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Polarized Ion Sources

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This discussion will cover the basics of polarized ion sources. State-of-the-art polarized proton, H-, D+, and He3 ion sources will be presented. The feasibility of new techniques is currently being investigated at BNL and other laboratories. Polarized deuteron beams will be required for the polarization program at the Dubna NICA collider and for the deuteron Electric Dipole Moment experiment. Experiments with polarized 3He2+ ion beams are part of the experimental program at the future Electron Ion Collider

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1. Introduction

In quantum mechanics, spin is an essential quantum number of all subatomic particles and exists in two states: up (↑) and down (↓). The degree of polarization is defined as P = (N↑ - N↓) / (N↑ + N↓) for a collection of particles of the same type. For protons, a high degree of polarization at certain energies and scattering angles is common in proton scattering off certain fixed targets. The nuclear interaction between the proton and the fixed target serves as a polarizer for an initially unpolarized proton beam.

For example, in 1958, Hafner [1] achieved a highly polarized proton beam with an intensity of 3.8×10^6 protons per second by scattering a 0.3 μA proton beam from a thin carbon target using the 220 MeV Rochester cyclotron. This method for producing polarized protons resulted in a significant intensity reduction (approximately 10^{-6}) and deteriorated beam quality with a high energy spread and emittance.

To obtain higher intensities of polarized ions, atomic beam sources (ABS) with multipole magnetic fields and RF transitions were employed in the 1960s. The ionization efficiencies for polarized atomic beams were very low, typically around 10^{-4}. Subsequently, better ionizers (Penning, ECR) were developed, and intensities reached the order of 100s of μA [2,3,4,5].

Negative polarized ion sources were developed using electron transfer from an atom or ion to H^0. This technique produces polarized H^-/D^- ions with milliampere intensities. In modern polarized H^- sources, proton beams acquire polarized electrons from a polarized electron donor. This type of source (e.g., OPPIS at BNL [6,7]) can produce 1-2 mA of current with high polarization (P = 0.85 - 0.90).

Polarization is used to study particle structure and their interactions. Experiments with polarized beams at RHIC [8] and HERA [9] provide crucial tests of QCD and electroweak interactions. Polarization asymmetries and parity violation serve as strong signatures for identifying fundamental processes. One of the fundamental physics questions revolves around the proton spin puzzle, as experiments in the 1980s revealed that the three valence quarks contribute only a few percent of the proton's spin. Such experiments require the maximum available luminosity, and therefore polarization must be achieved as an additional beam quality without sacrificing intensity. Polarized deuteron beams will be required for the deuteron EDM (Electric Dipole Moment) experiment and are also planned for the NICA collider at JINR, Dubna [10]. Experiments with accelerated polarized $^3He^{+2}$ ion beams will be part of the program at the future Electron Ion Collider [11]

2. Ion Polarization Techniques

Most polarized proton sources leverage the fact that the electron has a much larger magnetic moment than the proton in the hydrogen atom. The electron in the atom can be more easily acted upon than the proton. The proton within the H atom experiences a very strong magnetic field from the atomic electron. The magnetic interaction (hyperfine) between the electron and proton in the H atom is utilized to transfer electron polarization to the proton.

Polarized ion sources generally employ RF discharge or ion sources (P or H^0) to dissociate gaseous molecules into atomic form. For solid elements (e.g., Li, Na), an oven is used. Polarization typically involves three steps: atomic electron polarization, electron spin transfer to the nucleus, and ionization to positive or negative ions (Figure 5)

2.1 Atomic Electron polarization

The atomic electron can be polarized by filtering (separating) atoms with one type of spin (up of down), or adding polarized electron to proton beam from an optically pumped alkali vapor.

2.1.1 *Spin Filtering Techniques*: These techniques exploit the fact that the separation between nuclear substates arises from the difference in energy associated with the nuclear magnetic moment for the two different orientations of the electrons in the magnetic field. The energy of hydrogen increases as the external magnetic field strength increase (Figure 1)

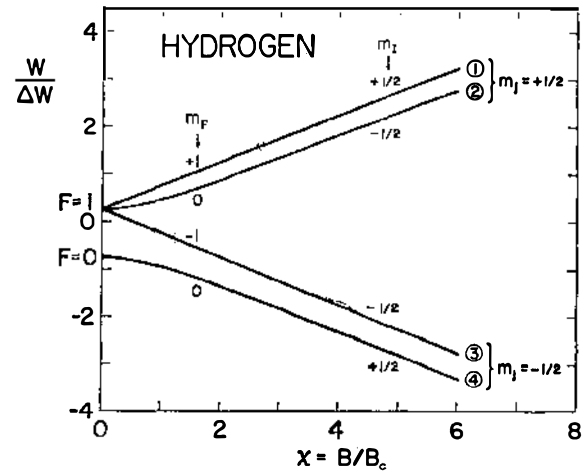


Figure 1: Energy-level diagram of the hydrogen atom in a magnetic field. The energy measuremen units: ΔW = h X 1429.4 MHz and magnetic field measurement unit: B_c=507 G [2]

In an inhomogeneous magnetic field, the energy becomes a function of position. This results in hydrogen atoms experiencing a force that spatially separates the different magnetic states.

Generally, atomic hydrogen is produced by dissociating hydrogen molecules in an RF discharge. The atomic hydrogen beam is formed from the central part of the jet emerging from the RF dissociator using skimmers and diaphragms. A typical velocity of the atomic hydrogen beam is about 1-2 x 10^3 m/s, which is achieved by cooling the dissociator nozzle to a temperature of 50-80 degrees K.

This atomic beam with thermal velocity is directed into a multipole (sextupole) magnetic field. In this field, atoms with electron spin up are driven towards the axis of the magnet, while atoms with the opposite spin are driven away from the axis. This focusing action can be explained as follows

The energy dependence of a substate in an atom depends on the magnitude of the external field B. In a multipole magnet, the magnitude of the magnetic field exhibits axial symmetry, and therefore the force on the atom is radial.

