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POLARIZED PROTON BEAMS IN RHIC

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Abstract. The polarized beam for RHIC is produced in the optically-pumped polarized H^- ion source and then accelerated in Linac to 200 MeV for strip-injection to Booster and further accelerated 24.3 GeV in AGS for injection in RHIC. In 2009 Run polarized protons was successfully accelerated to 250 GeV beam energy. The beam polarization of about 60% at 100 GeV beam energy and 36-42% at 250 GeV beam energy was measured with the H-jet and p-Carbon CNI polarimeters. The gluon contribution to the proton spin was studied in collisions of longitudinally polarized proton beams at 100×100 GeV. At 250×250 GeV an intermediate boson W production with the longitudinally polarized beams was studied for the first time.

I. Introduction.

Collisions of protons at energies $\sqrt{s} = 200\text{-}500$ GeV and large transfer momentum ($p_T > 10$ GeV/c) are described as a parton collisions (quarks, gluons) and for polarized proton beams these partons are polarized too. The analyzing powers for polarized parton scattering can be directly calculated in the frame of perturbative QCD. This provides unique opportunity for the proton spin structure studies, fundamental tests of QCD predictions with possible extension to probe the physics beyond “Standard Model”/1,2/. RHIC is the first collider where the “Siberian snake” technique was successfully implemented to avoid the resonance depolarization during beam acceleration in AGS and RHIC /3/ (see Fig.1). A luminosity of a $60 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ (peak $120 \cdot 10^{30}$) for polarized proton collisions in RHIC at $\sqrt{s} = 500$ GeV energy was produced by colliding 112 bunches in each ring at $1.4 \cdot 10^{11}$ protons/bunch intensity.

Fig.1. Polarization hardware layout of the RHIC Collider-Accelerator complex.

It is also for the first time the intensity of the polarized beams produced in an Optically Pumped Polarized H^- Ion Source (OPPIS) was sufficient to charge RHIC to the maximum intensity limited by the beam-beam interaction. Polarimetry is another essential component of the polarized collider facility. A complete set of polarimeters includes: Lamb-shift polarimeter at

the source energy, a 200 MeV polarimeter after the linac, and polarimeters in AGS and RHIC based on proton-Carbon scattering in Coulomb-Nuclear Interference (CNI) region. A polarized hydrogen-jet polarimeter was used for the absolute polarization measurements in RHIC [4].

Longitudinally polarized beams for the STAR and PHENIX experiments are produced with the spin rotators, which are tuned using “local polarimeters” based on asymmetry in neutron production for pp collisions. The STAR and PHENIX detectors provide complimentary coverage of the different polarization processes.

II. Polarized sources development at RHIC.

Feasibility study of new techniques for the production of polarized electron, H^- (proton), D^- (D^+) and $^3He^{++}$ ion beams are in progress at BNL. The OPPIS delivers beam for polarization studies in RHIC. The polarized deuteron beam will be required for the future deuteron Electron Dipole Moment (EDM) experiment, and the polarized electron (see I. Ben-Zvi talk in this Workshop) and $^3He^{++}$ ion beam is a part of the experimental program for the future eRHIC (Electron- Ion) collider.

Fig.2. Layout of the RHIC OPPIS: 1) Electron -Cyclotron Resonance primary proton source; 2). Super-conducting Solenoid; 3) Optically-Pumped Rubidium Cell; 4). Correction coil; 5). Sona-shield; 6). Na-jet ionizer.

