12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB016

SMALL LONGITUDINAL EMITTANCE SETUP IN INJECTORS WITH GOLD BEAM FOR BEAM ENERGY SCAN IN RHIC*

H. Huang†, C. J. Gardner, C. Liu, V. Schoefer, K. Zeno
Brookhaven National Laboratory, Upton, New York, 11973, USA

Abstract

In recent years, Relativistic Heavy Ion Collider (RHIC) physics program calls for gold beam collisions with energies at and lower than the nominal RHIC injection energy. To get shorter bunches at the three higher energies (9.8 GeV, 7.3 GeV and 5.75 GeV), RHIC 28MHz cavities were used. The longitudinal emittance out of injectors needs to fit in the 28 MHz cavities in RHIC. At two lower energies (4.59 GeV and 3.85 GeV), the 9 MHz RF cavities were used, which set different requirements from injectors. Extensive beam studies were carried out to establish needed beam parameters, such as bunch intensities and longitudinal emittances. In general, enough intensity can be provided for all energies within the longitudinal emittance constraint. This paper summarizes the recent injector operation experiences for various energies.

INTRODUCTION

In recent years, RHIC physics program calls for gold beam collisions with energies at and lower than the nominal RHIC injection energy. The program scans the collision energies to parse out the nature of the phase transition between quark-gluon-plasma and hadronic gas [1]. Although the lower energy can be reached by fixed target experiment and the experiment data can be collected very quickly, the center-of-mass is boosted beyond the acceptance of the detector. In principle, experiment detector was built as a collider detector, and it works the best with colliding beams. For these reasons, RHIC needs to operate at energies lower than the designed injection energy. RHIC runs at five energies which are at or below nominal injection energy: 9.8 GeV, 7.3 GeV, 5.75 GeV, 4.59 GeV and 3.85 GeV. Most of these energies were run in phase one of the Beam Energy Scan (BES-I) operation. Phase two experiment (BES-II) requires on average a four-fold luminosity increase.

GENERAL CONSIDERATION

At lower energies, aperture limitation requires smaller transverse emittance. The space charge effect requires longer bunches. To increase the integrated luminosity, Low Energy RHIC electron Cooling (LEReC) system is implemented in RHIC [2]. The system was used for the two lowest energies, 4.59 GeV and 3.85 GeV.

To get shorter bunches at the three higher energies (9.8 GeV, 7.3 GeV and 5.75 GeV), RHIC 28 MHz cavities were used. The longitudinal emittance out of injectors needs to fit in the RF buckets provided by these cavities in RHIC. At the two lower energies (4.59 and 3.85 GeV) the 9 MHz RF cavities were used to reduce space charge effect and LEReC system was used to cool the beam. This set different requirements for injectors. Extensive beam studies were carried out to establish needed beam parameters, such as bunch intensities and longitudinal emittances. In general, enough intensity can be provided for all energies within the longitudinal emittance constraint. This paper summarizes the recent injector operation experiences for various energies.

Two ion beam sources can provide gold beam for the AGS Booster: the Electron Beam Ion Source (EBIS) source and the Tandem source. The EBIS can switch among different ion species quickly and is easy to operate. The Tandem can provide beam with smaller longitudinal emittance but requires constant attention during operation. Typically, several loads of Booster beam are merged in the AGS to reach higher bunch intensity RHIC required. The detail of the setup is given in Refs. [3–5]. While bunch intensity is doubled by merging two bunches, the longitudinal emittance is also doubled in the process.

In addition, there is longitudinal emittance growth during acceleration. This growth is affected by the power supply noise. Study was carried out to compare the emittance growth with low noise power supply and high noise power supply. The results showed that for the low energy ramp, such as 3.85 GeV, using only the low noise power supply has advantage of smaller longitudinal emittance at the end of energy ramp.