Since the magnitude of the magnetic field increases with the radial distance (r) in a multipole magnet, the force points towards the axis for substates whose energy increases with the magnitude of the magnetic field (states with m_j = +1/2). Conversely, the force points away from the axis for substates whose energy decreases with the magnitude of the field.

The multipole magnet acts as a spherical lens. The acceptance angle (α) of the magnet depends on the absolute temperature (T) of the beam and the magnitude of the pole tip field (B_m but is independent of the magnet's diameter and length. (Figure 2)

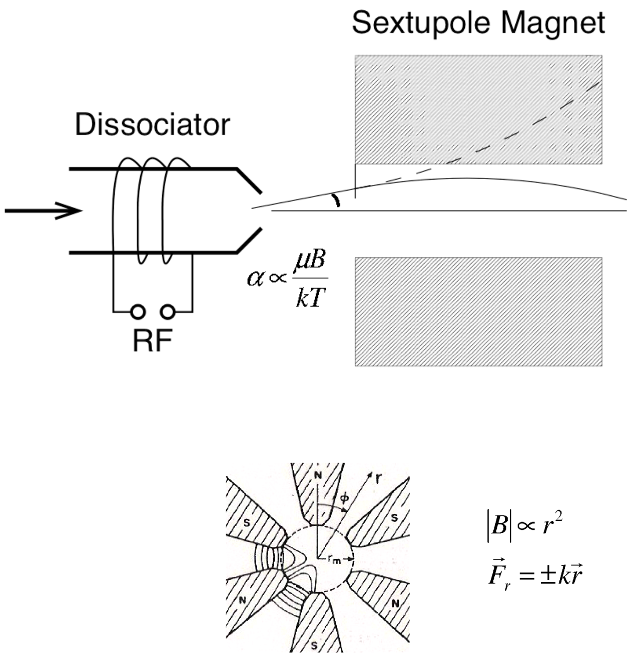


Figure 2: Schematic of an atomic beam source. Hydrogen gas at a low pressure is dissociated by an RF discharge. The inhomogeneous magnetic field of a multipole magnet deflect the atom with spin up towards the axis, while atoms with opposite spin are rejected [2,3].

In a multipole (sextupole) magnet, the field direction alternates azimuthally. This causes the average polarization of the beam at the magnet's exit to be zero. If the multipole magnet is followed by a homogeneous dipole field, the polarization vector of the atoms will align with the dipole field, provided the change in field direction between the multipole and dipole satisfies the condition of adiabaticity. This condition requires that the angular velocity of the field direction as seen by the H atoms is slow compared to the Larmor precession angular velocity of the atom in the B-field

2.1.2 *Atomic electron polarization vis optical pumping*

Absorption of a polarized photon and subsequent spontaneous emission of an unpolarized photon (optical pumping) alters the angular momentum of the atom's electron shell, resulting in electron polarization of the atom. Direct optical pumping of the H atom requires a 121.5 nm laser, which is currently unavailable. In this case, an alkali metal (Rb), which is optically pumped by circularly polarized light (wavelength 795 nm to excite the $5S_{1/2} \rightarrow 5P_{1/2}$ transition), is used to transfer polarized electrons to the proton via charge exchange. For ^{3}He, optical pumping is achieved using a 1083 nm laser to excite the 2 2 $3S_1 \rightarrow$ 2 $3P_0$ transition [12] and for ^{7}Li 670.8 nm circularly polarized laser is proposed for transition $2^2S_{1/2} \rightarrow (2^2P_{1/2}$ and $2^2P_{3/2})$ [13].

2.2 Electron spin transfer to nucleus

The spin of an electron in an atom can be transferred to the nucleus by weak guide field, strong guide field with RF transitions, and Sona transition.

2.2.1 Weak guide field

This is the simplest method to obtain nuclear polarization and utilizes a weak field (weak compared to the hyperfine interaction field of 507 Gauss for Hydrogen). In this case, 50% of the atoms are in a pure state with a polarization of P = 1 (nuclear and electron spin aligned), while the other 50% are in a mixed state with a polarization of P = 0. Hence, the total nuclear polarization is P = 0.5. The disadvantage of this method is that, since the field is low, the atomic velocity must be thermal, resulting in a low intensity of the polarized beam with a maximum polarization of P = 0.5 [2]

2.2.2 Strong field Rf Transition

To overcome the limitations of the weak field method, RF transitions were developed in a strong field (higher than the hyperfine interaction field of 507 Gauss), which changes slowly in space. This method allows for polarization to be changed without affecting beam intensity or beam optics [2].

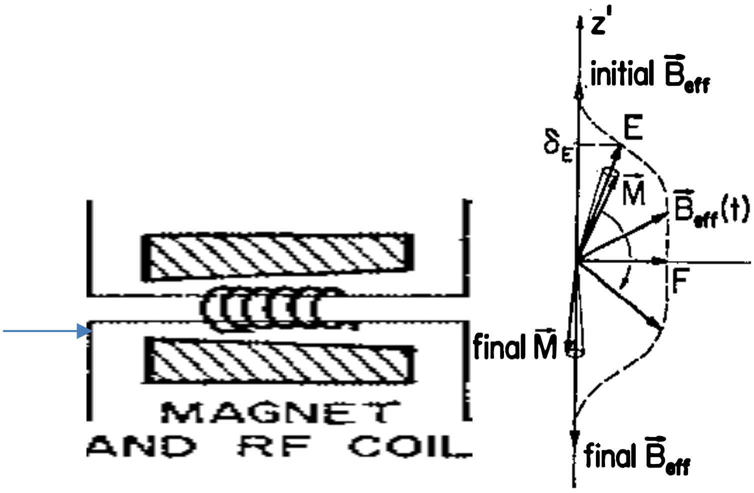
Considering the classical motion of a magnetic moment $M = \gamma I$ in a magnetic field B_0, where I is the angular momentum and γ is the gyromagnetic ratio. The torque causes M to precess about B_0 with an angular velocity $\omega_0 = -\gamma B_0$.

