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Preparation for the Beam Energy Scan II at RHIC in 2020

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PREPARATION FOR THE BEAM ENERGY SCAN II AT RHIC IN 2020

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Abstract

RHIC will provide Au-Au collisions at beam energies of 5.75, 4.59 GeV/nucleon for physics program in 2020, and at beam energy of 3.85 GeV/nucleon for physics program in 2021 as part of the Beam Energy Scan II (BES-II). The operational experience gained in the first year (2019) of BES-II operation will be applied toward operations in the coming years. This article will present some technical details and the outlook of the BES-II operations in the coming years.

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 physics goals at beam energies of 9.8 and 7.3 GeV/nucleon were achieved or exceeded in 2019 [4]. The collisions at 4.59 and 3.85 GeV/nucleon were established in 2019 for electron cooling demonstration. These experience gave us guidance on the operations in 2020/21. The discussion in this report will be limited to collision mode operation which is the more challenging part compared to the fixed target mode.

SELECTION OF RF SYSTEMS

As stated in [4], the luminosities at 3.85 and 4.59 GeV/nucleon in 2019 were improved due to higher beam intensity and longer lifetime (Fig. 1) with employment of the new 9 MHz cavities.

However, the ratio of the luminosity within the +/- 70 cm vertex (Fig. 2) to the total luminosity was reduced due to longer bunch length. The increase of the total luminosity and the reduction due to vertex cut compensated each other with the beam parameters in 2019.

The LEReC accelerator [5] was designed to cool gold ion beams in both RHIC rings with 9 MHz cavity system for the ion beam. The electron beam will be over-focused by the high density ion bunch if the 28 MHz cavity was chosen for operation at 3.85 and 4.59 GeV/nucleon. Therefore, the 9 MHz cavities will be used at these energies so electron cooling can be optimized. Due to time constraint, electron cooling will not be available at 5.75 GeV/nucleon, therefore 28 MHz cavities will be employed instead.

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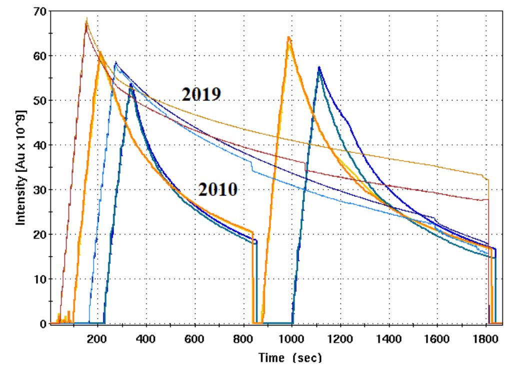

Figure 1: Comparison of physics stores at beam energy of 3.85 GeV/nucleon in 2019 and 2010.

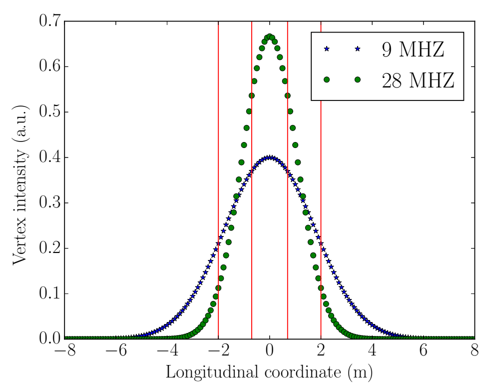

Figure 2: The relative vertex intensity distribution comparison. The blue stars are for longer bunches with 9 MHz cavities; green dots represent short bunches with 28 MHz cavity. The middle pair of vertical red lines indicate the +/- 70 cm vertex cut; the outer pair of vertical red lines indicate the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

BUCKET ACCEPTANCE AND BEAM INTENSITY

In this section, the bucket acceptance and achievable beam intensity will be presented for beam energy of 3.85, 4.59 and 5.75 GeV/nucleon.

