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RHIC progress and future

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RHIC PROGRESS AND FUTURE

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Abstract

The talk reviews RHIC performance, including unprecedented manipulations of polarized beams and recent low energy operations. Achievements and limiting factors of RHIC operation are discussed, such as intrabeam scattering, electron cloud, beam-beam effects, magnet vibrations, and the efficiency of novel countermeasures such as bunched beam stochastic cooling, beam scrubbing and chamber coatings. future upgrade plans and the pertinent R&D program will also be presented.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) consists of two independent storage rings, making it a highly flexible facility to study collisions of hadron beams ranging from polarized protons to fully stripped gold ions. Collisions of 100 GeV/nucleon gold ions probe the conditions of the early universe, where quarks and gluons form a new state of matter. As a polarized proton collider, RHIC provides unique physics opportunities to study spin effects in hadronic interactions in high-luminosity proton-proton collisions at beam energies up to 250 GeV. To preserve beam polarization on the energy ramp, pairs of full Siberian snakes are installed on opposite sides of each ring (Fig. 2), thus avoiding intrinsic and imperfection spin resonances during acceleration. Two interaction regions around the experiments STAR and PHENIX are equipped with pairs of spin rotators, which allow manipulation of the polarization direction at these interaction points.

During its first eight years of operation RHIC has exceeded its design parameters for gold-gold collisions, and has successfully operated in an asymmetric, mode colliding deuterons and gold ions. Additionally, record luminosities were reached in copper-copper collisions. Furthermore, RHIC has performed very successfully as a polarized proton collider at 100 GeV beam energy. Fig. 1 shows achieved integrated nucleon-pair luminosities for various modes of operation since 2000.

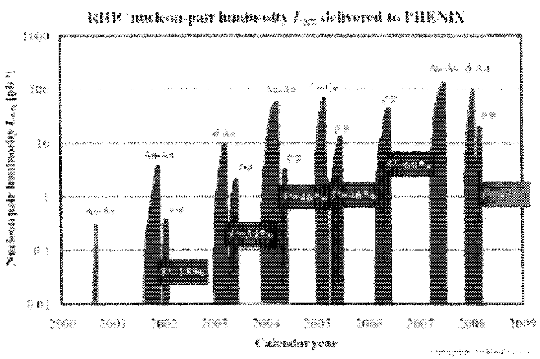

Figure 1: Integrated nucleon-pair luminosity for all RHIC physics running modes since the start of operation in 2000.

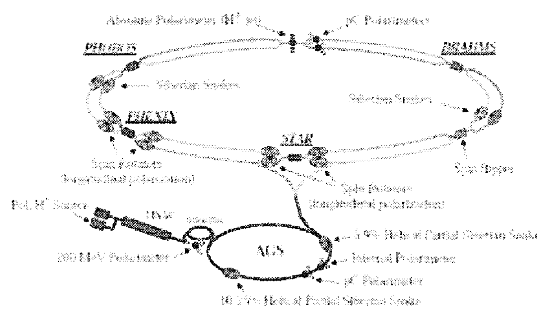

Figure 2: Layout of the RHIC accelerator complex. Two Siberian snakes are installed on opposite sides of each ring to preserve polarization. Spin rotators around the two experiments PHENIX and STAR allow for manipulation of the spin direction at the collision points.

RECENT DEVELOPMENTS

Polarized proton collisions at 250 GeV

During Run-9, RHIC provided first polarized proton collisions at 250 GeV [1]. With spin resonances beyond 100 GeV being being more than twice as strong as those below 100 Gev (Fig. 3), a much more precise control of machine parameters such as orbits and betatron tunes is required to preserve polarization during the acceleration ramp.

Achieved polarization levels were 42 percent at top energy in both rings (Fig. 4), while the average polarization at injection energy was 55 percent. As polarization measurements during the acceleration ramp indicate, polarization is preserved up to a beam energy of 100 GeV, while losses occured around the three strongest intrinsic spin resonances at 136 GeV, 199 GeV, and 221 GeV. A peak luminosity of $122 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ was achieved.

