BEAM OPTICS AND THE PP2PP SETUP OF THE STAR EXPERIMENT AT RHIC*

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Abstract

The newly installed forward detector system at the STAR experiment at RHIC measures small angle elastic and inelastic scattering of polarized protons on polarized protons. The detector system makes use of a pair of Roman Pot (RP) detectors, instrumented with silicon detectors, and located on either side of the STAR intersection region downstream of the DX and D0 dipoles and quadrupole triplets. The parallel to point optics is designed so that scattering angles are determined from position measurements at the RP's with small error. The RP setup allows measurement of position and angle for a subset of the scattered protons. With this position/angle correlations at the RP's can be compared with optics model predictions to get a measure of the accuracy of the quadrupole triplet current settings. The current in each quadrupole in the triplets is comprised of sums and differences of up to six power supplies and an overall 1% error in the triplet field strengths results in a 4% error in four-momentum transfer squared. This technique is also useful to check the polarity of the skew elements located in each quadrupole triplet. Results of the analysis will be presented.

INTRODUCTION

The Solenoid Tracker At RHIC (STAR) experiment [1] is one of two experiments making use of colliding beams at the Relativistic Heavy Ion Collider (RHIC). During a typical year of RHIC operations both heavy ion and polarized proton collisions are used to explore the properties of nuclear matter. The STAR central detector is the Time Projection Chamber that, together with other specialized detector systems, is used to track and identify the thousands of particles that emerge from the ion collisions. In 2009 the STAR experiment was instrumented with arrays of silicon strip detectors housed within RPs located at 55.5 and 58.5 meters on either side of the interaction point (IP) for use with polarized proton collisions in RHIC. The RPs allowed the silicon detector arrays to be moved to within about 10 mm of the circulating beams allowing the detection of protons scattered with angles greater than about 400 μrad. This translates to a four-momentum transfer squared (t) of about 0.002 $(GeV/c)^2$. This gives the experiment a unique ability to measure not only small angle high-energy proton-proton (pp) elastic scattering but also pp inelastic scattering sampled using the STAR detector system and tagged by small angle pp events using the RPs ("pp2pp" setup). The RPs were first used in RHIC at the 2 o'clock Interaction Region (IR) in a stand-alone experiment [2] and [3].

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EXPERIMENT ISSUES

The RP Configuration

The STAR experiment took data using the RPs in 2009 [4] with √s = 200 GeV polarized protons. A schematic layout of the STAR experiment with the RPs is shown in Fig. 1. Each RP station incorporates two x and two y planes of silicon strip detectors with a 79 mm by 48 mm active area with 100 μm pitch 400 μm thick strips and a trigger scintillator array. Each arm in the Blue and Yellow ring has four such stations configured so that the first two RP stations encountered by the scattered beam are positioned left and right of the beam and the following two stations positioned up and down. With this configuration a uniform t acceptance from about 0.002 to 0.02 $(GeV/c)^2$ is achieved in each arm. In addition, in each arm there are four overlap regions in xy position measurements that allow the angle of scattered particles that are sampled in these overlap regions to be determined.

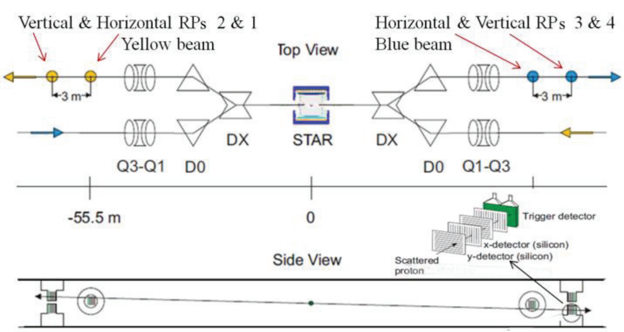

Figure 1: The layout of the RPs. The RPs are located in the "Blue" and "Yellow" outgoing beams.

