RHIC POLARIZED PROTON-PROTON OPERATION AT 100 GeV IN RUN 15*

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Abstract

The first part of RHIC Run 15 consisted of ten weeks of polarized proton on proton collisions at a beam energy of 100 GeV at two interaction points. In this paper we discuss several of the upgrades to the collider complex that allowed for improved performance. The largest effort consisted in commissioning of the electron lenses, one in each ring, which are designed to compensate one of the two beam-beam interactions experienced by the proton bunches. The e-lenses raise the per bunch intensity at which luminosity becomes beam-beam limited. A new lattice was designed to create the phase advances necessary for a beam-beam compensation with the e-lens, which also has an improved off-momentum dynamic aperture relative to previous runs. In order to take advantage of the new, higher intensity limit without suffering intensity driven emittance deterioration, other features were commissioned including a continuous transverse bunch-by-bunch damper in RHIC and a double harmonic RF cature scheme in the Booster. Other high intensity protections include improvements to the abort system and the installation of masks to intercept beam lost due to abort kicker pre-fires.

INTRODUCTION

RHIC provided polarized proton ($\vec{p}$) collisions at a beam energy of 100 GeV for ten weeks during the FY15 physics run. RHIC has a pair of spin rotators in each ring at each colliding IP that allow for collisions with an arbitrary stable spin direction at the point of collision. The run is divided here into three periods. The stable spin direction at the PHENIX experiment was kept vertical for all three periods (no spin rotation at PHENIX). The stable spin direction at STAR was oreiented longitudinally, vertically and then longitudinally again for each respective period. Figure 1 summarizes the performance relative to previous runs.

LATTICE

In order for the electron lenses to provide beam-beam compensation without exciting additional resonances, the betatron phase advances between the lenses and the proton-proton interaction need to be compensated needs to be a multiple of π. An early iteration of a lattice that met this phase advance requirement was tested (without an electron lens) in Run 13 at 255 GeV [1]. The Run 13 experience indicated that careful control of the 2/3 betatron resonance driving terms is important to preserving the transverse emittance and the beam lifetimes even at injection energy. For Run 15 a new lattice was developed [2]. The new lattice has a phase advance of π between the electron lens location and the proton-proton collision point at PHENIX. In addition, the lattice has 90 degrees betatron phase advance per cell, which produces passive compensation of the 2/3 resonance driving terms from the lattice sextupoles. Attaining the 90 degrees phase advance per FODO cell requires increasing the integer part of the tunes in each plane by 1 unit, a change from $(Q_x, Q_y) = (28.690, 29.685)$ to $(29.690, 30.685)$. The final β^* at the two proton-proton collision points is 0.85 m.

The β function at the point of each proton-electron collision is kept as large as possible (15 m) in order to prevent electron lens-driven transverse mode coupling instabilities [3].

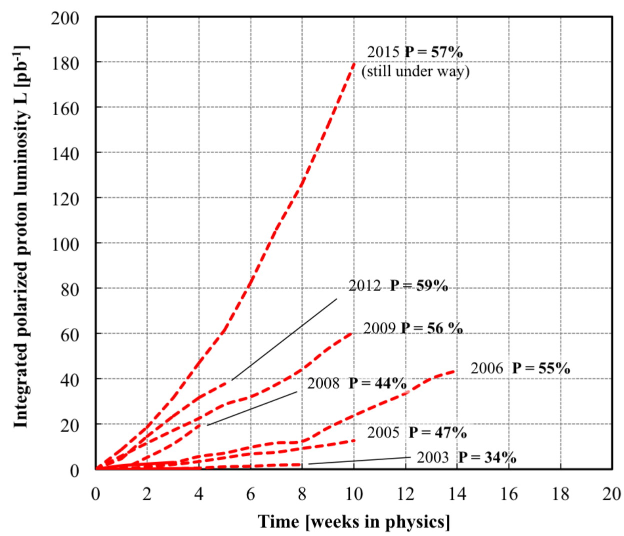

Figure 1: Integrated luminosity and polarization for all RHIC 100 GeV polarized proton runs.

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Dedicated experiments where beams were brought into collision without the electron lenses show that lattice improvements alone have produced a dynamic aperture which can support a beam-beam parameter of 0.008/IP without beam-beam driven emittance growth. This exceeds the 0.006/IP accomplished at 100 GeV in Run 12.

