Chapter 10
Polarized Ion Sources

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Abstract State-of-the art of polarized proton, H^- ion, D^+ (D^-) and $^3He^{2+}$ ion beam sources are presented. Feasibility studies of new techniques are in progress at BNL and other laboratories. Polarized deuteron beams will be required for the polarization program at the Dubna NICA collider and at the deuteron Electric Dipole Moment experiment. Experiments with polarized $^3He^{2+}$ ion beams are a part of the experimental program at the future Electron Ion Collider.

10.1 Introduction

Polarization is an intrinsic property of light (photons), electrons, protons, nuclear beams, and the study of polarization effects provides essential information on particle structure and their Interactions. Collider experiments with polarized beams at RHIC [1] and HERA (at HERA, the experimental program with polarized electron beam and polarized internal target, HERMES, has been completed) provide crucial tests of QCD and Electroweak interaction. Polarization asymmetries and parity violation are strong signatures for the identification of the fundamental processes, which are otherwise inaccessible. Such experiments require the maximum available luminosity, and therefore polarization must be obtained as an extra beam quality

This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy. The United States Government and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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F. Méot et al. (eds.), *Polarized Beam Dynamics and Instrumentation in Particle Accelerators*, Particle Acceleration and Detection,
https://doi.org/10.1007/978-3-031-16715-7_10

without sacrificing intensity. This is already the case for electron accelerators. In a storage ring, an electron beam is self-polarized by the Sokolov-Ternov effect. For linear accelerators, a great effort in polarized electron source development was finally rewarded by achievement of up to 90% polarization and high beam intensity, which will be sufficient to run high-current accelerators at Jefferson Laboratory or the future International Linear Collider at maximum intensity with polarized beam. There were proposals to polarize the high-energy proton beam in a storage ring by the Stern-Gerlach effect (or antiprotons by the spin-filtering technique). But so far, the only feasible option is to accelerate the polarized beam produced in the source and make sure that polarization will survive during acceleration and storage. High intensity polarized H^- ion sources are presently a common choice for high-energy accelerators due to the advantage of stripping injection into the accelerator ring. Polarized deuteron beam will be required for the deuteron EDM (Electric Dipole Moment) experiment and is also planned for NICA collider at JINR, Dubna [2]. Experiments with accelerated polarized $^3He^{2+}$ ion beams will be a part of the program at future Electron Ion Collider [3].

10.2 Polarization Techniques

10.2.1 Spin Filtering Techniques

The basic feature of these polarization techniques is an attenuation: scattering out, adsorption, defocusing, quenching of unwanted part of light, electron, atomic, proton, or nuclei beams having "unwanted" direction of polarization. The adsorption of one component of linear polarization of light in some materials is called dichroism and is widely used in science, technology, and everyday life (polarization sunglasses, photography). A strong spin dependence of thermal energy neutron beam capture in a polarized ^3He gas cell is often used for neutron beam polarization and polarization analysis. In Lamb-shift polarized sources the metastable hydrogen atoms in unwanted spin states are quenched by the "spin-filter" to the ground states and remaining polarized atoms can be produced by selective ionization from metastable states.

Selective focusing by sextupole separating magnets is used for hydrogen (deuterium) beam polarization by electron spin in Atomic Beam Sources (ABS) of polarized ions and polarized internal targets. In these sources the atomic hydrogen is produced by dissociation of hydrogen molecules in RF discharge. Hydrogen gas flows out the dissociator volume to vacuum forming gaseous jet. The atomic hydrogen beam is formed then from central part of the jet using skimmers and diaphragms. A typical velocity of atoms in the beam is about $(1-2) \times 10^5$ cm/s, which is achieved by cooling of the dissociator nozzle to a temperature of 30–80 K. The sextupole magnetic field acts on electron magnetic moment axially aligned with the field gradient towards magnet tips as a focusing lens. The other component having opposite electron spin direction is defocused. Then the electron polarization is transferred to the protons by means of radio-frequency transitions. The atomic beam of a selected spin-state is directed into an ionizer (or a storage cell). The polarized proton or H^- ion beam can be produced by ionization of atomic beam in magnetic field of about 1.5 kG, which is sufficient to break electron-proton spin coupling while preserving proton polarization. The ABS beam can be used as an internal target in accelerator-collider storage ring (polarized H-jet polarimeter at RHIC [4]), or for feeding storage cell type of internal targets. There is a proposal to use polarized atomic hydrogen storage cell for antiproton polarization in the storage ring by filtering (removing) of unwanted states (PAX proposal for HESR at FAIR [5]).