Optics Issues

The RHIC lattice was setup with special optics in the STAR IR for experiments that use the RPs in order to maximize the t coverage. Each scattered proton travels from the IR in the direction of the outgoing RHIC beam through two dipole magnets, DX and D0, then through a quadrupole triplet, Q1-Q3 and onto the RP stations. In addition to Q1-Q3 there are correction magnets included, a skew quadrupole, a skew sextupole, a normal sextupole and dipole correctors, plus the Q1-Q3 quadrupoles have known axial rolls. These magnets in RHIC then form the spectrometer systems, one in the Blue beam and one in the Yellow beam, used to analyze the scattered protons. The full transfer matrix that characterizes the beam

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transport from the IR to the RPs is not a simple linear matrix. Multipole components in the quadrupoles as well as in the DX and D0 dipoles were, however, measured prior to installation in RHIC so multipole effects could be taken into consideration in the experiment analysis. Multipole effects on the scattered beam were found to not significantly contribute to errors in the experiment results. The first order optics design for the experiment is "parallel to point" (Fig. 2).

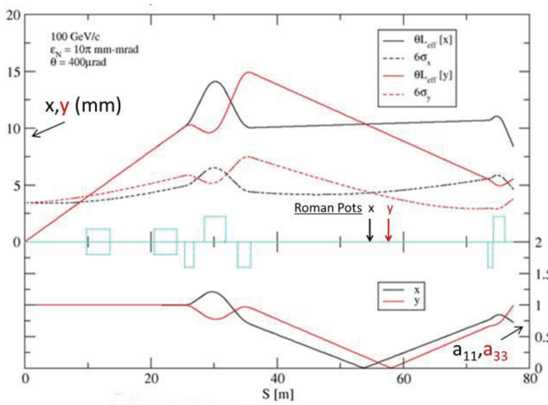

Figure 2: MAD-X [5] parallel to point optics at the STAR IR with $\beta^* = 21$ meters, $\nu_x = 28.73$ and $\nu_y = 29.72$.

With this the first order transport matrix from the IR to the RPs is dominated by the so the called L_{eff} matrix elements that relate the scattering angle, θ_x and θ_y, at the IR to the position measured in the RPs. The first order relationship is:

$$x^{RP} = a_{11}x^{IR} + L_x^{eff}\theta_x^{IR} + a_{13}y^{IR} + a_{14}\theta_y^{IR} \quad (1)$$

$$\theta_x^{RP} = a_{21}x^{IR} + a_{22}\theta_x^{IR} + a_{23}y^{IR} + a_{24}\theta_y^{IR} \quad (2)$$

$$y^{RP} = a_{31}x^{IR} + a_{32}\theta_x^{IR} + a_{33}y^{IR} + L_y^{eff}\theta_y^{IR} \quad (3)$$

$$\theta_y^{RP} = a_{41}x^{IR} + a_{42}\theta_x^{IR} + a_{43}y^{IR} + a_{44}\theta_y^{IR} \quad (4)$$

The Blue beam IR to horizontal RP3 and IR to vertical RP4 transport (MKS units) gives using field integrals derived from quadrupole current read-backs:

$$x^{RP3} = -.08x^{IR} + 25.60\theta_x^{IR} - .003y^{IR} + .080\theta_y^{IR} \quad (5)$$

$$\theta_x^{RP3} = -.04x^{IR} + .030\theta_x^{IR} - .0001y^{IR} + .0060\theta_y^{IR} \quad (6)$$

$$y^{RP4} = -.003x^{IR} - .080\theta_x^{IR} - .02y^{IR} + 23.10\theta_y^{IR} \quad (7)$$

$$\theta_y^{RP4} = .0002x^{IR} + .0080\theta_x^{IR} - .043y^{IR} - .620\theta_y^{IR} \quad (8)$$

So from equations (5) and (7) one can conclude that using only the dominate L_{eff} matrix elements a measured position at the RPs translates to a scattering angle at the IR with a small error. Assuming an exact knowledge of the above matrix elements, the dominate error in the determination of t comes from an imprecise knowledge of the beam crossing angle at the IP together with the transverse beam position at the IR and quadrupole and RP alignment errors. So the issue of what error should be assigned to the L_{eff}'s then is important since a 1% error in the triplet field strength results in a 2.8/2.3% error in L_x^{eff}/L_y^{eff} 's resulting in a 5.6/4.6 % error in the determination of t for a single proton. It is interesting to note that the currents in the quadrupoles are comprised of sums and differences of up to six power supplies. The dominate current (~90%) comes from the RHIC main quadrupole bus and a 1% change in the main bus current translates into a 1.11/1.12/1.05% change in the Q1/Q2/Q3 field integrals. The quadrupole field strengths were determined using the current read-backs from the power supplies together with field maps with a small ~0.1% hysteresis correction. The expected accuracy in the current measurement is on the order of 0.1% or better.

