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Perspective for development of an universal source of highly polarized ions

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High beam polarization is essential to the scientific productivity of a collider. Polarized H and D ions are an essential part of the nuclear physics programs at existing and future ion-ion and electron-ion colliders such as the BNL RHIC and eRHIC and JLab's ELIC. Ion sources with performance exceeding those achieved today are a key requirement for the development of these next generation high-luminosity high-polarization colliders. A new version of a polarized H, D ion source is needed.
In this article one universal H^-/D^-, H^+/D^+ ion source design is proposed, which combines the most advanced developments in the field of polarized atoms and, in particular, a new resonance charge exchange ionizer to provide high-current high-brightness ion beams with greater than 90% polarization and improved lifetime, reliability and power efficiency. The new source design is based on the atomic beam polarized ion source (ABPIS) with resonant charge-exchange ionization of neutral atoms by negative and positive ions generated by the interaction of plasma with a "cesiated" surface. The ABPIS design is improved by using new materials, an optimized magnetic focusing system, and novel designs of the dissociator, plasma generator and surface-plasma ionizer, which are expected provide greater beam polarization by suppressing parasitic generation of unpolarized H^-/D^-, H^+/D^+ ions.

1 Speaker

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1. Introduction

The beam parameters necessary to achieve the design luminosity of the polarized Medium-energy Electron-Ion Collider (MEIC) at JLab are presented in Ref. [1]. At MEIC, in addition to polarized protons, there is a particular nuclear physics interest to polarized d/He/Li and even heavier ion beams. The special design of the accelerators and storage rings (figure-8 shape) in this project should provide a good polarization P preservation for all ion species including deuterons. It becomes possible to efficiently control the polarization of a beam of particles with any anomalous magnetic moment including particles with small anomalous moments, such as deuterons. This means that the final beam polarization after acceleration will be determined by the beam polarization extracted from the ion source, which must be made as high as possible. Availability of polarized deuterons and of other polarized light and even heavy ions opens new physics opportunities and is particularly important for maximizing the discovery potential of the electron-ion collider.

The evolution of polarized ion sources has been presented recently by W. Haeberli [2].The most advanced versions of polarized H^- sources are:

1. Atomic Beam Polarized Ion Source (ABPIS) with resonant charge-exchange ionization of polarized atoms by negative ions, developed and presented by A. Belov [3];
2. Optically-Pumped Polarized H^- Sources (OPPIS) with Rubidium and Sodium targets, developed and presented by A. Zelenski [4,5].

Since the experimental efficiency is proportional to P^2, having the highest possible polarization P is very important. It has been proposed to upgrade the BNL OPPIS by optimizing its plasma generation, beam formation, extraction, neutralization, and reionization systems with the intent of increasing the polarization with acceptable intensity and emittance. OPPIS uses very expensive components such as a superconducting solenoid with magnetic field of ~50 kG, a very high frequency microwave source, powerful lasers, and a significant quantity of Rubidium and Sodium, which complicates the source operation and maintenance [5].

The BNL OPPIS used in RHIC operation was upgraded recently [4] and a maximum polarization of 84% (in the 200 MeV polarimeter) was measured at 0.3 mA beam intensity and 80% polarization was measured at 0.5 mA. In this ion source, fast protons (2.5-3.5 keV)