An RF field with frequency ω_0 and magnitude $2B_1$ perpendicular to B_0 can be replaced by a field B_1 rotating around B_0 with angular velocity ω_0. In the rotating coordinate system S', which rotates with angular velocity ω_0 about B_0 the magnetic moment M is fixed, $B'_0 = 0$, and B_1 remains fixed in the y' direction.

As the beam travels through a tapered dipole with a varying magnetic field from $B_0 + \delta$ to $B_0 - \delta$ (Fig. [insert figure reference]), in the S' frame, the initial field in the +z' direction changes slowly to -z' (Fig. [insert figure reference]). The resultant field of B_1 and δ in frame S', B_{eff}, changes direction by approximately 180 degrees, and M follows B_{eff}, provided $B1 \ll \delta$.

The second condition is that at all points, the angular velocity with which B_{eff} turns must be small compared to the Larmor precession angular velocity γB_{eff}.

At the most critical point where $B_{eff} = B_1$, the second condition becomes $(1/B_1)(dB_z/dt) \ll \gamma B_1$ because dB_z/dt is the same in both the S and S' coordinate systems.



(a) (b)

Figure 3: (a) Tapered dipole with RF coil, beam enter from left side. The difference in field from left to right 2 δ_0 .(b) Rotating coordinate system S', B_{eff} is the sum of $\delta(t)$ and a applied RF filed component B_1 in the y' direction.[2]

2.2.3 *Sona Transition*

Another method to transfer electron spin to the nucleus is to utilize the so-called Sona transition [14,15]. The Sona transition is a process used to transfer electron polarization to nuclear polarization. It involves carefully manipulating (reversing) the magnetic field to change the quantization axis of the external magnetic field faster than the electron spin can follow its redirection through Larmor precession. This leads to an inversion of occupation numbers in the pure states of the hyperfine splitting where both the proton and electron spin are aligned in the same direction.

The key steps are: **(**a) Electron Polarization: Initially, the protons are unpolarized, while the surrounding electrons are polarized using techniques like optical pumping. (b) Magnetic Field Manipulation: The protons are passed through a decreasing magnetic field parallel to the beam. If the decrease is slow enough, each eigenstate follows the corresponding energy line until the external field is equal to the critical field B_c of the atom. For hydrogen and deuterium, it is 6.34 mT and 1.46 mT, respectively. Conventionally, if B >> B_c, it is called the high-field region, and if B << B_c, it is called the low-field region. At very low field, a sudden reversal of the field direction forces the atom to not follow the field but continue in the same direction (see Figure 4). In the low-field region, off-center atoms experience a radial field component B_r given by $B_r = -dB_z/dz \cdot r/2$, where r is the distance from the axis of symmetry. The sudden reversal is defined as the angular velocity of the rotation of the B-field direction being faster than the angular velocity of the Larmor precession.

Zero crossing and 'sudden' requirements for hydrogen

$$eB^2_t/2m_e v \ll dB_z/dz \quad \textit{zero crossing}$$

$$dB_z/dz \ll 8m_e v/er^2 \quad \textit{sudden}$$

The fulfilment of the 'sudden' conditions ensures that atoms continuously stick on the energy lines while magnetic field changes. A Sona transition unit transfer the atoms from the initial $|m_J, m_I>$ state to the final $|m'_J, m'_I>$ state, as shown in Figure 4.

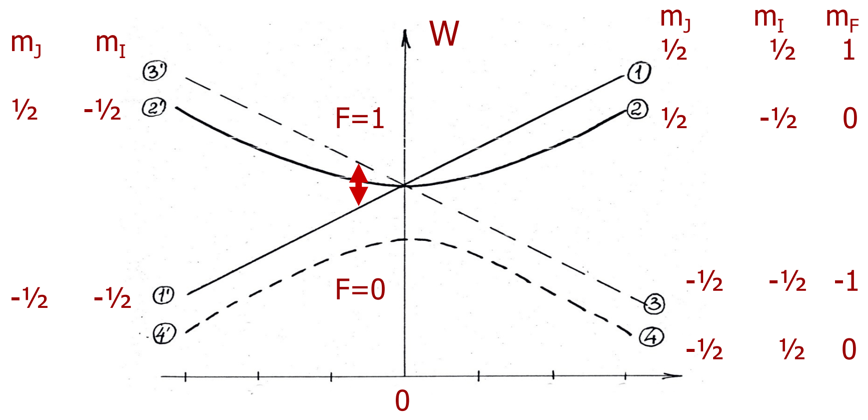


Figure 4: Hyperfine splitting for hydrogen atoms in $2S_{1/2}$ state as function of exertional magnetic field. Hydrogen atom with spin up (solid lines) entering magnetic field from the right. The initial $|m_J, m_I>$ and the final $|m'_J, m'_I>$ states are shown.

3.2 Ionization to Positive or negative ions.

Atoms with nuclear polarization are ionized in the presence of a magnetic field to preserve the polarization. The strength of the magnetic field depends on the hyperfine state being ionized. Ionization within a magnetic field can cause emittance growth due to the introduction of angular motion (charge being acquired in the presence of a magnetic field). Several techniques are used to ionize the nuclearly-polarized atomic beam: electron beam, He-cell for positive ions and Cs vapor or beam, resonant plasma ionizer, and Na-cell for negative ions to accelerate in tandem or injected into synchrotrons.

