PROCEEDINGS OF SCIENCE

The Polarized Hydrogen Gas Jet Target. From RHIC to EIC.

A.A. Poblaguev*

Brookhaven National Laboratory,
Upton, New York 11973, USA

E-mail: poblaguev@bnl.gov

The Polarized Hydrogen Gas Jet Target Polarimeter (HJET) at the Relativistic Heavy-Ion Collider (RHIC) is employed for the precise measurement of absolute transverse (vertical) polarization of proton beams, achieving low systematic uncertainties of approximately $\sigma_P^{\text{syst}}/P \le 0.5\%$. Extensive studies have evaluated HJET performance, including measurements of the *pp* and *pA* analyzing powers over a broad range of proton and ion beam energies (4–250 GeV/nucleon). These findings support the proposition of employing HJET for proton and ^{3}He beams polarimetry at the future Electron-Ion Collider (EIC) with a required accuracy of 1%. In this review, we discuss the HJET data analysis methods used at RHIC, emphasizing their relevance for the EIC. Additionally, suggestions are presented for enhancing HJET performance to reliably meet the specific polarimetry requirements of the EIC.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

*Speaker

https://pos.sissa.it/

PoS(SPIN2023)091

1. Introduction

Scientific requirements and detector concepts for the Electron-Ion Collider (EIC) [1] encompass the monitoring of beam polarizations with minimal systematic uncertainties, aiming for an accuracy of

$$\sigma_P^{\text{syst}}/P \lesssim 1\%. \tag{1}$$

Since the hadron beam energies and intensities at the Electron-Ion Collider (EIC) are expected to be nearly the same as those at the Relativistic Heavy Ion Collider (RHIC), the experience gained from proton beam polarization measurements at RHIC provides guidance for the development of hadron polarimetry at the EIC. Nevertheless, new studies are necessary, considering that (i) the EIC bunch spacing will be much shorter than at RHIC (107 ns → 10 ns), and polarized $^3\text{He}^{\uparrow}$ beams will be utilized at the EIC.

During RHIC store, the beam polarization profile, decay, and the spin tilt are monitored (a short measurement every several hours) by the pCarbon polarimeters [2]. Meanwhile, the absolute calibration of the beam polarization is continuously measured using the hydrogen jet polarimeter (HJET) [3]. The statistical accuracy of such calibration is approximately $\sigma_P^{\text{stat}} \approx 2\%$ per 8-hour RHIC store [4]. Systematic errors in these measurements were estimated as

$$\sigma_P^{\text{syst}}/P\Big|_{\text{RHIC}} \lesssim 0.5\%, \tag{2}$$

which satisfies the requirement (1).

The primary goal of this paper is to discuss improvements to the HJET that can enhance the reliability of achieving the required precision (1) for proton and helion beams polarization at the EIC.

2. The Polarized Atomic Hydrogen Gas Jet Target (HJET)

HJET has successfully measured polarized proton beams at RHIC for nearly two decades. The measurement scheme is illustrated in Fig. 1. The vertically polarized proton beam, comprising alternating spin-up/down bunches, intersects the vertically polarized hydrogen gas jet, and the recoil protons are detected in the silicon detectors. The jet spin is reversed every 5 minutes. Measurements of the polarizations of both the so-called *blue* and *yellow* RHIC beams are conducted simultaneously and continuously. A detailed description of the data analysis is given in Ref. [4].

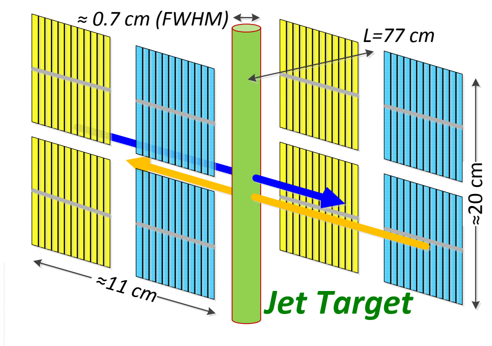

Figure 1: Schematic view of the HJET polarimeter, consisting of eight detectors, each with 12 silicon strips. The waveform fit, performed for every detected event, accurately determines the recoil proton kinetic energy T_R and time of flight (TOF). Vertically oriented Si strips tag the recoil angle θ_R.

