Performance of silicon detectors in polarized proton-proton elastic scattering at RHIC

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Abstract. The STAR experiment at RHIC is equipped with insertion devices (Roman Pots) that allow the detectors to be moved close to the beam, in order to measure protons at small scattering angles. This setup, together with the unique capability of RHIC to collide spin-polarized proton beams, allows STAR to study both unpolarized and spin-dependent proton-proton ($pp$) elastic scattering process. With silicon strip detectors installed in Roman Pots, $pp$ elastic scattering is accessible in the Coulomb Nuclear Interference (CNI) region, where a measurable single spin asymmetry arises. By using a dedicated run with special beam optics during the RHIC 2009 data taking period, the collaboration was able to collect more than 30 M elastic triggers with transversely polarized proton beams at $\sqrt{s} = 200$ GeV and in the momentum transfer squared ($t$) range of $0.005 \text{ GeV}^2/c^2 \leq -t \leq 0.035 \text{ GeV}^2/c^2$. In here we describe the experimental setup and performance during the last data taking period, with a specific focus on alignment and efficiency of the silicon detectors.

1. Introduction
The Relativistic Heavy Ion Collider (RHIC) has the unique capability of accelerating and colliding polarized proton beams with a high average polarization of 0.7 per beam and high luminosity reaching $L \approx 2 \times 10^{32} \text{ cm}^2 \text{ sec}^{-1}$, at a wide center of mass (cms) energy range of $\sqrt{s} \leq 500$ GeV. This enables the study of both unpolarized and polarized diffractive scattering processes in $pp$ collisions at high cms energies. Integration of forward detectors, Roman pots (RP), with the STAR detector allows the study of both elastic and inelastic $pp$ scattering processes. Figure 1 shows the diagrams of the two processes of main interest of the physics with tagged forward protons program at RHIC: Elastic Scattering, figure 1(a) and Central Production (CP) in double Pomeron exchange (DPE) process, figure 1(b), [1].

![Figure 1](https://example.com/figure1.png)

Figure 1. (a) $pp$ Elastic scattering diagram and (b) Central Production diagram in DPE
In elastic scattering, silicon detectors installed in Roman pots and positioned on both sides of the interaction point (IP) at STAR, are used to simultaneously detect elastically scattered protons in the very forward direction \[2\], \(0.005 \text{ GeV}^2/c^2 \leq -t \leq 0.035 \text{ GeV}^2/c^2\), where \(t\) is the squared four-momentum transfer between the incoming and the outgoing protons. The use of Roman pots as insertion devices allows the detection of protons scattered at small scattering angles, thus allowing the study of the low-\(t\) region or the nonperturbative regime of QCD. In central production, forward scattered protons are detected in RP’s and also the STAR detector is used in order to measure particles produced at central rapidity region. Diffractive processes at high energies occur via the exchange of colorless objects, with quantum numbers of the vacuum. In pQCD, Pomeron exchange can be described as a color singlet combination of gluons \[3\].

In the small-\(t\) region where the contributions from the Coulomb and nuclear amplitudes are of comparable magnitude, the Coulomb-nuclear interference (CNI) region, a measurable asymmetry \(A_N\) arises, mainly due to the interference between electromagnetic single-flip and hadronic non-flip amplitudes \[4\]. However, a measurement of \(A_N\) in the CNI region is a sensitive probe to measure a possible hadronic spin-flip amplitude \[5\]. The analyzing power \(A_N\), was measured by the pp2pp experiment at RHIC in 2003, at \(\sqrt{s} = 200 \text{ GeV}\) \[6\].

As described above, the “physics with tagged forward protons” program at RHIC utilizes RP’s, located at 55.5 m and 58.5 m (Phase I) on both sides of the interaction point (IP) at STAR. The STAR detector, shown in figure 2, has good acceptance and particle identification. The current setup, indicated in figure 2 as Phase I, focuses on low-\(t\) measurements and requires special proton beam optics. In Phase II an upgrade of the detector is planned, with new RP stations closer to the IP, for measuring protons with high-\(t\), figure 2. With the current setup (Phase I), the collaboration had a successful physics run during the RHIC 2009 data taking period. The experimental setup and the detector performance during Run09, including the alignment and efficiency of the silicon detectors, are discussed here.