The present operational polarized source (OPPIS) for RHIC is based on spin-transfer proton (or atomic hydrogen) collisions in the optically-pumped Rb vapor cell. In the BNL OPPIS, an ECR-type source produces primary proton beam of a 2.0 – 3.0 keV energy, which is converted to electron-spin polarized H atoms by electron pick-up in an optically pumped Rb vapor cell (see Fig.2). A pulsed Cr:LISAF laser of a 1 kW peak at 500 us pulse duration is used for optical pumping. Electrostatic deflection plates downstream of the polarized alkali remove any residual H^+ or other charged species. The electron-polarized H^0 beam then passes through a magnetic field reversal region, where the polarization is transferred to the nucleus via the hyperfine interaction (Sona-transition). The nuclear polarized H atoms are then negatively ionized in a Na-jet vapor cell to form nuclear polarized H^- ions. Alternatively, the H atoms can be ionized in a He gaseous cell to form polarized protons. After ionization polarized H^- ions are accelerated from 3.0 keV to 35 keV energy by a negative 32 kV pulsed voltage applied to the ionizer cell.

The OPPIS technique is a multi-step polarization-transfer process. At each step there is some loss of polarization. Detailed studies of polarization losses in the RHIC OPPIS and the source

parameters optimization resulted in the OPPIS polarization increase to 86-90%. The significant gain of about 5% was obtained from experimental studies and numerical simulations of the Sona-transition efficiency. The simulations were done using code, which was developed at INR, Moscow/5/.

The OPPIS produces routinely 0.5-1.0 mA (maximum 1.6 mA) H^- ion current with 400 μs pulse duration and 80-85 % polarization /6/. The beam is accelerated to 200 MeV with an RFQ and linac for strip-injection to the Booster. About 60% of the OPPIS beam intensity can be accelerated to 200 MeV. The 400 μs H^- ion pulse is captured in a single Booster bunch which contains about $4 \cdot 10^{11}$ polarized protons. Single bunch is accelerated in the Booster to 2.5 GeV kinetic energy and then transferred to the AGS, where it is accelerated to 24.3 GeV for injection to RHIC.

was moved from the 750 keV line to the 35 keV line to align the spin to the vertical direction before injection to the RFQ. The upgrade resulted in reduced spin precession, better optics matching between RFQ and Linac which reduced the emittance degradation in the Linac (in both transverse and longitudinal phase space). This smaller emittance was propagated through the accelerator chain, and resulted in smaller emittance and higher polarization in RHIC.

OPPIS upgrade with the Atomic Hydrogen Beam Injector. The ECR proton source is operated in high magnetic field. It has low hydrogen gas consumption, which makes possible a dc OPPIS operation with intensity in excess of 1.0 mA. However, the proton beam produced in the ECR source has a comparatively low emission current density and high beam divergence. This limits further current increase and gives rise to inefficient use of the available laser power for optical pumping. In fact only about 15% of the electron-spin polarized hydrogen atoms produced in Rb cell is within the ionizer cell acceptance.

FIG.3. Layout of the OPPIS with atomic hydrogen injector: 1–high-brightness proton source; 2-focussing solenoid; 3-pulsed hydrogen neutralization cell; 4- super conducting solenoid 30 kG; 5-Pulsed He ionizer cell; 6-optically-pumped Rb cell; 7-Sona shield; 8-sodium-jet ionizer cell.

In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations can be overcome by using instead of ECR a high brightness proton source outside the magnetic field /7/. Following neutralization in hydrogen, the high brightness 5.0-8.0 keV atomic H^0 beam is injected into a superconducting solenoid, where both a He ionizer cell and an optically-pumped Rb cell are situated in the same 25-30 kG solenoid field, which is required to preserve the electron-spin polarization. The injected H atoms are ionized in the He cell with 80% efficiency to form a low emittance intense proton beam, which enters the polarized

Rb vapor cell (see FIG.3). The protons pick up polarized electrons from the Rb atoms to become a beam of electron-spin polarized H atoms (similar to ECR based OPPIS). A negative bias of about 2.0-5.0 kV applied to the He cell decelerates the proton beam produced in the cell to the 3.0 keV beam energy optimal for the charge-exchange collisions in the Rb and sodium cells. This also would allow the energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in Rb vapor and residual hydrogen atoms of the primary beam. Residual higher energy atoms will be neutralized with lower efficiency in Rb cell (due to cross-section decrease at higher energy) and unpolarized component will be further suppressed by lower H⁻ ion yield at 5.0-8.0 keV atomic beam energy. The H⁻ ion beam acceleration (by -32 kV pulsed voltage applied to the ionizer cell) will produce polarized H⁻ ion beam of a 35 keV beam energy and unpolarized beam of a 40-43 keV beam energy. Further suppression of unpolarized higher energy ion beam can be done in the Low Energy Beam Transport Line (LEBT).

