

# RHIC LUMINOSITY UPGRADE PROGRAM\*

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## Abstract

The Relativistic Heavy Ion Collider (RHIC) operates with either ions or polarized protons. After increasing the heavy ion luminosity by two orders of magnitude since its commissioning in 2000, the current luminosity upgrade program aims for an increase by another factor of 4 by means of 3D stochastic cooling and a new 56 MHz SRF system. An Electron Beam Ion Source (EBIS) is being commissioned that will allow the use of uranium beams. Electron cooling is considered for collider operation below the current injection energy. For the polarized proton operation both luminosity and polarization are important. In addition to ongoing improvements in the AGS injector, the construction of a new high-intensity polarized source has started. In RHIC a number of upgrades are under way to increase the intensity and polarization transmission to 250 GeV beam energy. Electron lenses will be installed to partially compensate the head-on beam-beam effect.

## INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been in operation since 2000. RHIC is the first and one of two existing heavy ion colliders (the LHC has not yet collided heavy ions), and the the only existing polarized proton collider. So far four combinations of particle species collided (Au-Au, d-Au, Cu-Cu, polarized p-p), at 12 different center-of-mass energies [1]. Over the last decade the heavy ion luminosity increased by 2 orders of magnitude (Fig. 1) and exceeds the design luminosity by a factor of 10 (Tab. 1). The polarized proton luminosity increased by more than one order of magnitude (Fig. 1), and the average store polarization reached 55% and 34% at 100 GeV and 250 GeV respectively. At the highest rigidities the beam is colliding 55% of calendar time (including all interruptions such as setup, maintenance, failures, and accelerator physics experiments) [1].

After the RHIC heavy ion design parameters were demonstrated in 2001, enhanced design parameters were formulated calling for a quadrupling of the average store luminosity. The achieved luminosity exceeds this goal, and new goals are set (Tab. 1). The current upgrade program aims to increase the heavy ion luminosity by more than a factor 2 from current levels, to bring into operation a new Electron Beam Ion Source (EBIS), and to extend the operation to energies below the nominal injection energy.

For polarized protons it is planned to bring the spin polarization to the design value of 70% at the highest energies

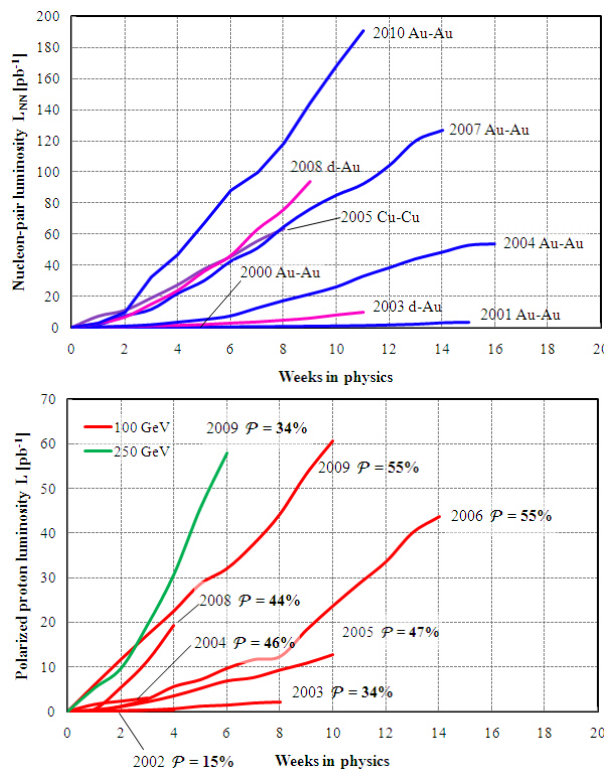


Figure 1: Time evolution of the integrated luminosity of the RHIC heavy ion runs at 100 GeV/nucleon (top) and polarized proton runs at 100 GeV and 250 GeV (bottom) from 2000 to 2010. For heavy ions the nucleon-pair luminosity  $L_{NN} = LN_1N_2$  is plotted, where  $L$  is the luminosity and  $N_{1,2}$  are the number of nucleons for the species in the two beams respectively. For protons the average store polarization is noted.

(250 GeV) and to increase the luminosity by up to a factor of 6 over current levels (Tab. 1).

