ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBA6

ACCELERATOR PERFORMANCE DURING THE BEAM ENERGY SCAN II AT RHIC IN 2019

C. Liu*, I. Blacker, M. Blaskiewicz, K.A. Brown, D. Bruno, K.A. Drees, A.V. Fedotov, W. Fischer, C.J. Gardner, C. Giorgio, X. Gu, T. Hayes, H. Huang, R. Hulsart, D. Kayran, N. Kling, Y. Luo, D. Maffei, B. Martin, G. Marr, A. Marusic, K. Mernick, R. Michnoff, M. Minty, C. Montag, J. Morris, C. Naylor, S. Nemesure, I. Pinayev, S. Polizzo, V. Ranjbar, D. Raparia, G. Robert-Demolaize, T. Roser, J. Sandberg, V. Schoefer, F. Severino, T. Shrey, K. Smith, S. Tepikian, P. Thieberger, A. Zaltsman, K. Zeno, I. Zhang, W. Zhang, Brookhaven National Lab, Upton, NY, USA

Abstract

RHIC provided Au-Au collisions at beam energies of 9.8, 7.3, 4.59 and 3.85 GeV/nucleon during the first year of the Beam Energy Scan II in 2019. The physics goals at the first two higher beam energies were achieved. At the two lower beam energies, bunched electron beam cooling has been demonstrated successfully. The accelerator performance was improved compared to when RHIC was operated at these energies in earlier years. This article will introduce the challenges to operate RHIC at low energies and the corresponding countermeasures, and review the improvement of accelerator performance during the operation in 2019.

INTRODUCTION

The Beam Energy Scan was proposed [1, 2] to explore the nature of the transformation from Quark-Gluon plasma (QGP) to the state of hadronic gas [3]. In particular, the Beam Energy Scan at relatively low energies at RHIC is designed to investigate the first-order phase transition and determine the location of a possible critical point. The beam energy scan I (BES-I) [4] was completed in 2014 and resulted in improved understanding of many physics phenomena [5]. However, the transition between QGP and hadronic gas has not been understood yet due to limited statistics at lower energies. Therefore, the beam energy Scan II (BES-II) was conceived with a planned luminosity improvement of factor of ~ 4 at the same beam energies as BES-I (3.85, 4.59, 5.75, 7.3 and 9.8 GeV/nucleon).

In the first year of BES-II, RHIC operated in colliding mode at 9.8 and 7.3 GeV/nucleon for physics data taking, also at 4.59 and 3.85 GeV/nucleon for electron cooling commissioning. In addition, RHIC also operated in fixed target mode as part of the Beam Energy Scan II operation, of which the operational experience is reported separately [6].

MACHINE CONFIGURATION

At BES-II energies, the beam lifetime is limited by some physical effects [7–9], of which the most significant are intrabeam scattering (IBS), space charge, beam-beam, and persistent current effects. To combat IBS, Low Energy RHIC electron Cooling (LEReC) has been commissioned at beam energies 3.85 and 4.59 GeV/nucleon. The physics program with operation of LEReC is planned for 4.59 GeV/nucleon in 2020 and 3.85 GeV/nucleon in 2021. The progress of LEReC cooling is briefly introduced in the "LEReC cooling" section in this report and more details are available in [10].

To reduce the space charge effect, three 9 MHz cavities were used instead of the 28 MHz cavities at 3.85 and 4.59 GeV/nucleon to lengthen the bunches to 50 ns full width. As a consequence, the spacing between consecutive bunches is reduced to 60 ns. Therefore, the injection kicker termination was reconfigured [11, 12] to shorten the rise time and also to flatten the top part of the kicker pulse. The 28 MHz cavities were used for operation at 9.8 and 7.3 GeV/nucleon to concentrate the collision events in a short vertex region [13].

The working points at 9.8 and 7.3 GeV/nucleon were chosen to be (0.093, 0.085) for a large tune space for the space charge dominated beams with beam-beam effects [9]. The lifetime of the first injected beam is better with this working point instead of (0.235, 0.229), which is the nominal heavy working point, when injecting the second beam. The working point at 3.85 and 4.59 GeV/nucleon was set at (0.235, 0.229) because the lifetime was better when the ion beams were interacting with the electron beam for cooling in addition to their collision at the experiment [10].

