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RHIC BEAM ENERGY SCAN OPERATION WITH ELECTRON COOLING IN 2020*

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Abstract

RHIC provided Au+Au collisions at beam energies of 5.75 and 4.59 GeV/nucleon for the physics program in 2020 as part of the Beam Energy Scan II experiment. The machine configuration and operational experience at these energies are presented in this report with emphasis on their unique features which include but are not limited to the addition of a second RF system to enable large longitudinal acceptance and to reduce the intrabeam scattering rate at 5.75 GeV/nucleon, the exploration of the tune space for better performance, the use of lower frequency cavities for alleviating space charge effects, and the world-first operation of cooling on colliding beams with an RF-accelerated bunched electron beam.

INTRODUCTION

The second year of RHIC [1] Beam Energy Scan phase II (BES-II) [2, 3] was performed with collisions at beam energies of 5.75 and 4.59 GeV/n. The Beam Energy Scan was proposed [4, 5] to explore the nature of the transformation from Quark-Gluon Plasma (QGP) to the state of Hadronic gas [6]. In particular, the Beam Energy Scan at relative low energies at RHIC is designed to investigate the first-order phase transition and determine the location of a possible critical point. The BES-II physics program requires a factor of ~ 4 improvement of the luminosity compared to the BES-I [7–11] which was completed before 2014. This goal was achieved at the two energies, thanks to the improvement of bunch intensity from the injectors, improvement of RHIC machine performance with high intensity low energy beam, and the world's first operation of electron cooling at 4.59 GeV/n with colliding beams.

In addition, RHIC also operated in a few other modes in 2020. This includes a few energies for the fixed target experiment, which is reported separately [12], the Coherent electron Cooling experiment, the test run of collisions at 3.85 GeV/n in preparation for 2021 and accelerator physics beam studies.

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OPERATION WITH COLLISIONS AT 5.75 GEV/N

The average luminosity was improved by a factor of five in 2020 compared to the operation in 2010 for collisions at 5.75 GeV. During the course of the 2020 run, the average luminosity was improved by a factor of two. The goal for the total good events (230 Millions) was achieved (235 Millions) in 9 weeks. The integrated luminosity at 5.75 GeV/n is shown in Fig. 1, together with the maximum and minimum projections. The steeper slope of the integrated luminosity curve during the later part of the run is a result of the improvements made in RHIC and its injectors, which will be detailed in the following sections.

The machine configuration for collision at 5.75 GeV/n is listed in the following. The beta function at the interaction point was chosen to be 3.5 m to maximize the luminosity but keep the background controllable. The 28 MHz cavities (400 kV) were used as the main RF system to provide a short collision vertex. Three 9 MHz cavities (180 kV) were used as the secondary RF system to provide large bucket acceptance and also extra longitudinal focusing. The transverse betatron tunes were first set to be 0.09 then 0.12 due to space charge concern which will be detailed later. The chromaticities in both planes were set to be around -8 to provide enough Landau damping. The Tandem ion source [13] was used for 5.75 GeV/n operation to provide up to 1.9E9 ions per bunch and four bunches per AGS cycle [14, 15]. The store length was set to be 25 minutes.

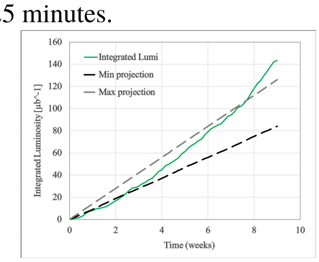

Figure 1: The integrated luminosity and the projections at 5.75 GeV/n in the 2020 RHIC operation.

Bunch Intensity

The bunch intensities at 5.75 GeV/n increased significantly over the course of operation as shown in Fig. 2. With

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an 8 to 4 bunch merge in AGS [14, 15], the Tandem source was always capable of providing high intensity in short fill time. The intensity in RHIC was much improved when the working point was moved up to 0.12 which resulted in higher injection efficiency and better lifetime. This also prompted the request of raising the intensity limit in the AGS, which was increased from 8E9 to 9.6E9 ions (total intensity per cycle) on January 15th. Reasonable transmission efficiency at the Booster-to-AGS stripping foil was maintained by rotating the foil even when the foil was damaged as found out later on.

