The SPI source of polarized ions for the NUCLOTRON (September 2018)

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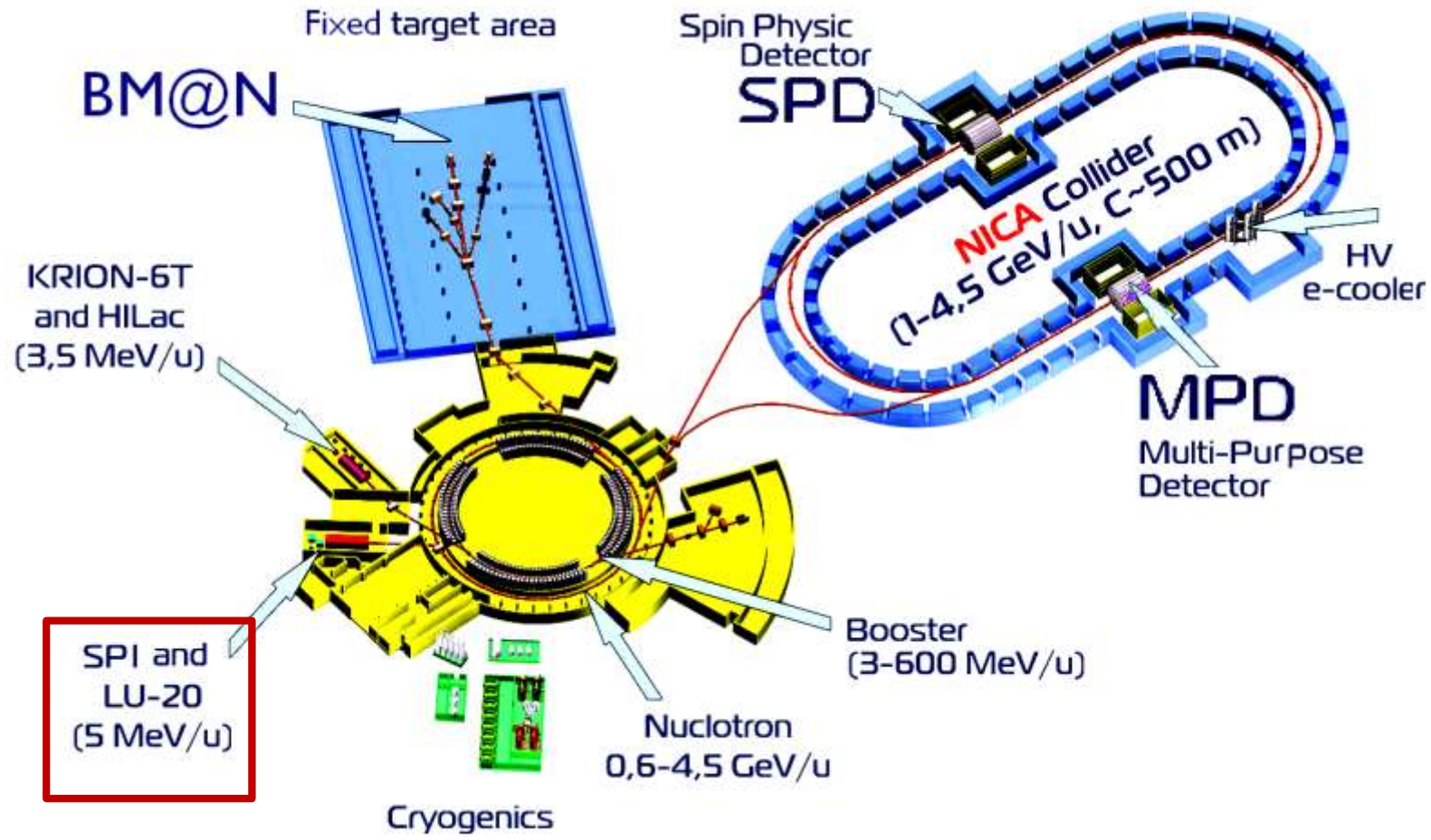
General view of the NICA facility



