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REPORT OF RHIC BEAM OPERATION IN 2021

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Abstract

The first priority of RHIC operation in 2021 was the Au+Au collisions at 3.85 GeV/nucleon, which is the lowest energy to complete the 3-year Beam Energy Scan II physics program, with RF-based electron cooling. In addition, RHIC also operated for several other physics programs including fixed target experiments, O+O at 100 GeV/nucleon, Au+Au at 8.65 GeV/nucleon, and d+Au at 100 GeV/nucleon. This report presents the operational experience and the results from RHIC operation in 2021. With Au+Au collisions at 3.85 GeV/nucleon reported in a separate report, this paper focuses on the operation conditions for the other programs mentioned above.

INTRODUCTION

RHIC [1] operation in 2021 ran from the end of January to the beginning of July for a total of 28 weeks including cool-down and warm-up of the superconducting magnets. Table 1 show the physics programs for RHIC operation in 2021. These programs were categorized in three tiers of priority, with the Au+Au collision at 3.85 GeV/nucleon beam energy [2,3] with cooling [4] as the top priority. There was a risk that not all parts of the program could be completed due to the difficulty of 3.85 GeV/nucleon operation. With the exceptional success of this top priority program, we were able to complete all proposed programs and an additional d+Au program. The goals of all the programs listed in Table 1 were either achieved or exceeded.

In addition to the physics programs, Coherent electron Cooling Proof of Principle experiment and accelerator physics beam studies continued in 2021. They alternated with the physics programs so the RHIC operations crew had to switch back and forth between different operational modes frequently which added complexity to operation. The switching involved mode switching (automated archiving and loading of machine settings), hardware changes (for example injection kicker and RF cavities termination), and cycling the magnets to establish stable machine conditions.

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FIXED TARGET OPERATION

Fixed target experiments [5] were carried out at beam energies 3.85, 44.5, 70 and 100 GeV by scraping Au beam halo vertically at a gold foil installed in the beam pipe ~ 2 m upstream of the STAR detectors. Twelve bunches with moderate intensity (1.5E9 ions per bunch) were equally distributed in the yellow ring to avoid pile-up issue. The beams were brought close to the target by vertical orbit bumps of various amplitudes, and the bump amplitude was adjusted to maintain the rate.

Operation of 100 GeV FXT was challenging because the transverse beamsize is the smallest. An orbit bump of ~17 mm was established with maximum available strength on IR correctors. In addition, we had to introduce a few measures to dilute the beam emittance to obtain and maintain a stable collision rate. These measures are injection mismatch, applying single-turn kicks to individual bunches using tune meter kickers, introducing coupling to couple intrabeam scattering to the vertical plane, and applying continuous sinusoidal kicks to all bunches. With the maximum available orbit bump, the beam was still too small to generate collisions at first. The aforementioned measures were implemented to stimulate the growth of the beam size. The physics data taking only started when beam emittance in both planes grew to 7.5 mm mrad ~ 2 hours after beam was available (Fig. 1).

O+O COLLISIONS AT 100 GeV/NUCLEON

This was the first time in RHIC to run oxygen beams, produced by EBIS [6] using Alumina target, for collisions. The beam setup took 3 calendar days with the FXT programs running overnight. With much-reduced space charge and intrabeam scattering, beam lifetime was supreme. The store length was over 20 hours and 15 hours for the min-bias and central event data taking (Fig. 2). To reduce rms vertex length to 12 cm, beam was re-bucketed from 28 MHz to 197 MHz cavities and a crossing angle of 1.65 mrad was implemented. The experiment took 400 M min-bias events in 6 days, 200 M central events in 5 days and 100 M min-bias events with experimental solenoid reversed.

The luminosity and rms vertex length were recorded with various crossing angles. The dependence was not consistent with the prediction of analytic formula for Gaussian bunches.

