# STATUS AND PLANS FOR THE POLARIZED HADRON COLLIDER AT RHIC*

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*Abstract*

As the world's only high energy polarized proton collider, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) has been providing collisions of polarized proton beams at beam energy from 100 GeV to 255 GeV for the past decade to explore the proton spin structure as well as other spin dependent measurements. With the help of two Siberian Snakes per accelerator plus outstanding beam control, beam polarization is preserved up to 100 GeV. About 10% polarization loss has been observed during the acceleration between 100 GeV and 255 GeV due to several strong depolarizing resonances. Moderate polarization loss was also observed during a typical 8 hour physics store.

This presentation will give an overview the achieved performance of RHIC, both polarization as well as luminosity. The plan for providing high energy polarized He-3 collisions at RHIC will also be covered.

## INTRODUCTION

The quest for understanding the spin structure of protons as well as neutrons is presently led by experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) to be the only high energy polarized proton collider. However, accelerating polarized proton beams to high energy is challenged by depolarizing mechanisms in an accelerator.

In a circular accelerator, the motion of a particle's spin vector $\vec{S}$ in the particle's rest frame is governed by the Thomas-BMT equation [1]:

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}]. \quad (1)$$

Here $\gamma$ is the Lorentz factor and $G$ is the anomalous $g-$factor and $G = 1.7928474$ for protons, and $G = -4.191$ for He-3. $\vec{B}_{\perp}$ and $\vec{B}_{\parallel}$ are the magnetic fields perpendicular and parallel to the beam direction, respectively. Eq. 1 shows that in a perfect planar accelerator with only the vertically oriented guiding dipole field, the spin vector precesses $G\gamma$ times per orbital revolution. The spin tune $Q_s$ is then equal to $G\gamma$.

Eq. 1 also shows that the beam polarization can be compromised by depolarizing mechanisms from non-vertically orientated magnetic fields. In general, there are two types of first order spin resonances, i.e. imperfection spin resonances from machine imperfections such as dipole errors and quadrupole misalignments, and intrinsic spin resonances driven by the horizontal magnetic fields sampled due to vertical betatron oscillations [2]. The imperfection spin resonances are located at $G\gamma = k$ and the intrinsic spin resonances are located at $G\gamma = kP \pm Q_y$. Here, $k$ is an integer, $P$ is the super-periodicity of the machine and $Q_y$ is the vertical betatron tune. Depending on the strength of the resonance and how fast the resonance is crossed, the amount of depolarization can vary. For imperfection resonances, the resonance strength is proportional to the size of the closed orbit distortion, and for intrinsic resonances, the strength is proportional to the size of the betatron oscillation amplitude.

To preserve the polarization during the acceleration, RHIC employs two Siberian snakes [3] in each of its two accelerators (Blue ring and Yellow ring). The two snakes are located diametrically opposite across the ring. Fig. 1 is the schematic layout of RHIC polarized proton complex. In each of RHIC's two accelerators, each snake rotates the spin vector of the polarized proton beam by $180^o$ around an axis in the horizontal plane, i.e. the snake axis. Let $\Delta\phi$ be the angle between the axes of the two snakes, the precession tune $Q_s$ in RHIC then becomes

$$Q_s = \frac{1}{\pi}\Delta\phi \quad (2)$$

Eq. 2 shows that the spin precession tune becomes a constant, which not only avoids all the imperfection resonances but also all intrinsic resonances as long as the betatron tune is different from half integer. With the axes of the two snakes perpendicular to each other, the spin precession tune then becomes $\frac{1}{2}$.