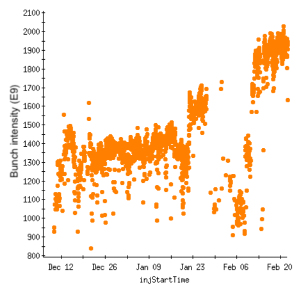


Figure 2: The average bunch intensity in RHIC at 5.75 GeV/n over the course of operation in 2020. The intensity around early February was kept lower for the fixed target operation.

Double RF Systems

The 9 MHz cavities were engaged in addition to the 28 MHz main RF cavities for two benefits. The bucket acceptance was increased from 0.34 to 0.45 ev*s with the two RF systems running in phase. This was initially intended to accept beam with a possible larger longitudinal emittance. The addition of the second RF also improved the Intra-beam Scattering (IBS) lifetime (Fig. 3) by increasing the beam energy spread. The latter turned out to be more beneficial in the end since the Tandem beam longitudinal emittance was small. As a side-effect, bunch peak intensity was increased therefore the space charge effect was stronger with two RF systems.

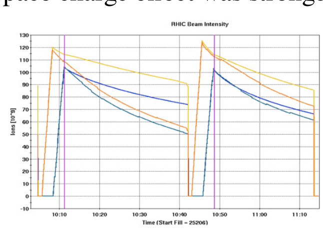
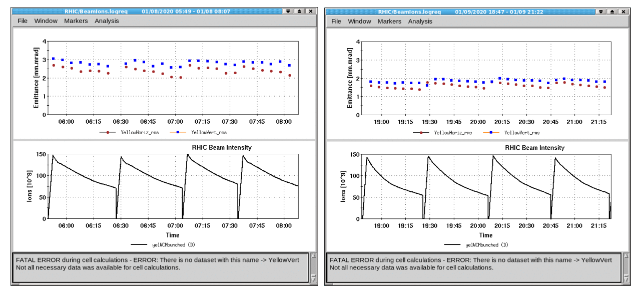


Figure 3: The intensity evolution over two stores, the first one with 28 MHz RF system only, the second one with both 28 and 9 MHz RF systems. The total beam current and the bunched beam current are shown for both beams in collision. The decay of the bunched beam intensity was slower with two RF systems.

Exploration of the Working Point

The tunes were raised from the initial value of around 0.09 to 0.12 to avoid observed transverse emittance dilution while filling. With high beam currents, the space charge tune shift was close to 0.1 so the beam core was sitting near the integer resonance due to its strongest tune depression. The initial luminosity was improved by more than 40% because the beam emittance was smaller (see Fig. 4a and 4b) and the injection efficiency and beam lifetime was better. We moved up the tunes again after injected bunch intensity was increased again with raised AGS intensity limit. The practice was established to start with a slightly high tune (0.122) for injection and manually lower tunes during store as intensity drops.



(a) (b)

Figure 4: The measured rms transverse emittance in the upper plot, and the beam intensity in the lower plot. In (a) the tune was at 0.09, the initial transverse emittance was blown up by space charge effect. The drop of emittance during stores was due to beam scraping at aperture limits in RHIC at this energy. In (b) the tune was at 0.12, the initial transverse emittance was reduced compared to the ones in (a).

OPERATION WITH COLLISIONS AT 4.59 GEV/N AND LEREC COOLING

The average luminosity achieved in 2020 at 4.59 GeV/n was 4.2 times of that interpolated from BES-I. The experimental trigger rate was improved by more than a factor of 2 compared to that in 2019 test run. The goal for the total good events (160 Millions) was achieved (162 Millions) in a total of 14 weeks thanks to stable operation of electron cooling [16, 17], improved intensity and lifetime in RHIC and its injectors. The integrated luminosity at 4.59 GeV/n is shown in Fig. 5, together with the maximum and minimum projections.

The machine configuration at 4.59 GeV/n are listed in the following. Three 9 MHz cavities were used as the RF system to alleviate space charge effect and also for sufficient bucket acceptance. The beta star at the collision point at the start of a store is 4 m. With cooling the beta star was squeezed to 3.5 m, and then to 3 m. The working point was chosen to be 0.235 for the optimal cooling performance. The other tune space was explored as well. The EBIS ion source [18] was used for this operation mode. In order to achieve higher bunch intensity (1.40E9 ions), the AGS bunch merge scheme was changed from 3-to-1 to 4-to-1 [14, 15]. The store length was 30 minutes without cooling, 40 minutes with cooling.

