Editors' Suggestion

Experimental Demonstration of a Large Transverse Emittance Ratio 11∶1 in the Relativistic Heavy Ion Collider for the Electron-Ion Collider

Y. Luo,* D. Xu, M. Blaskiewicz, and C. Montag
Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 18 December 2023; accepted 16 April 2024; published 13 May 2024)

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 1.0×10^{34} cm^{-2} s^{-1} in the center-of-mass energy range of 20–140 GeV. To achieve such high luminosity, the EIC will employ small and flat beams at the interaction point. In the hadron storage ring of the EIC, the ratio of horizontal to vertical emittances is approximately 11∶1. In contrast, in previous or existing hadron colliders, the horizontal and vertical emittances are typically similar or closely matched. At the Relativistic Heavy Ion Collider (RHIC), we experimentally demonstrated a large transverse emittance ratio of 11∶1 with gold ion beams at a particle energy of 100 GeV per nucleon, thanks to stochastic cooling and fine decoupling. Furthermore, we demonstrated collisions with flat beams, featuring a transverse beam size ratio of 3∶1 for the first time at the RHIC.

DOI: 10.1103/PhysRevLett.132.205001

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 1.0×10^{34} cm^{-2} s^{-1} in the center-of-mass energy range of 20–140 GeV [1]. The EIC consists of two storage rings: the hadron storage ring (HSR) and the electron storage ring (ESR), both of which will be housed within the existing tunnel of the Relativistic Heavy Ion Collider (RHIC) [2]. RHIC has two storage rings, the blue ring and the yellow ring. The HSR consists of arcs from both RHIC rings and new straight sections between the arcs. RHIC is set to be decommissioned in 2025.

Luminosity, a key collider performance metric, signifies the rate of physics events per unit cross section per second during beam collisions [3]. The maximum luminosity in the EIC is limited by a range of factors. The primary factors are attainable beam-beam parameters (ξ_h, ξ_e), maximum beam divergences (σ'_h, σ'_e) at the interaction point (IP) defined by the interaction region magnet apertures and detector forward acceptance requirements, and maximum beam currents. The luminosity can be rewritten as [1,4]

$$L = f_b \frac{\pi \gamma_h \gamma_e}{r_{0,h} r_{0,e}} (\xi_h \sigma'_h)(\xi_e \sigma'_e) \frac{(1+\kappa)^2}{\kappa} H, \qquad (1)$$

where f_b is the bunch repetition rate, $\gamma_{h,e}$ are the relativistic factors of the respective beams, and $r_{0,h,e}$ are the classical radii of the electron and the hadron. Flatness $\kappa = \sigma_y^*/\sigma_x^*$ is the aspect beam size ratio at the IP, where the beam sizes of electron and hadron beams are assumed fully matched. The factor H describes the luminosity modification due to the hourglass effect and crossing angle.

The luminosity in the EIC is maximized with flat beams at the IP with $\kappa \ll 1$, as indicated by Eq. (1). This is realized by both unequal transverse β functions at the IP, $\beta_y^* \ll \beta_x^*$, and unequal transverse emittances, $\epsilon_y \ll \epsilon_x$. Electron storage rings naturally have a very small vertical emittance. The magnitudes of the hadron design emittances are chosen such that they can be achieved and maintained by the projected strong electron cooling facility, which must counterbalance the emittance growth rates due to the intrabeam scattering (IBS). As an example, Table I presents the design parameters for the collision mode involving 275 GeV protons and 10 GeV electrons [1]. In this table, paired values in the parentheses are ordered as (horizontal, vertical). In this mode, both the electron and proton beams reach their maximum beam-beam parameters in the EIC, and its peak luminosity reaches 1×10^{34} cm^{-2} s^{-1}. The

TABLE I. Main machine and beam design parameters for the collision mode involving 10 GeV Electrons and 275 GeV Protons in the EIC.

Quantity	Unit	Proton	Electron
Beam energy	GeV	275	10
No. of bunches	⋯	1160	
Bunch intensity	10^{11}	0.668	1.72
Beam sizes at IP	m	(95, 8.5)	
(β_x^*, β_y^*) at IP	cm	(80, 7.2)	(45, 5.6)
Transverese emittances	nm	(11.3, 1.0)	(20.0, 1.3)
Flatness $\kappa = \sigma_y^*/\sigma_x^*$	⋯	0.09	
Beam-beam parameter	⋯	(0.012, 0.012)	(0.072, 0.1)
Transverse tunes	⋯	(0.228, 0.210)	(0.08, 0.14)
peak luminosity	cm^{-2} s^{-1}	1.0×10^{34}	

design horizontal and vertical emittances are 11.3 and 1.0 nm for the proton beam. This large transverse emittance ratio also applies to other collision modes in the EIC design.

