Source of Polarized Ions for the JINR accelerator complex

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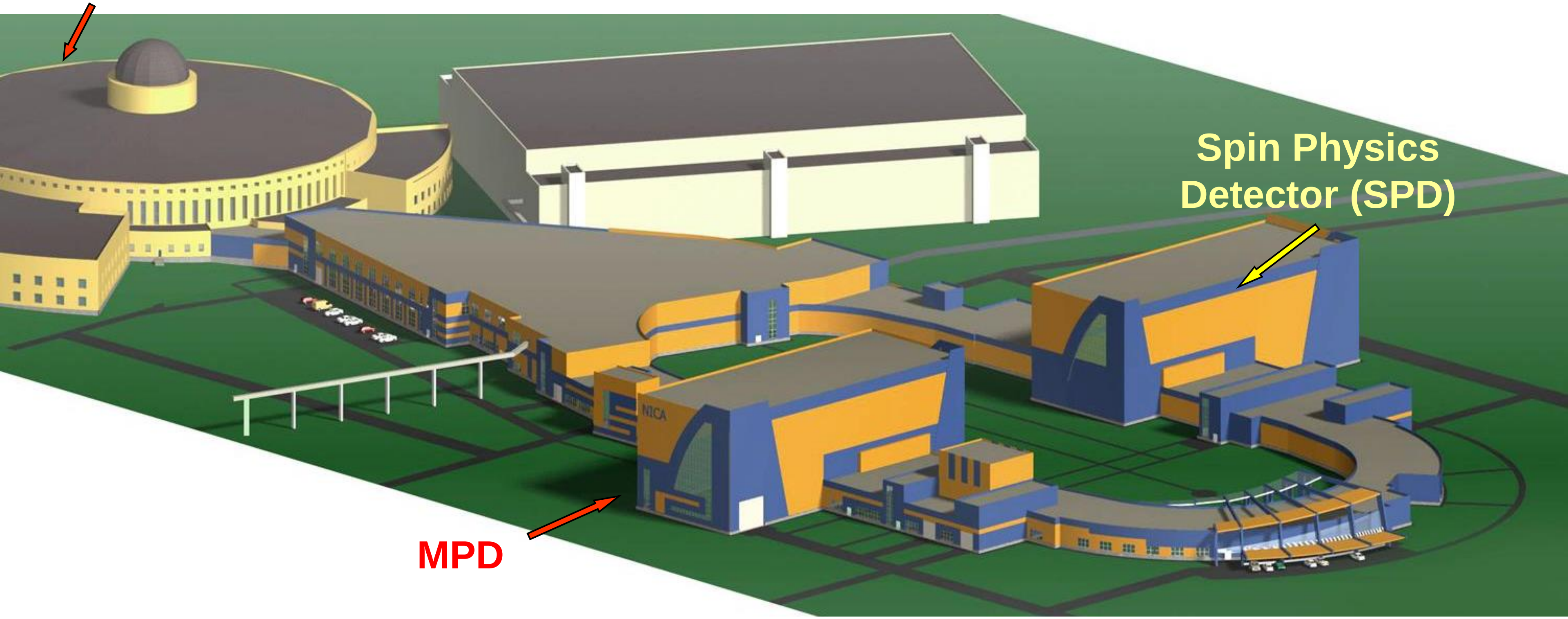
General view of the NICA facility

The new flagship JINR project in high energy nuclear physics, **NICA**
(**N**uclotron-based **I**on **C**ollider f**A**cility), aimed at the study of phase transitions in strongly interacting nuclear matter at the highest possible baryon density, was put forward in 2006



The NICA program consists of several subprojects

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

The expected luminosity of polarized beams is planned at the level of 10^{32} $cm^{-2} \cdot s^{-1}$

- Development of the polarization program at NUCLOTRON/NICA facility supposes the substantial increasing of pulsed intensity of source of the polarized light nuclei
- **The new project: S**ource of **P**olarized **I**ons project (**SPI-project**) assumes the design and production of **the universal high-intensity source of polarized deuterons & protons**
- As the first step the increase of intensity of the accelerated polarized D^+ beam is supposed
- The important fact is depolarization resonances are absent in the total energy range of the NUCLOTRON-M but only for the deuteron beam

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/pulse**

The **SPI-project** assumes the development of the source using charge-exchange ionizer

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

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

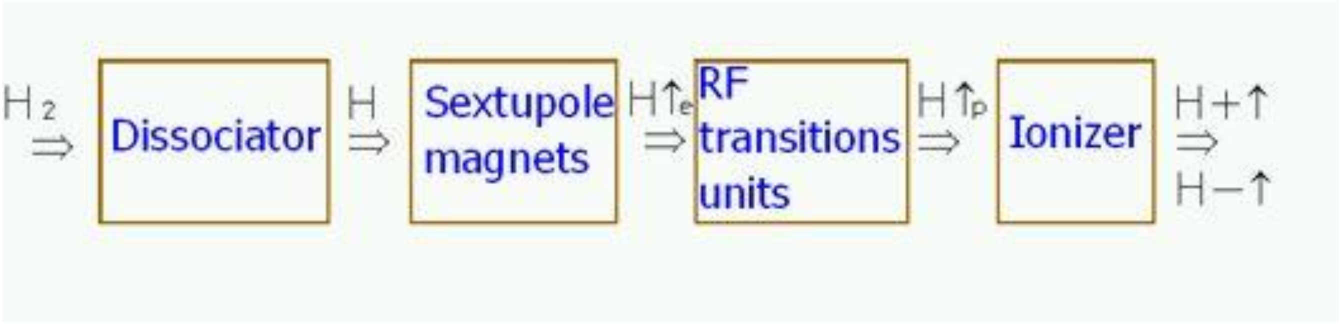
- The design output current of the **SPI** is up to **10 mA** for **$\uparrow D^+$ ($\uparrow H^+$)**
- The **D^+** polarization will be up to 90% of the maximal vector **($\pm$1)** & tensor **(+1,-2)** polarization
- The **SPI** is based in substantial part on the equipment from IUCF(Bloomington, USA)

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

The SPI-project includes the following stages:

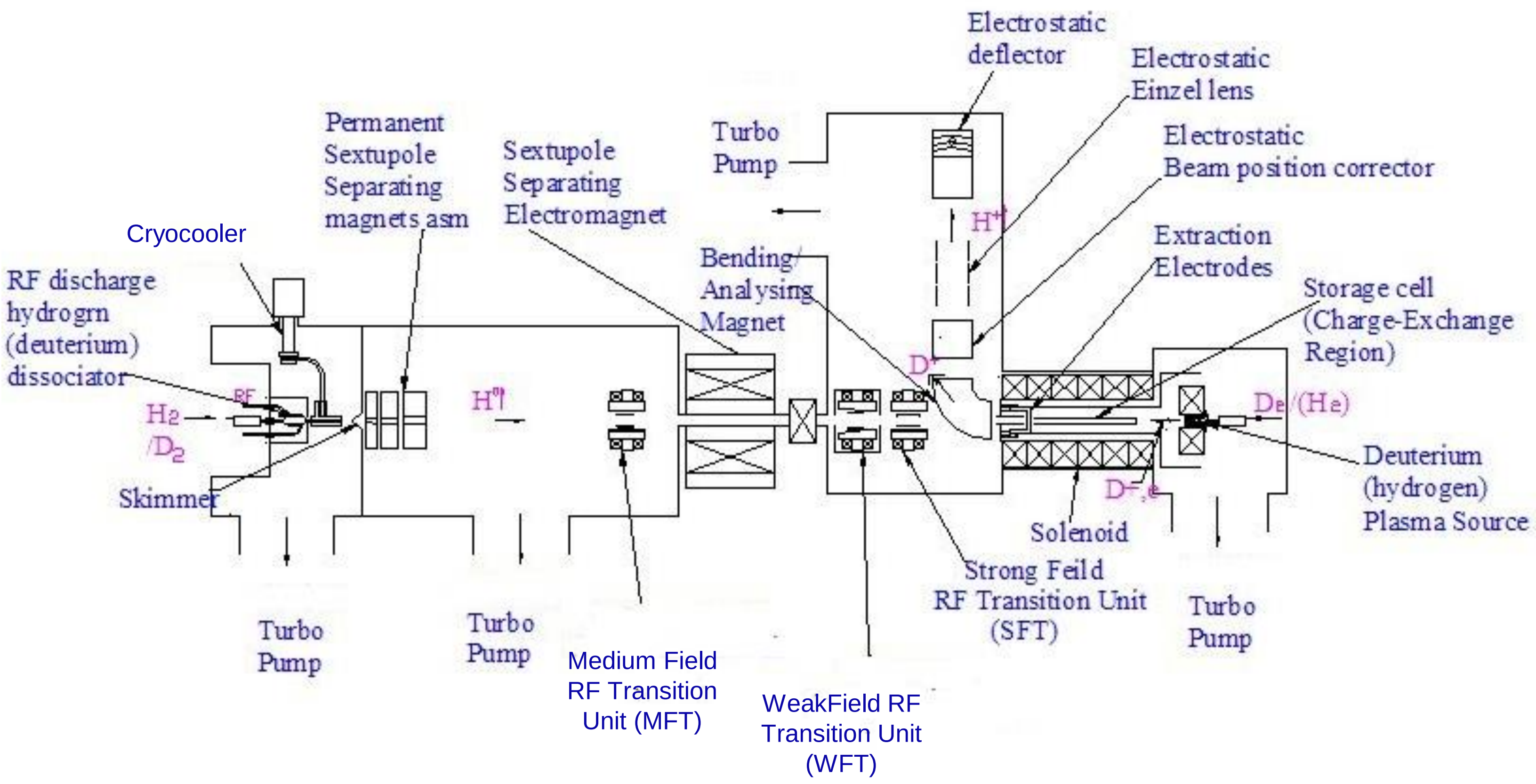
- development of the high-intensity **Source of Polarized Ions**
- complete tests of the **SPI**
- modification of the linac pre-accelerator platform & power station
- **SPI** matching with Low Energy Beam Transfer (LEBT), RFQ & linac
- remote control system (console of linac) of the **SPI** under the high voltage
- **SPI** & **Linac** runs with polarized beam and polarization measurements at the NUCLOTRON

The SPI is atomic beam type polarized ion source

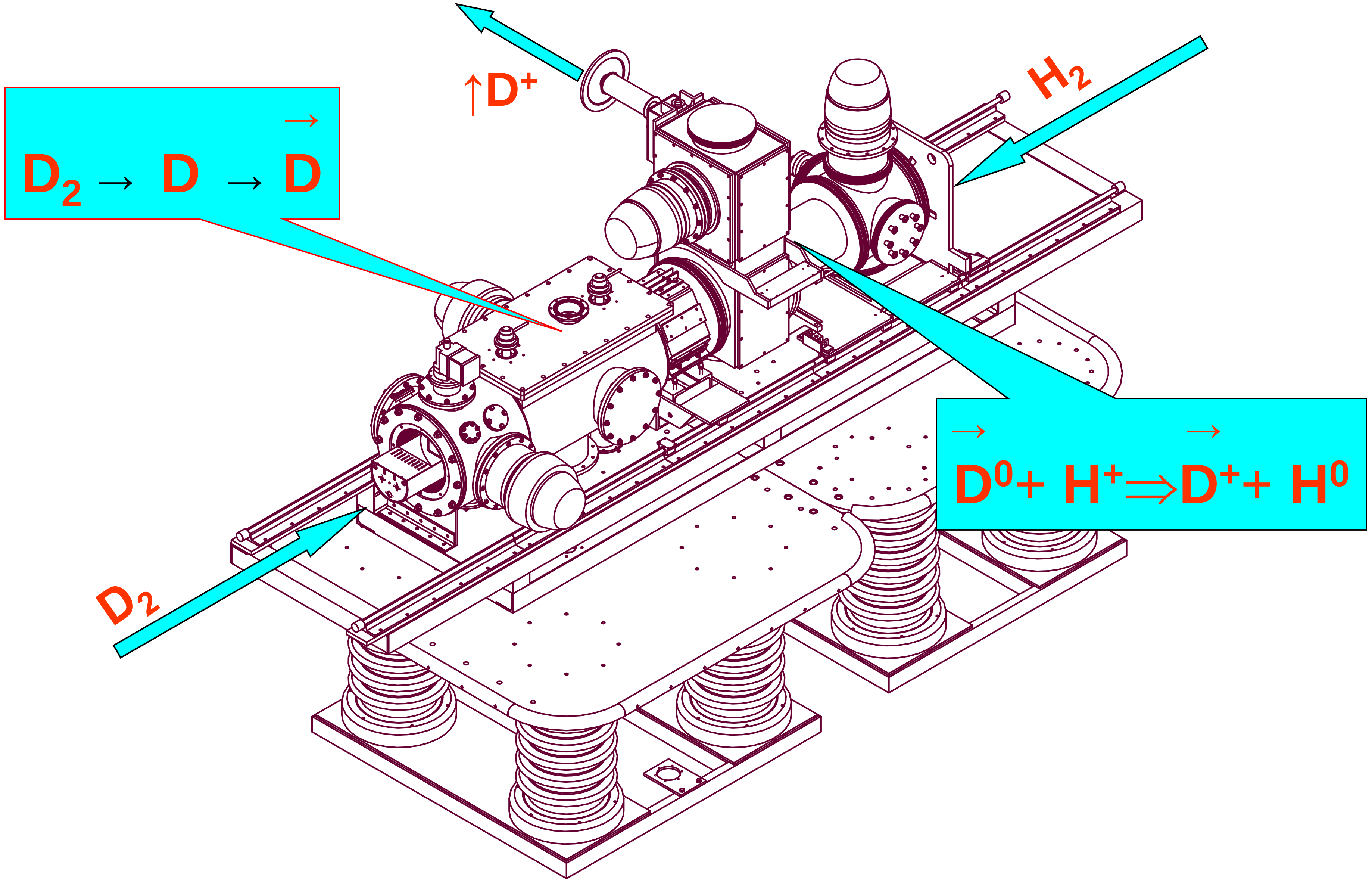


- Thermal hydrogen (deuterium) atoms are produced in RF discharge dissociator.
- The atoms are polarized by passage through inhomogeneous magnetic field of sextupole magnets.
- Nuclear polarization is increased with RF transitions.
- Polarized atoms are converted into polarized ions.

Schematic layout of the SPI



NEW SOURCE OF POLARIZED IONS (DEUTERONS)



The NUCLOTRON feature is that the injection is possible only for positive ions

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-source** assumes to use the storage of polarized deuterium atoms and production of **positive polarized deuterons** by resonance charge-exchange in the hydrogen plasma

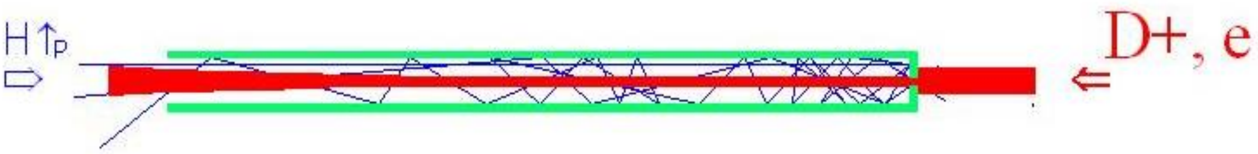
The ionizer with storage of polarized atoms for the SPI allows

- increase intensity of the polarized **D^+** 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

INR RAS polarized ion source

- atomic beam-type source with resonant charge-exchange plasma ionizer and with a storage cell in the charge-exchange region

(Belov et. al. INR RAS, 1986, 1999)