## UPGRADES FOR HEAVY IONS

The goal of the heavy ion luminosity upgrade is to bring the luminosity close to a level where the dominant beam loss is from burn-off, i.e. particle loss from collisions with the other beam. With the highest luminosities listed in Tab. 1 the luminosity lifetime from burn-off is 9 h. When burn-off is the dominant beam loss the luminosity can be increased further only by storing and colliding more beam of the same density, not by reducing  $\beta^*$  or the emittance.

The luminosity upgrade at full energy has 3 main components: a reduction of  $\beta^*$  from currently 0.75 m to 0.50 m, the full implementation of stochastic cooling in all 3 dimensions, and the installation of a 56 MHz superconducting radio frequency system.

The reduction of  $\beta^*$  is an ongoing effort.  $\beta^*$  values of

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Table 1: Enhanced design, achieved and further RHIC upgrade parameters. The design average Au-Au luminosity is  $2 \times 10^{26} \text{cm}^{-2} \text{s}^{-1}$ , the design peak p-p luminosity is  $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ , and the design spin polarization for proton beams is 70%.

parameter	unit	enhanced	achieved	next	achieved	enhanced	next
		design	2010	upgrade $\geq 2012$	2009	design $\geq 2012$	upgrade $\geq 2014$
Au-Au operation					polarized p-p operation		
particle energy $E$	GeV/n		— 100 —		100 / 250	100 / 250	250
no of bunches $N$	...		— 111 —			— 109 —	
bunch intensity $N_b$	...	1.1	1.1	$1.0 \times 10^9$	1.3 / 1.1	1.3 / 1.5	$2.0 \times 10^{11}$
IP envelope function $\beta^*$	m	1.0	0.75	0.5	0.7 / 0.7	0.85 / 0.5	0.5
norm. rms emittance $\epsilon_n$	mm-mrad	2.5	2.8	2.5	3.0 / 2.5	2.5	2.5
rms bunch length $\sigma_s$	m	0.3	0.3	0.3	0.8 / 0.6	0.55	0.3
hourglass factor $h$	...	0.96	0.93	0.88	0.72 / 0.80	0.86 / 0.88	0.88
beam-beam parameter $\xi/\text{IP}$	$10^{-3}$	1.6	1.5	1.5	6.5 / 4.7	6.5 / 7.2	10
peak luminosity $L_{peak}$	$\text{cm}^{-2} \text{s}^{-1}$	36	40	$55 \times 10^{26}$	50 / 85	50 / 250	$500 \times 10^{30}$
average luminosity $L_{avg}$	$\text{cm}^{-2} \text{s}^{-1}$	8	20	$40 \times 10^{26}$	28 / 55	$30^\dagger / 150$	$300 \times 10^{30}$
average polarization $P$	%				55 / 34	70	70
calendar time in store	%	60	53	55	60 / 53	55	55
integrated $L$ per week	...	300	650	$1300 \mu\text{b}$	8.3 / 18	10 / 50	$100 \text{pb}^{-1}$

<sup>†</sup>Until the 2009 polarized proton run, the enhanced design goal for the average store luminosity at 100 GeV was  $60 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ . In the current machine configuration this appears unachievable due beam lifetime limitations.

0.75 m were reached in the most recent run [2], far below the design value of 2.0 m.  $\beta^* = 0.65$  m was tested but poor beam lifetime of off-momentum particles prevented stable operation. Low  $\beta^*$  values require that chromatic corrections are implemented at the lattice design stage [3] since a small radial aperture prevents beam-based correction of an otherwise uncorrected lattice.

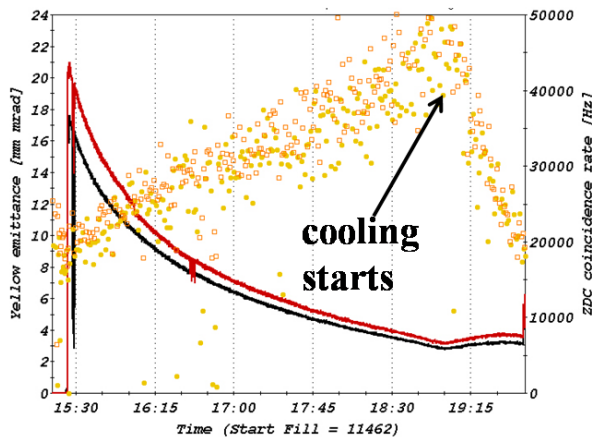


Figure 2: First Au store with vertical stochastic cooling. When the cooling starts the emittance of both transverse planes is reduced through cooling of the vertical plane and coupling. This is observable with an Ionization Profile Monitor. (left scale). The luminosity signal of both experiments (right scale) increases visibly [4, 5].