The standard merge scheme in the AGS for beam from EBIS source is 12->6->2 (with 12 Booster loads). This merge scheme is used for the two higher energies, 9.8 GeV and 7.3 GeV. For the lower energies, the required intensity from RHIC is lower due to space charge and Intra-Beam Scattering (IBS) effects [6]. Bunch merge schemes with less bunches were used. The bunch merge in the Booster is four to one merge for EBIS beam and six to one merge for the tandem beam. The bunch merge is needed because the injected beam has to be captured with higher RF harmonics due to limited RF frequency range. In addition, merging into one bunch breaks the requirement that the AGS injection harmonic has to be four times the Booster extraction harmonic. This allows for more Booster transfers to be merged into a bunch in the AGS. It also reduces longitudinal emittance growth from the foil because the merged bunch has a higher dp/p and the energy loss from passing through the foil no longer causes longitudinal emittance growth in the AGS. At lower energies, the bunch length is longer but the rigidity is lower. The AGS extraction is modified to have longer flattop with lower kick power to extract the long bunches.

* This work was supported by Brookhaven Science Associates, LLC, under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
† huaanghai@bnl.gov

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB016

9.8 GeV AND 7.3 GeV

For the top two energies, electron cooling was not used. The projected four folds luminosity increase has to come mainly from higher bunch intensity. In RHIC, at the two highest energies the 28 MHz RF system was used to maximize the average luminosity by providing stronger longitudinal focusing against IBS and a smaller vertex distribution. This requires shorter bunches out of AGS. Although the acceptance of RHIC 28 MHz cavity is 0.89 eV-s with 400 kV, smaller longitudinal emittance is still preferred.

For these two energies, since Siemens motor generator was in maintenance, the Westinghouse motor generator was used instead. These two motor generators supply power to the AGS main magnets. The acceleration took longer but there was no effect on beam quality from it.

To reach the desired bunch intensity, six bunches were merged into one in the AGS for operation at 9.8 GeV and 7.3 GeV. Two bunches were injected into RHIC during each AGS cycle. Initially the RHIC intensity was limited by the experimental background to 1.6×10^9/bunch. This intensity-driven background was due to the beam-gas scattering in the detector beam pipe. After beam scrubbing effect of operation, the intensity was gradually increased to 2×10^9 in RHIC, which corresponds to 2.6×10^9/bunch at the AGS extraction. The typical longitudinal emittance for 9.8 GeV is 0.8 eV-s for 2.6×10^9 bunch intensity at AGS extraction.

The energy of 7.3 GeV is closer to but below the transition energy in the AGS and it makes the extraction setup more difficult. There is continuous emittance growth during acceleration. The emittance at 7.3 GeV was 0.7 eV-s, which is smaller than that at 9.8 GeV as it is lower energy and below transition. Similar to 9.8 GeV/c, the AGS extraction intensity was 2.6-2.7×10^9/bunch. About half way through the 7.3 GeV run, the RF harmonic on the AGS ramp was lowered from h=12 to 10, so that the bucket area can be larger and more beam can be put in. The percentage of beam in neighboring buckets is also reduced. RHIC bunch intensity increased to 2.1×10^9. The bunch intensity was doubled from BES-I operation.The intensity increase from the injectors was a major contribution to the improvement of RHIC luminosity [7, 8].

5.75 GeV

5.75 GeV was a difficult energy to operate. The required longitudinal emittance is 0.5 eV-s with bunch intensity higher than 1.3×10^9. On RHIC side, both 9 MHz and 28 MHz cavities were used so that a larger bucket area is obtained. The LEReC system does not work for this energy, which leaves the luminosity increase mainly from bunch intensity increase. For 5.75 GeV, the desired beam parameters may be reached with 6-1 merge and relaxed squeeze with 15% more EBIS output.

Various bunch merge schemes were first tested with EBIS beam and the results are shown in Table 1. With more pulses merging into one bunch, the intensity goes up with longitudinal emittance. As longitudinal emittance is a bottleneck for RHIC injection, maintaining small longitudinal emittance is critical. By mistuning the bunch merge, the longitudinal emittance can be reduced along with intensity. With all these efforts and EBIS could not reliably to provide 15% more intensity, RHIC injection requirements could not be met from EBIS source.