3.2.1 Electron Beam: This is achieved by producing an intense electron beam using a hot filament in a solenoid magnet. The space charge forces of the intense electron beam introduce an energy spread in the polarized ions, which limits the amount of polarized beam that can be injected into an accelerator. Ionizing efficiencies are limited to a few times 10^{-4}. On the other hand, electrons generated in an electron-cyclotron-resonance (ECR) heated plasma avoid space charge problems by utilizing the electrons within a quasi-neutral plasma. The resulting polarized beam is considerably brighter. In this configuration, ionizing efficiencies can reach up to a few times 10^{-1} [2].

2.3.1 He-Cell: When a polarized hydrogen atom interacts with a helium atom, the helium can potentially ionize the hydrogen atom by transferring sufficient energy to eject its single electron, creating a positively charged polarized hydrogen ion (H+). This occurs due to helium's higher ionization potential. Typically, this technique is employed in fast neutral beam injectors in OPPIS sources. Ionization efficiencies can reach approximately 70% [4].

2.3.3. Cs Vapor or Beam: This technique is used with atomic beam ion sources to produce negatively charged ions. Positively charged ions at approximately 4-7 keV pass through an alkaline vapor target. Via double charge exchange, negatively charged ions are produced. The conversion efficiency is low, typically around 7%. To produce a polarized negative ion beam from a nuclearly-polarized atomic beam, a slow-moving atomic beam is directed into a counter-flowing, coaxial, neutral beam of Cesium atoms at about 40 keV. This approach results in a highly polarized beam with excellent emittance [16].

2.3.4 *Resonant Plasma Ionizer:* Another way to ionize polarized nuclear hydrogen atoms is to utilize charge exchange collisions between thermal polarized hydrogen atoms and unpolarized 1-2 keV negative deuterium ions to produce polarized H^{-}. The cross-section for this process is orders of magnitude higher than the electron ionization cross-section. There is an additional advantage of a nearly resonant charge exchange reaction for the ionizer. However, in this low-energy ion beam, the current is severely limited by space charge effects. If a plasma is used instead of a low-energy ion beam, space charge issues can be overcome due to plasma quasi-neutrality [17]

2.3.5 *Ionization with Sodium:* Ionization with sodium will produce negatively charged polarized ions. This method is generally used at higher energies than the thermal energy. To prevent depolarization through hyperfine interaction during charge exchange, the process must occur within a magnetic field. The magnetic field also increases emittance due to the introduction of angular momentum. Therefore, the magnetic field strength is determined by the hyperfine strength and the acceptance of the accelerator. Typically, the jet cell operates at a sodium reservoir temperature of approximately 500°C, which is required for H^- ion yield saturation (the estimated total jet thickness is approximately $2\text{-}10^{15}$ atoms/cm^2). Multiple charge-exchange processes are more likely at high sodium vapor thickness, which can cause some depolarization at each collision. A stronger ionizer field would suppress this depolarization process and reduce polarization losses [6,7].

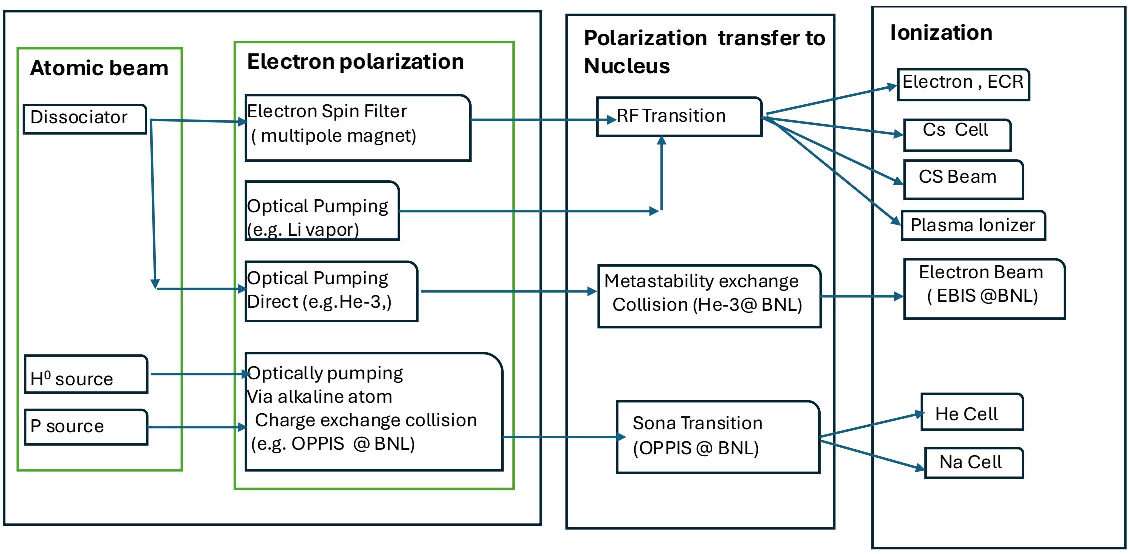


Figure 5: Ion Polarization techniques. Three step process: electron spin polarization, electron to nucleus polarization transfer, and ionization to positive or negative ions.

3. Examples of polarized ion -source

3.1 Brookhaven's pulse polarized H- source (1982)

The source was based on the co-linear colliding beam principle. A polarized thermal atomic hydrogen beam, generated using spin-filtering techniques, collides within a solenoid with 40 keV neutral cesium particles, producing negative hydrogen ions through the charge exchange process [16]:

$$\overrightarrow{H^0} + Cs^0 = \overrightarrow{H^-} + Cs^+$$

The source layout is shown in Figure 6. The atomic hydrogen beam was thermalized to approximately 100 Kelvin by cooling the dissociator nozzle with a helium refrigerator. Four sextupoles were used to filter and select electron spin in the atomic beam. The spin-filter section was followed by two RF transition cavities to transfer electron spin to the nucleus on a pulse-to-pulse basis. The density of the nuclearly polarized H^0 beam near the interaction region (solenoid) was approximately 2-3 x 10^{11} atoms/cm^3.