Turtle Simulation vs. Data

As was mentioned earlier in this article the RPs allow for both position and angle measurements for a subset of the data. With this one can check the accuracy of the Q1-Q3 field integral determinations by comparing predicted position angle correlation plots at the RPs to that measured in the experiment. The beam simulation program Turtle [6] was used to generate the simulation plots. The longitudal input beam distribution at the IR was taken from inelastic events collected during the 2009 experiment. The distribution was centered in the IR with a two meter full width half maximum width. The scattered input beam phase space was chosen to uniformly fill the acceptance of the beam line spectrometer elements. No IR x,y offsets were included.

Field maps of the DX and D0 dipoles and Q1-Q3 quadrupoles were included to third order in the simulation together with known axial rolls for the Q1-Q3 quadrupoles. The quadrupole triplets have a separate skew quadrupole and skew sextupole corrector together with a sextupole corrector and two dipole kicker magnets (one horizontal and one vertical) and were all included in the simulation along with appropriate magnet apertures and the STAR solenoid field (very minor effect).

Fig. 3 shows the result of a simulation for the Blue beam compared to the data. The quadrupole field strengths for the simulation shown in Fig. 3(a) and 3(c) is as determined from the read-back currents and field maps. Note the slope of the position vs. measured angle for this case for the data and simulation are different. In Fig. 3(b) and Fig. 3(d) the quadrupole field integrals in the TURTLE simulation were decreased by 2%. Note the rather large change in slopes in the position vs. angle plots. So, one can simply change quadrupole strengths in the simulation and find where the slopes of the data and simulation agree. The position vs. angle slopes as determined by the TURTLE simulation are consistent with the first order MAD-X transport matrix slopes calculated as the ratio of a_{22}/L_x^{eff} or a_{44}/L_y^{eff}. Results for the Blue and Yellow beam are shown in Fig. 4. The best fits for both the Blue and Yellow beam favor about +0.5% increase in the Q1-Q3 strengths and was used in the final analysis of the experiment to determine the IR to RP transfer matrix elements. Note that a 0.5% increase in the Q1-Q3 field integrals would occur if the main quadrupole bus current is off by +0.45%. This solution to the problem is certainly not unique since other nested power supply current errors could yield the same results but would require considerably more than a 0.5% error.

It should be noted that a shift in the IR vertex zero position of 0.5 meters would cause about the same slope change (L^{eff}'s remain ~ constant and a_{22}, a_{44} change) as a 0.5% change in the quadrupole strength but would result in opposite slope changes for the Blue and Yellow beams, inconsistent with the data.

