Upgrading Polarized Beam Equipment at the JINR Accelerator Facility: Future Prospects

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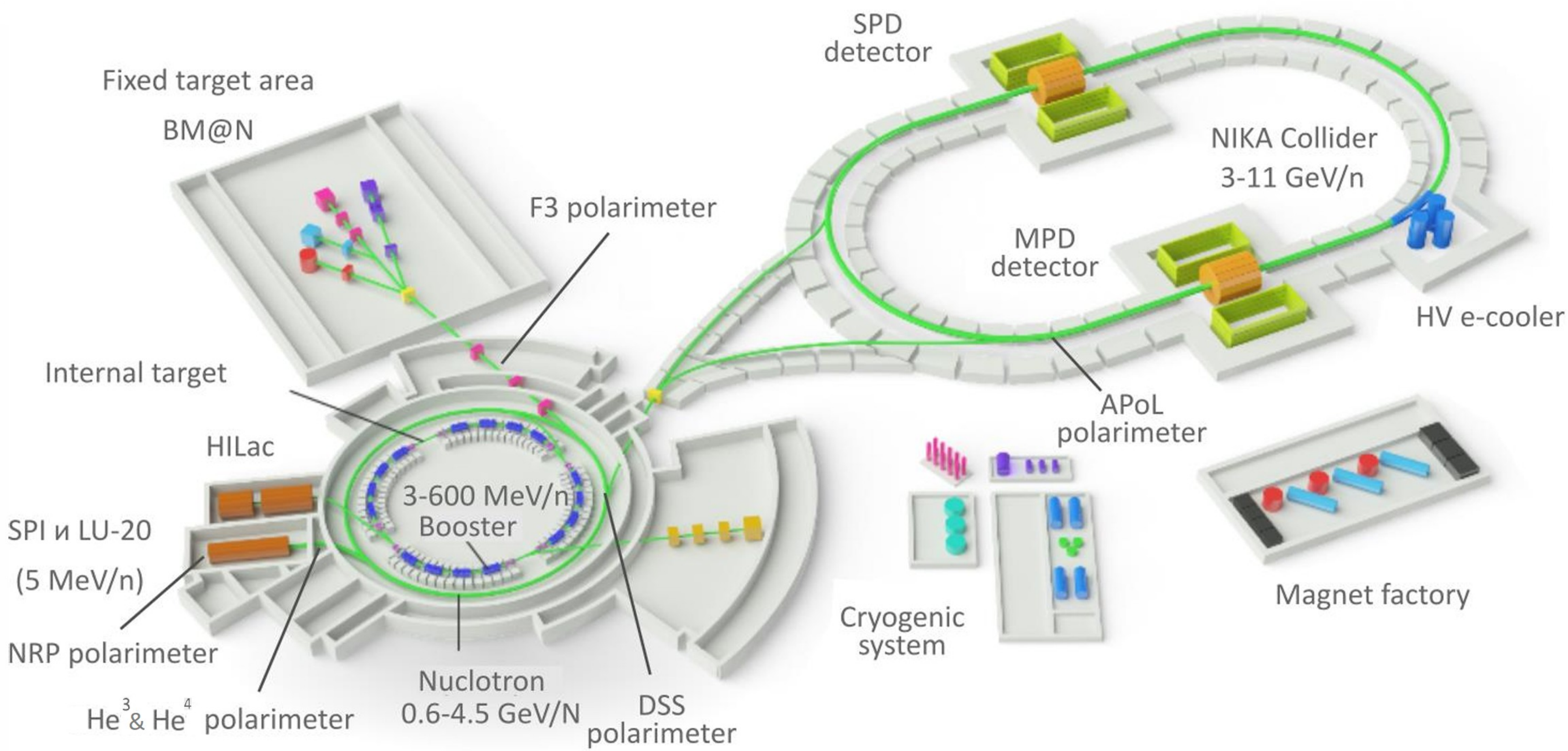
Implementation of the polarization program



Polarization facilities are being developed at the JINR accelerator complex in the framework of the polarization research program under the NICA project

- polarized deuteron and proton source SPI
- SPI low energy and linac output polarimeters
- the absolute polarimeter at the NICA collider

The status of the above facilities and the results achieved are presented

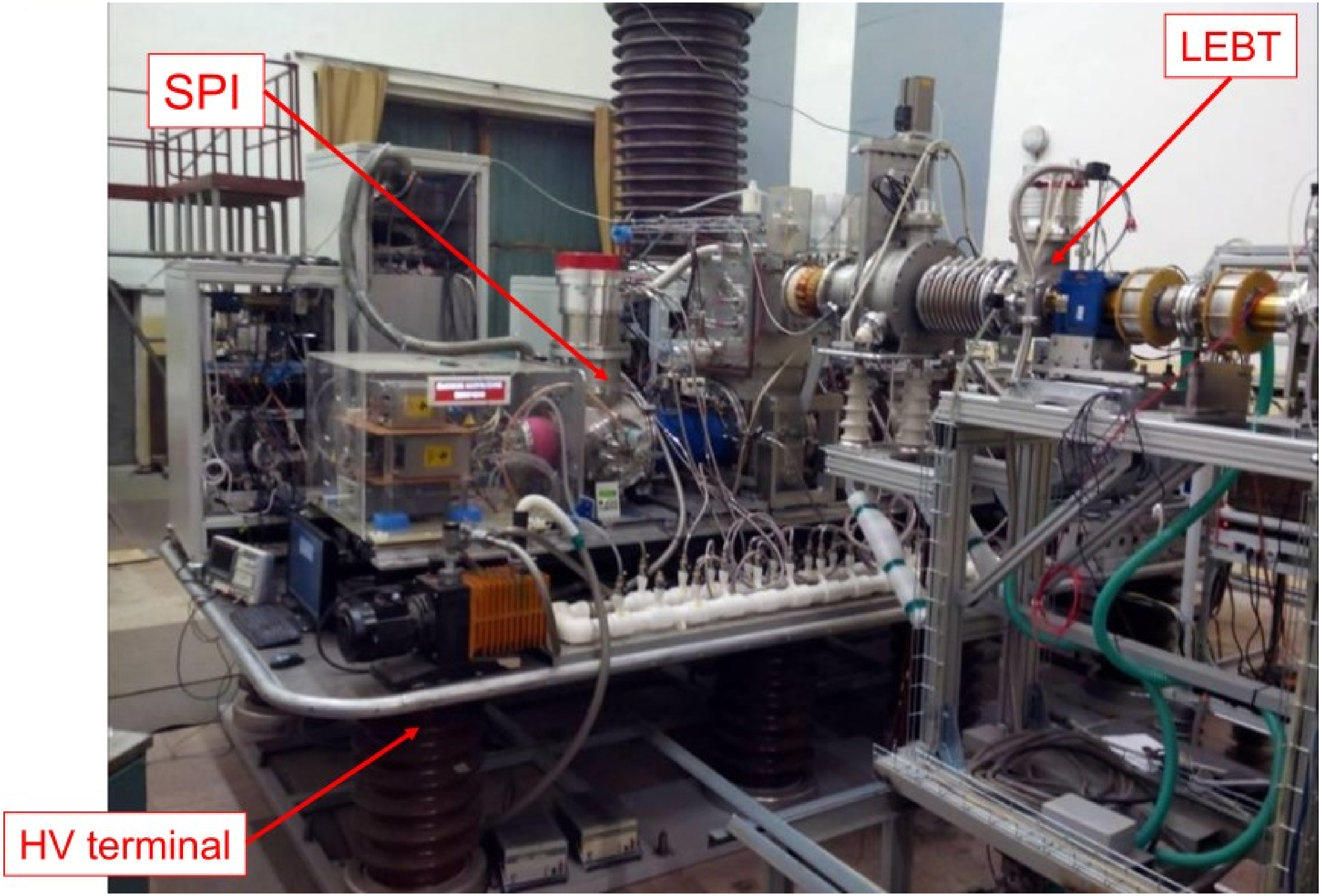
The project is realized <u>in close cooperation with INR of RAS (Moscow, Russia)</u>

Source of **P**olarized **I**ons **(SPI-project)** being developed is a **high-intensity setup of polarized deuterons & protons beams**

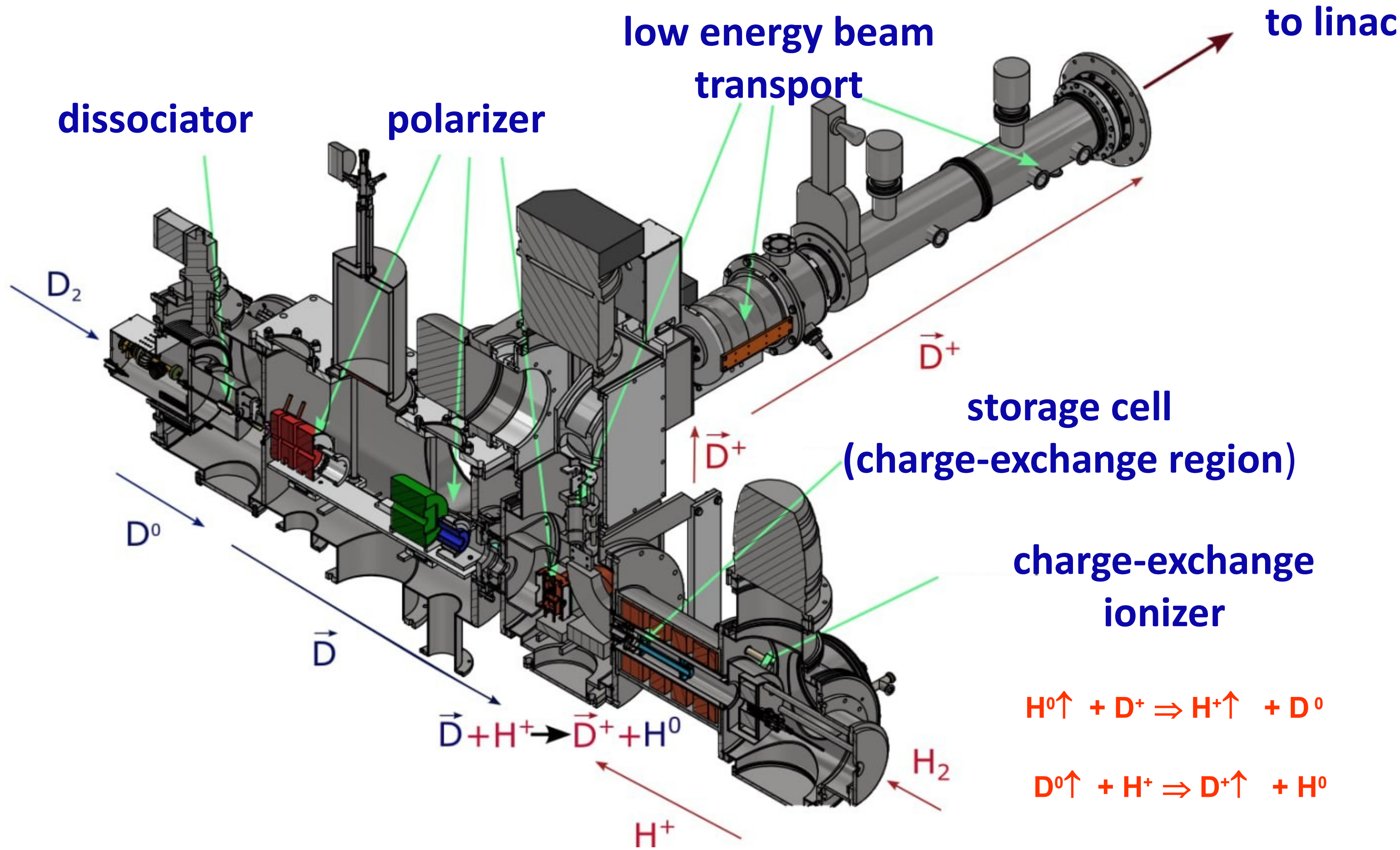
The main purpose of the SPI-project is to increase the intensity of the accelerated polarized beams at the JINR Accelerator Complex up to **$5 \cdot 10^{10}$ d(p)/pulse**

