

Experimental demonstration of accelerating a beam with a large transverse emittance ratio in the relativistic heavy ion collider for the electron-ion collider

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The electron-ion collider (EIC), to be constructed at Brookhaven National Laboratory, will collide polarized high-energy electron beams with hadron beams, achieving luminosities of up to $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in the center-of-mass energy range of 20–140 GeV. To reach such high luminosity, the EIC will employ small, flat beams at the interaction point. According to the design of the EIC hadron storage ring (HSR), hadron beams with a large transverse emittance ratio of 11:1 will be generated at the injection energy using an electron cooling technique and then accelerated to high energies for collisions. Accelerating hadron beams with such a large emittance ratio had never been demonstrated elsewhere—until our recent beam experiment at the relativistic heavy ion collider (RHIC). In this experiment, we successfully generated a large transverse emittance ratio of 13:1 with a gold-ion beam at 31 GeV/nucleon using stochastic cooling. We then accelerated this beam, with a transverse emittance ratio of 11:1, from 31 to 100 GeV/nucleon. Thanks to RHIC's high-performance orbit, tune, and decoupling feedback systems, the large emittance ratio was well maintained throughout the 5-min-long acceleration process. This experiment fully validated the EIC/HSR design assumptions—namely, that large-emittance-ratio hadron beams can be generated at injection energy and then accelerated to high energies for collisions.

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The electron-ion collider (EIC) [1], to be built at Brookhaven National Laboratory, will uniquely address profound questions about nucleons—neutrons and protons—and how they assemble to form atomic nuclei. The design requirements for the EIC were defined in the 2015 long range plan for U.S. Nuclear Physics [2]. The EIC will collide high-energy polarized electrons with polarized protons and light-to-heavy ions in the center-of-mass energy range of 20–140 GeV. The peak luminosity will reach $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for collisions between 10 GeV electrons and 275 GeV protons, about 2 orders of magnitude higher than that achieved by the previous electron-proton collider HERA [3,4]. Once built, the EIC will be the only accelerator collider in the U.S.

Figure 1 shows a schematic plot of the EIC accelerator complex. The EIC consists of two storage rings: the Hadron Storage Ring (HSR) and the Electron Storage Ring (ESR), both housed in the existing tunnel of the relativistic heavy ion collider (RHIC) [5]. A new electron injection

accelerator chain will deliver highly polarized, high-energy electron beams to the ESR. RHIC consists of two rings, known as the blue ring and the yellow ring. The HSR will reuse the arcs of the yellow ring, with new interaction regions and straight sections between the arcs. RHIC is scheduled to be decommissioned at the end of 2025.

To maximize its luminosity, the EIC design adopts high bunch intensities, high beam-beam parameters, flat beam sizes at the IP, and more than 1000 bunches in each ring. The flat beams, with a rms beam size ratio between the horizontal to vertical ones of about 11:1, are achieved through both unequal transverse β^* -functions at the IP, with $\beta_x^* : \beta_y^* \approx 11 : 1$, and unequal transverse emittances, with $\epsilon_x : \epsilon_y \approx 11 : 1$.

As we know, electron storage rings naturally have very small vertical emittance due to synchrotron radiation effects. However, for hadron beams, the transverse emittances are typically the same or closely matched. Flat-beam collisions with a transverse emittance ratio greater than 10:1 were once proposed for a 50 TeV hadron collider to achieve a peak luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, where the small vertical emittance could be generated by the proton's synchrotron radiation effects [6]. However, for lower proton energies, such as 41 to 275 GeV in the EIC, hadron beam cooling is required to generate such a large emittance ratio.