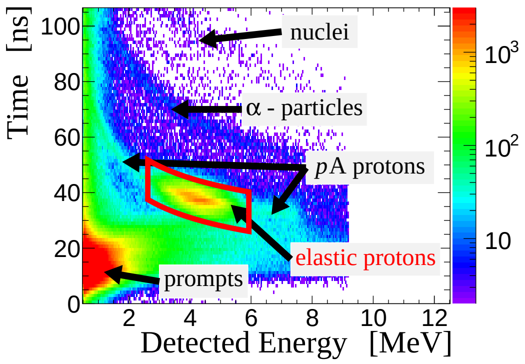

Figure 2: A typical time-amplitude distribution in a Si strip, with the number of events per bin limited to 3000 to clearly isolate elastic protons in the plot. The prompt event rate is nearly two orders of magnitude higher compared to that of elastic protons.

A typical result of measurements in a Si strip is demonstrated in Fig. 2. To verify that the detected particle is a proton, the measured time of flight (TOF) is compared with that derived from the measured kinetic energy T_R of the recoil proton. To check that it was elastic scattering, $\sqrt{T_R}$ is compared with the value of $\sqrt{T_{\text{strip}}}$, corresponding to the z-coordinate of the silicon strip, in accordance with the equation

$$\tan\theta_R = \frac{z_R - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}\frac{E_{\text{beam}}+m_p}{E_{\text{beam}}-m_p+T_R}}. \tag{3}$$

Here, z_R is the recoil proton coordinate in the detector, z_{jet} is the coordinate of the scattering point, E_{beam} is the beam energy, m_p is the proton mass, and L is the distance to the detector. For elastic scattering, possible fluctuations of $\sqrt{T_R} - \sqrt{T_{\text{strip}}}$ in the measurements are defined by the jet width, and thus, the elastic event selection cut should be the same for all Si strips at HJET.

To determine the beam polarization P_{beam}, the beam asymmetry $a_{\text{beam}} = A_\text{N}(t)P_{\text{beam}}$ and the target (jet) asymmetry $a_{\text{jet}} = A_\text{N}(t)P_{\text{jet}}$ are calculated based on the numbers of elastic events (dependent on the beam and jet spins) counted in the left and right side detectors [4]. Since the beam and target particles are identical, the analyzing power $A_\text{N}(t) \sim 4\%$ is the same for the beam and jet spins. Generally, $A_\text{N}(t)$ is a function of the momentum transfer squared $t = -2m_pT_R$. Using the same events to calculate the beam and jet asymmetries allows us to utilize the measurement average values of a_{beam} and a_{jet} to determine the beam polarization:

$$P_{\text{beam}} = \frac{\langle a_{\text{beam}}\rangle}{\langle a_{\text{jet}}\rangle} P_{\text{jet}}. \tag{4}$$

Since the jet polarization is well-known, $P_{\text{jet}} \approx 0.96 \pm 0.001$ [3], the precision of the beam polarization measurement is limited mainly by the accuracy of the background subtraction and can be as low as displayed in Eq. (2).

One can observe that detailed knowledge of the elastic *pp* analyzing power is not necessary for the precision measurement of the proton beam polarization. Nevertheless, HJET measurements allow us to experimentally determine $A_\text{N}(t)$, and such an analysis is critically important for studying systematic errors in the measurements.

Omitting some small terms, the high-energy forward elastic $p^\uparrow p$ analyzing power can be expressed [5, 6] via single spin-flip $\phi_5(t)$ and non-flip $\phi_+(t)$ helicity amplitudes as

$$A_\text{N}(t) = \frac{\sqrt{-t}}{m_p} \times \frac{(\kappa_p - 2I_5)\,t_c/t - 2R_5}{(t_c/t)^2 - 2(\rho+\delta_C)\,t_c/t + 1 + \rho^2}, \tag{5}$$

where $\kappa_p = 1.793$ is the anomalous magnetic moment of the proton, ρ is real-to-imaginary ratio, $\delta_C(t)$ is the Coulomb phase, and $t_c = -8\pi\alpha/\sigma_{\text{tot}}$. Real and imaginary parts of the hadronic spin-flip amplitude parameter r_5 [6] are denoted as R_5 and I_5, respectively. At HJET, the analyzing power was measured with accuracy $\delta A_{\text{N}}(t) \sim 2\times10^{-4}$ for two beam energies, 100 and 255 GeV [7] and parameter $|r_5| \sim 0.02$ was determined with accuracy $|\delta r_5| \sim 0.004$. The HJET experemental studies of the pp and pA elastic and pp inelastic analyzing powers are reviewed in Ref. [8].