The design output current of the SPI is up to 10 mA for **↑D^+ (↑ H^+)**
The D^+ (H^+) polarization will be up to 90% of the maximal vector (±1) & tensor (+1,-2) polarization

General view at linac preaccelerator hall (operational assembly)



Source of Polarized Ions (SPI)



- Hydrogen (deuterium) atoms are produced in RF discharge dissociator
- The production of an electron polarized atomic beam is done in an inhomogenious magnetic field of three permanent sextupole magnets (polarizer)
- Nuclear polarization is produced by RF transitions units (polarizer)
- Polarized atoms are converted into polarized ions by charge-exchange ionizer
- Polarized ions are transported to linac by low energy beam transport (25 keV)

Polarization facilities at the JINR accelerator complex

NICA

Current SPI equipment upgrade work in 2024–2025

- modernization of the SPI dissociator. The intensity of atomic beams has been doubled (**JINR**)
- multichannel control pulse generator and a complex of automation and protection systems for the SPI source have been developed (**JINR**) and tested for the **SPI** source (**JINR**)
- universal SFT unit with 90% efficiency of RF transitions has been developed and tested for the **SPI** source (**JINR**)
- emittance meter at the output of the SPI source has been developed(**JINR**)
- modeling of the plasma beam formation system was performed (**Budker Institute of Nuclear Physics**)
- electric arc generator for hydrogen and deuterium plasma has been developed and is being tested at the **Budker Institute of Nuclear Physics**
- magnetohydrodynamic (MHD) model of plasma transport inside the SPI ionizer was developed (**MEPhi**)

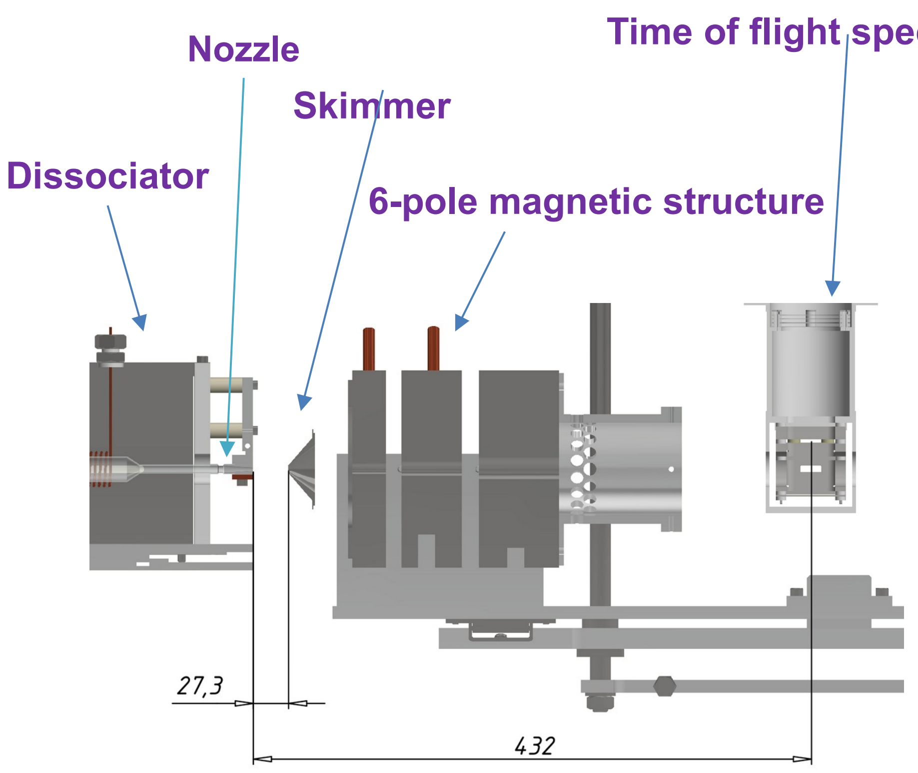
Low-energy polarimetry of polarized protons and deuterons beams

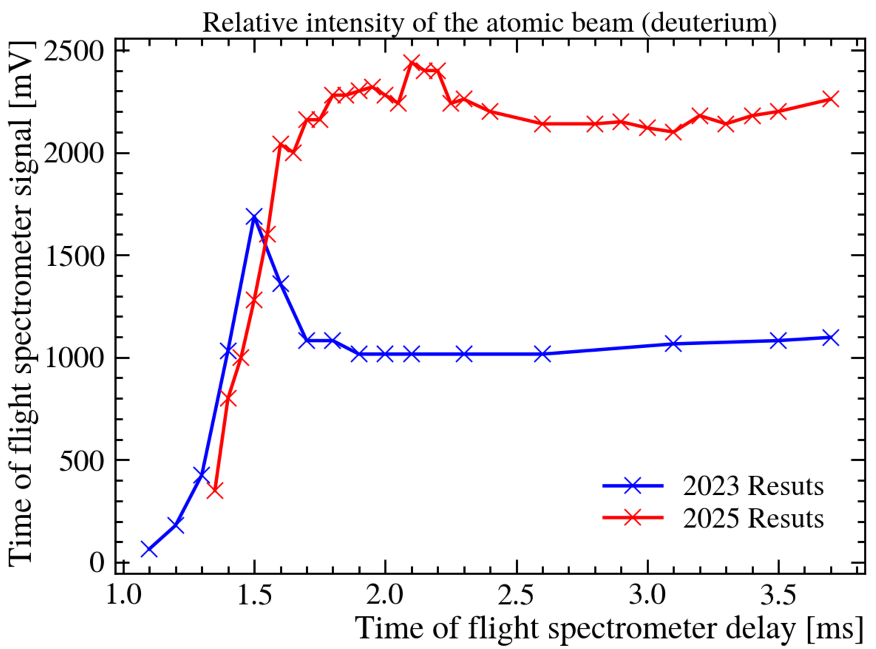
- development of low-energy Nuclear Reaction Polarimeter (**NRP**) for measuring the protons and deuterons beams polarization directly at the exit of the **SPI** source of polarized ions to operate with beam energies from **100 to 150 keV** is being completed (**JINR, MIPT**)

- the development of low-energy **^{3}He & ^{4}He** polarimeters at the output of a linear accelerator (**5 MeV/nucleon p, d polarized beams**) is being completed (**JINR, MIPT**)

