# Polarization facilities at the JINR accelerator complex

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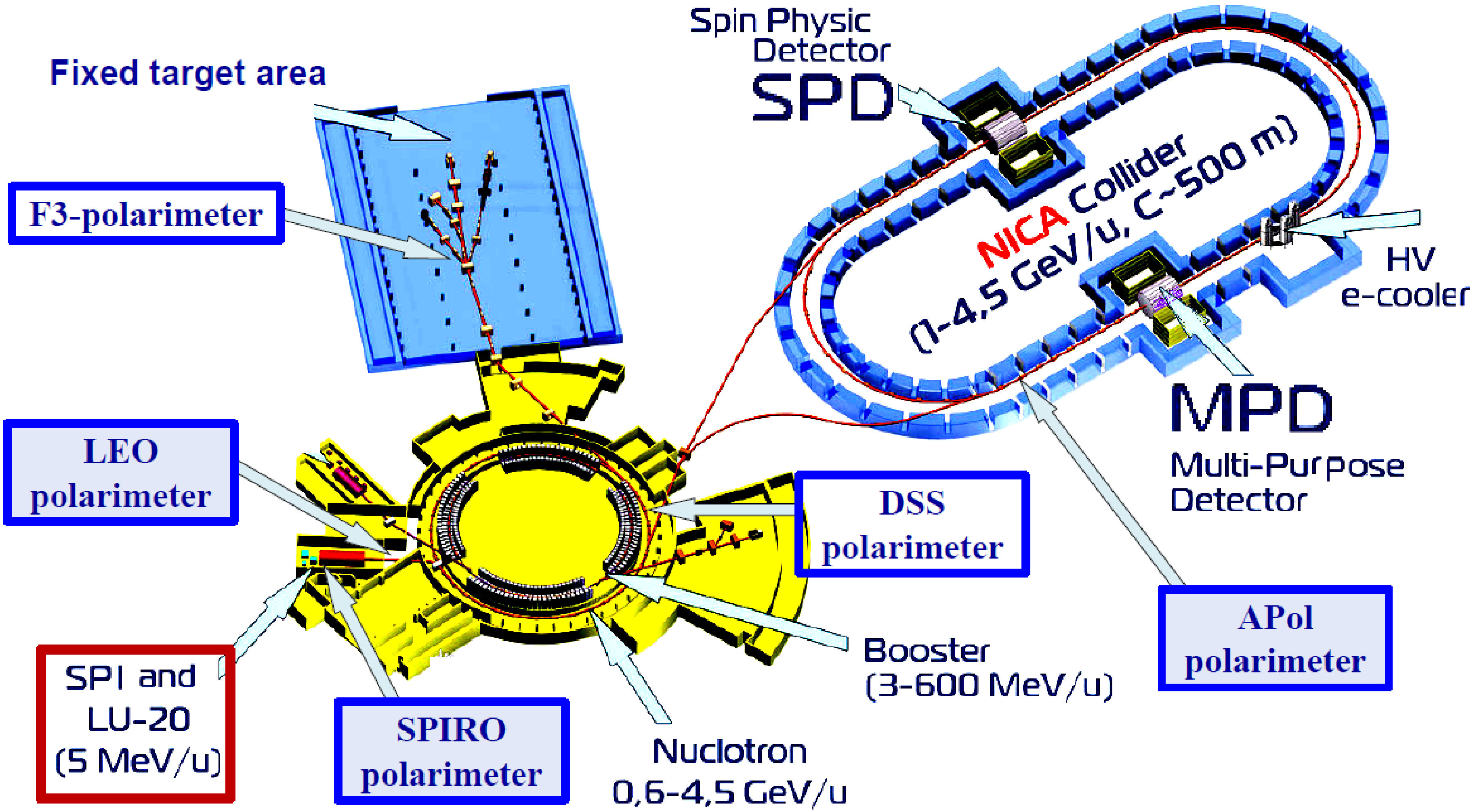
Polarization facilities are being developed at the JINR accelerator complex in the framework of the polarization research program under the NICA project. Those are the polarized deuteron and proton source SPI, SPI low energy and linac output polarimeters, and the absolute polarimeter at the NICA collider. The status of the above facilities and the results achieved are presented.

# Implementation of polarization program




**Physics with polarized light ion beams is considered as an important part of the NICA program**

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

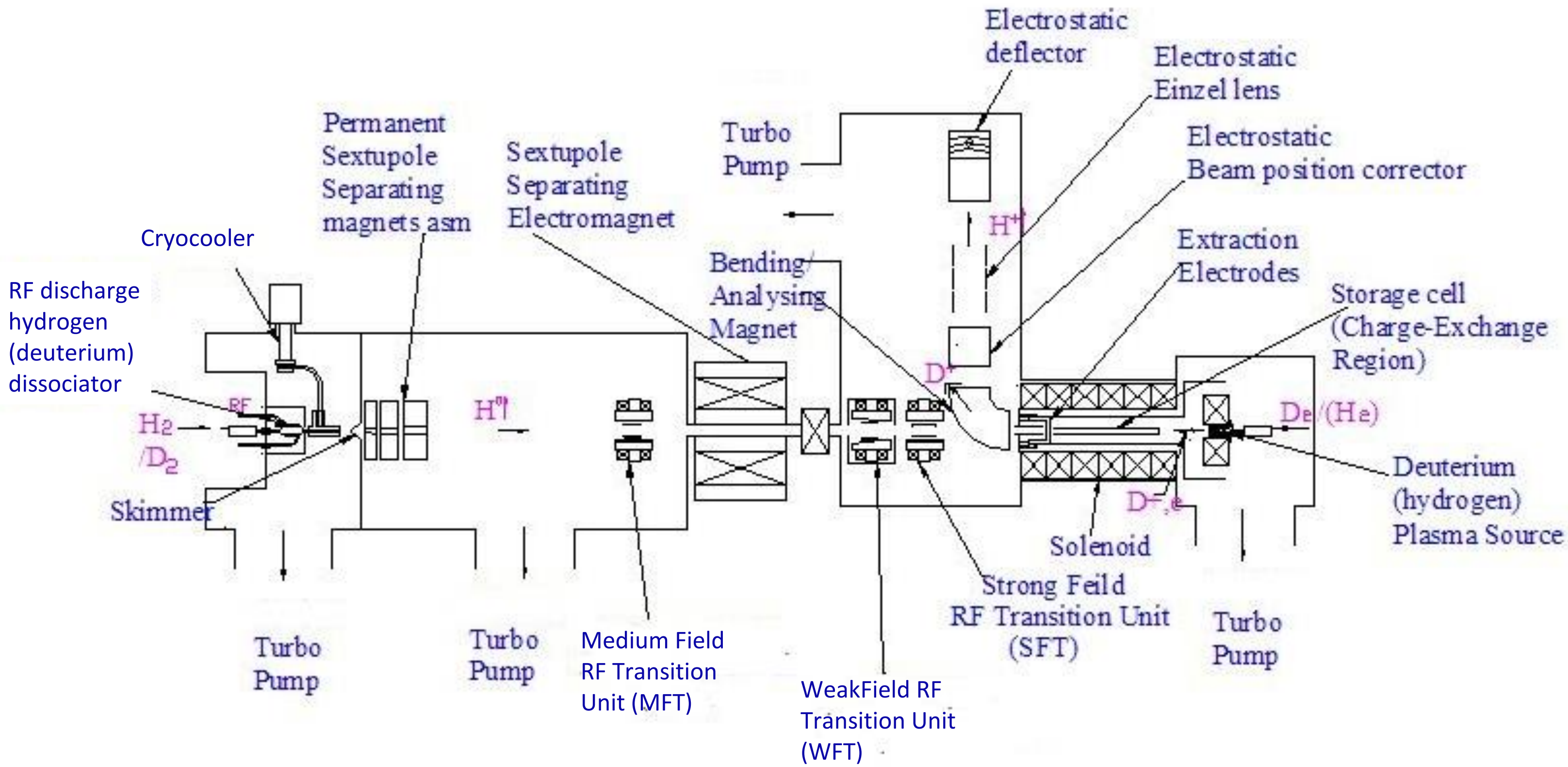
The main purpose of the SPI-project is to increase the intensity of the accelerated polarized beams at the JINR Accelerator Complex up to **$5 \cdot 10^{10}$ d(p)/pulse**

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

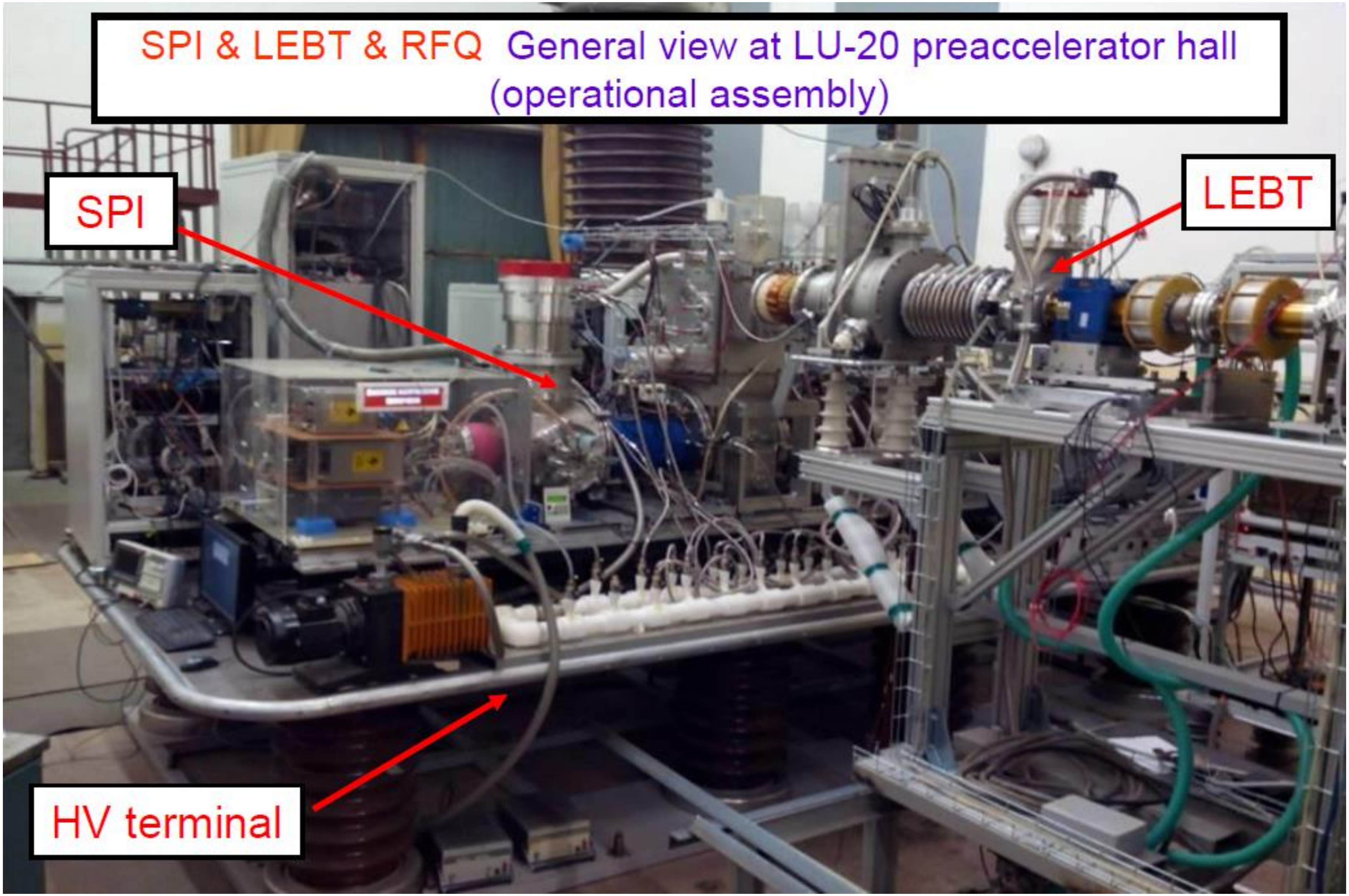
The **SPI** is based in substantial part on the equipment from IUCF(Bloomington, USA)