The main luminosity lifetime limit for heavy ions is intrabeam scattering. To overcome the emittance increase and particle loss from that effect, bunched beam stochastic cooling was implemented in the longitudinal plane in

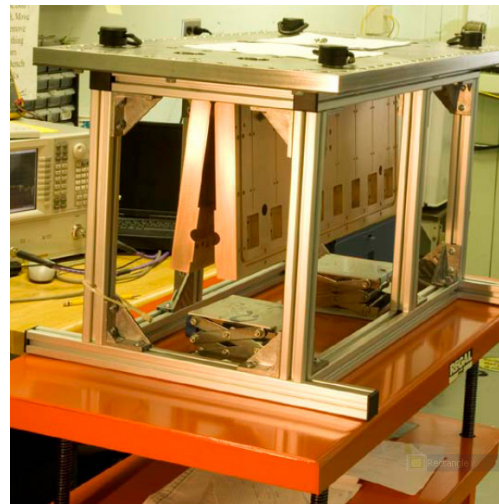


Figure 3: Vertical stochastic cooling kicker. The kicker is open for injection and acceleration (shown) and closed for cooling operation at store.

2007 [4, 5] and in the vertical plane in 2010 (Fig. 2). Figure 3 shows one of the vertical kickers installed in both rings. Horizontal cooling systems are under construction. With stochastic cooling an increase in the average luminosity of a factor 4 is planned (Fig. 4), half of which has been realized in the most recent Au-Au run [2]. The cooling system operates in the 4-8 GHz range, and cooling times in both the longitudinal and transverse dimension are of order 1 h.

Even with longitudinal stochastic cooling intrabeam scattering still drives particles out of the RF buckets. This effect can be ameliorated through stronger longitudinal fo-

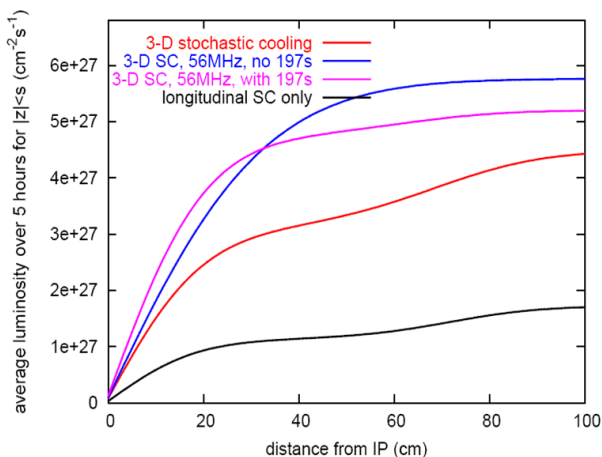


Figure 4: Calculated average store luminosity as a function of the longitudinal vertex cut for longitudinal stochastic cooling only, and 3-D cooling with different RF systems (courtesy M. Blaskiewicz).

cusing. A 56 MHz beam-driven superconducting RF cavity, common to both beams, is under construction. This cavity is expected to increase the luminosity by another 30-50% (Fig. 4) [6]. The 56 MHz RF system ( $h = 2 \times 360$ ) is in addition to the existing normal conducting 28 MHz ( $h = 360$ ) accelerating, and the 197 MHz ( $h = 7 \times 360$ ) storage RF systems. Bunches are filled in every third bucket of the 28 MHz system.

The ion beam intensity is currently limited by beam loading effects in the four 197 MHz normal conducting storage cavities common to both beams (there are 3 more 197 MHz cavities in each ring). The common cavities will be removed and placed in both rings separately. This is possible because new RF windows allow for higher voltages [7].