To reduce the persistent current effects, demagnetization cycles were implemented for all above-mentioned beam energies in 2019. The persistent current induced magnetic field errors and their variations in time were significantly reduced [14]. The switching between physics mode (at 9.8 and 7.3 GeV/nucleon) and LEReC commissioning mode (at 4.59 and 3.85 GeV/nucleon) were as frequent as twice a day. Therefore, quickly establishing stable machine condition was essential. This was achieved by a combination of mode-switch, automatic restoration of system settings for different energies, and demagnetization cycles (Fig. 1).

ACCELERATOR PERFORMANCE

To reach the design bunch intensity, 6 bunches were merged into 1 in AGS for operation at 9.8 and 7.3 GeV so that 2 bunches were injected into RHIC during each AGS cycle. As a comparison, nominally only 2 bunches are merged into 1 in AGS at 4.59 and 3.85 GeV/nucleon, however, 6 bunches can be extracted from AGS during each cycle therefore the

* cliu1@bnl.gov

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBA6

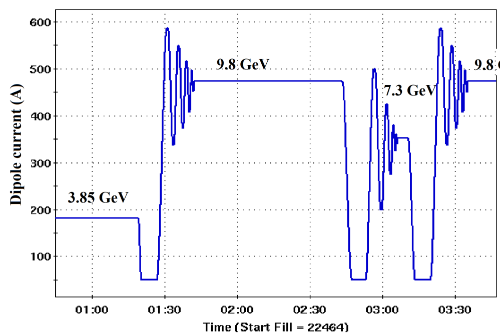

Figure 1: The dipole current was switched from that for 3.85 GeV/nucleon to 9.8 GeV/nucleon, to 7.3 GeV/nucleon and back to 9.8 GeV/nucleon. System settings are automatically restored for the various energies during the switches. One demagnetization cycle was exercised on the dipole magnet to stabilize the field for beam operation.

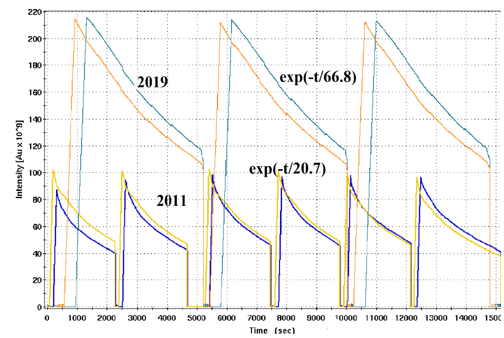

Figure 2: Comparison of physics stores at beam energy of 9.8 GeV/nucleon in 2019 and 2010.

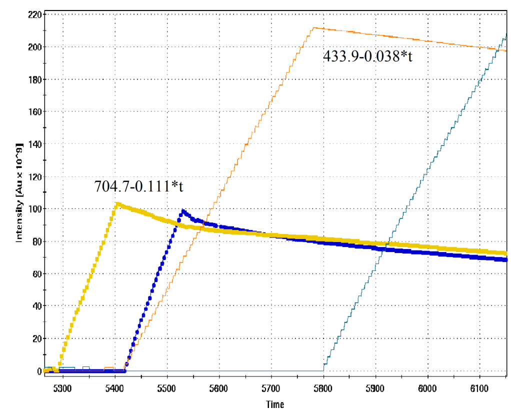

Figure 3: Comparison of the Yellow beam lifetime while injecting the Blue beam. The Yellow beam intensities were fitted using linear functions, which are displayed on the plot for 2019 and 2010 respectively. Due to the new working point below 0.1, beam intensity drops much slower in 2019 than in 2010.

timing for filling RHIC is significantly reduced. It is possible to increase the bunch intensity with more bunch merges, but the increase of filling time and bunch longitudinal emittance (bunch length) [15] are not favorable.

The β^* was further squeezed for both 9.8 and 7.3 GeV/nucleon. The squeeze of β^* from 3 to 2 m was successfully implemented with increased but still manageable background at 9.8 GeV/nucleon. At 7.3 GeV/nucleon, only the Blue beam β^* was squeezed from 3 to 2.5 m due to increased background when squeezing the Yellow beam.

9.8 GeV/nucleon

With the PHENIX detector removed for upgrade, beams only collided at the STAR experiment. The lattice design with one collision point allowed RHIC to increase the bunch intensity at 9.8 GeV/nucleon. The bunch intensity in 2019 was twice of that in 2010 (Fig. 2). The store length in 2019 was about twice of that in 2010. The lifetime in 2019 was more than 3 times of that in 2010. However, RHIC was operated with continuous gap cleaning [16] in 2010 but not in 2019, which is responsible for some of the higher bunched beam decay in 2010.

