Polarization facilities at the JINR accelerator complex

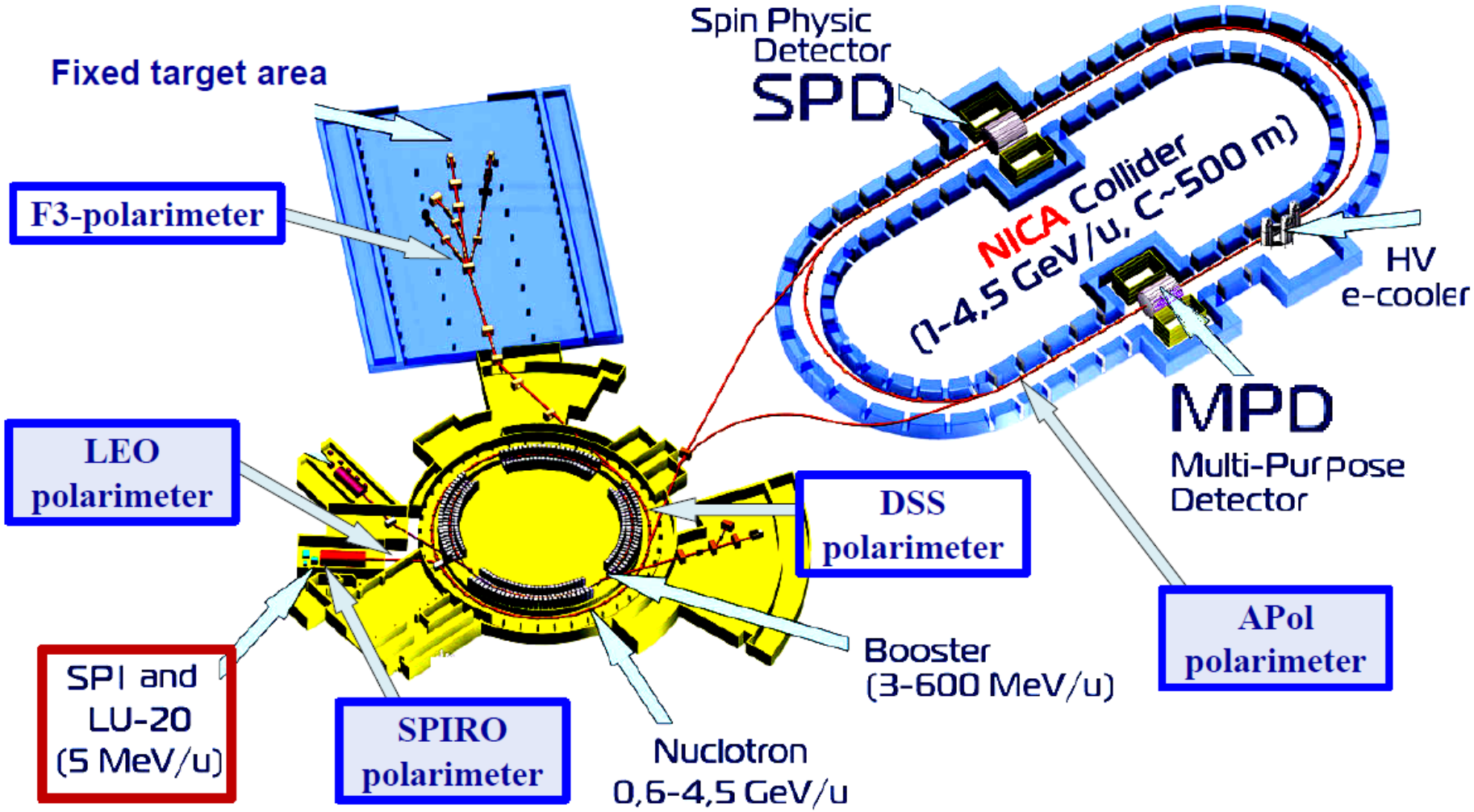
V.V. Fimushkin[1], V.B. Dunin[1] , R.A. Kuzyakin[1] , M.V. Kulikov[1] , L.V. Kutuzova[1] , Yu.V. Prokofichev[1] , A.M. Shumkov[1] , N.I. Zamyatin[1] , A.S. Belov[2] , and A.Ya. Kutov[3]

[1]Joint Institute for Nuclear Research, Dubna, Russia
[2] Institute for Nuclear Research of RAS, Moscow, Russia
[3] Institute of Physics and Mathematics Komi SC UrD RAS, Syktyvkar, Russia