10.2.2 Optical Pumping

Electron or nuclear polarized atoms can be obtained in process of absorption of polarized photons from external source of polarized light and subsequent spontaneous emission of un-polarized photon (optical pumping). Angular momentum of atom electron shell is changed during the process and atom takes on electron polarization. The electron polarization is transferred to nuclear through spin-spin interaction if optical pumping takes place in sufficiently low magnetic field. Population of spin states of atoms is changed during the optical pumping without filtering process due to absorption of external polarized photons which angular momentum is transmitted to atoms. For optical pumping of rubidium atoms laser radiation with wavelength of 795 nm is used to excite transitions: $5S_{1/2} \rightarrow 5P_{1/2}$. Polarized ^3He atoms are obtained by exciting transitions $23S_{1/2} \rightarrow 23P_0$ (1083 nm). Direct optical pumping of hydrogen atoms cannot be used so far for polarized proton production due to absence of suitable lasers with wavelength of 121.5 nm (Lyman alpha radiation). Doppler-shift for counter propagating relativistic atomic hydrogen and laser beam can shift the transition wavelength to an accessible range. The relativistic atomic hydrogen beam of a 500–800 MeV energy can be produced by stripping of accelerated H^- ion beam in the carbon stripping foil. For these energies the 121.5 nm transition wavelength will be shifted to 330–410 nm range, which can be produced by using the second harmonics of tunable lasers [6].

10.2.3 Polarization-Transfer Technique

In any type of polarized proton (H^- ion) source the first step is the generation of an electron-spin polarized atomic beam (see Fig. 10.1). The polarization is then transferred to the protons by hyperfine interaction and finally the beam is ionized. The difference is in the velocity of the atomic beam. It is comparatively easy to polarize a “slow” (thermal energy) beam by using separating magnets, as discussed

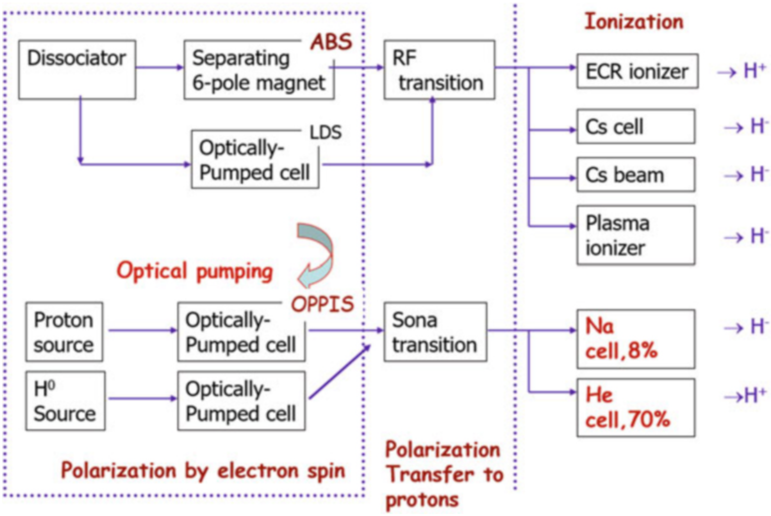

Fig. 10.1 Ion polarization techniques. Three-step process: first-electron spin polarization; second-electron to proton polarization transfer; third-ionization to positive or negative ion beam

above. The advantages of using "fast" (a few keV energy) beams are higher intensity and simple, more efficient ionization. The electron-spin polarization of the "fast" H^- beam is produced either in a charge-exchange process, when primary protons capture polarized electrons from polarized atoms in a vapor cell, or in spin-exchange collisions. In this technique optical pumping is used to get polarized alkali atoms. This technique is called an "Optically-Pumped Polarized Ion Source" (OPPIS), although polarized electrons can also be captured from a ferromagnetic foil (as in the original Zavoiski's proposal), or from hydrogen, or an alkali-metal atomic beam polarized by separating magnets [7].

There is no space-charge limitation in the spin-exchange collisions between hydrogen and Rb atoms therefore higher beam intensity can be achieved in this scheme. But the cross-section of the spin-exchange collisions is smaller than that of the charge-exchange collisions and higher (about 10^{15} atoms/cm^2) alkali vapor thickness is required, which can be produced only in a cell 100 cm long (due to radiation trapping limit on the maximum vapor density). The proposed scheme in which atomic H collisions in the mixture of He gas and Rb vapor in the same cell, i.e. combining charge-exchange and spin-exchange collisions allows the Rb vapor thickness to be reduced to 4×10^{14} atoms/cm^2, which can be produced in a cell 40 cm long.

10.3 Atomic Beam Source with Resonant Plasma Ionizer

A polarized ABS ion source with resonant plasma ionizer has been developed at INR Moscow [8]. A deuterium plasma injector is used in this source for production of polarized H^- ions. The injector generates plasma consisting mainly from D^+ and D^- ions. The present version of the plasma injector is shown schematically in Fig. 10.2. The plasma flux from the arc-discharge plasma source is enriched by negative ions in a surface-plasma converter. Positive ions are converted into neutral atoms with eV energy in collisions with a neutralizer internal surface. Polarized atomic hydrogen beam is injected into the plasma and polarized H^- ions are produced via reaction: $\vec{H}^0 + D^- \rightarrow \vec{H}^- + D_0$.

