POLARIZED ION SOURCES FOR HIGH-ENERGY ACCELERATORS

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Development of polarized ion sources for high–energy accelerators is reviewed. Significant progress in intensity of polarized negative hydrogen (H^-) ion beams produced by atomic beam–type and optically pumped polarized ion sources has been achieved in recent years. Polarized H^- beam with a peak current of 1 mA and polarization of 0.87 has been obtained from the atomic beam polarized ion source (ABS) with a resonant charge–exchange plasma ionizer developed at the Institute for Nuclear Research, Moscow. Storage of polarized hydrogen atoms in a charge–exchange region of the ABS has been tested at the INR for polarized protons production. A pulsed polarized proton beam with peak current of 11 mA and polarization 0.8 has been extracted from the source. The possibility to use this method for polarized H^- ions production is discussed. An H^- ion current of 1.6 mA DC with a polarization 0.6 has been obtained from the optically pumped polarized ion source (OPPIS) developed at TRIUMF. An OPPIS for RHIC based on these achievements is being tested at TRIUMF. Further order of magnitude increase in intensity is expected in the OPPIS scheme with an external high–brightness pulsed injector of neutral hydrogen atoms. This scheme has been proposed and tested at the Institute for Nuclear Research, and now a new OPPIS based on this scheme is being developed at TRIUMF for HERA.

Introduction

The development of high–intensity polarized ion sources is an important part of all projects of acceleration of polarized ions in high–energy machines. The first high energy polarized proton beam had been accelerated at the ZGS in 1973. The ZGS polarized proton source as originally constructed by ANAC produced a DC current of 8 μA [1]. This intensity was quite high for polarized sources but at that time was at least three to four orders of magnitude less than the intensity of unpolarized ion sources used for high–energy accelerators. In some cases, and especially for experiments in high–energy storage rings, it is neccessary to have a polarized beam intensity comparable to that for the unpolarized beam. This goal was set at the Ann Arbor Workshop on Polarized Ion Sources in 1981. Since that time the polarized sources intensity has been increased by three orders of magnitude. Now, the intensity of polarized beams exseeds the 10 mA for polarized protons and 1 mA for polarized H^- ions. This progress has been achieved by the parallel development and improvement of the ABS and OPPIS technologies. Special attention was given to polarized H^- ion sources because in this case it is possible to use stripping injection of a polarized beam into accelerator rings.

Intensity (I) and polarization (P) are the most important parameters for comparison of polarized sources. Another conventional parameter for polarized beams is the figure of merit $P^2 \cdot I$. For injection into high–energy machines the important characteristic is the number of injected particles, which is determined by source intensity, beam emittance, pulse duration, and repetition rate.

Operational principles and progress of ABS development are described in detail in many reviews, see for example ref. [2-4]. For recent reviews of OPPIS progress see ref. [5,6]. In this paper the general principles of ABS and OPPIS are described, and milestones in development of polarized sources for high–energy accelerators are outlined. The most intense ABS with resonant charge–exchange plasma ionizer and recent results of OPPIS development will be consider in more detail.

1 Atomic beam-type polarized ion sources

1.1 General principle of the method

Operation of the ABS is based on a spatial separation of atoms in different spin states in inhomogeneous magnetic fields by the well known Stern–Gerlach method. Hydrogen atoms with thermal energy are usually produced in an rf discharge. Atomic hydrogen flows out of the dissociator tube into vacuum where atomic hydrogen beam is formed by passing through appropriate collimators. The hydrogen atoms then pass through an inhomogeneous magnetic field which is typically created by sextupole magnets where hydrogen atoms with electron spin $m_j = +1/2$ are focused and atoms with electron spin $m_j = -1/2$ are defocused. Thus after passing the region with inhomogeneous magnetic field atoms are mainly in spin state $m_j = +1/2$. Nuclear polarization of the hydrogen atoms is increased by inducing transitions between spin states by rf magnetic fields. Then atoms are ionized. Polarized ions formed are collected, accelerated to an energy of several keV and extracted from the source.

The intensity of the polarized ion beam is determined by the forward intensity of unpolarized atomic beam from a dissociator, the acceptance angle of the sextupole magnets for atoms and by the efficiency of ionizing the atoms.