The neutral cesium beam was produced by a 40 keV, 10-15 mA pulsed Cs^+ beam generated through surface ionization of cesium on a hot porous tungsten button. The cesium ion beam was subsequently neutralized in a cesium vapor neutralizer.

A 6-10 particle-mA neutral cesium beam and the polarized atomic hydrogen beam interacted within a 30 cm long collision region located within the magnetic field of a solenoid to prevent depolarization. The H^- ions, produced by charge exchange, were accelerated and directed towards the extraction end, where they were focused, accelerated, and deflected by a 90-degree electrostatic mirror into the transfer line.

The normalized emittance was approximately 0.65 π mm mrad at 20 keV, with a polarization of approximately 75%, a current of 25 µA, and a pulse length of 500 µs. This source was decommissioned when OPPIS became available in 2000.

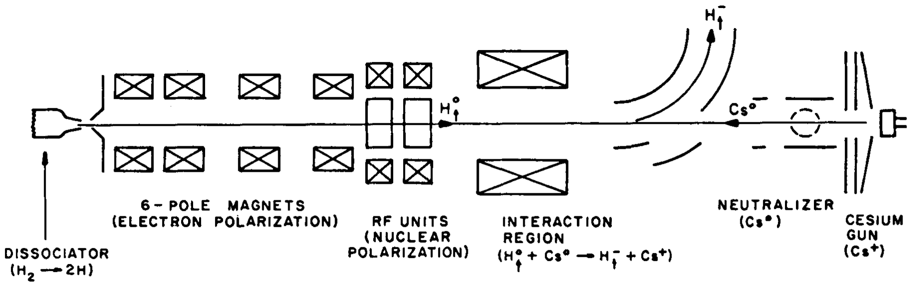


Figure 6: Schematic arrangement of the polarized negative ion source at BNL.

3.2 INR Polarized H/D source with Resonant Plasma Ionizer.

In this source, atomic hydrogen is produced in a dissociator with pulsed RF discharge and exits the dissociator into a vacuum through a channel cooled with liquid nitrogen (20-80 K). The measured atomic beam intensity downstream of the skimmer (see Figure 7) is 2.8 x 10^{20} atoms/ster/s [18] Two 23 cm long sextupole magnets, separated by 34 cm (the first with a tapered aperture and the second with a constant aperture), are used for spin selection of the atoms. An RF transition unit is used to transfer electron spin to the nucleus. The peak intensity of the nuclearly polarized atomic beam is approximately 2 x 10^{17} atoms/s. The atomic beam is injected into the charge exchange interaction region through a three-electrode extraction system

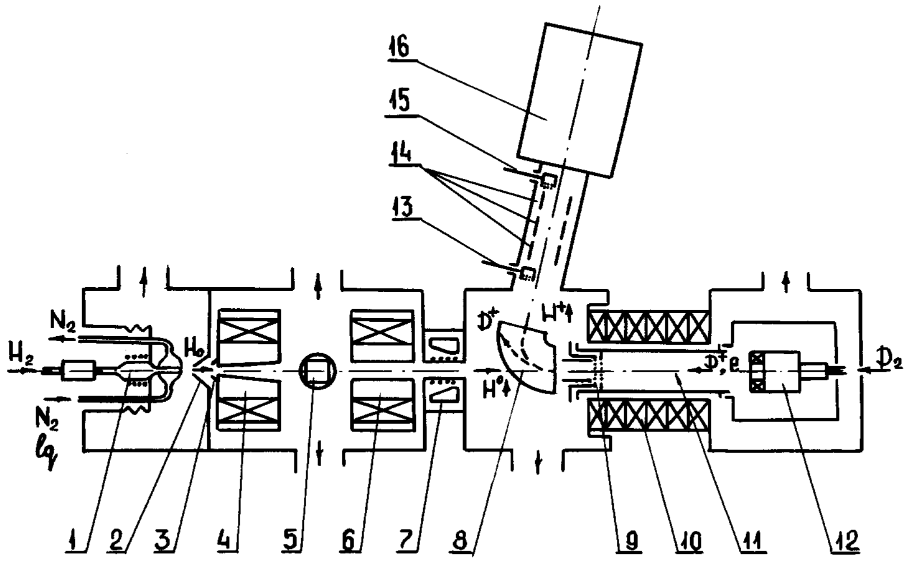


Figure 7: Layout of INR source. (1) Dissociator, (2) skimmer, (3) collimator, (4 and 6) sextupole spin filter magnets, (5) mass spectrometer, (7) RF transition unit, (8) deflecting magnet, (9) electrostatic accelerating and focusing system, (1) solenoid,(11) interaction region, (12) deuterium plasma source,(13, and 15) Faraday cup (14) Einzel lens, and (16) low energy polarimeter [18].

Deuterium plasma, produced by a plasma source, is injected into the interaction region along the axis of the 1.3 kG solenoid. Polarized protons undergo charge exchange reactions with a cross-section of 5.10^{-15} /cm^2

$$\overrightarrow{H^0} + D^+ = \overrightarrow{H^+} + D^0$$

Polarized protons are extracted in the direction opposite to that of the polarized hydrogen atoms. At 25 keV, the polarized protons are separated from D^+ ions using a bending magnet, resulting in a polarized proton beam with an intensity of 6 mA, a pulse length of 100 μs at 10 Hz, and a normalized emittance of 2 π mm mrad.

For the polarized H^- ion beam, a plasma injector consisting primarily of D^+ and D^- ions is shown in Figure 8. Plasma flux from the arc-discharge plasma source is enriched with negative ions within a surface-plasma converter. Positive ions are converted into neutral atoms with eV energy through collisions with the neutralizer's internal surface. A polarized atomic hydrogen beam is injected into the plasma, and polarized H^- ions are produced via the following charge exchange reaction:

$$\overrightarrow{H^0} + D^- = \overrightarrow{H^-} + D^0$$

The plasma flux is guided towards the internal surface of the neutralizer by the combined magnetic fields: longitudinally from the plasma coil and transversely from the converter electromagnet. Plasma ions interact with the neutralizer surface, and most are reflected as hot neutral atoms. These reflected atoms strike the converter cylinder's internal (molybdenum) surface, where they are partially converted into negative ions and subsequently injected into the ionization region along the fringing solenoid field lines. Using this ionizer, a polarized H^- ion beam with a peak current of 4 mA was obtained alongside a D- ion beam current of 62 mA. The polarization of the H- ion beam was measured to be 0.91 ± 0.03 [10].