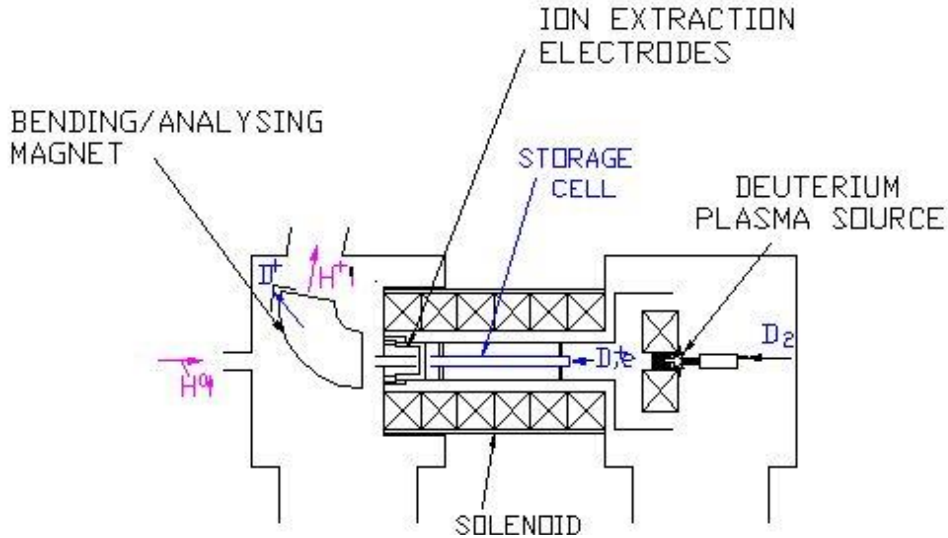


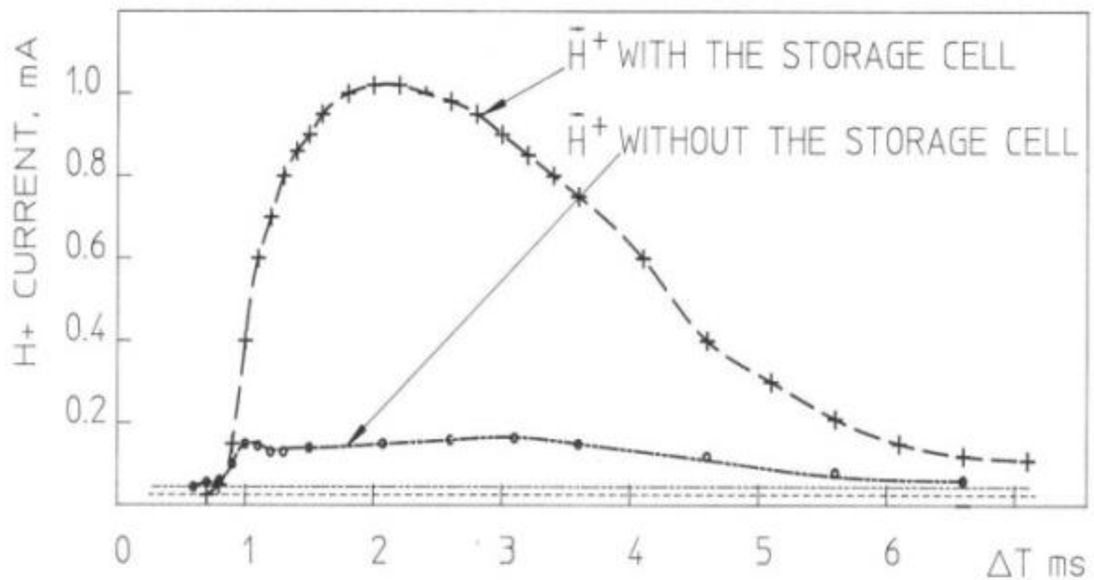
from ABC

storage cell

plasma source

11 mA of $H^+\uparrow$ 80 % polarization has been obtained from the INR source


ION EXTRACTION
ELECTRODES
BENDING/ANALYSING
MAGNET
STORAGE
CELL
DEUTERIUM
PLASMA SOURCE
SOLENOID


H+ CURRENT, mA
H̄+ WITH THE STORAGE CELL
H̄+ WITHOUT THE STORAGE CELL
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
ΔT ms

ABS development

Atomic Beam Source (ABS) of the SPI has been producted and tested at INR RAS

- ✓The pulse density of atomic D beam at the distance of 150 cm from the cooling nozzle outlet is $2.5 \cdot 10^{+10}$ at/cm^3 at the most probable velocity of $1.5 \cdot 10^{+5}$ cm/s

- ✓Functional tests of WFT&MFT of the RF cells of the nuclear polarization of deuterium (hydrogen) atoms were performed

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

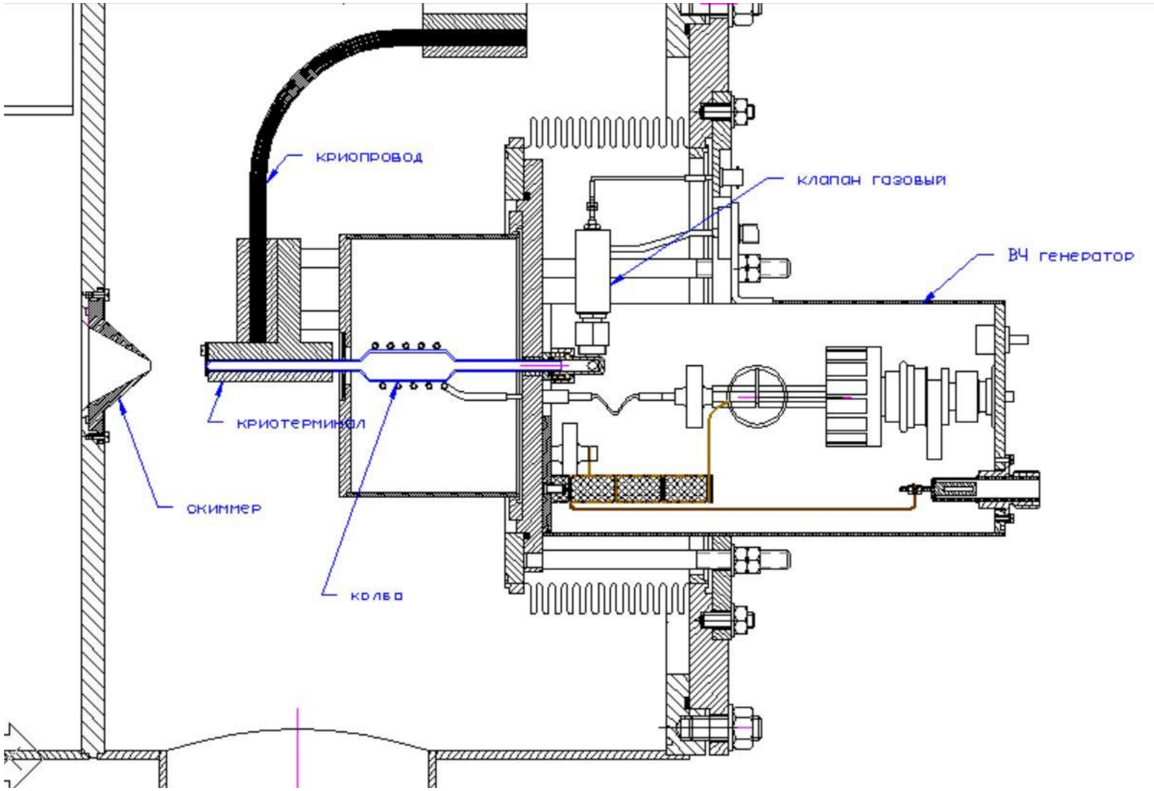
- Nozzle temperature was scanned over a range of 16…80 K