3. Data Processing

From a data analysis perspective, the achievement of low systematic errors in beam polarization measurements at HJET is primarily attributed to two methods: the reconstruction of the kinetic energy of the recoil protons that penetrate through and the approach to background subtraction. Additionally, ensuring accurate energy calibration of the detectors is critically important for measuring analyzing power.

3.1 Energy Calibration

For energy calibration, two alpha sources, ^{148}Gd (3.183 MeV) and ^{241}Am (5.486 MeV), are utilized [4], enabling the determination of the gain and the dead-layer thickness $x_{\text{DL}} \sim 0.37$ mg/cm^2 for each Si strip. The energy resolution, $\sigma_E \sim 20$ keV, is primarily predefined by electronic noise. However, significantly different energy losses in the dead-layer for alpha-particles and protons question accuracy of such a calibration.

An alternative calibration method has been developed [9, 10]. Leveraging the micron accuracy in the detectors' geometry (strip width and spacing), Eq. (3) precisely fixes, with an accuracy of $\sim\delta L/L \approx 0.3\%$, the energy difference for the elastic $dN/d\sqrt{T_R}$ distribution peaks in two Si strips. This can be effectively utilized for calibration.

The results from both calibrations were found to be in good agreement, and the estimated systematic errors in the alpha calibration can be approximated by a quadratic sum:

$$\delta^{\text{syst}} T_R = (0 \pm 15)\,\text{keV} \oplus (0 \pm 0.01)\,T_R. \tag{6}$$

3.2 Reconstruction of the Recoil Proton Kinetic Energy

For recoil proton energies below 7.8 MeV, the proton is stopped in the Si detector, and the full kinetic energy (excluding energy losses in the dead layer) is measured. However, for higher kinetic energies, the proton punches through the Si strip, and only part of the energy is observed.

In the data analysis, the signal waveform was parameterized by the following function:

$$W(t) = p + A\left(\frac{t-t_i}{n\tau_s}\right)^n \exp\left(-\frac{t-t_i}{\tau_s} + n\right), \tag{7}$$

if $t > t_i$ and $W(t) = p$ if $t < t_i$. Here, p is the pedestal, A is the signal amplitude, t_i is the signal start time, n and τ_s are signal shape parameters. The waveform has a maximum at $t_m = t_i + n\tau_s$.

It was found that the signal shape is not the same for stopped and punch-through recoil protons, as shown in Fig. 3. This allows us to reconstruct [11] the kinetic energy of the recoil proton from the measured deposited energy and to correct the measured signal time t_m. After reconstruction, a measured time-amplitude distribution (Fig. 2) is altered to that shown in Fig. 4.

PoS(SPIN2023)091

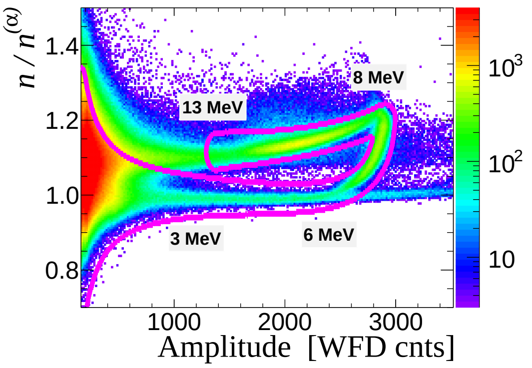

Figure 3: Event selection cut (solid magenta line) to separate punch-through and stopped protons for the $0.5 < T_R < 13$ MeV energy range. No other event selection cuts had been applied in this plot.

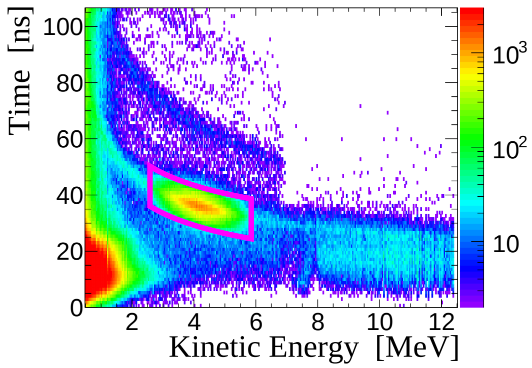

Figure 4: The same data as in Fig. 2, but after the reconstruction of the recoil proton kinetic energy and time t_m.