1.2 Milestones of the development of ABS for high–energy accelerators

The first "high-energy" ABS at the ZGS has been improved significantly by pulsing of the dissociator operation [1]. Both RF power and hydrogen gas flow were pulsed. This was essential because the duty factor of the ZGS injector was about 0.1%. The gas pulsing reduced atomic beam scattering by residual gas molecules, and the RF pulsing eliminated the problem of dissociator tube cooling and resulted in a decrease of the hydrogen atom velocity. As a result the ZGS polarized source intensity was increased from 12 μA to $30 - 40$ μA, i.e., a gain factor of about 3 was obtained.

The next increase in ABS intensity was obtained by cooling the hydrogen atoms escaping from the dissociator to a temperature of $30 - 100$ K. It is well known that the acceptance solid angle of sextupole magnets is inversely proportional to the kinetic energy of hydrogen atoms in an atomic beam or, roughly speaking, to the temperature to which hydrogen atoms are cooled in the dissociator. But the total picture of the cooling of atomic hydrogen is more complex because of the dependence of scattering cross–sections and gas dynamic on the temperature to which the atoms are cooled. At the Argonne ZGS, the ion beam intensity from their source was found to be proportional to $T^{-1/2}$ down to the lowest temperature of the dissociator cooled nozzle, $T = 28$ K [7]. The ZGS polarized ion source with the cooled dissociator produced up to 100 μA proton pulsed beam with polarization of 0.75 [7].

It was realized then that for the cooled atomic hydrogen beam a redesign of sextupole magnets was neccessary. It was found [8] that a combination of two sextupole magnets separated by some distance has achromatic focusing properties. This is important for focusing a thermal atomic hydrogen beam which has a very large velocity dispersion.

At the JINR, the cryogenic deuteron polarized source POLARIS has produced 200 μA of ion current [9]. The high intensity has been obtained due to the cooling of the dissociator, use of two sextupole magnets and a high-field Penning-discharge ionizer.

At the Saturne laboratory, intensity of the ABS of polarized protons and deutrons was increased up to 700 μA by cooling of a dissociator, optimization of a sextupole magnet and improvements of a strong field electron beam (ANAC–type) ionizer [10]. Pulsing of the electron beam ionizer operation made possible the accumulation of polarized protons in the ionization region. In this accumulation mode of operation, short pulses (about 30 μs) of polarized protons with a peak current of 2.5 mA have been obtained [10].

The AGS ABS produced up to 40 μA of polarized H^- ions in 500 μs pulses [11]. In this source H^- ions were produced directly in a colliding beam ionizer. The reaction of charge–exchange between thermal polarized hydrogen atoms and 40 keV neutral cesium atoms was used. Use of this reaction for polarized H^- ion sources was first proposed by W. Haeberli [12]. Both the dissociator and the colliding beam ionizer of the source were pulsed. The emittance of the polarized H^- ion beam was very small due to absence of a radial electric fields in a neutral cesium beam and its small radius. The normalized emittance has been measured to be only 0.2 π $mm\ mrad$ [11]. Similarly, the ABS at COSY–Jülich delivers pulsed H^- current of over 20 μA with a polarization of 0.85, pulse duration of 20 ms, and within a normalized emittance of less than 0.5 π $mm\ mrad$ [13].

Another reaction proposed by Haeberli for the production of $H^- \uparrow$ was a nearly resonant charge–exchange between polarized thermal hydrogen atoms and fast ($\sim 1\ keV$) deuterium negative ions [12]. This idea was studied by the AGS group with a magnetron–type ionizer [14-15]. Encouraging results were obtained by ionizing unpolarized warm hydrogen atoms, but only several microamperes of $H^- \uparrow$ were obtained with a cold polarized H beam due to strong scattering of the H atoms on D_2 molecules in the ring–magnetron [15].

The AGS group also studied cooling of atomic hydrogen to 6 K [15] with the goal to increase the solid angle acceptance of the sextupole magnet by one order of magnitude in comparison with more conventional cooling to $30 - 100\ K$. It was found that the focusing factor for the cold atomic hydrogen beam decreased with increasing intensity of the cold hydrogen atom flux, making 6 K beam less efficient in comparison with 30 K beam. It has been suggested that this effect is due to intrabeam scattering [15-16]. The effective cross–section for H atoms scattering increases with a decrease of their temperature and was estimated to be 100 $\mathring{A}^2$ at 6 K [16].