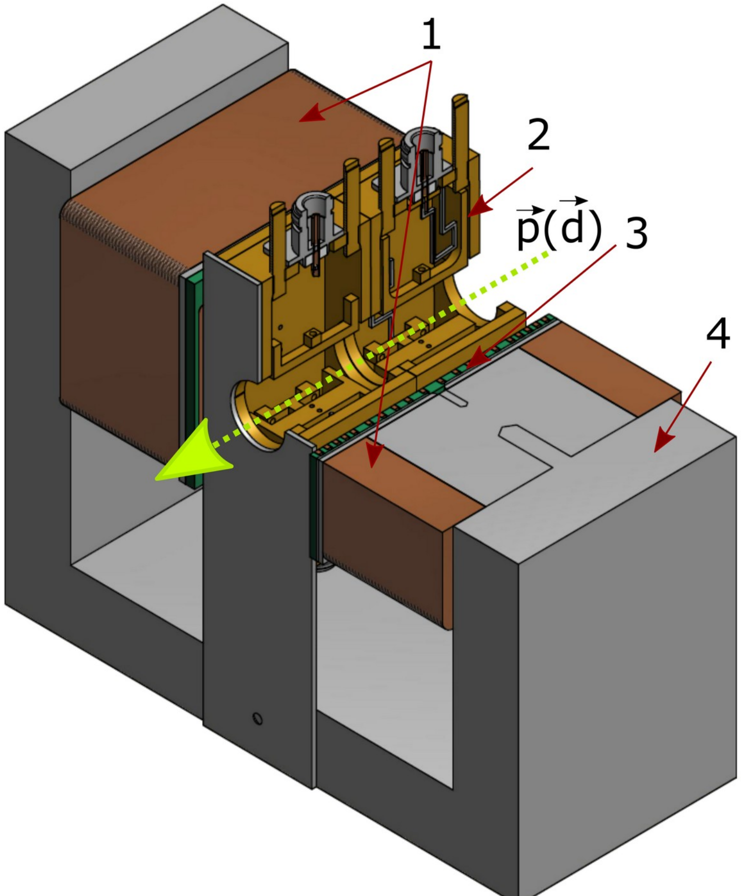
Atomic Beam Source beam tuning progress

the intensity of atomic beams has been doubled

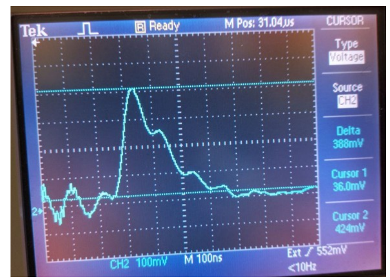




Universal SFT cell



1 - Dipole magnet
2 - RF cell
3 - Gradient Field Coils
4 - magnetic core



ToF signal for hydrogen

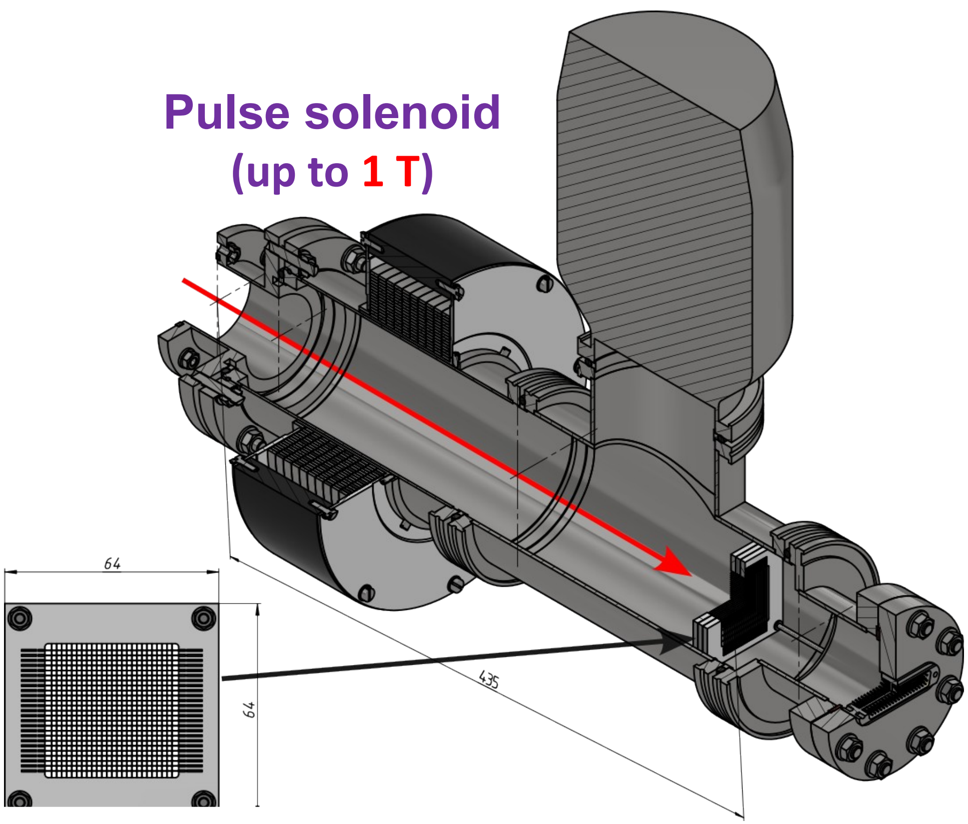
RF cells are switch on

Gas	Transition	Frequency, MHz	Current of the static magnetic field, A	Efficiency %
Hydrogen	SFT 2-4	1431	0.26	95%
Deuterium	SFT 2-6	387	0.18	98%
Deuterium	SFT 3-5	387	0.56	94%

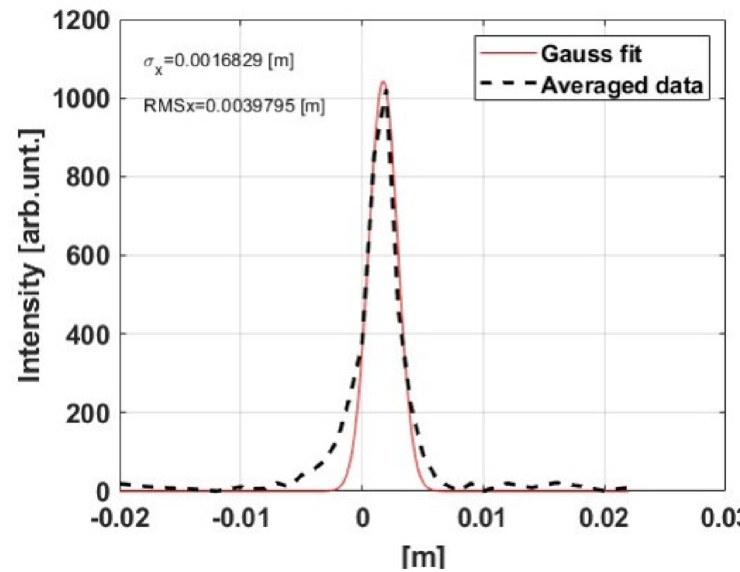
Emittance meter of H_2^+,$D^+\uparrow$,$H^+\uparrow$ beams

Turbomolecular pump

Pulse solenoid
(up to 1 T)



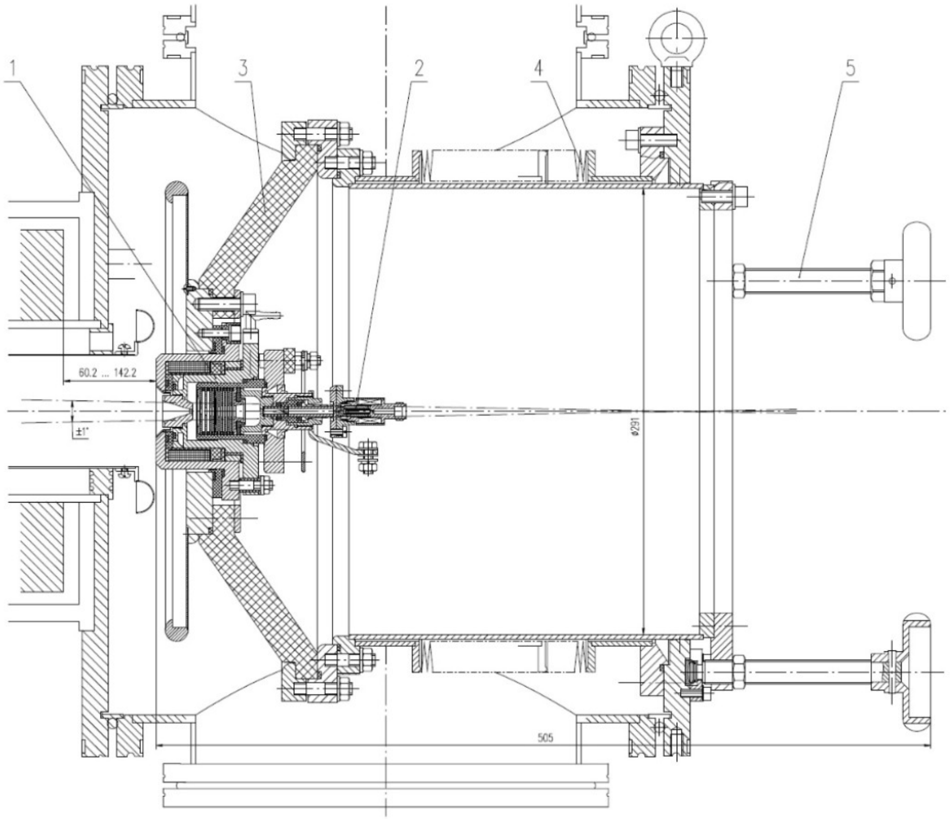
Dual Axis Wire Detector (35x35)



Beam profile taken at HiLAC in 2023
Shpakov V. et al, "Technical note regarding the emittance measurements at HiLAC", 2024

New Arc plasma generator (BINP)

Generation of a plasma jet



General view of the APG suspension unit: ***1 - arc generator, 2 - gas valve, 3 - insulator, 4 - bellows assembly, 5 - adjustment screws***

Arc plasma generator (APG) on bellow insulation assembly:

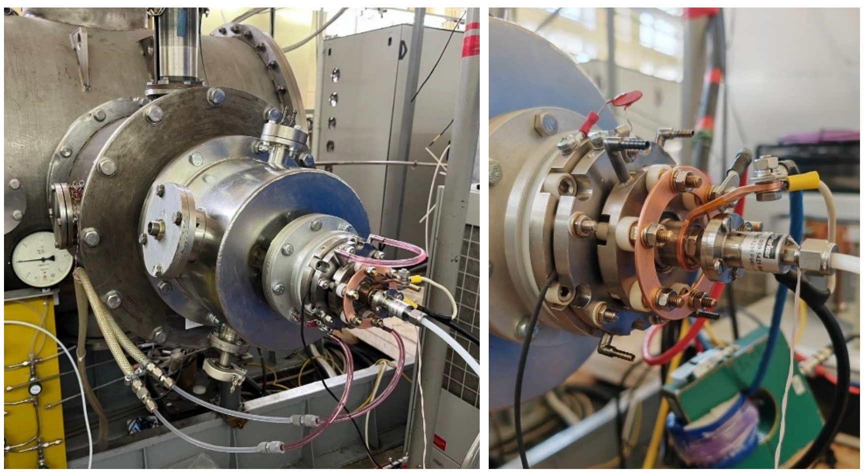
- **The plasma jet is formed by an upgraded arc generator, featuring a wide range of jet cross-section and plasma flow adjustments, along with a high service life**
- **The plasma generator of an injector of fast atom beam developed at the (BINP) was used as a prototype**
- **The plasma generator is a separate unit located outside the vacuum chamber and is accessible for maintenance and replacement**
- **Developed and manufactured is a bellows assembly that allows for 80 mm of axial movement of the APG**
- **The design provides high-voltage insulation up to 45 kV**

Manufactured plasma generators

Arc plasma generator (APG) tests

At the BINP SB RAS testing of the main and auxiliary systems of the arc generator was carried out:

- discharge current from 150 to 500 A
- magnetic field in the discharge channel of about 1 kG
- pulse duration - 1 ms



APG test chamber – on the left
APG with upgraded Parker valve – on the right

The Parker solenoid valve model 009-1421-900 (20VDC) is used as the gas valve
Its standard response time is 2 ms

As a result of the valve modernization, a response time of 200 μs was achieved:

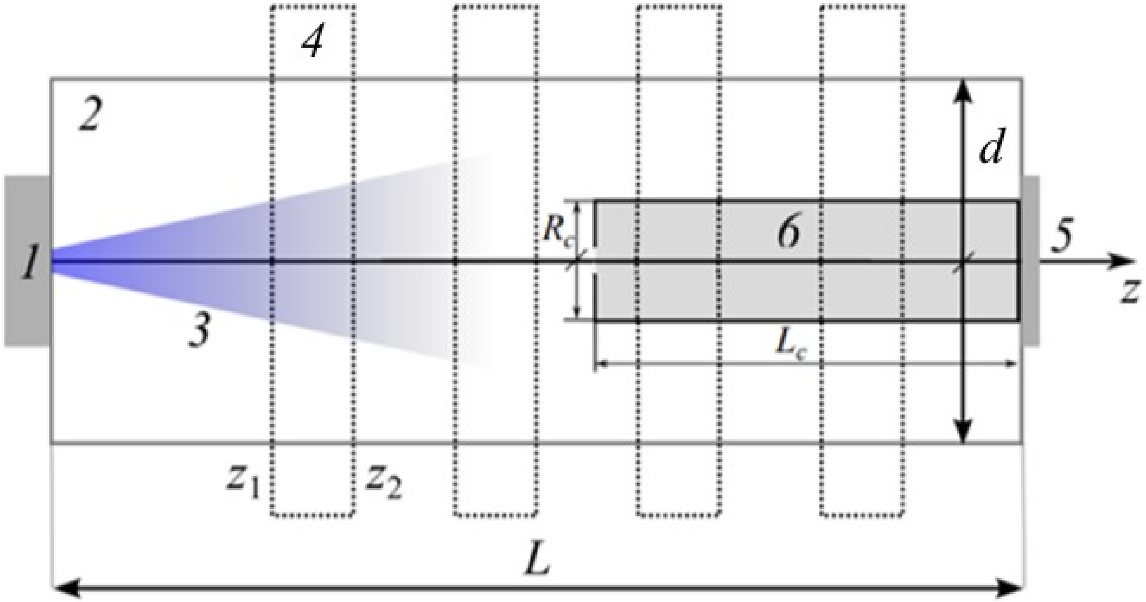
- The valve coil was replaced - inductance and resistance were reduced
- A boosted power system was installed
- The electromagnet armature was lightened by 30%

The time of valve opening was determined by the measurements of the specific features at the current and voltage curve of the valve coil and also by the establishment of electrical contact between the armature and the valve body

Numerical modeling of plasma flow transport from a hydrogen/deuterium plasma generator for the SPI source (MEPhi)

Problem formulation

1. To assess the effectiveness of polarized neutral conversion and extraction, an MHD model of plasma transport inside SPI vessel was developed.
2. The model approximates the SPI vessel geometry including the plasma source, magnetic coils and storage cell installed.



1 – plasma source

2 – vacuum chamber

3 – plasma flow;

4 – magnetic coils

5 – ion optical system (IOS);

6 – storage cell.

Model of plasma transport

Equations governing plasma dynamics are as follows

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{V}) = 0,$$

$$m_i n \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla(p_i + p_e) - 0.71 n \nabla T_e + \omega_{ci} \mathbf{V} \times \mathbf{b}.$$

$$\frac{\partial T_e}{\partial t} + \mathbf{V} \cdot \nabla T_e + (\gamma_e - 1) T_e \nabla \cdot \mathbf{V} = 0.$$

$$\frac{\partial T_i}{\partial t} + \mathbf{V} \cdot \nabla T_i + (\gamma_i - 1) T_i \nabla \cdot \mathbf{V} = 0.$$

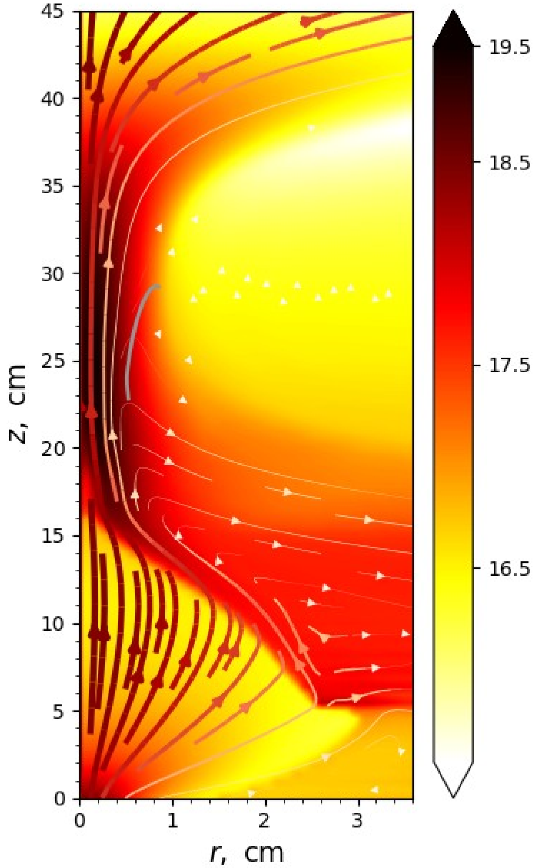
Model is solved numerically with BOUT++ library [Dudson 2009]

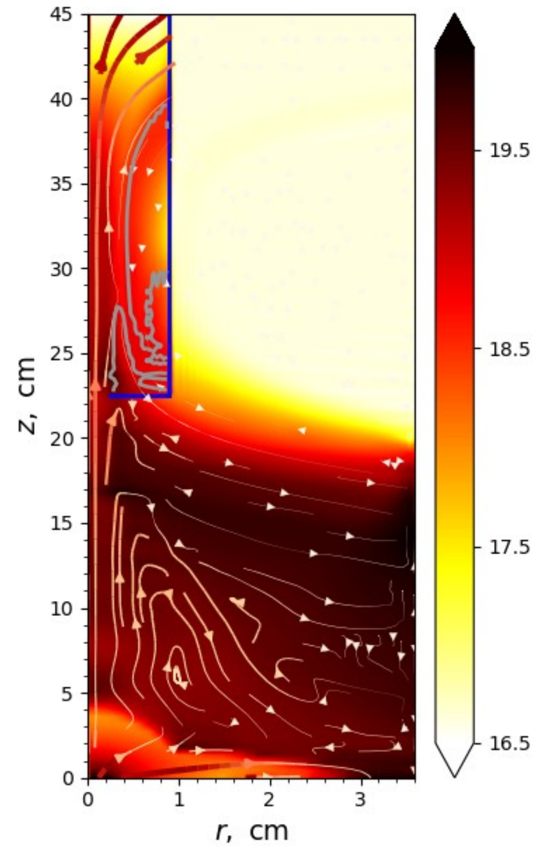
Simulations parameters:

- L = 45 cm, R = 3.6 cm
- Storage cell: L_c = 22.5 cm, R_c = 9 mm
- Extractor aperture: r_{extr} = 1 cm
- Plasma source parameters: $n = 5\times10^{20}$ 1/m^3 , $T_e = T_i$ = 5 eV, V_z = 60 km/s
- Ambient plasma parameters: $T_{amb} = 3\times10^{-2}$ eV, $n_{amb} = 4.2\times10^{16}$ 1/m^3
- Ions are adiabatic, electrons are isothermal

Plasma dynamics w/o vs w/storage cell

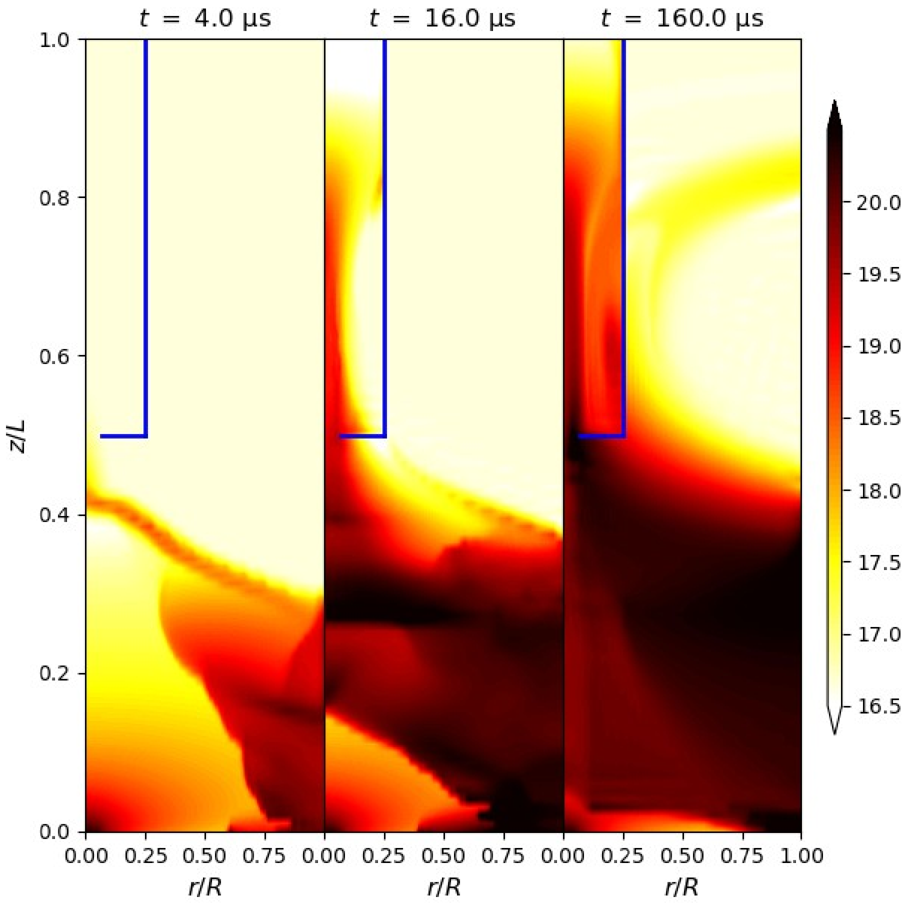
- Plasma accumulates in the vicinity of the magnetic mirror, **counterflow forms**
- Upon passing the bottleneck, **plasma expands freely**
- In the IOS vicinity the **plasma density is reduced**, injected polarized **neutrals** can **freely expand** inside vessel → **low conversion effectiveness**





- Plasma accumulates in the vicinity of the magnetic mirror **inside the storage cell, counterflow also forms**
- Upon passing the bottleneck, **plasma jet is confined**
- Inside the storage cell, the **plasma density is increased** polarized **neutrals** are **confined** to the small physical space **→ high conversion effectiveness**.