* Work supported by Department of Energy and RIKEN Japan, USA

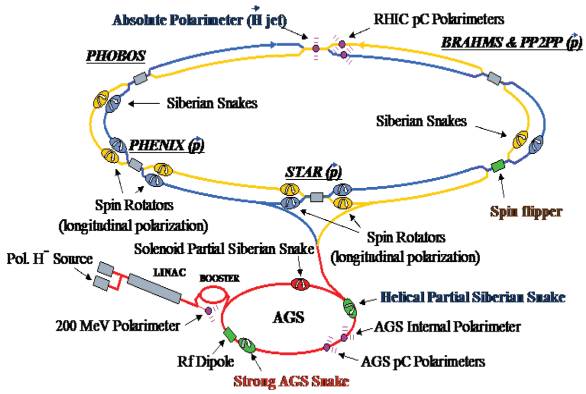


Figure 1: Polarized proton acceleration complex at Brookhaven National Laboratory. Polarized $H^-$ ion beam from the Optically Pumped Polarized Ion Source (OPPIS) is accelerated to 200 MeV through the linear accelerator (LINAC) and then strip-injected in the Booster where the polarized proton beam is accelerated to a kinetic energy of 1.42 GeV. At the end of each Booster acceleration cycle, the polarized proton beam is injected into the AGS and accelerated to a beam energy of 24 GeV. The local spin rotators at the entrance/exit of the two large detectors (STAR and PHENIX) are to provide longitudinally oriented spin polarized proton beams for the experiments [4].

## CHALLENGES IN POLARIZED PROTON COLLISIONS

In addition to the beam-beam limit on the RHIC polarized proton luminosity performance, the main challenge in RHIC polarized proton operation is its polarization performance. Even in the presence of dual Siberian snakes in each of the two accelerators, polarization loss can still occur due to the snake resonance, a depolarizing mechanism discoverd by Lee and Tepikian [5]. They showed that the perturbations on the spin motion can still add coherently and depolarization can still happen even in the presence of snakes when certain betatron tunes were chosen. For a single snake case, the accumulated spin perturbations can't be perfectly canceled out if

$$mQ_y = Q_s + k. \tag{3}$$

Here, $m$ and $k$ are integers. $m$ is the order of the snake resonance [2]. This was experimentally observed at IUCF [8]. The snake resonances are derived from the intrinsic resonances, and the stronger the intrinsic resonance, the stronger the snake resonances. Hence, the challenge of accelerating/colliding high energy polarized beams is to keep the betatron tune within the snake resonance free areas to avoid polarization loss.

Careful simulation studies show that to accelerate polarized protons with a 95% normalized emittance of $20\pi$ mm-mrad, the imperfection resonance strength should be below 0.075 to avoid polarization loss at the strong intrinsic resonances around 136 GeV, 203 GeV and 221 GeV [4, 6, 7]. The imperfection resonance strengths for RHIC are bounded by

$$\epsilon_{imp} = 0.25\frac{\gamma}{250}\sigma_y. \tag{4}$$

Here, $\sigma_y$ is the rms value of the vertical closed orbit distortion in mm. Hence, a closed orbit with $\sigma_{y,rms} \leq 0.3$ mm is needed to keep the imperfection resonances below 0.075 at all energies in RHIC [4, 10].

Polarized protons in RHIC have been successfully accelerated to 100 GeV with minimum or no polarization loss with careful control of the betatron tunes and the vertical orbit distortions [11]. However, the first collisions of polarized protons at 250 GeV in 2009 suffered significant polarization losses due to the much stronger intrinsic resonances around 136 GeV, 203 GeV and 221 GeV [4, 11]. The polarization loss beyond 100 GeV is due to the high order snake resonances. Fig. 2 shows the polarization transmission efficiency, the ratio of the polarization measured at store and at injection, as a function of the vertical tune [14]. The snake resonance at $5Q_y = Q_s + 3$ is clearly visible.

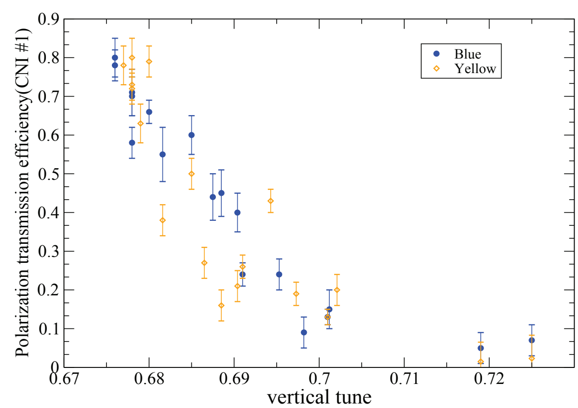


Figure 2: The beam polarization as a function of the vertical tune during the acceleration from 100 GeV to 250 GeV. Three strong intrinsic resonances around 136 GeV, 203 GeV and 221 GeV are encountered during this part of the acceleration ramp. They can derive strong snake resonates if the betatron tune sits satisfies the resonance condition, and result insignificant polarization loss.