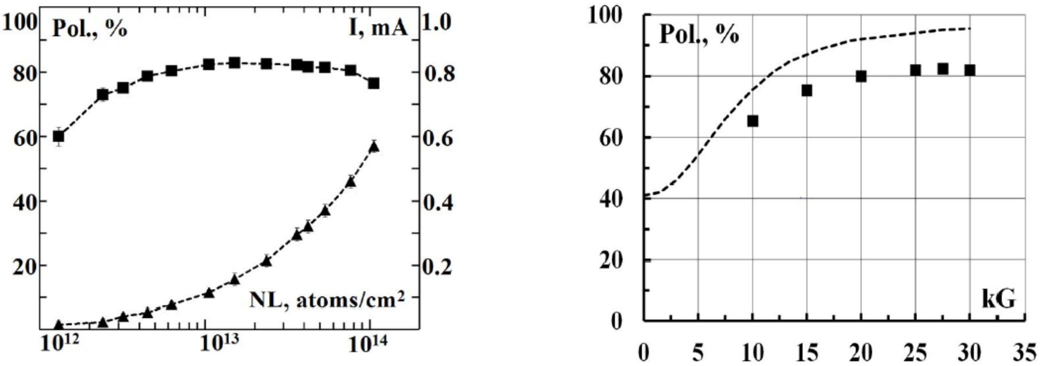

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Figure 1: a) Upgraded BNL OPPIS polarization (shown by squares on the left axis) and beam intensity (shown by triangles on the right axis in mA) vs. Rb vapor thickness; b).Optimized H- beam polarization from BNL OPPIS as a function of magnetic field in the superconducting solenoid. The squares show the experimentally measured polarization vs. the magnetic field in the Rb-cell. The dashed line shows calculations (from [4]).

produced by high brightness arc discharge source are converted to fast atoms in Hydrogen gas target, injected into a strong magnetic field, stripped in He gas target and protons can then pick up polarized electrons from optically pumped Rb vapor, pass through a Sona-Transition region, and pick up a second (unpolarized) electron from Na vapor forming a beam of nuclear-polarized H^- ions. To prevent depolarization in the charge-exchange collisions, the optically pumped cell is located inside a strong (25-30 kG) superconducting solenoid. Examples of H- beam polarization and intensity dependences are shown in Figs. 1a,b [4].

Moreover, there are many factors limiting the possibility of producing polarization close to 100% as shown in Fig. 2 from [4] (plus dimmers in the Rb optically-pumped charge-exchange target, molecular ions,…).

Depolarization factors

$P = E_{H2} \cdot P_{Rb} \cdot S \cdot B_{RG} \cdot E_{LS} \cdot E_{ES} \cdot E_{Sona} \cdot E_{ion} \sim 85\text{-}90\%$

Depol. factor		Process	Estimate
1	E_{H2}	Dilution due H_2^+ in the new source (LEBT)	0.99 - 0.99
2	P_{Rb}	Rb-optical pumping (Laser system)	0.99 - 0.99
3	S	Rb polarization spatial distribution (Collimators)	0.97 - 0.98
4	B_{RG}	Proton neutralization in residual gas (Vacuum)	0.98 - 0.99
5	E_{LS}	Depolarization due to spin-orbital interaction	0.98 - 0.99
6	E_{ES}	Dilution due to incomplete energy separation not polarized component of the beam (LEBT)	0.98 - 0.99
7	E_{Sona}	Sona-transition efficiency (Adjustment)	0.96 - 0.98
8	E_{ion}	Incomplete hyperfine interaction breaking in the ionizer magnetic field	0.98 - 0.99

G.Atoian Total: 0.85 - 0.90

Figure 2: Depolarization factors in OPPIS (from [4]).

In our opinion, the ABPIS [3, 6] has a higher potential for efficient production of different negative and positive ions with polarization greater than 95%. It can be less expensive to manufacture and operate, and is therefore more attractive as a commercial product.

1.1Status of ABPIS

The most advanced version of an Atomic Beam Polarized Ion Source (ABPIS) with ionization of polarized atoms by resonant charge exchange with negative ions was developed at the Institute of Nuclear Research (INR RAN) in Troitsk, Russia [3,6,7,8]. A schematic diagram of this ABPIS is shown in Fig. 3. A version of an ABPIS with permanent magnet sextupoles CIPIOS-CIS ABPIS was built and used for injection into Indiana storage ring with electron cooling [8,9].Recently some parts of this ABPIS were used for rebuilding of polarized deuteron ABPIS for the Dubna accelerator system [10].