![Figure 2. Phase I (current) and Phase II (future) setup configurations. In Phase I, RPs are located behind DX and D0 dipole magnets and the quadrupole triplet. In Phase II, new RPs will be installed between the DX and D0 magnets.](image)

2. Experimental setup and measurement technique

The experimental layout is shown in figure 2. The protons scattered at small angles at the interaction point, stay within the beam pipe of the accelerator and follow trajectories determined by the accelerator magnets. Thus, in order to detect the scattered protons at the lowest \(|l|l\), the detectors need to be moved close to the beam without disturbing the accelerator vacuum. This is achieved by using Roman pots (RP), which are insertion devices in the shape of cylindrical vessels \[7\], figure 3(a). One detector package, consisting of four silicon microstrip detector planes and a trigger scintillator, figure 3(b), is inserted in one RP. Silicon detector planes have an active area of 75×45 mm² and consist of silicon strips with strip pitch 100 µm for position measurements. The detectors exist in two variants, an \(x\)-view detector with vertical strips and a \(y\)-view with horizontal strips. In each RP there are two \(y\)-view and two \(x\)-view detectors, providing redundancy in measuring each coordinate. The RP can be moved close to the beam for data taking, while the detectors inside the pot remain isolated from the...
beam vacuum. Two RP stations with detectors inserted horizontally (at 55.5 m from IP) and vertically (at 58.5 m) are installed in the outgoing beams on either side of the IR at STAR, figure 2.

Figure 3. (a) Roman Pots and (b) Silicon detector package which is inserted in one pot. The detector package being surveyed: the surveying pin is measuring the position of the reference point on the upper-left corner of the package and the surveying tools are positioned on the upper and lower-right corners, pointing away from the package.

The position of the detectors along the beamline is chosen to be where the scattered protons are well separated from the beam protons. The scattered particles pass through bending and focusing magnets until they reach the detectors, which measure the particles’ coordinates in the transverse plane. The coordinates and angles measured at the detection point relate to the corresponding values at the IP by the beam transport equations:

\[
\begin{align*}
    x_{RP} &= a_{11} \cdot x_{IP} + a_{12} \cdot \theta^x_{IP} \\
    \theta^x_{RP} &= a_{21} \cdot x_{IP} + a_{22} \cdot \theta^x_{IP}
\end{align*}
\]

with analogous equations for the \(y\)-coordinate. The coefficients are the beam transport matrix elements and are determined by the accelerator optics. The optimum condition of the experiment is to minimize the dependence of the measured coordinates on the unknown collision vertex coordinates at the IP. This requires using special accelerator optics (\(\beta^* = 21\) m) and is achieved by minimizing \(a_{11}\) and maximizing \(a_{12}\) in the beam transport equations. The minimum distance of approach of the detectors to the beam, or the minimum achievable \(|t|\), depends on the beam size at the detection point and can be optimized by beam collimation. The acceptance of the detectors was studied by using the simulator program called Hector [8]. Having horizontal and vertical RP stations (3 m apart, with horizontal RPs closer to IP) provides full coverage in the azimuthal angle \(\phi\), as shown in the simulation, figure 4(a). However, the presence of the horizontal RPs (which are made of stainless steel) in front of the vertical RPs, introduces an inefficiency region on the vertical detectors, which then reduces the acceptance in \(\phi\) very slightly. The range in \(t\) with maximum acceptance that can be accessed with the detectors in Phase I was determined to be \(0.003\) GeV^2/c^2 < \(t\) < \(0.023\) GeV^2/c^2 for \(\sqrt{s} = 200\) GeV [9], where the acceptance in high-\(t\) is limited by the magnets’ apertures, figure 4(b).

Figure 4. (a) Simulated transverse positions of scattered protons and detector planes (red lines) and (b) Simulated acceptance as a function of \(t\) for Phase I at \(\sqrt{s} = 200\) GeV.
3. Performance and Alignment of the detectors during Run09

By using a dedicated run with special beam optics (β* = 21 m at STAR IP) during the RHIC 2009 data taking period, the STAR collaboration was able to collect more than 30 M elastic triggers with transversely polarized proton beams (beam luminosity ∼ 2⋅10^{29} \, \text{cm}^{-2}\text{sec}^{-1}; average beam polarization ∼ 0.6) at √s = 200 GeV and four-momentum transfer squared range of 0.005 GeV²/c² ≤ -t ≤ 0.035 GeV²/c². The trigger for elastic events requires hits in the collinear scintillator counters on both sides of the IP, as well as no simultaneous hits in the scintillators of the same RP station [10].