The plasma flux is guided to the internal surface of the neutralizer by the magnetic field created by the plasma coil (in longitudinal direction) and by the converter electromagnet (transversal direction). Plasma ions interact with the neutralizer surface and most of them are reflected as neutral hot atoms. The reflected hot atoms hit the converter cylinder internal (molybdenum) surface where the atoms are converted partially into negative ions and injected into the ionization region along the fringing solenoid field lines. With this ionizer a polarized H^- ion beam with peak current of 4 mA has been obtained with D^- ion beam current of 62 mA. The polarization of the H^- ion beam was measured to be 0.91 ± 0.03. The Lamb shift polarimeter has been used for the polarization measurements. Figure of merit of the polarized H^- ion beam produced $\mathbf{P^2I}$ has record value of 3.2 mA. Efficiency of direct conversion of polarized hydrogen atoms into polarized H^- ions reached of 12.5%. Polarized D^- ion beam with peak intensity up to 2 mA

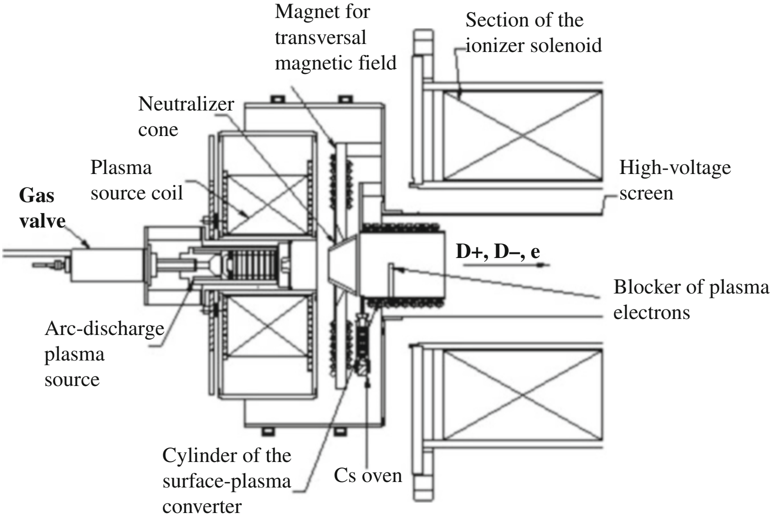

Fig. 10.2 The plasma injector of D^+ and D^- ions

and polarization up to 90% from nominal of vector polarization ±1 and tensor polarization of +1,-2 have been obtained from the polarized ion source CIPIOS at IUCF [9]. The source was developed in a collaboration of IUCF and INR Moscow. The source had a nearly resonant charge-exchange plasma ionizer and produced also polarized H^- ions (1.8 mA peak) and unpolarized H^- and D^- ion beams (40 mA and 30 mA respectively) with pulse duration of 300 μs and repetition rate of 2 Hz. The emittance was minimized by a carefully designed focusing of an atomic hydrogen beam by permanent magnet sextupoles with magnetic field up to 1.4 T and by restriction of magnetic field in a charge-exchange region to value ≤ 1.0 kG. The normalized emittance of the polarized ion beams was measured to be $1.2\,\pi$ mm mrad.

10.4 Polarized Source for NICA

The program of polarization research at NICA Ion Collider (Joint Institute for Nuclear Research at Dubna, Russia) is based on the acceleration of polarized proton beams up to 12 Gev and deuteron beams up to 5.6 GeV/nucleon beam energy in the NUCLOTRON accelerator and beam injection in the collider rings. A high intensity pulsed source of polarized protons and deuterons is required to achieve the number of accelerated deuterons of $\sim 10^{10}$ deuterons/cycle (with the present one turn injection scheme, 10 μs pulse duration, 1 Hz repetition rate). A new polarized ABS was developed in a collaboration of JINR and INR Moscow. Parts of the CIPIOS source from IUCF were delivered to JINR and will be used for the Dubna polarized deuteron source (see Fig. 10.3) [10].

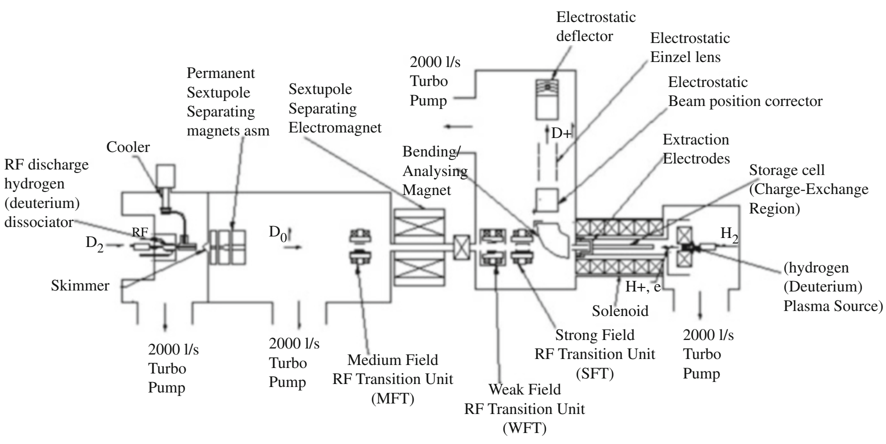

Fig. 10.3 NICA polarized proton, D^+ ion sources with the resonant plasma ionizer