3.3 Background Subtraction

In the HJET measurements at RHIC, two main sources of background events, contributing approximately the same event rate, were considered:

Molecular hydrogen, including any hydrogen (protons) in the beam gas, such as atomic H, molecular H_2, H_2O vapors, etc. Given the expected uniform distribution of *molecular hydrogen* along the beam line, the recoil proton rate for this background should be consistent (for a fixed value of T_R) across all Si strips of an HJET detector.

pA Scattering. This occurs when a beam proton scatters off a nucleus in the beam gas or the HJET polarimeter materials, leading to nucleus breakup and the emission of a proton that hits the Si detector. Due to the small solid angle of the detector, such protons uniformly expose the detector strips.

As depicted in Fig. 5, the high-intensity diagonal in a z_R-T_R correlation plot is primarily populated by the studied events originating from the elastic scattering of the beam off the jet, as described by Eq. (3). Events away from the diagonal were used to evaluate the background rate as a function of $\sqrt{T_R}$. It is important to note that inelastic scattering, if present, may contribute [8] to the area above the diagonal. In such cases, only events below the diagonal should be considered for

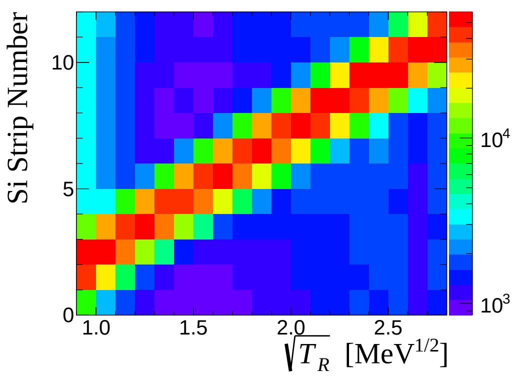

Figure 5: Recoil proton $dN/d\sqrt{T_R}$ distribution for all Si strips of a detector. For signals from the beam proton elastic scattering off the jet, the linear $z_R \propto \sqrt{T_R}$ dependence can be easily identified (3).

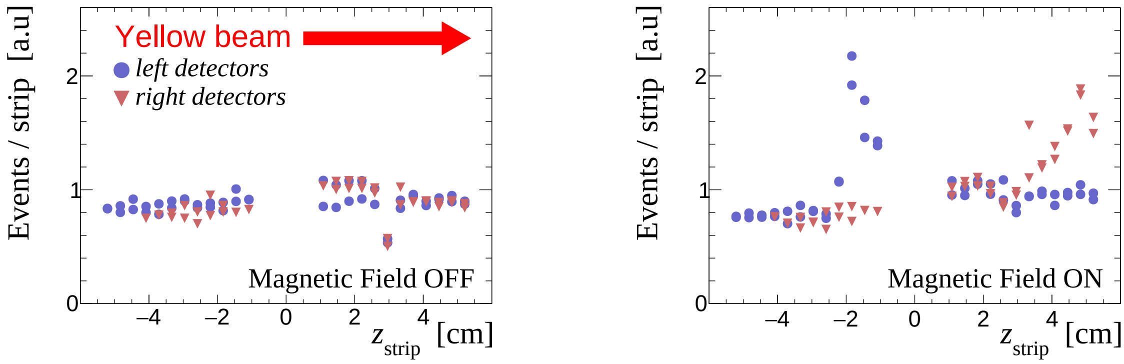

Figure 6: Recoil proton z-coordinate distribution for $T_R = 1.0 \pm 0.1$ MeV with the holding field magnet On and Off. The measurements were done with *yellow* Gold beam and H_2 injected to the HJET scattering chamber.

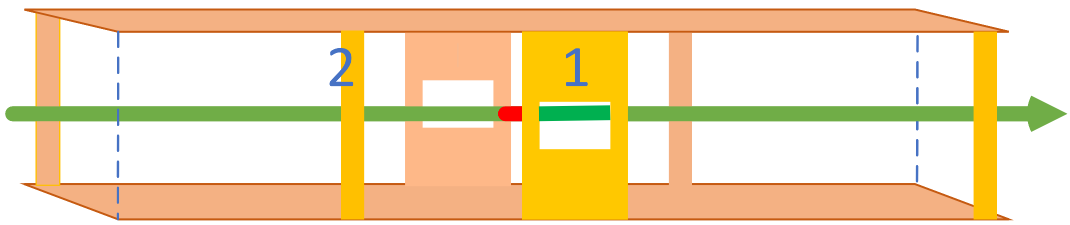

Figure 7: A sketch of the HJET RF shield. Recoil proton absorption in the side wall 1 was utilized [4] to evaluate *molecular hydrogen* background rate. In the measurements shown in Fig. 8, the effect of wall 2 was evaluated.

the background evaluation.