Atomic hydrogen beam current equivalent densities greater than 100 mA/cm² can be obtained at the Na jet ionizer location (about 200 cm from the source) by using a very high brightness fast atomic beam source developed at BINP, Novosibirsk. This was tested in experiments at TRIUMF, where more than 10 mA polarized H⁻ and 50 mA proton beam intensity was demonstrated [6]. Higher polarization is also expected with the fast atomic beam source due to: a) elimination of neutralization in residual hydrogen; b) better Sona-transition transition efficiency for the smaller ~ 1.5 cm diameter beam; c) use of higher ionizer field (up to 3.0 kG), while still keeping the beam emittance below 2.0 π mm·mrad, because of the smaller beam – 1.5 cm diameter. All these factors combined will further increase polarization in the pulsed OPPIS to ~ 90% and the source intensity to over 10 mA.

The RHIC polarized source upgrade for higher intensity and polarization is approved and fully funded for implementation in 2009-12. The source will provide the high intensity low emittance (high brightness) beam for polarized RHIC luminosity upgrade and for future eRHIC facilities.

Proposal for polarized ³He⁺⁺ source for eRHIC. Polarized neutrons collisions can be studied with the deuteron beams. Unfortunately due to small deuteron anomalous magnetic moment G-factor ($G = -0.143$) the “Siberian snakes” and spin rotators will be too weak to be effective for the polarized deuteron acceleration in AGS and RHIC. Polarized beams of ³He⁺⁺ ions also contain the polarized neutron component (as a deuteron) and its G-factor: $G = -4.184$ is even larger than the proton G_p value, therefore the AGS and RHIC Siberian snake can be operated at lower field to preserve polarization during acceleration¹⁷. In this case the difficulty is the polarized ³He⁺⁺ source. The proposed polarized ³He⁺⁺ acceleration in RHIC (and also for future RHIC upgrade to electron ion collider eRHIC) will require about $2 \cdot 10^{11}$ ions in the source pulse and about 10^{11} ions in the RHIC bunch. To deliver these ions in a 20 us pulse duration for injection to Booster, the source peak current has to be about 1000 μ A, which is 10000 times higher than ever achieved in any ³He⁺⁺ ion sources. A new technique has been proposed for production of high intensity ³He⁺⁺ ion beam. It is based on ionization of nuclear polarized ³He gas in the Electron Beam Ion Source (EBIS) [8] (see FIG.4). The highest ³He nuclear polarization in excess of 80% was achieved so far by the metastability exchange technique. In this method, ³He gas at typically 1 torr pressure is contained in a glass bulb and a weak RF discharge is maintained in the gas. Metastable atoms in the 2 ³S₁ state are produced in the discharge and may be polarized by means of optical pumping with circularly polarized (2³S₁ - 2³P₀) 1083 nm light. The polarization is transferred to the ground state atoms by the metastability-exchange collisions. In the cesium coated quartz cell the long (>100h) polarization relaxation time was obtained resulting in high ground state polarization. In the proposed technique, the polarized ³He atoms consumption for injection to an ionizer (another polarized atoms loss factor) is very small, of the order of 10^{13} - 10^{14} He atoms sec⁻¹ and high polarization is expected.

Fig.4. Schematic diagram of the polarized ${}^3\text{He}^{++}$ ion source. 1-metastability-exchange polarizing cell; 2- ${}^3\text{He}$ transfer line; $3 \cdot 10^{12}$ polarized ${}^3\text{He}^{++}$ ions for injection to RFQ.