A project goal is a polarized deuteron beam from the source with a peak intensity of 10 mA and polarization of 90% from nominal vector polarization ±1 and tensor polarization +1, −2. The polarized current of a 6 mA and polarization 88+/−5% were obtained in Run-2016-17. A nearly resonant charge-exchange deuteron plasma ionizer with storage cell will be used to increase intensity of the polarized ion beam from the source, reduce the polarized ion beam emittance and the unpolarized proton current in the charge-exchange region, in comparison with a source without the storage cell, and respectively reduce background current of H_2+ ions, which will not be separated from polarized deuterons in the bending magnet. The source development is in progress for further beam intensity and polarization improvements.

10.5 Polarized Source with Cesium Beam Ionizer at COSY

The principle of the source is an ionization of pulsed polarized hydrogen or deuterium beams (20 ms pulse duration, 0.5 Hz repetition rate) in collisions with a pulsed neutral cesium beam having a kinetic energy of about 45 keV [11]. The Cs ion emitter is a porous tungsten button on a molybdenum heater. The pulsed operation of the Cesium gun is controlled via a high voltage electrode. The parameter space for the operation of the gun was carefully mapped to find a setting that delivered a nearly rectangular pulse shape. This was an important prerequisite for the precise transport of this beam, which is strongly governed by space charge effects in the initial phase. After the Cs+ beam formation to match the polarized hydrogen beam in the ionizing region the Cs+ beam is neutralized in the cesium neutralizer cell. In a charge exchange reaction is taking place in a solenoid field, negatively charged hydrogen, or deuteron, ions are created and accelerated toward the extraction elements. Then the ions are bent magnetically by 90°, passed through a Wien-filter and enter the transporting source beam line that guides them into the cyclotron. The new record value of 50 μA and 90% polarization was reached during routine source operation in 2005. This exceeds the original design value of 30 μA. It was the result of the optimization of all source components [12].

A breakthrough decision was to develop a pulsed cesium beam matched to the short injection period of up to 20 ms for COSY, thus virtually eliminating the severe sputtering damage that had been an obstruction for reliable operation. Beam diagnostics, like beam scanner, Faraday cups and viewer, for the cesium beam were added to successfully shape the transverse phase space for optimal overlap with the atomic hydrogen or deuterium beam.

10.6 Optically Pumped Polarized H^- Ion Source at RHIC

A novel polarization technique successfully implemented for the upgrade of the RHIC polarized H^- ion source to higher intensity and polarization for the first production Run-2013 [13]. In this technique, a proton beam inside the high magnetic field solenoid produced by ionization of the atomic hydrogen beam (from an external source) in the He-gas ionizer cell. Proton polarization is produced by the process of polarized electron capture from the optically-pumped Rb vapor. Polarized beam intensity produced in the source exceeds 4.0 mA. Strong space-charge effects cause significant beam losses in the LEBT (Low Energy Beam Transport, 35.0 keV beam energy) line. The LEBT was modified to reduce losses. As a result, 1.4 mA of polarized beam was transported to the RFQ and 0.7 mA was accelerated in linac to 200 MeV. A maximum polarization of 84% (in the 200 MeV polarimeter) was measured at 0.3 mA beam intensity and 80% polarization was measured at 0.6 mA. The upgraded source reliably delivered beam for the 2013 polarized run in RHIC at $\sqrt{S} = 510$ GeV. This was a major factor contributed to the RHIC polarization increase to over 60% for colliding beams.

10.6.1 OPPIS with the Atomic Hydrogen Beam Injector

The polarized beam for the RHIC spin physics experimental program is produced in the Optically-Pumped Polarized H^- Ion Source (OPPIS) [14]. An Electron Cyclotron Resonance (ECR) ion source was used as the primary proton source in the old operational polarized source. The ECR source was operated in a high magnetic field. The proton beam produced in the ECR source had a comparatively low emission current density and high beam divergence. In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations can be overcome by using a high brightness proton source outside the magnetic field instead of the ECR source. In this technique (which was implemented for the first time at INR, Moscow [15]), the proton beam is focused and neutralized in a hydrogen cell producing the high brightness 6.0–8.0 keV atomic H0 beam. The atomic H0 beam is injected into the superconducting solenoid, where both the He ionizer cell and the optically-pumped Rb cell are situated in the 25–30 kG solenoid field. The solenoid field is produced by a new superconducting solenoid with a re-condensing cooling system. The injected H atoms are ionized in the He cell with 60–80% efficiency to form a low emittance intense proton beam and then enter the polarized Rb vapor cell (see Fig. 10.4). The protons pick up polarized electrons from the Rb atoms to become a beam of electron-spin polarized H atoms (similar to the ECR based OPPIS). A negative bias of about 3.0–5.0 kV applied to the He cell decelerate the proton beam produced in the cell to the 2.0–3.0 keV beam energy, optimal for the charge-exchange collisions in the rubidium and sodium cells. This allows energy separation of the polarized hydrogen atoms produced after