  The optimum nozzle temperature is about 80 K

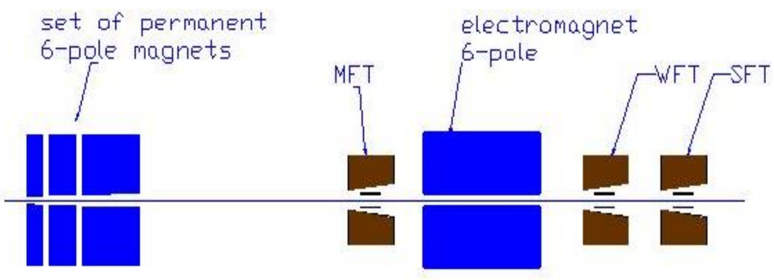
  The optimum feed rate is about 0.045 mbar · l / pulse

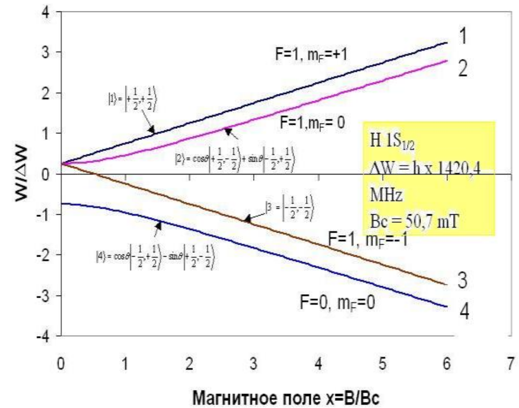
Hydrogen (deuterium) RF discharge dissociator

- INR RAS design
- Pulsed mode of operation
- Pulsed gas valves H_2 (D_2), O_2
- Pulsed RF discharge: 3 ms, 1 Hz pulse of RF discharge
- Long pyrex cooling channel
- Cooling to 80 K using cryocooler

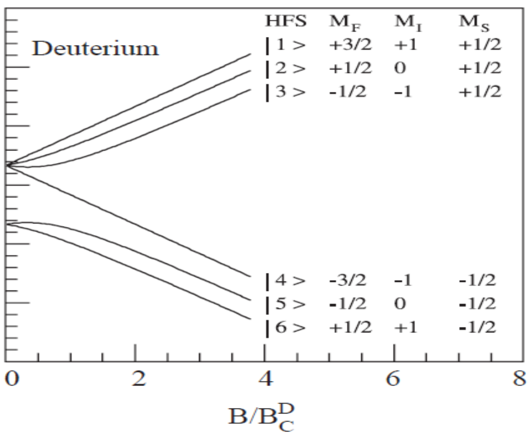


SPI Nuclear polarization





Energy diagram of hfs of hydrogen atom in ground state $1S_{1/2}$



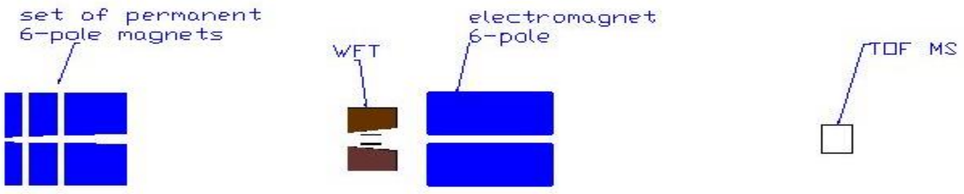
Deuterons

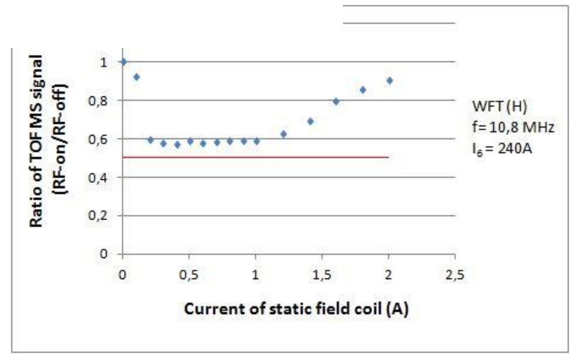
HFT between 6poles	HFT after 6poles	Final D hfs	P_Z	P_{ZZ}
MFT 3 → 4	WFT 1,2 → 3,4	3,4	-1	+1
MFT 3 → 4	SFT 2 → 6	1,6	+1	+1
MFT 1 → 4	SFT 3 → 5	2,5	0	-2
MFT 1 → 4	SFT 2 → 6	3,6	0	+1

Protons

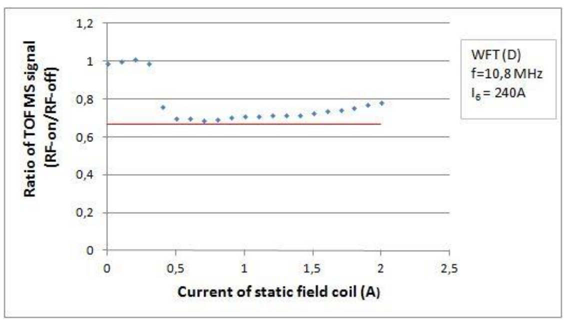
MFT - off	WFT 1→ 3	2,3	-1
MFT - off	SFT 2→ 4	1,4	+1

