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High-intensity polarized H^- (proton), deuteron, and $^3He^{++}$ ion source development at BNL

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DISCLAIMER

High-Intensity Polarized H$^-$ (Proton), Deuteron and $^3He^{++}$ Ion Source Development at BNL

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Abstract

New techniques for the production of polarized electron, H$^-$ (proton), D$^-$ (D+) and $^3He^{++}$ ion beams are discussed. Feasibility studies of these techniques are in progress at BNL. An Optically Pumped Polarized H$^-$ Ion Source (OPPIS) delivers beam for polarization studies in RHIC. The polarized deuteron beam will be required for the deuteron Electron Dipole Moment (EDM) experiment, and the $^3He^{++}$ ion beam is a part of the experimental program for the future eRHIC (Electron Ion) collider.

INTRODUCTION

Studies of polarized proton collisions in RHIC at energies of $\sqrt{S}$ =200-500 GeV provide a unique opportunity for proton spin structure studies and fundamental tests of QCD /1, 2 /. The RHIC complex is the first where the "Siberian snake" technique was very successfully implemented to avoid resonance depolarization during beam acceleration in the AGS and RHIC /3/. A luminosity of a $1.6 \cdot 10^{32}$ cm^{-2} sec^{-1} for polarized proton collisions in RHIC will be produced by colliding 110 bunches in each ring at $2 \cdot 10^{11}$ protons/bunch intensity. For the first time, the intensity of the polarized beams produced in an optically- pumped polarized H$^-$ ion source was sufficient to charge RHIC to the maximum intensity limited by the beam-beam interaction.

The RHIC OPPIS routinely produces 0.5-1.0 mA (maximum 1.6 mA) current in 400 μs long pulses. The polarized H$^-$ ion beam (of 35 keV beam energy out of the source) is first accelerated to 750 keV in an RFQ and then to 200 MeV in a linear accelerator, for strip-injection to the Booster. The 400 μs H$^-$ ion pulses, each having about $4 \cdot 10^{11}$ polarized protons, are captured in a single Booster bunches. Each bunch is accelerated in the Booster to 2.5 GeV energy, and then transferred to the AGS, where it is accelerated to 24.3 GeV for injection to RHIC.

THE RHIC OPPIS

In the OPPIS (Figure 1), an ECR-type source produces a primary proton beam of 2.8 ~ 3.0 keV energy, which is converted to electron-spin polarized H atoms by electron pick-up in an optically pumped Rb vapor cell. Electrostatic deflection plates downstream of the polarized alkali remove any residual H$^+$ or other charged species. The electron-polarized H beam then passes through a magnetic field reversal region, where the polarization is transferred to the nucleus, via the hyperfine interaction (Sona-transition). The 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. This source is capable of producing in excess of 1.6 mA polarized H$^-$ ion current in dc operation /4/.

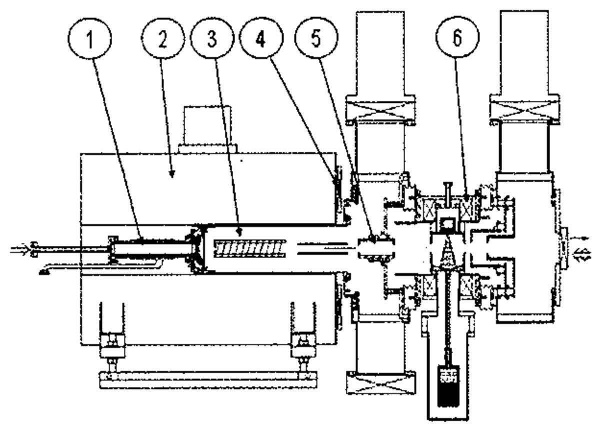

Figure 1. Layout of the RHIC OPPIS. 1) ECR 2) Solenoid 3) Rubidium Cell 4) Steel plate 5) Sona shield 6) Na ionizer.

The AGS cycle for polarized beam operation is 3 seconds, while OPPIS usually operates at 1 Hz repetition rate. Pulses not sent to the Booster are directed to a 200 MeV p-Carbon polarimeter for continuous polarization monitoring, by a pulsed bending magnet in the high-energy beam transport line.

The OPPIS initial longitudinal polarization is converted to the transverse direction while the beam passes two bending magnets, before injection into the RFQ. The second of these bending magnets (47.4°) is pulsed to switch injection between polarized and unpolarized (of about 100 mA intensity) H$^-$ ion beams. A pulsed focusing solenoid in front of the RFQ is tuned for the optimal transmission for either beam. This solenoid also rotates the polarization direction by about 360°, but keeps it in the transverse plane. Final polarization alignment to the vertical direction is adjusted by a spin-rotator solenoid in the 750 keV beam transport line before injection to the linac /3/.