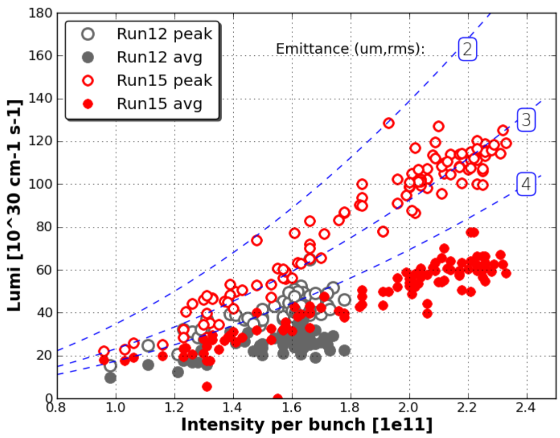

Figure 2: Peak and average luminosity for all stores as a function of bunch intensity. Peak luminosity in Run 12 saturated at $50 \times 10^{30} cm^{-1} s^{-1}$ due to beam-beam induced emittance blowup. Electron lens compensation and improved off-momentum DA allowed higher luminosity in Run 15. The blue dashed lines are curves of constant emittance.

ELECTRON LENSES

In the previous 100 GeV $\vec{p}$ Run 12 [4], strong emittance growth was observed at a luminosity of $50 \times 10^{30} cm^{-1} s^{-1}$, corresponding to a beam beam parameter per IP of $\xi = 0.006$. In response, a pair of electron lenses have been commissioned in Run 15 in an effort to reduce the incoherent tune spread produced by the proton-proton collisions [5]. Typical e-lens operation is as follows. The electron current is brought on at top proton energy with the proton beams separated from the electron beam with a horizontal closed orbit displacement and the proton beams separated vertically from one another at both colliding IPs. One proton-proton interaction is introduced and then (after a short delay of 15 seconds), the other proton collision and the electron-proton collisions are introduced simultaneously. The delay between onset of collisions was to limit the peak losses during the process. The electron beam is kept on for an hour and then stepped down in current gradually. The electron lenses produce a linear tune shift in addition to a decrease in spread, so the central tune (as measured by a Schottky cavity) is maintained at a constant value to avoid emittance growth associated with the tune distribution coming too close to the 2/3 orbital resonances.

With the electron lenses a beam-beam parameter of 0.011 per IP has been achieved routinely in RHIC stores without the large emittance growth experienced in Run 12. This has led to a doubling of the peak and average luminosities relative to Run 12 and Run 15 stores regularly have average luminosities higher than the peak luminosity in Run 12 (Fig. 2).

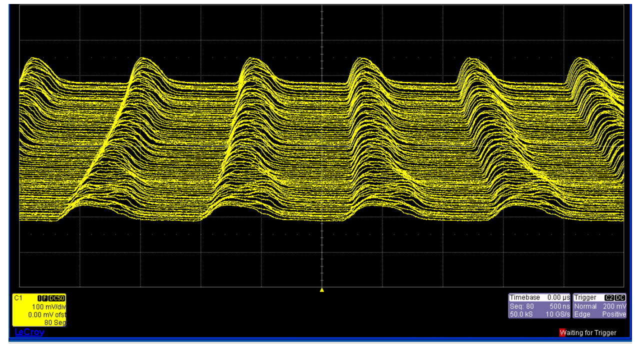

Figure 3: A mountain range of the Booster wall current monitor signal during early acceleration after capture using double-harmonic cavities to produce a longer, flat bunch distribution.

INTENSITY IMPROVEMENTS

Injector Improvements

In order to take advantage of the increased beam-beam limit afforded by the electron lenses it was necessary to ensure that the injectors could deliver bright beam at high intensity. Measurements of emittance in the Booster to AGS transfer line during 2014 indicated that there was significant intensity dependent blow up of the emittance in the Booster. In normal operation, a 300 μs long pulse of protons is injected into the Booster from the Linac every cycle over many turns (the revolution frequency at injection in the Booster is about 1 μs). In previous runs, this coasting beam is then adiabatically captured by the RF at a harmonic number of 1. Space charge calculations using parameters at Booster injection showed the space charge tune shift of the bunched beam to be in excess of 0.1, which indicated that space charge forces at injection be driving the growth. As a consequence in Run 15, the capture scheme included a voltage at h=2, phased 180 degrees from the main h=1 capture voltage. This defocuses the center of the bunch longitudinally and reduces the peak current (and the peak space charge tune shift).

