

BEAM EMITTANCE MEASUREMENTS IN RHIC

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Abstract

The RHIC proton polarimeters can operate in scanning mode, giving polarization profiles and transverse beam intensity profile (beam emittance) measurements. The polarimeters function as wire scanners, providing a very good signal/noise ratio and high counting rate. This allows accurate bunch-by-bunch emittance measurements during fast target sweeps (<1 s) through the beam. Very thin carbon strip targets make these measurements practically non-destructive. Bunch by bunch emittance measurements are a powerful tool for machine set-up; in RHIC, individual proton beam transverse emittances can only be measured by CNI polarimeter scans. We discuss the consistency of these measurements with Ionization Profile Monitors (IPMs) and vernier scan luminosity measurements. Absolute accuracy limitations and cross-calibration of different techniques are also discussed.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) is the first polarized proton collider. Siberian snakes were successfully used to avoid resonance depolarization during beam acceleration [1]. Polarized beam emittance reduction is of a great importance for polarized proton beams, since it reduces the possible depolarisation during acceleration in the AGS and RHIC along with improving luminosity. Emittances in RHIC can be measured in a number of different ways, such as with IPMs and through vernier scans. Each technique has its own systematic errors and limitations. There is no conventional wire-scanner in RHIC, but beam intensity profiles can be measured with p-Carbon CNI polarimeters [2]. In a scanning mode, the polarimeter counting rate dependence on the target position can be used for beam intensity profile as well as polarization measurements. Recoil carbon atoms knocked out of the target in elastic scattering are detected in silicon-strip detectors. The recoil carbon energy and time-of flight are measured for elastic collisions reconstruction. The delayed arrival time of the recoiled carbons is advantageous since the detection can be done in a noise-free environment after all beam-induced disturbances are gone. Every elastic event has a time stamp attached and each event is sorted by the bunch crossing. With the high event rate, large statistical samples can be accumulated in a short time (of a few hundred milliseconds for the target fast scan through the beam), which is used for bunch-by-bunch beam profile (or emittance) measurements. These

measurements have negligible effect to the beam losses and are a valuable tool for setup and monitoring.

In the 2009 run, polarized beams were accelerated and collided at maximum RHIC energy of 250 GeV ($\sqrt{s}=500$ GeV) [3]. The 200 MeV linac injector upgrade and high current polarized source operation (which allows additional vertical beam scraping after the Booster) as well as work on improving the Booster to AGS injection optics matching resulted in beam emittance reduction at RHIC injection. Assuming conservation of normalized emittance from injection at 23.7 GeV through acceleration to 250 GeV, the physical beam size should shrink by $\sqrt{(250/23.7)}=3.2$ times. The beam size in the RHIC horizontal IPMs of about 0.5 mm (σ) is smaller than the IPM resolution, therefore polarimeter intensity scans are the only available measurements of horizontal emittances.

The CNI polarimeters were upgraded for the 2009 run. Two identical target motion mechanisms and detectors assemblies were installed in new vacuum chambers in each ring. One polarimeter is used for the vertical polarization and intensity profile measurements and the other is used for the horizontal profile measurements (or vice versa). As a result the systematic polarization, polarization profiles and emittance measurements were obtained for both transverse planes. This is in contrast to previous runs where measurements were limited to one plane due to long target switch times.

POLARIMETER HARDWARE

The use of thin targets in a polarimeter is essential to reduce multiple scattering for recoil carbon ions and keep the event rate within detector and DAQ capabilities. Carbon strips used in polarimeter are 5-15 μm wide (~ 5 $\mu\text{g}/\text{cm}^2$ thickness), and contain about 10^{13} carbon atoms per mm of target length. The target length is 25 mm. High intensity circulating beam knocks out about 10^7 - 10^8 carbon nuclei/s, which cause the eventual target destruction. It was experimentally demonstrated that targets survive in the RHIC beam for at least 100-200 measurements at the full beam intensity, which corresponds to the one target lifetime of about one-to-two weeks. Manufacturing of the ultra-thin polarimeter carbon (amorphous graphite) targets requires high skill and is a time-consuming process. Multiple targets (six vertical and six horizontal) are attached to a target ladder to extend the time between maintenances. The precision procedure was developed to provide about ± 0.1 mm target alignment accuracy on the ladder, therefore the target positioning accuracy is limited only by the target straightness. A combination of linear and rotational

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motion in the target mechanism provides the target replacement and polarization scans operation. Use of precision linear stages and rotational vacuum feed-throughs gives target position accuracy of +/-0.2mm.

Two identical polarimeter vacuum chambers are located in the warm RHIC sections, which are separated for two circulating beams and have separate vacuum systems. The chambers are situated between two isolation valves and each is equipped with an ion-pump in combination with Ti-sublimation pump and a NEG-cartridge pump, which are isolated by 8.0" gate-valves. This vacuum system allow polarimeter maintenance such as target and detector replacement in short 12 hr shutdowns. Silicon detectors and carbon strip-targets can not sustain any baking, but with the powerful pumps and out-gassing by the beam (beam scrubbing) the vacuum in the polarimeter was reduced to $1.3 \cdot 10^{-9}$ Torr level, which is acceptable for RHIC operation.