LEBT/MBET Upgrade

Some problems with the present injection scheme are: a) unnecessary spin rotation, which may cause polarization losses, b) poor matching between the RFQ and Linac, which causes beam loss and beam emittance degradation. The injection will be upgraded in time for the 2009 polarized run. Only one bending magnet will be used, thus eliminating a 180° spin rotation. The focusing solenoid in front of the RFQ will be replaced with an Einzel lens, eliminating a 360° spin rotation, and the spin-rotator will be moved from the 750 keV line to the 35 keV line to rotate the spin to the vertical direction before injection to the RFQ. The upgrade will result in reduced spin precession, better optics matching into the RFQ and Linac, and smaller emittance degradation in the Linac (in both transverse and longitudinal phase space). This smaller emittance should be propagated through accelerator chain, and should result in smaller emittance and higher polarization in RHIC.

Polarization Optimization

The OPPIS technique is a multi-step polarization-transfer process. At each step there is some loss of polarization. The detailed studies and optimization of each of these factors resulted in 86% polarization in Run 2006 and further increase to 88~90% in Run 2007 /2/. The recent increase is a result of the Sona-transition optimization. The electron polarization is transferred to protons by the Sona-transition technique as the electron-spin polarized atomic H beam passes through a magnetic field reversal region in between high field "polarizer" solenoid and ionizer solenoid. Very strict restrictions are applied to the transverse magnetic field in the zero-crossing region (where the longitudinal field reverses direction) to avoid depolarization. The longitudinal field gradient generates a transverse field **Br**: $\mathbf{Br} = \mathbf{r/2(dB/dz)}$, and to fulfill Sona-transition conditions (for a Ø 2.0 cm atomic hydrogen beam) the condition $\mathbf{dB/dz} \ll 0.2$ G/cm is required at the **Bz=0** crossing point. A "soft" steel cylindrical Sona-shield and Correction Coil (CC) were designed and built to reduce the field gradient in the limited space between the superconducting solenoid 25 kG field and ionizer solenoid -1.5 kG field. As a result of Sona-shield and correction coil optimization, the gradient was reduced to less than 0.09 G/cm. For the Sona-transition efficiency studies and optimization the polarization dependence on correction coil current was measured for a wide range of CC field. Polarization was measured in the Lamb-shift polarimeter at 35 keV beam energy and at 200 MeV in the p-Carbon polarimeter.

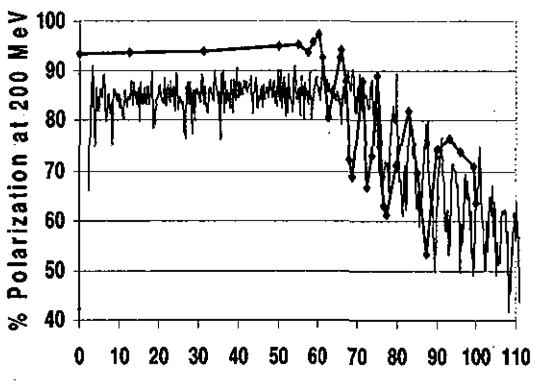

Figure 2. Measured (thin) and simulated (thick/diamond) polarization (%) vs. correction coil current (A).

Typical results are presented in Fig. 2. Since the CC field direction is opposite to superconducting solenoid field, the zero-crossing point is moving upstream inside the Sona-shield, when CC current is increased. This reduces the gradient and slightly increases polarization. At some current value the zero-crossing point is pushed out of the shield and the gradient is greatly increased, which causes a steep polarization drop.

A new and stronger correction coil (and additional magnetic shielding at the superconducting solenoid flange) allowed significant expansion of the field variation range, which revealed unexpected periodic polarization quantum oscillations. The polarization almost completely recovered at higher CC field, and the oscillations have a period of about 5 A correction coil current increment. The amplitude of the oscillations is slowly decreased with higher CC field. To further explore this effect, the CC field was reversed. This pushed the zero-crossing downstream outside of the shield, and polarization oscillations were also observed.

The numerical simulations of the Sona–transition efficiency were done by using a code which was developed at INR, Moscow /5/. Results of numerical integration of Schrodinger equations with time-dependent magnetic fields for hydrogen atoms moving along z-axis with velocity of $7.6 \cdot 10^5$ m/sec (2.8 keV beam energy) are shown in Fig. 2. The resulting beam polarization is calculated by averaging over effective beam diameter of a 10 mm. The calculation correctly reproduces experimentally observed polarization dependence on the magnetic field distribution in the Sona-transition region. The minimal field gradient and maximum polarization is obtained just before the field dips (providing that all the other transverse field sources are eliminated by the Sona shield). An additional μ-metal shield layer was inserted inside the "soft" steel cylinder to suppress the small residual field of the steel itself. The polarizations for different beam diameters – 1.2 cm, 1.6 cm and 2.0 cm (beam diameter is defined by the collimator at the entrance of Sona-shield) were measured after this optimization and within the errors the maximum polarization values are the same. This means that Sona-transition efficiency is close to 100% (the best value for further estimations is: $E_{Sona} = 0.99 \pm 0.01$).

