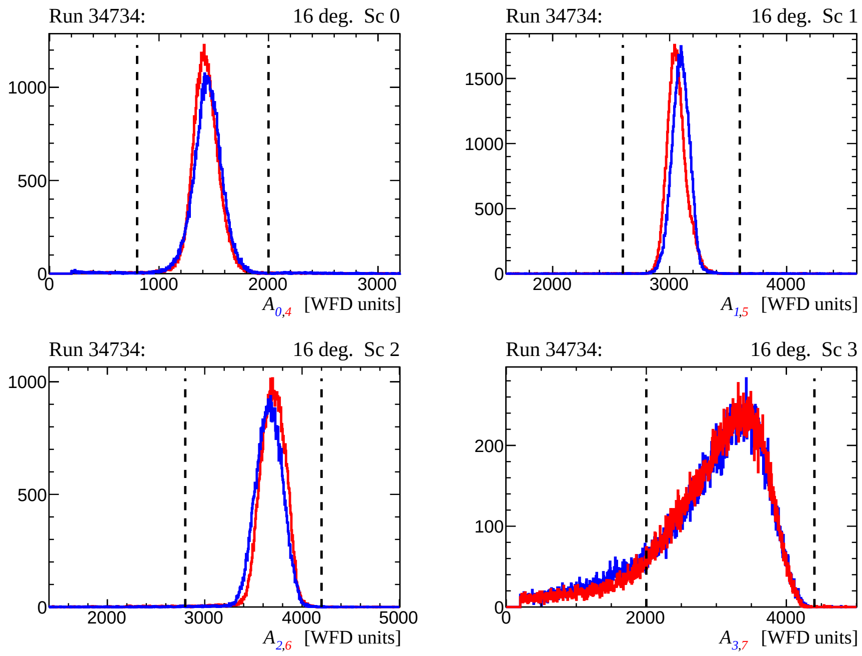

Figure 7: Signal amplitude distributions in the 16.2° scintillators. Red and blue colors represent the left and right arms, respectively. Vertical dashed lines indicate the event selection cuts.

minimal. Nevertheless, a relatively high lower limit of 2000 was applied to the selected events to ensure robust background suppression.

By varying the event selection cuts within reasonable bounds, it was demonstrated that any potential bias in the measured asymmetry due to background does not exceed 0.1%. For instance, Fig. 8 illustrates that the asymmetry shows no dependence on the signal amplitude in scintillator 3. Furthermore, the average asymmetry values for selected and excluded events are consistent within statistical uncertainties.

4.1 Inelastic Background

Increasing the thickness of the variable copper absorber by 1.6 mm effectively reduces the energy of the elastically scattered protons from 198.5 MeV to 194.1 MeV, corresponding to an energy loss of $\Delta = 4.44$ MeV. In a special measurement with the increased absorber thickness, we found that the efficiency for detecting an inelastic proton as an elastic one is about 0.7% of the elastic-proton detection efficiency, as shown in Fig. 9.

Since the inelastic cross section for $\Delta = 4.44$ MeV at a 16.2° scattering angle is an order of magnitude smaller than the elastic cross section, and the inelastic analyzing power is approximately 80%, the potential inelastic correction to the measured asymmetry is estimated to be less than 0.02%. This contribution is therefore negligible.

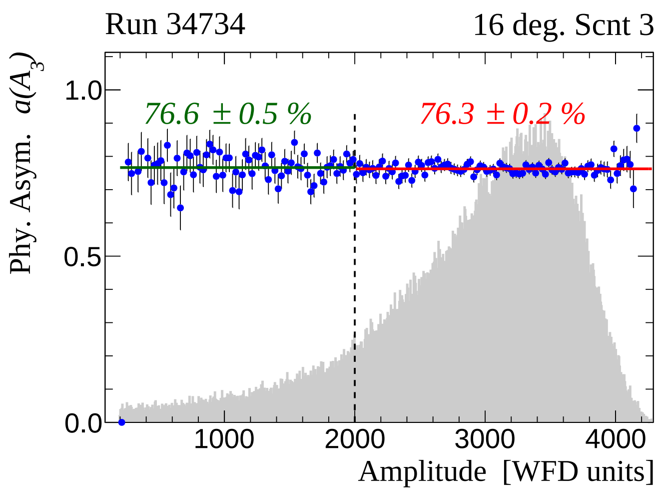

Figure 8: Spin asymmetry as a function of the signal amplitude in the 16.2° scintillator 3. The average values for selected and excluded events are shown.