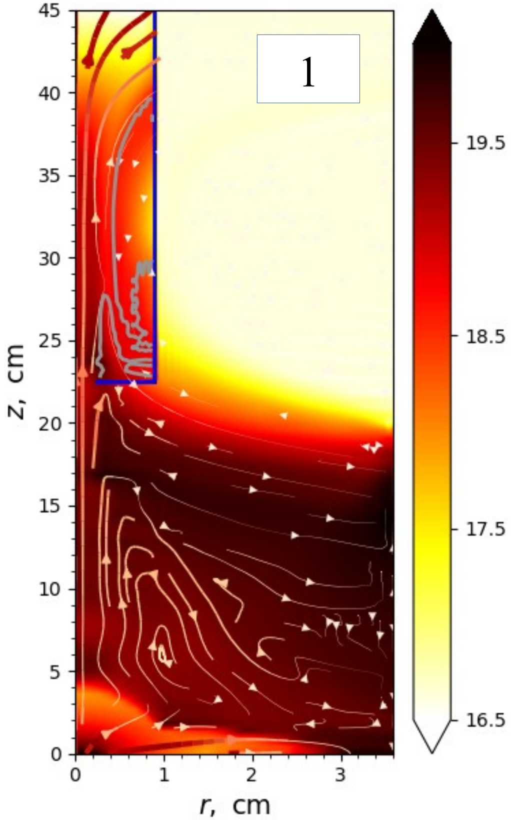
Temporal plasma dynamics

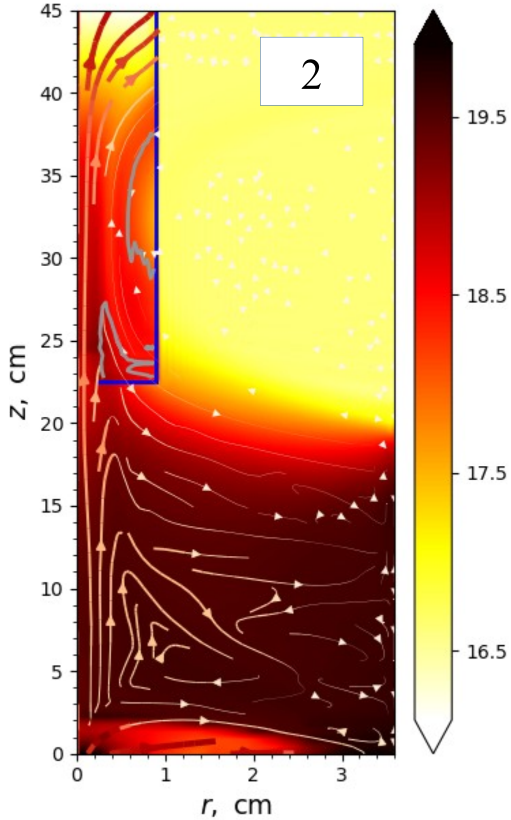


1. Plasma accumulation at the entrance into the magnetic mirror, at the storage cell face, during the initial pulse phase
2. The storage cell begins to fill with plasma once plasma starts leaking through the magnetic mirror
3. Formation of the homogeneous ion distribution inside the cell at the pulse end must lead to the more efficient conversion of the polarized neutrals

Scan through experimental cases

Mag. conf.	Non-polar. ion, $<I_{IOS}>$, mA	Non-polar. ion, $<N>$, 10^{17} part.	Polar. exper. I_{pol}, mA
1	265	7	3.68
2	312	8.6	3.2
3	369	7.3	3.16
4	564	8.9	2.36
5	427	-	2.22
6	267	13.0	2.14





- Clear anti-correlation of $<I_{IOS}>$, $<N>$ vs experimental values of polarized ion current, $\boldsymbol{I_{pol}}$.
- Such a behavior can be potentially attributed to polarized particles trapping inside the storage cell with the increase of **$<N>$**

Note:

Resolving the issue requires incorporation of neutral particle physics

Conclusions

Magnetohydrodynamic (MHD) model of plasma transport inside the SPI ionizer was developed

By using this model, peculiarities of plasma transport were analyzed:

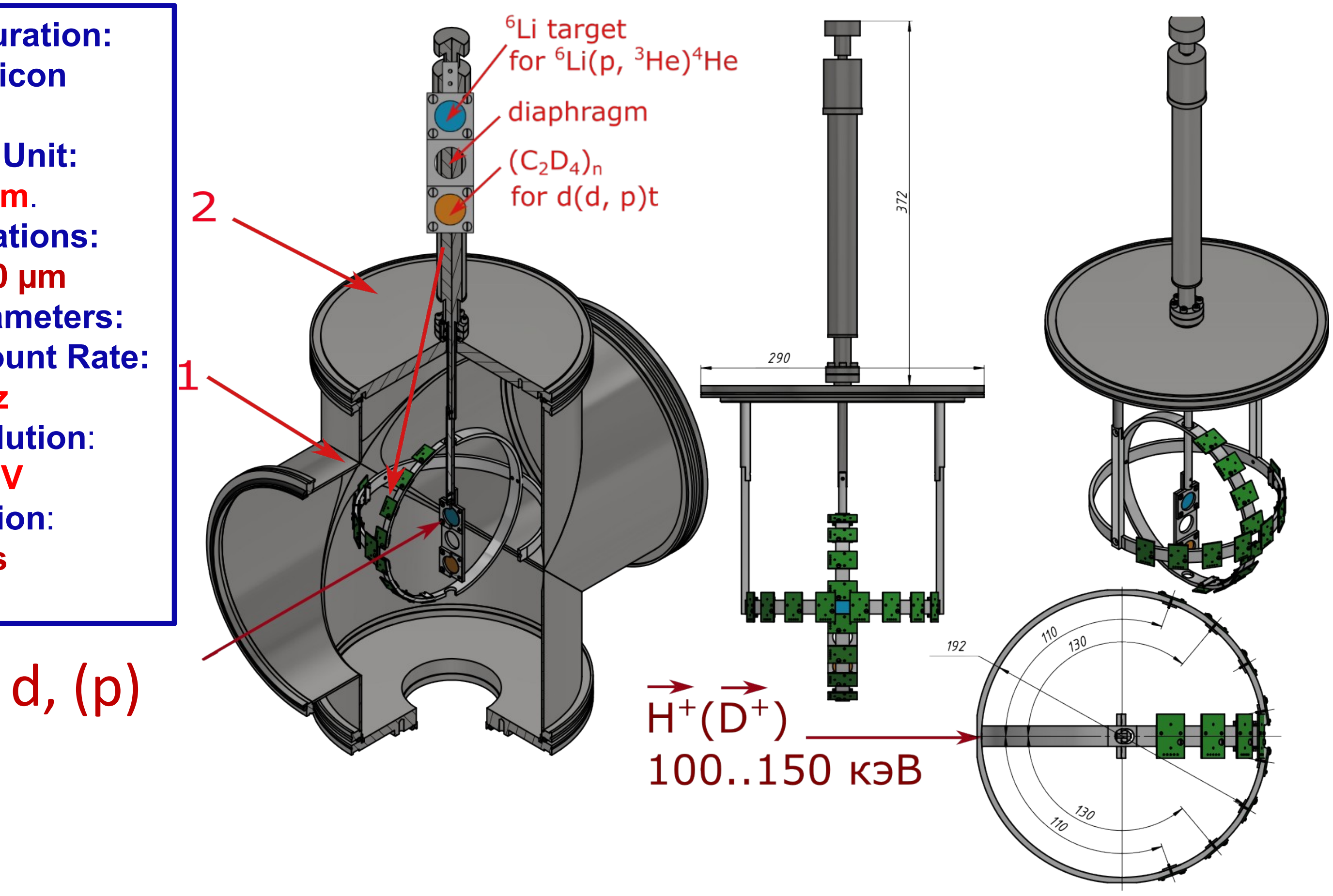
- plasma flow passing through the magnetic mirror is partially reflected backwards, forming the counterflow at the storage cell entrance
- the strong radial expansion of the jet passing through the magnetic mirror region leads to the reduction of the plasma density in the vicinity of the extractor, reducing the conversion / extraction effectiveness
- the installation of the storage cell is required to sustain high density of polarized neutrals and to confine the ionization region to a small physical volume located near the ion extraction system

Direct assessment of the neutral extraction effectiveness requires incorporation of the physics of neutral-plasma interactions

SPI Nuclear Reaction Polarimeter (NRP)

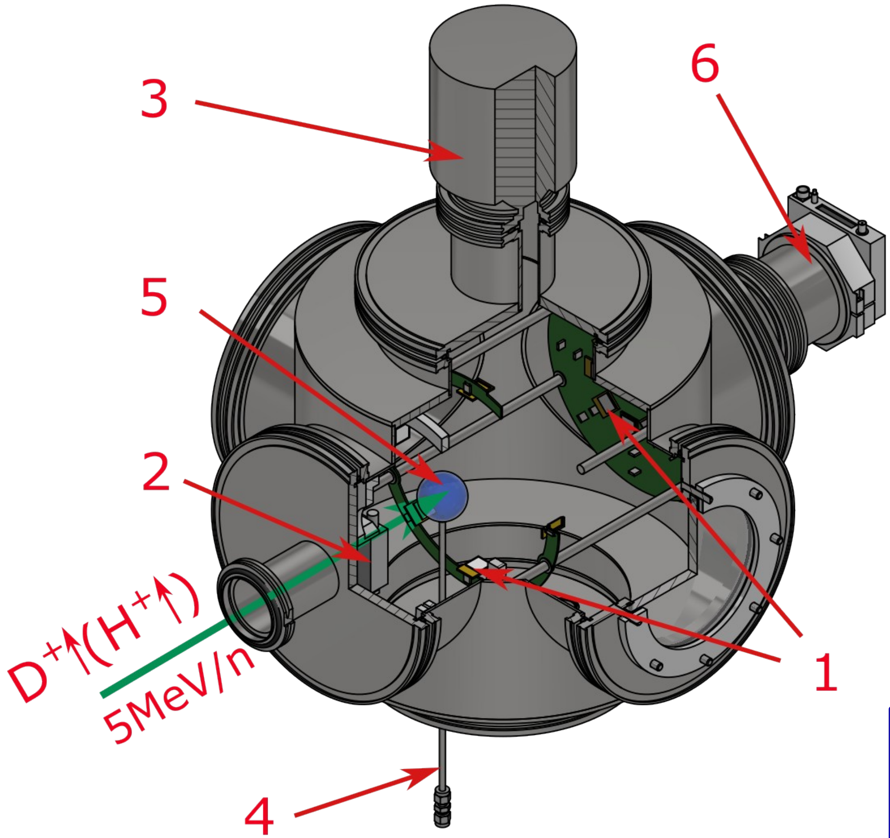
Detector Configuration:

- **1 - array of 16 silicon detector units**
  active Area per Unit:
  5 x 20 mm.
  sensor Specifications:
  - thickness: **300 μm**
  Performance Parameters:
  - **maximum Count Rate:** **2 MHz**
  - **energy Resolution**: < **30 keV**
  - **time Resolution**: **500 ns**
- **2 – manipulator**



Low-energy polarimetry of polarized protons and deuterons beams

Linac ^{3}He & ^{4}He Polarimeter (first version)