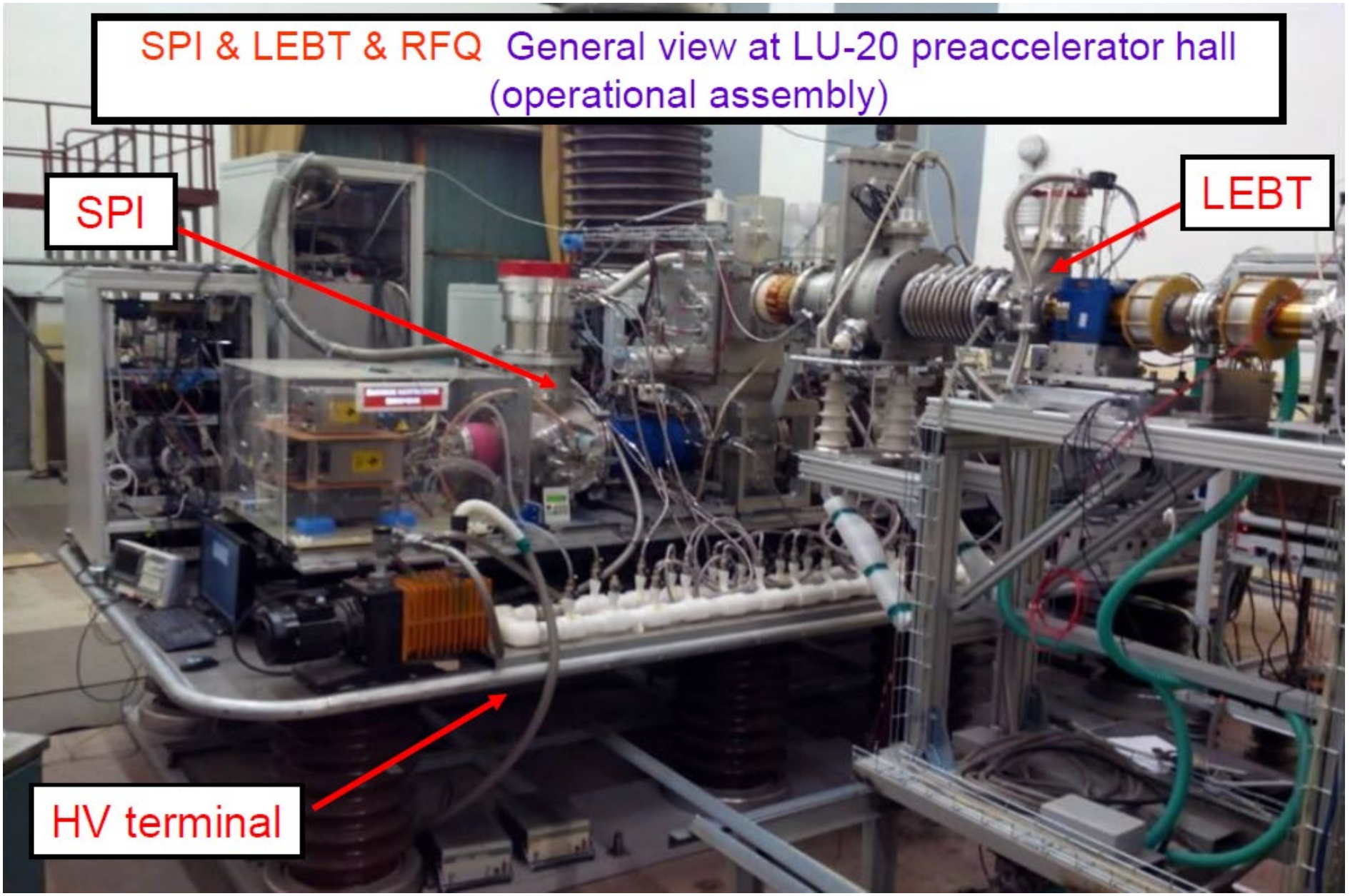
Polarization facilities are being developed at the JINR accelerator complex in the framework of the polarization research program under the NICA project. Those are the polarized deuteron and proton source SPI, SPI low energy and linac output polarimeters, and the absolute polarimeter at the NICA collider.

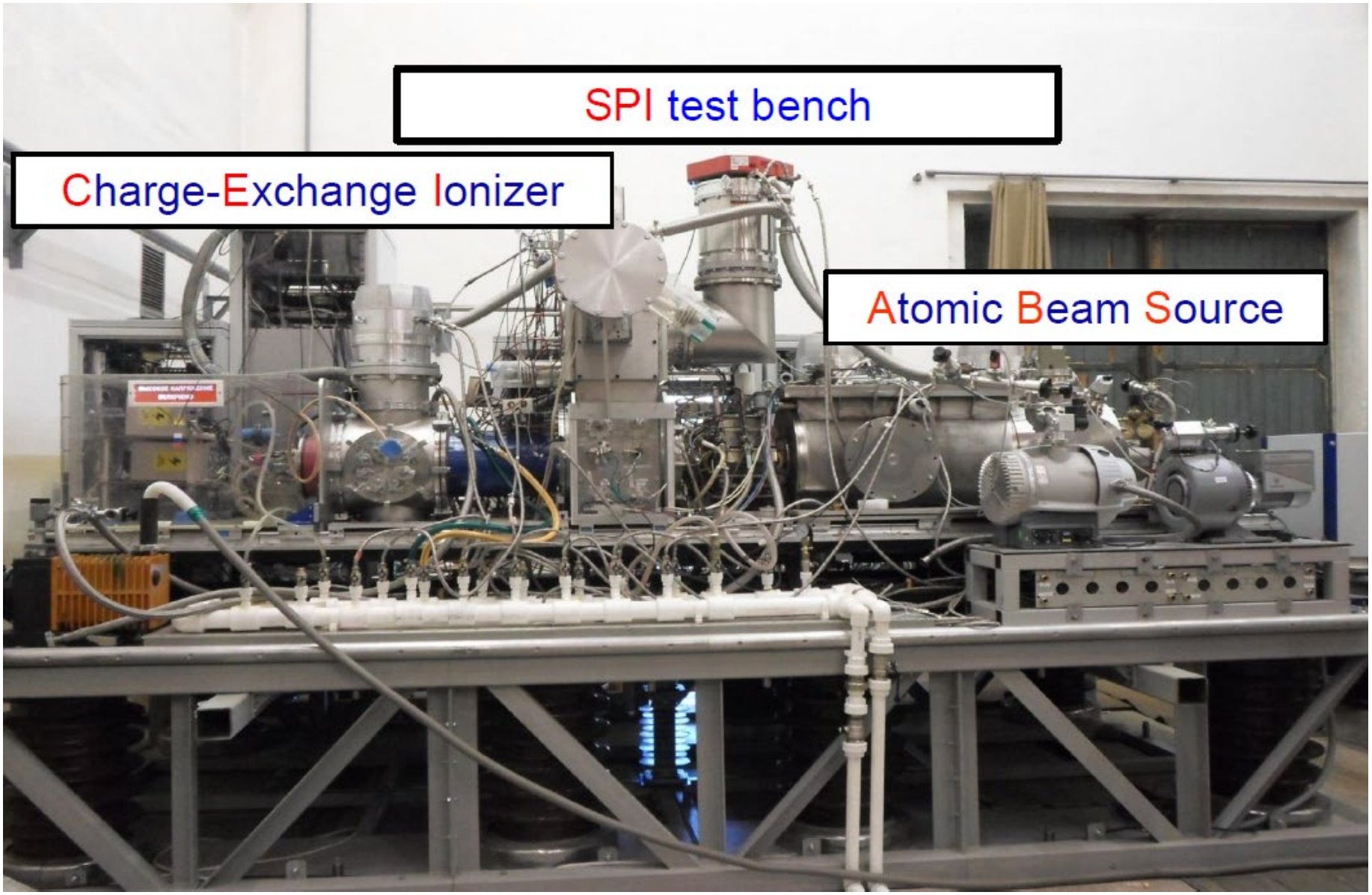
The status of the above facilities and the results achieved are presented.