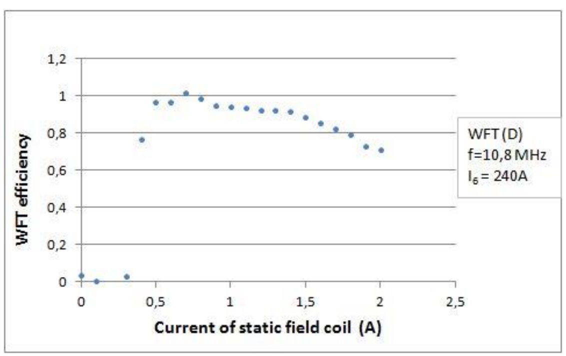
Tests of the WFT

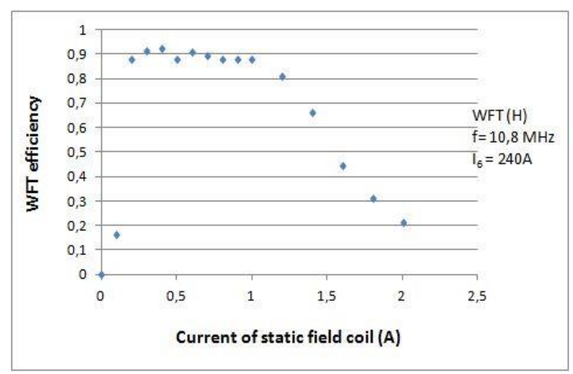




Deuterium atoms



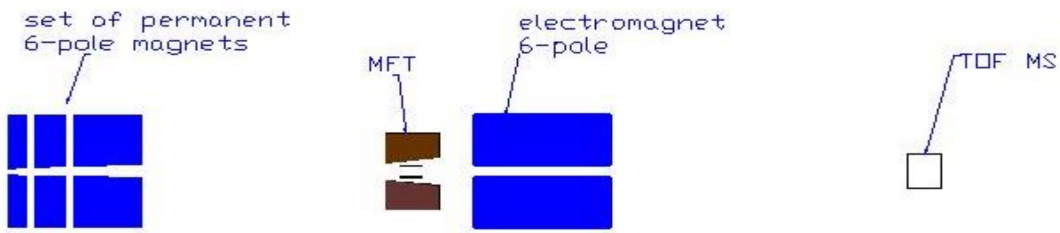




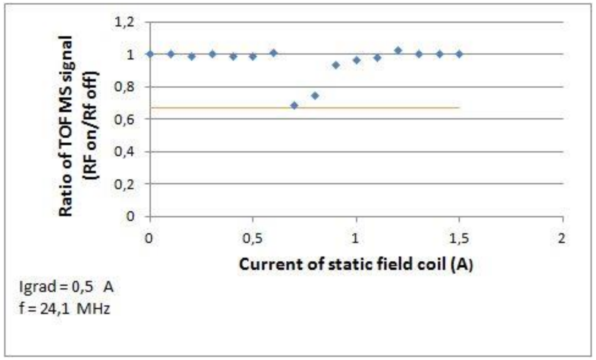
D atoms WFT efficiency – 0.95

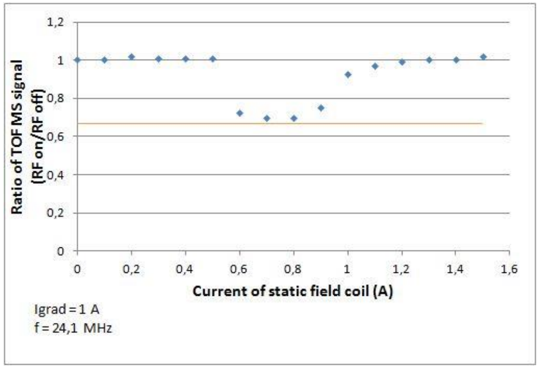
H atoms WFT efficiency – 0.90

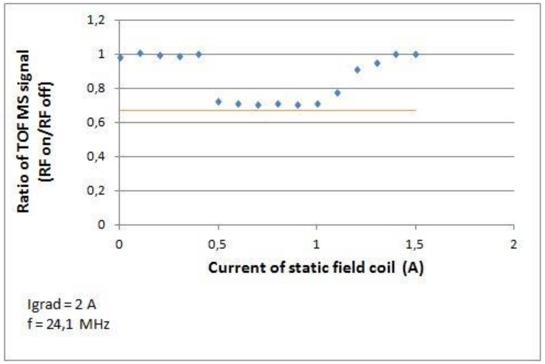
Tests of the MFT



Deuterium atoms







$3 \rightarrow 4$ mode

$1 \rightarrow 4$ mode

SPI Plasma Ionizer

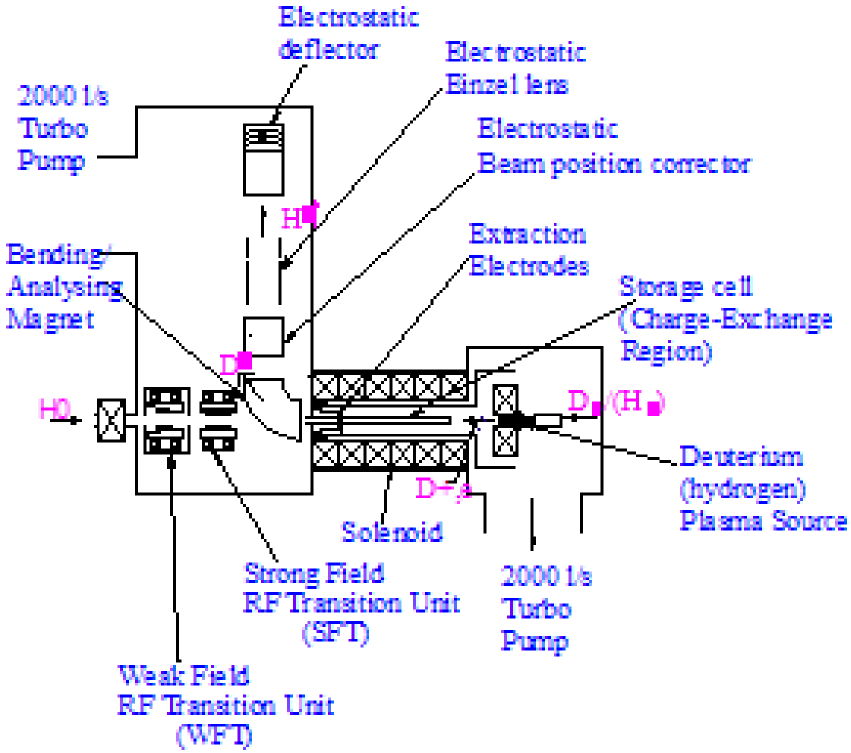
Two options:

• With free atomic hydrogen beam in the charge-exchange region

• With storage cell in the charge – exchange region

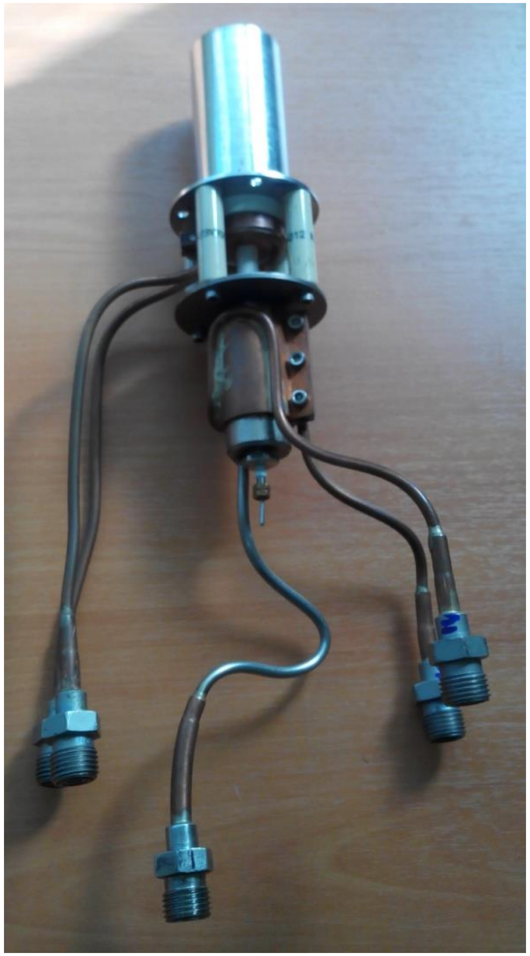
SPI tests started with free atomic hydrogen beam in the charge-exchange region

Ionizer efficiency depends on intensity of plasma jet in the charge-exchange region and respective unpolarized ion current extracted from the ionizer



SPI Plasma source

- Cold cathode arc – discharge plasma source:
- ~200 A, 200 μs pulsed discharge current
- 6 kV, 10 μs discharge ignition voltage
- Pulsed gas valve
- Ion flux in plasma – in Ampere region
- Exracted unpolarized ion fluxes proportional to extraction voltage in 3/2 degree: $I_b \propto U^{3/2}$



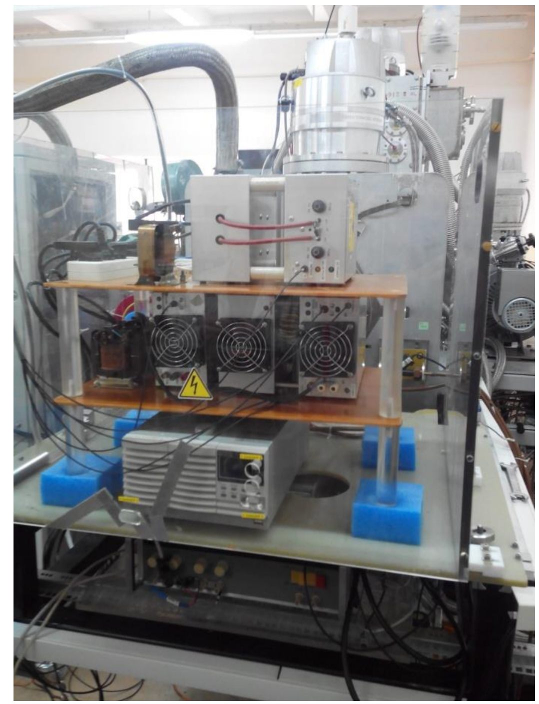
Specially designed power supplies are necessary

Power supplies for the SPI plasma source

- Specially designed power supplies for the plasma source were developed and tested in agreement with INR RAS in 2014-2015 and delivered to JINR in 2015