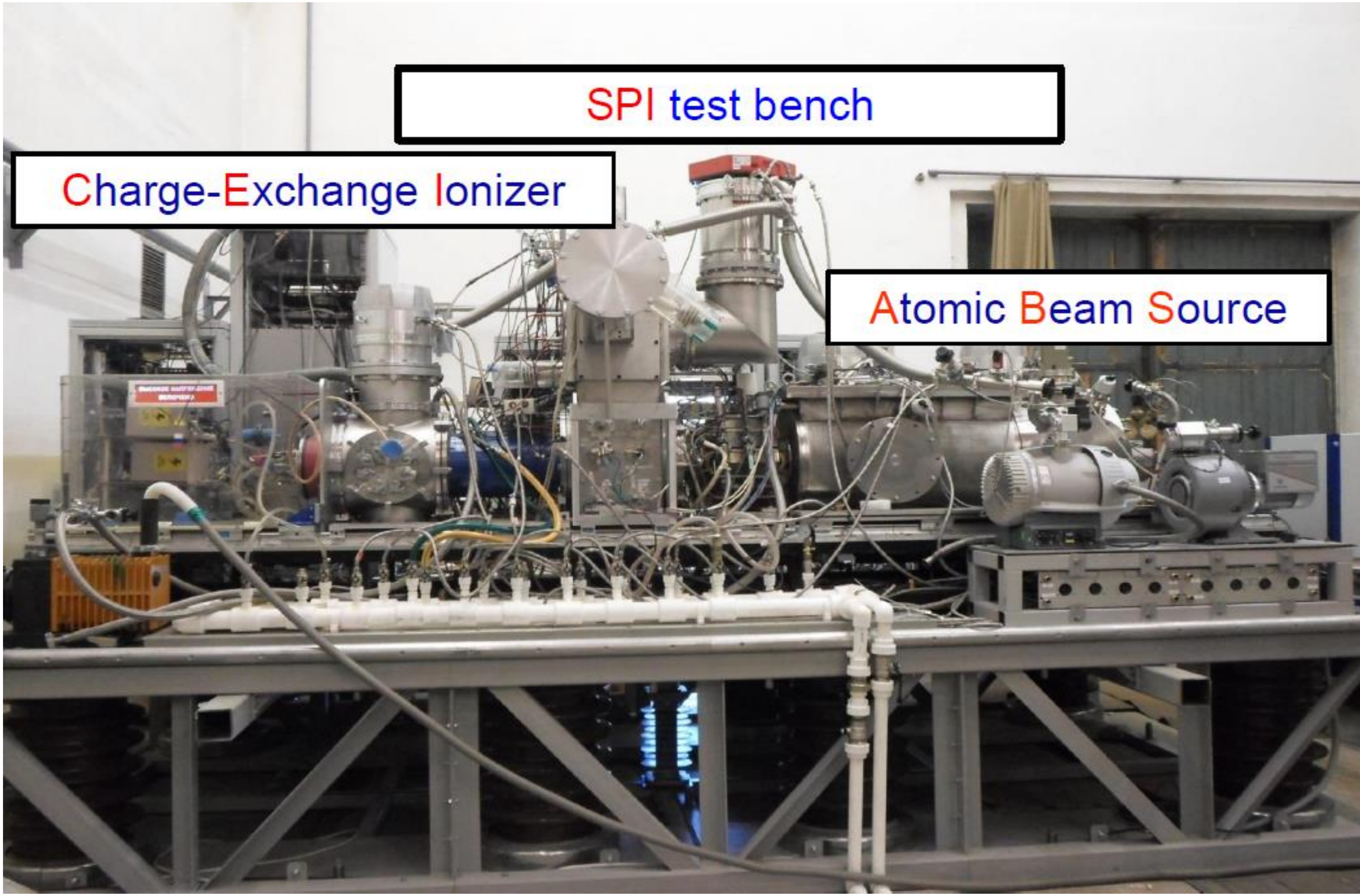
- The design output current of the **SPI** is up to **10 mA** for **↑$D^+$ (↑ $H^+$)**
- The **$D^+$ ($H^+$)** polarization will be up to 90% of the maximal vector **(±1)** & tensor **(+1,-2)** polarization