A polarized atomic H^- beam source with selective resonant charge-exchange ionization has a good potential to produce H^-/D^- ion beams with the highest polarization [3,6-10]. Low energy unpolarized H^-/D^- ions can transfer electrons only to H or D atoms but not to molecules. This method of ionization allows one to produce H^-/D^- ion beam polarization higher than that of the atomic beam by eliminating unpolarized molecules from the beam. A pulsed mode of operation is favorable for high-intensity and high-polarization production. An efficient pulsed operation can be attained using a fast gas valve [11], a small-volume RF discharge dissociator with a helicon antenna in a magnetic field and AlN chamber [12] for efficient cryogenic cooling (a new design of the dissociator).

In the ABPIS, hydrogen or deuterium atoms are formed by the dissociation of molecular gas, typically in an RF discharge dissociator. The atomic flux is cooled to a temperature of 30K

- 80K by passing through a cryogenically cooled nozzle. The atoms escape from the nozzle orifice into the vacuum and are collimated to form a beam. The beam passes through a region with inhomogeneous magnetic field created by sextupole magnets where atoms with one orientation of the electron spin relative to the magnetic field are focused while atoms with the opposite orientation of the electron spin are defocused. Nuclear polarization of the beam is increased by inducing transitions between the spin states of the atoms.

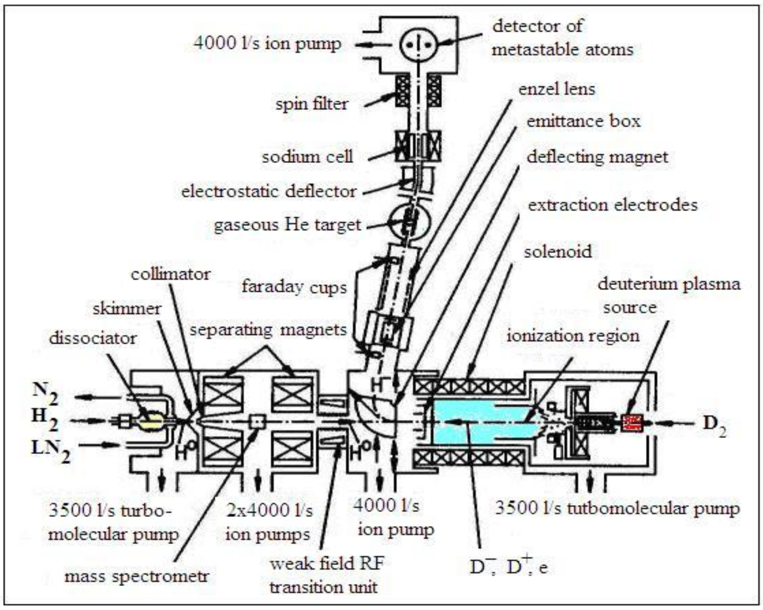

Figure 3: Schematic diagram of an ABPIS with a resonant charge exchange ionization [6].

The RF transition units are also used for fast reversal of the nuclear spin direction without changing the atomic beam intensity and divergence. The main components of this ABPIS shown in Fig. 3 are:

1. Source of a polarized atomic H or D beam (left).
2. Surface-plasma source of cold unpolarized negative D^- or H^- ions with an arc discharge plasma source and a surface-plasma ionizer with cesium catalysis (right).
3. Charge exchange solenoid with a grid extraction system (middle).
4. Deflecting magnet for separation of the polarized and unpolarized H^- and D^- beams (transition to the top part).
5. Beam line and polarimeter (top part). The online polarization measurement is very important for optimization of many parameters influencing the polarization.