Table 1: Longitudinal Emittance and Bunch Intensity for Various Merge Schemes at 5.75 GeV

Merge	Early (eV-s)	Top (eV-s)	Growth Ratio	Int. (10^9)	Max No. Bunches
3-1	0.322	0.407	1.26	1.2	3
3-1	0.322	0.420	1.30	1.2	3
8-4-2	0.465	0.604	1.30	1.6	3
6-3-1	0.539	0.644	1.19	2.3	2
6-3-1	0.539	0.667	1.24	2.3	2
6-3-1[1]	0.269	0.391	1.45	1.7	2

[1] With bunch merge mistuned, the bunch emittance can be reduced for less intensity.

On the other hand, with the modest intensity requirements, smaller longitudinal emittance beam from tandem is very attractive for RHIC operation. For the same longitudinal emittance, Tandem provides twice intensity as EBIS. In addition, Tandem beam intensity can be increased with longer pulse. In addition, Tandem also provides a smaller injection time, which for short low energy stores is a substantial fraction of the duty cycle. For these reasons, Tandem beam was used. In the past, the AGS gold intensity limit was set as 8×10^9 for nominal extraction energy of 9.8 GeV as machine protection limit, stemming from risk of vacuum failure after beam loss, and risk of damage to extraction elements from beam loss. The intensity limit in the AGS was raised after careful evaluation of the safety from 8×10^9 to 9.6×10^9 for 5.75 GeV. This greatly improved RHIC luminosity. The typical AGS extraction intensity was 9.2×10^9 in four bunches, or 2.3×10^9. With total of eight tandem pulses merging into four AGS bunches, the longitudinal emittance was 0.28 eV-s, which met the RHIC requirement [9]. This energy was not run in BES-I. The RHIC luminosity was improved by a factor 4.7 of projection from other energies in BES-I.

The BtA foil strips electrons of gold ions to increase its charge from 32 to 77. For 9.2×10^9 intensity at AGS flattop, the beam intensity before the foil is about 20×10^9. Such a high intensity caused significant damage to the foils as shown in Fig. 1. The dropping stripping efficiency is indicative to such a damage. These foils have been used for many years before this higher intensity operation and the stripping efficiency was not changed for a long running period. During this high intensity operation, the efficiency dropped in a few days of operation. Since the foil can be moved in steps and beam size is small, the foil was moved to a new spot after stripping efficiency dropped. Fortunately, there were enough area for this two months operation.

4.59 GeV

For 4.59 GeV, LEReC system was used to cool the beam. The luminosity gain was expected from both the intensity

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB016

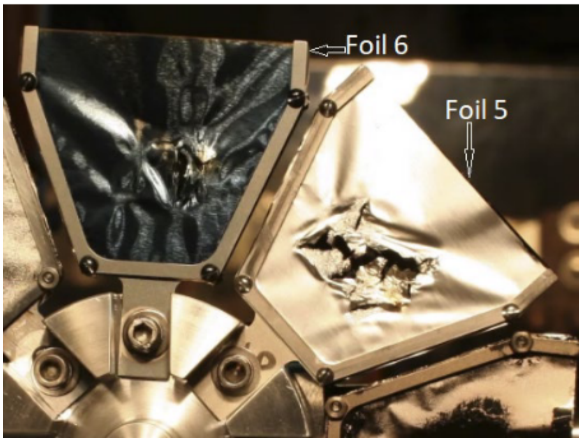

Figure 1: The stripping foils 5 and 6 after they were removed from BtA line. They are still attached to their holders and still on the foil wheel. Foil 6 has a Carbon coating on top of the Aluminum which makes it black.

increase and beam cooling. As the energy gets lower, the required RHIC bunch intensity is lower due to space charge and IBS effects. The expected bunch intensity was about $1{\times}10^9$ with longitudinal emittance of 0.5 eV-s. Due to the COVID-19 pandemic, the operation was halted for more than two months. The motor generator used before the halt was Westinghouse and was Siemens after. The bunch merge scheme in the AGS was 12-3, so that four EBIS pulses were merged into one AGS bunch. The typical longitudinal emittance was 0.53 eV-s with $2{\times}10^9$ bunch intensity. The RHIC luminosity was improved by a factor 4.2 from BES-I.