Low energy Au-Au collisions

Gold-gold collisions at energies of only a few GeV in the center-of-mass are required to search for the QCD crit-

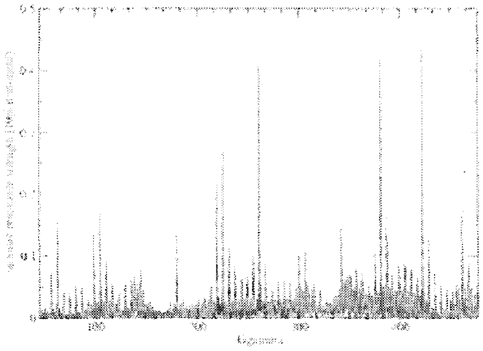

Figure 3: Calculated RHIC intrinsic spin resonance strength as a function of beam energy, usin a β-function of $\beta^* = 0.7\,\mathrm{m}$ at STAR and PHENIX, and $\beta^* = 7.5\,\mathrm{m}$ at the non-colliding interacton points.

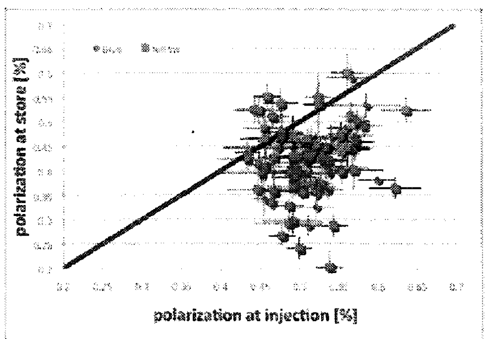

Figure 4: Measured polarization at store vs. measured injected polarization, in both the blue and yellow RHIC rings.

ical point. To study the feasibility of providing low-energy collisions, RHIC operated with gold beams at two different beam energies, 2.5 and 4.6 GeV/nucleon, well below the regular RHIC injection energy of 10.4 GeV/nucleon [2]. RF frequency limits required harmonic number changes from the nominal value of $h = 360$ to $h = 366$ at 4.6 GeV, and $h = 387$ at 2.5 GeV. During a first attempt at 4.6 GeV in 2007 chromaticities were dominated by the sextupole component of the main dipoles. The polarity of the defocusing RHIC sextupoles had to be reversed to correct the chromaticity. This gave a significant improvement of beam lifetimes in 2008, as shown in Fig. 5. 2.5 GeV tests were hampered by dominant nonlinearities, causing orbit corrections to fail. In preparation for further attempts a new orbit correction algorithm is being developed that takes these nonlinearities into accout [3].

PERFORMANCE LIMITATIONS

Electron cloud and pressure rise

When high intensity beams are injected into RHIC, electron clouds are created in some warm sections. These electron clouds can cause significant vacuum pressure rise due to gas desorption. Two measures have been taken to avoid this vacuum pressure rise. Nearly all warm beam pipes have been coated with NEG material, improving vacuum conditions. The effect on dynamic pressure rise is shown in Fig. 6. High-intensity beams are also injected into RHIC for a few hours at the beginning of each run to scrub the inner surface of the beampipe. The remaining surface contains only a small amount of adsorbed gas molecules that can be desorbed, thus reducing the dynamic pressure rise (see Fig. 7).

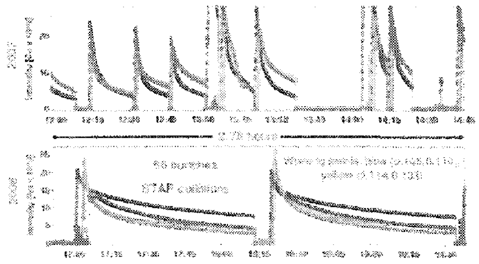

Figure 5: Beam intensities during 5 GeV low-energy running in Run-7 and Run-8. With reversed polarities of the defocusing sextupoles the lifetime is significantly improved in Run-8.

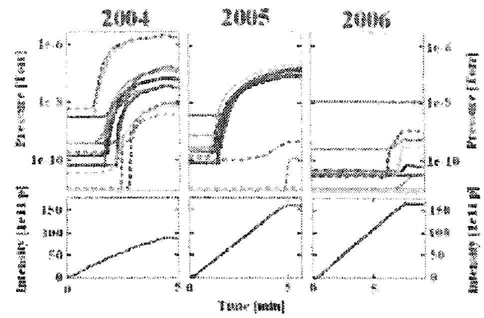

Figure 6: Measured dynamic pressure rise during beam injection for three consecutive years. The pressure rise is mitigated by successive NEG-coating of the warm RHIC beam pipes.