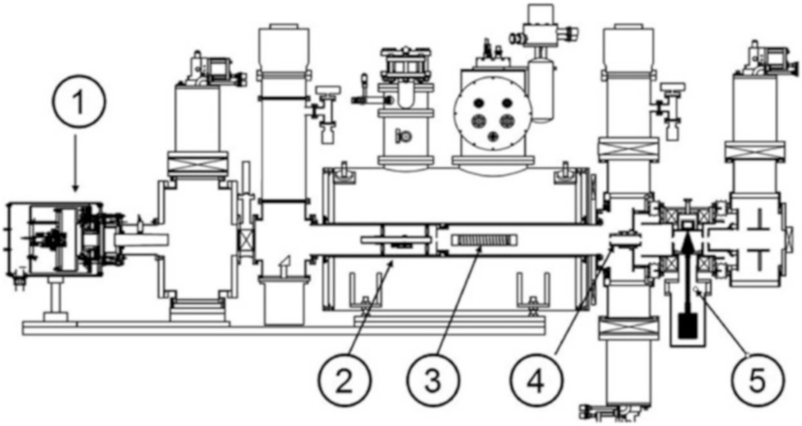

Fig. 10.4 A new polarized source layout: (1) atomic hydrogen injector; (2) pulsed He—gaseous ionizer cell; (3) optically-pumped Rb-vapor cell; (4) Sona-transition; (5) Na-jet ionizer cell

lower energy proton neutralization in Rb-vapor and residual hydrogen atoms of the primary beam.

10.6.2 *Fast Atomic Beam Source Development*

In the atomic hydrogen beam source, the primary proton beam is produced by a four-grid multi-aperture ion extraction optical system and neutralized in the H_2 gas cell downstream from the grids. A high-brightness atomic hydrogen beam was obtained in this injector by using a plasma emitter with a low transverse ion temperature (of about 0.2 eV), which is formed by plasma jet expansion from the arc plasma generator [16]. The multi-hole grids are spherically shaped to produce "geometrical" beam focusing. The grids are made of 0.4 mm thick molybdenum plates. Holes (0.8 mm diameter) in the plates were produced by photo-etching techniques. The hole array forms a hexagonal structure with a step of 1.1 mm and outer diameter of 5.0 cm. The grids were shaped by re-crystallization under pressure at high temperature and were welded to stainless steel holders by a pulsed CO2 laser. At an emission current density of 470 mA/cm^2, the angular divergence of the produced beam was measured to be ≈10–12 mrad.

The focal length of the spherical ion extraction system was optimized for the OPPIS application, which is characterized by a long polarizing structure of the charge-exchange cells and small (2.0 cm diameter) Na-jet ionizer cell, which is located 240 cm from the source (see Fig. 10.4). An optimal drift-space length of about 140 cm is required for convergence of the 5 cm (initial diameter) beam to 2.5 cm diameter He-ionizer cell. About 20% of the total beam intensity (≈3.5 A) can be transported through the Na-jet cell acceptance by using the optimal extraction grid system with a focal length: F≈200 cm. Three spherical IOS were tested on the test-bench at BNL. The focusing lengths of IOS #1 and #3 were 150 cm and for IOS#3 F≈250 cm, which allowed study of optimal beam formation. IOS#2 produced about 500 mA equivalent atomic H beam within the 2.0 cm diameter Na-jet ionizer acceptance (at the distance 240 cm from the source) and 16 mA H^- ion beam current.

10.6.3 Helium Ionizer Cell: Beam Energy Separation

The He-ionizer cell is a 40 cm long stainless-steel tube with an inside diameter 25.4 mm (see Fig. 10.5). A new fast "electro-magnetic" valve for He-gas injection to the cell was developed for operation in the 30 kG solenoid field. In this valve, a pulsed current of about 100 A is passed through the flexible springing plate (made of beryllium bronze foil with a thickness of 0.5 mm). The Lorentz force: F = eL [I×B] = 15 N for a L=5 cm long plate. The plate is fixed at one end and this force bends the plate and opens the small (0.5 mm diameter) hole which is sealed with a Viton O-ring. The pulsed current rise-time is ≈50 μs and gas pressure rise time is about 100 μs.