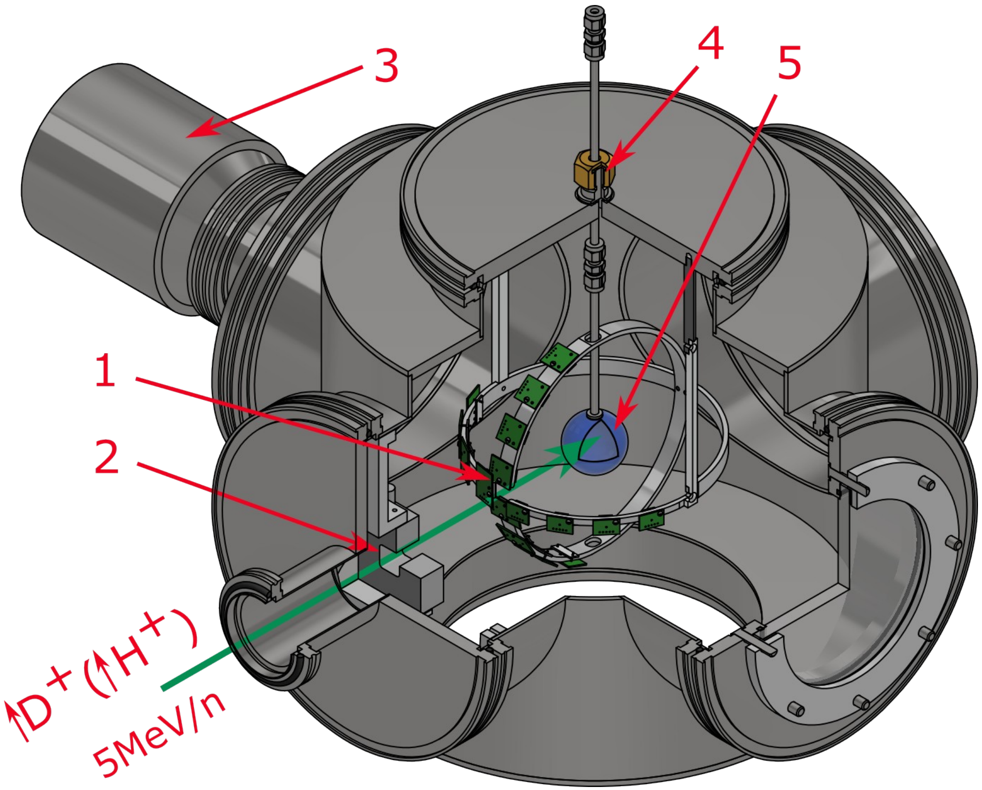
The experimental setup includes:

1 - array of 16 silicon detectors with the active area of 20x20 mm each
2 - variable diaphragm
3 - turbomolecular pump
4 - gas inlet system
5 - high-pressure (3 bar) mylar spherical target (150 µm) filled with gaseous ^{3}He or ^{4}He
6- electronic box

- **Detector Configuration:**
- array of 16 silicon detector units
- **active area per unit: 20 x 20 mm**
- **Sensor Specifications:**
  - Thickness: **300 µm**

Low-energy polarimetry of polarized protons and deuterons beams

Linac ^{3}He & ^{4}He Polarimeter (second version)



The experimental setup includes:

1 - array of **16** silicon detectors with an active area of **5x20 mm** each
2 - variable diaphragm
3 - turbomolecular pump
4 - gas inlet syste
5 - a high-pressure (**3 bar**) mylar spherical target (**150 μm**) filled with ^{3}He or ^{4}He

The polarimeter operates by detecting protons at approximately 32° and alpha-recoil particles at around 132°, generated from the ^{3}He(d, p)^{4}He reaction https://dx.doi.org/10.1016/0029-554x(80)90946-5

- **Detector Configuration:** An array of 16 silicon detector units.
- **Active Area per Unit: 5 mm x 20 mm.**
- **Sensor Specifications:**
  - Thickness: **300 μm**
- **Performance Parameters:**
  - Maximum Count Rate: **2 MHz**
  - Energy Resolution: < **30 keV**
  - Time Resolution: **500 ns**

NICA Absolute Polarimeter current status

- Preliminary tests of the dissociator and atomic beam source have been conducted
- The intensity of the atomic hydrogen beam is about **$7 \cdot 10^{16}$** atoms/s, with a dissociation degree of **80%**
- A universal MFT nuclear polarization cell for the absolute polarimeter has been developed and manufactured
- A system for measuring the intensity of atomic beams has been developed for the absolute polarimeter

Note

Coordination of the location of the polarimeter in the ring is required
Final design of the interaction region is an open question up to now
It is sufficient to measure the vector polarization for polarized protons and deuterons for the Apol main tasks

NICA Absolute Polarimeter

To measure absolute values of proton or deuteron polarization at NICA collider rings an Absolute Polarimeter **APol** with the internal polarized atomic hydrogen/deuterium jet target is being built

APol consists of:

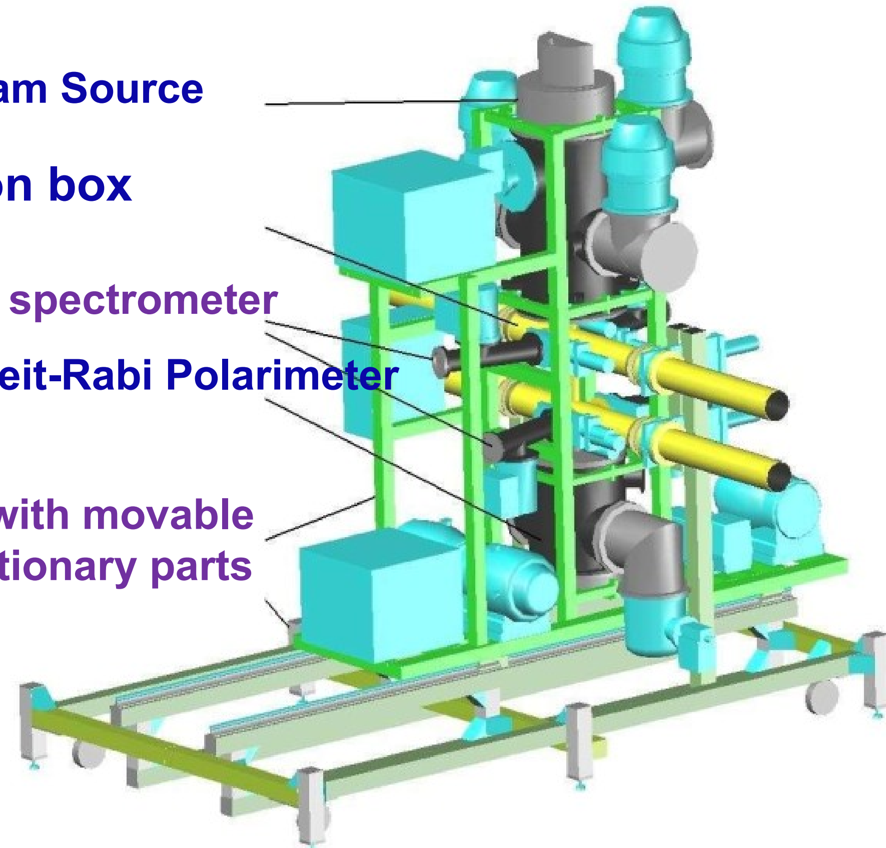
Atomic Beam Source

Interaction box

Four- arm spectrometer

Jet catcher&Breit-Rabi Polarimeter

Frame with movable and stationary parts



APol 3D view

Main tasks for Apol

- beam polarization testing in tuning of the **NICA** polarization control system

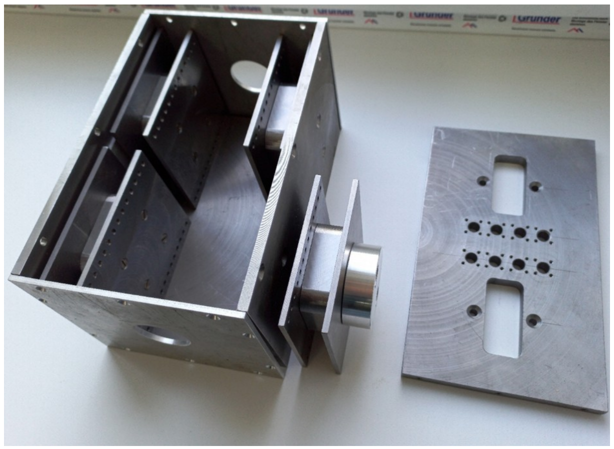
- determination the effect of disturbing **NICA** Collider devices on beam polarization

- monitoring the degree of beam polarization during operation of the **NICA** Collider

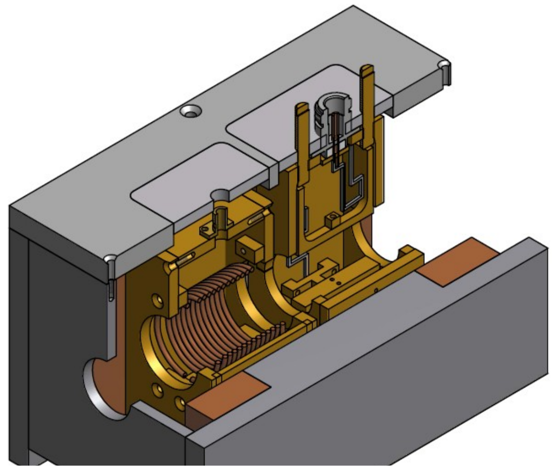
Main operational parameters of APol

- steady operation mode
- throughput of H_2/D_2
  Q = 1 torr·l/s = $3.4 \cdot 10^{19}$ molecule/s = $6.8 \cdot 10^{19}$ atom/s
- nozzle temperature T_N=80°K
- speed of nozzle outflow (=speed of sound):
  for hydrogen - $c_H=(\gamma k_B T/m_H)^{0.5}$ = 1 km/s
  for deuterium – $c_D=(\gamma k_B T/m_D)^{0.5}$ = 0.75 km/s
- Mach number in atomic beam M=2.9
- most probable velocity for atomic beam velocity distribution:
  for hydrogen – 1940 m/s
  for deuterium – 1370 m/s
- beam temperature (=width of velocity distribution) T=23°K
- pole tip magnetic field of Nd-Fe-B sextupole magnets B_0=1.5T
- atomic beam intensity in the interaction region – 10^{17} atom/s
- target thickness of the atomic beam in the box – 10^{12} atom/cm