The subsequent subtraction of the background from the studied data was carried out independently for each combination of the beam and target (jet) spins, allowing for a proper account of potential spin effects in the procedure. Systematic uncertainties in the beam polarization measurement due to inaccuracies in the subtraction were assessed to be $\delta P/P \sim 0.2\%$.

Adjustments to the currents in the Helmholtz coils of the HJET holding field magnet were made to eliminate any additional displacement of z_R when the scattering occurs in the center of the jet, $z_{\text{jet}} = 0$. However, for the beam scattering off the uniformly distributed (along the z axis) *molecular hydrogen*, Eq. (3) is effectively invalidated, resulting in a non-flat $dN/d\sqrt{T_R}$ distribution for this background. This effect, which strongly depends on the recoil proton energy and varies between left and right side detectors, is illustrated in Fig. 6.

The non-uniformity of dN/dz_R may impact the results of background subtraction and, therefore, should be considered in the data analysis. To address this, a simulation of recoil proton tracking in the magnetic field was performed. This simulation, however, requires knowledge of the relative fraction of the *molecular hydrogen* background.

In the context of HJET data analysis, the normalization of the *molecular hydrogen* background was achieved in a straightforward and well-controlled manner by considering the partial shadowing

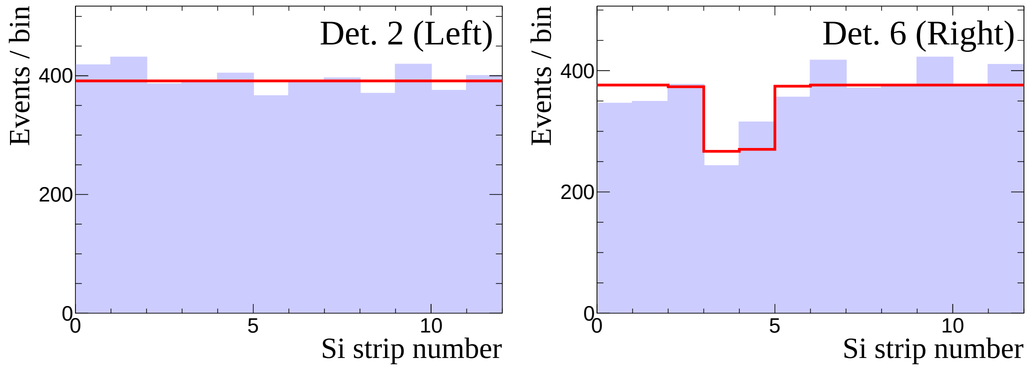

Figure 8: Experimental evaluation of the background rates [12]. The measurements have been done with a single (*blue*) 3.85 GeV/nucleon gold beam. The holding field magnet was switched off. The recoil protons $\left(1.3 < \sqrt{T_R} < 1.4\,\text{MeV}^{1/2}\right)$ were detected in the *backward* detectors. The effect of the recoil proton shadowing (by wall 2) is clearly seen in the right side detector. There was no shadowing in the left side detector.

of the recoil protons by the HJET RF-shield. The recoil proton absorption in the side walls of the RF shield (refer to Fig. 7) results in a dip in the measured event rate in the Si strips. Given the well-known dimensions of the walls and Si strips, the *molecular background* fraction in the event rate can be easily calculated. In the standard HJET data analysis [4], shadowing in wall 1 was employed, as depicted in Fig. 25 of Ref. [4]. A more visually intuitive representation of this effect, obtained in a single gold beam measurement with the holding beam magnet switched off, is provided in Fig. 8.

4. Bunch Spacing

The time range in Fig. 2 corresponds to the bunch spacing of 107 ns at RHIC. Clearly, for $T_R > 0.6\,\text{MeV}$ threshold used in the data analysis, the signals from different bunches are well separated. However, with a 10 ns bunch spacing at EIC, the time-amplitude distribution (shown in Fig. 2) will be multiplied with a time shift step of 10 ns [13]. Consequently, the stopped recoil proton signals from one bunch can easily mismatch with punch-through protons and/or prompts from other bunches.