The area of a stationary bucket [6] is given by

$$A_{bucket} = \frac{8C}{\pi hc}\sqrt{\frac{qVE_s}{2\pi h|\eta|A}}, \quad (1)$$

where C is the circumference of the accelerator, h is the harmonic number, c is the speed of light, q is the charge number, V is the peak cavity voltage, E_s is the synchronous beam energy and η is the slip factor.

Based on Eq. 1, the bucket acceptance at various BES-II beam energies are listed in Table 1. The bucket acceptance at 5.75 GeV/nucleon is relatively small therefore it is challenging to achieve the required bunch intensity.

Table 1: Bucket acceptance and required bunch intensities at three BES-II energies for operation in 2020/21.

E (GeV/nucleon)	3.85	4.59	5.75
h_{Cavity}	120	120	363
V_{Cavity} (kV)	180	180	400
$A_{bucket}(ev \cdot s)$	0.6	0.81	0.34
Bunch intensity (10^9)	0.8	0.9	1.35

The beam parameters at AGS extraction at various energies [7] are listed in Table 2, for both the case of EBIS and Tandem as the ion sources. With Tandem, comparable bunch intensity can be produced with smaller longitudinal emittance. At 3.85 and 4.59 GeV/nucleon, EBIS is chosen as the ion source because the required intensity can be achieved with a 2->1 merge in the AGS. Tandem is not preferable in this case because smaller longitudinal emittance results in stronger space charge effect and stronger focusing of LEReC electron beam by the ion beams. At 5.75 GeV/nucleon, Tandem will be used as the ion source because EBIS can not provide enough bunch intensity with sufficiently small longitudinal emittance. To infer the longitudinal emittances and bunch intensity at beam energies not listed in Table 2, one can extrapolate the existing data points with assumption that longitudinal emittance slightly increase and bunch intensity slightly drops with beam energy.

Table 2: Bunch merge scheme, longitudinal emittance, bunch intensity and number of bunches per cycle in the AGS with EBIS and Tandem as ion sources.

	EBIS			Tandem	
E (GeV/nucleon)	3.85	4.59	4.59	3.85	9.8
Merge	2->1	2->1	3->1	1->1	2->1
ϵ_{long}(ev$\cdot$ s)	0.26	0.27	0.41	0.15	0.38
Intensity (10^9)	0.95	0.95	1.46	1.0	1.96
Bunches/cycle	6	6	3 or 4	3-6	1-3

Experiments were performed to look into possible gain of average luminosity with higher bunch intensity at the two lowest energies. Higher bunch intensity at 3.85 and 4.59 GeV/nucleon were achieved with a 3->1 in place of a 2->1 merge in the AGS. However with higher intensity, LEReC electron beam was over-focused by the ion beam. In addition, beam lifetime was deteriorated due to stronger space charge effect and the filling time was longer since the number of bunches per cycle are less. With worse beam lifetime, average luminosity was comparable for higher and nominal initial bunch intensity at 3.85 GeV/nucleon. At 4.59 GeV/nucleon, the gain of average luminosity was about 50% as shown in Fig. 3.

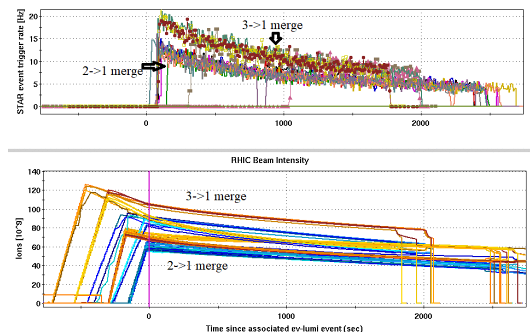

Figure 3: Comparison of luminosity for the cases of 3->1 and 2->1 merge in the AGS. The lower plot shows the total beam intensity and the evolution for the two cases; the upper plot shows that the collision rate was 50% higher with 3->1 merge compared to that with 2->1 merge.