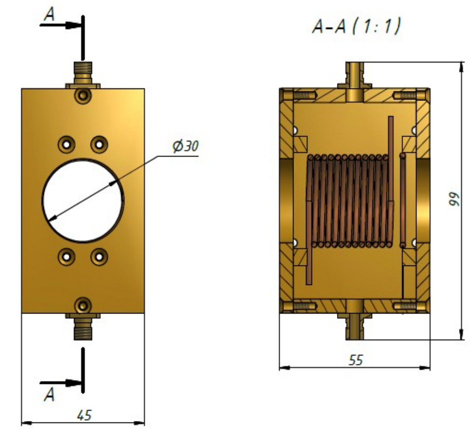
Universal MFT cell (APol)



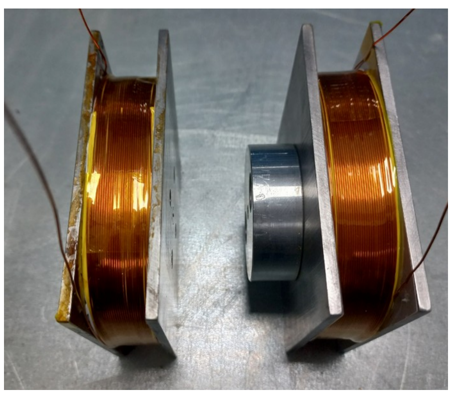
Magnetic yoke



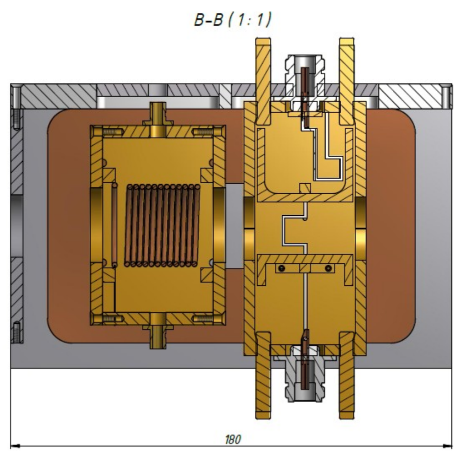
MFT cell model

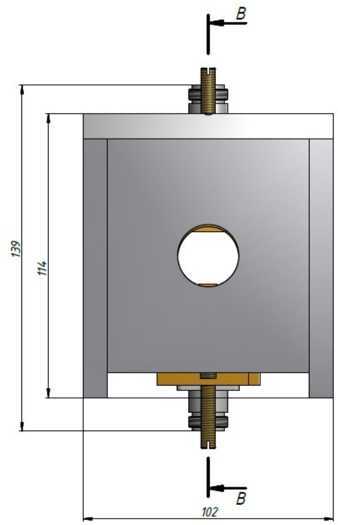


Resonator model



Static magnetic field coils

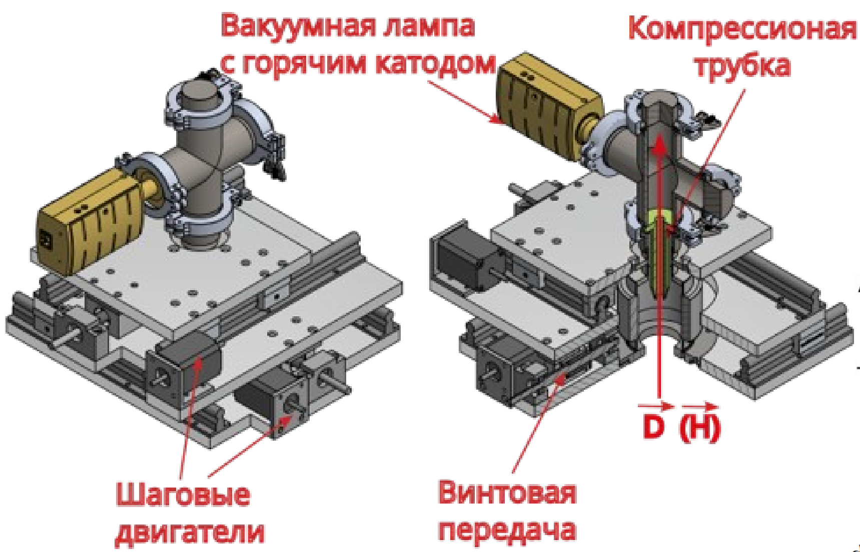


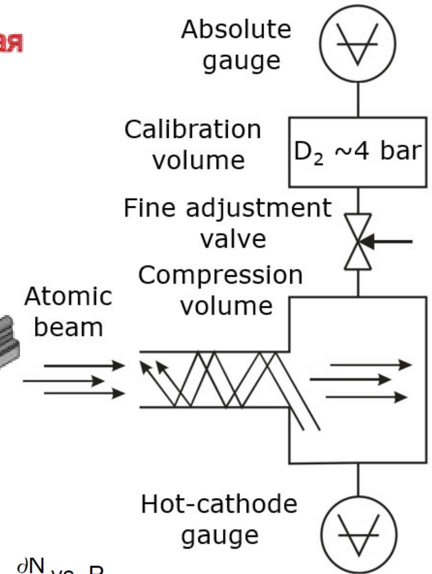


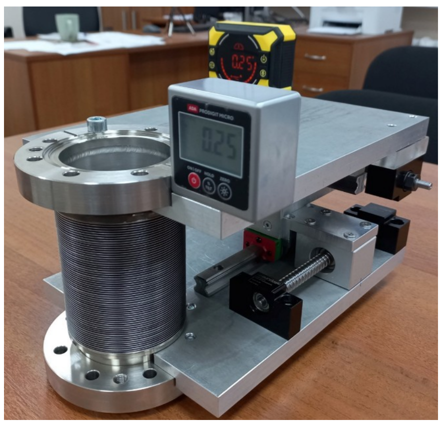
Atomic Beam Intensity Meter

$$\frac{\partial N_{D_2}}{\partial t} = \frac{V_{cal} \cdot \mu_{D_2}}{m_{D_2} \cdot R \cdot T_{cal}} \cdot \frac{\partial P_{cal}}{\partial t}$$

Formula for calculation





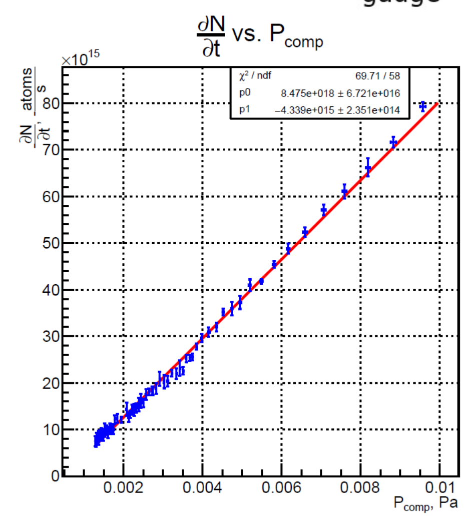


Two-axis manipulator

B-RAX 3400 Controller

BA 601

Calibration volume



Example of a calibration curve

Future Prospects

- Development of a new version of the transverse injection atomic beam **SPI** source (**JINR, INR RAS, MIPT**)

To achieve higher parameters of the polarized ion source (**SPI**) it is proposed to utilize the effect of an increased thickness of the charge-exchange target during transverse injection of a beam of polarized atoms into the stocell of a plasma charge-exchange ionizer

- Proposal for the development of an optically pumped polarized ion source for $^{3}He^{++}$ (**JINR, INR RAS, MIPT**)

To obtain a beam of polarized $^{3}He^{++}$ ions with high intensity, it is proposed to inject polarized gas ^{3}He (using the Metastability Exchange Optical Pumping, MEOP method) into an EBIS (Electron Beam Ion Source) for ionization and accumulation of $^{3}He^{++}$ ions (the high magnetic field of **~5.0 T** in the source should preserve the polarization during ionization)