This situation can be significantly improved by reconstructing the kinetic energy of the punch-through protons [13]. For this case, HJET performance for an 8.9 ns bunch spacing was emulated [13] using 255 GeV proton beam data obtained in RHIC Run 17. The measured time of each event was shifted $t \to t + k\tau/12$, where k is randomly chosen from $k \in (-1.5, -0.5, 0.5, 1.5)$ and $\tau = 106.6$ ns is the bunch spacing in Run 17. This transformation approximates the proposed bunch splitting into four at EIC. In addition, every event was triplicated by the time shifts $\pm\tau/3$.

The emulated data was processed using the regular HJET data analysis software. In Fig. 9, the emulated result for the beam polarization determined at EIC is compared with the measurement at RHIC. Since the same experimental data was used in both data fits, some discrepancy in the results can be attributed to the effect of the bunch spacing. For $T_R > 2\,\text{MeV}$, the 12-fold compression of the bunch spacing at EIC will not alter, within $|\delta P/P| \lesssim 0.3\%$ uncertainty, the measured beam

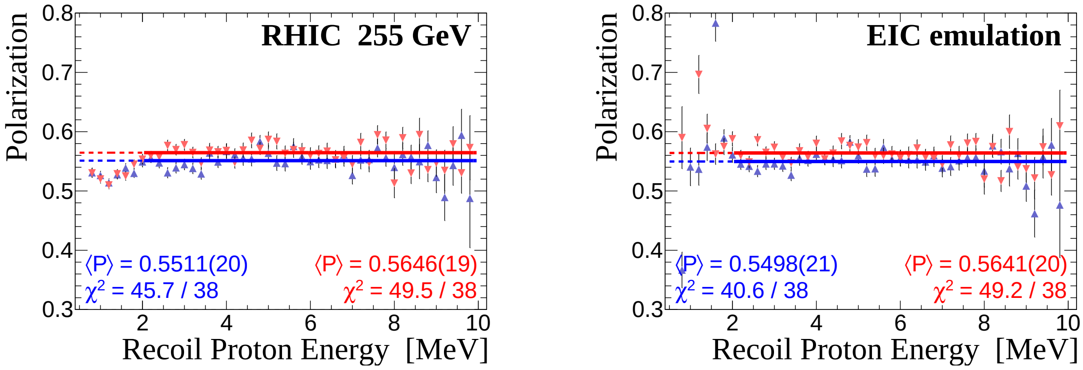

Figure 9: Comparison of the measured beam polarization in RHIC Run 17 and the emulation of the EIC bunch spacing (based on the same Run 17 data). Blue and red colors refer to *blue* and *yellow* beam measurements, respectively.

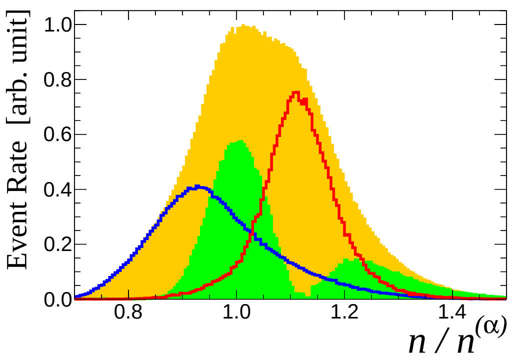

Figure 10: The orange-colored histogram represents the distribution of waveform shape parameter n for prompt signals in the first layer of the double-layer detector prototype. The red line corresponds to the component with coincident signals in the second layer, while the blue line represents signals originating from the beam halo (coincident signals in two or more Si strips of the first layer). The remaining component is depicted in green.

polarization. However, misseparation of the elastic events and prompts significantly alters the measured polarization for $T_R < 2$MeV.

Assuming that prompts are fast charged particles penetrating through the Si detectors, the possibility to veto prompt events was investigated using a double-layer detector prototype [13]. It was observed [14] that the efficiency of such a tagging of prompts is approximately 30%. The analysis of the prompt waveform shape (in the first layer) is illustrated in Fig. 10. Nearly 30% of all prompt signals exhibit a waveform shape typical for stopped recoil protons, contradicting the assumption about the nature of prompts.