We tested the viability of the 11:1 ion emittance ratio through a series of beam experiments at the RHIC, starting in 2017. Two main effects must be considered for our experiments to demonstrate a large emittance ratio: the IBS effect, akin to thermalization, and the betatron coupling between horizontal and vertical oscillations. IBS arises from multiple small-angle Coulomb scatterings between charged particles in a bunch, leading to 3D beam emittance increase [5–7]. To counteract the IBS effects and achieve or maintain small transverse emittances, especially in the vertical plane, phased cooling techniques are adopted in the current EIC design: (i) Traditional electron cooling [8–10] is used to precool the proton beam at the injection energy of 24 GeV/nucleon, reaching the design normalized emittances and transverse emittance ratio. (ii) Strong hadron cooling [11–13] or storage electron cooling [14–16] is employed at collision energies to balance the IBS effect and maintain the proton beam emittances.

Betatron coupling resonance couples the horizontal and vertical motions of particles, leading to changes in the betatron tunes and the mixing of transverse emittances [17,18]. Also, when cooling is operative, it will make it difficult to selectively cool a single transverse emittance. The sources of betatron coupling include the detector solenoids, skew quadrupoles, and residual coupling sources, such as roll errors of quadrupoles and vertical closed orbits in sextupoles. Using Hamiltonian perturbation theory of linear difference betatron coupling [18], the transverse tune split with coupling is

$$|Q_x - Q_y| = \sqrt{|Q_{x,0} - Q_{y,0}|^2 + |C^-|^2}. \quad (2)$$

Here $Q_{x,y}$ are the fractional tunes with coupling, while $Q_{x,y,0}$ are the fractional tunes without coupling. $|C^-|$ is the amplitude of coupling coefficient. The pseudo horizontal and vertical emittances with coupling, denoted as $\epsilon_{x,y}$, are given by

$$\epsilon_x = \epsilon_{x,0} - \frac{|C^-|^2/2}{|Q_{x,0} - Q_{y,0}|^2 + |C^-|^2}(\epsilon_{x,0} - \epsilon_{y,0}), \quad (3)$$

$$\epsilon_y = \epsilon_{y,0} + \frac{|C^-|^2/2}{|Q_{x,0} - Q_{y,0}|^2 + |C^-|^2}(\epsilon_{x,0} - \epsilon_{y,0}). \quad (4)$$

Here $\epsilon_{x,y,0}$ represent the emittances without coupling.

In 2006, we successfully demonstrated and implemented a global decoupling feedback system at RHIC [19,20]. This system relies on continuous measurements of the coupling coefficient, achieved through a baseband phase-lock-loop tune meter. The coupling coefficient is derived from the measured eigenmode amplitude projections onto the transverse axes. As the coupling coefficient is a complex number, we organized the existing skew quadrupoles at RHIC into two orthogonal families to effectively correct global coupling. Since then, decoupling feedback has become an integral part of routine RHIC operation, applied during injection, at store, and during acceleration. Correcting betatron coupling is essential for managing large emittance ratio beams during their generation, maintenance, acceleration, and collision.

To demonstrate a large transverse emittance ratio at RHIC for the EIC, we opted to use gold ion $^{197}Au^{79+}$ beams instead of proton beams. This choice was motivated by the more pronounced IBS growth effect for gold ion beams compared to proton beams. In high-energy hadron synchrotrons like RHIC, where the beam's stored energy is much higher than the transition energy, longitudinal IBS growth is much faster than transverse IBS emittance growth. Horizontal emittance growth due to IBS mainly results from horizontal momentum dispersion and the enlarged momentum spread caused by longitudinal IBS growth. Given the typical design with zero vertical dispersion in a ring, vertical emittance growth due to IBS is much smaller than in the other two planes. In our experiments, with effective betatron coupling correction, vertical emittance growth due to the IBS effect is negligible for the initial beam emittances.