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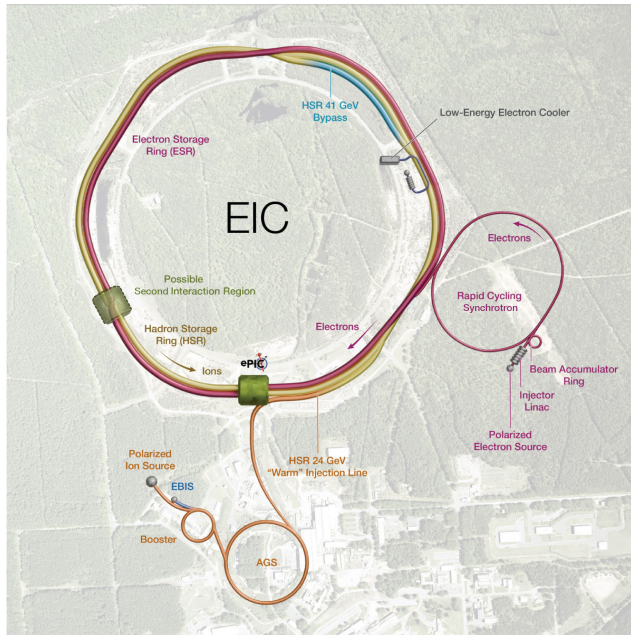


FIG. 1. Schematic plot of the EIC accelerator complex at Brookhaven National Laboratory.

There are two major effects to be considered for the generation and maintenance of large-emittance-ratio hadron beams: intrabeam scattering (IBS) and transverse betatron coupling. IBS arises from multiple small-angle Coulomb scatterings between charged particles in a bunch, leading to a 3D increase in beam emittances [7–9]. Linear betatron coupling couples the horizontal and vertical motions of particles, leading to changes in the betatron tunes and mixing of the transverse emittances [10,11]. In the EIC/HSR, when cooling is active, betatron coupling makes it difficult to selectively cool a single transverse emittance—for example, the vertical emittance.

To counteract IBS effects and achieve/maintain small transverse emittances, phased cooling techniques were proposed for the EIC design: (1) Traditional electron cooling [12–14] is used to precool the proton beam at the injection energy of 24 GeV/nucleon, reaching the design emittances and a large transverse emittance ratio. The resulting “flat” proton beam is then accelerated to high energies for collisions. (2) Strong hadron cooling—possibly coherent electron cooling [15–17] or storage-ring electron cooling [18–20]—is employed at collision energies to balance IBS effects and maintain the proton beam emittances and beam sizes, thereby achieving high average luminosity.

Recently, strong hadron cooling was removed from the EIC baseline design and deferred as a future upgrade project. The main reason is that the technology is not yet mature enough. The EIC project can still meet the DOE “Mission Need” requirements without strong hadron cooling, relying instead on cooling at injection. As a result, large-emittance-ratio (11:1) proton beams can only be

generated at the injection energy of 24 GeV/nucleon and then accelerated to collision energies. This large ratio must be maintained during acceleration to ensure high luminosities at collision energies. However, accelerating hadron beams with such a large emittance ratio has never been demonstrated before. The RHIC 2025 run will be the final year of RHIC operation before its shutdown, making it crucial to experimentally demonstrate the feasibility of accelerating a large-emittance-ratio beam while preserving the ratio during acceleration.

In 2023, we successfully demonstrated an 11:1 emittance ratio with gold-ion beams at 100 GeV/nucleon [21,22], thanks to the existing RHIC stochastic cooling [23,24] and decoupling feedback [25,26]. To avoid transverse emittance mixing and maintain the 11:1 ratio, the amplitude of the global coupling coefficient needed to be about 10 times smaller than the fractional transverse tune split.

From RHIC operation experiences, the transverse emittances of hadron beams are typically close to each other at injection. Both horizontal and vertical emittances often increase somewhat after about 5–6 min of acceleration, possibly due to faster IBS growth rates at lower energies, crossing the transition energy, beam instabilities, imperfect beam optics control, or power supply stability issues.

RHIC’s stochastic cooling system was originally designed for high-energy cooling at 100 GeV/nucleon. In the 2016 deuteron-gold run, it was successfully operated at 31 GeV/nucleon. To generate a large transverse emittance ratio at this energy, we planned to cool only the vertical emittance and allow IBS to increase the horizontal emittance. To reduce experimental setup time, we would not employ longitudinal cooling in this experiment.