The proton beam produced in the He-cell is decelerated from 6.5 keV to 2.5 keV by a negative potential of 4.0 keV applied to the cell. At the 2.5 keV beam energy, the H^- ion yield in the sodium ionizer cell is near maximum (≈8.4%) and the polarized electron capture cross-section from Rb atoms is also near the maximum of $\approx 0.8 \times 10–14\,\text{cm}^2$. The deceleration was produced by a precisely aligned (to reduce beam losses) three wire-grid system. A negative bias applied to the first grid at the cell entrance and second grid at the cell exit to trap electrons in the cell for space-charge compensation. Fine tuning of the grids voltages is required for the polarized beam current optimization and total current reduction of the He-cell pulsed power supply.

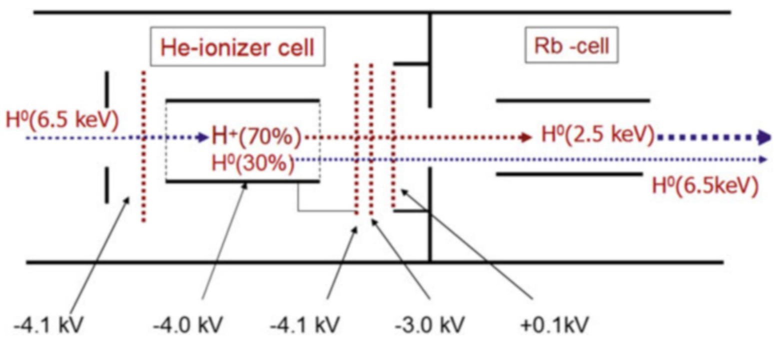

Fig. 10.5 A schematic layout of the He-ionizer cell and deceleration system for the polarized beam energy separation

About 40% residual (which passed the He-cell without ionization) atomic beam component at 6.5 keV energy will pass through the deceleration system and Rb cell and be ionized in Na-cell producing H^- ion beam. The H^- ion yield at 6.5 keV is about 4%. This is a significant suppression in comparison with the main 2.5 keV beam, but it would be a strong polarization dilution unless further suppression is applied. The H^- ion beam acceleration produces polarized H^- ion beam with 35 keV beam energy and un-polarized beam with 39.5 keV energy. The un-polarized 39.5 keV beam component is well separated after the 23.7 degree bending magnet in the LEBT. In measurements of beam separation, the beam energy was varied by the accelerating voltage applied to the Na-jet ionizer cell. The residual 6.5 keV un-polarized beam component is strongly suppressed (to less than 2% of polarized beam component).

10.7 RHIC Polarized Source Performance

The new source with atomic beam hydrogen injector and He-ionizer cell was developed in 2010–2012 and commissioned for operation in Run-2013. The use of the high brightness primary proton source resulted in higher polarized beam intensity and polarization delivered for injection to Linac-Booster-AGS-RHIC accelerator complex. Very reliable operation and reduced maintenance time were demonstrated. The new OPPIS intensity and polarization exceeded the old ECR-based source parameters and the source performances were improved in Runs 2014–2015. Further beam intensity and polarization increase were achieved in Run-2017 with; the new IOS for the primary proton beam production, He-ionizer cell operation optimization, and improved LEBT tune efficiency. As a result, of these upgrades, the polarized source delivered 0.5–1.0 mA H^- ion beam intensity at 82–85% polarization as measured after the Linac at 200 MeV beam energy. The source current is significantly higher (in excess of 4.0 mA). The largest beam losses occur during 35 keV beam transport in the long LEBT line and energy separation process. These losses can be reduced by continued optimization of the energy separation system in the He-ionizer cell, optimization of beam acceleration system after the Na-jet ionizer cell, and LEBT line optics improvements.

The beam polarization was measured in the absolute polarimeter at 200 MeV beam energy after the Linac. Polarization losses in AGS depend on beam emittance and corresponding bunch intensity. When extrapolated to zero intensity (small emittance) polarization numbers are consistent with the absolute 200 MeV polarimeter measurements. The AGS bunch intensity for injection to RHIC was about 2.0×10^{11} protons/bunch and polarization 70–72% optimized for best RHIC operation. The beam polarization in RHIC was measured with an absolute H-jet polarimeter. As a result, of recent H-jet intensity, detectors, DAQ upgrades and ongoing systematic errors analysis, the statistical accuracy for the single RHIC fill measurement reduced to less than $\pm 3\%$ and systematic error for absolute polarization value to $< 0.5\%$ [13]. The steady source and AGS performances resulted in production of high (55–60%) average beam polarization in RHIC. The polarization for colliding beams is higher than average polarization and exceeded 60% for a good fraction of fills.