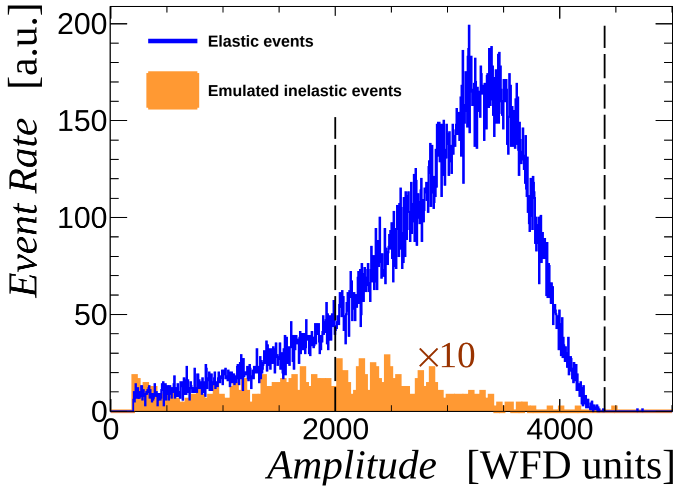

Figure 9: Amplitude distribution in Scintillator 3 during regular measurements (blue) and measurements with an additional 1.6 mm copper absorber (orange, scaled by a factor of 10). The event rate in the 12° polarimeter was used for relative normalization of the distributions.

4.2 Rate Correction

Although the new DAQ system provides dead-time-free measurements, the results can still be affected by pileup effects. To assess the impact of pileup, n_b consecutive waveforms with the same spin were superimposed (see Fig. 10), and the resulting composite waveform was processed in the usual manner.

By processing the data file with different numbers of piled-up waveforms n_b, the dependence of the measured polarization $P(n_b)$ on n_b can be calculated, as shown in Fig. 11. Since the same dataset is used to calculate all values of $P(n_b)$, the statistical and systematic errors are nearly

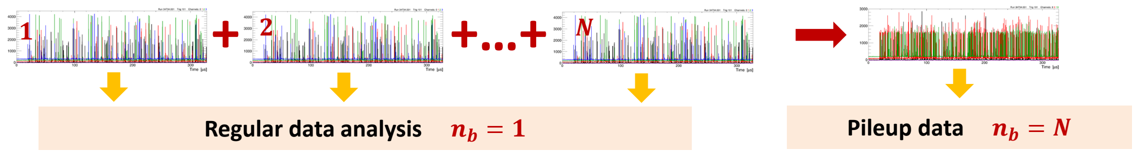

Figure 10: Illustration of bunch pileup used for studying the rate effect.

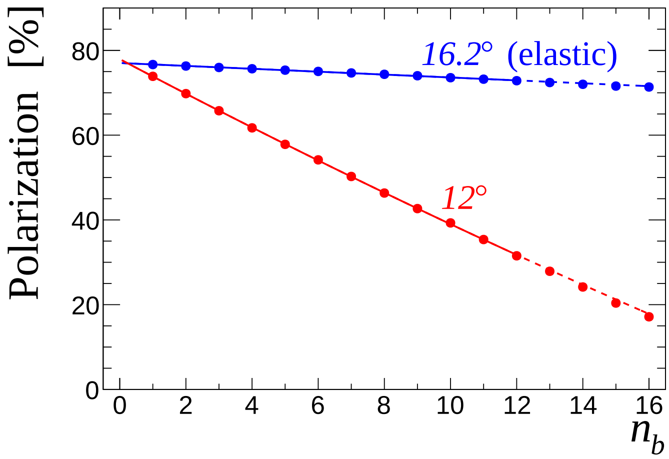

Figure 11: Polarization dependence on the number of piled-up bunches for 16.2° (blue) and 12° (red) measurements. The analyzing powers from Table 1 were used in the calculations.