For our experiment, we planned to generate a flat gold-ion beam with an 11:1 transverse emittance ratio at 31 GeV/nucleon and then accelerate it to 100 GeV/nucleon. Achieving this required two acceleration stages (energy ramps): one from the standard RHIC ion injection energy of 9.8 to 31 GeV/nucleon, and another from 31 to 100 GeV/nucleon. In total, 48 h of beam time were allocated across three sessions: the first two for ramp development and stochastic cooling setup, and the final session for the physics experiment.

The newly designed ramp from 31 to 100 GeV/nucleon lasts 320 s. To simplify operations, we only use the yellow ring. We do not perform β^* -squeezing during acceleration, unlike standard RHIC operation. The transition energy for ions in RHIC is about 23 GeV/nucleon, so the second ramp with the flat beam does not cross transition energy. For the EIC/HSR, the proton beams will not go through transition energy.

This experiment requires tight control of orbit, tune, and coupling at 31 GeV/nucleon for flat-beam generation, and during the 31 to 100 GeV/nucleon ramp for maintaining the large emittance ratio. Since 2006, RHIC has been equipped with orbit, tune, and coupling feedback systems for energy

ramps. In this experiment, we set the transverse fractional tunes to (0.238, 0.212) at 31 GeV/nucleon and maintained them during the second energy ramp, with a tune split of 0.026 which is large enough to avoid coupling-induced transverse emittance mixing.

The first experimental session took place on June 25, 2025. Our goal was to develop the two energy ramps. Normally, RHIC operates with only one energy ramp. In this experiment, we needed to integrate these two ramps into one complete ramp cycle. If time permitted, we also planned to set up vertical stochastic cooling at 31 GeV/nucleon. This session went smoothly. We used a total of 12 h and achieved all the planned experimental goals.

In the final part of this session, we injected 12 bunches into the yellow ring with an average bunch intensity of about 1.5×10^9 ions per bunch. After accelerating the beam to 31 GeV/nucleon, we began cooling the vertical emittance to generate a large-emittance-ratio beam.

The transverse emittances were measured with an ionization profile monitor (IPM). Within about 2 h, we obtained an emittance ratio of 6:1. At that point, the normalized rms horizontal and vertical emittances were (3.2, 1.6) μm . Unfortunately, when we turned on the base-band tune meter (BBQ) to double-check the tunes and coupling, the vertical emittance blew up. The issue was traced to chromaticities that were not properly corrected and were close to zero. We dumped this beam and concluded the first session.

During this session, we also measured β -functions at 31 and 100 GeV/nucleon. At both energies, the measured β -functions differed from the model by less than 10%. Therefore, we used the model β -functions at the IPM for emittance measurement in this experiment. The main uncertainty in the emittance measurement comes from β -function calibration at the IPM.

The second experiment session took place on July 9, 2025. At the beginning of this session, we fine-tuned both energy ramps. The chromaticities at 31 GeV/nucleon were measured and set to their typical values of about 4 units. We then began the physics experiment. As before, we used 12 bunches in the yellow ring, with a bunch intensity of about 1.5×10^9 ions per bunch at injection. Due to several machine failures and subsequent repairs, we had only about 9.5 h of beam time in this session.

Figure 2 shows the measured emittances and emittance ratio for this session. In the plot, the red and purple vertical lines indicate the start and end of the two energy ramps. In about 2.5 h at 31 GeV/nucleon, we achieved a transverse emittance ratio of 6:1. However, reaching a higher emittance ratio would have required significantly more time due to asymptotic behavior of emittances. Therefore, when the emittance ratio reached 6.7:1, we decided to accelerate this beam to 100 GeV/nucleon. We stopped vertical cooling before acceleration.