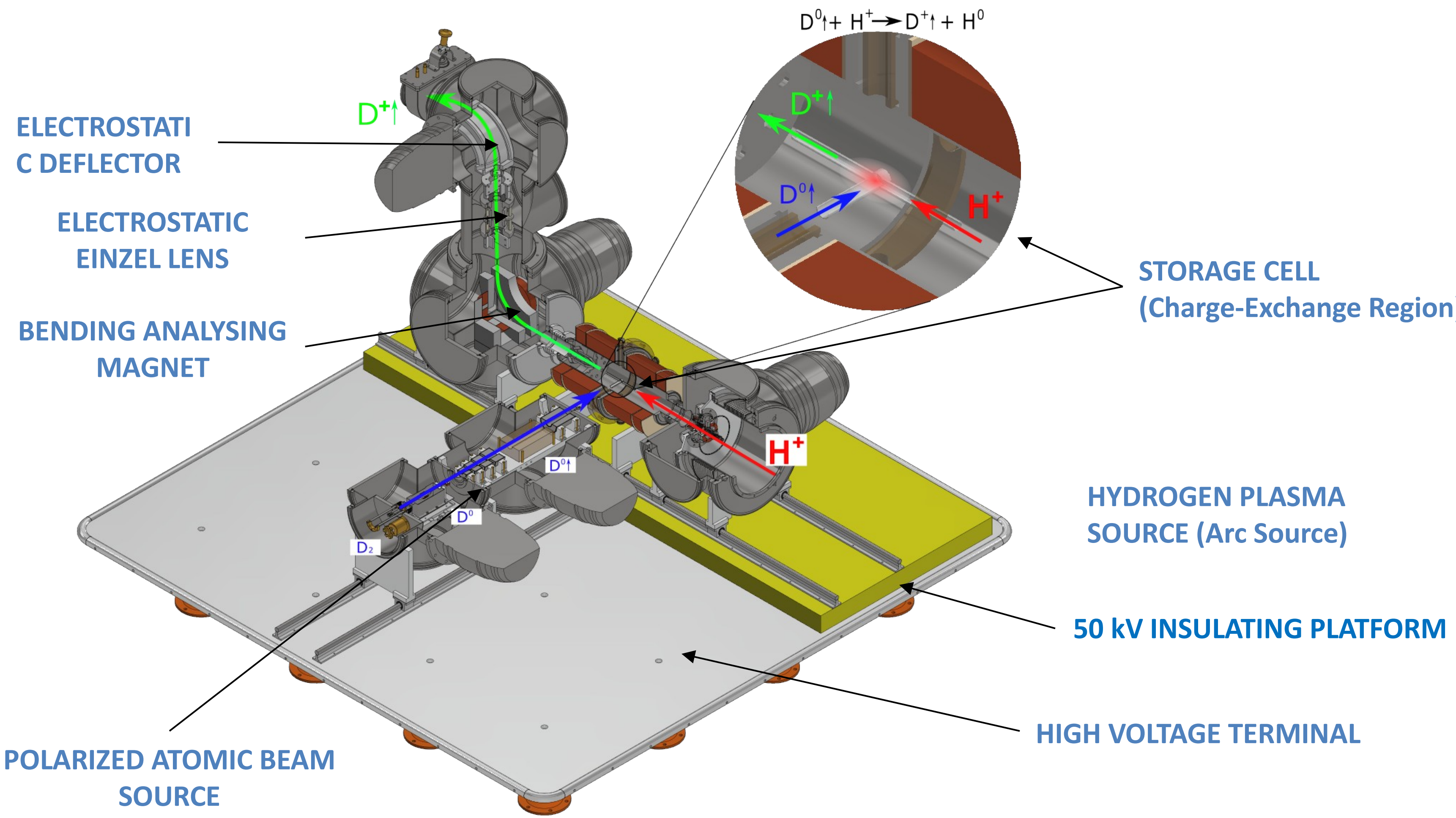
SPI source update

- The use of transverse injection into a T-shaped storage cell in a charge-exchange plasma ionizer makes it possible to reduce the emittance of polarized ion beams by transitioning to a single-aperture ion-optical system and reducing the emission surface radius in the plasma electrode of the ion-optical system
- It is possible to increase the magnetic field in the storage cell **~250 mT**, which leads to higher polarization of the generated beams of polarized protons and deuterons by suppressing depolarization from collisional and spin-exchange relaxation
- An increase in polarized ion beam intensity is anticipated, resulting from raising the accelerated beam energy in the ion-optical system to **45 keV**
- The resulting increase in the beam quality factor from the source - **$P^2 \cdot I/\mathcal{E}m^2$** by approximately an order of magnitude is of substantial importance for achieving the design luminosity of polarized proton and deuteron beams in the NICA collider

Note:

- *Testing of the method with transverse injection of the atomic beam and the T-shaped storage cell will be carried out at the **INR RAS***
- *The basic components of the test bench (**JINR**) will be used for a future source of polarized deuterons and protons with a transverse scheme*

Preliminary configuration of a test bench with transverse injection of an atomic beam (JINR version)



Polarized 3He^{++} ion source

- In the source of polarized $^{3}He^{++}$ ions, ^{3}He atoms are polarized by the method of optical pumping (**MEOP**) in a glass cell at a pressure of **1–10 mbar** in an electron beam ion source (**EBIS**) with a magnetic field of **5.0 T** inside the solenoid

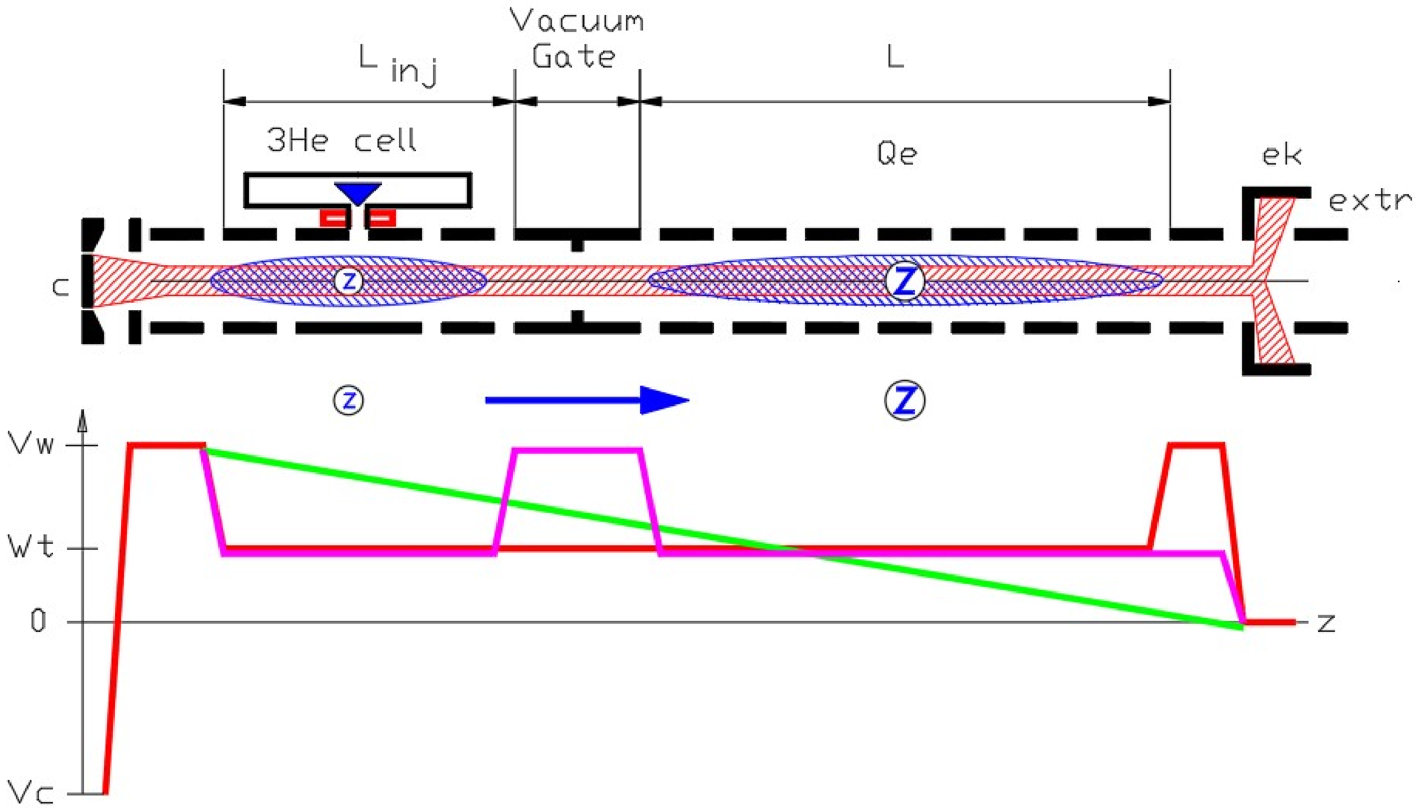
- Subsequently, the polarized **3He** is introduced into the **EBIS** drift tube for ionization and accumulation

- A high (**90%**) nuclear polarization of **3He** was achieved in the strong **3-5 T** magnetic field during the **MEOP** process

- It is proposed to develop a new ion source (based on the **BNL EBIS** prototype)
- In the **EBIS, 3He^{++}** ions can be produced and accumulated in the **EBIS** trap region with an effective length of **100 cm** and a total charge of about **10^{12}** (for a **10 A** electron beam current)

Conceptual framework of an electron-l m ion source for producing polarized 3H

Electron beam focusing for creating an ion trap with a capacity > 5×10^{11} elemen charges



Conclusions

Modernization of the **SPI** source to improve its basic parameters will continue in 2026 (**JINR, BINP SB RAS, INR RAS**)

Numerical modeling of the process of transporting a plasma flow from a hydrogen (deuterium) plasma generator in the **SPI** source will continue (**MEPhI, JINR**)

Work on low-energy polarimeters at the output of the **SPI** source will continue in collaboration with **MIPT**

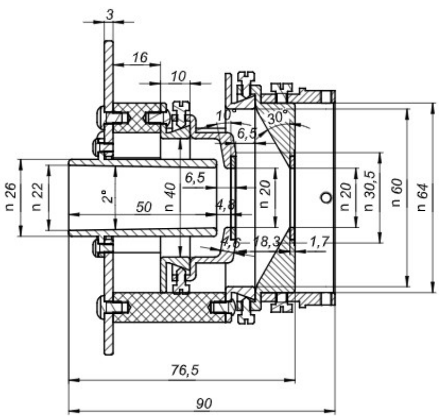
A docking of the **SPI** source with the linear accelerator is planned to measure the polarization of a deuteron beam with an energy of up to **5 MeV/nucleon**

In 2025-2026, the creation of a test bench with transverse injection of polarized atomic beams into the storage cell of the charge-exchange ionizer will begin (**JINR, IAP RAS, MIPT**)

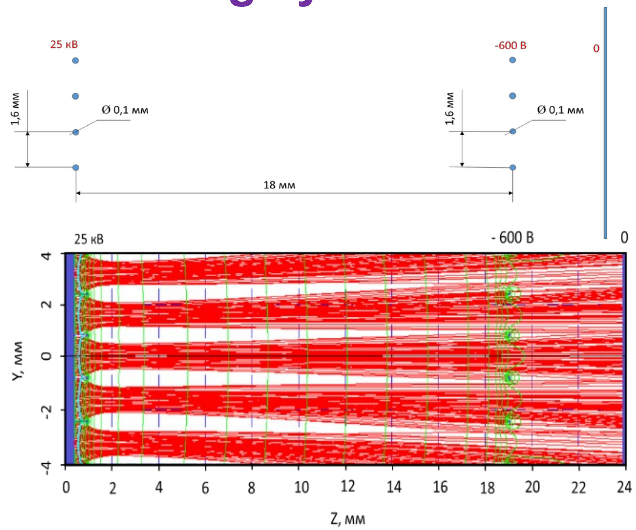
The concept of a **3He^{++}** ion source for the **NICA** collider will be further developed (**JINR, MIPT, INR RAS**)

Thank you

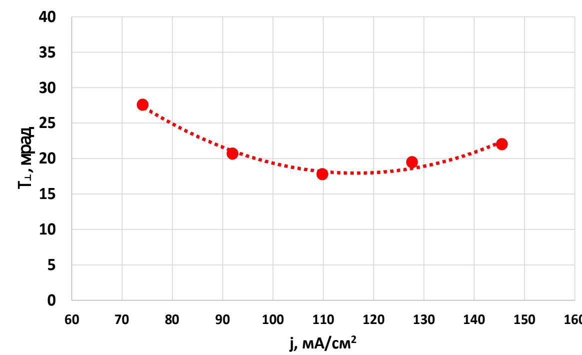
Beamforming system simulation



Three-electrode IOS design



Geometry of IOS (top), deuteron trajectories in IOS, PBGUNS code for 5 cells (bottom)



Estimated angular divergence vs. emission current density
Optimum - 18 mrad at 110 mA/cm²

Methods for improving beam characteristics:

1. The use of a 4-electrode system (instead of a 3-electrode system) makes it possible to double the optimal current density to ~200 mA/cm² at an angular divergence of 10 mrad
2. The use of square-cell electrodes in a 3-electrode system improves the divergence across the wires by a factor of two and increases the potential barrier for electrons

First electrode with a square grid