Several schemes of sextupole magnets and RF transition units are used in hydrogen or deuterium ABPIS. For atomic hydrogen, a typical scheme consists of two sextupole magnets followed by weak-field and strong-field RF transition units. In this case, the theoretical proton polarization will reach $P_z = 1$. Switching between the two $P_z = \pm 1$ states is performed by switching between the operation of the weak-field and strong-field RF transition units. For atomic deuterium, two sextupole magnets and three RF transitions are used in order to get deuterons with vector polarization of $P_z = 1$ and tensor polarization of $P_{zz} = 1, -2$. The polarized atomic beam intensity is proportional to the solid angle $\Delta\Omega = \pi\alpha^2$, of the focusing system which is determined by the magnetic focusing system and magnetic field B:

$$\Delta\Omega = \pi\alpha^2 = \pi\mu B/\kappa T$$

$$\text{For } B=1.6\ T;\ \Delta\Omega = 1.5.10^{-2}\ sr;\ \alpha = 0.07\ rad$$

For B=4.8 T; $\Delta\Omega = 4.5.10^{-2}$ sr; α =0.21 rad;(superconducting magnets)

Different methods for ionizing polarized atoms and their conversion into negative ions were developed in many laboratories. The techniques depended on the type of accelerator where the source was used and the required characteristics of the polarized ion beam (see ref. [3] for a review of the existing sources). For a pulsed ABPIS, the most efficient method was developed at INR, Moscow [6-10]. Polarized hydrogen atoms at thermal energy are injected into an ionizer solenoid with an incident flux of deuterium plasma where polarized protons or negative hydrogen ions are formed due to the quasi-resonant charge-exchange reactions:

$$H^0\uparrow + D^+ \Rightarrow H^+\uparrow + D^0$$
$$D^0\uparrow + H^+ \Rightarrow D^+\uparrow + H^0$$
$$H^0\uparrow + D^- \Rightarrow H^-\uparrow + D^0$$
$$D^0\uparrow + H^- \Rightarrow D^-\uparrow + H^0$$
$$^3He^0\uparrow + {}^4He^+ \Rightarrow {}^3He^+\uparrow + {}^4He^0$$
$$^3He^0\uparrow + {}^4He^{++} \Rightarrow {}^3He^{++}\uparrow + {}^4He^0$$

In an ABPIS, a D^+ plasma jet emerging from an arc discharge source is converted into a low-energy D^- ion jet in a surface plasma ionizer. The design of a Surface Plasma (SP) ionizer (INR version) is shown in Fig. 4a from [3].

By using the resonant charge exchange ionization, it is possible to have an efficiency of the polarized atom to polarized H^- transformation of over 12%. The high selectivity of the polarized atom ionization allows polarization values above 0.9. The arc-discharge plasma source developed at BINP [13] is used as a plasma jet generator. A converter with cesium deposition is used for conversion of the plasma flux into negative ions. The first cesiated converter for negative ion generation was proposed by V. Dudnikov [6] and was further optimized by A. Belov [3].

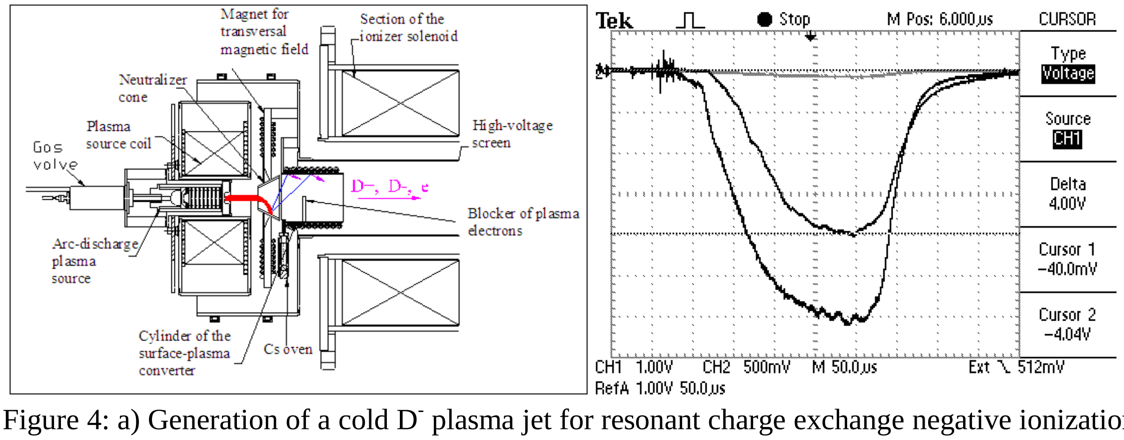

Figure 4: a) Generation of a cold D^- plasma jet for resonant charge exchange negative ionization of polarized hydrogen atoms (INR version) [3]; b) Oscillograms of a polarized H^- ion current of up to 4 mA (the vertical scale is 1 mA/div) and of an unpolarized D^- ion current of up to 60 mA (10 mA/div) in INR ABPIS [3].