Fast transverse instability at transition

When ion beams cross the RHIC transition energy of $\gamma_t \approx 23$, the bunch length scales as $\sigma_s \propto (\gamma - \gamma_t)^4$, giving very short bunches near γ_t. At the same time, the chromaticity sign must change from negative for $\gamma < \gamma_t$ to positive for $\gamma > \gamma_t$. Therefore chromaticities are zero at - or very close to - transition. These zero chromaticities result in lack of Landau damping, and electron clouds lead to a fast transverse instability which chops of part of the bunch tail. Fig. 8 shows a tomographic reconstruction

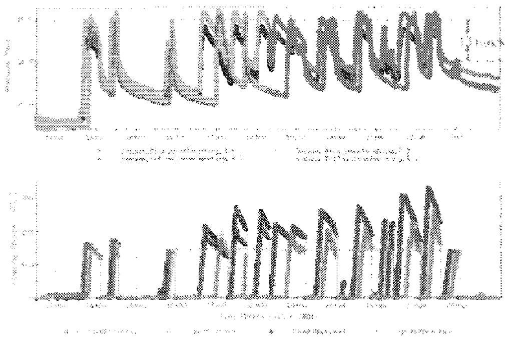

Figure 7: Effect of beam scrubbing on dynamic pressure rise at the RHIC RF cavities during injection.

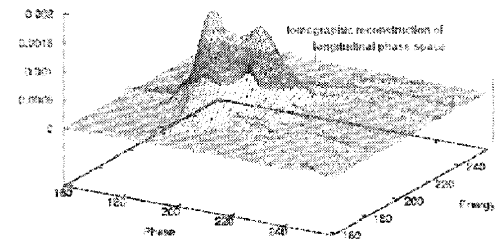

Figure 8: Tomographic reconstruction of the longitudinal phase space distribution of a RHIC bunch after the fast transverse transition instability has occured.

of the longitudinal phase space shortly after the instability has occured.
This instability can be overcome by restoring Landau damping with octupoles, and careful adjustment of the time when the chromaticity crosses zero. For future improvements, implementation of a fast chromaticity jump is under consideration.

LUMINOSITY LIFETIME IMPROVEMENTS WITH HEAVY IONS

IBS suppression lattice

Intrabeam-scattering (IBS) accounts for a significant luminosity lifetime reduction in heavy ion collisions. The emittance growth rates due to IBS can be calculated as

$$\tau_{\|}^{-1} \approx \frac{r_i c N_i \Lambda}{8\beta^3\gamma^3\epsilon_x^{3/2}\langle\beta_\perp^{1/2}\rangle\sigma_x\sigma_p^2}, \quad (1)$$

$$\tau_x^{-1} = \frac{\sigma_p^2}{\epsilon_x}\left\langle\frac{D_x^2+(D_x'\beta_x+\alpha_x D_x)^2}{\beta_x}\right\rangle\tau_{\|}^{-1}. \quad (2)$$

As Eq. (2) shows, the transverse emittance growth rate is proportional to the "curly $\mathcal{H}$" function,

$$\mathcal{H} = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x {D_x'}^2. \quad (3)$$

Reducing $\mathcal{H}$ therefore reduces the transverse emittance growth due to IBS.

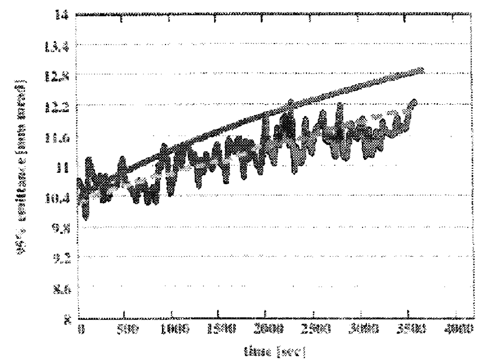

Figure 9: Measured (red) and simulated transverse emittance evolution due to IBS, for a betatron phase advance of 82° (green) and 92° (blue) per FODO cell. Measured data are for a phase advance of 92° per FODO cell.

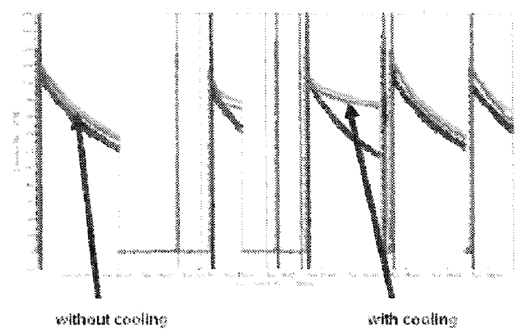

Figure 10: Effect of longitudinal stochastic cooling on Yellow beam lifetime.