INCREASE OF BUCKET ACCEPTANCE USING DOUBLE RF SYSTEMS

To increase the bucket acceptance, double RF systems was also proposed at beam energy 5.75 GeV/nucleon. The 28 MHz and 9 MHz cavities will be operated in phase with harmonic number 363 and 121 respectively. In the following, the bucket area with these double RF systems will be calculated analytically by finding the new peak voltage and harmonic number. The wave forms of 28 MHz and 9 MHz cavity voltages and the sum are shown in Fig. 4. The bunches will sit at the +/- 180 deg phase of the 9 MHz wave since the beam energy is below the transition energy. The new peak voltage and the cavity harmonic number are 493.5 kV and 339 respectively. The calculated bucket acceptance with the double RF systems is 0.41 ev$\cdot$ s, which is 20% higher than the one with 28 MHz RF cavities only.

IBS CALCULATION

In this section, the experimental measurements and simulations of beam emittance growth due to intra-beam scattering will be presented.

At beam energy 3.85 GeV/nucleon, the simulation was performed using Betacool [8] starting with initial beam intensity of 0.5 $\times 10^9$ particle per bunch. The Martini mode was used and no transverse coupling was implemented. The transverse emittance growth was shown in Fig. 5 together with measurements from RHIC Ionization Profile Monitors (IPMs). The discrepancy is partly attributed to the calibration of IPM measurements, which will be cross-checked

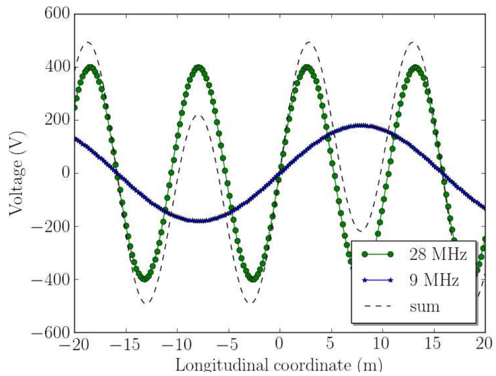

Figure 4: The voltage wave forms of 9 MHz (blue) and 28 MHz cavity (green) and the sum (black).

with other measurements, like H-jet and Vernier scan. The bunch length evolution from simulation and measurements are shown in Fig. 6. The agreement of beam emittance growth in both transverse and longitudinal planes are reasonably good.

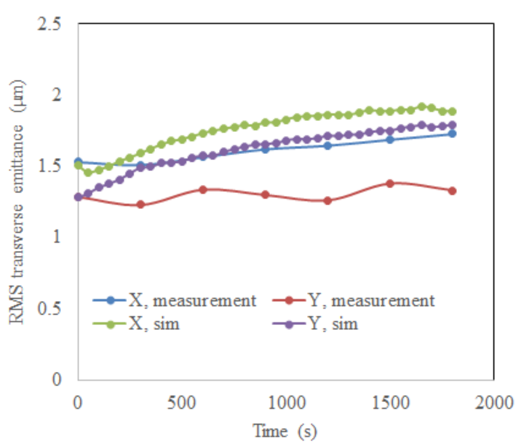

Figure 5: Comparison of the evolution of RMS transverse emittance from simulations with Betacool and experimental data measured by IPMs.

The simulation results of IBS growth time at 5.75 GeV/nucleon with various bunch intensity are shown in Fig. 7. The upper limit of the bunch intensity was chosen so that the space charge tune shift does not exceed 0.06 which is an empirical limit at RHIC.