The development and adaptation of a high-polarization ABPIS promises to improve the productivity of very costly polarized colliding beam experiments at RHIC and is crucial for the electron ion colliders under development at JLab and BNL. Polarized H^-/D^- currents were increased up to 4 mA with measured polarization P of up to 0.95. Unpolarized D^-/H^- currents were 60/100 mA. The co-extracted electron current was efficiently suppressed by a blocker.

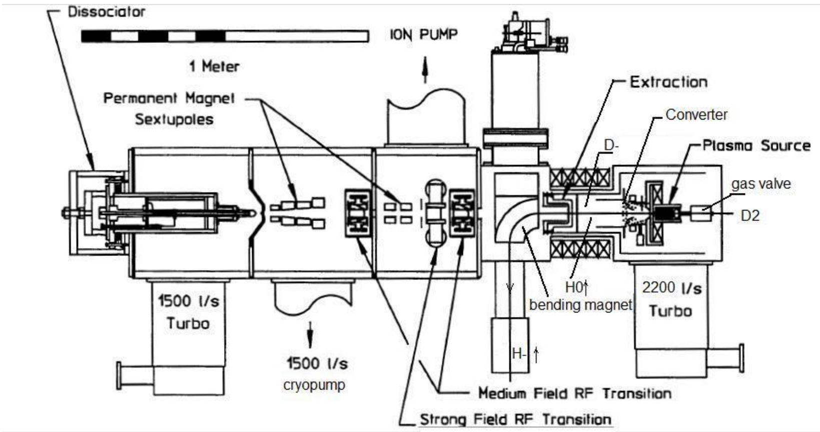

Figure 5: Design of the CIPIOS-CIS ABPIS [9]. The beam is extracted from the ionizer toward the ABS and is then deflected downward with a magnetic bend and towards the RFQ with an electrostatic bend. This results in a nearly vertical polarization at the RFQ entrance.

The signals of polarized and unpolarized beams from the INR ABPIS are shown in Fig. 4b [3]. The pulsed polarized negative ion source (CIPIOS) produced multi-mA beams for injection into the Indiana Cooler Injector Synchrotron (CIS) under regular operation for several years [8,9]. A schematic of the ion source and LEBT is shown in Fig. 5. Parameters of the existing polarized sources are listed in Table 1.

Table 1: Existing source parameters

OPPIS/BNL, H^- only	Pulse Width	500 µs (up to DC?)
(In operation)	Peak Intensity	1.6 mA
	Max Pz	84% of nominal
	Emittance (90%)	2.0 π·mm·mrad
IUCF/INR CIPIOS:	Pulse Width	Up to 500 µs
(Shutdown 8/02)	Peak Intensity H^-/D^-	2.0 mA/2.2 mA
	Max Pz/Pzz	85% to > 90%
	Emittance (90%)	1.2 π·mm·mrad
INR Moscow:	Pulse Width	> 100 µs
(Test Bed Only)	Peak Intensity H^+/H^-	11 mA/4 mA
	Max Pz	80%/95%
	Emittance (90)%	1.0 π·mm·mrad/ 1.8 π·mm·mrad

1.2 Proposed Modifications of a Universal ABPIS

For polarized proton and deuteron accumulation in the EIC, we propose to use an atomic beam polarized ion source (ABPIS) of negative H^-/D^- ions. This version of the source can be used with minor modifications for production of polarized and unpolarized H^-, D^-, H^+, D^+.