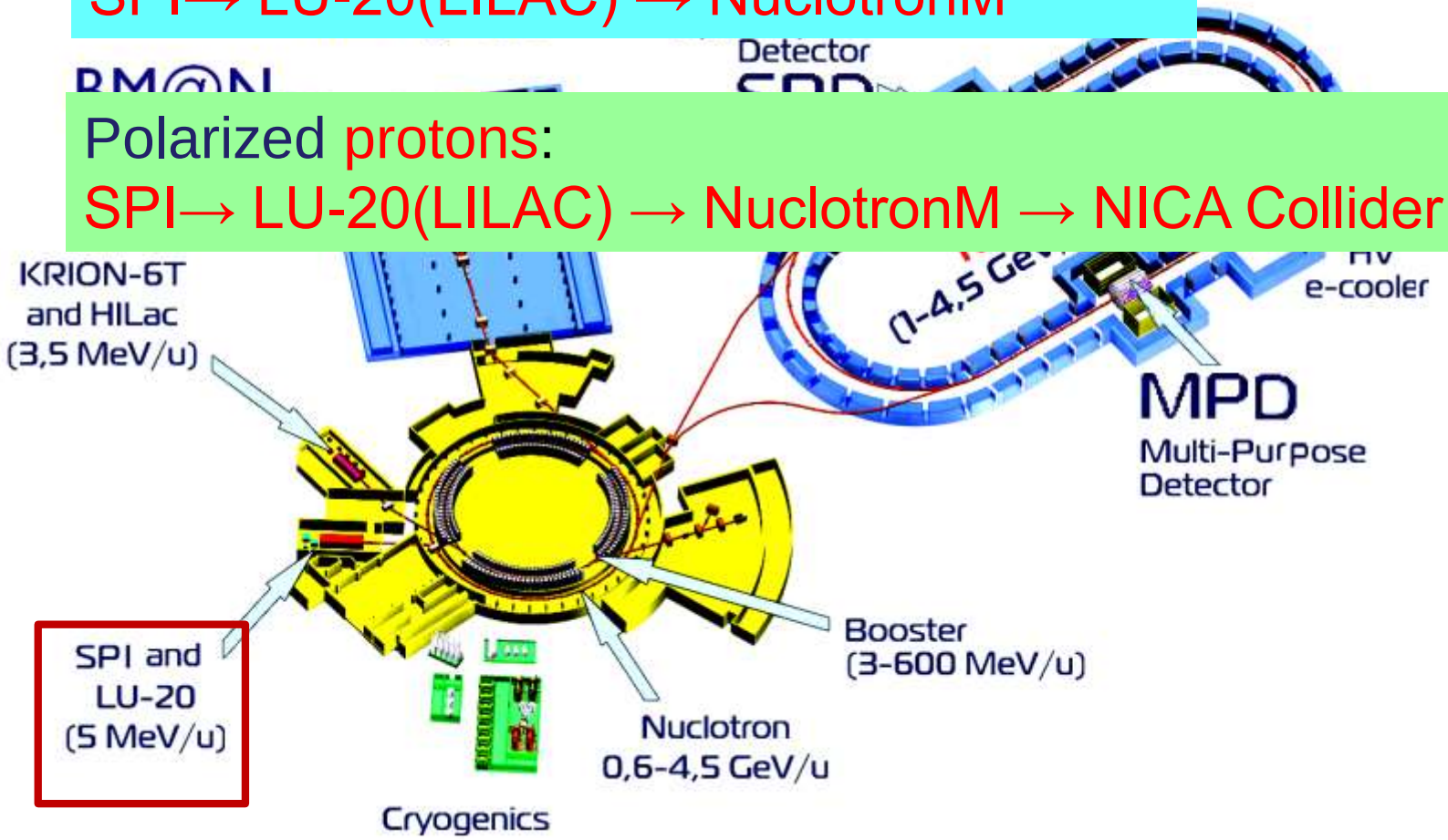
Physics with polarized light ion beams is considered as an important part of the NICA program. The expected luminosity of polarized beams is planned at the level of 10^{32} $cm^{-2} \cdot s^{-1}$.