5. Measurement of the ^{3}He beam polarization with HJET

Detail analysis of the HJET feasibility to measure ^{3}He (h) beam polarization at the EIC was conducted in Refs. [15–17]. Since proton $p^{\uparrow}h$ and helion $h^{\uparrow}p$ spin analyzing powers in the proton-helion scattering are different, to determine ^{3}He polarization, Eq. (4) should be replaced by

$$P^h_{\text{meas}}(T_R) = P_{\text{jet}}\frac{a_{\text{beam}}(T_R)}{a_{\text{jet}}(T_R)} \times \frac{\kappa_p[1+\omega^p_\kappa] - 2I^{ph}_5[1+\omega^p_I] - 2R^{ph}_5[1+\omega^p_R]\,T_R/T_c}{\kappa_h[1+\omega^h_\kappa] - 2I^{hp}_5[1+\omega^h_I] - 2R^{hp}_5[1+\omega^h_R]\,T_R/T_c}, \tag{8}$$

where $\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$ [18], μ_h is the magnetic moment of ^{3}He, and $T_c = 4\pi\alpha Z_h/m_p\sigma_{\text{tot}}^{ph} \approx 0.7\,\text{MeV}$. Symbol ω is used to denote possible corrections $\omega(T_R)$ due to the beam ^{3}He breakup.

Although, hadronic spin-flip amplitudes $r_5^{ph} \approx r_5^{pp}$ [17, 19] and $r_5^{hp} \approx r_5^{pp}/3$ [17, 20] are not experimentally known, they can be related, with sufficient accuracy, to the proton-proton r_5^{pp} precisely determined at HJET.

In HJET measurements, breakup corrections $\omega(T_R)$ may be as large as 4% (the estimated upper limit). Nevertheless, since each $\omega(T_R) = 0$ if $T_R \to 0$ (no breakup can occur without momentum transfer in the scattering), extrapolation of the measured $P_{\text{meas}}^h(T_R)$ to $T_R \to 0$ will provide the helion beam polarization with essentially no ^{3}He beam-specific systematic errors. Moreover, as all $\omega(T_R)$ are equal within a $\sim 10\%$ accuracy [8], breakup corrections in Eq. (8) essentially cancel out, allowing for a smooth extrapolation of $P_{\text{meas}}^h(T_R)$ (measured in the $2 < T_R < 10\,\text{MeV}$ energy range) to $T_R \to 0$.

6. Discussion

Based on the results of proton beam polarization measurements and an intensive study of the forward transverse *pp* and *pA* analyzing powers at RHIC, it is anticipated that HJET can be employed for the precise calibration (1) of the proton and ^{3}He beam polarizations at the EIC. However, considering the potentially more challenging environmental conditions at the EIC, every opportunity to enhance HJET performance should be explored.

It is worth noting that the development of the data analysis methods described in Section 3 was constrained by the specific requirements for proton beam polarization measurements at RHIC. Consequently, there is still room for improvement in these methods. In particular, the reconstruction of the recoil proton kinetic energy may benefit from the adjustment of bias voltage in the Si detectors, as discussed in Ref. [13].

At RHIC, four HJET detectors are used to measure the *blue* beam polarization, and another four detectors are for the *yellow* beam. At EIC, there will be only one hadronic beam, and consequently, only one *forward* set of detectors is needed for the polarization measurements. However, it's worth considering keeping *backward* detectors for accurate background normalization. For instance, with two *absorption walls* for the left side detectors and two for the right side (but at different z coordinates), $dN/dz(T_R)$ rates can be determined for both *molecular hydrogen* and *pA scattering* backgrounds at up to four (depending on the value of T_R) points in z, and the background rates could be reliably extrapolated to the jet location.

Additionally, it might be beneficial to add one more (third) set of Si detectors to extend the z_R-coordinate range. This may not only improve the background rate estimate but also provide better control for inelastic (pion production) and breakup (for ^{3}He beam) events.

The recoil proton tracking in the holding field magnet is currently considered a dominant source of systematic errors in HJET measurements at RHIC. Therefore, the technical possibility to operate HJET in a weak field should be thoroughly investigated.

Acknowledgments

The author acknowledges the support from the Office of Nuclear Physics in the Office of Science of the U.S. Department of Energy. This work is authored by an employee of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.

References

[1] R. Abdul Khalek et al., *Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report*, *Nucl. Phys. A* **1026** (2022) 122447 [2103.05419].