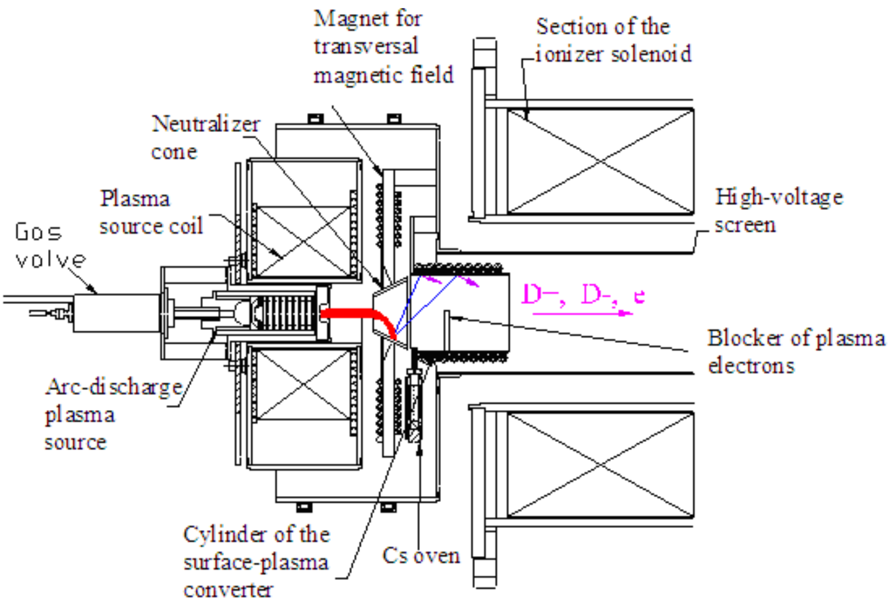


Figure 8: Generation of cold jet of D^- plasma for resonant charge exchange H^- [19].

3.3 Source of Polarized ions for NICA at JINR

The high intensity pulsed source of polarized ions (SPI) was developed at Joint Institute for Nuclear Research (JINR) at Dubna, Russia for injecting polarized deuterons and proton into NUCLOTRON and future collider of heavy and light ions NICA [20]. The SPI schematic is shown in Figure 9. Deuterium molecules dissociate into atoms in the RF discharge plasma. Atomic deuterium flows out the dissociator through 100 mm long 5mm diameter, cooled at 80 degrees K, Pyrex channel which ends with sonic nozzle of 2 mm in diameter. The electron spin selection is accomplished with help of three permanent and one electromagnet. Nuclear polarization of deuterium atoms is achieved with system of the HFT units which includes a medium field transition unit (MFT), a weak field (WFT) and a strong field (SFT) transition units which are installed downstream the electromagnet sextupole. For polarized deuterium use of MFT, WFT and SFT will allow switching deuteron vector polarization between +1 and -1 and tensor polarization between +1 and -2. Many another deuteron polarization states can be produced using different combinations of the HF. The hydrogen plasma jet generated by a plasma arc-discharge source is injected into the storage cell in direction opposite to the deuterium atomic beam through the orifice of 3 mm in diameter at end of the storage cell. Polarized deuterons are produced in the storage cell via charge-exchange collisions between polarized deuterium atoms and unpolarized protons:

$$\overrightarrow{D^0} + H^+ = \overrightarrow{+} + H^0$$

For production of polarized protons:

$$\overrightarrow{H^0} + D^+ = + + D^0$$

The polarized ion moved slowly opposite direction of polarized atomic beam towards an extraction electrode system extracted at 25 KeV with unpolarized plasma ions. A 90-degree bending magnet separate polarized and unpolarized ions. The unpolarized ion beam is dumped at bending magnet. The polarized beam passes through the electrostatic Einzel lens and then is deflected by the 90-degree electrostatic deflector into the horizontal plane to x direction. Direction of ions spin remains unchanged during passage the deflector. At the source exit the polarized ion beam passes through a solenoid which is used to rotate the deuterons or protons spin to vertical direction.

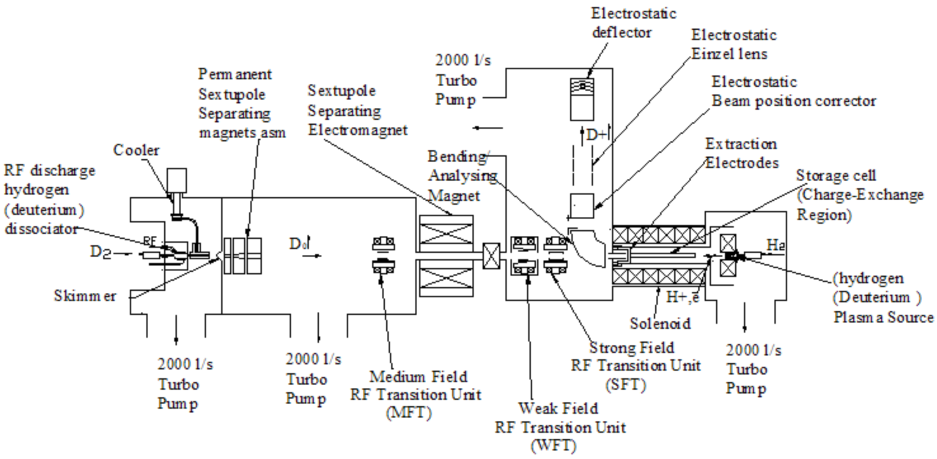


Figure 9: Schematic diagram of source of polarized ions [20].