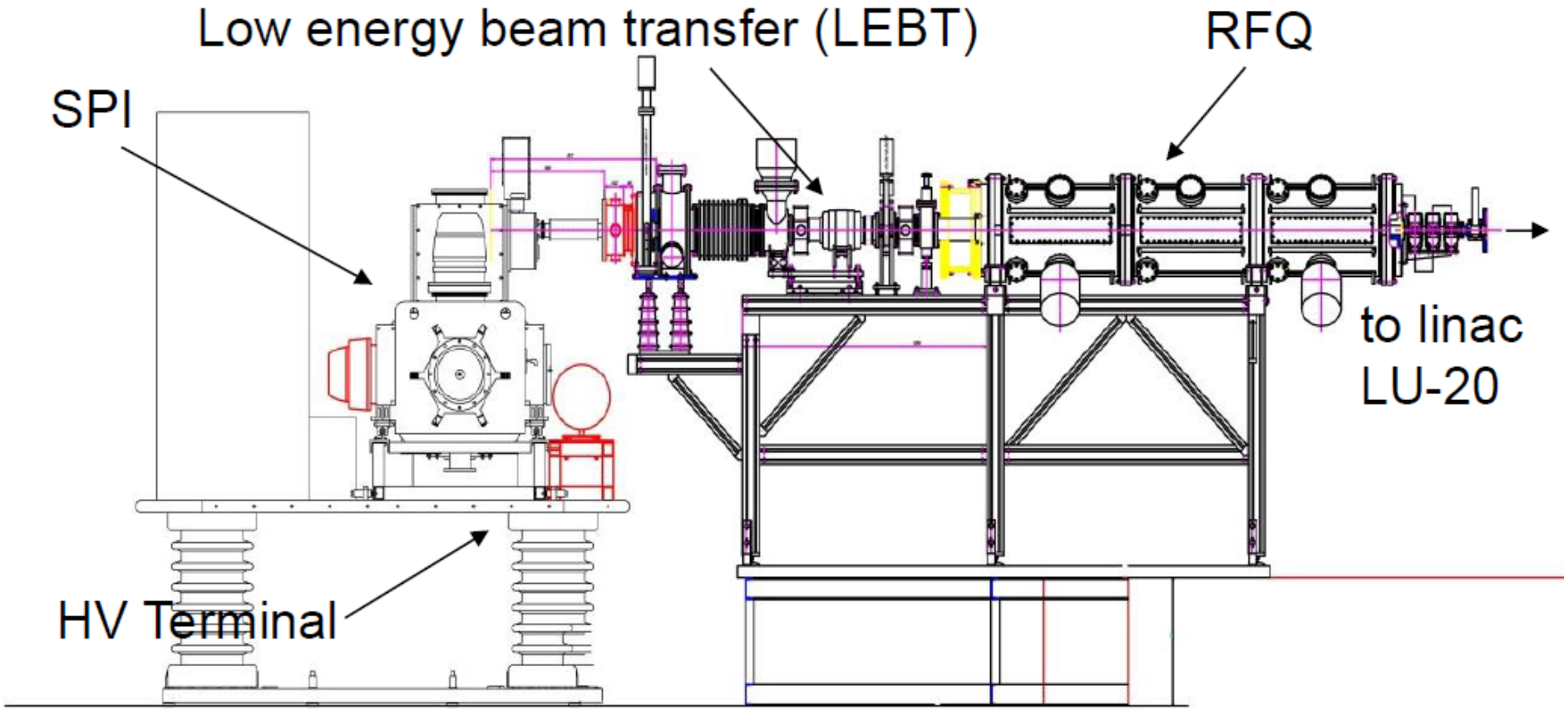
Implementation of polarization program



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


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

- ✓ 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 **(±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

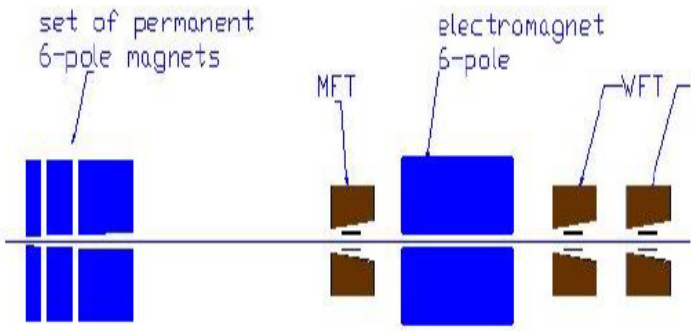
Nozzle temperature was scanned over a range of **16…100 K**

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

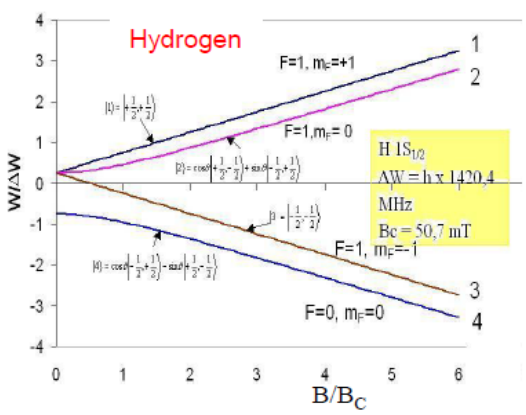
The optimum feed rate is about **0.045 mbar · l / pulse**