The beam intensity is also limited by instabilities at transition [8, 9], driven by the machine impedance and electron clouds [10]. In the 2010 run the intensity threshold for the instability was found to be higher than in previous years. This could be due to 2 short scrubbing runs with high intensity proton beams in 2009 [11], which could have cleaned parts of the beam pipe surface in the cold arcs. Most of the warm sections are coated by NEG material, and to reduce the electron cloud density further the secondary electron yield (SEY) in the cold arcs also needs to be reduced. Scrubbing with beam is expected to be time consuming [12], and tests with protons showed that the beam losses associated with scrubbing need to be controlled in order not to upset any electronic equipment in the tunnel [11]. An in-situ coating technology for the arcs is under development [13].

A new Electron Beam Ion Source (EBIS) (Fig. 5) is under commissioning. EBIS is followed by an RFQ and a short linac, both also new, before the ions are injected into the AGS Booster [14]. This setup replaces the currently used two Tandem Van de Graaff electrostatic pre-

accelerators, in service since 1970 and upgraded several times. Without EBIS the Tandems would need to undergo a comprehensive reliability upgrade EBIS will also be able to deliver U beams at intensities comparable to Au, which is not possible with the Tandems. With U collisions larger densities of nuclear matter can be achieved than with Au collision due to the shape and mass of the U nuclei. EBIS can be also be used as an ionizer for spin polarized  $^3\text{He}$  gas.

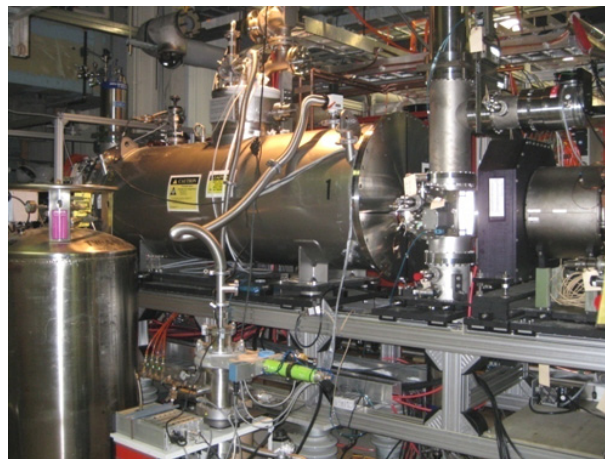


Figure 5: Electron Beam Ion Source (EBIS) under commissioning [14].

The search for a critical point in the QCD phase diagram requires operation at several energies below the nominal injection energy. At these low energies, magnet field errors from persistent currents in the superconducting magnets are particularly pronounced, the beam size is large, both intrabeam scattering and space charge effects are strong, and beam-beam effects are present. This presents unique challenges for colliding beams [15]. Beam and luminosity lifetimes are only minutes, and store lengths are limited to 20 min. Frequent refills are essential to produce a good average luminosity. Event rates in the detectors are of order 1 Hz only. Figure 6 shows the ion intensities in the 2 ring during a day (30 April) in the 2010 operation at a beam energy of 3.85 GeV/nucleon. To operate at this energy, the defocusing sextupole polarities need to be reversed, and octupoles were found to improve the beam lifetime. Due to the low luminosity lifetime, interception of the lost ions in well controlled areas (collimators, abort) is required to avoid material activation in uncontrolled areas. The experimental program at these low energies has just started and electron cooling is considered to increase the luminosity by up to an order of magnitude in future years [16].

Heavy ion operation also requires frequent changes in particle species and collision energy [1]. For ramp development simultaneous orbit, tune, coupling, and chromaticity feedbacks are now available, which considerably shorten the time to commission a new ramp [17].

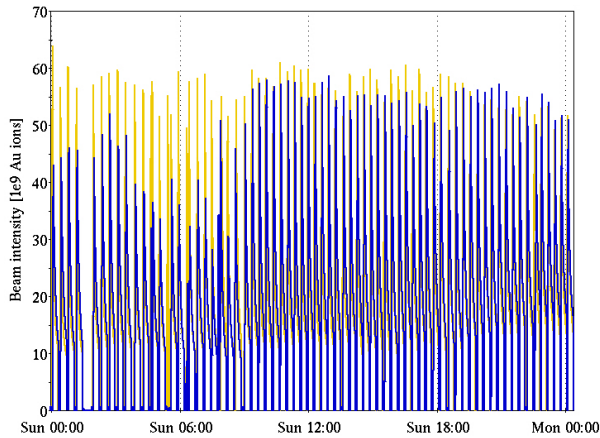


Figure 6: Beam intensity of stores of gold beam at 3.85 GeV/nucleon (total energy), corresponding to 38% of the nominal injection rigidity.