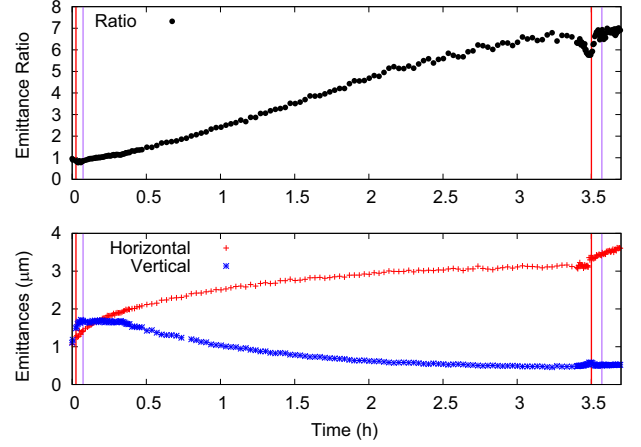


FIG. 2. Measured transverse emittances in the bottom plot and the transverse emittance ratio in the top plot for the experiment conducted on July 9, 2025.

Figure 3 shows the measured transverse emittances and emittance ratio during the acceleration from 31 to 100 GeV/nucleon. The vertical gray lines mark the key time points of the ramp. From the plot, the emittance ratio decreased slightly from 6.7:1 to 5.8:1 before acceleration began. We observed about 5.8% ion intensity loss due to debunched beam at the start of acceleration. The entire acceleration took about 320 s. During acceleration, the large emittance ratio was well maintained. The measured emittances after acceleration were (3.45, 0.52) μm , with a transverse emittance ratio about 6.5:1. This is the first successful demonstration of accelerating a large-emittance-ratio hadron beam in an accelerator.

The third experimental session was conducted on July 23, 2025. To produce an 11:1 transverse emittance ratio beam comparable to the EIC/HSR design, we reduced the bunch intensity from 1.5×10^9 to 0.8×10^9 ions per bunch. Lower bunch intensity improves the efficiency of stochastic cooling and further reduces vertical emittance, but it also

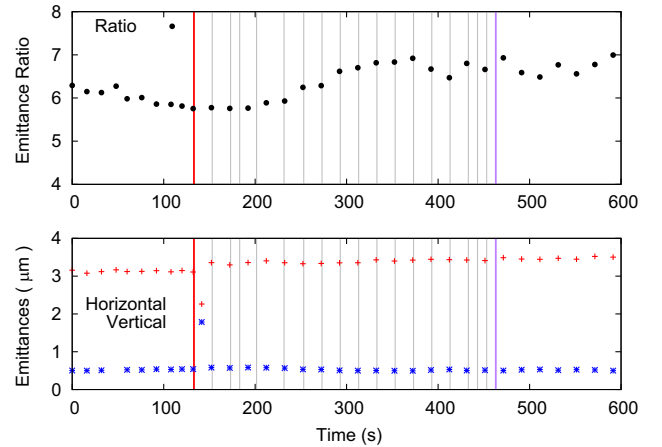


FIG. 3. Measured transverse emittances in the bottom plot and the transverse emittance ratio in the top plot during acceleration for the experiment conducted on July 9, 2025.

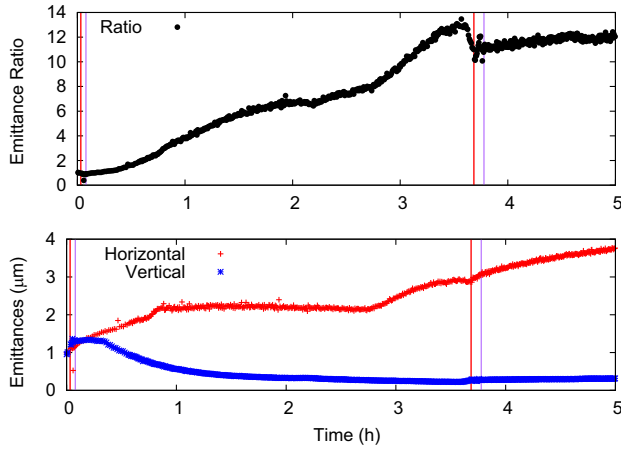


FIG. 4. Measured transverse emittances in the bottom plot and the transverse emittance ratio in the top plot for the experiment conducted on July 23, 2025.

slows horizontal IBS growth. To counter this, we planned a controlled horizontal emittance increase. For reliable IPM measurements, the number of gold ion bunches was increased from 12 in the first two sessions to 28.