NICA Collider constructing status

NICA operation in Polarized Mode

Polarized deuterons:
SPI→ LU-20(LILAC) → NuclotronM

Polarized protons:
SPI→ LU-20(LILAC) → NuclotronM → NICA Collider



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

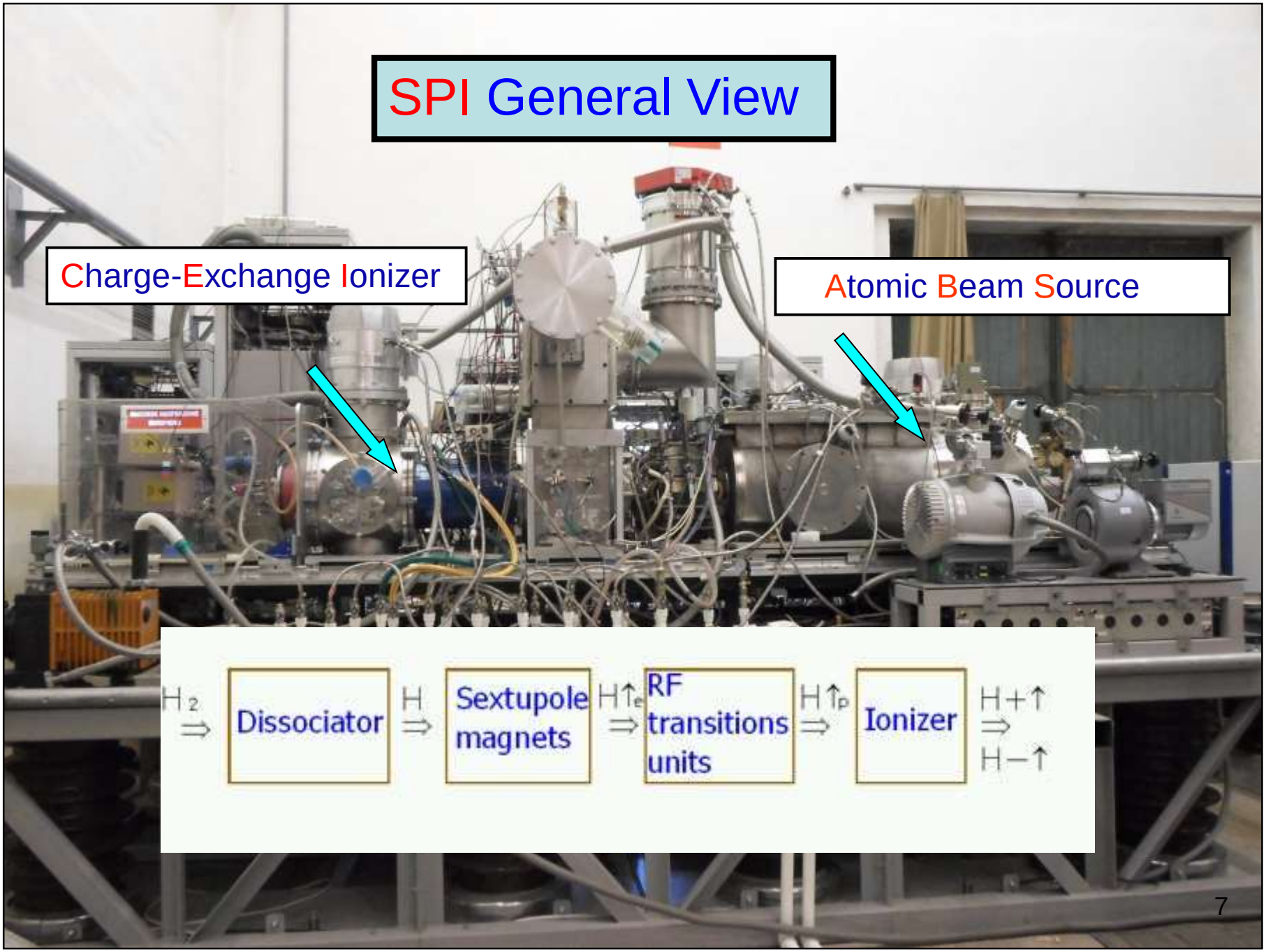
The main purpose of the SPI-project is to increase the intensity of the accelerated polarized beams at the JINR Accelerator Complex up to **$5 \cdot 10^{10}$ d(p)/pulse**