An EBIS is under construction at BNL as an alternative to the Tandem heavy ion injector for RHIC. It is proposed to use the EBIS to produce ${}^3\text{He}^{++}$ by ionization of the polarized ${}^3\text{He}$ gas, which is fed from the polarizing cell. The ionization in the EBIS is produced in a 50 kG magnetic field, which preserves the nuclear ${}^3\text{He}$ polarization while in the intermediate single-charged ${}^3\text{He}^+$ state. The ionization efficiency to the double-charged ${}^3\text{He}^{++}$ will be close to 100% and the number of ions is limited to the maximum charge, which can be confined in the EBIS. From experiments with Au^{32+} ion production, one expects about $2.5 \cdot 10^{11}$ ${}^3\text{He}^{++}$ ions/pulse to be produced and extracted for subsequent acceleration and injection to RHIC.

After ${}^3\text{He}^{++}$ acceleration to a few MeV/nucleon He-D or He-Carbon collisions can be used for polarization measurements. The Lamb-shift polarimeter at the source energy of 10-20 keV can be used in the feasibility studies (similar to the OPPIS polarimeter). In this technique ${}^3\text{He}^{++}$ ions are partially converted to He^+ (2S) – metastable ions in the alkali vapor cell. Then the hyperfine sublevel populations can be analyzed in the spin-filter device to extract the primary ${}^3\text{He}^{++}$ nuclear polarization.

A study of limitation on the maximum attainable nuclear polarization in the metastability exchange technique (at the very low polarized ${}^3\text{He}$ gas consumption rate) will be required to define the maximum attainable polarization. Possible depolarization effects during polarized ${}^3\text{He}$ gas injection to existing EBIS prototype and multi-step ionization process should be also studied. The expected ${}^3\text{He}^{++}$ ion beam intensity is in excess of $2 \cdot 10^{11}$ ions/pulse with polarization in excess of 70%.

III. Polarized beam acceleration in AGS and RHIC.

Polarized beams in AGS. Two partial Siberian snakes were installed in AGS to preserve polarization during beam acceleration from Booster energy 2.4 GeV to 24 GeV (see T.Roser talk at PSTP 2007 /9/). With this snake configuration the polarization losses at all imperfection and vertical intrinsic resonances was eliminated except a few vertical intrinsic resonances near injection energy. As a result a polarized proton beam with $1.5 \cdot 10^{11}$ intensity/bunch and 65% polarization has been delivered for injection to RHIC in 2006-09 Runs. A spin tracking simulations showed that the remaining polarization losses $\sim 15\%$ (beam polarization at injection to AGS was about 80-85%) can be caused by: the loss due to horizontal intrinsic resonances along the ramp; loss associated with snake resonances near the strongest $36+v$; the loss from vertical intrinsic resonances near injection. All these losses can be reduced by the smaller beam emittance. In 2009 Run smaller beam emittance out of Linac, shorter strip-injection time to Booster (see above) and better beam injection matching from Booster to AGS resulted in smaller beam emittance in AGS and RHIC. Also a new lattice with the vertical tune in the spin tune gap near injection has been used to reduce the loss near injection energy. As a result 65-70% polarization was consistently delivered for injection to RHIC (see Fig.5). A new pulsed quadrupoles were installed in AGS to produce fast tune jump during the energy rump in attempt to eliminate all residual depolarization at the horizontal spin resonances /10/.

Fig.5. Polarization vs. bunch intensity in AGS.

Polarized beams in RHIC. The RHIC–heavy ion collider is the first high-energy machine where polarized proton acceleration was included in the primary design. The RHIC “full Siberian snake” (which rotates spin direction for 180°) is a superconducting helical magnet system of about 10 m long. Two 90° helical spin rotators in each ring produce the longitudinal polarization for experiments in STAR and PHENIX detectors.

Up to 120 beam bunches can be accelerated and stored in each ring. The polarization direction of every RHIC bunch is determined by the spin-flip control system in the polarized ion source. Every single source pulse is accelerated and becomes the RHIC bunch of the requested polarity. By loading selected patterns of spin direction sequences in the rings (such as: +-+ in one ring and +--+ in another) the experiments have all possible spin directions combinations for colliding bunches which greatly enhance the systematic error control.