10.8 Polarized $^3He^{2+}$ Source for EIC

The nuclear polarization in polarized ^3He nuclei is mostly (88.6%) carried by neutrons. The $^3He^{2+}$ beam polarization produced in the source can be preserved during acceleration in high-energy synchrotron accelerators like AGS and RHIC by using the "Siberian snake" technique [17]. In effect, in electron-^3He nuclei collisions at EIC we can study the fundamental interactions of polarized electron beam with high-energy polarized neutron beam, complementary to the studies of the polarized electrons with polarized proton beam collisions. The proposed polarized $^3He^{2+}$ acceleration in RHIC will require about 2×10^{11} ions in the source pulse and 10^{11} ions in the RHIC bunch. To deliver this intensity in a 20 µs pulse duration for the injection to the Booster, the source peak current must be about 2000 µA, which is 1000 higher than ever achieved in existed $^3He^{2+}$ ion sources. We proposed a new polarization technique for production of high intensity $^3He^{2+}$ ion beam, which is based on ionization of ^3He gas (polarized by metastability exchange technique) in the Electron Beam Ion Source (EBIS) [18]. The development of the source for EIC is now in progress in collaboration between BNL and MIT.

The EBIS currently produces high charge state ions for injection to the RHIC and will remain the primary source of charged ions from P to U for the eRHIC. In the EBIS, the high intensity (10 A) electron beam is produced by the electron gun with cathode diameter 9.2 mm and injected into the 5.0 T solenoid magnetic field. The electron beam is radially compressed by the magnetic field to the diameter of about 1.5 mm in the ionization region and then expanded before dumping into the electron collector at the other end. Ions are radially confined by the space charge of the electron beam and longitudinally trapped by electrostatic barriers at the ends of the trap region. The ions are extracted by raising the potential of the trap and lowering the barrier [19]. A second 5.0 T solenoid has been constructed as the part of the extended EBIS upgrade. The polarized ^3He gas will be injected and ionized in the upstream solenoid, and $^3He^+$ ions will be trapped and further ionized to the $^3He^{2+}$ state in the downstream solenoid (see Fig. 10.6).

The ^3He gaseous cell will be placed inside the EBIS "injector" solenoid and the pulsed gas valve (similar to OPPIS valve) will be used for the gas injection into the center of the EBIS drift tube system to minimize depolarization and increase ionization efficiency. The second "injector" EBIS section allows using differential pumping between the "gas injector" and the main EBIS. This is especially beneficial for gas species production (including the ^3He gas). An isolation valve between the two EBIS sections will simplify the ^3He polarizing apparatus maintenance. The ionization in the EBIS is produced in a 5.0 T magnetic field, which preserves the nuclear ^3He polarization while in the intermediate single-charged $^3He^+$ state. The

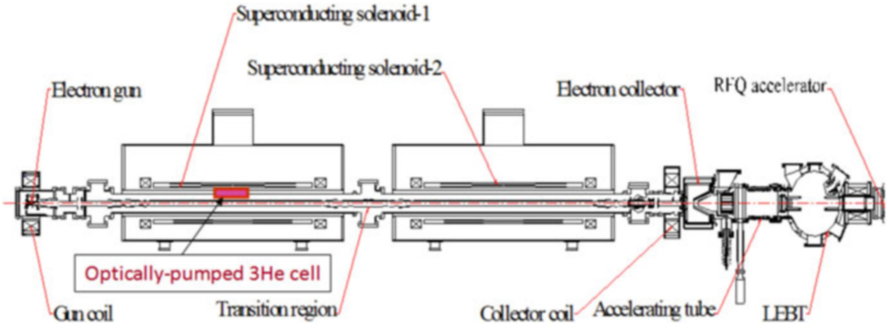

Fig. 10.6 Schematic diagram of the extended EBIS. The polarized ^3He gas is injected into the drift tube of the new "injector" EBIS part

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 more than 2.0×10^{11} $^3He^{2+}$ ions/pulse to be produced and extracted for the subsequent acceleration and the injection in the RHIC. After the $^3He^{2+}$ beam acceleration to the energy 6 MeV/nucleon the absolute nuclear polarimeter based ^3He-^4He collisions will be used for the polarization measurements.

The high ^3He nuclear polarization more than 80% was achieved by the metastability-exchange technique in the sealed glass cell in the high 2.0–4.0 T magnetic field [20]. In these measurements, the ^3He gas at 1.0–3.0 torr pressure was contained in the glass cell and the weak RF discharge was introduced to populate the meta-stable states. Meta-stable atoms in the 2^3S_1 state was polarized by optical pumping with circularly polarized (2^3S_1 - 2^3P_0) 1083 nm laser light. Any contamination in the helium gas cell (hydrogen, water vapor etc.) reduces the ^3He polarization due to meta-stable states quenching. In the polarized source, the optically pumped cell must be connected to the valve for gas injection to the drift tube and the line for the gas refill. To eliminate the contaminations and maintain the necessary gas purity we developed the system for ^3He gas purification and filling based on the cryo-pump, which pumps all gases except for helium. We installed inside the conventional CTI-8 cryo-pump the additional cold vessel (attached to the cold head of the cryo-pump) filled with charcoal granules. It was connected to the ^3He filling system by the thin wall tube. At a temperature of 46 K the pump continuously absorbing and reducing partial pressures of hydrogen, water, hydrocarbons, and argon to the level below 10^{-7} torr. This pump absorbs also quite a significant amount of ^3He gas (of about 100 sccm). The absorbed gas is released by the pump vessel heating. This provides gas storage and supply for ^3He-cell operation at the optimal pressure value. The optically pumped ^3He glass cell was attached to the gas filling system with a 200 cm long stainless tube. The cell and filling system were mounted on a movable support and inserted inside superconducting solenoid. To prevent ^3He atoms depolarization due to travel through the solenoid gradient field we installed an additional isolation valve close to

