Source of Polarized Ions for JINR Accelerator Complex

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The active beginning of polarization researches at LHEP (JINR, Dubna) behaves to 1980

To this time for the base JINR accelerator Synchrophasotron (4.5 GeV/nucl) 0.2 mA the cryogenic source of polarized deuterons (D⁺) POLARIS was developed
Cryogenic source POLARIS was used long time at the synchrophasotron to produce polarized deuteron beam.

This setup was designed at the end of 1970-ies.

An atomic beam forming process is required to pump a large mass of injected gas. There was no developed turbopump technology that time yet. It was decided to apply cryocondensation of deuterium molecules on cooled surfaces.

The source consists of two LHe cryostats: a pulsed atomic beam stage with two superconducting sextupole magnets, the Penning plasma ionizer with high field SC solenoid.

The energy of the deuteron beam at the output of the source is about 3 keV, the current: 0.3-0.4 mA.

The vector and tensor polarizations are:

\[ P_z \sim \pm 0.54 \]
\[ P_{zz} \sim \pm 0.76 \]
After creation of the superconducting accelerator NUCLOTRON and closing of the Synchrophasotron (2002) in 2002 – 2005 the first runs with the $D^+$ polarized beam have been carried successfully out at this machine.

**Note:**

This accelerator will be upgraded to the NUCLOTRON-M in the coming three years to work with proton beam with energy up to 12 GeV and nuclei up to 6 AGeV.

As a source of polarized deuterons the setup POLARIS was used.
• Further development of the polarization program at NUCLOTRON supposes the substantial increasing of intensity of source of the polarized particles.

• As the first step the increase of intensity of the accelerated polarized D\(^+\) beam is supposed.

• The estimations and first runs with the polarized D\(^+\) beam at NUCLOTRON show depolarizing resonances for accelerated deuterons are absent in all of energy range of accelerating.
The Source of Polarized Ions for JINR Accelerator Complex (SPI-project) assumes the development of the universal high-intensity Source of Polarized Deuterons & Protons using charge-exchange ionizer

Nearly resonant charge-exchange reactions for production of polarized protons & deuterons are

\[
\begin{align*}
\text{H}^0 \uparrow + \text{D}^+ & \Rightarrow \text{H}^+ \uparrow + \text{D}^0 \\
\text{D}^0 \uparrow + \text{H}^+ & \Rightarrow \text{D}^+ \uparrow + \text{H}^0
\end{align*}
\]

\[\sigma \sim 5 \times 10^{-15} \text{ cm}^2\]

The design output current of the SPI will be up to 10 mA for \(\uparrow \text{D}^+ (\uparrow \text{H}^+)\)

The \(\text{D}^+\) polarization will be up to 90% of the maximal vector (±1) & tensor (+1,-2) polarization

The project is based on the equipment which was supplied within the framework of the Agreement between JINR & IUCF (Bloomington, USA)

The project will be realized in close cooperation with INR of RAS (Moscow, Russia)
• The main purpose of the SPI-project is to increase the intensity of the accelerated polarized beams at the JINR Accelerator Complex up to $10^{10}$ d/pulse
The SPI-project includes the following stages:

- development of the high-intensive Source of Polarized Ions
- modification of the linac preaccelerator hall platform & power station (upgrading of the HV (400 kV)
- improvement of the preaccelerator tube vacuum using the turbomolecular pumping
- adaptation of the existing remote control system (console of LU-20 linac) of the polarized ion source under the high voltage
- complete tests of the source
- assembly of the designed source and equipment at the linac preaccelerator
- LU-20 runs with polarized beams & polarization measurements at the output of the linac
• The most labour-consuming and expensive work is development of the **Source of Polarized Ions** based on the equipment of **Cooler Injector Polarized IOn Source (CIPIOS)** developed at Indiana University Cyclotron Facility (IUCF, USA) in cooperation with the **INR of RAS (Moscow)** in 1999

**Acknowledgements**

• The big work on transfer of the CIPIOS equipment from IUCF in Dubna has been done by

  V.P. Derenchuk
  *Indiana University Cyclotron Facility, USA*
Some CIPIOS parts delivered to LHEP-JINR from IUCF
• **CIPIOS includes**

- source of the polarized atoms using the permanent sextupole magnets ($B = 1.4$ T) for focusing and electron spin separation
  - radio frequency transitions units of nuclear polarization
  - resonant charge-exchange ionizer. The polarized ions are formed at resonant charge-exchange of the polarized atoms and unpolarized ions in plasma
  - special spin orientation system at the output of CIPIOS in vertical position

