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POLARIZED ION SOURCES: STATUS AND PERSPECTIVES

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Modern polarized ion sources generate polarized ion beams with high intensity and polarization. Mainly, atomic beam-type and optically pumped polarized ion sources are used to provide polarized ion beams to accelerators. Principles of both methods are outlined in the paper. Characteristics as well as possible improvements of polarized ion sources are considered.

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INTRODUCTION

Development of polarized ion sources started in the 1960s years from Atomic Beam-type Polarized Ion Sources (ABPIS) and Lamb shift-type ion sources. While starting from polarized ion currents of nA scale, polarized ion sources produced great increase of polarized beam intensities in comparison with a double scattering method.

Atomic beam-type polarized ion sources are based on Stern–Gerlach and Breit–Rabi methods of spin separation of atoms with thermal energy during passage through inhomogeneous magnetic field and use of high frequency (HF) transitions between hyperfine states (hfs) of the atoms [1].

Lamb shift-type sources are based on selective quenching of hfs of hydrogen (deuterium) atoms in metastable ($2S_{1/2}$) state and then selective ionization of remaining metastable states [2].

Appearance of lasers gave impulse to development of Optically Pumped Polarized Ion Sources (OPPIS) of hydrogen ions. In this method unpolarized protons with energy of ~ 3 keV pick up polarized electron from optically polarized alkali atoms and then polarized hydrogen atoms are converted into negative ions in nonresonant charge-exchange reaction in sodium vapor target [3].

Constant development of polarized ion sources in many laboratories during past 50 years resulted in increase of polarized ion beam intensities from nA to mA level for 6 orders of magnitude. Many different types of polarized ion sources were developed during this time meeting requirements of different types of accelerators. Survived technologies are atomic beam-type polarized ion sources and OPPIS. Lamb-shift method is used now mainly for low-energy polarimeters.

Status of polarized ion sources development has been reviewed regularly at Workshops on Polarized Ion Sources and Polarized Targets (e.g., [4, 5]).

Existing and new projects with polarized beams (RHIC, COSY, eRHIC, EIC, NICA, FAIR, FNAL) require further development and improvement of polarized ion sources.

1. ATOMIC BEAM-TYPE POLARIZED ION SOURCES

1.1. Atomic Beam Apparatus. Any ABPIS consists of an atomic beam source (ABS) and an ionizer. ABS produces polarized atomic hydrogen (deuterium) beam which is injected into an ionizer where the polarized atoms are converted either into polarized positive ions or polarized negative ones.

Atomic beam method is described in many papers (e.g., [1, 6]). ABPIS's and atomic beam-type polarized gaseous targets have similar atomic beam apparatus. Briefly, ABS works as follows. Thermal hydrogen (deuterium) atoms are produced typically in RF discharge dissociators. Atoms are cooled to temperature of $\sim 30{-}100$ K in collisions with cryogenically cooled accommodator surface. Hydrogen gas flows out the dissociator to vacuum through a sonic nozzle. Atoms are accelerated in forward direction by pressure gradient and are cooled additionally during adiabatic expansion of hydrogen (deuterium) gas in vacuum. Atomic beam with low divergence is formed from hydrogen (deuterium) gaseous flux using skimmer and collimators. The atomic beam is passed through near axis region of sextupole magnets where atoms in different spin states are separated spatially in inhomogeneous magnetic field. Sextupole magnets focuse polarized hydrogen atoms in hfs $|1\rangle$ and $|2\rangle$* (deuterium atoms in hfs $|1\rangle$, $|2\rangle$, $|3\rangle$) and defocuse hydrogen atoms in hfs $|3\rangle$ and $|4\rangle$ (deuterium atoms in hfs $|4\rangle$, $|5\rangle$, $|6\rangle$). Acceptance angle of a sextupole magnet is proportional to magnetic field of the magnet pole-tip and inversely proportional to averaged kinetic energy of atoms. Permanent magnet sextupoles with magnetic field on pole-tip up to 1.7 T are used providing acceptance angle of $\sim 5^\circ$ for atoms cooled to ~ 80 K.