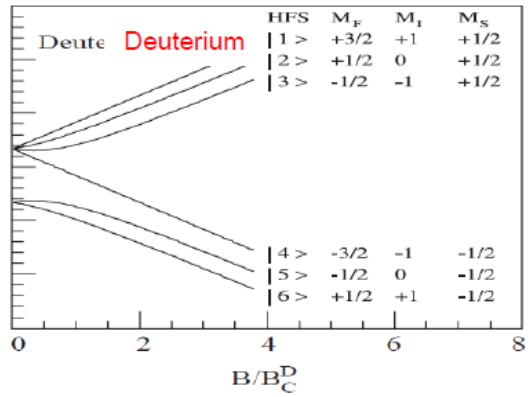
Source of Polarized Ions (SPI)

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:

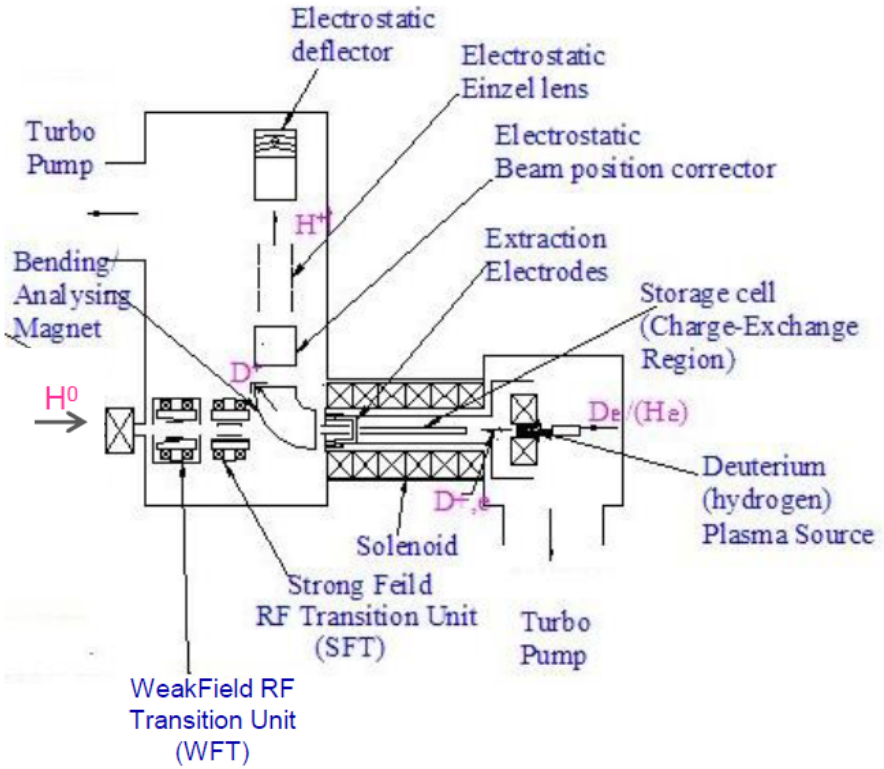
$$H^0\uparrow + D^+ \Rightarrow \mathbf{H^+\uparrow} + D^0$$

$$D^0\uparrow + H^+ \Rightarrow \mathbf{D^+\uparrow} + H^0$$

$$(\sigma \sim 5 \cdot 10^{-15}\ cm^2)$$

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

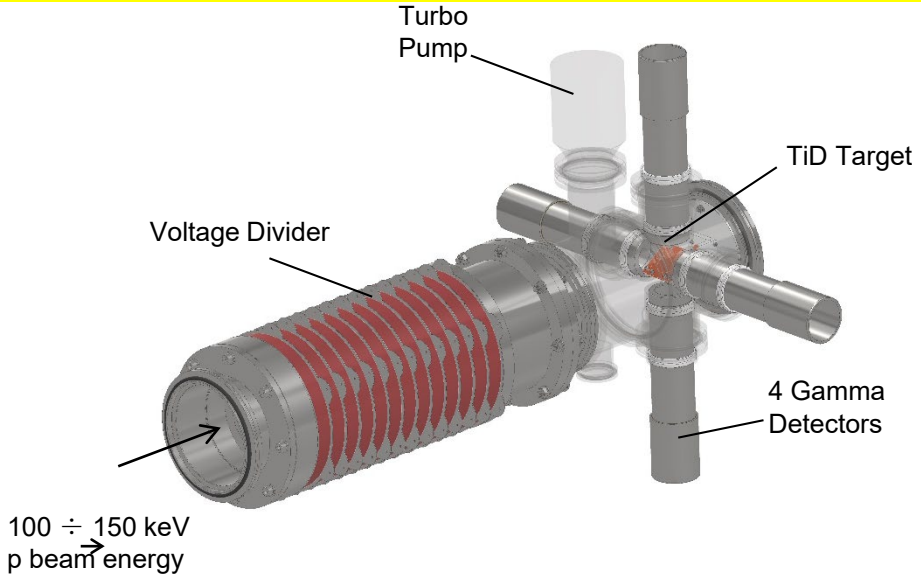
  - increase intensity of the polarized D^+ (H^+) beam
  - reduce emittance of the polarized beam
  - considerably reduce H_2^+ ion current which is difficult to be separated from polarized D^+ due to similar mass of the ions