A high–efficiency resonant charge–exchange plasma ionizer has been developed at the Institute for Nuclear Research, Moscow for their pulsed ABS. In this ionizer a resonant charge–exchange reaction between polarized hydrogen atoms and unpolarized positive deuterium ions in a deuterium plasma has been used for the production of polarized protons. The cross–section of this reaction at relative energy of colliding particles of $\sim 10\ eV$ (typical energy for a low temperature plasma in ion sources) is $4 \cdot 10^{-15}\ cm^2$ [17]. This cross–section is two orders of magnitude larger then the cross–section for hydrogen atom ionization by electron impact. The large cross–section and high density of the plasma used has resulted in a high efficiency of charge transfer (up to 70%). Scattering of hydrogen atoms in this scheme was eliminated by locating the plasma injector outside the charge–exchange region in a separate vacuum chamber with differential vacuum pumping. The source had a pulsed rf dissociator and a combination of two electromagnet sextupoles. A pulsed polarized proton beam with peak current of 6 mA, polarization 0.76 and normalized emittance of 0.16 π $mm\ mrad$ $\times$ 0.22 π $mm\ mrad$ (for horizontal and vertical directions respectively) has been obtained from the source with free atomic hydrogen beam in the ionizer [18].

The INR ABS was then modified for production of polarized H^- ions [19].

In this source the charge–exchange between unpolarized D^- ions and polarized H atoms takes place in plasma at a relative energy of about 10 eV. The cross–section of the resonant charge–exchange reaction at this energy is $1 \cdot 10^{-14} cm^2$ [20]. The low energy unpolarized D^- ions are produced by a specially designed surface–plasma converter. Several improvements of the D^- ion convertor have resulted in a polarized H^- ion current of 1 mA. The beam was measured to have a polarization of 0.87 and a normalized emittance of 1.8 π mm $mrad$ [21]. The duration of the $H^- \uparrow$ pulse was 180 μs at repetition rate 10 Hz. A similar ABS is under construction at the IUCF [22]. The work at the INR has been stimulated in part by a SPIN Collaboration study of acceleration of polarized protons at Fermilab [23]. A polarized $H-$ ion source with an intensity of 1 mA could produce a luminosity of stored beams at the Fermilab Tevatron comparable with the luminosity of unpolarized beams [23].

An upper intensity limit of the polarized ion beams produced by ABS has not yet been reached. Intensity of the ABS can be increased further by increasing the density of polarized hydrogen atoms and their ionization efficiency, as discussed below.

1.3 Discussion of possible improvements of ABS

Ionization efficiency. Efficiency of conversion of polarized hydrogen atoms into polarized protons in the most intense ABS with the resonant charge-exchange ionizer is close to unity. For $H^- \uparrow$ ions the conversion efficiency in the INR source is about 3%, and it can be increased further by increasing the unpolarized D^- ion current in the charge-exchange region.

Several schemes for D^- ion injection into the ionizer from external surface–plasma D^- ion sources have been proposed [24]. A prospective method is the use of the conventional double charge–exchange reaction of positive ions into negative ions in an alkali metal vapor target at low energy and injection of the negative ion beam produced into an ionizer [25]. However, it is not quite clear how to eliminate the space charge problem arising from transport of the high-intensity and low energy $D^-(H^-)$ beams. This problem is certainly diminished at an ion energy of several keV, but the cross–section of resonant charge transfer for conversion of hydrogen atoms into negative ions drops abruptly with increasing of the collission energy to several keV.

This problem is absent for the INR D^- plasma ionizer due to low energy of D^- ions and plasma quasi–neutrality. Further investigations of the INR-type surface–plasma converter parameters which determine the D^- generation efficiency, such as its surface work function, transverse magnetic field strength, and geometry of the converter are necessary for a determination of the maximum possible D^- ion yield and the ionization efficiency of this type of ionizer.

Atomic beam intensity. One direct way to increase the intensity of the polarized atomic hydrogen beam is to use high–field sextupole magnets. It is well known that the acceptance solid angle of sextupole magnets is proportional to the magnetic field at the magnet pole tip. Calculations show that a gain factor of 2.7 in atomic beam density in the ionization region could be achieved for the INR source by the use of high–field sextupoles with a magnetic field of up to 4.5 T in comparison with the present sextupoles which have a pole tip magnetic field of 0.9 T [26]. A respective gain in the intensity of $H^- \uparrow$ ions can be obtained this way.