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Table 1: Physics Programs for RHIC Operation in 2021, Scheduled Run Time and Their Priority, FXT Stands for Fixed Target Experiment, Run Time Includes Beam Setup Time

Beam energy E (GeV/nucleon)	$\sqrt{s_{NN}}$ **(GeV)**	**Run time**	**Species**	**Events** (MinBias)	**Priority**
3.85	7.7	13 weeks	Au+Au	100 M	1
3.85	3 (FXT)	4 days	Au+Au	300 M	2
44.5	9.2 (FXT)	1 day	Au+Au	50 M	2
70	11.5 (FXT)	1 day	Au+Au	50 M	2
100	13.7 (FXT)	1 day	Au+Au	50 M	2
100	200	2.3 weeks	O+O	400 M 200 M (central)	3
8.65	17.3	2 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3
100	200	1.5 weeks	d+Au	123 M 109 M (central)	3

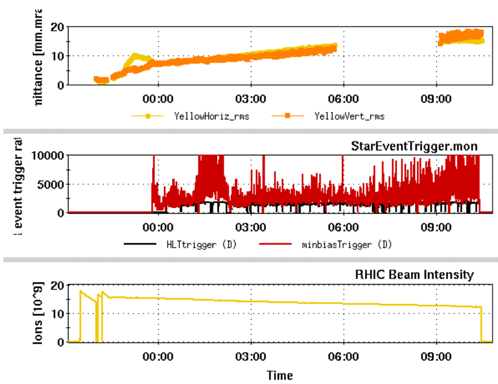

Figure 1: A physics store for 100 GeV Au fixed target operation. The bottom plot shows the total intensity of 12 Au bunches. The middle plot shows the physics event rates, the high level trigger event in black and the MinBias event in red.

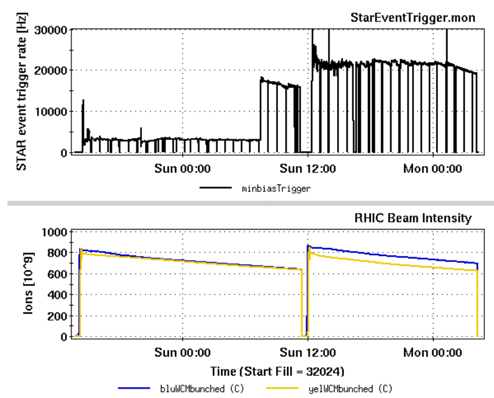

Figure 2: Physics store for O+O collisions. The bottom plot shows the total beam intensity and the upper plot shows the collision event rates. The event rate was leveled by adjusting the vertical orbit bump. The event rate was capped at ~4 K for the min-bias data taking while it was increased to ~20 K for the central event data taking.

The crossing angle was less effective to reduce the rms vertex length due to non-Gaussian bunch profile. The recorded data were fitted with bunch length as a variable (Fig. 3).

Au+Au COLLISIONS AT 8.65 GeV/NUCLEON

8.65 GeV/nucleon was a new energy for RHIC operation of Au+Au collisions. With the operational experience at 9.8 and 7.3 GeV/nucleon, we came to the following optimal configuration for the operation at 8.65 GeV/nucleon: two RF systems–the primary 28 MHz RF at 450 kV and the secondary 9 MHz RF at 150 kV– used for better bunched beam lifetime, the fractional betatron tunes at ~ 0.09 for better collision lifetime, 12 EBIS pulses merged to 2 bunches in AGS [7, 8] with ~ 2×10^9 ions per bunch, these bunches were then injected straight into collisions in RHIC. In addition, beam setup in AGS and its extraction to RHIC took more time and effort due to the fact that 8.65 GeV/nucleon is close to AGS transition energy (7.92 GeV/nucleon). The achieved average rate (~ 450 Hz) was well above the set goal of 260 Hz.

d+Au COLLISIONS AT 100 GeV/NUCLEON

Deuterium beam was generated from Tandem [9] with a TiD cathode while gold beam came from EBIS. To shorten the bunch length and therefore the vertex length, the 197 MHz storage RF cavities were conditioned and engaged for operation.

With a 1 mrad crossing angle to further reduce the vertex length, transverse beam size blew up quickly which generated high background. However, with zero crossing angle and vertical offset for luminosity leveling, the collision vertex showed three peaks. The three-peak vertex distribution was caused by the fact that the luminosity generated by the