POLARIZED D^- (D^+) ION SOURCE

Replacing the hydrogen bottle with deuterium in the OPPIS will produce vector polarized D^- ions with theoretical 66% (practical ~56%) vector polarization. The D^- beam intensity will be similar to above discussed H^- beam. A tensor polarization must be zero, which makes such a source attractive for experiments on Deuteron Electrical Dipole Moment searches /6/. Higher (100% theoretical, 85% practical) vector polarization can be obtained in a dual optical pumping scheme. A 300 μA polarized D- ion current of a 70% vector polarization was achieved in the KEK OPPIS /7/. To produce maximal tensor polarization an additional RF transition will be required /8/. The deuteron beam can be accelerated in the proton 200 MeV Linac but efficiency will only be about 12%. A new RFQ for the deuteron beam is also required.

In another option, the polarized D beam for D-EDM experiment at BNL will be accelerated and injected to Booster by the EBIS injector (RFQ and Drift Tube Linac designed for acceleration of ions with Z/A<=2 /8/. In this case, the second polarized source can be also of the Atomic Beam Source type, with the resonant plasma ionizer /9/. In this scenario the RHIC H-jet polarimeter will be a good prototype for the atomic beam source. A D^+ ion beam of about $2{\cdot}10^{11}$ D^+/pulse (pulse duration about 30 us) is required for injection to Booster. This current of a few mA was demonstrated in the tests at INR, Moscow.

There is an interest in experiments with colliding D beams in RHIC, but the acceleration of the polarized deuterons in the AGS and RHIC is a big challenge, because the Siberian snake does not work due to the small magnetic moment of deuterons /10/.

FEASIBILITY STUDY OF THE HIGH INTENSITY POLARIZED $^3HE^{++}$ ION SOURCE WITH EBIS IONIZER

Polarized beams of $^3He^{++}$ ions also contain the polarized neutron component (as deuterons) and its magnetic moment is close to the proton magnetic moment value, therefore the AGS and RHIC Siberian snake should preserve polarization during acceleration /10/. In this case the problem is the polarized $^3He^{++}$ source. The proposed polarized $^3He^{++}$ acceleration in RHIC (and also for the future RHIC upgrade to electron ion collider - eRHIC) will require about $2{\cdot}10^{11}$ $^3He^{++}$ ions in the source pulse and about 10^{11} ions in the RHIC bunch. To deliver these ions in a 20 μs pulse duration for injection to Booster, the source peak current has to be about 1000 μA, which is 10^4 times more than achieved in existing $^3He^{++}$ ion sources /11/. A new technique has been proposed for production of this very high intensity $^3He^{++}$ ion beam. It is based on ionization of ^3He gas (polarized by metastability exchange technique) in the Electron Beam Ion Source (EBIS) /12/.

The highest ^3He nuclear polarization close to 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 $^3S_1$ state are produced in the discharge and may be polarized by means of optical pumping with circularly polarized (2 ^3P – 2 ^3S) 1.083 μm light. This polarization is subsequently transferred to the much more numerous 1 $^1S_0$ ground-state atoms via spin-exchange collisions. The polarization in the glass cell can be determined using a measurement of the circular polarization of the 667 nm line in the discharge. Recently, ytterbium fiber lasers have produced 20~40 W of 1.083 μm radiation for metastability exchange optical pumping. Large volume systems at the University of Mainz have delivered polarizations of over 70% at a polarization rate of $8{\cdot}10^{18}$ atoms/s. In the proposed technique, the polarized ^3He consumption for injection to an ionizer is very small, of the order of 10^{13}~10^{14} ^3He atoms sec^{-1} and higher polarization is expected.

An EBIS is under construction at BNL as an alternative to the Tandem heavy ion injector for RHIC /13/. It is proposed to use the EBIS to produce $^3He^{++}$ by ionization of the polarized ^3He 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 ^3He polarization while in the intermediate singly-charged $^3He^+$ state. The ionization efficiency to the doubly-charged $^3He^{++}$ 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 $2.5{\cdot}10^{11}$ ($^3He^{++}$ ions)/pulse to be produced and extracted for subsequent acceleration and injection to RHIC.

After $^3He^{++}$ 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 $^3He^{++}$ ions are partially converted to He^+ (2S) – metastable ions in the alkali vapor cell. Then the hyperfine sublevel populations will be analyzed in the spin-filter device to extract the primary $^3He^{++}$ nuclear polarization.

Limitations on the maximum attainable nuclear polarization in the metastability exchange technique will be studied at the low polarized ^3He gas consumption rate. Possible depolarization effects during polarized ^3He gas injection to the existing EBIS prototype, and the multi-step ionization process will be studied. The ^3He polarization will be measured by optical pumping and NMR techniques. The expected $^3He^{++}$ ion beam intensity is in excess of $2{\cdot}10^{11}$ ions/pulse, with polarization in excess of 70%.

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