3.4 Optically Pumped Polarized Ion source (OPPIS) at BNL

The Optically Pumped Polarized Ion Source (OPPIS) has been providing polarized H^- since 2000 for the RHIC spin physics experimental program and gone through several upgrades [21,22]. The upgraded OPPIS comprises of (a) Fast Atomic Beam Source (FABS), (b) pulsed hydrogen neutralization cell, (c) super conduction solenoid at 3 Tesla for polarization, (d) pulse helium ionizer cell for efficiently ionize neutral hydrogen atom, (e) optically pumped rubidium cell for transferring electron spin polarization to protons. (f) Sona transition for transferring spin from electron to the nucleus in the polarized hydrogen atom and (g) sodium-jet ionizer cell for efficient conversion of polarized H atoms to H^- ions. The high brightness 6 keV proton beam focused by electrostatic spherical grids system goes through in hydrogen cell, where it gets neutralized to H^0. Then it injected into a superconducting solenoid, where both a helium ionizer cell and an optically pumped Rubidium cell are situated in the 25-30 kG solenoid field, which is required to preserve the electron-spin polarization. The injected H atoms are ionized in the Helium cell with 80% efficiency to form a low emittance intense proton beam. Now protons enter in the polarized Rubidium vapor cell (see Figure 10).

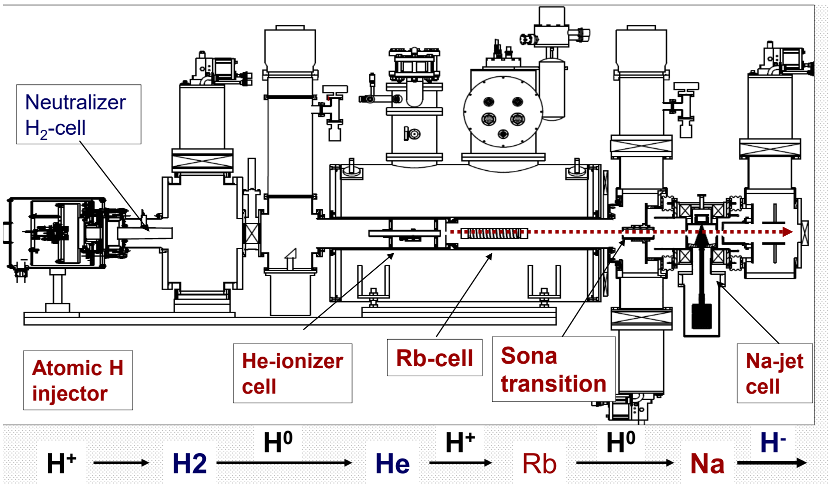


Figure 10: Layout of the OPPIS with atomic hydrogen injector.

Residual higher energy atoms are neutralized with lower efficiency in Rubidium cell, due to cross-section decrease at higher energy, and un-polarized component is further suppressed by lower H^- ion yield in the sodium cell at 5.0- 8.0 keV atomic beam energy. The electron-polarized Hydrogen beam then passes through a magnetic field reversal region, where the electron polarization is transferred to the nucleus, via the hyperfine interaction (Sona-transition). The polarized hydrogen atoms are then negatively ionized in a sodium-jet vapor cell to form nuclear polarized H^- ions. Applying a -32 kV pulse voltage to the ionizer cell accelerate the H^- ion to 35 keV and un-polarized H^- ion to a 40-43 keV. Further suppression of un-polarized higher energy ion beam is done in the LEBT.

3.5 Polarized ^{3}He Ion Source at BNL

The proposed polarized $^3He^{++}$ ion source builds upon the existing Electron Beam Ion Source (EBIS) at Brookhaven National Laboratory (BNL) in collaboration with MIT [23,24,25,26]. It employs a distinct approach for ^{3}He polarization and ionization, outlines as follows. (a) Polarization of ^{3}He atoms: ^{3}He atoms are polarized using the Metastability Exchange Optical Pumping (MEOP) technique. This occurs within a glass cell maintained at a pressure of 1-10 mbar. A high-field 5.0 T magnetic field is applied within the EBIS solenoid to facilitate polarization, (b) Injection into EBIS ionizer: The polarized ^{3}He atoms are subsequently injected into the EBIS ionizer, via a innovative Lorenz fast valve (c) Ionization process within EBIS: A high-intensity electron beam (10 A) is generated by an electron gun with a 9.2 mm cathode diameter. This electron beam is injected into the 5.0 T solenoid magnetic field, leading to radial compression to a diameter of approximately 1.5 mm in the ionization region. The compressed electron beam interacts with the polarized ^{3}He atoms, causing ionization. The electron beam then expands before being collected at the end of the EBIS. (d) ^{3}He Ion confinement and extraction: ^{3}He Ions are radially confined by the space charge of the electron beam. Longitudinal confinement is achieved using electrostatic barriers at the ends of the trap region. Ion extraction is performed by raising the potential of the trap and lowering the barrier.

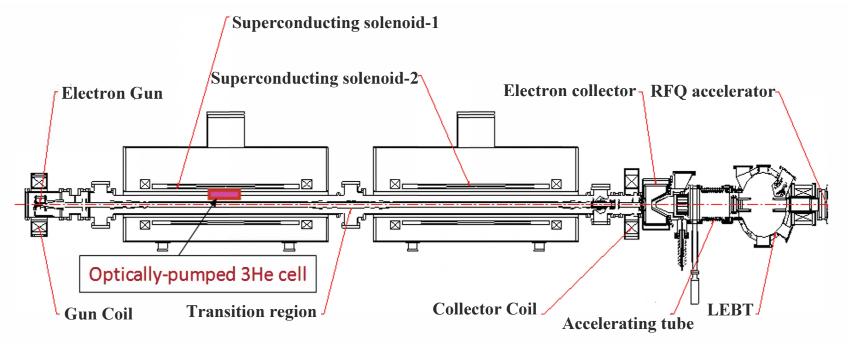


Figure 11: Schematic diagram of the extended EBIS. The polarized ^{3}He gas is injected into the drift tube in the Gas Trap of EBIS. Low Energy Beam Transport (LEBT) transfer the extracted beam from EBIS to the Radio Frequency Quadrupole (RFQ) e accelerator.