Note:

**CIPIOS** was intended for high-intensity negative polarized and unpolarized beams production
Cooler Injector Polarized IOn Source (CIPIOS)

**Beam Properties**
- Pulsed @ 1Hz to 4Hz
- 25 keV Beam Energy
- Polarized H⁻ or D⁻
- Nominal polarization ≥ 80%
- ≈ 1.5 mA (peak) from source
- ≥ 25 mA (peak) unpolarized available

CIPIOS - CIS Injection Layout

Resonant Charge Exchange Ionizer

- 90° Vertical Magnetic Bend
- Followed by 90° Transverse Electrostatic Bend

Spin Rotation Solenoid

RFQ - DTL
Characteristics of the source of negative polarized ions IUCF (CIPIOS):

- peak current of polarized ion beam $H^- (D^-) - 1.8 (2) \ mA$
- peak current of polarized ion beam $H^- (D^-) - 40 (30) \ mA$
- polarization $H^- - 80-85\%$
- polarization $D^-$:

<table>
<thead>
<tr>
<th>Type of polarization</th>
<th>$Pz$ nominal</th>
<th>$Pz$ measured</th>
<th>$Pzz$ nominal</th>
<th>$Pzz$ measured $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>vector (+)</td>
<td>+1</td>
<td>0.909 (31)</td>
<td>+1</td>
<td>0.891 (13)</td>
</tr>
<tr>
<td>vector (-)</td>
<td>-1</td>
<td>-0.684 (30)</td>
<td>+1</td>
<td>0.695 (14)</td>
</tr>
<tr>
<td>tensor (+)</td>
<td>0</td>
<td>0.003 (32)</td>
<td>+1</td>
<td>0.875 (13)</td>
</tr>
<tr>
<td>tensor (-)</td>
<td>0</td>
<td>0.020 (33)</td>
<td>-2</td>
<td>-1.591 (13)</td>
</tr>
</tbody>
</table>

- normalized emittance $H^- (D^-) - 1.2 \ \pi \ mm \ mrad$
- pulse duration – up to 500 microsec. @ 1-4 Hz from source
- energy of polarized ion beam - 25 keV
• The source CIPIOS had high reliability and high stability of polarization and intensity of the beam during of typically 1000 hours accelerator runs

• Scheduled stops were necessary for the cryocooler regeneration and dissociator unit every two weeks of continuous work

• CIPIOS also generated unpolarized beams of negative ions of hydrogen and deuterium with a current up to 30 mA
INR source of polarized protons

- It is known that at INR the source of polarized protons with the charge-exchange plasma ionizer and the polarized atom storage in the ionization volume has been developed.

**Characteristics of polarized H\(^+\) (H\(^-\)) ion beam of the INR source**

\(H^+\)

**Without polarized atom storage**

- Intensity: 6 mA
- Polarization: 85%

**With polarized atom storage**

- Intensity: 11 mA
- Polarization: 80%

\(H^-\)

- Intensity: 4 mA
- Polarization: 90%
Schematic layout of the polarized proton source with nearly resonant charge-exchange plasma ionizer
Schematic diagram of nearly resonant charge-exchange plasma ionizer with a storage cell
INR source with a storage cell

- Density of polarized hydrogen atoms in an ionization region of a polarized ion source can be increased in comparison with free polarized atomic hydrogen beam by using of a storage cell.

- This was tested at INR: 11 mA H$^+$ beam has been obtained with 80% polarization.
The ionizer with storage of polarized atoms allows

- increase intensity of the polarized ion beam,
- reduce emittance of the polarized beam
- considerably reduce $\text{H}_2^+$ ion current which is difficult to be separated from polarized $\text{D}^+$ due to similar mass of the ions.
• At the **NUCLOTRON** one-turnaround injection is used.

• Transition to the re-charge injection of negative ions is not provided.

• Therefore it is expedient to use the source of positive polarized deuterium ions.

**Note:**

The highest intensity of the beam is reached for **positive** polarized ion sources with charge-exchange plasma ionizer and the storage cell.
SPI-project assumes to convert the charge-exchange ionizer of CIPIOS into the ionizer using storage of polarized deuterium atoms and production of positive polarized deuterons by resonance charge-exchange in the hydrogen plasma.
The transferred equipment of a source CIPIOS is not fully completed.