In our first experiment in 2017, we loaded the yellow ring of RHIC with nominal intensity bunches (2×10^9 ions/bunch) for the first half of the bunch train, followed by half-intensity bunches for the remainder. After accelerating the beams to 100 GeV/nucleon, we applied betatron coupling correction using the decoupling feedback system. The transverse beam tunes were set to (0.237, 0.228). Approximately 2 h into the store, maximum emittance ratios of 2:1 and 1.7:1 were achieved for the full and half intensity bunches. The bunch intensity did not play a big role in this experiment.

For RHIC ion operation, we are equipped with 3D stochastic cooling to counteract the IBS effect for ions at 100 GeV/nucleon. Operational longitudinal stochastic cooling for high-energy bunched ion beams was implemented in RHIC in 2007 [21,22], while horizontal and vertical stochastic cooling capabilities were added in 2012. With 3D stochastic cooling, to maximize the transverse emittance ratio, we can switch off horizontal-plane stochastic cooling and only employ vertical-plane stochastic cooling. This allows IBS to grow horizontal emittance while the stochastic cooling effectively reduces vertical emittance, thus maximizing the transverse emittance ratio.

In the 2018 beam experiment, we investigated the necessary decoupling conditions to stop transverse emittance exchange. Using gold ion beams at 100 GeV/nucleon, we intentionally switched off horizontal stochastic cooling while keeping vertical-plane cooling on. We scanned the tune split to determine the point at which horizontal emittance would no longer be affected by vertical cooling due to betatron coupling. Our conclusion was that the global coupling coefficient amplitude $|C^-|$ should be at least 10 times smaller than the transverse tune split without coupling $|Q_{x,0} - Q_{y,0}|$ to prevent transverse emittance exchange. This finding was later confirmed through analytical estimates and numerical multiparticle simulations [23]. However, due to limited beam time in this experiment, we were unable to maximize the transverse emittance ratio.

In the following years, RHIC underwent low-energy scan experiments from 2019 to 2021, followed by a polarized proton run in 2022. In 2023, RHIC returned to 100 GeV gold ion operation to commission the new sPHENIX detector. With longitudinal and vertical stochastic cooling properly tuned, we were ready to resume our experiment to maximize the transverse emittance ratio under optimal experimental conditions. Another goal of our experiments is to test the capability of the existing RHIC global coupling correction system for the purpose of the EIC.

In the first beam experiment on June 14, 2023, we had 56 gold ion bunches in the blue ring, each with a bunch intensity of about 1×10^9 ions per bunch. After reaching the stored energy of 100 GeV/nucleon, we turned on both longitudinal and vertical cooling. Global betatron coupling was automatically corrected using the decoupling feedback at the beginning of the store. We then adjusted the transverse tunes to (0.236, 0.216) with a tune split of 0.02, comparable to the tune split for the HSR design tunes (0.228, 0.210).

Figure 1 shows the measured horizontal and vertical emittances in the bottom plot and the transverse emittance ratio in the upper plot. The emittances were measured using ion profile monitors (IPMs), and the rms normalized emittances are presented in units of μm, as conventionally used in RHIC operation. From the plot, the horizontal and vertical emittances were initially close to each other, at approximately 1.1 μm at the beginning of the store. As IBS led to the growth of the horizontal emittance, while stochastic cooling effectively reduced the vertical emittance, the transverse emittance ratio reached 11:1 within 2.5 h. At this point, the normalized emittances of the gold ion beam were 2.27 μm for horizontal and 0.21 μm for vertical emittance. Given that the horizontal emittance was still increasing, it was possible to achieve an even higher transverse emittance ratio than 11:1. The key to generate and to maintain the flat beam with a large emittance ratio is the fine decoupling performed at the beginning of this experiment.

At the end of the store, we deliberately pushed the vertical tune closer to the horizontal tune to check the minimum betatron tune split $|Q_x - Q_y|$ needed to stop the transverse emittance exchange. Figure 2 shows the betatron tune split and the emittance ratio during this scan. We found that when the tune split was smaller than 0.018, the vertical emittance began to grow due to coupling, and the transverse emittance ratio started to decrease. However, even with a tune split of 0.015, the emittance ratio was still maintained at 10:1.

