BEAM ENERGY SCAN WITH ASYMMETRIC COLLISION AT RHIC*

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Abstract

A beam energy scan of deuteron-gold collision, with center-of-mass energy at 19.6, 39, 62.4 and 200.7 GeV/n, was performed at the Relativistic Heavy Ion Collider (RHIC) in 2016 to study the threshold for quark-gluon plasma (QGP) production. The lattice, RF, stochastic cooling and other subsystems were in different configurations for the various energies. The operational challenges changed with every new energy. The operational experience at each energy, the operation performance, highlights and lessons of the beam energy scan are reviewed in this report.

INTRODUCTION

RHIC consists of two circular accelerators with counter circulating beams; the clockwise one is called the Blue and the counter-clockwise one is called the Yellow ring.

The 6-week deuteron-gold beam energy scan was in-between two periods of the 200 GeV/n gold-gold collision [1], 10 weeks and 1 week respectively. The center-of-mass energies of the collision are 19.6, 39, 62.4 and 200.7 GeV/n for the scan [2]. The first two energies are below while the latter two are above transition energy (γ_t~23.5).

OPERATION REVIEW

The deuteron beam was provided by the Tandem while the gold beam was provided by the Electron Beam Ion Source (EBIS). The deuteron beam was merged from 4 to 2 bunches in the Alternating Gradient Synchrotron (AGS); the gold beam was merged from 12 to 6 then to 2 bunches (12-6-2 merge) in the AGS. The operation of the Booster and the AGS in 2016 was reviewed in Ref. [3, 4]. The beam parameters for deuteron and gold beams in the Booster, AGS and RHIC were summarized in Ref. [5].

Orbit and Aperture

Aperture restrictions were due to the fact that the beam orbits are tilted horizontally and to the reduced physical aperture of the undulator for the coherent electron cooling proof of principle experiment (CeC PoP) [6]. The common angle of the beams with respect to the straight line from the center of the dipole magnet close to the interaction points (DX magnet) on one side to the other is 1 mrad.

Several measures were taken to mitigate the aperture restriction. We reduced the beam common angle from 1 mrad to 0.7 mrad by setting up an angle bump at the undulator for both beams. After thorough aperture studies with beam, a new injection scheme was conceived and applied operationally: first we injected the deuteron beam that has low IBS growth rates with no vertical offset. Once the Blue ring is filled with deuterons, we moved the beam down to -3 mm vertical offset at the undulator. Then we injected the gold beam in the Yellow ring with +5 mm vertical offset.

Beam Intensity

The 12-6-2 merge scheme for gold beam in the AGS was briefly tested in 2015; it was operational for the RHIC gold-gold and deuteron-gold program in 2016 with better control of the longitudinal emittance. With a bunch intensity of $3.0x10^9$ from the AGS, the gold beam intensity in RHIC was found to be limited to $2.3 x10^9$ due to the Landau cavity power amplifier.

The deuteron bunch intensity could be as high as $3.5x10^{11}$ with 8-4-2 bunch merge scheme in the AGS. The deuteron intensity was limited at transition crossing in RHIC as well. The deuteron beam was accelerated to top energy with the revolution frequency locked to that of the gold beam [7]. Therefore, it crossed transition energy at a time slightly different from the gold beam due to the path length difference. The equivalent bunch intensity limit for deuteron beam is $1.8x10^{11}$ assuming the same longitudinal profile. The observed intensity limit at transition for deuteron was lower than expected at the start of the energy scan program. It was found this was due to the short bunch length of the deuteron beam. The energy spread of the deuteron beam from the source was small. There was no stripping foil for the deuteron beam from the Booster to the AGS, and the deuteron be- am went through less bunch merges [4] in the AGS. Therefore, the longitudinal emittance of the deuteron beam was smaller than that of the gold beam and the bunch was shorter. To better match the 3D sizes of the two beams in RHIC and for more deuteron intensity, the deuteron bunch was lengthened to match the gold beam. As a result, the intensity limit due to the Landau cavity at transition crossing increased to as expected.

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Beam Emittance

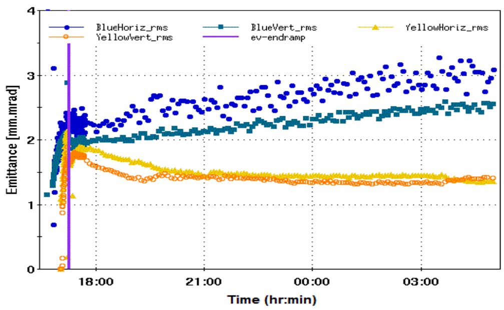

Figure 1: Beam transverse emittance evolution of the two beams for the 39 GeV/n program. The gold beam emittances in both planes (the yellow and orange) were reduced with only vertical cooling engaged.

The 3D beam emittance evolution was dominated by intra-beam scattering [8] for the gold beam, not for deuteron beam. The counter-measure for intra-beam scattering is 3D stochastic cooling [9], which is operational in both rings. However stochastic cooling is inefficient for the deuteron beam due to the high bunch intensity. The longitudinal and horizontal cooling was on for the 200.7 GeV/n program. The longitudinal and vertical cooling was on for the 62.4 GeV/n program. Excessive beam loss at the closed stochastic cooling kicker prevented engaging the horizontal cooling at 62.4 GeV/n. Global coupling had to be introduced for emittance cooling in both planes. Only the vertical cooling was on for 39 GeV/n (Figure 1). Longitudinal IBS growth was slowed down due to equilibrium below transition. No cooling was engaged at 19.6 GeV/n due to the beam size being larger than the physical apertures of the cooling equipment.

