Source of polarized ions for the JINR accelerator complex

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Abstract. The JINR atomic beam type polarized ion source is described. Results of tests of the plasma ionizer with a storage cell and of tuning of high frequency transition units are presented. The source was installed in a linac injector hall of NUCLotron in May 2016. The source has been commissioned and used in the NUCLotron runs in 2016 and February – March 2017. Polarized and unpolarized deuteron beams were produced as well as polarized protons for acceleration in the NUCLotron. Polarized deuteron beam with pulsed current up to 2 mA has been produced. Deuteron beam polarization of 0.6-0.9 of theoretical values for different modes of high frequency transition units operation has been measured with the NUCLotron ring internal polarimeter for the accelerated deuteron and proton beams.

1. Introduction
The high intensity pulsed source of polarized ions (SPI) has been developed at JINR in collaboration with INR RAS for 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 a charge-exchange plasma ionizer and a storage cell in an ionization region [2-4]. Many parts of the polarized ion source CIPIOS from IUCF [5] are used in the project. General description of the source is given in chapter 2 of the paper. Results of tests of the source ionizer and tuning of the high frequency transition (HFT) units are presented in chapter 3. Commissioning of the SPI is described in chapter 4.

2. General description of the SPI
A schematic diagram of the SPI is shown in figure 1. The source consists of an atomic beam apparatus, the plasma charge-exchange ionizer and a system for polarized ion beam transport and spin turn to vertical direction.

2.1. Atomic beam apparatus
Polarized deuterium or hydrogen atoms with thermal energy are produced by the atomic beam apparatus consisting from a pulsed radio frequency (RF) discharge dissociator, sextupole magnets and HFT units. For definiteness we describe further generation of polarized atomic deuterium beam and of polarized deuterons unless otherwise noted.
Dissociation of molecular deuterium in RF discharge is used for production of atomic deuterium as in a conventional atomic beam type source. Molecular deuterium is injected by a pulsed electromagnetic gas valve into the dissociator tube where pulsed RF discharge is induced. Deuterium molecules dissociate into atoms in the RF discharge plasma in collisions with plasma electrons. Atomic deuterium flows into vacuum out the dissociator tube through 100 mm long 5mm internal diameter Pyrex channel which ends with sonic nozzle of 2 mm in diameter. Walls of the channel are cooled to ~80K with the cryocooler (model 350 Cryodyne refrigerator system).

Figure 1. Schematic diagram of the SPI.

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 atomic beam passes through the sextupole magnets where atoms in spin states with \( m_j = 1/2 \) are focused and those in spin state with \( m_j = -1/2 \) are defocused. Thus, after passage the sextupole magnets the atoms become polarized.

Nuclear polarization of deuterium atoms being ionized in strong magnetic field is increased with system of the HFT units which includes a medium field transition unit (MFT) (installed between the assembly of permanent sextupole magnets and electromagnet sextupole), a weak field (WFT) and a strong field (SFT) transition units which are installed downstream the electromagnet sextupole. For hydrogen atoms alternate turning on of the WFT (1 \( \rightarrow \) 3) and the SFT (2 \( \rightarrow \) 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]. Many another deuteron polarization states can be produced using different combinations of the HFT. The sextupole magnets and the HFT units were parts of the CIPIOS designed at IUCF [5].

2.2. Charge-exchange plasma ionizer with the storage cell
The polarized atomic deuterium beam produced by the atomic beam apparatus is injected into the storage cell installed inside a solenoid of the charge-exchange plasma ionizer. The atomic beam has duration of up to 3 ms determined by the pulse duration of the RF discharge dissociator. During the pulse time polarized deuterium atoms are injected and stored in the cell. Then 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:

$$D^0 + H^+ \rightarrow D^+ + H^0$$  \hspace{1cm} (1)

For production of polarized protons the next reaction is used:

$$H^0 + D^+ \rightarrow H^+ + D^0$$  \hspace{1cm} (2)

In this case the atomic beam apparatus produces the polarized atomic hydrogen beam and the plasma source produces deuterium plasma.

Cross-section of the charge-exchange reactions (1) and (2) increases with decrease of relative energy of colliding particles and reach of $5 \times 10^{-15}$ cm$^2$ at energy of incident particles of ~10 eV (typical for a gas discharge plasma).