The reduced polarization transmission efficiency when the vertical tune is above 0.7 is due to the snake resonance at $2Q_y = Q_s + 1$. There were also hints of higher order snake resonances $8Q_y = Q_s + 5$ as well as $11Q_y = Q_s + 7$ in the Yellow ring. In the RHIC polarized proton 250 GeV run in 2009, the vertical tune had to stay at 0.68 due to an irregular power supply glitch, that would cause the vertical tune to jump across the $3^{rd}$ order resonance and aborted the beam. The achieved average polarization during the store was 36% measured by the RHIC $H^-$ jet polarimeter [12].

The polarization performance in RHIC can also be limited by the deterioration of polarization during a store for physics data taking, i.e. limited polarization lifetime. It has been observed during the RHIC operation that beam polar-


ISBN 978-3-95450-122-9

ization can deteriorate during a typical 8-hour store at an average rate of 0.6-1% absolute polarization per hour for both beams [15]. In order to accommodate as much beam-beam tune shift as possible for high luminosity, the working point for RHIC polarized proton collision is set to be near the diagonal line just below 0.7, the location of snake resonance at $5Q_y = Q_s + 3$.

Even though the snake resonances at store are much weaker than the ones during the acceleration, depolarization can still occur if beam sits on a weak snake resonance. For an ideal case when spin tune is energy independent and at half integer, weak or negligible polarization loss due to higher order snake resonances is expected. However, spin tune can deviate away from half integer due to snake imperfection as well as local orbit difference between the two snakes [16].

In addition, the difference of the dispersion slope between the two snakes also makes the spin tune become slightly energy dependent, and induces a spin tune spread in a polarized beam [16]. All the above imperfections plus the beam betatron tune spread in the presence of collision can then result in lower average store polarization. Fig. 3 shows the average store polarization as a function of vertical tune at store during the current RHIC polarized proton operation. The correlation between polarization and vertical tune is evident. The closer the vertical tune to 0.7, the lower the polarization.

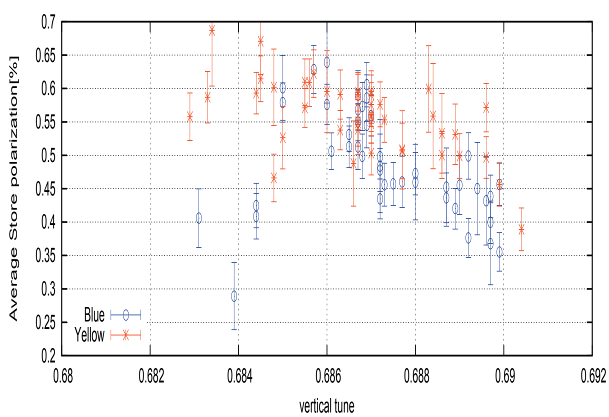


Figure 3: The average store polarization as a function of vertical betatron tune at store. The average store polarization was measured by the RHIC $H^-$ jet polarimeter [12].

## ACHIEVED RHIC PERFORMANCE

In addition to the tune/coupling feedback [17] for the precise tune and coupling control during the acceleration, numerous improvements were made throughout the RHIC complex over the past several years to improve both luminosity performance as well as polarization performance,

- AGS horizontal tune-jump for overcoming horizontal snake resonances [18]. A new type of intrinsic resonance due to the horizontal betatron oscillation, i.e. horizontal resonance located at $G\gamma = kP \pm Q_x$ was identified during the set-up of using two partial snakes in the AGS to overcome both imperfection resonance as well as intrinsic resonance. Here, $Q_x$ is the horizontal betatron tune. Each horizontal resonance is weak and yields to less than a percent depolarization with the AGS normal acceleration rate. A total of 82 horizontal intrinsic resonances are crossed during the acceleration from 1.5 GeV to 23 GeV in the AGS, resulting in a loss of polarization of 10-15%. A set of pulsed quadrupoles was then introduced to jump through each horizontal resonance. During RHIC polarized proton operation in 2012, the horizontal tune-jump system was successfully commissioned and yielded 70% polarization at the AGS extraction energy. Careful tuning of the machine optics also helped to avoid emittance growth.