## UPGRADES FOR POLARIZED PROTONS

RHIC has stored and collided the highest energy spin polarized proton beams [18]. For the experiments the figure of merit with longitudinally polarized beams, the main operating mode, is  $LP_B^2 L_P^2$  where  $L$  is the luminosity and  $P_{B,Y}$  the polarization of the Blue and Yellow beam respectively.

The polarization is limited by the source, the polarization transmission in the AGS, the polarization transmission in RHIC (for energies above 100 GeV), and the polarization lifetime in RHIC. The main luminosity limit comes from the beam-beam effect that creates tune spread. The beam-beam effect together with other nonlinear effects and parameter modulations limits the bunch intensity and luminosity lifetime. At 100 GeV this is now a hard limit (Tab. 1) [19].

An upgrade of the OPPIS source has started, to increase the current by an order of magnitude to 10 mA, and the polarization by about 5% to 85-90% [20,21].

In the Booster no polarization is lost during acceleration. In the AGS, however, the polarization transmission is only about 75% for bunch intensities of  $1.5 \times 10^{11}$  leading for a polarization of up to 65% for that intensity [22]. The lowest order depolarizing resonances are addressed with 2 partial snakes (one normal conducting and one superconducting). With partial snakes the stable spin direction is not vertical any more and polarization is also lost due to weaker horizontal resonances. A tune jump system has been built and tested to cross a total of 82 horizontal resonances in 100  $\mu$ s, much faster than with the normal ramp rate. This is expected to yield up to 5% more polarization (absolute). Figure 7 shows one of the two AGS tune jump quadrupoles.

In RHIC the polarization is preserved with two Siberian snakes [24] that create a constant spin tune of 0.5. No polarization loss is observed from injection up to 100 GeV [18]. With acceleration to 250 GeV not all of the polarization was preserved, due to depolarizing resonances

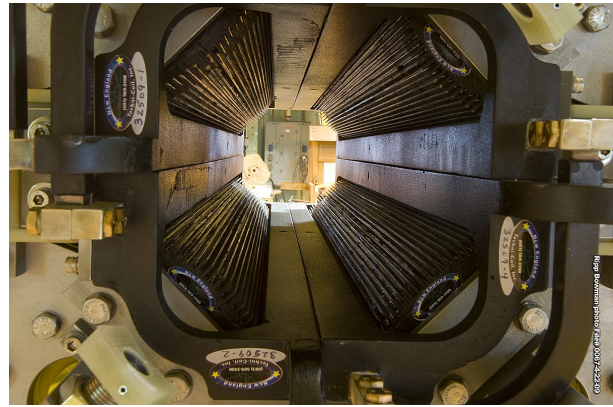


Figure 7: One of two AGS tune jump quadrupoles [23].

above 100 GeV, which are about twice as strong as the resonances at the lower energies. In experiments it was also found that the polarization transmission is strongly dependent on the vertical betatron tune (Fig. 8) and that acceleration near a vertical tune of  $2/3$  will preserve the polarization to 250 GeV. To accelerate a high-intensity beam near a low order resonance requires upgrades to the main power supplies, an improved control of orbit, tune, coupling, and chromaticity on the ramp (set through feedbacks [17]), and collimation on the ramp.

Polarized proton operation also requires a vertically well aligned machine, and polarimetry. Over the first few years the machine has settled several mm (depending on the location), and is realigned every few years. In RHIC there are 2 polarimeters: a polarized hydrogen jet that delivers absolute polarization but needs measurement periods of at least a store, and a Carbon Nuclear Interference (CNI) polarimeter that delivers instantaneous polarization but needs calibration with the hydrogen jet. The CNI polarimeter has been upgraded, and needs further upgrade in order to cope with the rates of higher intensity beams.

A spin flipper is under construction, based on an AC dipole, to flip the spin of all bunches. This way systematic effects in the experiments can be reduced.

The luminosity upgrade for polarized protons has two components: The reduction of  $\beta^*$  from currently 0.7 m to 0.5 m, and the increase of the bunch intensity from  $1.5$  to  $2.0 \times 10^{11}$  (Tab. 1) and perhaps beyond.