Nuclear polarization of atoms is increased by enterchanging population of hfs using high frequency transitions (HFT). HFT are based on adiabatic passage method [7]. Use of different combinations of HFT and sextupole magnets allows

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*The notation is based on a $|m_j, m_I\rangle$ basis where first number refers to electron spin projection; and second number, to proton spin:
$|1\rangle = |1/2, 1/2\rangle$
$|2\rangle = \cos\theta\,|1/2, -1/2\rangle + \sin\theta\,|1/2, 1/2\rangle$
$|3\rangle = |-1/2, -1/2\rangle$
$|4\rangle = -\sin\theta\,|1/2, -1/2\rangle + \cos\theta|-1/2, 1/2\rangle$,
where $\theta = \arctan(B_c/B)$, $B_c = 50.7$ mT for hydrogen. For deuterium ($B_c = 11.7$ mT) the hf states are defined similarly.

one to get the highest possible polarization of protons and deuterons as well as fast switching between different states of polarization.

Final nuclear polarization of atoms depends on separation efficiency of sextupole magnets, efficiency of HFT and magnetic field in an ionization region. Separation efficiency of sextupole magnets can be determined from focusing factor (ratio of polarized atomic beam density with sextupole magnets «on» and «off») and attenuation factor for defocused hfs. Sextupole magnet systems of ABS have focusing factor of 20–40 which means that efficiency of separation of hydrogen atoms in hfs with different projection of electron spin is about 0.995. Efficiencies of HFT differ depending on their design, but values as high as 0.999 were reported [8]. This high efficiency is a base for high polarziation of ion beams produced by ABPIS. Nuclear polarization of atoms in magnetic field depends on ratio of magnetic field to critical field for hyperfine interaction ($B_c = 50.7$ mT for H atoms in ground state and $B_c = 11.7$ mT for D atoms in ground state) [1]. For hydrogen atoms in hfs $|1\rangle$ and $|4\rangle$ or $|2\rangle$ and $|3\rangle$ which are provided by ABPIS with strong field ionizers, theoretical nuclear polarization in magnetic field of 150 mT is 0.974. Measured hydrogen atomic beam nuclear polarization produced by ABS reaches value of 0.97 ± 0.010 [9].

Intensity of polarized atomic hydrogen and deuterium beams produced by ABS was increased one–two orders of magnitude during many years due to optimization of dissociator and sextupole magnets design. Achieved intensities of nuclear polarized atomic hydrogen beams are $1.2 \cdot 10^{17}$ cm$^{-2} \cdot$ s^{-1} for DC ABS [8] and $2 \cdot 10^{17}$ cm$^{-2} \cdot$ s^{-1} for pulsed ABS [10]. There was not significant improvement in atomic beam intensity during past years. The saturation of ABS intensity is caused probably by processes like scattering of atoms on gas density bumps created by an intense atomic beam at a skimmer (beam-skimmer interference) and inside sextupole magnets [11–13].

1.2. ABPIS: Polarized Positive Ion Production. Methods of conversion of polarized atoms into polarized ions differ in ABPIS depending on mode of operation (DC or pulsed) and intensity and emittance requirements.

1.2.1. Ionization by Electron Impact. Initially, ionization of polarized atoms by electron impact was used for production of polarized protons and deuterons. Efficiency of polarized hydrogen atoms ionization in first electron bombardment ionizers was $\sim 10^{-4}$. Two-order increase in ionization efficiency has been obtained with development of strong field electron beam bombardment ionizer of ANAC type [14]. Polarized proton beam with current up to 400 μA in DC mode of operation had been obtained from the ETH ABPIS with electron beam-type ionizer [15]. In this source, intensity of polarized atomic beam was $\sim 10^{17}$ s^{-1} and ionization efficiency of the atoms reached 2.5%. Similar results were obtained at PSI and SATURNE [16, 17]. At SATURNE accumulation of polarized protons in electron beam of the strong field ionizer was tested. Short proton pulses with peak current up to 2.5 mA were obtained [18].