Since 2005, RHIC has successfully accelerated polarized protons up to 100 GeV with no polarization loss by carefully controlling the betatron tunes and the vertical orbit distortion. A record polarization of 60% was reached during the RHIC polarized proton operation in 2006 and routinely delivered in Run 9. However, between 100 GeV and 250 GeV, there are three strong intrinsic spin resonances which may cause polarization loss. These resonances are more than a factor of two stronger than the strong spin resonances below 100 GeV. Since the stronger the intrinsic resonance, the stronger the derived snake resonances, the tolerance on the nearby imperfection resonance, i.e. the vertical closed orbit distortion, is tighter. The numerical simulation shows that the imperfection resonance strength should be below 0.075 to avoid depolarization at these three strong intrinsic resonances /11/. This corresponds to a closed orbit distortion of 0.3 mm rms value. These accuracies of the orbit and tune control were achieved in 2009 Run. As a result the proton polarization transfer efficiency (from injection to store) was improved to about 80% and on average about 42% polarization was measured during the 250 GeV physics stores.

A maximum polarized beam luminosity of a $45 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ (about $30 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ averaged over 8 hrs store time) was obtained with 109 bunches of $1.6 \cdot 10^{11}$ bunch intensity in 2009 run.

IV. Polarization measurements in AGS and RHIC.

Proton polarization measurements in the AGS and RHIC are based on proton-carbon and proton-proton elastic scattering in the Coulomb Nuclear Interference (CNI) region /12/. This

process has a large cross-section and sizable analyzing power of a few percents which is expected to have weak energy dependence in the 24-250 GeV energy range. A very thin (5 $\mu\text{g}/\text{cm}^2$, 5-10 μm wide) carbon strip target in the high intensity circulating beam produces high collision rate and a highly efficient DAQ system acquires up to $5 \cdot 10^6$ carbon events/sec. High recoil carbon nuclei intensity from the scattering of the circulated proton beam in the thin carbon target is efficiently utilized in the silicon strip detectors and data acquisition system, which is capable to analyze the event rate up to a few millions/second. This gives unique possibilities for the fast, practically non-destructive polarization measurements. The polarization measurements during the beam energy ramp were also implemented in AGS and RHIC, which provides an insight of polarization losses pattern. Polarimeter operation in the scanning mode also gives polarization profile and beam profile (beam emittances including bunch by bunch measurements).

The CNI polarimeters were upgraded for the 2009 run. Two identical target motion mechanisms and detectors assemblies were installed in new vacuum chambers in each ring. One polarimeter was used for the vertical polarization and intensity profile measurements and the other for the horizontal profile measurements (or vice versa). As a result the systematic polarization, polarization profiles and emittance measurements were obtained for both transverse planes. This is in contrast to previous runs where measurements were limited to one plane due to long target switch times.

The absolute beam polarization at 100 GeV beam energy was measured with a polarized H-jet polarimeter [4,13]. The simultaneous measurements in p-Carbon and H-jet polarimeters provide the calibration for p-Carbon analyzing power. Fast pC polarimeter measures possible polarization losses during the energy ramp and possible polarization decay during the RHIC store.

Summary

The RHIC spin program is a great beneficiary of the latest development in the polarized ion source and polarized target technology. For the first time the polarized proton beam intensity in the high-energy accelerator is not limited by the polarized source intensity. In 2009 Run polarized protons was successfully accelerated to 250 GeV beam energy. The beam polarization of a 60% at 100 GeV beam energy and 42% at 250 GeV beam energy was measured with the polarized H-jet and p-Carbon CNI polarimeters. The gluon contribution to the proton spin was studied in collisions of longitudinally polarized proton beams at $\sqrt{s}=200$ GeV. At $\sqrt{s}=500$ GeV an intermediate boson W production with the longitudinally polarized beams was studied for the first time.

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