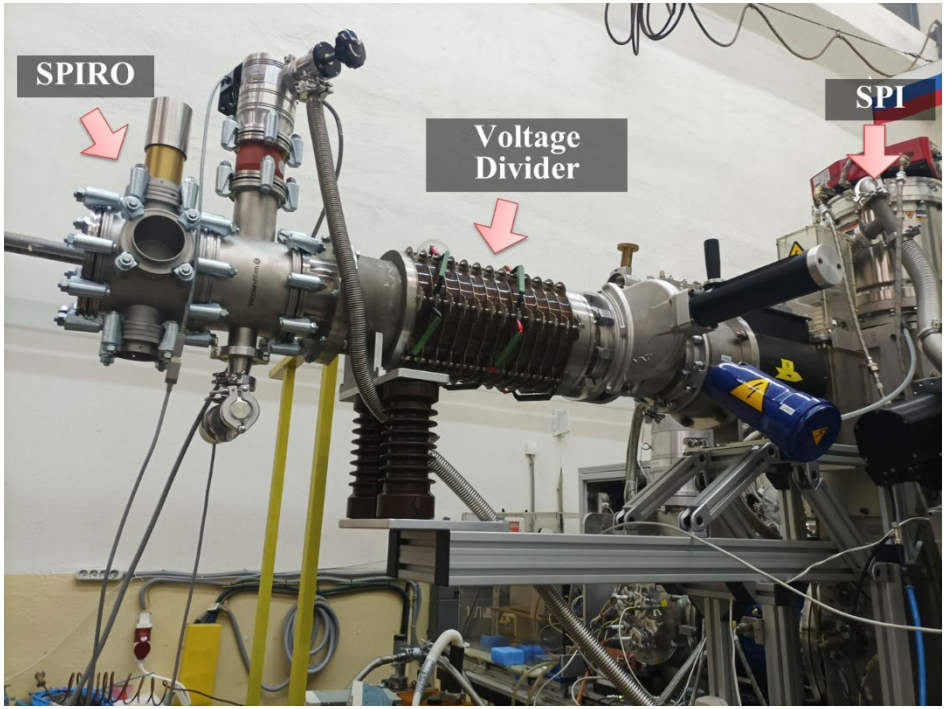


SPI Low Energy Polarimeter (SPIRO)

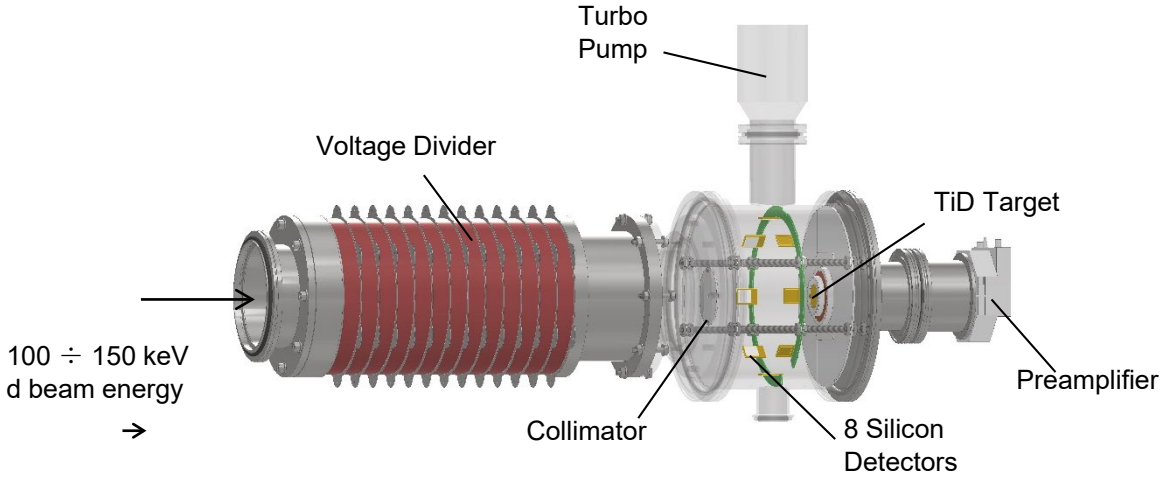
To measure the protons and deuterons beam polarization directly at the exit of the source of polarized ions SPI, the polarimeter **SPIRO** is being developed. It is designed to work with beam energies from **25 to 100 keV**. This polarimeter will make it possible to control the beam polarization and tune the operation of the SPI nuclear polarization cells, as well as to determine the influence of the perturbing devices of the installation on the polarization of the beams. For polarized protons, it is proposed to use the **$D(p,\gamma)^3He$** fusion reaction, where solid deuterated titanium TiD will be used as a target. For polarized deuterons, the **D(d,p)T** fusion reaction is used with the same TiD target.

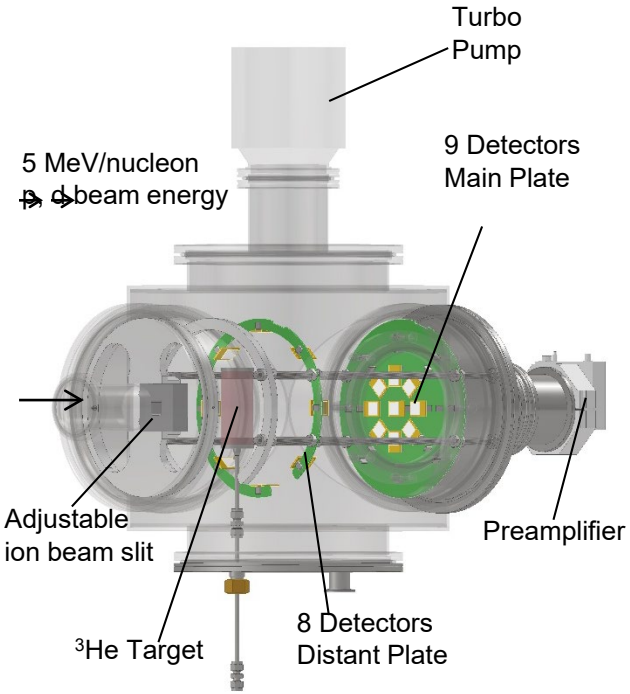
SPI Low Energy Polarimeter (SPIRO) for polarized protons