Figure 4 shows the measured transverse emittances and transverse emittance ratio during this experiment. At 0.75 h, we tested a method to blow up the horizontal emittance using horizontal stochastic cooling kicker. This was achieved by setting one cooling frequency's phase advance between the pickup and kicker to 180° , instead of 90° for cooling, and the method proved effective.

After this test, horizontal cooling was switched off, and only vertical stochastic cooling was applied. The vertical emittance continued to decrease, while the horizontal emittance remained nearly constant between 0.75 and 2.75 h. During this period, the measured beam decay was 5–15%/h, significantly higher than the 2–4%/h observed in the first two sessions. Ion loss in the horizontal plane, possibly due to not well optimized collimation settings, may explain the constant horizontal emittance readings.

At 2.75 h, we began to use the horizontal stochastic cooling kicker to further increase the transverse emittance ratio. The horizontal and vertical emittances were initially (2.17, 0.27) μm , yielding an 8:1 ratio. Within 1 h, the horizontal emittance rose to 2.92 μm while the vertical decreased to 0.22 μm , giving a 13:1 ratio. For comparison, the EIC/HSR normalized emittances are (3.02, 0.29) μm with a ratio 11:1.

Before accelerating this flat beam, all stochastic cooling was switched off, and the beam was observed for 5 min to confirm that the horizontal kicker no longer acted on the beam. During this interval, the vertical emittance increased rapidly, while the horizontal remained unchanged. Just before acceleration, the transverse emittance ratio had decreased to 11:1. The measured vertical emittance growth time was 0.5 h, consistent with IBS predictions.

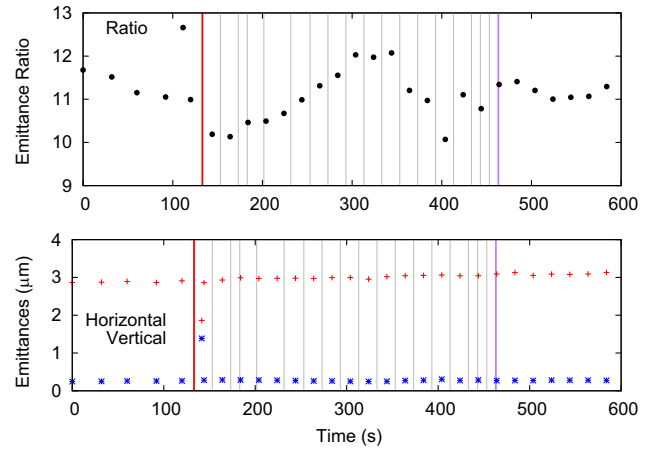


FIG. 5. Measured transverse emittances in the bottom plot and transverse emittance ratio in the top plot during acceleration for the experiment conducted on July 23, 2025.

Figure 5 shows the emittances and transverse emittance ratio during acceleration from 31 to 100 GeV/nucleon. Only about 1% beam intensity loss due to debunched beam occurred at the beginning of this energy ramp. During the 230 s acceleration, both horizontal and vertical emittances were well preserved, and the transverse emittance ratio of 11:1 was maintained.