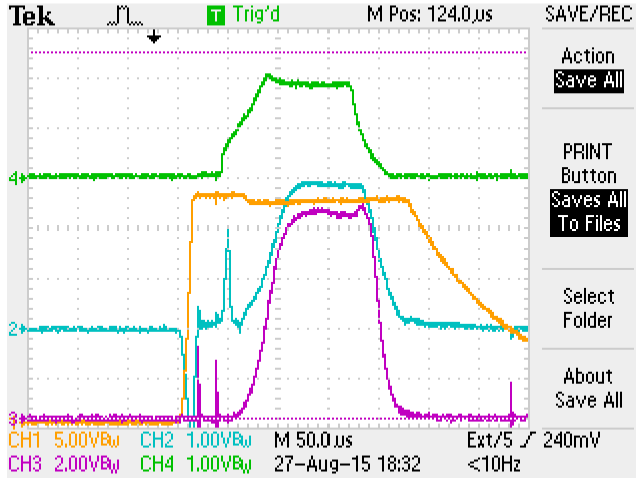
High-voltage pulse generator of the arc plasma source

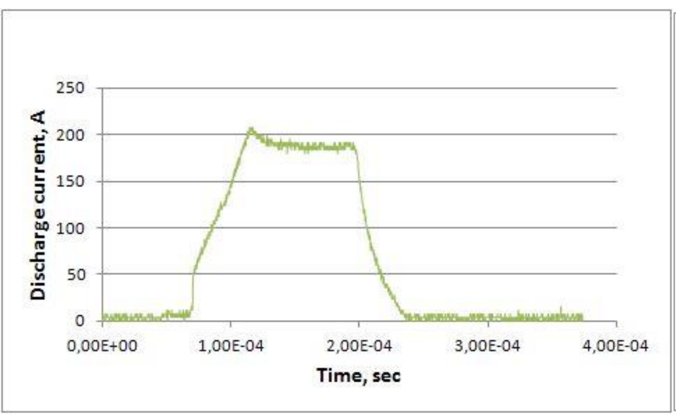
Mode of operation: 25 kV pulse
400 μs pulse length
pulse repetition rate of 1 Hz

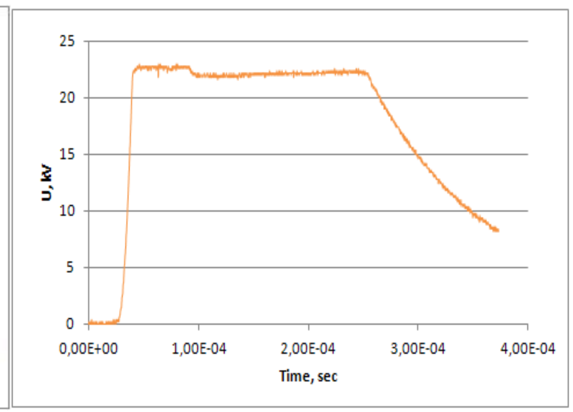


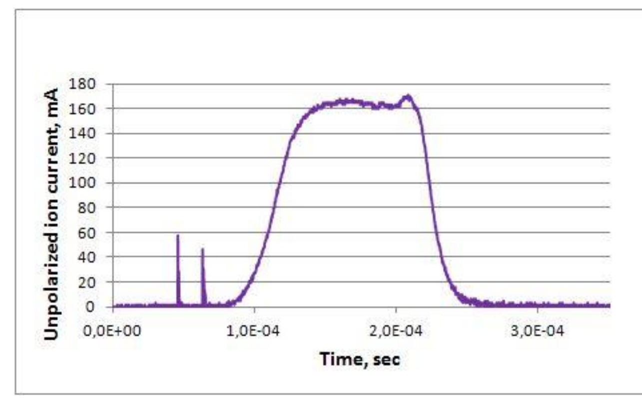
Power supplies for the plasma source. Control system of the PS was developed at INR and JINR

Operation of the ionizer (August 2015)







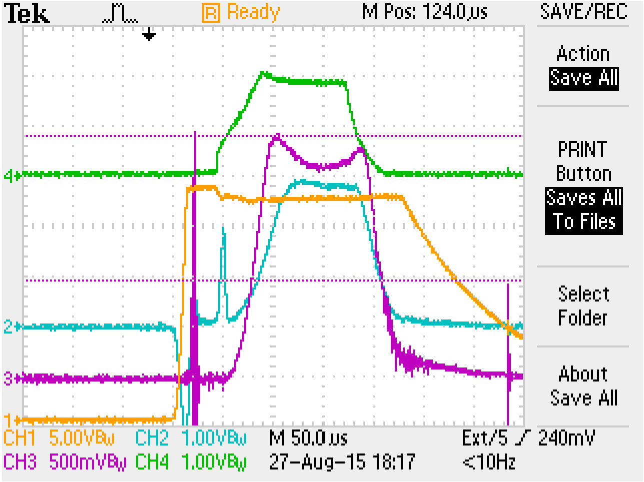


Discharge current pulse of the plasma source, 200 A peak, 100 µs

Accelerating voltage pulse: 22kV, 300 µs

Unpolarized ion current (D+) downstream the analysing magnet,
160 mA – peak, 100 µs

Tests of the polarized ion beam production with free atomic hydrogen beam (without storage cell)



Polarized proton beam with peak current of **1.3 – 1.4 mA**
(difference with atomic hydrogen beam “on” and “off”)
is recorded downstream the analyzing magnet

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

- optimization of the ion-optical system up to 25 keV and transportation of the high-current deuteron beam

- polarimetry of the accelerated beam at the NUCLOTRON

It is necessary to develop control system components for primary analysis & data acquisition and for fiber optic system of data transmission

General view of SPI (JINR test bench September 2015)

Tests bench program of the SPI in 2015

- operating with deuterium plasma arc source, running with the charge exchange ionizer

to date, the first phase of work was completed at the energy of the accelerated ions up to 25 keV

- start-up and testing of SPI mode of polarized protons obtaining

at present this work at the energy of the accelerated ions up to 25 keV is in progress

- operating with hydrogen plasma arc source, running with the charge exchange ionizer including the storage cell in the ionization volume

the storage cell is ready now

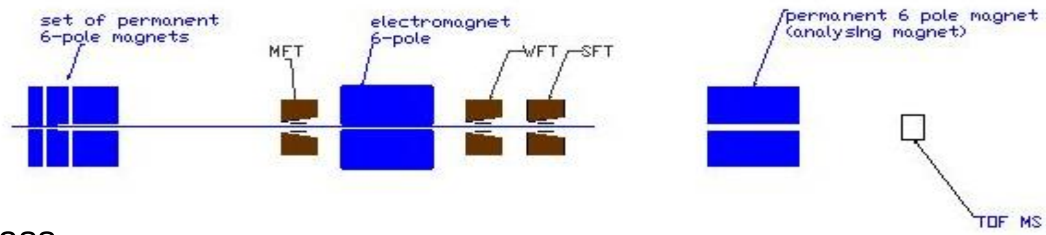
- start-up and testing of SPI mode of polarized deuterons obtaining

- development of control system components for primary analysis & data acquisition and for fiber optic system of data transmission is in progress now

- optimization of the ion-optical system up to 25 keV and transportation of the 5-10mA deuteron beam

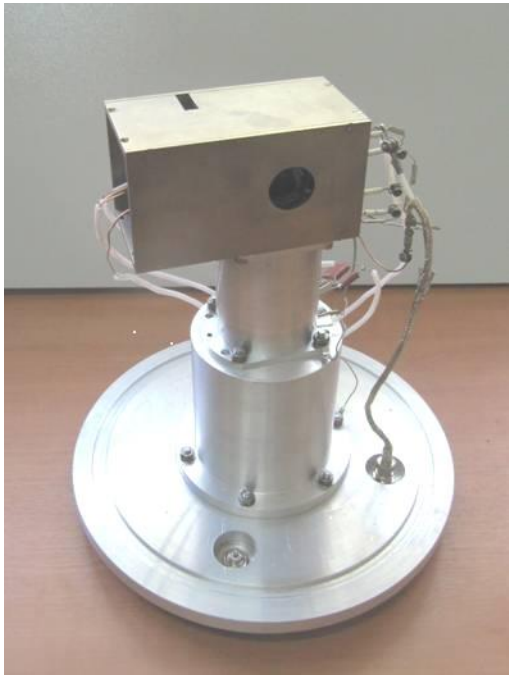
- optimization of WFT, SFT using Breit-Rabi polarimeter