In the second experiment conducted on June 28, 2023, our objective was to demonstrate a collision with flat beams. For this experiment, we loaded only 28 gold ion bunches into both the blue and yellow rings of RHIC for safety reasons. After reaching 100 GeV/nucleon, we first measured the amplitude of coupling coefficient $|C^-|$ by pushing the vertical tune as close as possible to the horizontal one. As an example, Fig. 3 shows the measured transverse tunes $Q_{x,y}$ in the yellow ring. We were able to push the vertical tune close to the horizontal tune with a small tune split $|Q_x - Q_y|$ of 0.002. From Eq. (2), this

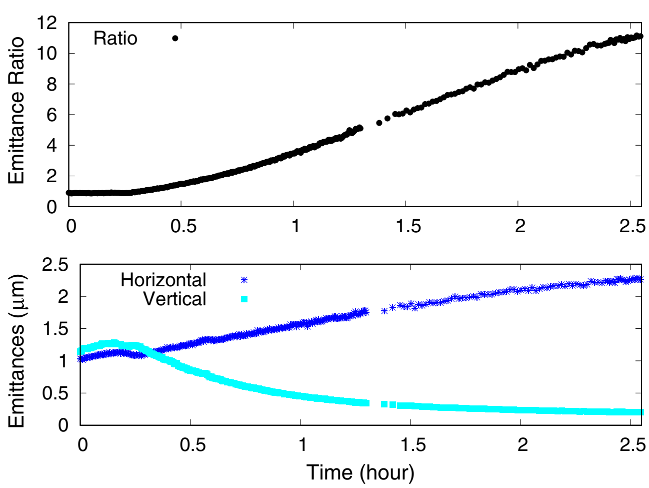

FIG. 1. Measured transverse emittances in the bottom plot and the transverse emittance ratio in the top plot for the experiment conducted on June 14, 2023.

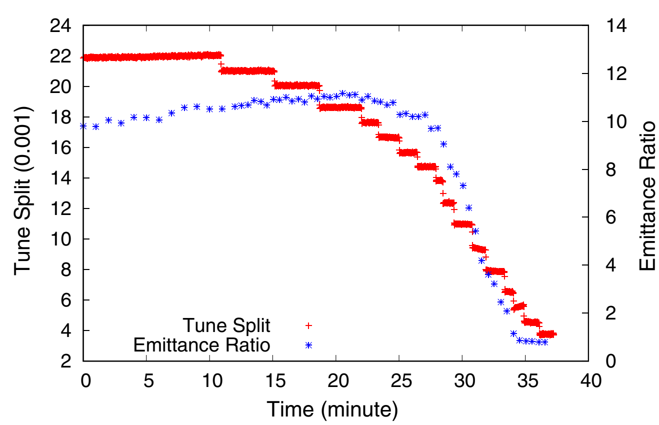

FIG. 2. Transverse tune split and emittance ratio during the tune split scan in the experiment conducted on June 14, 2023.

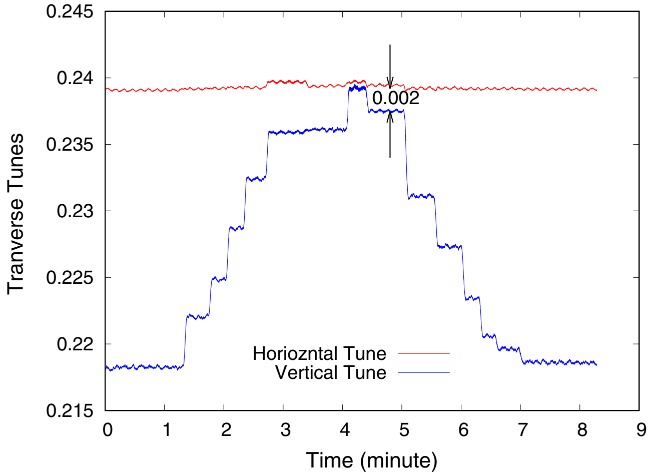

FIG. 3. Transverse tunes in the yellow ring during the measurement of amplitude of coupling coefficient $|C^-|$ in the experiment conducted on June 28, 2023.

suggests that the amplitude of coupling coefficient $|C^-|$ should be equal to or less than 0.02. Also as shown in the plot, when we pushed the vertical tune one step closer to the horizontal tune, unfortunately, the phase-lock-loop tune meter was unable to differentiate between them.