To explore the possible equilibrium state where longitudinal phase space shrinks when the transverse phase space grows, the simulation of longitudinal growth was also performed with various momentum spread. As shown in Fig. 8, the longitudinal growth time could become negative with increased momentum spread. However, the cavity voltage is limited to reach this state in reality. Fortunately, the longitudinal IBS growth time can be increased from 42 to 418 minutes, without significant change of transverse growth times, with employment of double RF systems. The relatively long

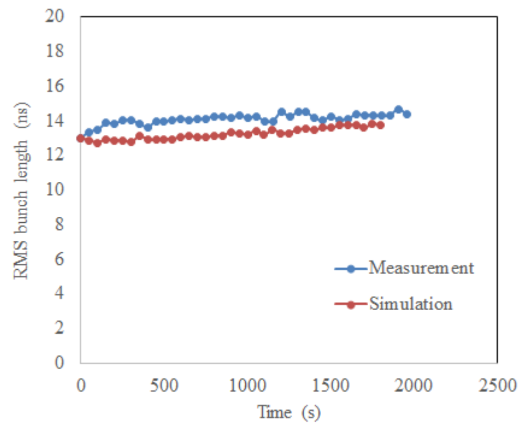

Figure 6: Comparison of the evolution of RMS longitudinal bunch length from simulations with Betacool and experimental data measured by the Wall Current Monitor.

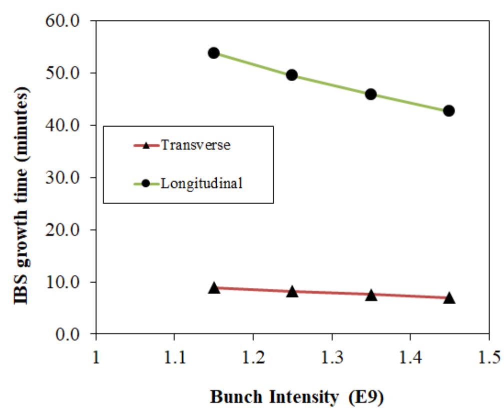

Figure 7: The dependence of IBS transverse and longitudinal growth time on bunch intensity at 5.75 GeV/nucleon.

IBS growth time in the longitudinal plane make the electron cooling at 5.75 GeV/nucleon less desirable.

DISCUSSION ON HARMONIC NUMBERS

To improve cooling efficiency, flattening the bunch longitudinal profile with a third harmonic cavity was proposed and tested at 3.85 GeV/nucleon [9]. The harmonic number for 28 MHz cavity was set at 369 because the tuning range is limited to (27.89, 28.169) MHz. The harmonic number for 9 MHz cavity was kept at 120 which is the nominal value. The first bunch, sitting at zero where the two cavities are 180 degree out of phase (Fig. 9), will be flattened. At the second bunch, the zero crossings of the cavity voltage wave forms are separated by $\delta = C/h_1 - 3 \cdot C/h_2$ in distance. The ratio of this separation to the wavelength of 28 MHz cavity is $\delta/(C/h_2) = 3/40$, therefore, the two systems come to be out of phase for every 40 bunches. So, bunch #1, #41 and #81, out of the 120 possible bunches, will be flattened.

It was also proposed to adjust the harmonic numbers of 9 MHz cavity so that all the bunches can be flattened with

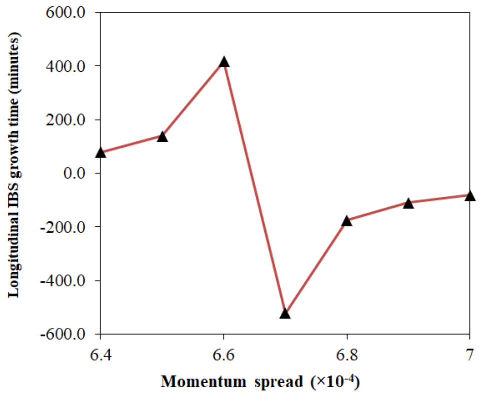

Figure 8: The dependence of IBS longitudinal growth time on momentum spread.