In these ABPIS, polarized H^- ions are produced in charge exchange of polarized H^0 with unpolarized D^-. H^- polarization is diluted by formation of unpolarized H^- and D^- in the D plasma interaction with the surface of the converter. These unpolarized H^- ions are produced from an admixture of H_2 gas in the D_2 gas, and from the hydrogen and water adsorbed in the gas delivery system of the arc discharge plasma source and on the ionizer surfaces.

We propose to increase the beam particle polarization up to the highest level by optimization of ABPIS components and suppression of parasitic depolarizing processes. The ABPIS of INR with the highest polarized beam parameters [7,3] was built nearly 30 years ago using the technology and components available at that time. Much more advanced components with better characteristics and better reliability are available now and can be developed for a novel and significantly improved ABPIS design. To date, there have been some large, expensive, multi-year efforts involving international experts in the development of polarized atomic beams for polarized target and polarimetry projects with a clear scientific payoff. These developments can use to improve an ABPIS design.

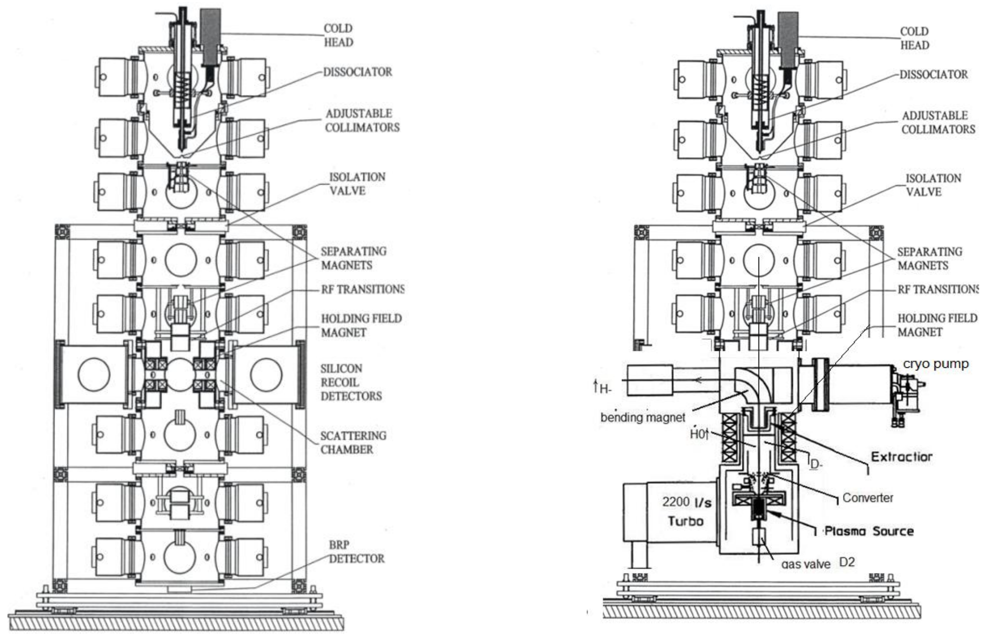

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Figure 6: a) Schematic of the BNL ABPS [14]; the H-jet polarimeter includes three major parts: polarized Atomic Beam Source (ABS), scattering chamber, and Breit-Rabi polarimeter. The polarimeter axis is vertical and the recoil protons are detected in the horizontal plane. The common vacuum system is assembled from nine identical vacuum chambers, which provide nine stages of differential pumping. The system building block is a cylindrical vacuum chamber 50 cm in diameter and of 32 cm length with four 20 cm (8.0”) ID pumping ports. There are 19 TMPs with 1000 l/s pumping speed for hydrogen.

b) An advanced ABPIS is a combination of an adopted pulsed BNL ABPS and a resonant charge exchange plasma ionizer with an arc discharge plasma source.