Next, we adjusted the transverse tune splits to be 0.02, which was about 10 times the amplitude of the coupling coefficient, in both rings to maximize the transverse emittance ratios. Figure 4 shows the total beam intensities, measured emittances, and transverse emittance ratios of both beams approximately 3 h into the experiment. From the plot, we observed that the maximum emittance ratio was 13.5 : 1 in the blue ring and 8.8 : 1 in the yellow ring. We attribute the difference in the emittance ratios in the two RHIC rings mostly to the initial vertical emittance difference. From Fig. 4, the ion intensity in the blue ring was smaller than that in the yellow ring. The reason was that we lost about 17% ions in the yellow ring when we accidentally placed its horizontal tune to 0.2412, which is too close to the fourth order betatron resonance at 0.25. A faster ion loss rate in the yellow ring during the cooling process was also caused by a high horizontal tune.

Before colliding the flat beams, we measured the IBS emittance growth rates for the flat beam in the blue ring. This experiment aimed to benchmark the IBS growth rate through analytical calculation. IBS is the main mechanism for the emittance growth in the HSR. Other possible mechanisms, such as beam-beam interaction, beam instabilities, and machine noises are under investigated. In this experiment, for a duration of 5 min, we temporarily switched off the vertical stochastic cooling in the blue ring. Figure 5 illustrates the emittance evolutions during this study. The change in horizontal emittance is less pronounced. The measured vertical emittance growth time was 1.2 h. Using the same machine and beam parameters as in this experiment, we analytically calculated the vertical IBS growth time to be about 1.5 h, which agrees well with the experimental measurement. After this, we also conducted another quick test in the blue ring and reconfirmed experimentally that with a tune split larger than 0.018 we were still able to maintain a transverse emittance ratio 11 : 1.

To collide the two flat beams, we removed the local separation bumps at IR6 in both rings. Figure 6 shows the

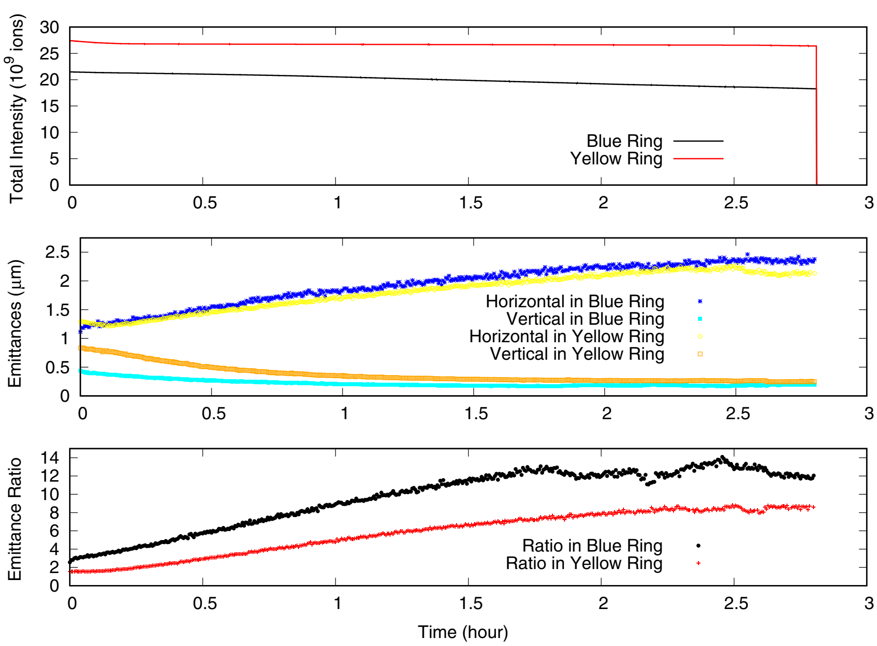

FIG. 4. Total beam intensities, transverse emittances, and transverse emittance ratios in the experiment conducted on June 28, 2023.