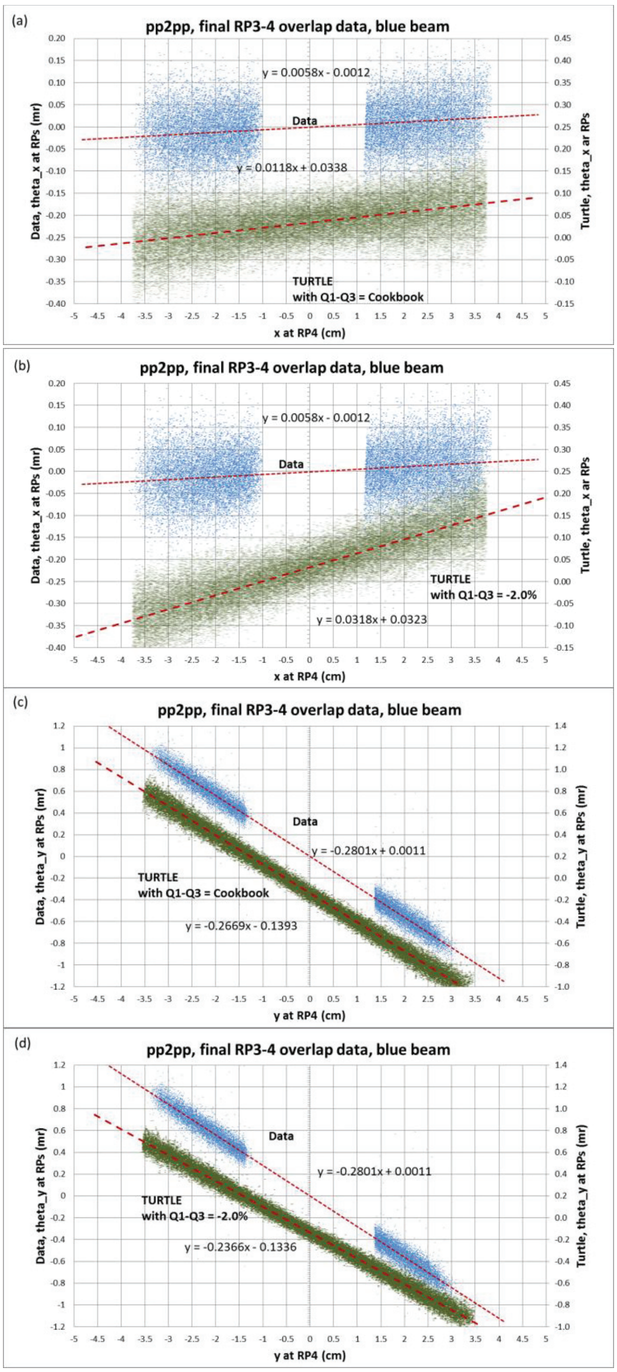

Figure 3: TURTLE simulation (green) of scattered beam compared to pp2pp data (blue) for the RHIC Blue beam.

Added Comments Turtle Simulation vs. Data

As was mentioned earlier in this article the Blue and Yellow IR to RP magnetic transport elements come with higher multipoles, both as magnetic field aberrations in the dipoles and quadrupoles as well as a separate sextupole and a separate skew quadrupole and skew sextupole together with known quadrupole axial rolls. As a result, if one considers the position/angle correlations shown in Fig. 3 one finds the correlation plots are different depending on the chosen RP overlap quadrant. The plots in Figure 3 average these effects together. These differences are also evident in the data and there are differences between the data and the TURTLE simulation. An understanding of these differences may lead to a better understanding of higher order optics of the pp2pp setup of the STAR experiment. These differences are presently under study.

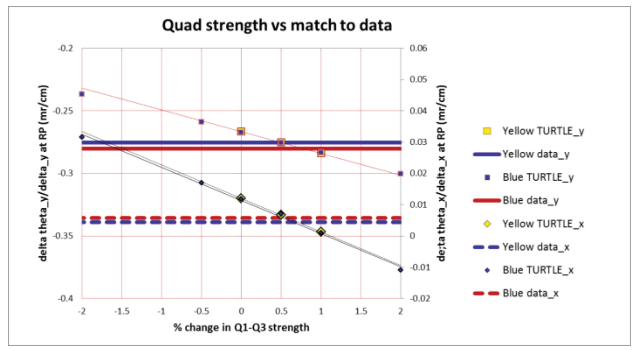

Figure 4: Plots of change in Q1-Q3 strength for Blue and Yellow beams vs. angle-position ratios at RP4 (Blue) and RP2 (Yellow).

SUMMARY

Overall the agreement between the TURTLE simulator and the data was good, giving one confidence that optics of the outgoing beams at the STAR IR are understood. However, in order to get agreement between the scattered beam data and the TURTLE simulation the Q1-Q3 quadrupole fields had to be adjusted by +0.5%. The magnitude of the adjustment is larger than the expected error in determining field integrals from the read-back currents and quadrupole field maps.

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