For the new ABPIS design, it is possible to use the general design of the CIPIOS-CIS ABPIS [8,9]shown in Fig. 5 as a prototype. It can be improved by using novel design concepts and the most advanced components including 1) a superconducting or strong permanent sextupole magnet; 2) a new advanced RF dissociator with helicon discharge in a magnetic field; 3) a new design of the arc-discharge plasma generator with hot cathode for suppression of the polarized hydrogen (deuterium) adsorption and depolarization; 4) a new surface-plasma ionizer with heating to suppress the polarized hydrogen (deuterium) adsorption and depolarization; 5) an optimized high-transparency heated extraction system, and 6) an optimized low-aberration bending magnet. A superconducting sextupole can be used for the highest intensity polarized beam production. An advantage of using a strong permanent sextupole magnet is that it has a lower cost of manufacturing and operation while still providing the highest polarization. The existence and availability of the components for the ABPIS construction is a great advantage of this project. Many of the necessary components and materials are now available with much better parameters.

The BNL polarized atomic H jet for polarimeter [14] has an intensity of up to 1.7 10^{17} atoms/s and polarization of ~0.97 in the DC mode of operation and it is possible to have an even higher intensity and polarization in a pulsed mode of operation. An ABS with very good parameters was developed for the internal target experiments at BINP [15]. This ABS uses a superconducting sextupole focusing system with magnetic field at the pole tip of up to 4.8 T. Sextupole focusing systems with permanent magnets have a magnetic field at the pole tip of up to 1.6 T. A schematic of the BNL ABPS [14] is shown in Fig. 6 a. Figure 6 b shows an advanced ABPIS combining an adopted pulsed BNL ABPS and a resonant charge exchange plasma ionizer with an arc discharge plasma source.

The probability of negative ion emission from a cesiated surface bombarded by plasma ions and atoms strongly depends on the surface work function (φ) as shown in Fig. 7 [16]. It is very important to keep the surface WF as low as possible. Special activation procedures were recently developed for production of efficient long-term stable cesiation in SPS [17] and can be reproduced in ABPIS. New advanced versions of arc discharge sources were recently developed that are more suitable for ABPIS ionizers (see Fig. 8). Using a hot cathode helps prevent polarized particle adsorption in the plasma source and suppresses parasitic generation of positive and negative ions from depolarized particles.

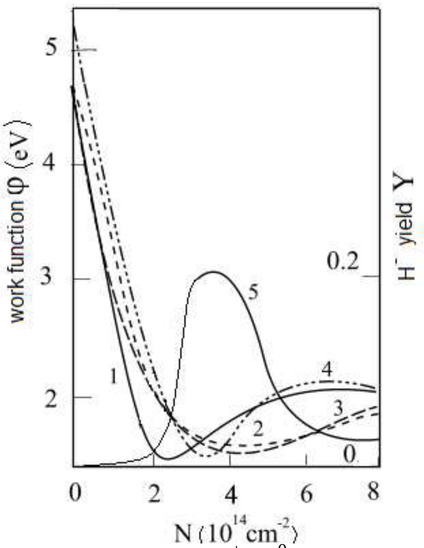
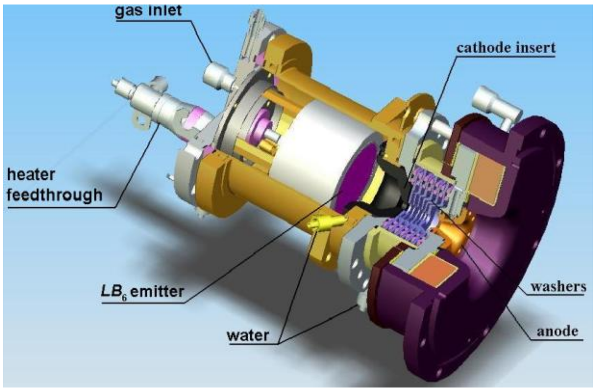


Figure 7: Conversion efficiency Y (5) of H^+, H^0 and surface work function φ (1-4) vs cesium surface concentration N.