The Yellow beam intensity while injecting the Blue beam was fitted as a linear curve for 2019 and 2010. The slope at which the intensity drops was much reduced in 2019 compared to that in 2010 as shown in Fig. 3 due to the new working point. The same conclusion was drawn for beam at 7.3 GeV/nucleon as well.

The integrated luminosity at the beam energy of 9.8 GeV/nucleon in 2019 is shown in Fig. 4. The physics data taking was interspersed with LEReC commissioning. The red curve is the integrated luminosity versus calender weeks; the green curve is the luminosity versus weeks for physics data taking.

7.3 GeV/nucleon

Similar to 9.8 GeV/nucleon, the performance at 7.3 GeV/nucleon was improved mainly due to the increase of bunch intensity. The bunch intensity in 2019 was 1.5 times that in 2014 (Fig. 5). The store length in 2019 was the same as that in 2010. The lifetime in 2019 was 2.5 times of that in 2014.

The integrated luminosity at beam energy of 7.3 GeV/nucleon in 2019 is shown in Fig. 6. The physics data taking was interspersed with LEReC commissioning. The red curve is the integrated luminosity versus calender weeks; the green curve is the luminosity versus weeks for physics data taking.

3.85 GeV/nucleon

The beam energy 3.85 GeV/nucleon was the first energy at which collisions were setup for LEReC cooling commissioning. The bunch intensity in 2019 was slightly higher than that in 2014. The store length in 2019 was initially twice of that in 2010 and then shortened for higher average lumi-

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBA6

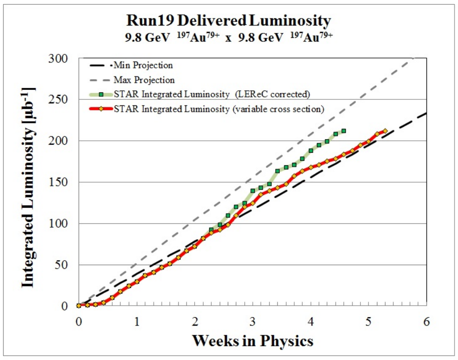

Figure 4: Integrated luminosity at the beam energy of 9.8 GeV/nucleon in 2019.

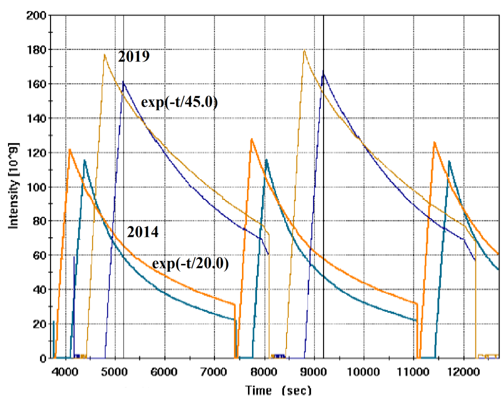

Figure 5: Comparison of physics stores at beam energy of 7.3 GeV/nucleon in 2019 and 2014.

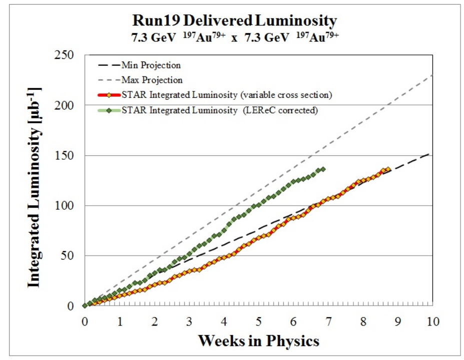

Figure 6: Integrated luminosity at the beam energy of 7.3 GeV/nucleon in 2019.

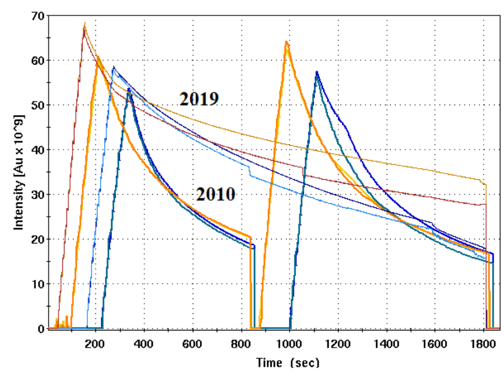

Figure 7: Comparison of physics stores at beam energy of 3.85 GeV/nucleon in 2019 and 2010.

nosity. The improvement of beam lifetime was mostly due to alleviation of the space charge effects with employment of the 9 MHz cavities. Due to increased intensity (Fig. 7), reduced β^* and improved lifetime, the average luminosity was ~2 times higher than that of 2010 (Fig. 8).