Alignment of the silicon detectors was studied for Run09 setup. First, all the detector packages were surveyed in the lab before installation in the RHIC tunnel. During survey in the lab, positions of fixed surveying tools on the package are measured with respect to a previously established reference point (0,0) on the package, figure 3(b). The detector packages were also surveyed in the actual setup in the RHIC tunnel (while inserted in the RPs), at the end of the run. During survey of the detectors in the RPs, positions of the surveying tools on the package are measured relative to the accelerator beam pipe center. The Roman pots were moved to 15 different positions from their fully retracted position relative to the beam pipe center and survey was repeated at each RP position. The displacement of the RP from the beam pipe center is measured by using a linear variable differential transformer (LVDT). The positions of the surveying tools during survey were measured to a precision of 100 µm.

The survey information of the detector packages was used to calculate the angle of rotation of the detector planes in the x-y plane and the (x,y) positions of the 1st Si strip/channel in each detector plane relative to the center of the outgoing beam pipe at STAR. The angle of rotation was measured to be small, ≈ 2 mrad. Positions of the 1st Si strip/channel in each plane (32 detector planes in total) were used to translate positions of the detected particles from Si strip# notation to (x,y) coordinates of hits relative to the beam pipe center. The study of the alignment using survey information completes the initial step of the study of the alignment of the silicon detectors. The geometry of our detector setup allows us to study alignment in further details and make possible corrections to the survey alignment. The vertical and horizontal RP stations, which are positioned 3 m apart from one another in the RHIC tunnel, have overlapping regions in the x-y plane, as shown in figure 4(a). Elastic events that fall in the overlapping regions of the detectors are being used to study the relative alignment between the detectors. Hit distributions, such as the measured collinearity distributions of the elastic events are sensitive to the measurement of the beam position during the run.

The efficiency of the silicon detectors for Run09 was also studied. Four independent collinear combinations of the detectors in our experimental setup, allow us to define four elastic arms (collinear detector pairs composed of eight planes, four on each side of the IP).

![Figure 5](image_url)

**Figure 5.** Calculated efficiency of each Si detector plane/chain (A,B,C,D), in each elastic arm: Arm 0 (EHI-WHO or east horizontal inner - west horizontal outer detectors); Arm 2 (EVU-WVD or east vertical up and west vertical down detectors); Arm 1 and Arm 3 likewise.

When studying the efficiency of a detector plane in one elastic arm, we required having a single cluster on all other seven detector planes, which are part of the same arm. A cluster is defined as a number of consecutive strips/channels (cluster width ≤ 4 consecutive strips) with charge values above 5σ of the pedestal, where the charge cut depends on the cluster width. All edge clusters (3 strips from
the edge of the silicon plane) and all identified hot/dead strips were rejected. Clusters in the planes that measure the same coordinate in one RP, were matched to be within 3*strip pitch distance. Transport equations were used to calculate the scattering angles at the IP, from the measured coordinates of the clusters. The measured angles on each side of the IP (East-West of STAR) are compared (\(\Delta \theta_x\) and \(\Delta \theta_y\)) and only events within 3\(\sigma\) of the angle distribution are taken into account. After these cuts, the overall plane efficiency was calculated to be above 99\%, see figure 5. Inefficiency of the Si detectors was caused mainly due to the dead/noisy Si channels (only five dead/noisy strips out of 14,000 active strips or \(\approx 0.04\%\) of the total number of strips), which were identified and excluded from analysis. The active region of the detectors is limited by the acceptance.

4. Summary
The performance of the silicon detectors during Run09 was good and this provided a clean data set. The alignment using survey of the silicon detectors is completed and corrections to the alignment using elastic events are being evaluated. The efficiency of each Si detector plane was determined to be above 99\%, and the inefficiency was introduced mainly due to the dead/noisy Si channels, which were rejected from analysis.

About 20 M elastic events were recorded, after all the cuts that were applied in the selection of elastic events [10]. The use of the Roman pots at STAR provides measurement in the low-\(t\) region, where measurements of spin dependent and spin averaged variables can be performed at the high energy range provided at RHIC. Preliminary results on single and double spin asymmetries were presented at this conference [10]. Preliminary result on single spin asymmetry \(A_N\), measured by the STAR collaboration in 2009, at 200 GeV and with improved statistics compared to 2003 measurement, is compatible with zero contribution of the hadronic spin-flip amplitude [10]. In addition, about 700k central production (CP) events were recorded during Run09. The analysis of the CP data is in progress. A future planned upgrade on the detector system (Phase II) with Roman pots closer to IP, will not require special running conditions and is important for higher-\(t\) measurements.

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