A very transparent multigrid extraction system shown in Fig. 8b can be used for improved beam formation and emittance decrease [13]. A four-electrode multislit extraction consists of three multi-wire grids and a fourth cylindrical grounded electrode. The grids are made of 0.2 mm molybdenum wire. The spacing between the wires is 1.0 mm. The wires are positioned on the mounting electrodes by precisely cut grooves and fastened by point welding. The mutual grid alignment accuracy is better than 0.02 mm. The gaps between the first and second grids are 1.0 mm, the second and third grids – 2.0 mm, the third and fourth – 2.0 mm. This design increases the beam brightness relative to the grids system used before. The secondary H- emission decreases during exposition of the cesiated surface to hydrogen plasma as shown in

Fig. 10 from [18]. The surface plasma ionizer design should have the ability for fast desorption of the accumulated hydrogen.



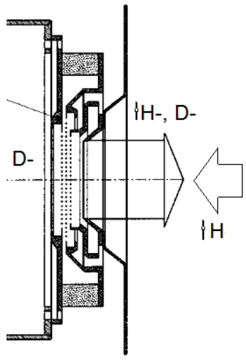


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Figure 8: a) Arc discharge plasma source with a hot cathode; b) transparent multigrid extraction system.

Computer simulations of all involved processes and components are now available and can be used to optimize the suppression of all depolarizing processes. The appropriate computer codes are available. New more advanced BINP-type arc discharge plasma jet sources and multigrid extraction systems have been developed allowing for a higher-intensity lower-aberration beam production. A bending magnet with low aberrations was developed for the high intensity H^-/D^- beam formation/transportation from a Surface Plasma Source [13]. Designs of the beam line and polarimeter for the polarized H^- beam transport and polarization monitoring are available and can be used in such a project. For manufacturing of an ABPIS, one must optimize the cesiated surface plasma ionizer, which converts the D^+ plasma jet emerging from the arc discharge source into a low energy D^- ion flux.

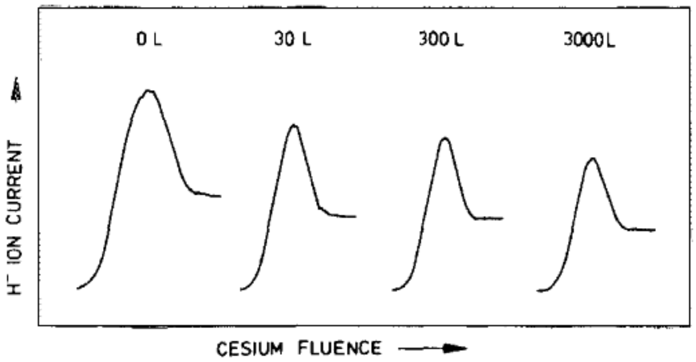

Figure 10: Reduction of the secondary H^- emission during exposition of the cesiated surface to hydrogen plasma (registration of secondary negative ion emission during cesium deposition after cesium evaporation from the surface) [18].

The proposed design of an Atomic Beam Source with a Resonant Charge Exchange Ionizer can have the following beam parameters:

H^- ~ 5-6 mA, 1.2 π·mm·mrad (90%), Pz > 95%
H^+ > 20 mA, 1.2 π·mm·mrad (90%), Pz ~ 85%

D^- ~ 4-5 mA, 1.3 π·mm·mrad (90%), Pz > 95%, Pzz=95%
D^+ > 20 mA, 1.3 π·mm·mrad (90%), Pz = 90%, Pzz=90%
Pulse width of up to 1 ms
Repetition rate of up to 5 Hz

However, for colliders operation [11], delivery of $\sim 10^{11}$ polarized particles per pulse may be enough. An excess intensity can be used for improvement of the beam polarization and brightness by collimation.

A new method for polarized $^3He^-\uparrow$ ion production using a high-brightness arc discharge source has been proposed in [19]. This method can also be used for production of some of the heavier polarized and unpolarized ions. Previous experience of the ABPIS development at the INR, Indiana University and Dubna JINR can be extensively applied in such project. An estimated cost of developing the described Universal ABPIS for highly-polarized H^-/D^- , H^+/D^+ production is ~$1 M.

2.References

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