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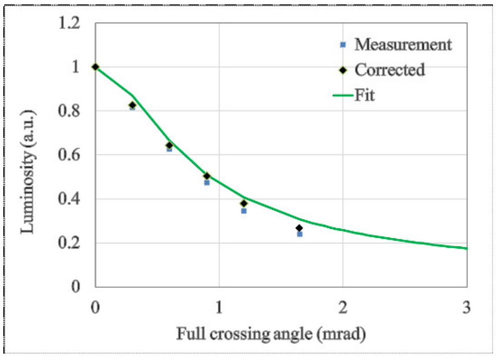
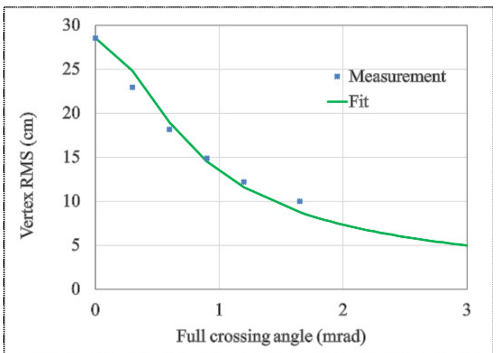


(a) luminosity versus crossing angle



(b) rms vertex length versus crossing angle

Figure 3: Luminosity and rms vertex length dependence on the crossing angle. The blue data points are measurement in both plots. The time evolution of luminosity due to loss of beam intensity and emittance dilution was removed from the data for correction, shown in black. The green curves in both plots are the fits to the measurement data with a variable bunch length.

center bucket was reduced by a larger factor than the luminosity generated by the satellite buckets of the Au beam, as shown in Fig. 4. The side peaks in the vertex distribution were suppressed (Fig. 5) by reducing beam intensity and vertical beam offset at IR6. They were later removed when STAR implemented a timing cut based on neutron detection in the Au beam direction, as shown in Fig. 5.

COHERENT ELECTRON COOLING AND BEAM STUDIES IN 2021

The CeC system [10] has seven high field solenoids, five of which serve as a 4-cell Plasma-Cascade micro-bunching amplifier [11] with 15 THz bandwidth and amplitude gain exceeding 100. The full CW beam was propagated with low losses through the newly built CeC amplification section. The team worked on solenoid alignment, ion and electron beam alignment in 2021. Parasitic fixed target data acquisition at 26.5 GeV/nucleon took place during CeC studies.

Accelerator physics beam studies accounted for ~ 120 hours in 2021. Electron cooling and Electron-ion Collider were the two main areas for beam studies.

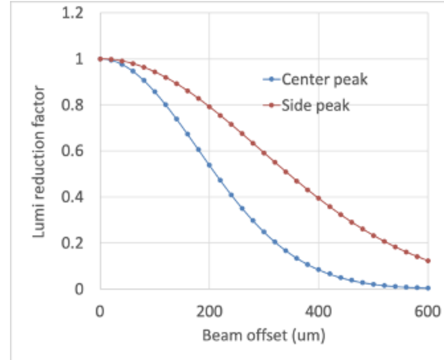
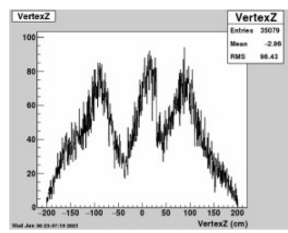
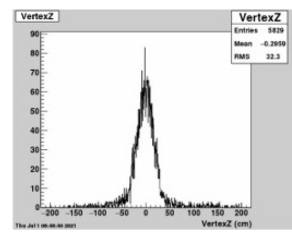


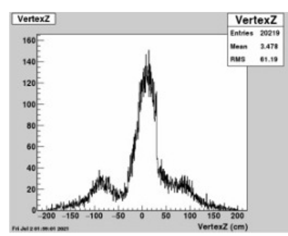
Figure 4: Luminosity reduction factor with beam offset in d+Au operation. With 400 um vertical offset between d and Au beams, the rates from the center peak is reduced by a factor of 4 more than those from the side peaks. The intensity of the center peak of Au beam was a factor of 3-4 higher than the side peaks. Therefore three peaks in the vertex distribution were observed.



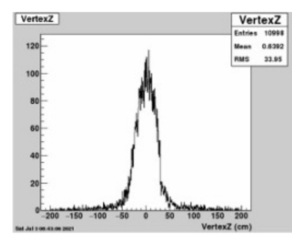
(a) 0 mrad, 400 μm



(b) 1 mrad, 400 μm



(c) 0 mrad, 200 μm



(d) 0 mrad, 200 μm and timing cut

Figure 5: Vertex distribution with various settings of crossing angles, vertical beam offsets and implementation of timing cut in d+Au operation.

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