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

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

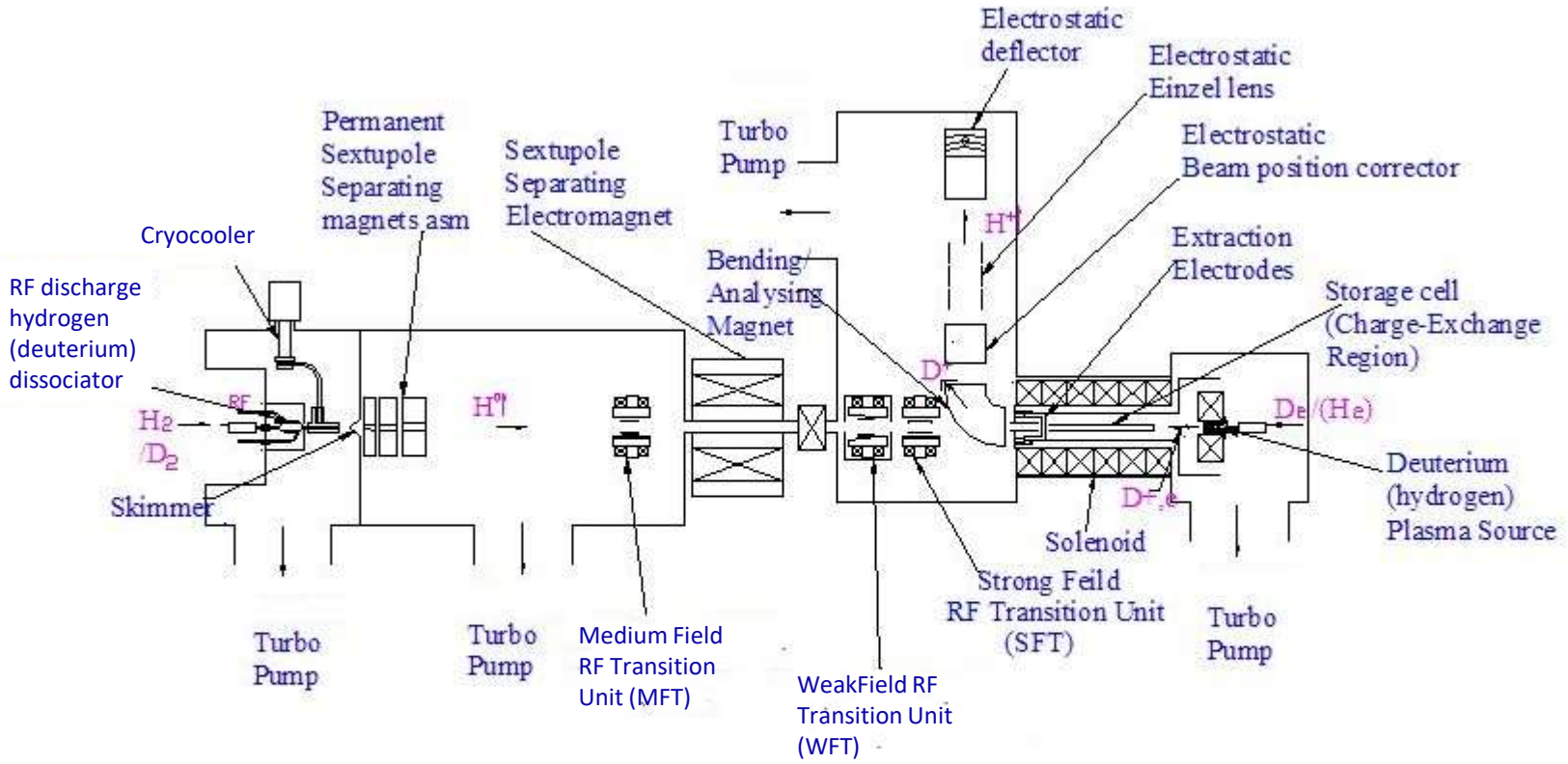
- The design output current of the **SPI** is up to **10 mA** for **↑D^+ (↑ H^+)**
- The **D^+** (**H^+**) polarization will be up to 90% of the maximal vector **(±1)** & tensor **(+1,-2)** polarization