Radial confinement of the low energy polarized ions formed in the charge-exchange region is provided by magnetic field of the ionizer solenoid.

The polarized ions move then slowly under influence of weak electric fields in plasma in direction toward an extraction electrode system where they are accelerated to energy of up to 25 keV together with unpolarized plasma ions. The three electrode accel-decel quasi Pierce system is used for the ion beam extraction and formation.

2.3. Beam transport and spin rotator system

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. 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. By this way it is possible to ensure at the source exit vertical direction of spin for polarized protons and deuterons.

3. Tests of the SPI with the storage cell and tuning of the HFT units

3.1. Tests of the ionizer with the storage cell

After tests of the SPI with free polarized atomic deuterium beam in the plasma ionizer described in [7] the storage cell has been installed into the plasma ionizer. The storage cell allows increasing density of polarized atoms in the charge-exchange region one order of magnitude in comparison with free polarized atomic beam. However, even in pulsed mode of operation unpolarized ion current which can be transported through the storage cell in noiseless mode is restricted to ~50 mA [4]. 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 from the source installed at the INR RAS test bench [4].

Initial tests of the SPI with the storage cell in the ionizer region resulted to low intensity of the polarized deuteron beam of ~0.4 mA. It has been found that this polarized deuteron beam low intensity was determined in part by low efficiency of collection and extraction of polarized ions from charge-exchange region inside the storage cell. The collection efficiency has been increased by increase of magnetic field in the charge-exchange region up to 2.4 kG and increase of internal diameter and shape of the storage cell. Initially the storage cell had cylindrical shape of the internal surface with diameter of 15 mm and length of 250 mm (as in ref. [4]). Now the storage cell has conical shape with internal diameter changing from 16 mm to 20 mm and length of 200 mm. The end of the cell directed to the
plasma source is closed by diaphragm of 3 mm in diameter through which hydrogen plasma in injected into the storage cell. The cell is manufactured from aluminum alloy.

With the storage cell of this geometry the polarized deuteron beam with peak current of 2 mA has been obtained from the source (difference of the ion current recorded downstream the analyzing/bending magnet with the polarized atomic deuterium beam “on” and “off”). Unpolarized pulsed proton beam extracted simultaneously with the polarized deuterons was about 40 mA as well as beam of H2+ ions of 2 mA peak. The beam of H2+ ions is not separated from the polarized deuteron beam in the analyzing/bending magnet and in the electrostatic deflector of the SPI. But after acceleration in a linac and passage through a stripping target unpolarized protons formed due to stripping of the H2+ ions are deflected from the polarized deuteron beam entirely in transport line bending magnets. Thus, the unpolarized H2+ ions do not dilute polarized deuteron beam injected into the NUCLOTRON.

3.2. Measurements of efficiencies of the HFT with a Breit – Rabi polarimeter

HFT of the PSI were tuned in their operational position with use of a Breit – Rabi polarimeter.

A schematic diagram of the ABS components and the polarimeter is shown in figure 2.

![Schematic diagram of the ABS with the Breit – Rabi polarimeter.](image)

**Figure 2.** Schematic diagram of the ABS with the Breit – Rabi polarimeter.

Two permanent multipole magnets are used in the polarimeter. Their parameters were determined using race-tracing calculations. 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 of both magnets is 1.6 T. These magnets were installed into a vacuum chamber inside of the ionizer solenoid instead of the storage cell. The time-of-flight mass spectrometer (TOF MS) was installed into a vacuum chamber of the plasma source and was used to measure the polarized atomic beam intensity (the plasma source was removed from the chamber during the tuning procedure).

If one of the 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 \(m_e = 1/2\) to \(m_e = -1/2\)) will be defocused by the multipole magnets of the polarimeter. For deuteron atomic beam this leads to decrease of its intensity measured by the TOF MS by one third. Simultaneous activation of two HFT working with 100% efficiency leads to decrease of intensity by two third. Measurement of relative change of density of the polarized atomic beam by the TOF MS with HFT “off” and “on” will allow one to determine efficiencies of the HFT of the ABS.