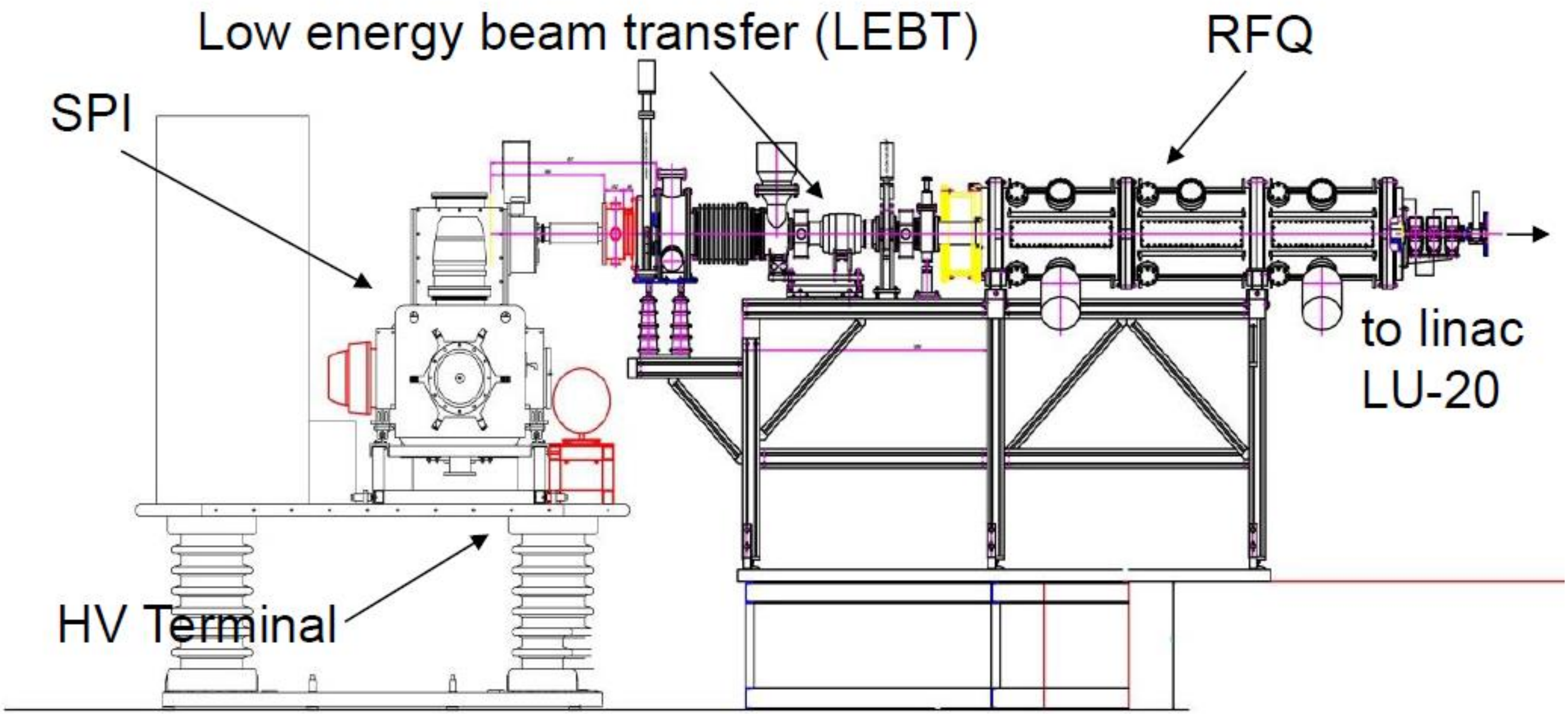
# Schematic layout of the SPI



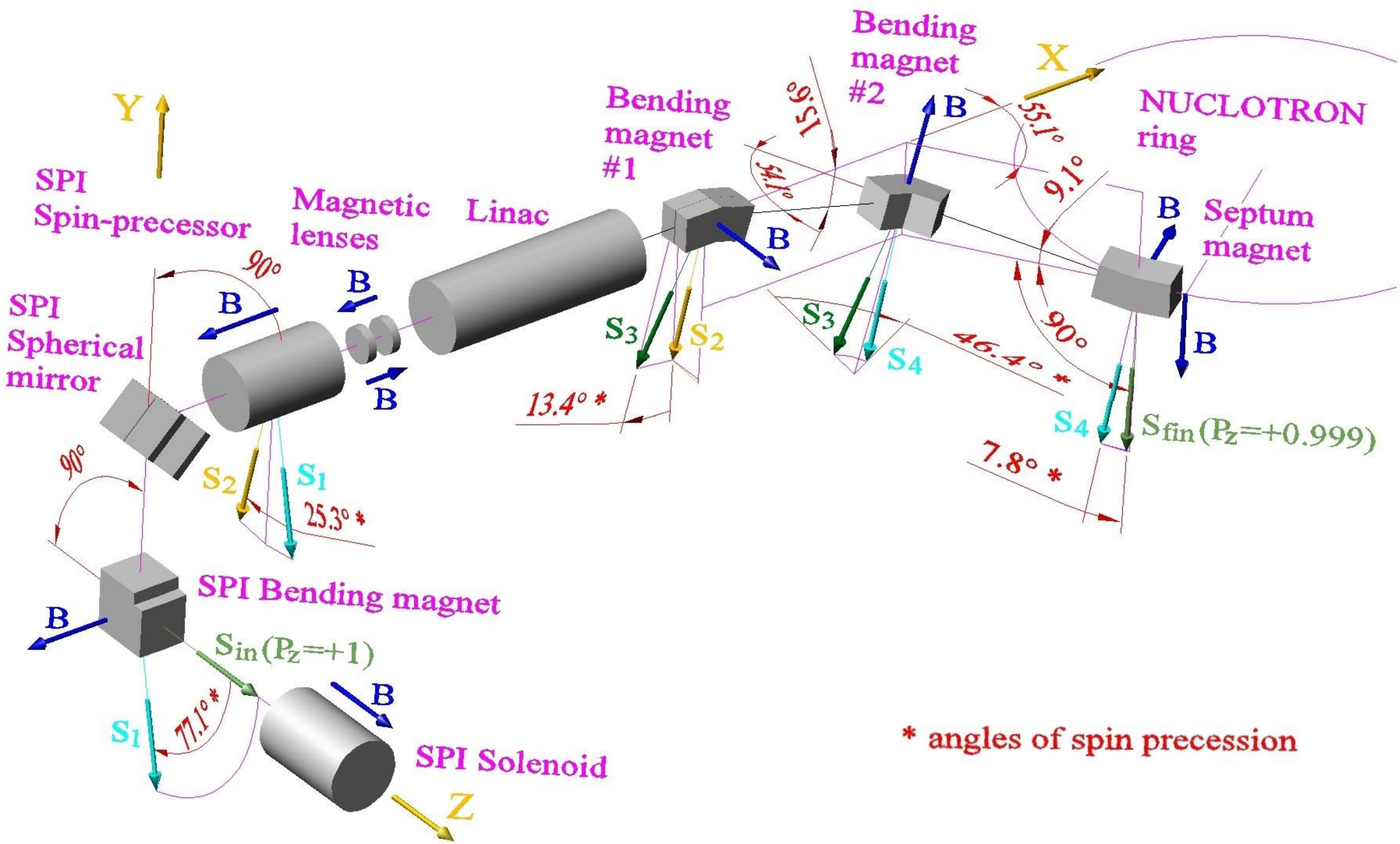

- Hydrogen (deuterium) atoms are produced in RF discharge dissociator.
- The production of an electron polarized atomic beam is done in an inhomogenious magnetic field of three permanent sextupole magnets
- Nuclear polarization is produced by RF transitions units
- Polarized atoms are converted into polarized ions


SPI & LEBT & RFQ General view at LU-20 preaccelerator hall
(operational assembly)
SPI
LEBT
HV terminal

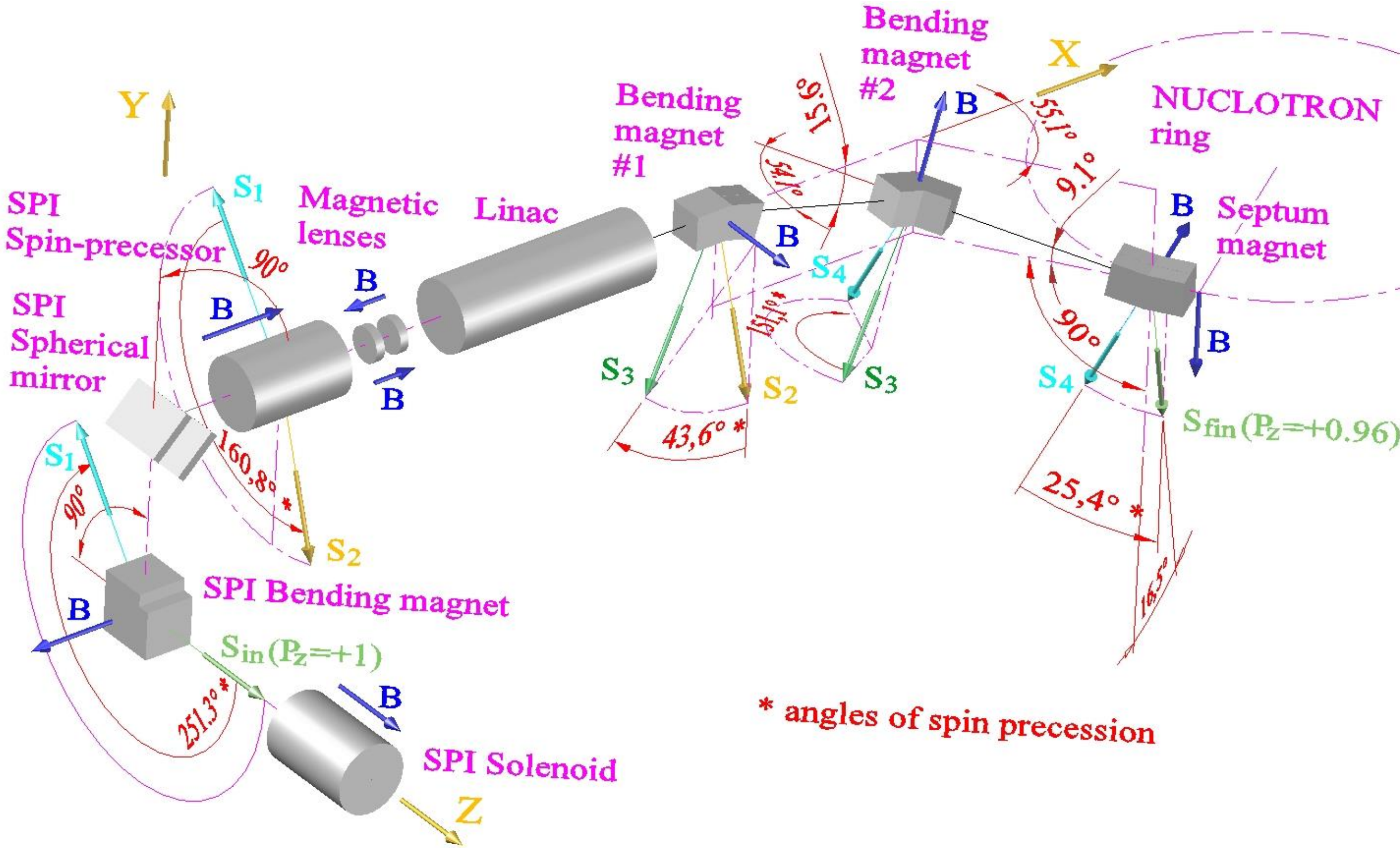

SPI test bench
Charge-Exchange Ionizer
Atomic Beam Source


Low energy beam transfer (LEBT)
RFQ
SPI
to linac
LU-20
HV Terminal

# Spatial orientation of the deuteron spin at linac injection channels of the NUCLOTRON



# Spatial orientation of the proton spin at linac injection channels of the NUCLOTRON




* angles of spin precession

- ✓ The SPI  was installed at linac preaccelerator 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&unpolarized deuteron and proton beams were produced 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 by internal polarimeter in NUCLOTRON ring
- ✓ SPI tests are ongoing and polarized deuteron beam with pulsed current up to 6 mA has been produced
- ✓ SPI operating improvements of parameters are continued

# Source of Polarized Ions (SPI)

The **S**ource of **P**olarized **I**ons (**SPI**) is developed as 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 **$\uparrow D^+$ ($\uparrow H^+$)**

The **$D^+$** (**$H^+$**) polarization will be up to 90% of the maximal vector **($\pm$1)** &

tensor **(+1,-2)** polarization

## SPI ABS

## ABS tests results

Atomic D & H beam intensities were measured. The averaged beam intensities are

**$I_D = 8 \cdot 10^{16}$ at/s** **$I_H = 5 \cdot 10^{16}$ at/s**

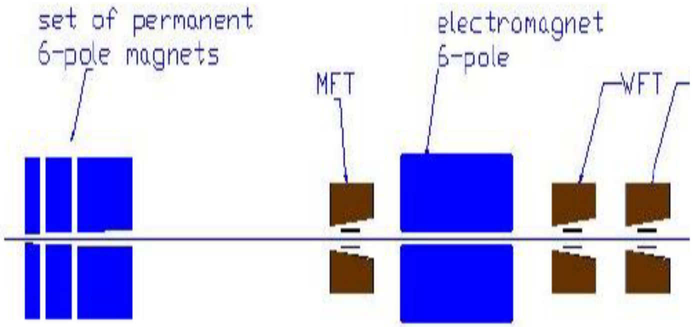
Nozzle temperature was scanned over a range of **16…100 K**

The optimum nozzle temperature is about **80 K**

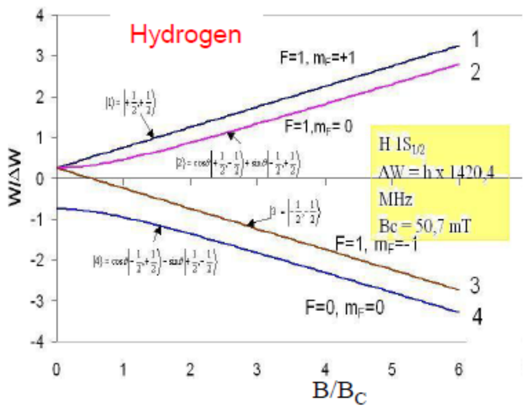
The optimum feed rate is about **0.045 mbar · l / pulse**

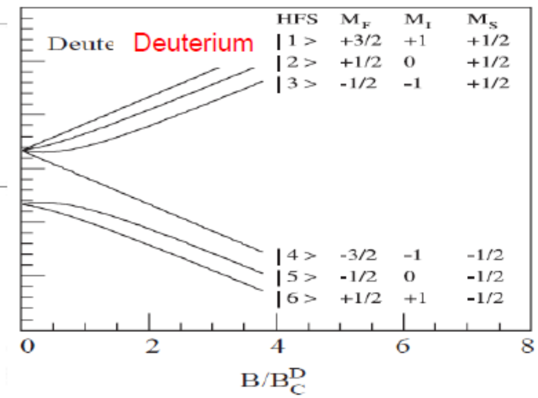
# Source of Polarized Ions (SPI)