SPI Low Energy Polarimeter (SPIRO) for polarized deuterons





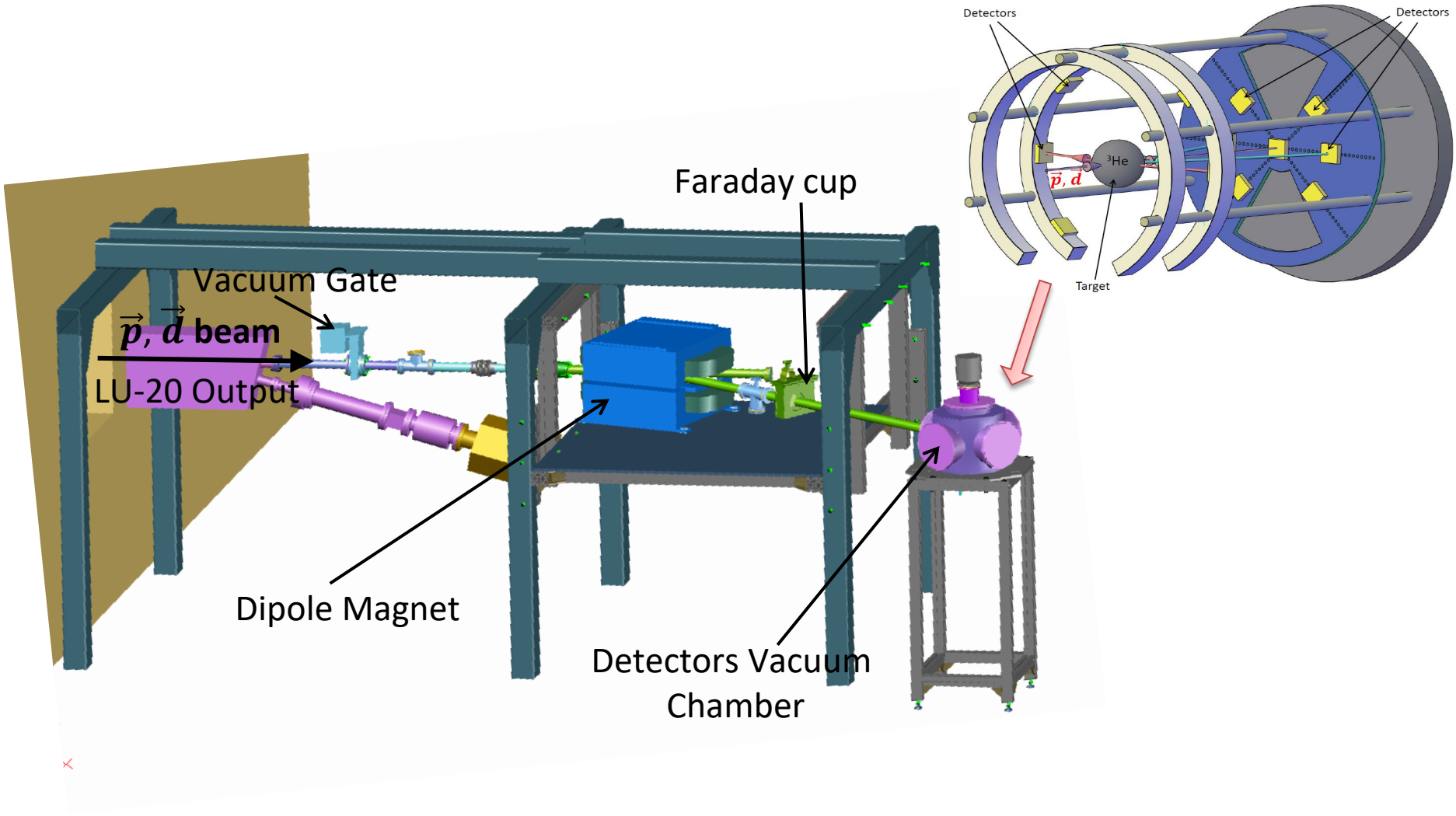
Low Energy Polarimeter (LEO)

Low energy polarimeter (**LEO**) is placed behind the linear accelerator Lu-20. Its operating energy is **5 MeV** per nucleon. The main advantage of this polarimeter is that the setup may be used not only for polarization measuring but also for tuning SPI RF transition units (WFT, MFT, SFT).

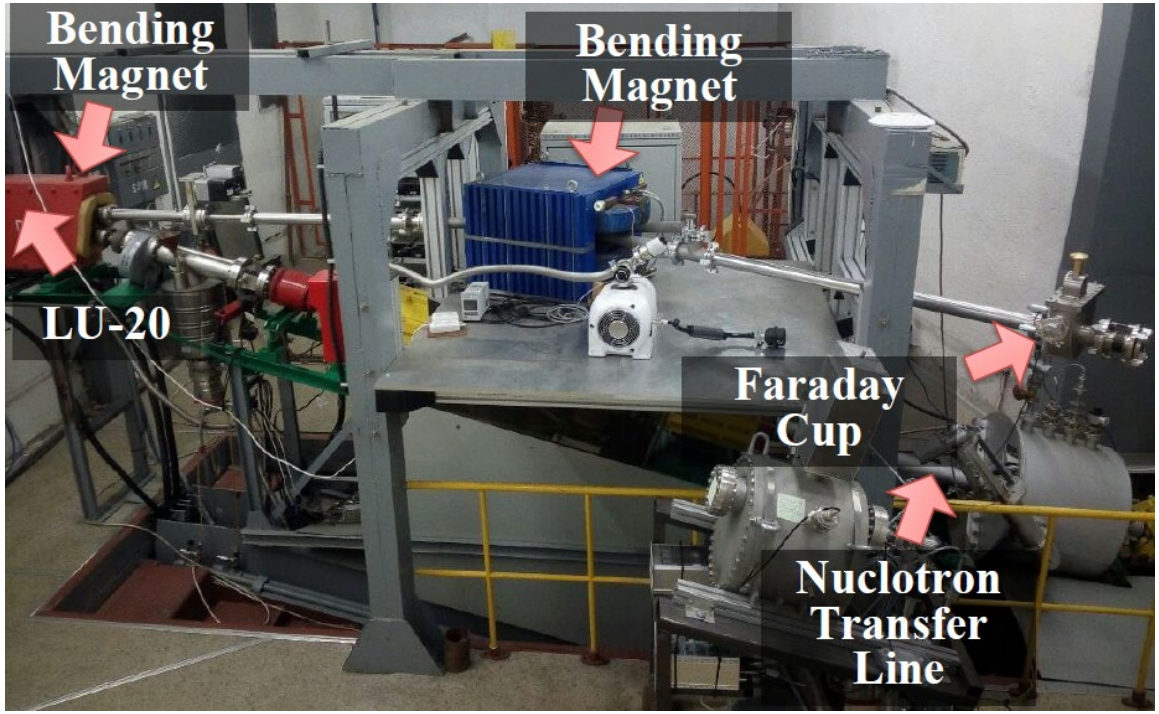
The ^{3}He target of this setup allows one to measure both the vector polarization of protons (with **^{3}He(p,p)^{3}He** elastic scattering reaction) and the vector and tensor polarization of deuterons (with **^{3}He(d,d)^{3}He** elastic scattering reaction and **^{3}He(d,p)^{4}He** nuclear reaction). The main features of the LEO are:

- Up-to-date fast detectors will be used. It is assumed to measure the polarization of each bunch.
- The data flow will be protected from electromagnetic noises.
- It is assumed that the design of the polarimeter will make it possible to measure vector and tensor polarization of deuterons with one setup at the same time.

Low Energy Polarimeter (LEO)

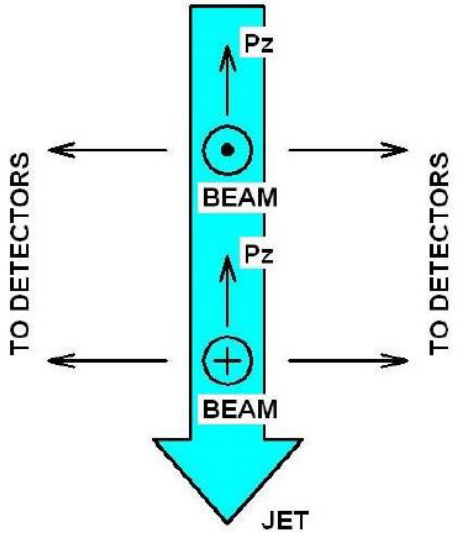


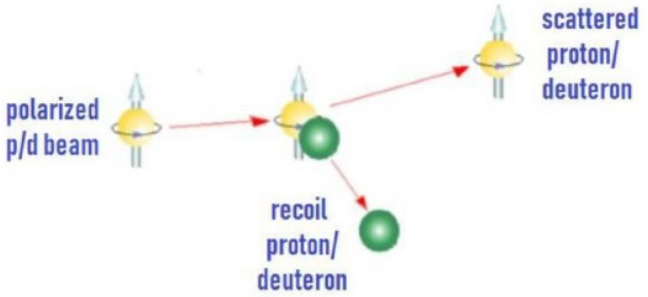
Low Energy Polarimeter (LEO)



Absolute Polarimeter (APol)

APol 3D view





Absolute Polarimeter (APol)

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.

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

APol parameters

Beam energy range: **3..11 GeV**
Recoil particle energy: **40 - 100 MeV**
Recoil particle registration angle (in lab system): **75°**
Analyzing power A_N range: **20% .. 8%**

APol Status (Oct. 2021)

• 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 beam intensity is about $7 \cdot 10^{16}$ atom/s, degree of dissociation is 80%).

Nearest plans

• Atomic Beam mass spectrometry of hydrogen and deuterium.
• Tunning of nuclear polarization cells

Статус поляризованного He^3 в ЛФВЭ ОИЯИ

Поляризация ^{3}He возможна двумя разными методами:

Оптическая накачка с метастабильным обменом (Metastability Exchange Optical Pumping, MEOP)

Спин-обменная оптическая накачка (Spin-Exchange Optical Pumping, SEOP).

По методу SEOP ядра ^{3}He поляризуются
при реализации спинового обмена при столкновениях с поляризованными щелочными металлами (Rb, K)

Разрабатываемый в ЛФВЭ ОИЯИ поляризатор ^{3}He по SEOP-методу позволит создать ^{3}He поляризованную мишень для физических экспериментов на выведенных поляризованных пучках из НУКЛОТРОНА

Наличие поляризатора ^{3}He позволит разработать источник поляризованных ионов $^3He^{++}$ по программе поляризационных исследований для NICA-коллайдера

Получение поляризованного ^{129}Xe (SEOP - метод) открывает возможность его использования в медицине как более дешевого газа в сравнении с поляризованным ^{3}He (современная томограф-диагностика легочных заболеваний, COVID-диагностика, в частности)

Поляризованные ионы $^3He^{++}$

Some history

Laval University group (Canada, Slobodrian et al.,1984) polarized ^3He atoms in the metastable state 2^3S_1 (lifetime of 7860 s) with electron spin $J = 1$ and then ionized them to $^3He^+$ in an electron impact ionizer

The subsequent ionization to $^3He^{++}$ was effected by stripping in the base of the Van de Graaf accelerator at 7.5 MV

More inspiring example from Saclay (France)

SATURNE group (P.Y. Beauvais et al., 1994) reported the results of tests conducted with use of the known HYPERION polarized ion source fed with ^3He gas.
The ionizer with a reflex electron beam yielded mostly $^3He^+$ ions with a pulsed beam current of 50 μA and pulse duration 1 ms

Поляризованные ионы $^{3}He^{++}$

Источники поляризованных ионов $^{3}He^{++}$ для инжекции в ускорители высоких энергий должны иметь сравнительно высокую интенсивность

На данный момент наиболее продвинутым является вариант источника, разрабатываемый в BNL. В источнике используется ионизация поляризованных атомов гелия в ионизаторе с электронным пучком (EBIS) в магнитном поле 5 Т. Поляризованные атомы получают методом оптической накачки атомов гелия-3 в метастабильном состоянии в сильном магнитном поле. Планируется получить интенсивность поляризованных ионов $^{3}He^{++}$ около $2 \cdot 10^{11}$ ионов в импульсе и поляризацией 70% для ускорения пучка поляризованных ионов в RHIC

Ионизатор $^{3}He^{++}$

V. P. Ovsyannikov

Параметры ионного пучка:

Интенсивность ионного пучка – $1x10^{9}$ – $5x10^{9}$ частиц в импульсе

Длительность ионного импульса – 250 микросекунд

Частота повторения – 1 Гц – 0,1 Гц

Электронно-лучевая ионная ловушка.