SPI General View



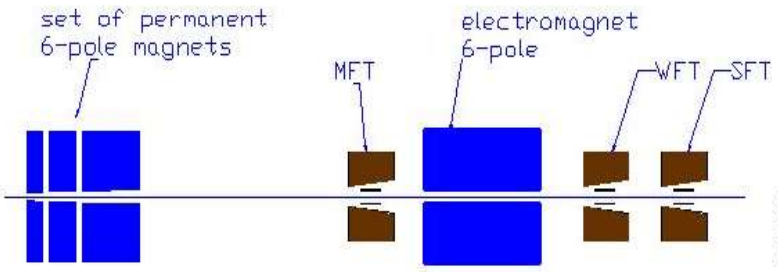

SPI General View

Schematic layout of the SPI

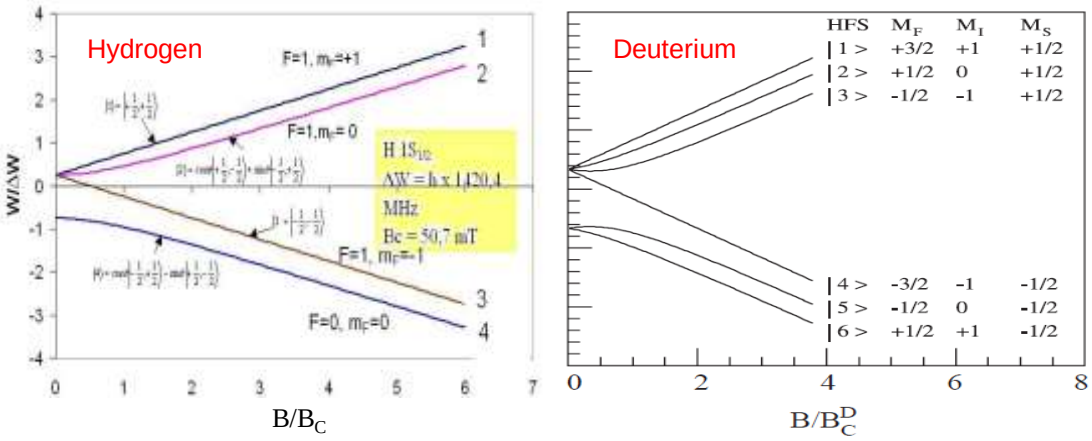


- Hydrogen (deuterium) atoms are produced in RF discharge dissociator.
- The production of an electron polarized atomic beam is done in an inhomogenious magnetic field of three permanent sextupole magnets
- Nuclear polarization is produced by RF transitions units
- Polarized atoms are converted into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

SPI Nuclear polarization



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



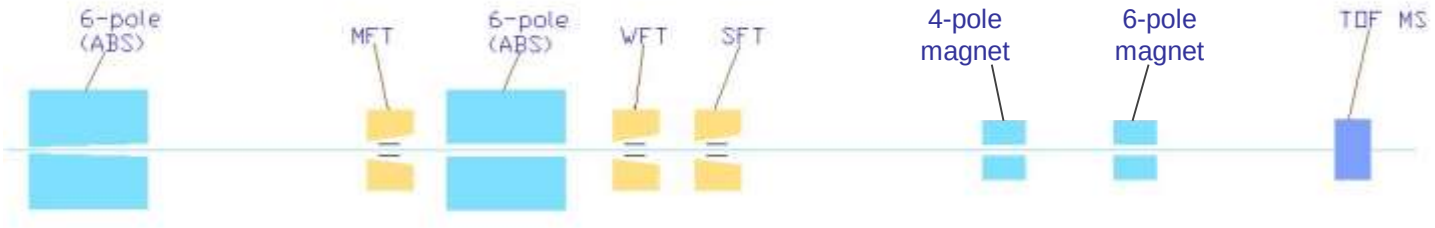
Deuterons

HFT between 6-poles	HFT after 6-poles	Final state	P_Z	P_{ZZ}	
MFT $3 \rightarrow 4$	WFT $1,2 \rightarrow 3,4$	3,4	-1	+1	
MFT $3 \rightarrow 4$	SFT $2 \rightarrow 6$	1,6	+1	+1	
MFT $1 \rightarrow 4$	SFT $3 \rightarrow 5$	2,5	0	-2	
MFT $1 \rightarrow 4$	SFT $2 \rightarrow 6$	3,6	0	+1	
MFT - off	SFT $3 \rightarrow 5$	1,2,5	+1/3	-1	**DSS -experiment**
MFT - off	SFT $2 \rightarrow 6$	1,3,6	+1/3	+1	
MFT - off	WFT $1 \rightarrow 4$	2,3,4	-2/3	0	ALPOM-2 experiment
MFT $3 \rightarrow 4$	SFT $2 \rightarrow 6$	1,6	+1	+1	