Due to the physical size of the Beryllium beam pipe, only the minimum-bias collision events in the +/- 70 cm region were accepted as "good" events. With longer bunches, the event rate in this vertex region relative to the total events decreases (Fig. 9). The event rate in +/- 70 cm region was reduced by ~ 40 % when the 9 MHz cavities were used instead of the 28 MHz cavities (Fig. 9). The increased total luminosity and the reduction due to vertex cut compensated each other, therefore the average good event rate in 2019 was similar to that in 2010.

4.59 GeV/nucleon

Both the bunch intensity and beam lifetime were significantly improved with the 9 MHz cavities at 4.59 GeV/nucleon compared to those in 2008 with the 28 MHz cavities (Fig. 10). The beam lifetime was much improved when beam energy was increased from 3.85 to 4.59 GeV/nucleon. The better lifetime facilitated LEReC cooling commissioning at this energy. To increase bunch intensity, a 3 to 1 bunch merge instead of 2 to 1 was implemented for a time period of four physics stores. The increase of uncorrected event rate was ~ 55% due to the increased intensity.

For future operation with LEReC cooling, a dynamic beta squeeze in the middle of a store was demonstrated which can be implemented when the beam transverse sizes are reduced significantly enough by electron cooling.

LEREC COOLING

LEReC cooling has been demonstrated successfully at 3.85 and 4.59 GeV/nucleon with 1.6 and 2 MeV bunched electron beam [10]. For energy matching, a lattice with a dispersion bump [17] in the arc section downstream of the cooling section was designed to detect the Au+78 produced by electron capture [18–20]. The ion beta function in the cooling section was first raised for matching electron and ion transverse profile, then was decreased to reduce heating effects. The working point was also scanned along the diagonal for better ion beam lifetime with electron cooling

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBA6

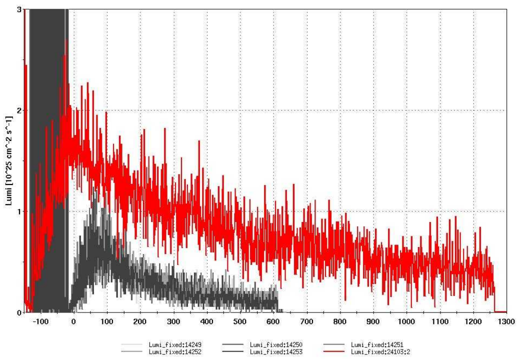

Figure 8: Comparison of luminosity in 2019 (in red) and in 2010 (in grey).

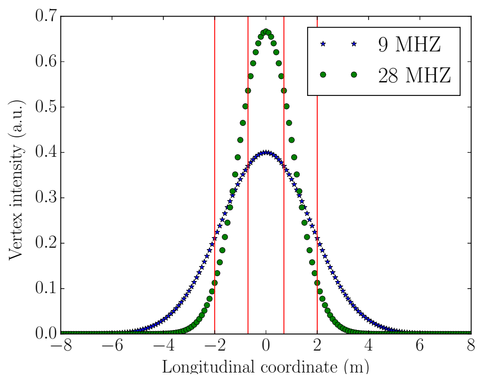

Figure 9: The relative vertex intensity distribution comparison. The blue stars are for longer bunches with 9 MHz cavities; green dots represent short bunches with 28 MHz cavity. The middle pair of vertical red lines indicate the +/- 70 cm vertex cut; the outer pair of vertical red lines indicate the +/- 2 m vertex cut.

and collision at the experiment. The best working point was found to be (0.235, 0.229) in 2019. It is planned to continue the search for a better working point. Improved beam lifetime has been demonstrated with a working point close to 0.25 for a few bunches, however, not for a full machine yet. In addition, time has also been spent on optimization of the beam lifetime without cooling. It was confirmed that injection kicker and beam dump area are the two physical aperture bottlenecks.

SUMMARY

This report summarized the challenges for BES-II operation planned for the years 2019-2020/21 at RHIC, and introduced the countermeasures to overcome these challenges. The accelerator performance in 2019 at 9.8, 7.3, 4.59 and 3.85 GeV/nucleon was reported as well. The improvement of accelerator performance includes contributions from the following: increased bunch intensity with stable injector input and RHIC lattice modifications, the new working point for alleviating the interplay of beam-beam and space charge effects, the new magnetic cycles for combating persistent current effects and smaller β^* values for smaller beam sizes at the collision point. At beam energies 9.8 and 7.3 GeV/nucleon, the luminosity goals have been achieved with these measures alone and without electron cooling being implemented.