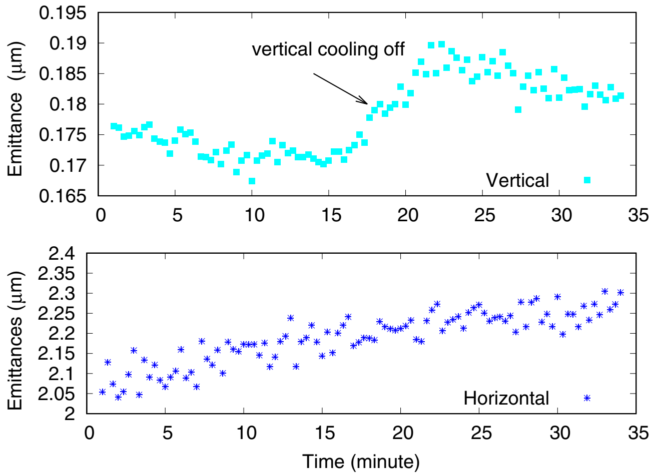

FIG. 5. Emittance evolution for a flat beam in the RHIC blue ring with a transverse emittance ratio of 11 : 1 when vertical cooling was temporarily turned off for 5 min.

total beam intensities, transverse emittances in both rings and the event rate from the zero degree calorimeter (ZDC) of the STAR experiment at IP6. We did not observe significant transverse emittance exchange when proceeding to collision. The transverse beam size ratio was approximately 3 : 1 in both rings. As per the 2023 RHIC run design, which includes a 1 mrad crossing angle at IP6 and a design $\beta^*_{x,y} = 0.7$ m, we estimated that the actual beam-beam parameter in this experiment was approximately 0.004. For comparison, the maximum beam-beam parameter for protons at collision energies in the HSR is about 0.012, and the ratio of horizontal to vertical beam sizes is about 11 : 1. In future EIC operation, we plan to have orbit, tune, and coupling feedback during collision to prevent transverse emittance exchange and maintain the design emittance ratio.

In summary, we successfully demonstrated the EIC design transverse emittance ratio of 11 : 1 in RHIC with stochastic cooling and fine decoupling. We also demonstrated collision with flat beams in the RHIC for the first time. These experiments validate the feasibility of having an 11 : 1 transverse emittance ratio as assumed in the present EIC design. They also confirm that the necessary betatron coupling correction to obtain and maintain the 11 : 1 emittance ratio can be achieved using the existing RHIC decoupling feedback system. The introduction of flat beams in RHIC enables various other EIC-related beam experiments, including studies on IBS growth rate with betatron coupling, space charge effects, beam-beam interaction, and synchrotron-betatron resonance with flat beams, and so on.

We express our gratitude to the RHIC Accelerator Physics EXperiment (APEX) program for providing valuable beam time for our experiments, and we extend our thanks to the RHIC Main Control Room operation crew for their support during these experiments. In particular, we would like to extend our thanks to W. Fischer, K. Mernick, C. Liu, Y. Hao, V. Ptitsyn, T. Shrey, I. Blackler, B. Lepore, P. Adams, and D. Maffei for their stimulating discussions and generous assistance. This work was supported by the U.S. Department of Energy under Contracts No. DE-SC0012704 and No. DE-AC05-06OR23177.

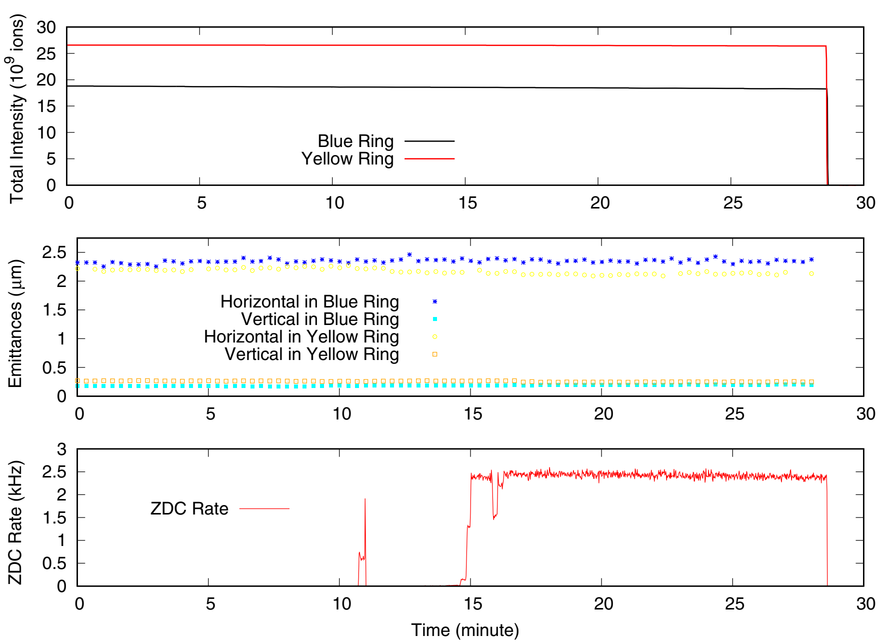

FIG. 6. Total beam intensities, transverse emittances, and the ZDC rate during the collision of flat beams.