Breit – Rabi polarimeter for tuning of the RF transition units



• The sensitivity of the mass spectrometer provides detection of atoms and molecules of the beam density 1010 - 1012 cm-3. The time resolution of the mass spectrometer is 10 microseconds

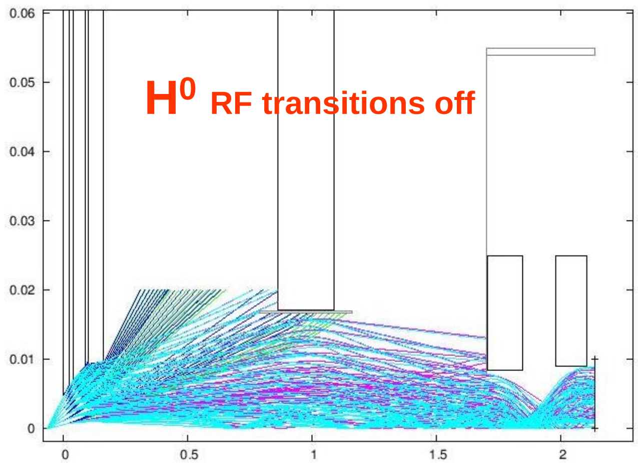
• Two additional permanent sextupole magnets are under construction.

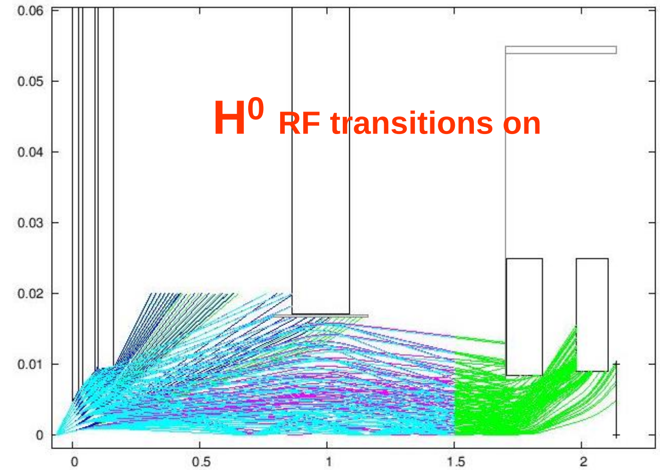


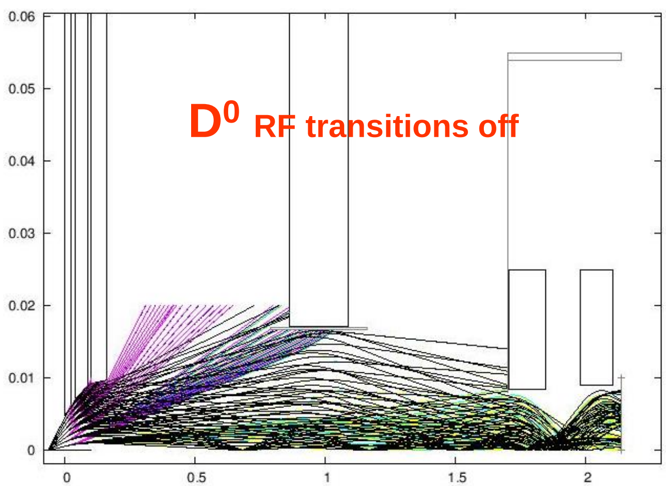
Simulation of the polarimeter

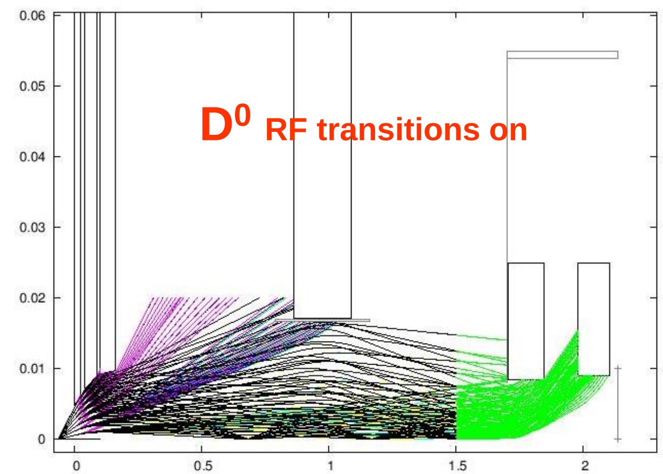
parameters of analyzing magnets

Permanent magnet	quadrupole	sextupole
aperture D, mm	17	18
length L, mm	140	125
magnetic field, T	1.6	1.6





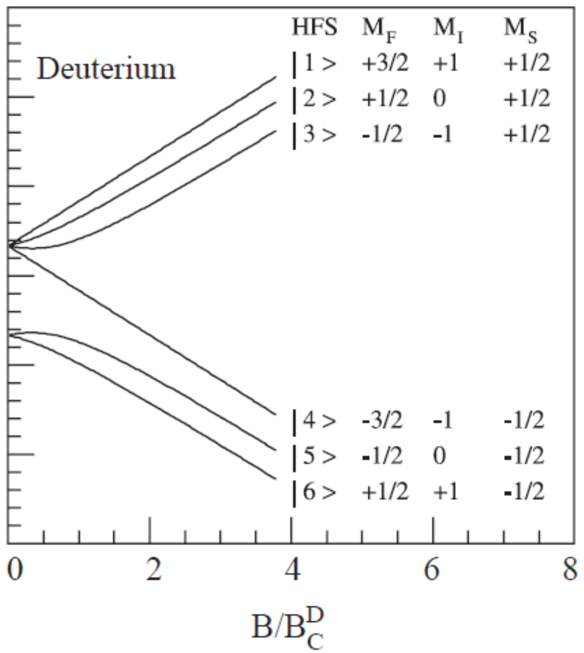




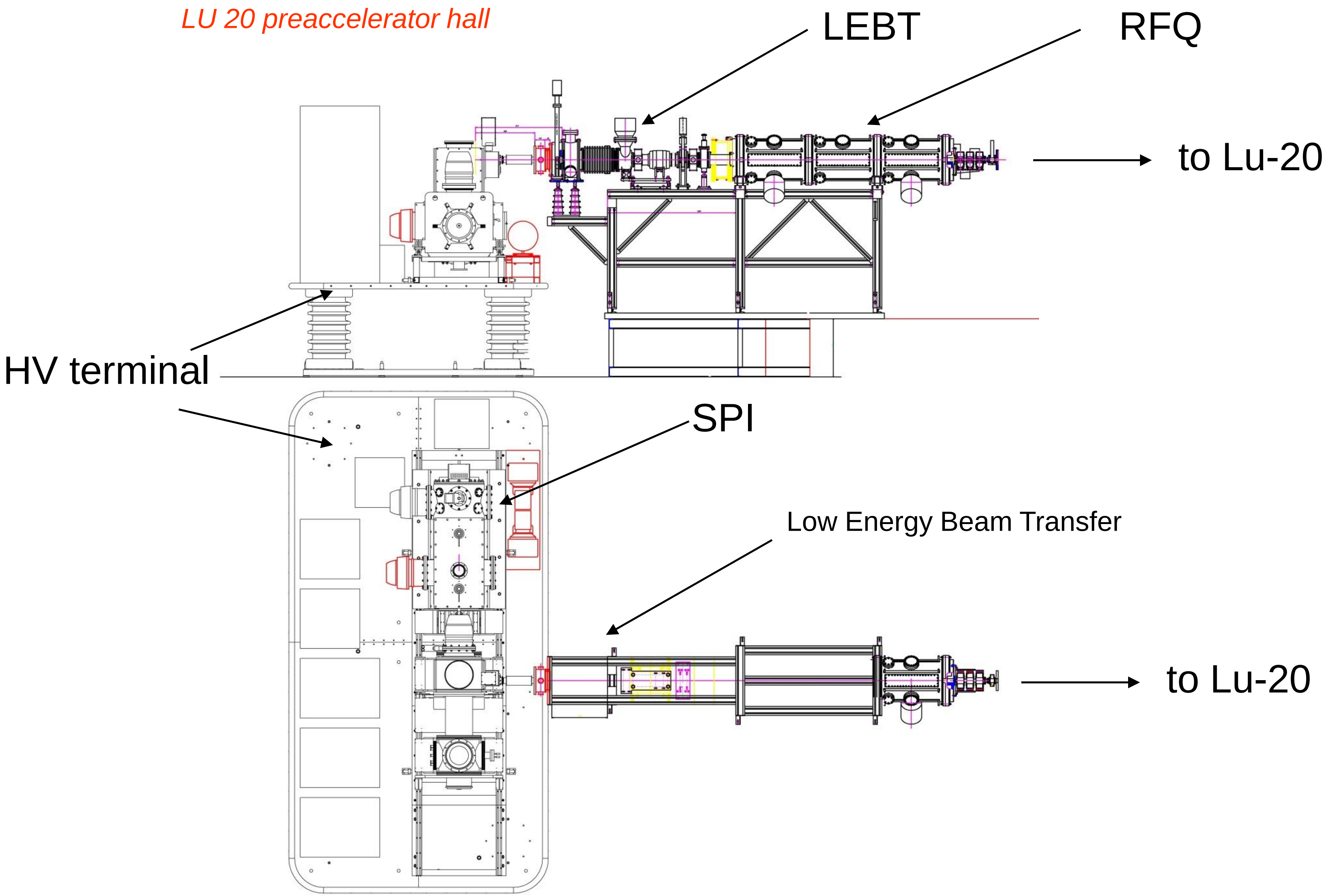
expected analyzer efficiency 95%
velocity of atoms 1700-2500 m/s