As for the ion lattices, chromatic aberrations have to be corrected for the reduction of  $\beta^*$ . For the increase of the bunch intensity three problems must be addressed. First, with higher bunch intensity the polarization drops. This can be mitigated by the source upgrade (see above), or improvements in the AGS (see above). Second, the higher bunch intensity also requires acceleration of a higher total intensity. In one of the rings (Yellow) the total intensity is currently limited, likely because of electron cloud effects [26]. Acceleration with a 9 MHz system ( $h = 120$ ), which has been tested in 2009, would reduce the electron cloud density. The 9 MHz system also allows to preserve the longitudinal emittance better through injection match-

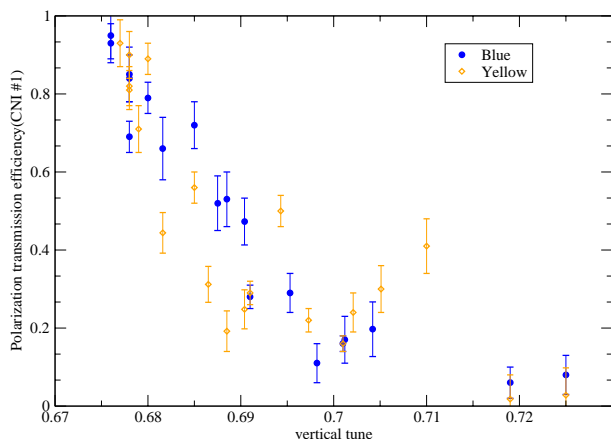


Figure 8: Polarization transmission from injection to 250 GeV as a function of the vertical tune (courtesy M. Bai).

ing and thereby reduce the hourglass effect at store. Third, the total intensity is now also limited by the beam abort system. Ramps that were aborted at the highest energies have repeatedly quenched the superconducting quadrupole that follows the (internal) beam dump [27]. After analysis and simulations [28] the beam pipe in the dump is now thickened to increase the acceptable intensity.

To mitigate the fundamental problem of beam-beam generated tune spread in head-on collisions, two electron lenses are under construction (Fig. 9) [29]. Electron lenses are installed in the Tevatron and used as abort gap cleaners [30]. The partial compensation of the head-on beam-beam effect, together the polarized source upgrade (see above), are expected increase the luminosity by a factor of two.

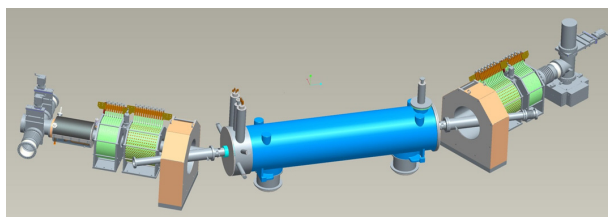


Figure 9: Layout of the RHIC electron lens. The electron beam travels from right to left, the proton beam in the opposite direction (courtesy J. Hock).

### SUMMARY

The Relativistic Heavy Ion Collider is in operation for 10 years and the heavy ion average store luminosity has reached 10 times the design value (Tab. 1). This was achieved through an increase in the bunch intensity and number of bunches, a reduction in  $\beta^*$ , and most recently, the implementation of longitudinal and transverse stochastic cooling during stores. A further upgrade of the stochastic cooling system and a beam-driven 56 MHz superconducting RF system are expected to yield another factor of 2.

### 01 Circular Colliders

#### A01 Hadron Colliders

The heavy ion program is now extended to energies below the nominal injection energy, where a luminosity increase through electron cooling is planned. An Electron Beam Ion Source is under commissioning allowing for high-intensity U beams.

RHIC has operated with polarized protons at 100 GeV and 250 GeV (Tab. 1). A source upgrade is expected to increase both the polarization and the bunch intensity. A tune jump system in the AGS is under commissioning to improve the polarization transmission in that machine. Acceleration with the vertical tune near a 2/3 resonance is planned to increase the polarization transmission to the highest energies. A 9 MHz RF system will allow longitudinal injection matching and acceleration with reduced electron cloud effects thereby better preserving both the longitudinal and transverse emittances. Electron lenses are under construction for both beams to mitigate the head-on beam-beam effect.

### ACKNOWLEDGMENTS

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