- Accelerating polarized protons with 9MHZ RF cavity in RHIC [19]. Earlier RHIC polarized proton operation showed emittance growth due to electron cloud [20]. This not only results in lower luminosity, but also results in higher polarization loss due to snake resonances during acceleration. A new RF cavity was then configured to accelerate the polarized proton beams at a harmonic of 120 instead of 360. The advantage of the new 9MHZ system is to reduce the peak current of each bunch by longer bunch length. Once reaching the store energy, the 28 MHZ RF cavity first hops its frequency back to the $3^{rd}$ harmonic of the bunch frequency at a voltage of 100 kV and then jumps to its full voltage to restore the short bunch length for collision. Fig. 4 shows the longitudinal bunch profile at store for RHIC operation in 2009 when 28 MHZ RF cavity was used for acceleration versus the store profile for current RHIC operation in 2013 with 9 MHZ RF cavity for acceleration. It is evident that the peak current at store is significantly improved, which directly resulted in the luminosity record RHIC has recently achieved.

- Precise orbit control with the slow orbit feedback during the acceleration and periodically through store [21]. Fig. 5 shows the measured closed orbit distortion as well as betatron tunes for a typical polarized proton acceleration. Within the limit of RHIC beam position monitor (bpm) alignment, the orbit distortion stays well below the requirement for polarization, and even under 0.1 mm during the acceleration from 100 GeV to 255 GeV.

- 10 HZ orbit feedback system to suppress the 10 HZ orbit variation [22]

- Upgrade of the BNL Optically Pumped Polarized Ion Source (OPPIS) [23]. The OPPIS has been the work horse for the RHIC polarized proton operation over the past decade. Recently, its primary ECR-

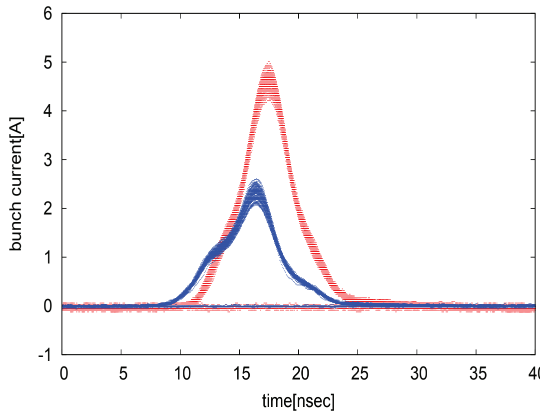


Figure 4: Bunch longitudinal profile at store in the Blue ring of RHIC. The red data set corresponds to the store profile for the current RHIC polarized proton operation, and the blue data set is the store profile during RHIC polarized proton run in 2009.

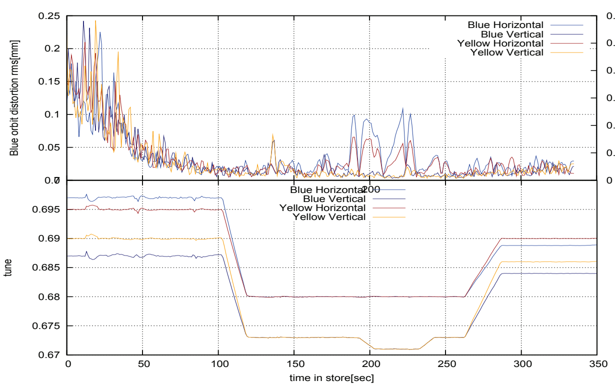


Figure 5: Orbit and tune of both RHIC beams during a typical RHIC acceleration ramp. Both beams are under the control of tune/coupling feedback as well as orbit feedback.

source based proton beam was replaced with the high-brightness external atomic hydrogen injector developed in collaboration with the Budker Institute of Nuclear Physics. The atomic hydrogen beam is then injected into the 3.0 Tesla superconducting solenoid, where it is stripped to protons in the pulsed He gaseous ionizer cell and polarized via a spin exchange mechanism with optically pumped Rubidium vapor. The new source now reliably delivers between 5.0e11 particles for the Booster input at polarization of 83 - 84% to 9.0e11 particle for Booster input at 77% polarization (0.53 mA beam current in 300 $\mu$s pulse duration accelerated in Linac to 200 MeV). This polarization is 3-4% higher for intensity 5.0e11 ions/pulse and nearly double our previous ECR-based source current at 77% polarization.