The 56 MHz SRF Cavity

The 56 MHz cavity [10] is the first superconducting cavity in RHIC. The voltage of the beam driven SRF cavity was limited by the higher order modes. Due to voltage limiting quenches in the HOM damper, the cavity was operated without any HOM dampers in 2016. With significant commissioning effort during the gold-gold program, the cavity was running operationally starting from the deuteron-gold energy scan program. The extra longitudinal focusing provided by the cavity reduced the bunch length, and slowed down the longitudinal beam growth rate from intra-beam scattering. There was an instant luminosity gain of 11% due to the 56 MHz SRF cavity. The instant gain of collisions within a short-range vertex (10 cm) at one of the experiments (PHENIX) was around 15% due to the 56 MHz cavity.

Actions for Protecting Detectors

There were some precautions taken for asymmetric collision to protect detectors from pre-fires of the abort kickers [11, 12]. Orbit bumps were employed in both rings for 200.7 GeV/n d-Au operations to enforce the beam loss in the arcs in case of unexpected beam aborts. The newly designed PHENIX Muon Piston Calorimeter (MPC) protection circuit raised the damage threshold by a factor of 400. The Sector-8 DX magnet was moved horizontally by 9 mm so that the aperture for Au beam in the d-Au configuration was the same as in the gold-gold configuration. The lattice was redesigned to adjust the phase advances between abort kickers and masks (~73 degree compared with ~180 degree in 2015) such that the masks were more effective in the case of a pre-fire. A dipole magnet quench protection diode failure, which happened during the gold-gold program is believed to be related to resultant chronic beam losses from the off-momentum beam at the orbit bumps [13].

Notes for 200.7 GeV/n

The yellow injection kicker ceramic pipe was replaced during the setup period of the 200.7 GeV/n deuteron-gold program. The gold beam intensity limit due to losses from beam-gas interactions in the poor vacuum was thus eliminated. The aperture limit was overcome with all the actions taken (see details in subsection "orbit and aperture") and the beam loss at the undulator was under control. The 56 MHz cavity has been operational since the first 200.7 GeV/n deuteron-gold physics store, with the voltage raised to 1 MV in the last three stores.

Notes for 62.4 GeV/n

It was possible to deliver long stores with very good luminosity lifetime with stochastic cooling engaged. Turn-on time of SC cooling was crucial because the early beam loss was very large without cooling. The excessive early beam loss prevented the engagement of the cooling. To be able to turn the cooling on right after the start of collisions, we delayed the ramping of the storage cavity voltage and also fine-tuned collimators settings to reduce the early beam loss. Beam instability at injection was suppressed by large chromaticity.

Notes for 19.6 GeV/n

The store length was ~1.5 h, compared to 0.5 h gold-gold store in 2011. The injection efficiency and beam lifetime were improved with the new lattice with 3.5 m beta star. The lifetime of the deuteron beam was better than that of the gold. Initially, beams were injected into collision, however losing too much deuteron beam while injecting the gold beam. We switched to filling with separation bumps and putting beams into collision later. The disadvantage was that one loses beam sometimes mostly due to beam coherence when establishing beam collision. It is recommended not to run magnets through hysteresis regularly for low energy programs, however, we had to do it when magnet currents dropped to zero due to various reasons. The machine at low energy lacks long term stability. It is hard to reproduce a good store with the same settings. The response amplitude of the beam transfer function (BTF) measurement at 19.6 GeV/n was much lower than at higher energies, which is consistent with the tune spread being larger. It turned out to be the biggest contributor to the low beam lifetime. Pushing chromaticity close to zero and engaging octupoles reduced the loss rates. And the spectrum from BTF was narrower which indicated narrower tune spread. However, we ran into instability problems when ramping into these configurations. It was recommended to run with low chromaticities for future low energy programs; the remedy for instability is transverse damper.

Notes for 39 GeV/n

This is the lowest energy for which SC cooling was engaged in RHIC. There are two challenges: beam energy is close to the transition energy, and beam sizes are large at the kickers. A new lattice was designed to fulfil the requirements of a large slip factor and small beam sizes at kickers. With vertical cooling only, the horizontal emittance was reduced due to coupling (Figure 1) and the longitudinal IBS growth rate was reduced. The main RF system was switched from 28 MHz to 197 MHz cavities (re-bucketing) successfully for the gold beam, however not for the deuteron beam. Due to limited running time and the fact the deuteron bunch was relatively short at this energy which is close to the transition energy, the beam stayed in the 28 MHz system for collision. The PHENIX narrow vertex ratio was almost identical with or without deuteron beam re-bucketed.

OPERATION PERFORMANCE

The switch-overs between different energies were very efficient during the deuteron-gold program. The high-efficiency saved enough time to allow switching back to gold-gold operation for one week at the end of the 2016 run. The delivered luminosity at all energies exceeded the goals. The luminosity per week of 200.7 GeV/n was over nine times of that achieved in the 2008 deuteron-gold program.

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