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# SUMMARY OF THE 3-YEAR BEAM ENERGY SCAN II OPERATION AT RHIC

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*Abstract*

Beam Energy Scan phase II (BES-II) operation in the Relativistic Heavy Ion Collider (RHIC), aiming to explore the phase transition between quark-gluon plasma (QGP) and hadronic gas, exceeded the goal of a four-fold increase in the average luminosity over the range of five gold beam energies (9.8, 7.3, 5.75, 4.59 and 3.85 GeV/nucleon) compared to those achieved during Beam Energy Scan phase I (BES-I). We will present the achievements in BES-II together with a summary of the measures taken to improve RHIC performance in the presence of several beam dynamics effects, and details on improvements made during the operation at 3.85 GeV/nucleon in 2021.

## INTRODUCTION

BES-I [1–5] and BES-II [6, 7] explored the structure of the phase diagram by taking gold beam collision data at five energies: 9.8, 7.3, 5.75, 4.59 and 3.85 GeV/nucleon. BES-I operated from 2007 to 2014 at various energies for short periods of time, in order to provide preliminary data for the experiments, and to study the various beam dynamics effects that limit machine performance.

A plan for major hardware upgrades was put in place at the end of the BES-I, including for example electron cooling and 9 MHz RF cavities. These upgrades were used during BES-II from 2019 to 2021 at descending beam energies, with well-defined physics goals at each energy. The main goal was to provide enough experimental data by increasing the average luminosity by a factor of four. This goal was achieved, and in some cases exceeded, in part by improving the initial luminosity at the beginning of a store and by increasing the luminosity lifetime. The electron cooling system was used at the two lowest beam energies (4.59 and 3.85 GeV/nucleon). The luminosities achieved in BES-I and BES-II are presented in Fig. 1, and the primary beam parameters are summarized in Table 1.

The beam energy scans were challenging because the energies are well below the nominal energy range in RHIC – at or below gold beam injection energy of 9.8 GeV/nucleon. The challengings and counter-measures for BES-II operation have been summarised in a separate report [7]. We will present the operational conditions and improvements achieved during the last year BES-II operation at beam energy 3.85 GeV/nucleon.

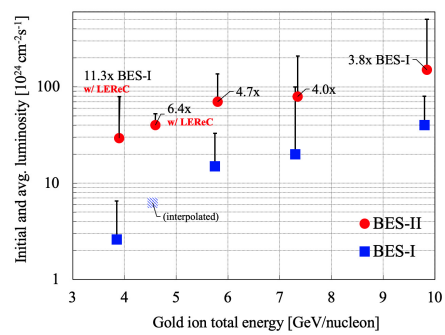


Figure 1: The initial and average luminosities at five gold beam energies achieved during BES-I and BES-II. Red dots and blue squares represent the average luminosity. A small horizontal bar marks the initial luminosity. The average luminosity at 4.59 GeV/nucleon during BES-I is interpolated based on data collected at 3.85 and 5.75 GeV/nucleon.

## OPTIMIZING RHIC DURING ELECTRON COOLING

Three-dimensional electron cooling of colliding beams in both RHIC rings was realized for the first time [8] during BES-II. The electron cooling system was used at the two lowest beam energies (4.59 and 3.85 GeV/nucleon).

Early operations at 3.85 GeV/nucleon were performed with fractional tunes at 0.23. Tune space was explored with the goal of optimizing the average luminosity rather than enhancing just the cooling efficiency, and in particular to find better betatron tunes that enhance the ion beam lifetime in the presence of the high-current electron beam. Performance at 3.85 GeV/nucleon improved significantly when the fractional betatron tunes were lowered from 0.23 to 0.12. The single beam lifetime and the beam lifetime in collision were both improved, the injected bunch intensity was increased, and the initial collision rate was boosted by a factor of two.

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Table 1: Beam Parameters for BES-I and II at Various Energies