This reduction is accomplished by increasing the betatron phase advance per FODO cell from the nominal value of $\phi = 82°$ to $92°$, and was implemented in the "Yellow" RHIC ring during the Run-8 deuteron-gold run. Fig. 9 shows the gold beam measured emittance, together with simulation results for phase advances of 82° and 92°.

Stochastic cooling

To compensate emittance growth of heavy ion beams due to IBS, a stochastic cooling system [4] is being installed in RHIC. At present, longitudinal stochastic cooling is operational in the "Yellow" RHIC ring. The lack of bunch lengthening during stores results in longer beam lifetimes, since no particles are lost from the RF bucket. Fig. 10 shows the beam intensity of stores with and without longitudinal stochastic cooling in the "Yellow" ring.

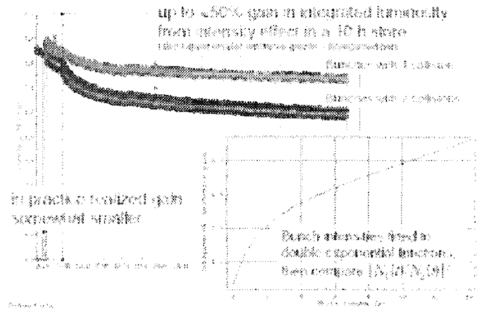

Figure 11: Intensity evolution of proton bunches with one and two collisions.

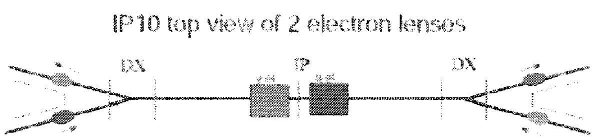

Figure 12: Schematic drawing of the electron lens configuration in IR 10.

PROTON BEAM LUMINOSITY LIMITATIONS

Beam-beam

The proton beam luminosity is limited by the beam-beam effect. In a regular RHIC fill, most bunches collide at both experiments, STAR and PHENIX, while a few others experience collisions only at one of the two detectors. The lifetime of bunches with only one collision per turn is higher than that of bunches that collide at both experiments, as Fig. 11 shows. To improve the situation, installation of electron lenses in an empty interaction region (IR10) is foreseen [5], as schematically depicted in Fig. 12. The electron beam will collide with the stored proton beam; parameters will be chosen such that the beam-beam parameter is equal to that of one of proton-proton beam collision points, but with opposite sign. This head-on compensation scheme will reduce the beam-beam footprint, thus in turn providing more tune space to be available for an increased beam-beam parameter.

10 Hz orbit oscillations

The orbits of both RHIC beams oscillate in the horizontal plane at frequencies around 10 Hz. This oscillation is caused by mechanical vibrations of the superconducting low-β triplet quadrupoles driven by helium flow [6]. The orbit oscillations lead to modulated beam-beam offsets at the interaction points, which may result in emittance growth. When RHIC was initally set up with near-integer tunes in Run-8, increased orbit oscillations led to unacceptably high background conditions in the detectors, and the

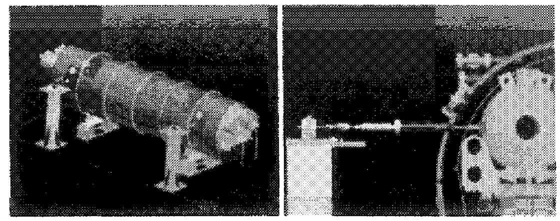

Figure 13: Schematic drawing of the mechanical vibration damping system.

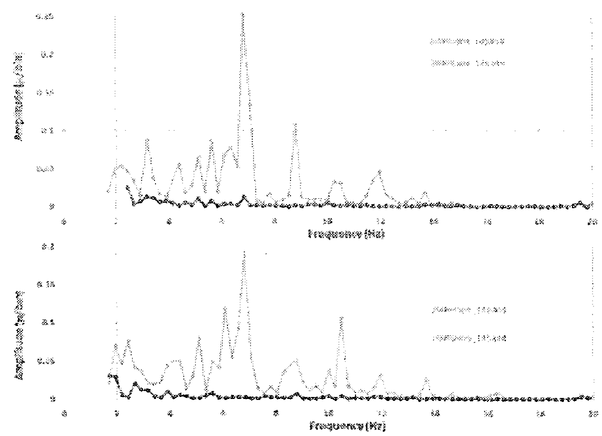

Figure 14: Measured vibration spectra with the feedback system turned on (red) and off (blue). To show the natural variation in these spectra, results of two separate measurements are shown.

near-integer working point was abandoned [7].
As a countermeasure, a mechanical feedback system has been developed and tested [8]. This system consists of a set of geophones attached to the triplet cold masses, and electromechanical actuators to compensate the measured vibration, as depicted in Fig. 13. This system is capable of reducing the vibration amplitude by more than a factor 10 (Fig. 14). A prototype system is currently installed at a single quadrupole cold mass in one of the RHIC triplets. Retrofitting all triplets in the two low-β interaction regions at the experiments PHENIX and STAR is planned for upcoming shutdowns.