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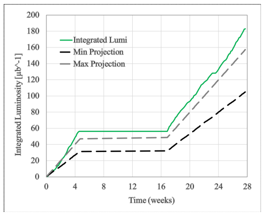

Figure 5: The integrated luminosity and the projections at 4.59 GeV/n in the 2020 RHIC operation. The flat portion was due to the pause of operation due to COVID-19.

LEReC Cooling at 4.59 GeV

Electron cooling [16,17] had been operational since the beginning of the 4.59 GeV/n operation. In addition to longitudinal cooling which shortens the bunch length and therefore the collision vertex distribution, the transverse cooling contributed significantly to the luminosity increase by shrinking the transverse emittance and as a result enabling the squeeze of beta function at the interaction point. As shown in Fig. 6, beta function was squeezed twice, the first one 12 minutes into the store the second 25 minutes into the store.

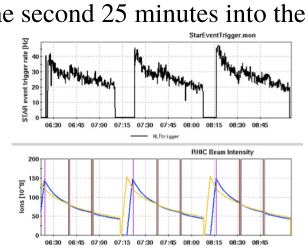

Figure 6: The experimental trigger rate in the upper plot, and the beam intensity in the lower plot for three stores at 4.59 GeV. The first vertical line is at the time when physics data acquisition starts, the second and the third vertical lines are at the time the two beta squeezes take place, each last for a minute.

The performance of stores with and without cooling are shown in Fig. 7.

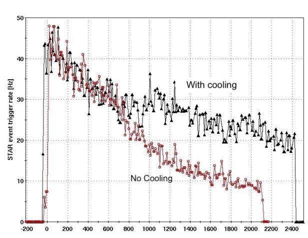

Figure 7: The experimental trigger rates for the case with cooling and without cooling, the store length was 40 and 30 minutes respectively.

Exploration of the Working Point

The tune space was explored with limited success mainly due to incompatibility with electron cooling. With the working point at 0.12, the single beam lifetime was better and the beam lifetime in collision was better as well. The stores at this lower working point without cooling had higher initial collision rate as shown in Fig. 8. The transverse and longitudinal cooling were observed at 0.12 working point, however, the effect of cooling was canceled out by the higher ion beam loss with electron beam present.

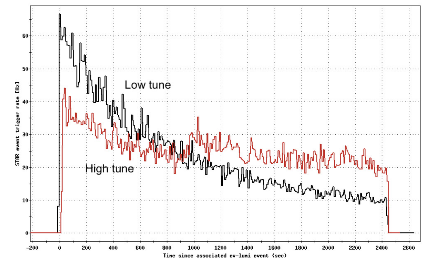

Figure 8: The experimental trigger rates for two stores one with high tune (0.235) and one with low tune (0.12). At high tune, the cooling efficiency was optimal, however at low tune the cooling and heating all together did not help the experimental rates.

The low tune was implemented successfully in 2021 at 3.85 GeV/n with two advances, one is that the electron beam current was reduced to reduce the heating effect on ion beam significantly, the other is the operation of 1.4 GHz cavity which improved the cooling efficiency by lengthening the electron bunch.

DEMAGNETIZATION CYCLE FOR ALLEVIATING PERSISTENT CURRENT EFFECTS

Demagnetization cycles were devised and applied to all energies in collision mode for BES-II. These cycles reduce considerably the sextupole component contributed by the persistent current in the superconducting dipoles and suppress significantly the decay of persistent current thus the decay of beam parameters (orbit, tune and chromaticity) [19]. As a result, the beam lifetime in RHIC was improved and quick switching between different operating modes/energies were made possible.

SUMMARY

The operation for the BES-II program with 5.75 and 4.59 GeV/n Gold beams in 2020 both achieved the physics goals with more than 4-fold higher average luminosity of those in BES-I, the former without cooling and the latter with LEReC cooling operational. The major contributions to the luminosity improvement at 5.75 GeV/n were the improvement of lifetime in RHIC to accept and maintain higher bunch intensity from the injectors, and the intensity improvement in the injectors. At 4.59 GeV, LEReC electron cooling was operational for the first time and made major contribution to luminosity improvement. In addition, the intensity and lifetime improvement in the injectors and RHIC contributed to the luminosity improvement.

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