A high–intensity ABS with high–field sextupoles for a polarized gas target has been designed and built at the Budker Institute of Nuclear Physics [27]. This source produces record dc flux of polarized deuterium atoms.

A new method for formation of atomic hydrogen or deuterium beams from a conventional dissociator with an additional circular supersonic carrier gas jet has been proposed [28]. Calculations described in ref. [28] show that this method should result in atomic beams with a high forward intensity and low beam temperature.

Storage of polarized atoms. The density of polarized hydrogen atoms can also be increased by storage of the atoms in the ionization region of polarized sources [4, 25, 26]. First tests of a storage cell placed into a resonant charge-exchange ionizer for production of polarized protons are described in ref. [29]. A cylindrical storage cell with uncoated aluminum walls was used in the tests. A pulsed polarized atomic hydrogen beam was injected into the storage cell from one side, and deuterium plasma was injected from the other side through an orifice with a diameter of 3 mm. The tests were made with a relatively low intensity pulsed deuteron flux of 5 mA. The intensity gain obtained with the storage cell in comparison with a free atomic hydrogen beam was measured to be 9, and the polarization of the 1 mA proton beam extracted from the cell reached 0.94±0.03.

Then the unpolarized D^+ current through the cell was increased one order of magnitude up to 45 mA [30]. Respectively, polarized proton pulses with peak current of 11 mA and a polarization 0.8 have been obtained. It is expected that the polarized proton beam intensity can be increased by cooling the storage cell walls to a temperature of about 100 K and by further increasing the deuterium plasma flux through the cell.

The use of a storage cell for direct production of $H^- \uparrow$ ions is a more difficult task due to the necessity to avoid contamination of the storage cell by cesium vapor which is used in the resonant charge-exchange ionizer for catalysis of unpolarized negative ion production.

In this respect it would be desirable to find cesium–free methods for generation of low energy unpolarized D^- ions. One of them may be the use of a converter like in the INR source but with substances other than cesium to get a surface with low work function. Other possibilities exist; for example, double charge–exchange of intense D^+ ion beam into D^- ions in a gas target can be used. A xenon gas target is probably the best choice due to the relatively high yield of negative ions at energy 2.5 $keV(\sim\ 7\%)$.

2 Optically pumped polarized ion sources

2.1 General description of the method

In an OPPIS, optical pumping by circularly polarized laser radiation is used to get electron–spin polarized atoms in an alkali metal vapor target. An unpolarized proton beam with an energy of several keV from an ion source passes through the target in which protons are neutralized by the pick up of a polarized electron from the electron–spin polarized target atoms. The hydrogen atoms are formed mainly in an excited $n = 2$ level. A magnetic field of about 2 T is required in order to avoid a partial electron–spin depolarization caused by spin–orbital interaction in the excited states. The resulting fast hydrogen atoms are electron–spin polarized. The beam of polarized hydrogen atoms leaves the strong longitudinal magnetic field region without emittance degradation due to the neutral charge–state of the polarized particles. The nuclear polarization of the atoms is increased after passage through a region where the longitudinal magnetic field changes its direction (Sona effect [31]). Finally, the nuclear polarized hydrogen atoms are converted into nuclear polarized negative hydrogen ions in a second alkali vapor target, or into polarized protons in a helium gas target.

The idea of producting a polarized ion beam by the capture of polarized electrons during the passage of a proton beam through a ferromagnetic magnetized foil was proposed by Zavoiskii [32]. Haeberli suggested using an optically pumped alkali vapor target instead of the ferromagnetic foil [33]. Anderson proposed and analysed in detail the full OPPIS concept [34].

2.2 Outline the OPPIS development

The first optically pumped polarized ion source had been developed at KEK for the acceleration of polarized protons in the KEK 12 GeV synchrotron. The OPPIS consisted of a 16.5 GHz electron cyclotron resonance (ECR) unpolarized proton source, a sodium neutralizer operating in a 0.9 T longitudinal magnetic field and optically pumped by two dye–lasers, and a sodium ionizer cell. A duoplasmatron was used initially instead of the ECR ion source. It was replaced by the ECR ion source in order to avoid the proton beam emittance degradation by fringing fields of the strong–field solenoid.