The resulting transverse emittances at AGS extraction and in RHIC were 20% smaller than in previous runs owing largely to this improvement. Figure 2 of luminosity versus bunch intensity includes lines of constant emittance which show the improvement relative to Run 12.

Figure 3 shows the flattening effect of the h=2 RF voltage on the captured bunches.

Intensity in RHIC

In order to successfully accelerate higher intensities in RHIC (for both proton and heavy ion beams) several upgrades were necessary. Prior to this run the vacuum window separating the beam dump from the circulating beam vacuum has been upgraded to withstand the additional deposited

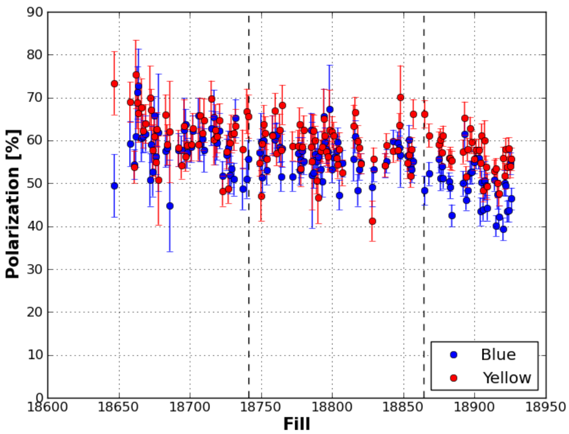

Figure 4: H-jet measured polarization for all fills. Vertical lines bracket the period described in the text and in Table 1.

energy of the higher intensity heavy ion beams. Additionally, it was found in Run 13 that high circulating peak current was heating the ferrites of the beam abort kicker magnets, which changed their inductance and reduced the available kick. This reduction in kick was producing magnet quenches due to losses in nearby superconducting magnets during beam aborts at high energy. New ferrites were installed prior to this run [6] and the installation of additional cooling for the ferrites continues throughout the run.

A pair of movable beam masks has been added (one in each ring), each located one arc away from the abort kickers. These masks are moved into position as we approach top energy during each RHIC ramp. They are placed to intercept beam kicked during an abort kicker pre-fire event. Such bunches were previously lost in the high-β function regions near the experiments and have caused equipment damage. Because the abort kickers have only been operated at low voltage for the 100 GeV run (top proton energy is 255 GeV), there have been no pre-fires since the mask installation and so no conclusions have been drawn yet about their efficacy.

Beam stability at higher intensity is a concern, particularly with operating electron lenses, which reduce the Landau damping afforded by beam-beam at top energy. As such a set of bunch-by-bunch transverse dampers are being commissioned during this run.

POLARIZATION

Polarization at RHIC is measured with two independent devices. Proton beam collisions with a fixed carbon target provide instantaneous measurements of the polarization and are routinely taken at injection, top energy and every few hours throughout the store. In addition a polarized hydrogen jet (H-jet) polarimeter runs throughout the stores and provides a full-store intensity and time-weighted average of the absolute beam polarization. The H-jet measurements are used to calibrate the carbon polarimeter measurements.

Figure 4 shows the H-jet measured polarization for all RHIC fills in Run 15. The vertical dashed lines divide the run into three periods with different spin direction configurations at the IPs.

Table 1 summarizes the polarization performance, as measured by the hydrogen jet, for each of the three running periods and the stable spin direction configurations at each of the colliding IPs. The third period has substantially lower polarization relative to the other two, owing largely to two separate problems. The rotator settings during this period appear to be causing a decay of the blue polarization over the course of the store of up to 2% (absolute percentage points) per hour, when the best achievable has been less than 1%/hour decay. In addition, there was intermittent loss of polarization in the AGS, the causes of which are not understood as of this writing.

Table 1: Summary of Polarization. Period averages have a relative statistical error of about 1%

Period	Spin direction STAR/PHENIX	Polarization [%] Blue,Yellow
1	Longitudinal/Vertical	58.6,61.9
2	Vertical/Vertical	56.2,58.5
3	Longitudinal/Vertical	49.2,56.5

SUMMARY

RHIC Run 15 polarized proton operations demonstrated the success of several important upgrades. In particular, the successful commissioning of the electron lenses has allowed for operation at a higher beam-beam parameter and therefore higher luminosity. Several improvements in the injector chain and at RHIC have allowed for operation at higher intensities and lower emittance. Factors in RHIC and the AGS that have impacted the polarization toward the end of the run are being investigated.

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