## SPI Nuclear polarization




**Energy diagrams of hfs of hydrogen & deuterium atoms in ground state**




## Deuterons

| HFT between 6-poles | HFT after 6-poles | Final state | $P_Z$ | $P_{ZZ}$ |
|---|---|---|---|---|
| MFT 3 → 4 | WFT 1,2 → 3,4 | 3,4 | -1 | +1 |
| MFT 3 → 4 | SFT 2 → 6 | 1,6 | +1 | +1 |
| MFT 1 → 4 | SFT 3 → 5 | 2,5 | 0 | -2 |
| MFT 1 → 4 | SFT 2 → 6 | 3,6 | 0 | +1 |
| MFT - off | SFT 3 → 5 | 1,2,5 | +1/3 | -1 |
| MFT - off | SFT 2 → 6 | 1,3,6 | +1/3 | +1 |
| MFT - off | WFT 1 → 4 | 2,3,4 | -2/3 | 0 |
| MFT 3 → 4 | SFT 2 → 6 | 1,6 | +1 | +1 |

## Protons

| | | | |
|---|---|---|---|
| MFT - off | WFT 1→ 3 | 2,3 | -1 |
| MFT - off | SFT 2→ 4 | 1,4 | +1 |

# Source of Polarized Ions (SPI)

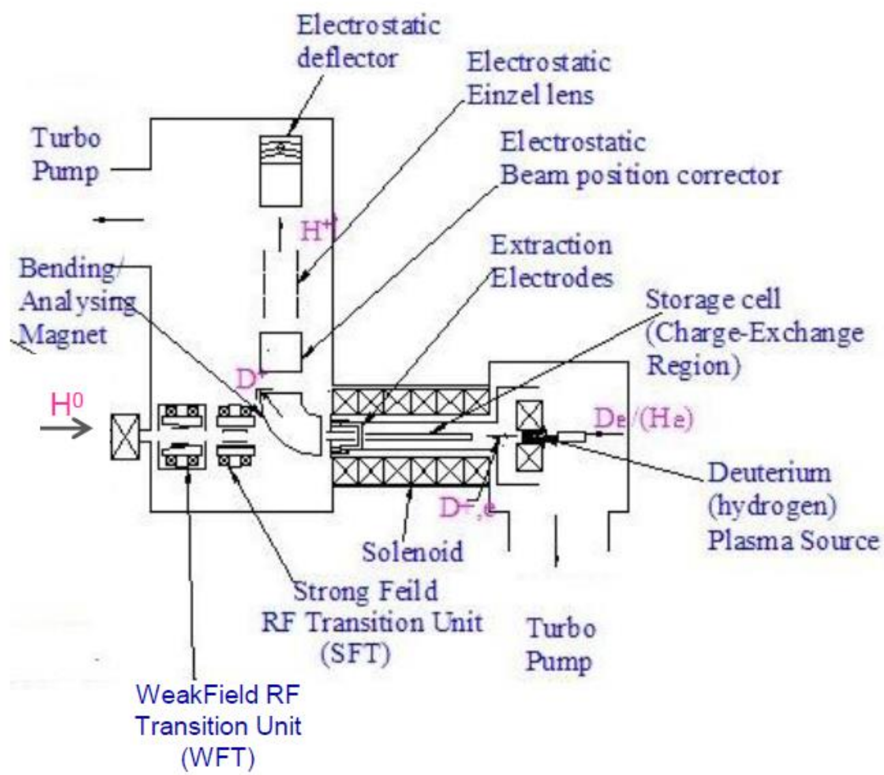
## SPI Charge-Exchange Ionizer

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

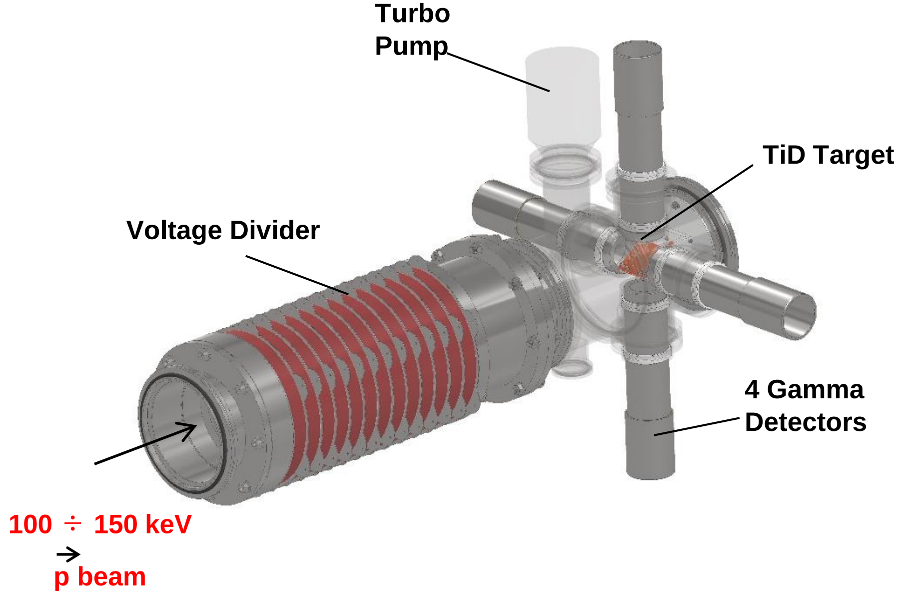
$$H^0\uparrow \; + D^+ \Rightarrow \mathbf{H^+\uparrow} \; + D^0$$
$$D^0\uparrow \; + H^+ \Rightarrow \mathbf{D^+\uparrow} \; + H^0$$
$$(\sigma \sim 5 \cdot 10^{-15}\ cm^2)$$

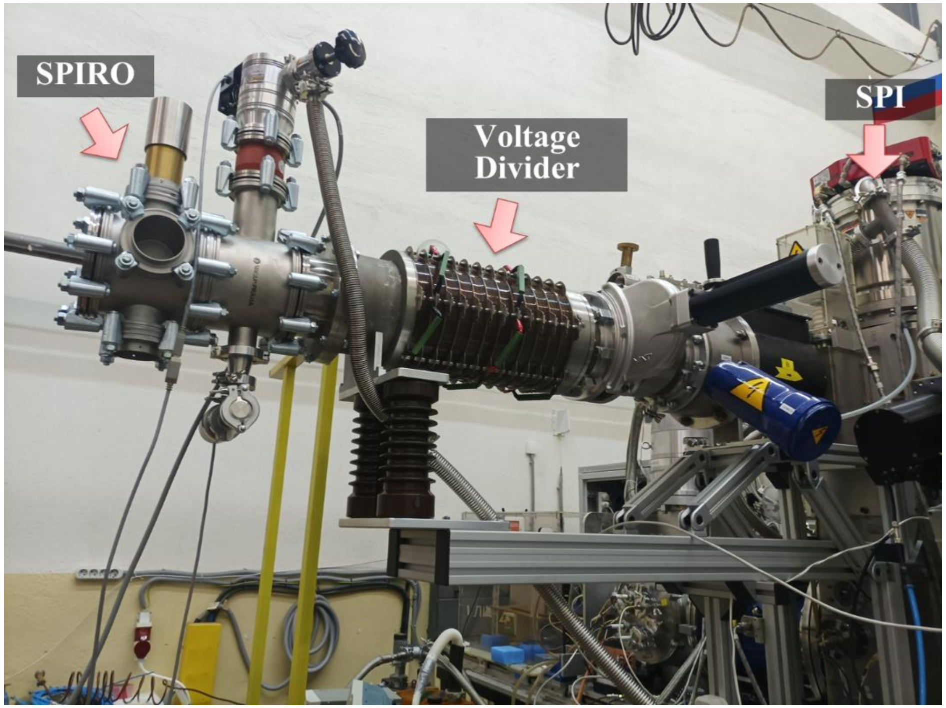
- Ionization efficiency is about 10%
- **$D^+\uparrow$ ($H^+\uparrow$)** beam energy 25 – 26 keV
- Normalized emittans 1.2 π mm mrad
- Pulse duration 100 μs
- Pulse repetition rate 0.2 Hz
- <u>The storage cell allows:</u>

  - increase intensity of the polarized $D^+$ ($H^+$) beam
  - reduce emittance of the polarized beam
  - considerably reduce $H_2^+$ ion current which is difficult to be separated from polarized $D^+$ due to similar mass of the ions