| Parameter | Units | 9.8 GeV/nucleon | | 7.3 GeV/nucleon | | 5.75 GeV/nucleon | | 4.59 GeV/nucleon | | 3.85 GeV/nucleon | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | BES-I | BES-II | BES-I | BES-II | BES-I | BES-II | BES-I | BES-II | BES-I | BES-II |
| Bunch int. $N^{\dagger}$ | $10^9$ | 0.9 | 1.8 | 1.1 | 1.75 | 1.1 | 1.7 | 0.4 | 1.1 | 0.5 | 1.5 |
| $\beta^*$ | m | 2.5 | 2 | 3.5 | 3 | 6 | 4 | 10 | 4.5 | 6 | 4.5 |
| Frac. tune | | 0.23 | 0.09 | 0.23 | 0.09 | 0.23 | 0.12 | 0.23 | 0.23 | 0.23 | 0.23/0.12 |
| Chrom.$^{\vee}$ | | NA | -10 | NA | -8 | NA | -7 | NA | -6 | NA | -5 |
| RMS emit. $\epsilon_{x,y}$ | $\mu$m | 2.5 | 1.8 | 1.7 | 2.2 | 2.5 | 2.1 | 1.5 | 1.5 | 1.7 | 1.5 |
| Bunch length $\sigma_s$ | m | 1.6 | 1.4 | 1.8 | 2.2 | 1.4 | 1.5 | 1.4 | 3.5 | 1.6 | 12$^{\wedge}$ |
| Harmonics | | 360 | 360 | 360 | 360 | 360 | 363/121 | 366 | 120 | 369 | 123/369 |
| RF freq.$^{\bullet}$ | MHz | 28 | 28 | 28 | 28 | 28 | 28/9 | 28 | 9 | 28 | 9/28 |
| Bucket area | eV s | 0.9 | 0.9 | 0.54 | 0.54 | 0.36 | 0.481 | 0.25 | 0.81 | 0.18 | 0.6 |
| Long. emit. | eV s | 0.7 | 0.82 | 0.5 | 0.5 | | 0.28 | | 0.5 | | 0.24 |
| Beam-beam para. | $10^{-3}$ | 2.1 | 4.1 | 1.7 | 3.4 | 2.1 | 3.4 | 0.076 | 3.8 | 0.095 | 3.5 |
| SC tune shift | | 0.013 | 0.05 | 0.036 | 0.07 | 0.058 | 0.11 | 0.01 | 0.09 | 0.036 | 0.1 |
| Cooling | | No | No | No | No | No | No | No | Yes | No | Yes |
| Demagnetization | | No | Yes | No | Yes | No | Yes | No | Yes | No | Yes |
| Store length | mins. | 35 | 60 | 45 | 45 | 20 | 23 | 15 | 40 | 10 | 25 |
| Ave. lumi. $L_{ave}$ | $10^{24}$cm$^{-2}$s$^{-1}$ | 40 | 150 | 20 | 79 | 15 | 70 | 6.25$^{\ddagger}$ | 40 | 2.6 | 29.4 |
| Improv. factor | | 3.8 | | 4.0 | | 4.7 | | 6.4 | | 11.3 | |

$^{\dagger}$ The bunch intensity was measured at the start of physics data taking. In all cases there were 111 bunches.
$^{\vee}$ BES-I chromaticities were difficult to measure and control, before the demagnetization cycle was devised.
$^{\wedge}$ This bunch length is the full width half maximum of the flattened longitudinal profile.
$^{\bullet}$ In the 28/9 and 9/28 cases of a double RF system, the first value is the primary RF frequency.
$^{\ddagger}$ This average luminosity is interpolated from those achieved at 5.75 and 3.85 GeV/nucleon.

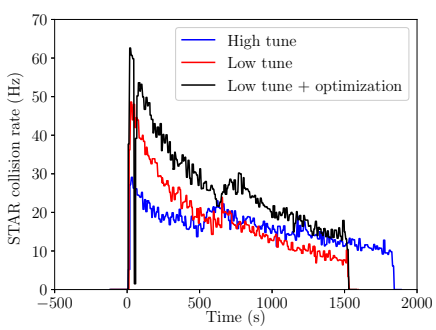


Figure 2: The experimental collision rates for stores at 3.85 GeV/nucleon with different fractional betatron tunes. The blue data was taken with fractional tunes of 0.23, when the electron cooling efficiency was higher. The red data corresponds to fractional tunes of 0.12, when the cooling efficiency was reduced but the ion beam lifetime was increased. The black data was taken after fine betatron tune adjustments and with smaller electron beam currents, further improving the ion beam lifetime with less heating.

However, these lower tunes reduced the transverse and longitudinal cooling rates, compared to fractional tunes at 0.23, because lower electron beam currents are required to maintain acceptable ion beam lifetimes. The average luminosity was comparable at the lower fractional tune, even though the luminosity lifetime suffered due to ion interactions with the electron beam. The electron beam current was then re-scanned, greatly alleviating the electron-induced ion-beam losses and increasing the average luminosity beyond the best achieved with the high fractional tune. Additional fine tuning of the betatron tunes of both ion beams increased the average luminosity even further, exceeding the best high fractional tune value by about 50%, as shown in Fig. 2.

## REDUCING THE PEAK CURRENT WITH THIRD HARMONIC CAVITIES

Reducing the peak current is a well-known way to alleviate space charge effects [9]. However, during BES-I/II it came with the side effect of reducing the fraction of collisions within the vertex cut. Nonetheless the luminosity increased significantly when this technique was applied at 3.85 GeV/nucleon, because it enabled collisions with much higher bunch intensities provided by the AGS [10, 11] with Tandem [12] as the ion source.

Figure 3 shows how the bunch profile was flattened when third harmonic cavities (28 MHz, 60 kV) were employed in addition to the fundamental RF system (9 MHz, 180 kV). Fast beam loss at injection without the third harmonic was observed with $1.6 \times 10^9$ injected bunch intensity, caused by a space charge tune shift of up to 0.14. RHIC was able to maintain 60% higher initial bunch intensities when fast losses were eliminated by bunch flattening. The benefits of higher bunch intensities and better lifetimes overcame the drawback of lower vertex cut efficiencies. The initial luminosity improved by a factor of two and the average luminosity improved by more than a factor of two.