The upgraded EBIS features three distinct sections: Gas Trap: to inject gaseous elements and initial ionization, Short Trap and Long Trap: to trap the externally injected or from gas trap low charge state ions and multiply to the desire charge state. The gas trap (40 cm long) and short trap (95 cm long) are in the upstream solenoid and long trap (178 cm long) in the downstream solenoid. The polarized ^{3}He gas will be injected into gas trap to ionized. The resulting $^3He^+$ ions will be trapped in short and long trap. Here, they will undergo further ionization to the desire $^3He^{++}$ state (see Figure 11). The EBIS is estimated to produce and accumulate (2.5–5.0) x10^{11} doubly charged helium ions($^3He^{++}$). The desired beam intensity of 2x10^{11} $^3He^{++}$ ions per pulse can be achieved by extracting and accelerating them during a single 20 μs pulse

3.6 Proposed Polarized Lithium Source at Argonne

The proposed polarized ^{6}Li and ^{7}Li source will be based on previous polarized Lithium sources [27,28,29,30]. This source will use Optical pumping for polarizing electron in lithium atoms. (See Figure 12) [13].

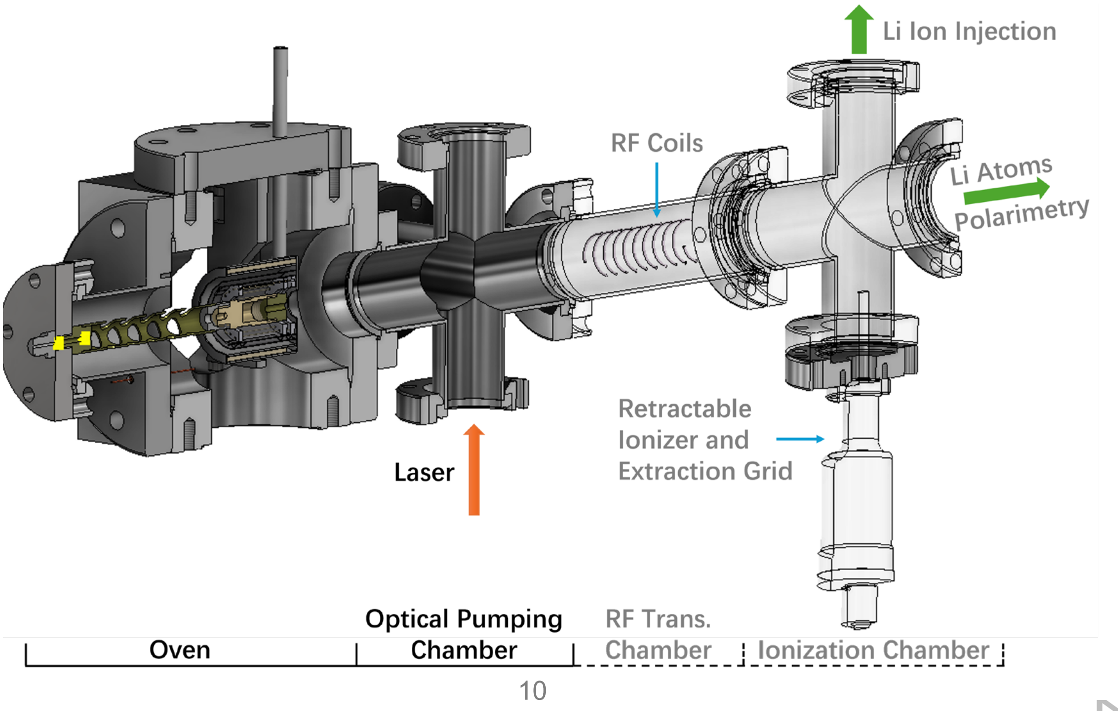


Figure 12: Proposed polarized Lithium Sources at Argonne [11].

Lithium vapors produced by the oven will be pumped with a 30-35 mW laser with a wavelength of 670.8 nm. Polarized atoms will pass through an RF transition to transfer polarization to the nucleus. The atoms with polarized nuclei will be ionized by a hot oxygenated Tungsten surface. The status of the project is that the Lithium vapor beam system has been built, and benchmarking for the vapor beam profile is underway with simulations.

4. Summary

Beams of high intensity and high polarization of protons, deuterons, and $^{3}He^{+2}$ will be required for new and existing accelerators and colliders. State-of-the-art atomic beam sources with resonant plasma ionizers and optically pumped polarized proton sources produce sufficient beam intensity (of a few mA H^{-} ion beam) for colliders where the intensity is limited by the beam-beam interaction. Proton polarization of about 90% has been achieved for these high-intensity beams. Furthermore, an increase to over 10 mA pulsed beam intensity has also been demonstrated.

A polarized $^{3}He^{+2}$ ion source based on an EBIS injector is under development at BNL for the future EIC collider. Extended EBIS operation for Au^{+32} ion beam production is planned for Run-2025. The next step will be the integration of the ^{3}He polarization apparatus. The development of the ^{3}He polarization apparatus, the spin-rotator, and the nuclear polarimeter at the $^{3}He^{+2}$ ion beam energy of 6.0 MeV is currently underway.

Currently, activity related to polarized ions is very limited, primarily confined to BNL, aside from some work in the former USSR. Argonne National Laboratory is developing polarized Lithium ions for incorporation into the BNL EBIS ion source.

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