Expected relative intensity of the TOF MS signals for different combinations of the turned on RFT (for polarized deuterons)

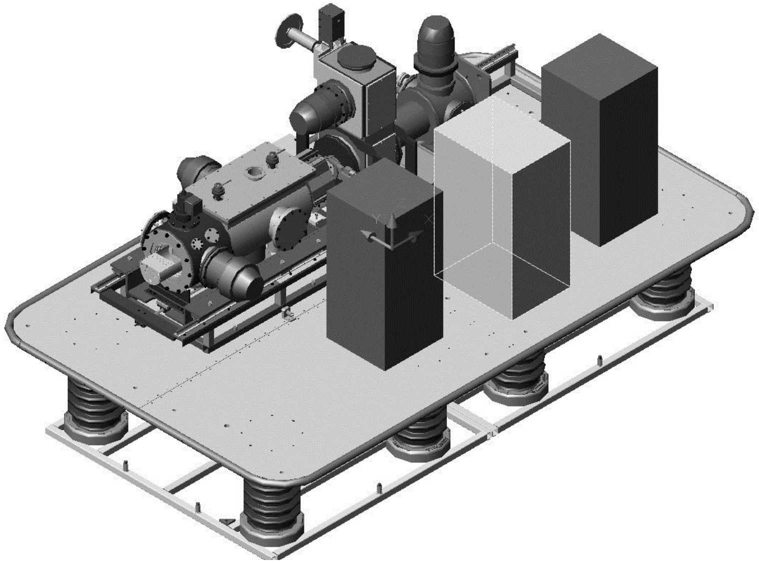
HFT between 6poles	hfs downstream the electromagnet 6pole	HFT downstream the electromagnet 6pole	hfs downstream the analyzing 6pole	AB relative Intensity at the TOF MS position
MFT -off	1,2,3	WFT - off, SFT - off	1,2,3	1
MFT -off	1,2,3	WFT 1-4 SFT - off	2,3	0,67
MFT - off	1,2,3	WFT –off, SFT 2-6	1,3	0,67
MFT -off	1,2,3	WFT –off, SFT 3-5	1,2	0,67
MFT 3-4	1,2	WFT - off, SFT - off	1,2	0,67
MFT 3-4	1,2	WFT - off, SFT 2-6	1	0,33
MFT 3-4	1,2	WFT 1,2-3,4 SFT 3-5	-	0
MFT 1-4	2,3	WFT - off, SFT 3-5	2	0,33
MFT 1-4	2,3	WFT - off, SFT – 2-6	3	0,33

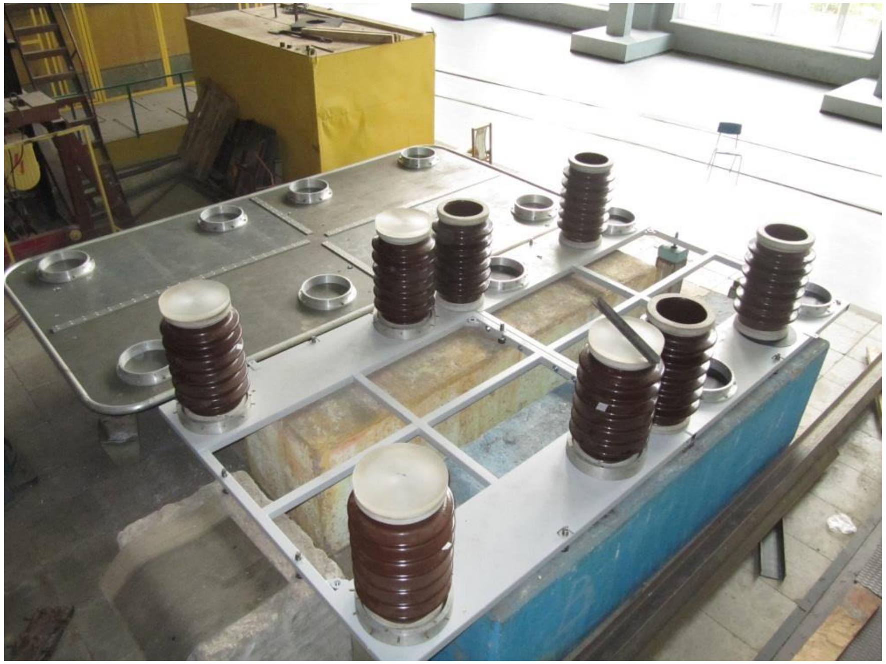


SPI & LEBT & RFQ layout at linac Lu 20



HV-terminal status production (September 2015)





Conclusions

- SPI is now under tests at the JINR test bench.
- ABS module and plasma ionizer operation has been tested and were found satisfactory.
- Polarized proton beam of 1.3-1.4 mA peak has been produced with free atomic beam in the charge-exchange region of the source.
- It is planned to continue tests with the storage cell installed into the ionizer
- RF transitions units will be retuned in their operational modes using Breit-Rabi polarimeter
- Assembling and commission of the SPI at the linac are planned by the end of 2015

Remark

The goal is to develop a source of polarized $^{3}He^{++}$ ions (helions) on the basis of the Source of Polarized Ions (protons&deuterons) for the JINR Accelerator Complex

The SPI RF dissociator is used with ^{3}He gas for production of ^{3}He atoms in the metastable $2^{3}S_{1}$ state

Stern–Gerlach separation with a sextupole magnet and an RF transition in a weak magnetic field are used for nuclear polarization of the metastable atoms

Yu. A. Plis, V.V. Fimushkin et al. ***"A study of polarized metastable 3He beam production"*** *(PSTP 09)*

Metastability exchange optical pumping of 3He atoms and ionization to $3He^{++}$ ions using nearly resonant charge-exchange collisions between polarized 3He atoms and unpolarized $4He^{++}$ ions in weak magnetic field:

$3He^{0}\uparrow + 4He^{++} \Rightarrow 3He^{++}\uparrow + 4He^{0}$ $\sigma \sim 5\cdot 10^{-16}\ cm^{2}$

(A. Belov - 1998)

Magnetic moment of helion μ_{h} = –– 2.127 μ_{N}

Magnetic moment of neutron μ_{n} = -–1.913 μ_{N}

Thank you