[*]yluo@bnl.gov

[1] J. Beebe-Wang *et al.*, Electron-ion collider: Conceptual design report, Brookhaven National Laboratory, Jefferson Lab, 2021, www.bnl.gov/EC/files/EIC_CDR_Final.pdf.
[2] M. Harrison, T. Ludlam, and S. Ozaki, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 235 (2003).
[3] M. A. Furman, in *Handbook of Accelerator Physics and Engineering*, edited by A. Chao, K. Mess, M. Tigner, and F. Zimmermann (World Scientific, Singapore, 2013), p. 311.
[4] V. Ptitsyn, Accelerator physics challenges for EIC, in *Proceedings of IPAC'23, Venice, Italy, 2023*, pp. 2621–2626.
[5] A. Piwinski, in *Proceedings of the 9th International Conference on High Energy Accelerators*, (Stanford, CA, USA, 1974), p. 405.
[6] M. Martini, CERN Report No. CERN-PS 84-9 (AA), 1984.
[7] J. D. Bjorken and S. K. Mtingwa, Part. Accel. **13**, 115 (1983).
[8] G. I. Budker, At. Energ. **22**, 346 (1967); Sov. At. Energy **22**, 438 (1967).
[9] S. Nagaitsev, D. Broemmelsiek, A. Burov, K. Carlson, C. Gattuso, M. Hu, T. Kroc, L. Prost, S. Pruss, M. Sutherland, C. W. Schmidt, A. Shemyakin, V. Tupikov, A. Warner, G. Kazakevich, and S. Seletskiy, Phys. Rev. Lett. **96**, 044801 (2006).
[10] A. V. Fedotov *et al.*, Phys. Rev. Lett. **124**, 084801 (2020).
[11] Y. S. Derbenev, AIP Conf. Proc. **253**, 103 (1992).
[12] V. N. Litvinenko and Y. S. Derbenev, Phys. Rev. Lett. **102**, 114801 (2009).
[13] D. Ratner, Phys. Rev. Lett. **111**, 084802 (2013).
[14] D. Cline *et al.*, IEEE Trans. Nucl. Sci. **26**, 3472 (1979).
[15] M. Gentner, R. Brinkmann, Y. Derbenev, D. Husmann, and C. Steier, Nucl. Instrum. Methods Phys. Res., Sect. A **424**, 277 (1999).
[16] H. Zhao, J. Kewisch, M. Blaskiewicz, and A. Fedotov, Phys. Rev. Accel. Beams **24**, 043501 (2021).
[17] D. Edwards and L. Teng, IEEE Trans. Nucl. Sci. **20**, 885 (1973).
[18] G. Guignard, Phys. Rev. E **51**, 6104 (1995).
[19] Y. Luo, P. Cameron, A. Dellapenna, L. Hoff, A. Marusic, S. Peggs, C. Schultheiss, and R. Jones, Phys. Rev. ST Accel. Beams **9**, 124001 (2006); P. Cameron, A. DellaPenna, L. Hoff, Y. Luo, A. Marusic, C. Schultheiss, S. Tepikian, M. Gasior, R. Jones, and C. Y. Tan, Phys. Rev. ST Accel. Beams **9**, 122801 (2006).
[20] P. Cameron, A. DellaPenna, L. Hoff, Y. Luo, A. Marusic, C. Schultheiss, S. Tepikian, M. Gasior, R. Jones, and C. Y. Tan, Phys. Rev. ST Accel. Beams **9**, 122801 (2006).
[21] M. Blaskiewicz, J. M. Brennan, and F. Severino, Phys. Rev. Lett. **100**, 174802 (2008).
[22] M. Blaskiewicz, J. M. Brennan, and K. Mernick, Phys. Rev. Lett. **105**, 094801 (2010).
[23] Y. Luo *et al.*, Fine decoupling test and simulation study to maintain a large transverse emittance ratio in hadron storage rings, in *Proceedings of IPAC'22, Bangkok, Thailand, 2022*, pp. 1935–1938, 10.18429/JACoW-IPAC2022-WEPOPT039.