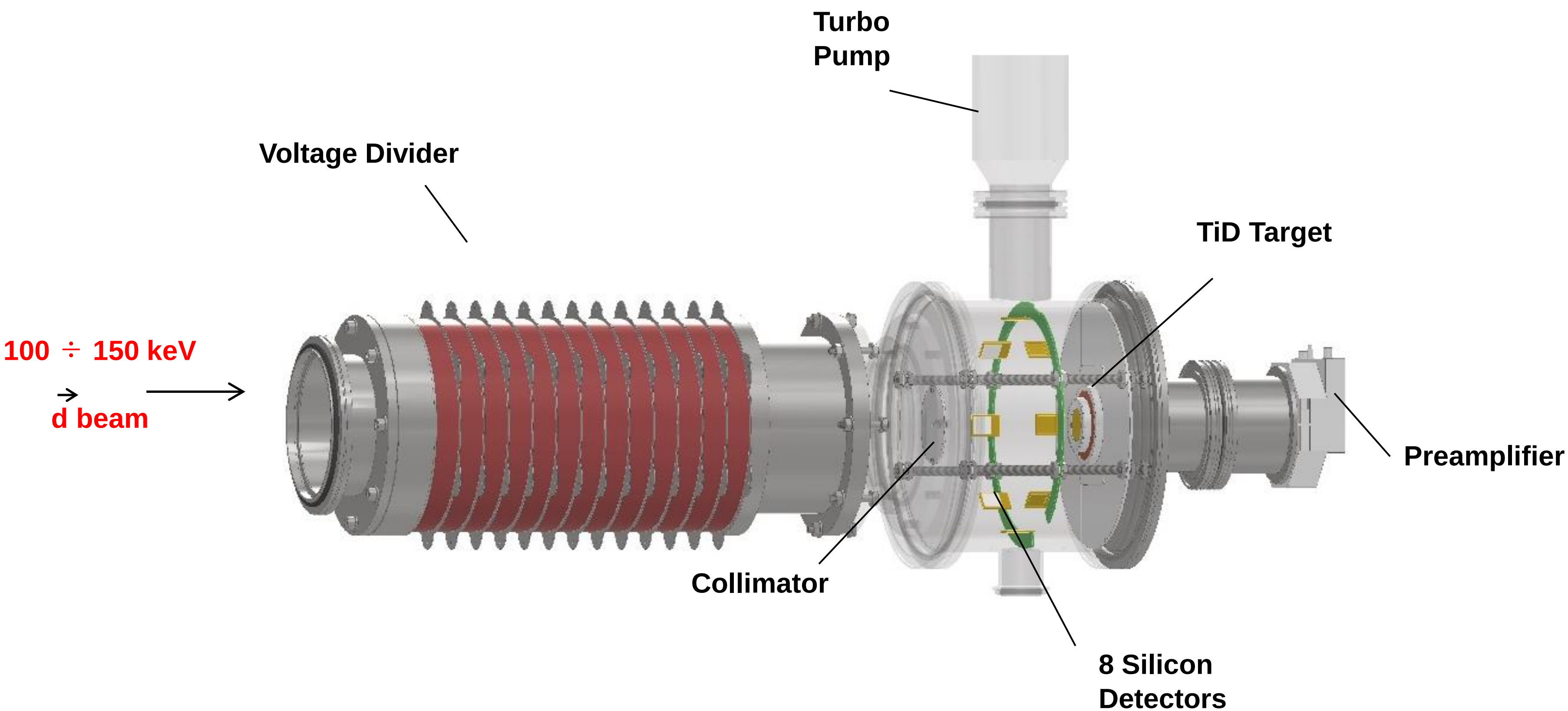


# SPI Low Energy Polarimeter (SPIRO) for polarized protons



# SPI Low Energy Polarimeter (SPIRO) for polarized deuterons



Low energy polarimeter SPIRO has been developed for measuring the proton and deuteron beams polarization directly at the exit of the SPI source of polarized ionsT

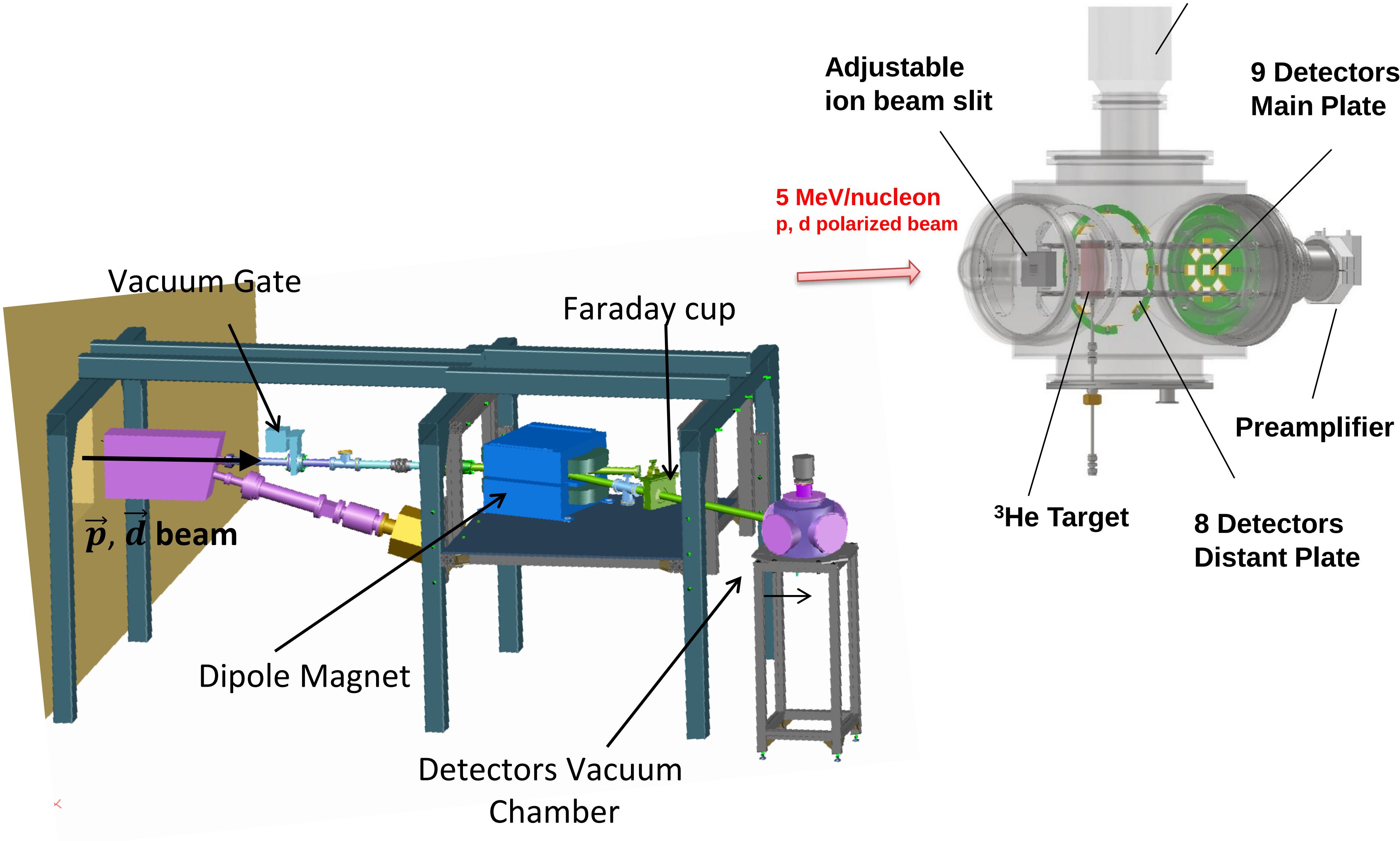
SPIRO has been designed to work with beam energies from 100 to 150 keV. This polarimeter will make it possible to control the beam polarization and tune the operation of the SPI nuclear polarization cells, as well as to determine the influence of the SPI perturbing devices on the beam polarization.

For polarized protons, it is proposed to use the D(p,γ)3He fusion reaction and detect gamma with energy near 5.5 MeV

Four GGG (Gadolinium Gallium Garnet) detectors will be used to register gammas

For polarized deuterons, it is proposed to take the D(d,p)T reaction having the same deuterated titanium target. Eight silicon detectors with $20\times20$ mm$^2$ size and 300 μm thick will be used to register protons at energies about 2.8 MeV. They will be located at 120 degree scattering angle including the up, down, left and right directions with respect to the interaction point. Such a detector scheme allows one to measure vector and tensor polarization of deuterons and monitor the spin direction. The efficiency of detector’s assembly is near 0.52%. The mean number of protons produced per bunch at 100 keV and 1mA current is assumed to be approximately 11000

# Low Energy Polarimeter (LEO)



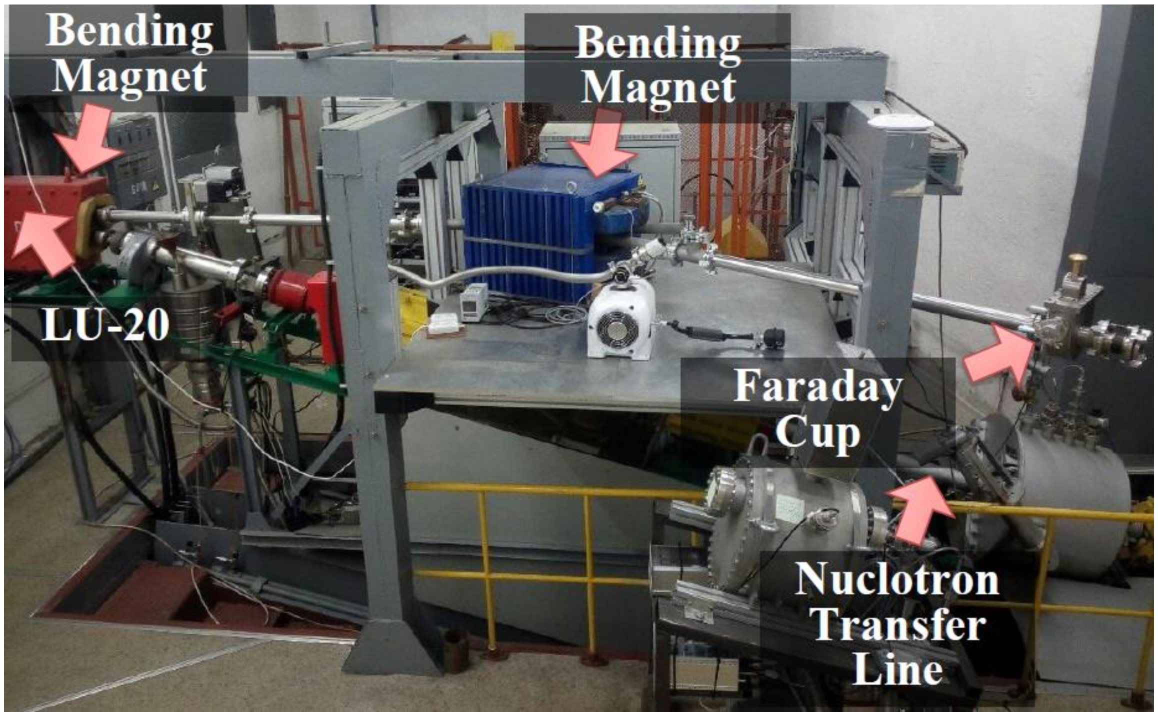
The 3He target of this setup enables one to measure both the vector polarization of protons – with 3He(p,p)3He elastic scattering reaction and the vector and tensor polarization of deuterons – with 3He(d,d)3He elastic scattering reaction as well as 3He(d,p)4He nuclear reaction

It is assumed that the design of the polarimeter will make it possible to measure vector and tensor polarization of deuterons with one setup simultaneously. It is necessary because SPI can produce beams polarized in different tensor and vector modes at the same time

The 3He target represents a mylar cylindrical vessel filled with 3He gas. The gas absolute pressure is ~ 3 bar. The mylar wall is 170 μm thick

The detectors will be placed in the vacuum chamber. It is assumed to use silicon detectors with the size of 20×20 $mm^2$ and 300 μm thick. The detectors at the remote plate will be taken to measure polarization of the deuteron beam. The detectors at the main plate will be used to measure polarization of the proton beam. This detector scheme allows one to measure not only the 2-dimentional but 3-dimentional beam polarization.