Example of tuning of the HFT units with the Breit-Rabi polarimeter is shown in figure 3. The TOF MS signal is shown vs. current in the static coil of the SFT. The SFT RF cavity was powered with 397 MHz. Changing of magnetic field results to inducing of different transitions between hfs of deuterium atoms passing through the SFT unit. Transitions 2-6, 2-5+3-6 and 3-5 are recorded and identified using magnetic field value in the SFT magnet (calibrated for the static coil current) and used frequency of the SFT cavity. A width of the each transition curve is determined by gradient of
magnetic field provided by a gradient coil of the SFT. We use here common notation of spin states of deuterium atoms. The RF cavity of the SFT produces oscillating magnetic field which is parallel to static magnetic field in the region where polarized atoms pass through the cavity. So, it is designed to induce $2\rightarrow 6$ and $3\rightarrow 5$ transitions ($\sigma$ transitions, $\Delta m_F = 0$). $2\rightarrow 5$ and $3\rightarrow 6$ transitions ($\pi$ transitions, $\Delta m_F = \pm 1$) should not be induced because it is necessary to have RF magnetic field to be perpendicular to the static magnetic field for these transitions. However, transitions $2\rightarrow 5$ and $3\rightarrow 6$ are induced also as can be seen in the figure 3 which can be explained by relatively big aperture of the TOF MS (27 mm) recording atoms passing the RF cavity far from the SFT axis where there is transversal RF field component to the static magnetic field.

Figure 3. TOF MS signal vs. current in static coil of the SFT (only the SFT is turned on). Transitions between spin states of deuterium atoms 2-6, 3-5, and 2-5+3-6 are shown.

Measured efficiencies of another HFT units and their combinations are shown in table 1.

| Table 1. The measured efficiencies of the HFT. |
|-----------------------------------------------|
| SFT 2-6 | SFT 3-5 | MFT 3-4 | MFT 1-4 | MFT 1-4 | WFT 1-4 | MFT 3-4+ |
| Efficieny 0.87±0.06 | 0.83±0.06 | 0.91±0.03 | 0.93±0.03 | 0.92±0.03 | 0.93±0.06 | 0.62±0.07 |

The efficiencies were calculated taking into account not complete (97%) defocusing of atoms undergoing the transition with the polarimeter multipole magnets into the TOF MS aperture (27 mm). The defocusing factor by the magnets of the polarimeter was estimated using MC simulation of tracking of polarized atoms through ABS and the polarimeter system. As shown in the table 1 the efficiencies of the most HFT are around 90% except WFT 1,2 – 3,4. We plan to rebuild the WFT and improve its efficacy.

4. Commissioning of the SPI

The SPI has been moved to the linac hall in May 2016. It was commissioned and used in the NUCLotron runs in 2016 and February – March 2017. In these runs the SPI worked in mode with polarized deuterons during 900 hrs and with unpolarized deuterons during 600 hrs. Also there was short test run during of 40 hrs with polarized protons.

Measurements of deuteron polarization made with an internal NUCLotron polarimeter [8] resulted to deuteron polarization of 0.6-0.88 of theoretically maximum values. Tensor deuteron polarization of 0.88±0.049; -1.47±0.031 (theoretically maximum +1, -2) has been measured with
additional tune of the HFTs with the internal polarimeter. Measurements show long term stability of polarization. This demonstrates the lack of depolarization in the plasma ionizer storage cell which was used for the first time for polarized ion source working during continuous accelerator runs. Proton beam polarization of -0.354±0.022 has been measured [9] which is close to expected polarization of -0.39 with present transport line between the linac and the NUCLOTRON ring [10].

5. Conclusions
The SPI of JINR has been tested with the storage cell installed into the charge-exchange region of the plasma ionizer. Polarized deuteron beam with pulsed current up to 2 mA has been produced after study of the storage cell operation. The HFT units were tuned with using of the Breit-Rabi polarimeter. The SPI was installed in the linac injector hall of the NUCLOTRON in May 2016. The source has been commissioned and used in the NUCLOTRON runs in 2016 and February – March 2017. Polarized and unpolarized deuteron beams were produced as well as polarized protons for acceleration in the NUCLOTRON. Deuteron beam polarization of 0.6-0.88 of theoretical values for different modes of the HFT units operation has been measured with the NUCLOTRON ring internal polarimeter for the accelerated deuteron and proton beams.

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