These machine improvements have led to a record performance of RHIC polarized proton operation. A peak luminosity of $230 \times 10^{32}\text{cm}^{-1}\text{s}^{-1}$ has been recently achieved in the current RHIC operation [24]. Fig. 6 shows the performance of luminosity as well as polarization of the best store of current RHIC operation.

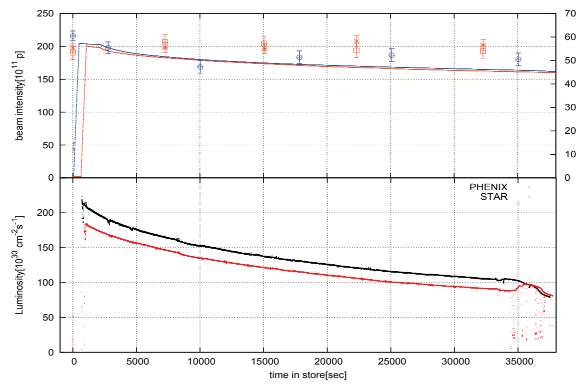


Figure 6: The golden store of RHIC polarized proton operation in 2013. A peak luminosity of $210 \times 10^{32}\text{cm}^{-1}\text{s}^{-1}$ was reached. No polarization deterioration during the long Physics store.

During the current RHIC polarized proton operation, the improved longitudinal matching between the AGS and RHIC as well as the elimination of RF phase jitter at the AGS transition further reduced the beam emittance to less than $15\pi$mm-mrad [24]. This not only directly contributed to the significant luminosity increase, but also helped to reduce polarization loss during acceleration. With the smaller beam and lower vertical betatron tune at store as shown in Fig 3, RHIC also reached its record high average store polarization at 57%. Table 1 summaries the achieved RHIC performance. Here, the average store polarization was measured with the RHIC $H^-$ jet polarimeter [12].

Table 1: RHIC Polarized Proton Achieved Performance

| operation year | **2009** | **2012** | **2013** |
|---|---|---|---|
| energy[GeV] | 100/250 | 100/255 | 255 |
| collision No. | 107 | 107 | 107 |
| bunch intensity $10^{11}$ | 1.3/1.1 | 1.6/1.7 | 2.0 |
| beta*[m] | 0.7 | 0.62 | 0.6 |
| average Luminosity $10^{30}\text{cm}^{-2}\text{s}^{-1}$ | 28/55 | 33/105 | 60/125 |
| average store polarization[%] | 56/35 | 59/52 | 57 |

## FUTURE PLANS

To overcome the current luminosity limit, a pair of electron lenses were installed to compensate the head-on beam-beam effect [25]. With the commissioning of electron lenses (E-lens), one expects partial compensation of beam-beam effect. A factor of two increase of luminosity is expected once the E-lens is successfully commissioned.




ISBN 978-3-95450-122-9

RHIC as a versatile collider can also accelerator light ions like polarized He-3. Compared with protons, He-3 has much larger anomalous G-factor. On the one hand, this means the RHIC Siberian snakes as well as the AGS partial snakes can be operated at a lower field. However, large G-factor also enhances all first order depolarizing resonances. For the AGS, due to the fast acceleration rate as well as limited strong intrinsic spin resonances, the current dual partial snake configuration is still sufficient for preserving the beam polarization of He-3 in the AGS. For RHIC, with the current dual snake configuration, to accelerator He-3 beam to high energy will require even tighter control of both orbit distortions as well as optics, which may be beyond the capabilities of available instrumentation and beam control. In order to relieve the tolerance on the beam parameters, a scenario of accelerating polarized He-3 beam with a total of six Siberian snakes was proposed [26]. Currently, polarized He-3 source development [27], as well as accelerating He-3 in the RHIC injector chain is a work in progress.

## CONCLUSIONS

RHIC as the world's only high energy polarized proton collider has been providing polarized proton collision at its record energy of 255 GeV since 2012. Thanks to the various machine improvements throughout the RHIC complex, the polarized proton operation has recently reached records in both luminosity performance as well as average store polarization performance. Limitations on polarization and luminosity are observed and have been studied.