# Low Energy Polarimeter (LEO)




# Summary

- ✓ The SPI was installed at linac preaccelerator 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&unpolarized deuteron and proton beams were produced 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 by internal polarimeter in NUCLOTRON ring

- ✓ The SPI has been tested with the storage cell installed into the charge-exchange region of the plasma ionizer and polarized deuteron beam with pulsed current up to 6 mA has been produced in 2018

- ✓ SPI operating improvements of parameters are continued

# 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* 3D view**

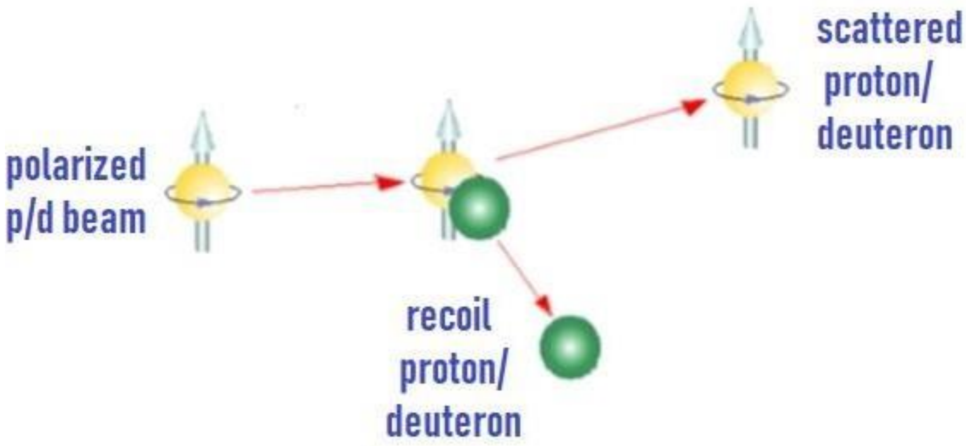
# Main tasks for Apol

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

- determination the effect of
  disturbing Collider devices on beam polarization

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

# Polarimetric reaction and polarization measurement basics




beam energy range: **3..11 GeV**

recoil particle energy: **200 MeV**

recoil particle registration angle (in lab system): **75°**

$A_N$ range: **20% .. 8%**

Measured beam polarization: $P_{beam} = -\frac{\varepsilon_{beam}}{\varepsilon_{jet}} P_{jet} = -\frac{\varepsilon_{beam}}{A_N}$

where $A_N = \varepsilon_{jet} / P_{jet}$ - analizing power of the polarimetric reaction

$\varepsilon \equiv \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$ - measured assymetry

# Mesurement time estimate

**Number of events needed to measure $A_N$ with an accuracy of 5%:** $N_A=(0.05\cdot A_N)^{-2}$

Time needed to measure $A_N$ with an accuracy of 5%: $T=N_A/N$.

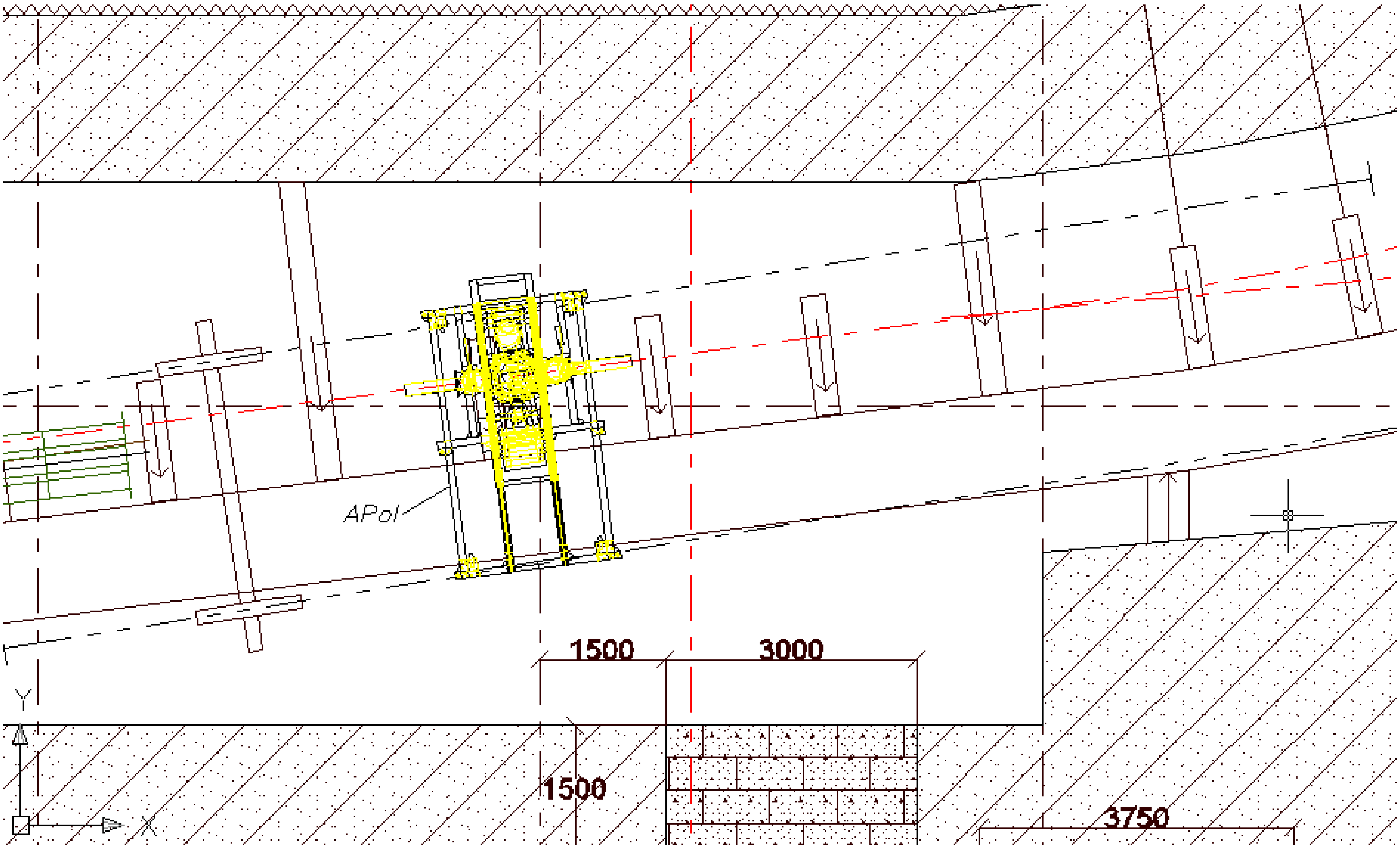
**If we put numbers in the table we see:**

| Beam, energy, GeV | Scattering cross-section, mb | Analizing power | Number of events needed for $\delta A_N$=5% | Time of measurement |
|---|---|---|---|---|
| 3 | 3.08 | 0.195 | 10500 | 18 seconds |
| 7 | 2.29 | 0.107 | 35000 | 73 seconds |
| 11 | 1.84 | 0.077 | 67500 | 182 seconds |

Data for cross-sections and analizing powers are taken from NIMA **211** (1983) 239-261.

# Proposed placement of the APol setup at NICA collider

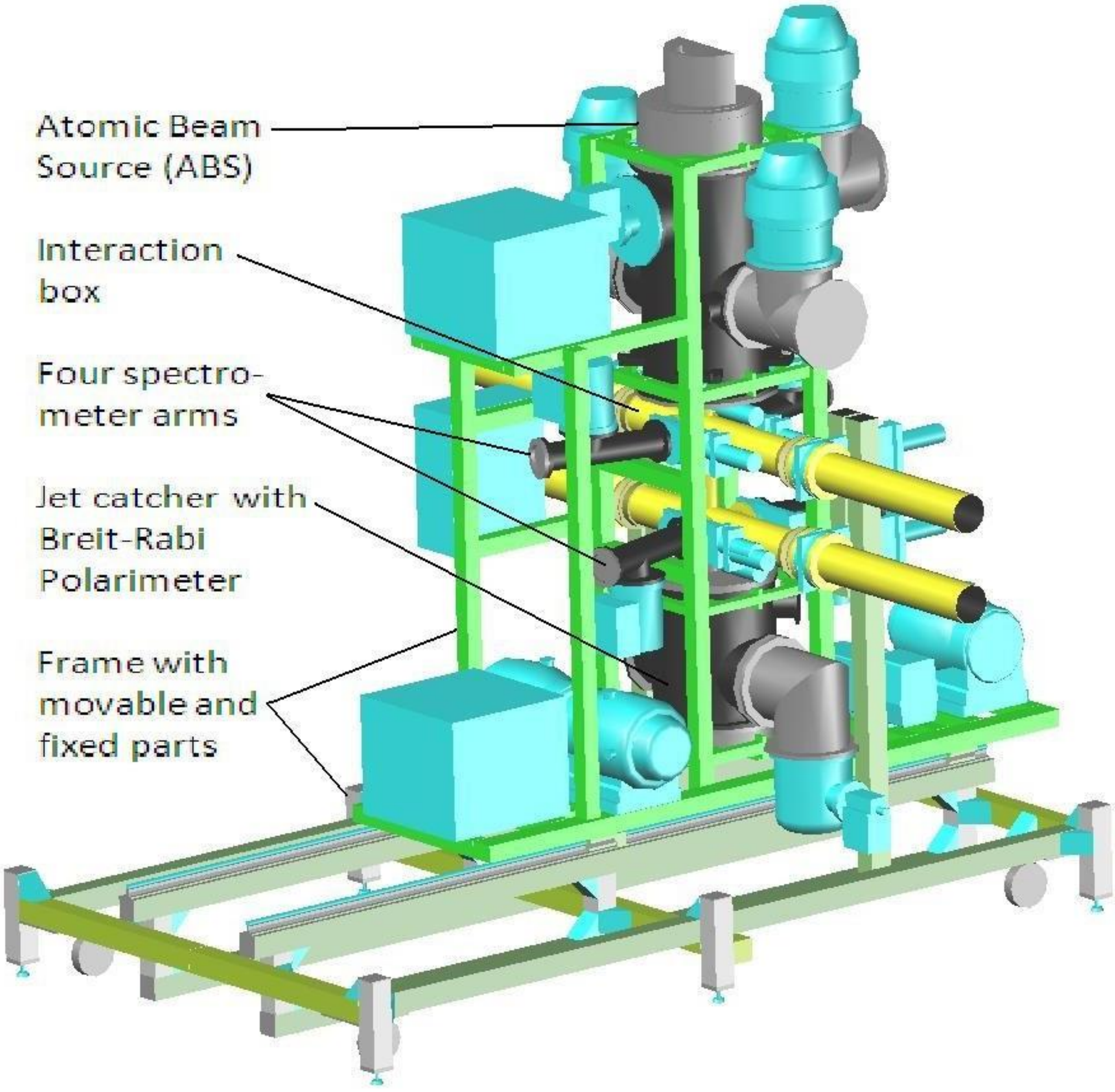
**60 cm** along the beam is needed for APol placement