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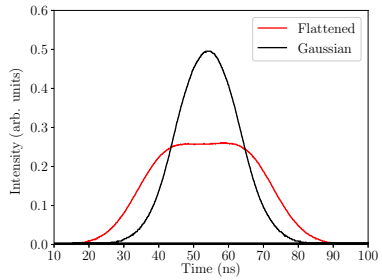


Figure 3: Gaussian longitudinal profile (the black curve) for a single RF system and flattened longitudinal profile (the red curve) for a double RF system, with the third harmonic cavities phased opposite to the primary RF.

## OPERATIONAL EXPERIENCE OF THE BUNCH-BY-BUNCH FEEDBACK SYSTEM

Two benefits emerged from operating at 3.85 GeV/nucleon with both the bunch-by-bunch damper and also the double RF system [13]. First, the beam instability was suppressed, minimizing the probability of losing stores and improving operational reliability. Second, the injected bunch intensity increased by as much as 10% and the luminosity increased by as much as 20% because beam emittance dilution was suppressed. Beam dilution with the feedback system off was a result of injecting beams directly into collision. Injection oscillations in one ring disturbed the stored beam in the other ring through the beam-beam effect, and enlarged the emittance. The reflection of the injection kicker pulse also excited a few bunches in the injected beam. Both of these disturbances were alleviated when bunch-by-bunch feedback was turned on.

## SUMMARY

The 3-year Beam Energy Scan phase II operation at RHIC was successfully completed in 2021. Average luminosities at all energies achieved or exceeded the goal of a fourfold increase over those achieved in phase I. This success was realized by implementing several measures that increased the initial bunch intensity, and the beam and luminosity lifetimes.

Intrabeam scattering growth rates were mitigated by Low Energy RHIC electron Cooling at the two lowest energies, 3.85 and 4.59 GeV/nucleon. The luminosity improved by 60% to 100% after cooling was optimized by tuning the electron and ion beam parameters. A secondary RF system provided a larger bucket area and stronger longitudinal focusing, further reducing emittance dilution due to IBS at 5.75 GeV/nucleon.

Space charge and beam-beam impacts on the beam lifetime were ameliorated by lowering the fractional tunes to around 0.1 at 9.8, 7.3 and 5.75 GeV/nucleon. This enabled the tune footprint to avoid as many strong resonances as possible.

Low frequency 9 MHz cavities were used at 4.59 and 3.85 GeV/nucleon, enabling lower peak currents and weakening the space charge effect. Third harmonic 28 MHz cavities were also used at 3.85 GeV/nucleon, to further reduce the peak currents. An equally large benefit of low frequency operation was the increased bucket acceptance, which was critical for accepting larger intensities from the injectors. Although the effective luminosity ratio (after a vertex cut) was lower at lower RF frequencies, this shortcoming was overcome by the higher bunch intensities.

A bunch-by-bunch transverse damper system was commissioned and implemented in operation at 3.85 GeV/nucleon. This eliminated beam instabilities and improved the injected bunch brightness by combating emittance dilution during the injection process.

Demagnetization cycles were used at all BES-II energies to reduce persistent current induced sextupolar and higher order field errors in the arc dipoles, and also the drift of the magnetic field. This not only improved beam lifetimes, but also facilitated quick and frequent transitions between multiple programs/studies at different energies.

The $\beta^*$ values were reduced at all energies, compared to BES-I. Dynamic reductions were possible mid-store at the two lowest energies, once ion emittances were sufficiently reduced by electron cooling.

### *Energy-by-Energy*

**9.8 GeV/nucleon.** Fractional tunes less than 0.1 gave better lifetimes in the presence of space-charge and beam-beam effects. Demagnetization cycles alleviated persistent current effects. Used 28 MHz RF only to increase the fraction of events within the vertex cut. Smaller $\beta^*$. Higher bunch intensities.

**7.3 GeV/nucleon.** Fractional tunes less than 0.1. Demagnetization cycle. Used 28 MHz RF only. Smaller $\beta^*$. Higher bunch intensities.

**5.75 GeV/nucleon.** Raised fractional tunes just above 0.1 to accommodate enhanced space charge and beam-beam tune shifts. Demagnetization cycle. Used 28 MHz primary and 9 MHz secondary RF to increase the bucket areas and strengthen longitudinal focusing. Smaller $\beta^*$. Higher bunch intensities. Smaller longitudinal emittance beam from the Tandem.

**4.59 GeV/nucleon.** Electron cooling on. Fractional tunes at 0.23 gave higher cooling efficiency. Used 9 MHz RF only to increase bucket areas and to reduce peak currents, weakening space charge effects. Demagnetization cycle. Smaller initial $\beta^*$. Dynamic $\beta^*$-squeezes after sufficient cooling. Higher bunch intensities.

**3.85 GeV/nucleon.** Electron cooling on. Fractional tunes lowered from 0.23 to 0.12 for luminosity optimization. Electron beam current scan. Used 9 MHz primary and 28 MHz secondary RF to flatten the bunch profile and weaken the space charge effect. Demagnetization cycle. Smaller initial $\beta^*$. Dynamic $\beta^*$-squeeze. Higher bunch intensities and short filling times with 4 bunches from the Tandem.

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