Towards the future, RHIC isexpecting a factor of two increase in luminosity once the electron lenses is successfully commissioned to compensate the head-on beam-beam effect. Various possibilities of accelerating polarized He-3 beam in RHIC complex are also under investigation and development.

## ACKNOWLEDGMENT

The authors would like to thank all the operation crews of Collider Accelerator Department of Brookhaven National Laboratory as well as all engineers and technicians who contributed. The author also would like to thank the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy un- der Contract No. DE-AC02-05CH11231, for use of their compute resources, especially the use of the Dirac GPU cluster.

## REFERENCES

[1] L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys. Rev. Lett. 2, 435 (1959).

[2] S. Y. Lee, *Spin Dynamics and Snakes in Synchrotrons*, World Scientific, Singapore, (1997)..

[3] Ya. S. Derbenev, A. M. Kondratenko, Sov. Phys. Dokl. 20, 562 (1976).

[4] I. Alekseev *et al.*, *Design Manual - Polarized Proton Collider at RHIC*, Nucl. Inst. and Meth. A499, 392 (2003).

[5] S. Y. Lee, S. Tepikian, Phys. Rev. Lett. 1635, vol. 56, Num. 16 (1986).

[6] A. Luccio, *Numerical Spin Tracking in a Synchrotron Computer Code SPINK -Examples (RHIC)*, AGS/RHIC/SN No. 011, 1996

[7] F. Meot, *The Raytracing Code zgoubi NIM* **A 427**, 1999

[8] R. A. Phelps *et al.*, Phys. Rev. Lett. 78, 2772-2774 (1997).

[9] E. D. Courant and R. Ruth, BNL report, BNL-51270 (1980).

[10] S. Y. Lee and E. D. Courant, *Tolerance of imperfections in high-energy circular accelerators for polarized protons*, Phys. Rev. D, 292, vol. 41, Num 1 (1990).

[11] M. Bai, *et al*, Phys. Review Letters 96, 174801 (2006).

[12] H. Okada *et al.*, Phys. Lett. B 638 (2006).

[13] D. N. Svirida *et al.*, proceedings of Spin2004, Trieste, Italy, 2004.

[14] M. Bai *at al.*, Proceedings of IPAC10, Kyoto, Japan (2010)

[15] http://www.phy.bnl.gov/cnipol/summary/

[16] M. Bai, V. Ptitsyn, T. Roser *Impact on Spin tune*, Collider Accelerator Tech Note, 2008.

[17] M. Wilinski *et al*, *Improvements for Operational Baseband Tune and Coupling Measurements and Feedback at RHIC*,Proc. of BIW10, Santa Fe, New Mexico, US, (2010).

[18] V. Schoefer *et al Increasing the AGS Beam Polarization with 80 Tune Jumps*, Proceedings of IPAC12, 2012

[19] M. Brennan *et al Presentation at RHIC Retreat 2007, and private discussions*

[20] W. Fsicher *et al Electron cloud observations and cures in the Relativistic Heavy Ion Collider*, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 11, 041002 (2008)

[21] A. Marusic, M. Minty *et al*, *Global orbit feedback at RHIC MOPEC029* Proceedings of IPAC10, Kyoto, Japan, 2010

[22] R. Michnoff,*et alRHIC 10 Hz Global Orbit Feedback System*, Proceedings of PAC11, New York (2011)

[23] A. Zelenski, private discussion

[24] V. H. Ranjbar *et al RHIC POLARIZED PROTON OPERATION FOR 2013*, Proceedings of IPAC13, Shanghai, China, 2013

[25] W. Fischer *et al TUPF1077*, Proceedings of IPAC13, Shanghai, China, 2013

[26] M. Bai, W. Fischer *et al Explore the Possibility of Accelerating Polarized He-3 Beam in RHIC*, Proceedings of IPAC12, New Orlean, USA, 2012.

[27] R. Milner, J. Maxwell, C. Epstein *Development of a Polarized* $^3$*He Beam Source for RHIC using EBIS*, Proceedings of 20th International Spin Physics Symposium (SPIN2012), Dubna, Russia.