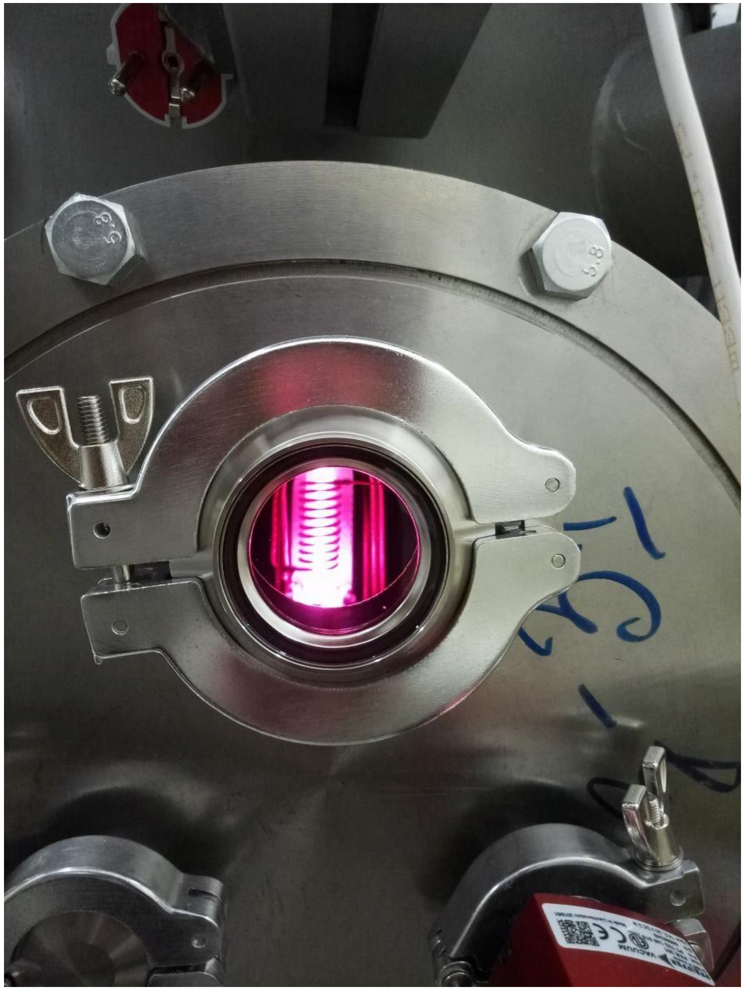
# Main subunits of APol

APol consists of:

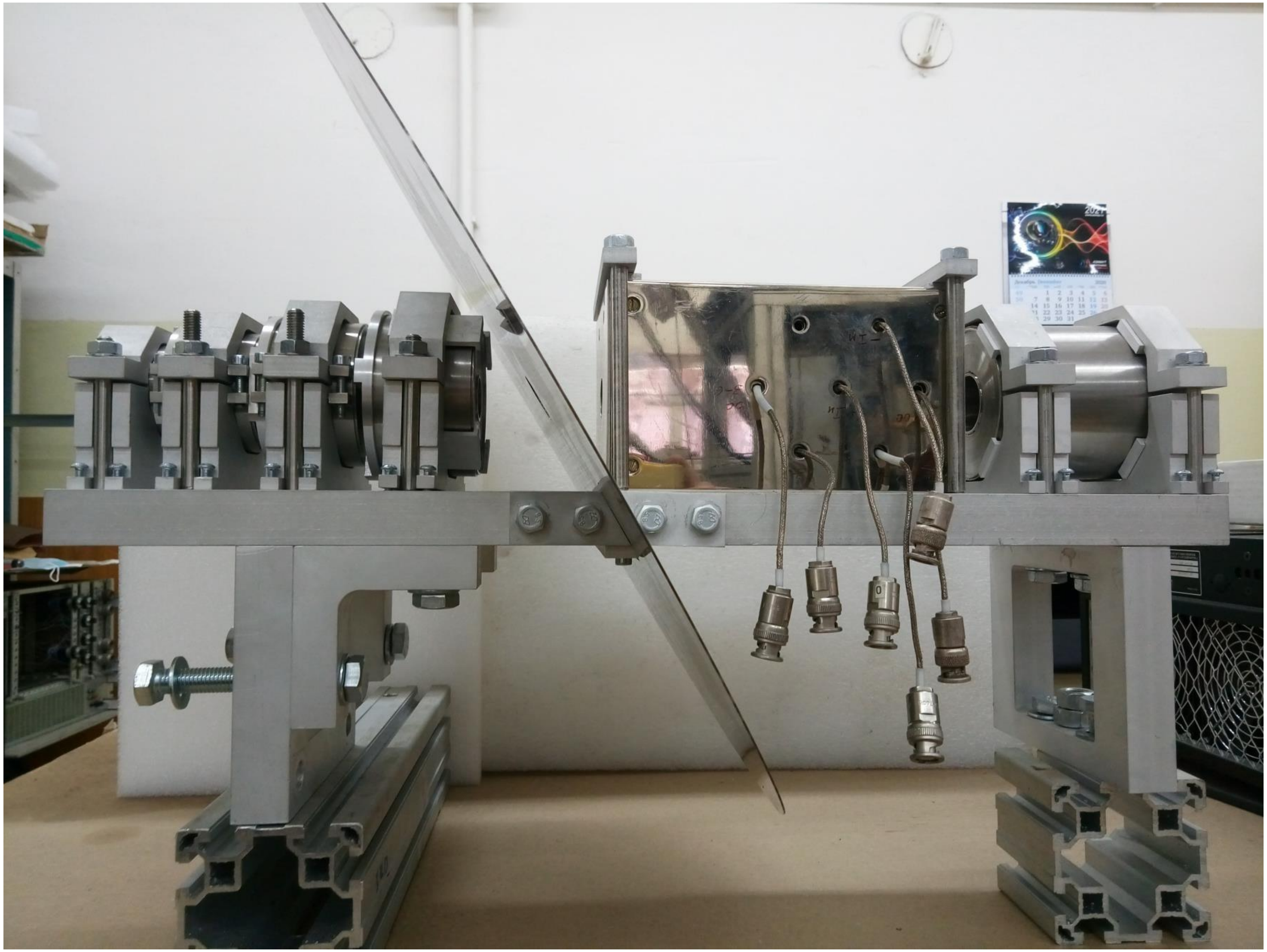
- Atomic Beam Source (ABS)
- Interaction box
- Four spectro-meter arms
- Jet catcher with Breit-Rabi Polarimeter
- Frame with movable and fixed parts



