Development of polarized ion source for the JINR accelerator complex

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Abstract. Status of the JINR polarized ion source development is described. The source is under tests at the test-bench of LHEP, JINR. A charge-exchange plasma ionizer has been tested initially without a storage cell in the ionization region. An unpolarized deuterium ion beam with peak current of 160 mA, 23 keV energy, pulse duration of 100 μs and repetition rate of 1 Hz has been extracted from the ionizer. With a free polarized atomic hydrogen beam injected into the ionizer a polarized proton beam with peak current of 1.4 mA has been obtained. The nearest plans for the source development include tests of the ionizer with the storage cell and tuning of the high frequency transition units installed in their operating position with a Breit-Rabi polarimeter.

1. Introduction

The high intensity pulsed source of polarized ions (SPI) is developed at JINR in collaboration with INR RAS to ensure injection of polarized deuterons and protons into the Nuclotron and future collider of heavy and light ions NICA [1].

The SPI is an atomic beam-type polarized ion source with nearly resonant charge-exchange plasma ionizer and storage cell in the charge – exchange region [2-4]. Some parts of the polarized ion source CIPIOS from IUCF [5] are used in the project.

2. General description of the source of polarized ions

A schematic diagram of the SPI is shown in figure 1. The source has been described in more detail in [6]. Atomic hydrogen (or deuterium for production of polarized deuterons) is produced in the source using an RF discharge dissociator. The dissociator works in a pulsed mode of operation with repetition rate up to 1 Hz and with RF discharge duration of up to 3 ms. Two electromagnetic valves are used for pulsed gas supply into the dissociator discharge tube: one of the valves is used for injection of gaseous molecular hydrogen (deuterium) and another for injection of molecular oxygen.

The atomic deuterium is cooled during the passage through the pyrex tube with a 5 mm internal diameter (cooling channel) ending by a sonic nozzle 2.3 mm in diameter. The channel walls are cooled to temperature of ~80 K by a cryocooler (model 350 Cryodyne refrigerator system). A skimmer is used to separate the central part of an atomic gas jet and form an atomic beam which is then injected into the sextupole magnets. The skimmer has a cone shape and its central orifice is 6 mm in diameter. The distance between the dissociator nozzle and the skimmer orifice is 30 mm.
The sextupole magnets system consists of assembly of three permanent sextupoles and one electromagnet sextupole. The sextupole magnets parameters are presented in ref. [5].

The system of high frequency transition (HFT) units includes medium field transition unit (MFT), which is installed between the assembly of permanent sextupole magnets and electromagnet sextupole, weak field (WFT) and strong field (SFT) transition units which are installed downstream the electromagnet sextupole. For hydrogen atoms alternate turning on of WFT (1→3) and SFT (2→4) will lead to switching between theoretical values of proton vector polarization -1 and +1. 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 [5,6].

The polarized atomic beam is injected then into the plasma ionizer where polarized ions are produced via nearly resonant charge-exchange reaction between polarized atoms and unpolarized ions of isotope relative the polarized atoms:

\[
H^0 \uparrow + D^+ \rightarrow H^+ \uparrow + D^0 \\
D^0 \uparrow + H^+ \rightarrow D^+ \uparrow + H^0
\] (1) (2)

The polarized ions move then slowly under influence of weak electric fields in plasma in direction to the extraction electrode system where they are accelerated to energy of up to 25 keV together with unpolarized plasma ions. Radial confinement of the low energy polarized ions is provided by the magnetic field of the ionizer solenoid.

The 25 keV ion beams extracted pass through the 90° bending magnet in which the polarized ion beam is separated from unpolarized ions. The unpolarized ion beam current is recorded using the ion beam collector downstream the bending magnet. The polarized beam comes out the magnet in vertical direction, passes through the electrostatic Einzel lens and then is deflected by the 90° electrostatic deflector into the horizontal plane to x direction. In the deflector spin of ions remains unchanged. At the source exit the polarized ion beam passes through a spin precessor solenoid which rotates the spin to vertical direction. By this way it is possible to ensure at the source exit vertical direction of spin for polarized protons or deuterons.

3. Tests of the source

The atomic beam section (ABS) has been tested at INR RAS [6]. Intensity of the polarized atomic beam 50 cm downstream the sextupole electromagnet was measured with the time-of-flight mass-spectrometer and found to be 1.5 \(10^{17}\) sec\(^{-1}\) cm\(^{-2}\). Efficiency of HFT was determined by placing a HFT between the assembly of permanent sextupole magnets and electromagnet sextupole and measuring the respective decrease of density of polarized atomic beam. Efficiencies of WFT and MFT for deuterium were determined from these measurements close to be 0.95±0.03 [6].
The plasma ionizer has been tested at the JINR test-bench initially without a storage cell. Efficiency of conversion of polarized atoms into polarized ions is proportional to plasma density in the charge-exchange region and, hence, to current of unpolarized ions extracted from the ionizer. The plasma is produced by an arc-discharge plasma source with cold cathode working in the pulsed mode of operation. The longitudinal magnetic field of ~500 G in the source is produced by the plasma source coil. Molecular deuterium (hydrogen) is injected into the plasma source by a pulsed electromagnetic gas valve similar to one used for the dissociator. An ignition voltage pulse with amplitude of 6 kV and duration of about 40 µs is applied between the cold cathode and the gas valve body to initiate arc-discharge in the source followed by 150 µs voltage pulse applied between the cathode and the anode of the source which produces arc-discharge with current of up to 300 A peak. The deuterium (hydrogen) plasma generated in the source flows out the source into vacuum through the 4 mm diameter hole in the anode and then injected into the ionizer solenoid with the longitudinal magnetic field of ~1 kG created by the ionizer solenoid. The ionizer solenoid coils are at ground potential while the plasma jet inside the solenoid should be at hv positive potential relative ground to make it possible acceleration of ions. Cylindrical screen (made of stainless steel) insulated relative ground is installed inside the solenoid to ensure the plasma injection into region which is at hv potential. The screen is connected electrically to the anode of the plasma source.