Another type of ionizers with ionization of polarized atoms by electron impact are Electron Cyclotron Resonance (ECR) discharge ionizer [19–21] and Penning discharge ionizer [22]. ECR discharge ionizer was used in many DC ABPIS due to high ionization efficiency of $\sim 5\%$ and small emittance of polarized ion beams produced.

1.2.2. Resonant Charge-Exchange Plasma Ionizer. Efficient plasma ionizer for a pulsed polarized proton source has been developed at INR RAS [10]. Polarized protons were produced in the source via nearly resonant charge-exchange reaction:

$$\mathrm{H}^0\uparrow + \mathrm{D}^+ \rightarrow \mathrm{H}^+\uparrow + \mathrm{D}^0. \quad (1)$$

Cross section of this reaction is $5 \cdot 10^{-15}$ cm^2 for collision energy of 10 eV which is two orders of magnitude larger than cross section for hydrogen atoms ionization by electron impact. Efficiency of conversion of polarized atoms into polarized protons of 20% has been achieved in the ionizer. Polarized pulsed proton beam with peak current of 6 mA and polarization of 0.76 has been obtained. Characteristics of the polarized proton beam were further improved with a storage cell placed into the charge-exchange region of the source [12]. Polarized proton beam with peak current up to 11 mA, pulse duration of 200 μs at repetition rate of 10 Hz has been obtained. Polarization of the 11 mA proton beam was measured to be 0.8. The normalized emittance was $\sim 1\ \pi\,\mathrm{mm}\cdot\mathrm{mrad}$.

Similar ionizer is planned to be used for a new atomic beam-type polarized deuteron and proton source which is under construction at JINR, Dubna [23].

1.3. ABPIS: Polarized Negative Ion Production. Polarized negative hydrogen ion beams are necessary for accelerators where charge exchange of H$^-$ into H$^+$ is used for stripping injection into buster and storage accelerator rings, stripping extraction from cyclotrons and stripping during acceleration (tandem electrostatic accelerators).

Conventional method for negative ion production is two-step charge exchange of H$^+$ (D$^+$) into H$^-$ (D$^-$) in sodium vapour target at incident beam energy of $\sim 3{-}5$ keV:

$$\mathrm{H}^+\uparrow + \mathrm{Na}^0 \rightarrow \mathrm{H}^{0*}\uparrow + \mathrm{Na}^+, \quad (2)$$

$$\mathrm{H}^0\uparrow + \mathrm{Na}^0 \rightarrow \mathrm{H}^-\uparrow + \mathrm{Na}^+. \quad (3)$$

Efficiency of conversion reaches 9%. Longitudinal magnetic field $B \gg B_c$ should be applied to the charge-exchange region to avoid depolarization in intermediate neutral state of hydrogen atoms due to spin–spin interaction. DC polarized H$^-$ (D$^-$) ion beams with current of $\sim$10 μA were obtained by this method from ABPIS with ECR and electron borbardment ionizers [21].

Another method is direct conversion of polarized hydrogen (or deuterium) atoms into polarized negative ions proposed in [24]:

$$\mathrm{H}^0\uparrow + \mathrm{Cs}^0 \rightarrow \mathrm{H}^-\uparrow + \mathrm{Cs}^+, \quad (4)$$

$$\mathrm{H}^0\uparrow + \mathrm{D}^- \rightarrow \mathrm{H}^-\uparrow + \mathrm{D}^0. \quad (5)$$

Reaction (4) is used in a colliding-beam ionizer in which neutral beams of polarized hydrogen atoms and unpolarized fast cesium atoms are injected in the opposite direction into charge-exchange region with longitudinal magnetic field of $\sim 100-150$ mT. Cross section of reaction (4) has maximum for energy of incident Cs atoms ~ 55 keV. Pulsed source of polarized H^- and D^- ions based on this method is in operation at COSY/Juelich [25]. The source produces up to 50 μA of polarized negative ions in 20 ms pulses with repetition rate of 1 Hz. Advantage of the source is high polarization 90% from nominal and small emittance of the beams $\sim 0.5\ \pi\,\mathrm{mm}\cdot\mathrm{mrad}$ normalized. Polarized deuterons are produced in the COSY source in fifteen different spin states with set of HFT.