After several improvements the KEK polarized source produced an H^- ion beam with an intensity of 100 μA, polarization 65%, and an emittance of 2 π mm $mrad$ [35]. Similar OPPIS have been developed at TRIUMF [36] for dc mode of operation and at LAMPF [37] for operation at a high repetition rate and a duty cycle of 0.1. The KEK group tested also the dual-optical pumping method for production of polarized deutrons with vector polarization theoretically close to unity. In such an OPPIS both neutralizer and ionizer cells are optically pumped. In the tests deuteron vector polarization 0.7 has been achieved [35].

At the INR Moscow a pulsed OPPIS with a duty cycle 10^{-4} has been developed in which 7 keV neutral hydrogen atoms were produced by a high–intensity and high–brightness unpolarized injector in zero magnetic field; the neutral atoms were injected into a strong longitudinal magnetic field without emittance growth and ionized in a gaseous helium target with an efficiency of about 70%. This combination of an external injector of unpolarized hydrogen atoms and a helium ionizer cell acts as a source of unpolarized protons placed into a strong longitudinal magnetic field and has been used instead of the ECR source. Other parts of the INR source were similar to other OPPIS systems but the intensity of the INR source was higher due to the high brightness of the hydrogen atom injector. A pulsed, polarized, H^- ion beam with a peak current of 400 μA, polarization of 0.65 and a normalized emittance of less then 1 π mm $mrad$ has been obtained from this source [38].

Significant progress in OPPIS characteristics has been achieved at TRIUMF in the past few years. Polarization of the dc H^- ion beam has been increased to more than 80% due to the use of Rb vapor pumped by two titanium sapphire lasers in the OPPIS neutralizer and by careful control of the OPPIS parameters [39]. Intensity of the source has been increased due to optimization of the ECR ion source brightness and by increasing both the aperture of the ionizer sodium cell to 20 mm and the number of emission holes of the ECR source to 199 (0.95 mm diameter each). A dc H^- ion current 1.6 mA within a normalized emittance of 2 π mm $mrad$ has been obtained in this mode of operation [40]. Polarization of this high current polarized H^- beam was measured to be 60% [41]. The OPPIS intensity can be increased by further increase of emission area of the ECR ion source. An increase in laser output power is necessary in order to get a high degree of polarization of the rubidium vapor in the neutralizing cell. This is not a problem for a pulsed mode of operation due to availability of high-power pulsed lasers [41].

These achievements will be used in the construction of a future RHIC polarized H^- ion source. The RHIC OPPIS should provide up to 1.5 mA dc ion beam with a pulsed polarization (produced by a pulsed laser) of 80% in $100-300$ μs pulses at 7.5 Hz repetition rate [42].

Even higher intensities are expected from the OPPIS based on the INR Moscow scheme with an external high–brightness injector of fast hydrogen atoms. This kind of OPPIS is developed at TRIUMF for HERA [42]. A neutral injector developed at the BINP Novosibirsk has been built and tested at TRIUMF for the HERA OPPIS project. This injector produces 8 A of 4 keV unpolarized protons which are neutralized with 95% efficiency in a H_2 gas target forming a low divergence, high-brightness beam of unpolarized hydrogen atoms. The injector produces the equivalent of about 400 mA of neutral hydrogen atoms into the OPPIS ionizer cell acceptance. With the ionizer cell turned on, 28 mA pulsed current of mass–analysed H^- beam (still unpolarized) has been obtained downstream of the ionizer, promising $10-20$ mA pulsed polarized H^- ion beam for the HERA OPPIS [42]. The respective intensity of polarized proton pulses (which can be obtained in the same source with a helium gas ionizer cell) can reach $100-200$ mA!

Conclusion

The intensity of the polarized H^- ABS and OPPIS has reached and exceeded the 1 mA level. A polarized proton beam with peak current of 11 mA and polarization of 0.8 has been obtained from the INR ABS with the storage cell placed into the resonant charge-exchange ionizer. Futher progress is expected both for the ABS and OPPIS. For the ABS it can be achieved by increasing the density of polarized hydrogen atoms in the ionization region due to use of high–field sextupole magnets and storage of polarized atoms as well as due to increase of efficiency of conversion of polarized hydrogen atoms into negative ions in the resonant charge-exchange ionizer.

Very high intensity of polarized H^- and H^+ ions is expected for OPPIS scheme with an external high–brightness injector proposed and tested at the INR, Moscow. The OPPIS based on this scheme is being developed now at TRIUMF for HERA. The project goal is $10-20\,mA$ of H^- within $2\,\pi\ mm\ mrad$ normalized emittance in pulsed mode of operation.

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