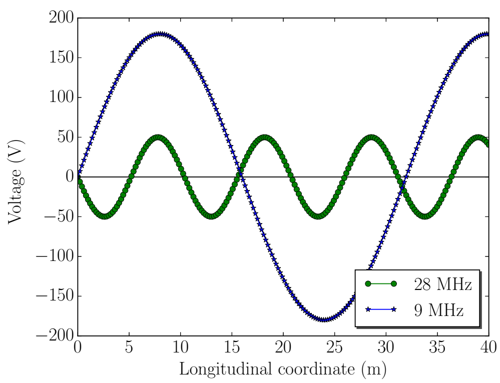

Figure 9: The voltage wave forms of 9 MHz cavity (blue) with harmonic number of 120 and 28 MHz cavity (green) with harmonic number of 369.

28 MHz at the exact third harmonic for energies at 3.85 and 4.59 GeV/nucleon and with the two systems being 180 deg out of phase [10]. In addition, the bucket acceptance at 5.75 GeV/nucleon can be increased with the two RF systems operated in phase. The frequencies of both RF cavities are listed in Table 3 with the proposed adjustments.

Table 3: The proposed changes to the harmonic number for 9 MHz cavity and the resulting frequencies.

E (GeV/nucleon)	3.85	4.59	5.75
h_9	123	122	121
f_9(MHz)	9.332	9.342	9.337
h_{28}	369	366	363
f_{28}(MHz)	27.996	28.025	28.012

An additional benefit of the proposed new harmonic numbers is that the switching of 9 MHz cavity frequency, between physics program at 5.75 (and 4.59) GeV/nucleon and LEReC cooling operation/commissioning at 4.59 (and 3.85) GeV/nucleon, will only need remote tuning of the cavity since the difference is small (~ 10 kHz). The 2-week LEReC commissioning at 4.59 GeV, interspersed during physics program at 5.75 GeV, will be more effective with the change of harmonic number. The same applies to the 2-week LEReC commissioning at 3.85 GeV interspersed during physics program at 4.59 GeV.

The disadvantage is that there will be longitudinal offsets between ion bunches and electron macro-bunches. The longitudinal offsets are 5.3, 21.4 ns at 3.85 and 4.59 GeV respectively. Partial overlapping of electron and ion bunches results in reduced average cooling rate. The electron macro-bunches can be splitted so one overlap with blue the other overlap with yellow bunches, however the optics will be different for these two splitted bunches due to ion focusing. The cogging can be adjusted to zero the longitudinal offsets then ions bunches will not collide exactly at IP6. In addition, the compensation of beam loading, which has harmonic component of 9 MHz if electron macro-bunches are splitted, will be less optimal.

SUMMARY

In 2020, RHIC will provide collisions at beam energy 5.75 GeV/nucleon without electron cooling, and at beam energy 4.59 GeV/nucleon with electron cooling operational as planned. Tandem will be used as the ion source for operation at 5.75 GeV/nucleon, while EBIS will be used at 4.59 GeV/nucleon. New harmonic configuration of the 9 MHz cavities was proposed to flatten the longitudinal bunch profile at 4.59 GeV for cooling optimization, to increase the bucket acceptance at 5.75 GeV/nucleon, and also reduce the transition time between physics program and LEReC commissioning because the frequency tuning can be performed remotely.

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. Liu *et al.*, "Accelerator Performance During the Beam Energy Scan II at RHIC in 2019", presented at the North American Particle Accelerator Conf. (NAPAC19), Lansing, MI, USA, Sep. 2019, paper MOYBA6.

[5] A. V. Fedotov *et al.*, "First Electron Cooling of Hadron Beams Using a Bunched Electron Beam", presented at the North American Particle Accelerator Conf. (NAPAC19), Lansing, MI, USA, Sep. 2019, paper THZBA5.

[6] D. A. Edwards and M. J. Syphers, "An Introduction to the Physics of High Energy Accelerators", J. Wiley, & Sons, Inc., New York (1993).

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

[8] I. Meshkov, A. Sidorin, A. Smirnov, G. Trubnikov and A. V. Fedotov, "Physics guide of BETACOOL code Version 1.1", BNL CA/AP/262, 2006.

[9] V. Schoefer, Private Communication.

[10] K. Mernick, Private Communication.