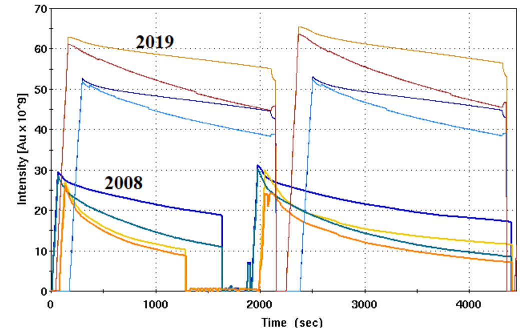

Figure 10: Comparison of physics stores at beam energy of 4.6 GeV/nucleon in 2019 and 2008. The bunch intensity in 2019 was twice of that in 2008. The store length in 2019 was about the same as that in 2008.

LEReC, first electron cooling with RF accelerated bunched electron beam, has been demonstrated successfully. For the future physics program with cooling at 4.59 and 3.85 GeV/nucleon, electron machine stability and cooling efficiency, especially transverse efficiency are expected to be improved.

REFERENCES

[1] "Can we discover QCD critical point at RHIC," RIKEN BNL Research Center Report No. BNL-75692-2006.

[2] G. Stephans, "critRHIC: the RHIC low energy program," *J. Phys. G*, 32(12):S447, 2006.

[3] M. Stephanov, K. Rajagopal, and E. Shuryak, "Signatures of the tricritical point in QCD," *Phys. Rev. Let.*, vol. 81, p. 4816, 1998.

[4] C. Montag and A. Fedotov, "RHIC low energy acceleration," in *Proc. of CPOD2013*, p. 44, 2013.

[5] L. Kumar and STAR Collaboration, "STAR results from the RHIC beam energy scan-I," *Nucl. Phys. A*, vol. 904, pp. 256c–263c, 2013.

[6] C. Liu *et al.*, "Fixed Target Operation at RHIC in 2019," presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Aug.-Sep. 2019, paper TUPLO05, this conference.

[7] T. Satogata *et al.*, "RHIC challenges for low energy operation," in *Proc. of PAC'07*, p. 1877, 2007.

[8] A.V. Fedotov *et al.*, "Beam dynamics limits for low-energy RHIC operation," in *Proc. of HB'08*, pp. 75-77, 2008.

[9] A.V. Fedotov *et al.*, "Beam lifetime and limitations during low-energy RHIC operation," in *Proc. of PAC'11*, paper THP081, pp. 2285-2287, 2011.

[10] A.V. Fedotov *et al.*, "First electron cooling of hadron beams using a bunched electron beam," presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Aug.-Sep. 2019, paper THZBA5, this conference.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBA6

[11] W. Zhang *et al.*, "Research and development of RHIC injection kicker upgrade with nanosecond FID pulse generator," in *Proc. IPAC'12*, paper THPPD085, pp. 3716-3718, 2012.

[12] V. Schoefer, "RHIC injection kicker measurement and emittance growth simulation," BNL C-A/AP/606, 2018.

[13] C. Liu, "Vertex distribution with 9 MHz cavities and comparison of 9 MHz versus 28 MHz cavities for 7.3 GeV operation," BNL C-A/AP/612, 2018.

[14] C. Liu, D. Bruno, A. Marusic, M. Minty, P. Thieberger, X. Wang, "Mitigation of persistent current effects in the RHIC superconducting magnets," in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 548–551.

[15] K. Zeno, "AGS longitudinal emittance measurements for upcoming RHIC low energy gold runs," BNL C-A/AP/615, 2018.

[16] A. Drees *et al.*, "Continuous abort gap cleaning at RHIC," in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, paper MOPLT162, pp. 908–910.

[17] G. Robert-Demolaize, A. Drees, Y. Luo, "Simulations of low energy Au78+ losses in RHIC," presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Aug.-Sep. 2019, paper WEPLS04, this conference.

[18] F. Carlier, "Detectors for low energy electron cooling in RHIC," BNL C-A/AP/557, 2016.

[19] S.Y. Zhang and M. Blaskiewicz, "Recombination monitor," BNL C-A/AP/582, 2017.

[20] A. Drees *et al.*, "Report on LEReC recombination monitor APEX study June 15th 2016," BNL C-A/AP/579, 2016.