FUTURE UPGRADES

EBIS

All RHIC heavy ion beams are provided by two Tandem Van-de-Graaff accelerators, located 800 m from the Booster synchrotron. Since these electrostatic accelerators require intense maintenance, they will be replaced by an electron-beam ion source (EBIS) at the 200 MeV linac in the near future.
In an EBIS, a conventional ion source injects ions into an

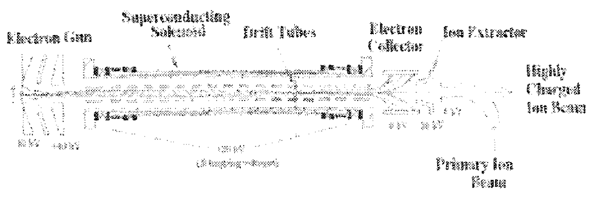

Figure 15: Illustration of the EBIS principle.

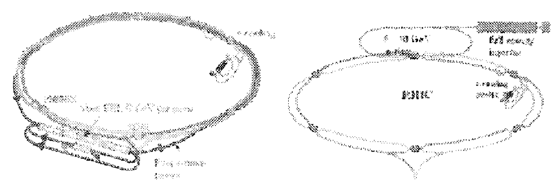

Figure 16: Schematic drawings of eRHIC, linac-ring (left) and ring-ring (right).

intense electron beam, where they are trapped and ionized to the desired degree (Fig. 15). Once the required charge state and intensity are reached, the ions are released from the trap and pre-accelerated into the linac. This principle has the additional avantage that both the ion species and charge state can be varied on a pulse-by-pulse basis, therefore providing different ions for parallel operations of RHIC and the Bosster-based NASA Space Radiation Laboratory (NSRL) from a single device.

eRHIC

To study collisions between electrons and polarized protons or heavy ions, adding a 10 – 20 GeV electron accelerator to the RHIC facility has been proposed. The main design line consists of an energy-recovery linac (ERL) with four return loops around the RHIC circumference. The e-p luminosity of this facility is in the 10^{33} – 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ range. A more conventional fallback design uses an electron storage ring [9]. In this case, the achievable luminosity would be a factor 2 – 3 lower than with the ERL due to the beam-beam limit on the electron beam. Fig. 16 shows schematics of both approaches.

We plan to realize eRHIC in a staged approach, starting with a 4 GeV ERL installed in the 2 o'clock interaction region [10]. To reduce civil construction costs, the return loops will have a dogbone shape such that the linacs are installed inside the existing RHIC tunnel, while the return arcs are housed by extensions to the existing infrastructure.

Coherent electron cooling

To maximize eRHIC luminosity, coherent electron cooling [11] will be used. A co-moving electron beam picks up fluctuations in the ion beam distribution. After amplifying these fluctuations in an FEL, the electron beam is merged

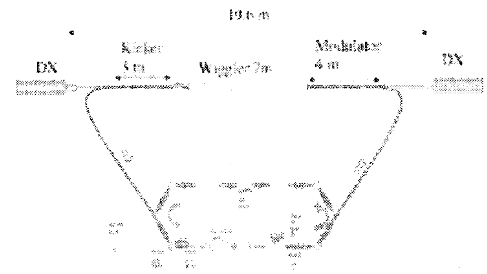

Figure 17: Schematic drawing of the coherent electron cooling test installation in a RHIC IR.

with the ion beam, such that the electron beam fluctuations correct the ion beam fluctuations in a manner very similar to conventional stochastic cooling, but with much higher bandwidth. To test the feasibility of this method, the BNL test-ERL currently under construction will be moved to a RHIC interaction region, where it will be converted into a coherent electron cooler for 40 GeV proton beams, (Fig. 17).

SUMMARY

The performance of RHIC has continuously improved over nearly a decade of operation. Further significant performance improvements require upgrades that are currently under way. In the future, RHIC will be converted into an electron-ion collider (eRHIC).

ACKNOWLEDGMENTS

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