Reaction (5) has very big cross section of 10^{-14} cm^2 at energy of D^- ions of ~ 10 eV. The reaction is used in a pulsed polarized ion source developed at INR RAS [12]. A new deuterium plasma injector has been developed for production of plasma consisting mainly from D^+ and D^- ions. The plasma jet and polarized atomic hydrogen beam are injected into charge-exchange region inside solenoid where polarized H^- ions are produced via reaction (5). Polarized H^- ion beam with peak current of 4 mA has been obtained with D^- ion beam current of 60 mA. The source works in pulsed mode with pulse duration of 200 μs and repetition rate up to 10 Hz. Polarization of the H^- ion beam was measured to be 0.91 ± 0.03. Efficiency of direct conversion of polarized hydrogen atoms into polarized H^- ions in the INR source reached 12.5%.

Polarized D^- and H^- ion beams with peak intensity up to 2 mA and polarization up to 90% from nominal of vector polarization ± 1 and tenzor polarization of $+1$, -2 have been obtained from the polarized ion source CIPIOS at IUCF [26] which had been developed in collaboration of IUCF and INR RAS.

1.4. ABPIS: Future Possibilities. Intensity and polarization of polarized beams produced by ABPIS can be improved by further optimization of ABS and ionization technique. In particular, atomic beam formation should be studied to overcome limitations connected with a beam-skimmer interference. Sextupole magnet system parameters should be optimized taking into account results of optimization of atomic beam formation system. With these improvements, pulsed polarized H^- (D^-) ion beams with peak intensity of ~ 10 mA (~ 20 mA for H^+ and D^+ ions) and polarization of $\sim 95\%$ seem to be possible.

2. OPTICALLY PUMPED POLARIZED ION SOURCES (OPPIS)

2.1. Optical Pumping Polarization Method. The well-known process of optical pumping is atoms polarization during consecutive absorbtion of circular polarized resonant photons and spontaneous emission of unpolarized radiation. Nuclear polarization is produced by optical pumping in weak magnetic field.

For direct optical pumping of hydrogen atoms in ground state it is necessary to induce transitions $1S_{1/2} \leftrightarrow 2P_{1/2,3/2}$ ($\lambda = 1216$ Å). Unfortunately, there is lack of lasers with necessary parameters in this vacuum ultraviolet wave length region. Quite the contrary, lasers for optical pumping of alkali atoms are widely available.

Method of operation of OPPIS for hydrogen ions is based on pick-up of polarized electron by initially unpolarized protons with energy of ~ 3 keV in charge-exchange collision with polarized alkali atoms (rubidium is used nowdays):

$$\mathrm{H}^{+} + \mathrm{Rb}^{0}\uparrow \rightarrow \mathrm{H}^{0*}\uparrow + \mathrm{Rb}^{+} \rightarrow \mathrm{H}^{0}\uparrow + \mathrm{Rb}^{+}. \tag{6}$$

The charge-exchange target must be placed into high-magnetic field of 2.5–3 T to avoid partial loss of electrons polarization due to spin-orbital interaction in excited state of hydrogen atom. Ion source of unpolarized protons is placed into strong magnetic field to eliminate strong overfocusing and emittance growth during injection into the charge-exchange target. Emerging from the target, fast hydrogen atoms having electronic polarization pass through region in which longitudinal magnetic field changes direction where the hydrogen atoms undergo «Sona transition» which increases nuclear polarization via hyperfine interaction. The polarized atoms are then converted into polarized H^{-} ions by picking up the second electron in sodium target or by ionization in collisions with helium atoms in gaseous helium target. Sign of nuclear vector polarization in the ion beam is changed by changing sign of circular polarization of laser light.