3.85 GeV

For 3.85 GeV, additional two 9 MHz cavities were used in RHIC, which resulted in larger bucket area and smaller space charge effect but also caused wider experimental vertex region. The 28 MHz cavities were also used with a defocusing phase to reduce the peak current and therefore space charge. This operation mode requires higher bunch intensity with smaller longitudinal emittance from AGS. The Tandem beam was used again for higher intensity and lower longitudinal emittance. The AGS intensity limit was set as $9.6{\times}10^9$ for four bunches with typical bunch intensity at AGS extraction as $2.4{\times}10^9$. Eight Tandem pulses went through 2-1 merge in the AGS to form four bunches at extraction. The longitudinal emittance was typically 0.2 eV-s. The BtA stripping foils were replaced before this 3.85 GeV operation. In foreseen the possible the BtA stripping foil damage, the quadrupole in front of the foil was adjusted to increase the beam size at the foil to extend the foil lifetime. The time interval for moving the beam position on the foil was greatly increased, compared to the 5.75 GeV operation. The RHIC luminosity was improved nearly by a factor 10 from BES-I.

SUMMARY

The longitudinal emittance and bunch intensity achieved for various energies are summarized in Table 2. Extensive

Table 2: Summary of Longitudinal Emittance and Bunch Intensity for Various Energies

Energy (GeV)	Source	Merge	Emit. (eV-s)	Int. (10^9)	Max No. Bunches
9.8	EBIS	12-2	0.817	2.66	2
7.3	EBIS	12-2	0.693	2.5	2
5.75	Tandem	8-4	0.28	2.3	4
4.59	EBIS	12-3	0.530	2.0	3
3.85	Tandem	8-4	0.2	2.3	4

beam studies were carried out in the injectors to establish beam parameters needed for BES-II runs. With lower bunch intensity requirement at the two higher energies, the longitudinal emittance at AGS extraction can be reduced by turning off squeeze cavity KL and lowering the L10 cavity voltage. For the lower energies, the smaller longitudinal emittance of tandem beam made it the excellent choice to meet the RHIC lower intensity and smaller longitudinal emittance requirements. Overall, AGS provided more than planned bunch intensities in all five energies, which established the base for RHIC to meet or exceed the goal to increase luminosity by four times.

REFERENCES

[1] G. S. F. Stephans, "critRHIC: the RHIC low energy program", *J. Phys. G: Nucl. Part. Phys.*, vol. 32, p. S447, 2006. doi:10.1088/0954-3899/32/12/S54

[2] A.V. Fedotov *et al.* "Experimental demonstration of hadron beam cooling using radio-frequency accelerated electron bunches", *Phys. Rev. Lett.*, vol. 124, p. 084801, 2020. doi:10.1103/PhysRevLett.124.084801

[3] C. Gardner *et al.*, "Operation of the RHIC injector chain with Ions from EBIS", in *Proc. of IPAC'15*, Richmond, VA, USA, May 2015, pp. 3804–3807. doi:10.18429/JACoW-IPAC2015-THPF046

[4] K. Zeno, "The 2019 gold run in the injectors", BNL, CAD Tech. Notes, Upton, NY, USA, Rep. BNL-212461-2019-TECH, Nov. 2019.

[5] K. Zeno, "The 2020 low energy gold run in the injectors", BNL, CAD Tech. Notes, Upton, NY, USA, Rep. BNL-220777-2021-TECH, Dec. 2020.

[6] A. Fedotov, "IBS for RHIC operation below transition energy and various RF systems", BNL, CAD Tech. Notes, Upton, NY, USA, Rep. BNL-99841-2013-IR, Feb. 2013.

[7] C. Liu *et al.*, "Improving the Luminosity for Beam Energy Scan II at RHIC", in *Proc. of IPAC'19*, Melbourne, Australia, May 2019, pp. 540-543. doi:10.18429/JACoW-IPAC2019-MOPMP044

[8] C. Liu *et al.* "Accelerator performance during the beam energy scan II at RHIC in 2019", in *Proc. of NAPAC'19*, paper MOYBA6, pp. 26-30.

[9] C. Liu *et al.*, "RHIC beam energy scan operation with electron cooling in 2020", presented at IPAC'21, Campinas, Brazil, May 2021, paper MOPAB010, this conference.