[2] H. Huang and K. Kurita, *Fiddling carbon strings with polarized proton beams*, *AIP Conf. Proc.* **868** (2006) 3.

[3] A. Zelenski, A. Bravar, D. Graham, W. Haeberli, S. Kokhanovski, Y. Makdisi et al., *Absolute polarized H-jet polarimeter development, for RHIC*, *Nucl. Instrum. Meth. A* **536** (2005) 248.

[4] A.A. Poblaguev, A. Zelenski, G. Atoian, Y. Makdisi and J. Ritter, *Systematic error analysis in the absolute hydrogen gas jet polarimeter at RHIC*, *Nucl. Instrum. Meth. A* **976** (2020) 164261 [2006.08393].

[5] B.Z. Kopeliovich and L.I. Lapidus, *On the necessity of polarization experiments in colliding pp and $\overline{p}p$ beams*, *Yad. Fiz.* **19** (1974) 218.

[6] N.H. Buttimore, B.Z. Kopeliovich, E. Leader, J. Soffer and T.L. Trueman, *The spin dependence of high-energy proton scattering*, *Phys. Rev. D* **59** (1999) 114010 [hep-ph/9901339].

[7] A.A. Poblaguev, A. Zelenski, E. Aschenauer, G. Atoian, K.O. Eyser, H. Huang et al., *Precision Small Scattering Angle Measurements of Elastic Proton-Proton Single and Double Spin Analyzing Powers at the RHIC Hydrogen Jet Polarimeter*, *Phys. Rev. Lett.* **123** (2019) 162001 [1909.11135].

[8] A. Poblaguev, *The $p^\uparrow$ and $^3He^\uparrow$ beam polarization measurements at the RHIC and future EIC using the Polarized Atomic Hydrogen Gas Jet Target*, *Universe* **10** (2024) 32 [2311.17792].

[9] A. Poblaguev, *New DAQ for the HJET polarimeter at RHIC*, in *Proceedings of XVIth International Workshop in Polarized Sources, Targets, and Polarimetry — PoS(PSTP2015)*, vol. 243, p. 032, 2016, DOI.

[10] A.A. Poblaguev, *A precise in situ calibration of the RHIC H-Jet polarimeter*, Tech. Rep. BNL-104363-2014-TECH, C-A/AP/504, Brookhaven National Laboratory (2014).

[11] A.A. Poblaguev, *Waveform dependence on signal amplitude in the RHIC H-Jet polarimeter*, Tech. Rep. BNL-104366-2014-TECH, C-A/AP/505, Brookhaven National Laboratory (2014).

[12] A.A. Poblaguev, *Experimental evaluation of the breakup rate in the pAu scattering at HJET (Run 2021)*, 2021.

[13] A.A. Poblaguev, A. Zelenski and G. Atoian, *The prospects on the absolute proton beam polarimetry at EIC*, *PoS* **PSTP2019** (2020) 007.

[14] A.A. Poblaguev, G. Atoian, N.H. Buttimore and A. Zelenski, *On the Possibility of Measuring the Polarization of a ^{3}He Beam at EIC by the HJET Polarimeter*, *JPS Conf. Proc.* **37** (2022) 021103 [2212.08628].

[15] A.A. Poblaguev, *Feasibility study for precisely measuring the EIC ^{3}He beam polarization with the Polarized Atomic Hydrogen Gas Jet Target polarimeter at RHIC*, *Phys. Rev. C* **106** (2022) 065202 [2207.09420].

[16] A.A. Poblaguev, *Breakup corrections to the ^{3}He beam polarization measurements at the future BNL Electron Ion Collider*, *Phys. Rev. C* **106** (2022) 065203 [2207.06999].

[17] A. Poblaguev, *Breakup corrections to spin asymmetries in the ^{3}He beam polarization measurements with the Polarized Atomic Hydrogen Gas Jet Target*, *Phys. Rev. C* **108** (2023) 025202 [2305.13099].

[18] N.H. Buttimore, *Forward helion scattering and neutron polarization*, *AIP Conf. Proc.* **1105** (2009) 189.

[19] B.Z. Kopeliovich and T.L. Trueman, *Polarized proton nucleus scattering*, *Phys. Rev. D* **64** (2001) 034004 [hep-ph/0012091].

[20] N.H. Buttimore, E. Leader and T.L. Trueman, *An absolute polarimeter for high-energy protons*, *Phys. Rev. D* **64** (2001) 094021 [hep-ph/0107013].