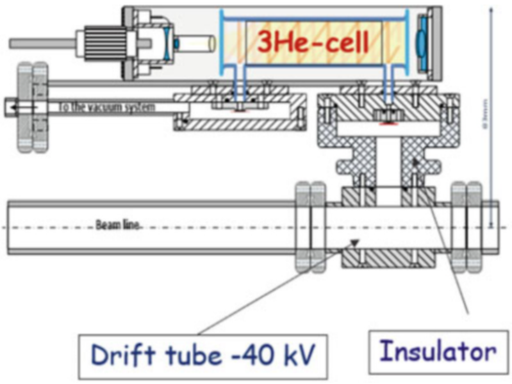

Fig. 10.7 The optically-pumped ^{3}He cell is attached to 300 mm long drift tube (storage cell) inside the 5 T solenoid. The ^{3}He cell is at ground potential and connected to the drift tube by ceramic insulator

the cell in the homogeneous field region. We use a remotely controlled (pneumatic) pumping-filling valve between the filling system and glass cell (see Fig. 10.7).

For the polarization measurements, we used the technique of the probe laser absorption [21]. The best results on optical pumping of ^{3}He gas in the "open" cell were 73% with the closed isolation valve and 20% with the open isolation valve at 3.0 torr pressure. We have studied a new EBIS drift-tube configuration to increase the gas efficiency (minimize amount of injected ^{3}He gas for the EBIS trap saturation). The ^{3}He gas will be injected into the small diameter (10–20 mm ID) drift tube by the pulsed valve. The estimations show that a very small amount of ^{3}He gas of about (5–10) $\times 10^{12}$ atoms will be required to be injected into the drift tube for 50% EBIS trap neutralization. We are developing the pulsed valve for the ^{3}He-gas injection into the EBIS drift tube, which operates in the 2.0–5.0 T solenoid field. In this valve, the pulsed current of 10–20 A passes through the flexible springing plate (made of phosphorus bronze with a thickness of 0.12 mm). The sealing silicon circular pad (5 mm in diameter 1.0 mm thick) was attached to the plate. The induced Lorentz (Laplace) force: $F = eL[I \times B] = 2\text{-}5\,N$ (for L=5 cm long plate) bends the plate and opens the small (0.1 mm in diameter) hole for the gas injection into the drift-tube. The valve prototype was tested in the 2.0 T solenoid field. The gas flow as low as 2×10^{12} atoms /pulse was measured at 12 A current through the plate. The valve was also operated with the four consecutive pulses 4 ms apart, producing up to 10^{13} atoms/per cycle. This might be an optimal mode for the gas injection distributed over 20 ms for the effective ionization by the EBIS electron beam, while limiting the injection gas cell pressure to $\approx 10^{-6}$ mbar. After $^3He^{2+}$ 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 $^3He^{2+}$ 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 $^3He^{2+}$ nuclear polarization. A study of limitation on the maximum attainable nuclear polarization in the metastability exchange technique (at the very low polarized ^{3}He gas consumption rate) will be required to define the maximum attainable polarization. Possible depolarization effects during polarized ^{3}He gas injection to existing EBIS prototype and multi-step ionization process should be also studied. The expected $^3He^{2+}$ ion beam intensity is $\approx 2\times 10^{11}$ ions/pulse with polarization $\geq 70\%$.

10.9 Summary

Polarization studies with polarized ion beams at new and existing accelerators and colliders will require high-intensity, high polarization proton, deuteron and $^3He^{2+}$ ion beams. State-of-the-art atomic beam sources with resonant plasma ionizer and optically pumped polarized proton sources produce sufficient beam intensity (of a few mA H^- ion beam) for charging the high-energy accelerators to full capacity (for colliders the intensity is limited by the beam-beam interaction). The proton polarization of about 90% has been achieved for the high intensity beams. The further increase to over 10 mA pulsed beam intensity has also been demonstrated and will be used at future Electron Ion Colliders. The polarized $^3He^{2+}$ ion source based on EBIS injector is under development at BNL for future EIC collider. The extended EBIS operation for the Au^{32} ion beam production is planned for the Run-2023. The next step will be integration of polarizing ^{3}He apparatus. The development of the ^{3}He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the $^3He^{2+}$ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac) is under development.

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