Для удовлетворительной интенсивности емкость ионной ловушки – 10^{10} эл. зарядов.

Ток электронного пучка – 0,3-0,5 А.

Энергия электронного пучка – 1 -3 кэВ.

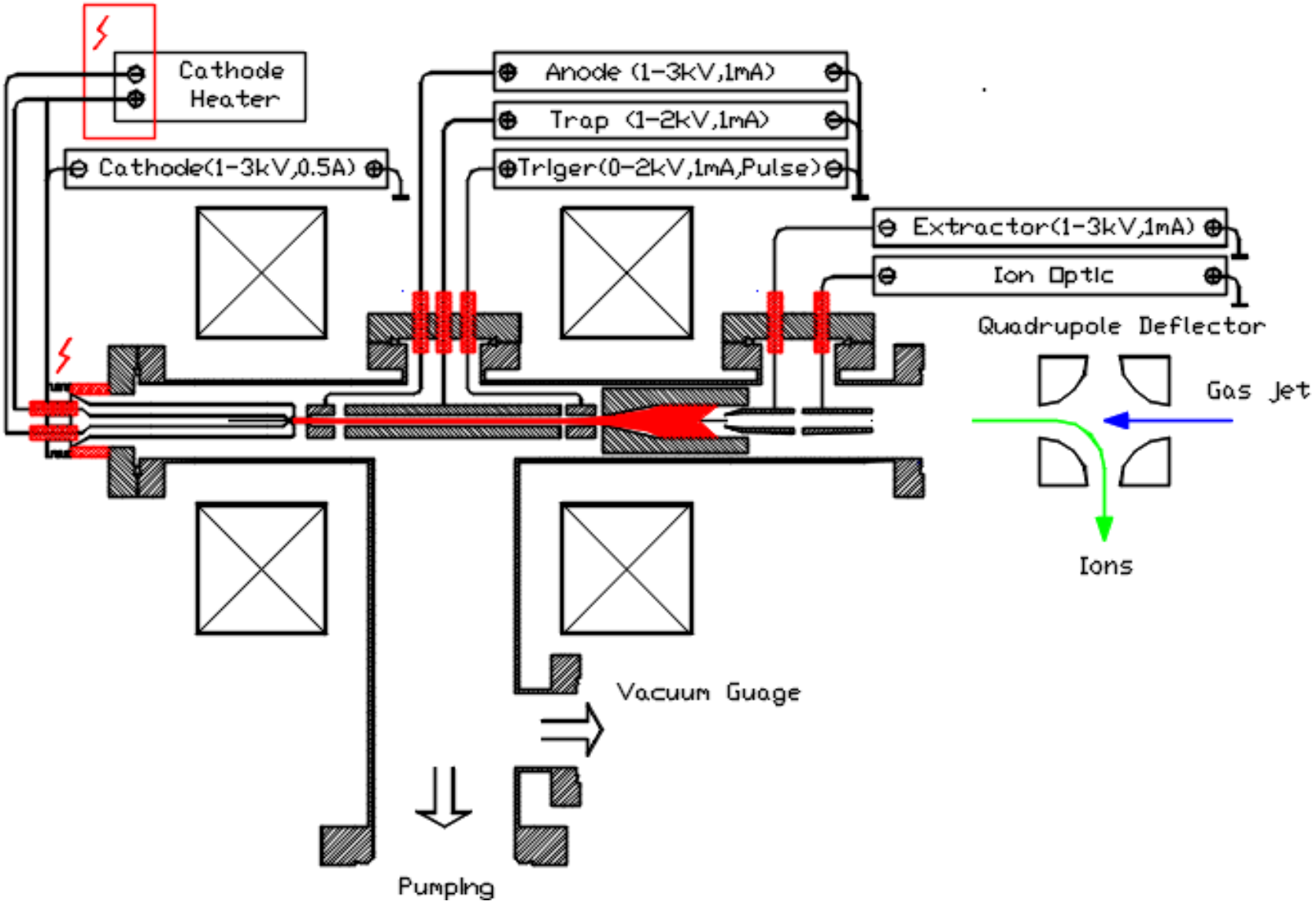
Первеанс электронного пучка – (5 – 10) $A/V^{3/2}$

Ионизация.

Расчеты ионизации проводились по программе IBIS_T для следующих параметров ионной ловушки:

- Базовый вакуум-$1x10^{-8}$ mbar (остаточный газ водород)
- Импульсный ввод рабочего газа ^{3}He представляет собой импульс длительностью 1-2 мс, при давлении в диапазоне $1x10^{-7}$ mbar-$1x10^{-5}$ mbar

Схема Ионизатора $^{3}He^{++}$



Статус проекта поляризованного $^{3}He^{++}$ в ЛФВЭ ОИЯИ

Поляризатор $^{3}He^{++}$

Базовое оборудование - 70-75 % приобретено

Электроника системы измерения поляризации ^{3}He и ^{129}Xe методом ЯМР в слабом магнитном поле (ИЯФ, Новосибирск – срок исполнения ноябрь 2021)

$^{3}He^{++}$ поляризованная мишень

Необходимо техническое задание (ЛФВЭ)

Ионизатор $^{3}He^{++}$

Техническое задание

Базовое оборудование - 25-30 % в наличии

Срок изготовления Ионизатора4-5 месяцев по Договору

Сотрудничество и взаимодействие:

ЛЯП ОИЯИ, ИЯФ Новосибирск, ФИАН Москва, НИИ пульмонологии ФМБА России

Thank you for your attention !