That is why the development and manufacturing of missing modules and parts of the future source is required.

Mainly it concerns missing elements of the Atomic Beam Source (ABS).

In addition acquisition of the missing equipment and devices for the source is also necessary.
- vacuum chamber of the ABS and sextupole magnets
- dissociator
- channel of the atomic deuterium (hydrogen) beam cooling
- fast pulse valve of molecular deuterium (hydrogen) injection into the dissociator bulb
- the power supply of the pulse gas valve
- high-frequency pulse generator (pulse power up to 5 kW, 50 MHz)
- modulator of the high-frequency generator (maximum voltage up to 4.5 kV and a pulse current up to 2 A)

should be development
For optimization of the atomic beam intensity it is necessary

- to measure the **atomic beam density** in the pulse mode using the time-of-flight mass-spectrometer
- to measure the **atomic beam velocity distribution**
- to compute the **optimum location** of the permanent sextupoles
The designing and manufacture of ABS parts, optimization of the intensity of the atomic beam, and functional tests of the RF cells of the nuclear polarization of deuterium (hydrogen) atoms will be performed at INR of RAS (Moscow)
The purpose is to get atomic D beam with the pulse density of $2.5 \cdot 10^{10}$ at/cm$^3$ at the distance of 150 cm from the cooling channel outlet and the most probable velocity of $1.5 \cdot 10^5$ cm/s
The work which is carried out at JINR includes:
- assembly and tests of the charge-exchange plasma ionizer, including the storage cell in the ionization volume
- transportation of hydrogen plasma with the flow of unpolarized protons up to 100 mA through the storage cell
- optimization of the ion-optical system up to 25 keV and transport of the high-current deuteron beam
- long-term tests of the SPI with the storage cell in the ionizer
- polarimetry of the accelerated beam at the output of linac

It is necessary to develop control system components for primary analysis & data acquisition and for fiber optic system of data transmission.
Status of the SPI - project

Now within the framework of the project and the JINR-INR Agreement the Atomic Beam Source is under development at INR

The beginning of tests of ABS is planned by the end of 2010

The testbench for the charge-exchange ionizer is under preparation at JINR

The missing equipment will be bought in the near future
Pulsed dissociator (INR-type), nozzle cooling to 70 K, set of permanent magnet sextupoles and electromagnet sextupole (CIPIOS), WF and SF RF transitions units

Expected intensity of polarized deuteron beam is $1.5 \cdot 10^{17} \text{sec}^{-1}$ (3 ms pulse), polarized hydrogen beam - $2 \cdot 10^{17} \text{sec}^{-1}$
RF generator of the dissociator
Atomic Beam Source setup general view

ready

ready

ready
Vacuum pumping system of the SPI
• Pump, Turbo-V 3K-T, 2300 l/s $\text{H}_2$, 2400 l/s $\text{He}$ - 2 item

• Pump, Turbo-V 2K-G, 1600 l/s $\text{N}_2$ - 2 item

• CTI - Cryogenics
  Cryocooler, Model 1020  77K - 35W  first stage
                      20K - 12W  second stage

equipment is already got

purchase plan in the end of this year
Atomic hydrogen beam formation for pulsed AB sources

• Peak intensity of polarized atomic hydrogen beam is $2 \cdot 10^{17}$ at/s

• Intensity increases with increase of distance between dissociator nozzle and skimmer

A. Belov, PSTP 2007
Atomic hydrogen beam formation for pulsed AB sources

Gaseous jet expansion through a sonic nozzle to a gas with ambient pressure $P_a$

$X_M/d \sim \sqrt{(P_0/P_a)}$

DSMC shows no Mach disk formation for expansion of jet into vacuum

Atomic hydrogen beam interaction with a skimmer
AB formation system of DC source (ANKE target)

AB formation system of pulsed source (INR&JINR)
Preliminary results of computer simulation are shown for the most probable velocity of $1.5 \cdot 10^5$ cm/s.
Dynamics of atomic hydrogen beam downstream the sextupole magnets & Atomic Hydrogen Breit-Rabi diagram

Preliminary results of computer simulation are shown for the most probable velocity of $1.5 \cdot 10^5$ cm/s
The results of computer simulation for $^3$He atom velocity 1200 m/s
The RF-transition units will be checked and tuned with a sextupole electromagnet as an analyzing device.
Time-of-flight mass-spectrometer with cross-beam ionizer

ready
High-voltage terminal at the linac (Lu-20)
(possible variant of improvement)
Thank you