We attribute the success of this experiment to the high-performance orbit, tune, and coupling feedback systems on the RHIC energy ramp. As an example, Fig. 6 shows the tunes and amplitude of coupling coefficient during the ramp. The tunes (0.238, 0.212) remained constant, while the coupling coefficient amplitude measured by the decoupling feedback system was around 0.003. This coupling level was higher than in routine physics operations in 2025, where it typically stayed below 0.002 during acceleration, except around transition energy. We did not have sufficient

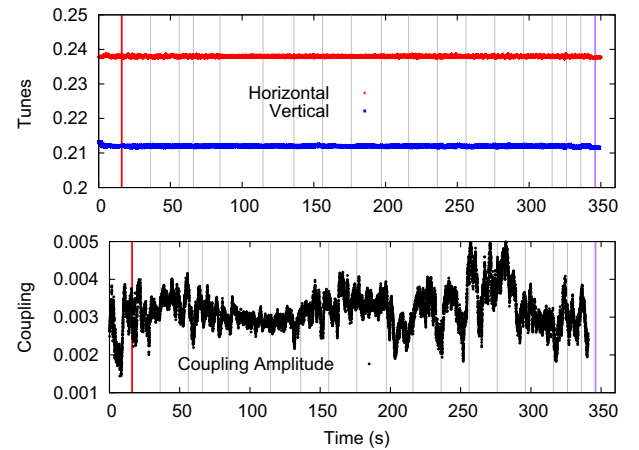


FIG. 6. Transverse tunes and amplitude of coupling coefficient during acceleration in the experiment conducted on July 23, 2025.

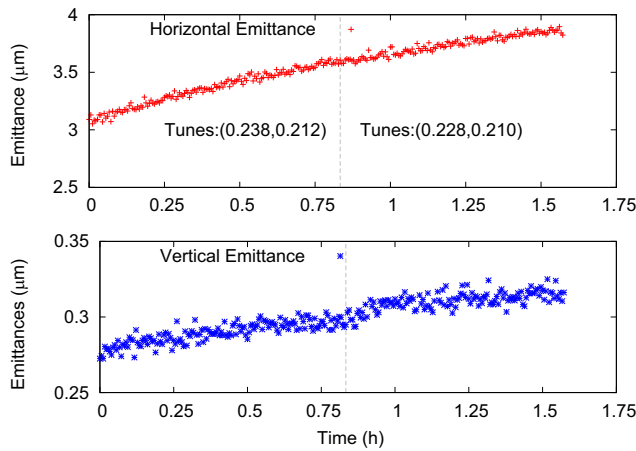


FIG. 7. Measured transverse emittances at 100 GeV/nucleon during the experiment conducted on July 23, 2025.

time to implement feed-forward coupling corrections for this experiment.

After reaching 100 GeV/nucleon, we kept the large-emittance-ratio beam for 1 h 45 min. Figure 7 shows the IPM measured horizontal and vertical emittances. In the first 50 min, we used the fractional tunes (0.238, 0.212) from the energy ramp. Afterward, we moved the tunes closer to (0.238, 0.210), the design collision tunes for the EIC/HSR. During this period, the emittance ratio slightly increased from 11:1 at the beginning of store to 12:1 at the end of store. The measured horizontal emittance growth time was 7.2 h, while the vertical growth time was 11.2 h. These values were reproduced by our IBS modeling. We also measured the amplitude of the coupling coefficient, which was about 0.001 at 100 GeV/nucleon. We used about 7.5 h of beam time in the third experimental session.

In summary, we successfully generated a gold-ion beam with a maximum transverse emittance ratio of 13:1 at an ion energy of 31 GeV/nucleon. The beam was accelerated to 100 GeV/nucleon in 320 s with less than 1% beam intensity loss. The horizontal and vertical emittances were well preserved, and the transverse emittance ratio of 11:1 was maintained. This large-emittance-ratio beam was stored for about 2 h, during which the emittance ratio remained stable. This experiment completely validated the EIC/HSR design assumptions—namely, that large-emittance-ratio hadron beams can be generated at injection energy and subsequently accelerated to high energies for high-luminosity collisions. More beam experiments with large-emittance-ratio beams are going on during the 2025 RHIC run, such as maximizing the beam-beam parameter for flat-beam collisions and mitigating vertical emittance growth using tune scans and compensation sextupoles.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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