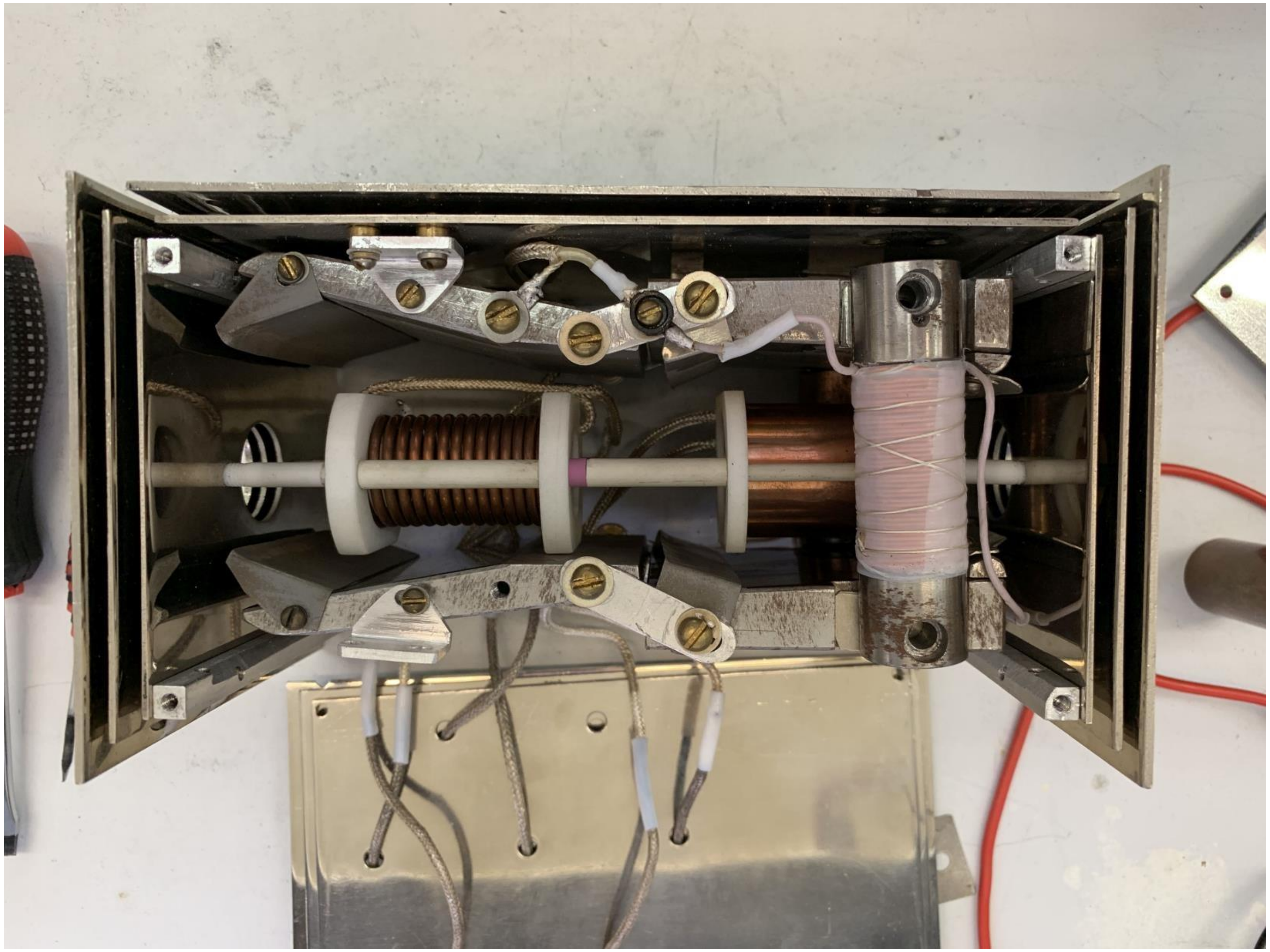
# APol dissociator



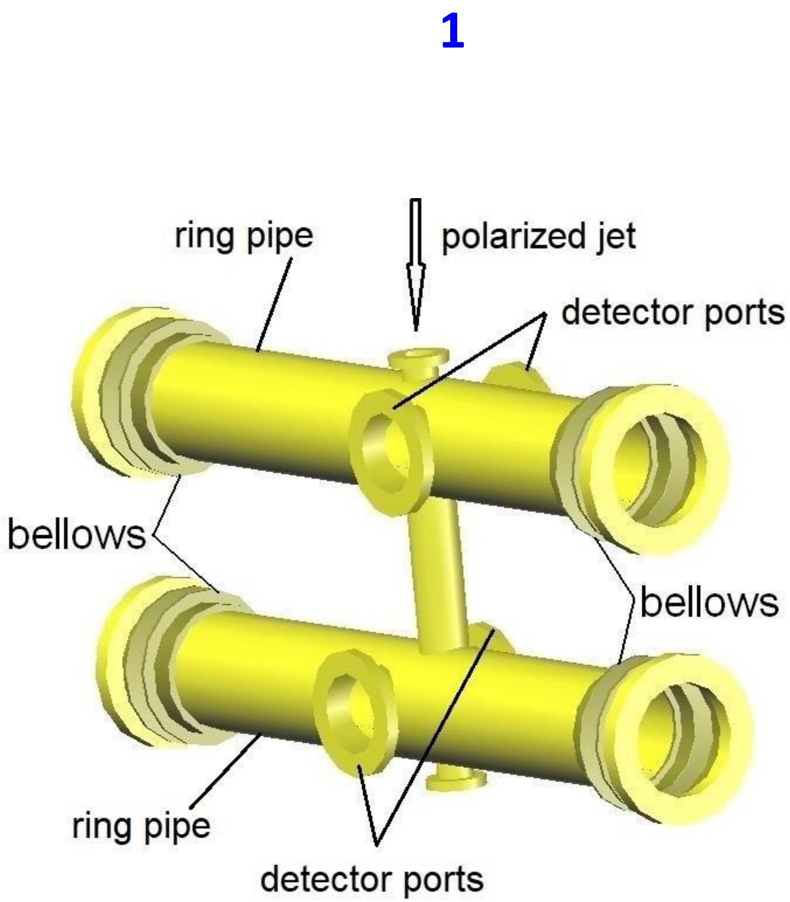
# APol permanent (Nd-Fe-B) sextupole magnet structure

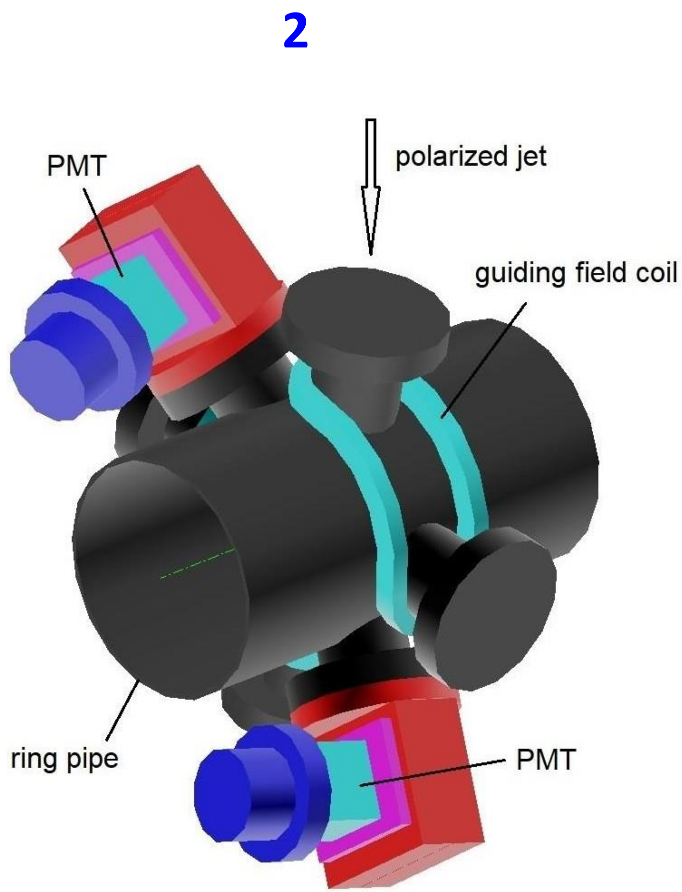


# APol nuclear polarization cell



# APol interaction box




1 – version for horizontal reaction plane

2 – version for 45° reaction plane (PMT – Photo Multiplier Tube)

# Main operational parameters of APol:

- **steady operation mode**
- throughput of $H_2/D_2$

  $Q$ = **1 torr·l/**s = **3.4·10$^{19}$ molecule/s** = **6.8·10$^{19}$ 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$^2$**

## Vacuum conditions:

- differencial vacuum pumping system is used
- vacuum in dissociator chamber (the 1st stage): **$5*10^{-4}$ mbar**
- vacuum in beam forming chamber (the 2nd stage): **$5*10^{-6}$ mbar**
-vacuum innuclear polarizing region chamber (the 3d stage):**$1*10^{-6}$ mbar**
- expected vacuum in interaction box: **$1*10^{-10}$ mbar**

## Operational requirements:

Electric power: 15 kW, single and three phase, 220 V, 50 Hz

Cooling water: 2 $m^3$/h, 3 atm

Pressurized air: 5,5 atm

Occupied area: 6.5 $m^2$ (3.5m x 2m)

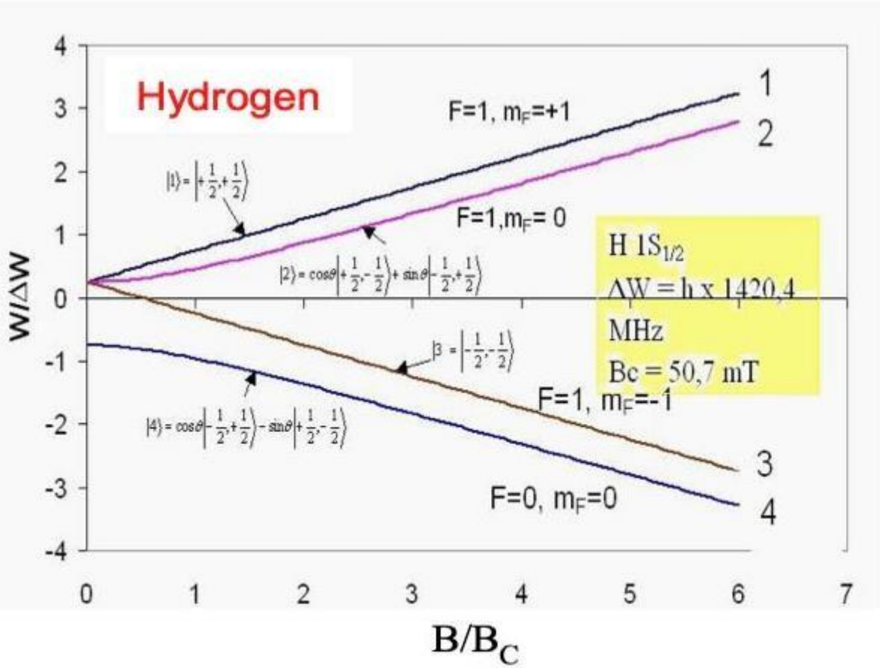
APol main dimensions (LxWxH): 3.5m x 2m x 3m

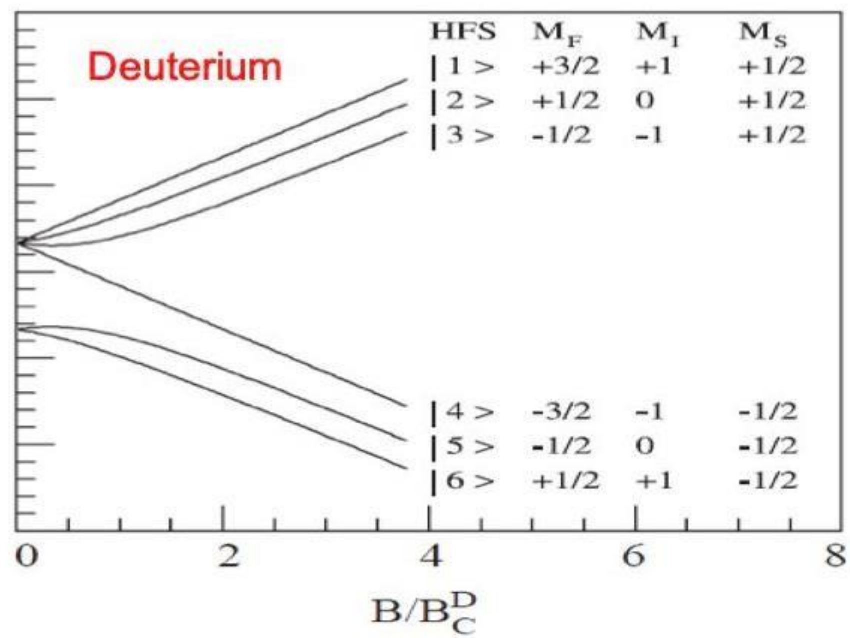
## APol Status (August 2023)

Purchased Equipment – 95%
Instruments and electronic equipment – 90%
Setup Control Software – 30%
DAQ Software – 50%

- Testing of vacuum equipment has been completely carried out
- Magnet system measurements and analysis have been carried out (Values are close to optimum)
- Preliminary tests of Dissociator and Atomic Beam Source performance have been carried out. (Atomic hydrogen intensity is about $7 \cdot 10^{16}$ atom/s, degree of dissociation is 80%)

# Energy diagrams of hfs of hydrogen & deuterium atoms in ground state




| Hydrogen | Final State | Pz |
|---|---|---|
| MFT 2->3 | 1 | +1 |
| Deuterium | Final State | Pz |
| MFT 3->4 + SFT 2->6 | 1 | +1 |

## Notes

- 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

**Thank you for your attention !**