identical for any n_b, resulting in a very smooth $P(n_b)$ dependence. To evaluate the rate-corrected polarization, one extrapolates $P(n_b)$ to $n_b = 0$.

For the 16.2° measurements, $P(n_b)$ exhibits an excellent linear dependence on n_b (up to $n_b = 12$), enabling a straightforward calculation:

$$P(0) = 2P(1) - P(2), \tag{5}$$

which is routinely applied in online data processing with the new DAQ system.

For the 16.2° measurements, the rate correction is approximately $\Delta P_{\text{rate}} = P(0) - P(1) \approx +0.3\%$ and can be determined with an accuracy better than 0.1%.

4.3 Combined Data Analysis

As explained above, three statistically independent datasets (elastic 16.2°, inelastic 16.2°, and 12°) can be used to determine the beam polarization. For the elastic 16.2° dataset, the analyzing power $A_N = 0.993$ (2) was applied. The analyzing powers for the inelastic datasets were adjusted to match the beam polarization derived from the elastic data.

A comparison of the polarization measurements from all three datasets is provided in Table 1. The inelastic analyzing powers used in this analysis were established approximately one month before the measurements in Table 1 had been performed.

Polarimeter	A_{N}	$n_b = 1$	$n_b = 2$	$n_b \to 0$
16.2° (elastic)	**0.993**	76.66 ± 0.18	76.31 ± 0.19	**77.00 ± 0.18**
16.2° (inelastic)	0.979	76.85 ± 0.13	76.54 ± 0.13	**77.15 ± 0.13**
12°	0.786	73.88 ± 0.12	69.80 ± 0.13	**77.04 ± 0.11**
			Total:	**77.07 ± 0.08**

Table 1: Comparison of the measured polarization (over 18 hours) in elastic and inelastic polarimeters. Results are presented for the standard analysis ($n_b = 1$), double-bunch pileup ($n_b = 2$), and rate-corrected values (5).

After applying rate corrections, the measured polarization values from all three datasets are in excellent agreement. For the elastic dataset, the statistical accuracy is approximately 1% per hour of measurement. By combining all three datasets, the statistical error improves by more than a factor of two.

5. Summary

During RHIC Run 2024, the new WFD-based DAQ system for the 200 MeV proton-carbon polarimeter at the Linac was successfully commissioned. It was demonstrated that the elastic asymmetry can be measured with systematic uncertainties of $\lesssim 0.1\%$. This implies that the precision of the polarization measurement is primarily limited by the uncertainty in the analyzing power, potentially achieving an accuracy as low as 0.2%.

However, it should be noted that the effective analyzing power in these measurements may be biased due to factors such as detector misalignments, deviations of the beam energy from the nominal 200 MeV, and potential contamination of the ^{12}C target material by other isotopes, particularly ^{13}C. While a detailed evaluation of these effects is ongoing, preliminary estimates suggest that the systematic uncertainty in the measured polarization could be as low as:

$$\frac{\sigma^{\mathrm{syst}}P}{P} \lesssim 0.5\%. \tag{6}$$

Since the beam polarization is measured using beam bunches different from those injected into the Booster, a detailed analysis of the bunch-to-bunch stability of the beam polarization should be performed. In particular, long term stability between elastic and inelastic measurements of the polarization can be checked using already acquired in Run 24 data. Additionally, the pre-injection timing interval used to calculate the average polarization value should be optimized.

To ensure the required stability and reliability of these measurements, further improvements in the detector configuration and data processing algorithms will be necessary.

Acknowledgments

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