Time-of-flight and recoil carbon energy measurements are required for elastic scattering identification. Silicon-strip detectors are used in the polarimeters, which allows measurements of energy and arrival time of recoil Carbons in the RHIC ring vacuum environment. At full RHIC design intensity, the bunch width is about 8 ns and bunch spacing is 106 ns. To avoid prompt background, carbon nuclei should arrive at the detectors in the time window between two bunches.

POLARIZATION AND BEAM INTENSITY PROFILE MEASUREMENTS

The carbon target width of 5-15 μm is much smaller than the beam size. Therefore intensity and polarization profiles can be measured by the target scan. In scanning mode the counting rate dependence on the target position can be used for the beam intensity profile measurements in addition to polarization measurements. Using waveform digitizers (WFD), every elastic event has a time stamp attached and each event is sorted by bunch crossing. The target position is defined by a synchronous step-motor counting in one WFD channel.

With high event rates, large statistics are accumulated in a very short time for fast target scans. Typical target velocity for emittance measurements is about 14 mm/s. At this velocity the target is swept through the beam in less than one second at injection, where beam size is $\sigma \sim 1.5$ mm, and even faster at store energies. Accumulated statistics during this fast sweep are sufficient to measure bunch-by-bunch beam width with statistical accuracy of +/-2%. An example measurement is shown in Fig. 1.

The application for emittance measurements imports β -functions from the on-line RHIC optical model and calculates beam emittances. The accuracy of β -function values is about 10%.

The absolute accuracy of these emittance measurements is limited by the target quality/straightness and counting rate saturation if the target effective thickness is too high.

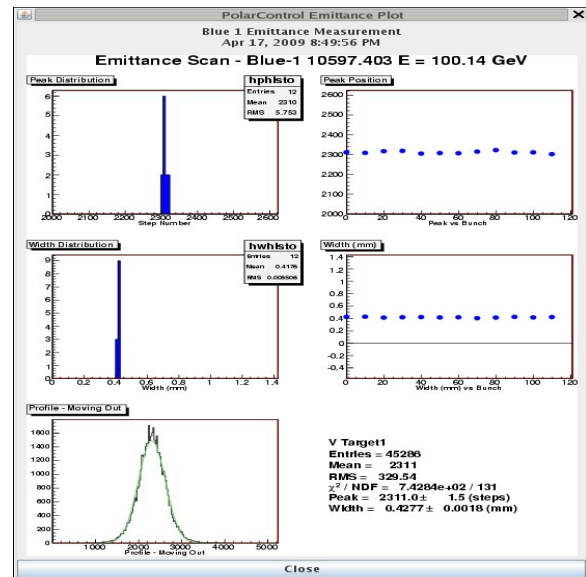


Figure 1: Beam position and bunch width measurement for the 12 bunch store.

After beam exposure the carbon target expands and the target is loosened, which may corrupt the profile measurement. Cross-checks with different (fresh, unexposed) targets were used to provide more reliable measurements.

A proton-carbon CNI polarimeter similar to the RHIC polarimeter is used for AGS polarization measurements. The polarimeter operates in a fast continuous sweep mode for 0.8s while beam is stored in the AGS at 23.7 GeV. This measurement produces very reproducible horizontal and vertical beam intensity profile measurements for the single AGS bunch. These measurements are used for cross-checking of the AGS IPMs measurements and machine set-up to minimize beam emittances [4].

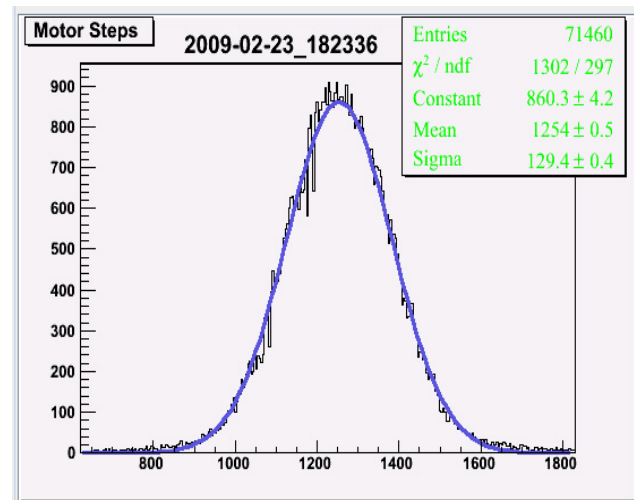


Figure 2: AGS beam intensity profile measured by the CNI polarimeter scan intensity $1.5 \cdot 10^{11}$ proton/bunch. Width: $\sigma=0.98$ mm, horizontal emittance $\sim 15\pi\text{mm mrad}$.