Three electrode extraction system has been installed for tests of the ionizer without the storage cell. The first (plasma) electrode and the second electrode are gridded with distance between grids of 4 mm. The extraction electrodes aperture is 17 mm. The plasma electrode is at the plasma source anode potential while the second electrode is at -1 kV potential (DC) relative ground. The third electrode is cylindrical with internal diameter of 20 mm and it is grounded. Potential up to 25 kV is applied to the anode of the plasma source to provide extraction of ions from the plasma region. Negative potential applied to the second electrode produces a trap for secondary electrons which compensate space charge of the intense unpolarized ion beam.

The 25 kV voltage pulse duration can be varied in range of 50-500 µs, rep. rate is up to 1 Hz. The pulse top is stabilized with feed-back system with accuracy of ±0.3%. The power supply has been designed and built at INR RAS.

Figure 2 shows typical oscillograms characterizing the ionizer operation.

![Figure 2](attachment:image.png)

Figure 2. The oscillograms characterizing the ionizer operation: green – the plasma source discharge current pulse with peak current of 190 A; yellow – the extraction voltage pulse with peak value of 23 kV, blue – the current of extraction electrodes with peak value of 560 mA, purple – unpolarized deuterium ion current recorded downstream the analysing magnet (peak value is 160 mA).

With the polarized atomic hydrogen beam “on” a polarized proton beam with peak current of 1.4 mA (difference in the ion beam peak current with atomic beam “on” and “off”) has been recorded downstream the bending magnet.

Figure 3 shows photo of the hv power supply for ions extraction from the plasma ionizer during its tests at INR RAS. Photo of the polarized ion source at the test-bench is shown in figure 4.
4. Nearest plans

4.1. Tests of the ionizer with a storage cell
A storage cell is planned to be used in the charge-exchange region to increase density of polarized atoms. This method has been tested at INR RAS [3] and the polarized proton beam with peak current of 11 mA and polarization of 80% has been obtained by this method [4].

A storage cell with the same dimensions (250 mm in length, 15 mm internal diameter) made from aluminum alloy will be installed into the ionizer of the polarized ion source. We plan to start the tests in 2015.

4.2. Measurements of efficiencies of the HFT with a Breit – Rabi polarimeter
HFT determine nuclear polarization of polarized ions but their efficiencies can be impacted by the external magnetic field. For this reason it is important to control efficiencies of HFT directly in their operating position.

To do this we plan use Breit – Rabi type polarimeter consisting of two multipole magnets and TOF mass-spectrometer. A schematic diagram of the ABS components and the polarimeter is shown in figure 5.

Two permanent multipole magnets will be used in the polarimeter. Their parameters were determined using race-tracing calculations and are shown in the table 1. The first magnet is a quadrupole with aperture of 17 mm and length of 140 mm. The second magnet is a sextupole with aperture of 18 mm and length of 125 mm.

The maximum magnetic field at the pole tip of both magnets is accepted to be 1.6 T. The magnets are now under construction.
Table 1. Parameters of multipole magnets of the polarimeter

| Magnet number | 1 | 2 |
|---------------|---|---|
| Poles number  | 4 | 6 |
| Aperture (distance between opposite poles in mm) | 17 | 18 |
| Length (mm)   | 140 | 125 |
| Magnetic field at pole tip (T) | 1.6 | 1.6 |

An example of the calculations of atoms trajectories in the source with the polarimeter installed is shown in figure 6.

It is seen from the results of the calculation that atoms focused by the ABS are refocused then by the multipole magnets of the polarimeter if no HFT are “on” in the ABS (figure 6a). If one of HFT is “on”, then respective part of the atoms undergoing transition between spin states (with change of their electron spin state in strong magnetic field from $m_j = 1/2$ to $m_j = -1/2$) will be defocused by multipole magnets of the polarimeter (figure 6b). Measurement of relative change of density of the polarized atomic beam by the TOF mass–spectrometer with HFT “off” and “on” will allow one to determine efficiencies of the HFT of the ABS.

![figure 6a](image1.png) ![figure 6b](image2.png)

Figure 6. Trajectories of atoms in the ABS and the polarimeter: a) HFT are “off” b) one of HFT is “on”.

5. Conclusions
Polarized ion source for the JINR accelerator complex is now under tests at the JINR test bench. The ABS part and the plasma ionizer operation have been tested and were found satisfactory. The polarized proton beam of 1.4 mA peak has been produced with free atomic beam in the charge-exchange region of the source. It is planned to continue tests with a storage cell installed into the ionizer. The HFT units installed in their operating position will be retuned with the Breit-Rabi polarimeter.

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