2.2. BNL/RHIC OPPIS of H^{-} Ions. *2.2.1. BNL/RHIC OPPIS with ECR Ion Source.* At BNL, OPPIS operates since 2000. The source produces pulsed polarized H^{-} ion beam for RHIC with intensity of 10^{12}ions/pulse (peak current of 0.5 mA), polarization of 0.8–0.85, pulse duration of 400 μs at repetition rate 1 Hz [27]. The source has been developed in collaboration between BNL, KEK and INR RAS. In the OPPIS, ECR source of unpolarized protons is used. It operates at a 29 GHz frequency and is placed into 1 T magnetic field created by a superconducting solenoid. The ECR source produces intense unpolarized proton beam with energy of 3 keV. The proton beam current passing through the rubidium vapour target is ~ 80 mA. About 50% of the proton beam is neutralized in rubidium target. The rubidium target placed in magnetic field of 2.7 T is optically pumped by Cr:LiSAF laser which provides more than 1 kW power of circular polarized light in a 400 μs pulse. A recirculating sodium jet target has been developed specially for the OPPIS to ensure large aperture of the target and small amount of sodium vapour escaping from the target to other parts of the source. This provides continuous stable operation of the whole system for hundreds of hours.

2.2.2. RHIC Polarized H^{-} Ion Source Upgrade. The upgrade of the RHIC polarized H^{-} ion source is performed with goal to increase intensity of polarized

H^- ion beam to 5–10 mA level and polarization to value of 0.85–0.9 [28]. The ECR source of unpolarized proton beam will be replaced by a high intensity and high brightness proton source placed outside the superconducting magnet of the OPPIS. To overcome a problem of injection of the proton beam into the high magnetic field of 3 T, the protons will be converted into neutral hydrogen beam by charge exchange in molecular hydrogen target. Then this neutral hydrogen atoms are injected into 3 T magnetic field and converted back to protons in gaseous helium target placed inside the solenoid. The upgrade is based on very high brigthness of the neutral hydrogen beam produced by the injector and on the possibility of separating unpolarized neutral hydrogen atoms by biasing of the helium gaseous target in the superconducting solenoid. The method has been tested earlier [29, 30] and feasibility of high intensity polarized beam production was already demonstrated but high polarization was not achieved in these tests yet. First results of the OPPIS upgrade at BNL are reported at this Symposium and results of polarization measurements and intensity optimization are expected this year.

2.3. Polarized ^{3}HE^{++} Ion Source for RHIC. New OPPIS of polarized $^3He^{++}$ ions for RHIC is developed at BNL in collaboration with MIT [31, 32]. The source is based on optical pumping of helium atoms in metastable states in low power RF discharge in weak magnetic field. The method is used for polarized helium gas production for polarized ^{3}He gaseous targets and for medical purposes [33, 34]. Nuclear polarization of 0.8 is achieved in this method with modern high power lasers. It is planned to inject polarized ^{3}He atoms into BNL electron beam ion source (EBIS) to ionize ^{3}He atoms to double-charge state. High magnetic field of the EBIS is important for suppression of nuclear depolarization in $^3He^+$ ion state due to spin–spin interaction. Number of polarized $^3He^{++}$ ions produced is determined by the EBIS trap capacity and should be $2.5 \cdot 10^{11}$ ions/pulse to fill RHIC to space charge limit. Injection of polarized ^{3}He atoms into strong magnetic field should be investigated to avoid depolarization in changing magnetic field during transport to EBIS.

CONCLUSIONS

Development of polarized ion sources of atomic beam and of optically pumped-type ones during decades resulted in polarized ion beams of high intensity and polarization allowing one to reach up the space charge limit of collider rings with polarized protons. In spite of high degree of state of the art there are still potentialities for further development and improvements both for atomic beam and for optically pumped polarized ion sources.

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