IONIZATION PROFILE MONITORS

RHIC IPMs are based on ionization of residual gas and collection of electrons, which are swept by an electric field that is transverse to the collector strips and parallel to the beam. Micro-channel plates (MCPs) are used to amplify the signal. A uniform magnetic field parallel to the electric field is applied to counter the defocusing effects of the space-charge and recoil momentum [5]. The ionization cross-section is proportional to $\sim Z^2$ so gold ion beams produce a sufficient number of electrons for single bunch detection. For proton beams only average bunch width measurements are possible. The collector strips are spaced about 0.5 mm apart, which limits their resolution for smaller beam sizes. RHIC vertical IPMs are situated in a region with large β -function of about 80m; horizontal IPMs are situated in a region with smaller β of ~ 25 m. At 250 GeV, the proton beam size shrinks to $\sigma \sim 0.5$ mm as measure at $\beta \sim 25$ m with the CNI polarimeter. The horizontal IPM measurement accuracy is limited by an insufficient resolution. Additionally, recoil electron momenta of about 100 eV introduce Larmor precessions with radii of about 0.5 mm. In the vertical IPMs the beam size is larger, $\sigma \sim 0.8$ mm. From cross-calibration with CNI polarimeter scan measurements, correction factors for the finite IPM resolution were calculated and applied to the IPM emittance measurements. Continuous periodic IPM measurements provide complimentary information about the beam emittance evolution during the store time (see Fig. 3).

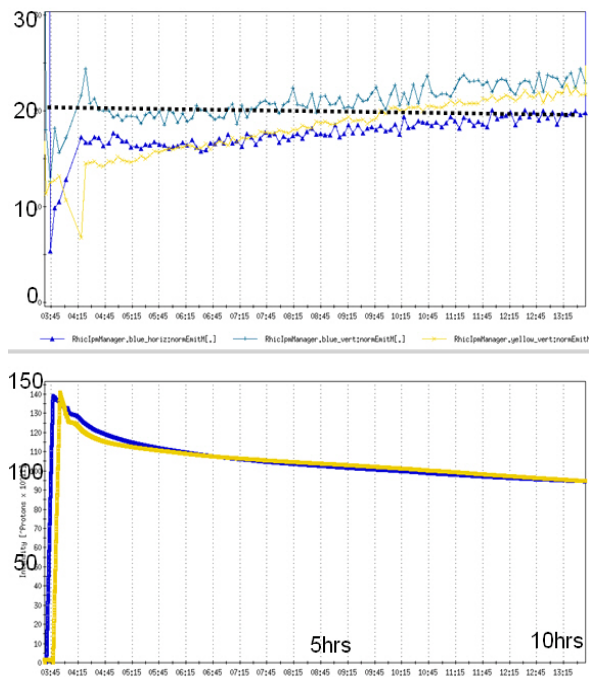


Figure 3: Beam emittances (measured with IPM) growth (18 to 22π mm mrad) to during the 10 hrs store (top picture). Beam intensity decay (bottom picture).

SUMMARY

The p-Carbon CNI polarimeters at the AGS and RHIC provide fast, practically non-destructive polarization and intensity profile measurements. A polarimeter upgrade has been completed for the 2009 polarized proton run, which allowed “complete” polarization measurements including polarization profile scans in both horizontal and vertical planes. Accurate beam intensity profiles measurements (beam emittances including bunch by bunch emittances) were additionally used as a complimentary diagnostics for machine set-up, operation and cross-calibration with the other techniques.

The Linac injector upgrade reduced emittances from 15π mm mrad to about 5π mm mrad. Higher polarized source intensity allowed reduction of the linac pulse duration, which reduced the multiple scattering in the stripping foil. Even with short linac pulses, the beam intensity is sufficient to use vertical scraping in the Booster (about 50%) to reduce vertical and horizontal beam emittances. Small emittances in AGS help to reduce depolarization. The ongoing work on injection optics matching to AGS resulted in smaller ($< 15 \pi$ mm mrad) beam emittances, as measured with the CNI polarimeter scans in AGS [4]. Similar emittance values were measured in the luminescent profile monitors in the ATR (AGS- To- RHIC) beam line and at injection to RHIC (by the CNI polarimeter scans). These emittances depend on beam bunch intensity and AGS set-up and periodical tuning and monitoring is required to maintain the smallest possible emittances for injection to RHIC.

Accurate measurements with CNI polarimeter scans demonstrated emittance preservation for acceleration to 100-250 GeV in RHIC, and resolved inconsistencies between IPM and vernier scan measurements. Vernier scan measurements produced averaged vertical and horizontal emittances of about $16-20 \pi$ -mm-mrad. Smaller beam emittances obtained after upgrades contributed to the RHIC luminosity increase in run 09.

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