Protons

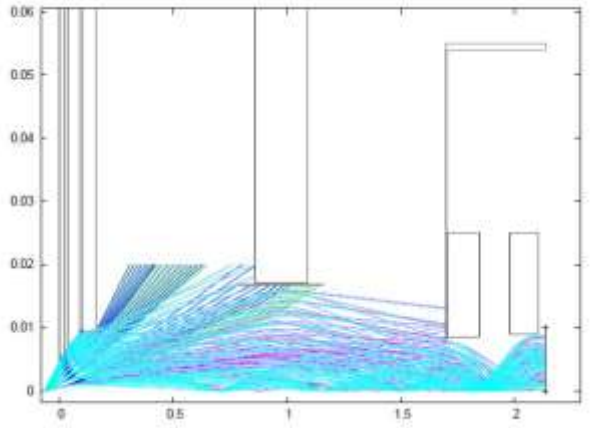
MFT - off	WFT $1 \rightarrow 3$	2,3	-1	
MFT - off	SFT $2 \rightarrow 4$	1,4	+1	

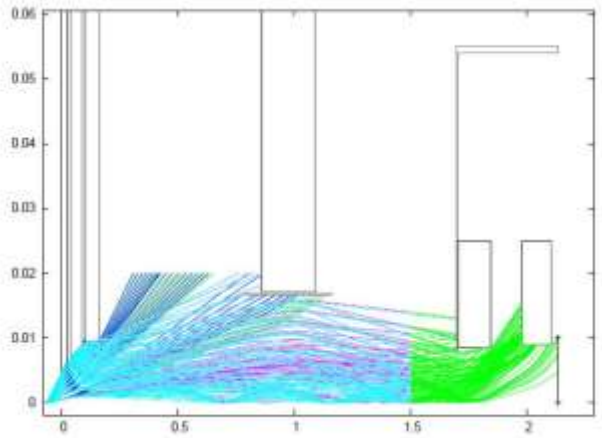
Breit – Rabi polarimeter for Tuning RF Transition Units



- The sensitivity of the TOF mass spectrometer provides detection of atoms and molecules of the beam density 10^{10} - 10^{12} cm^{-3}. The time resolution of the mass spectrometer is 10 μs.
- Two additional permanent magnets are used.

Simulation of the polarimeter



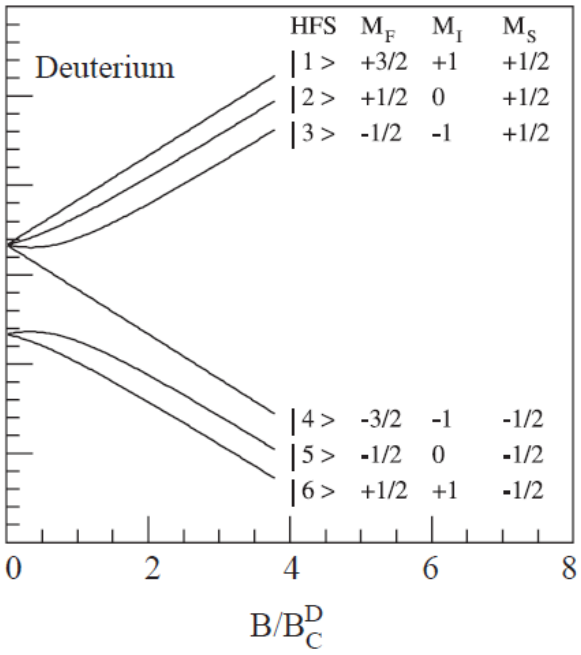


NdFeB Magnets parameters

	4 - pole	6- pole
aperture	Ø 17 mm	Ø 18 mm
length	140 mm	125 mm
magnetic field	1.6 T	1.6 T

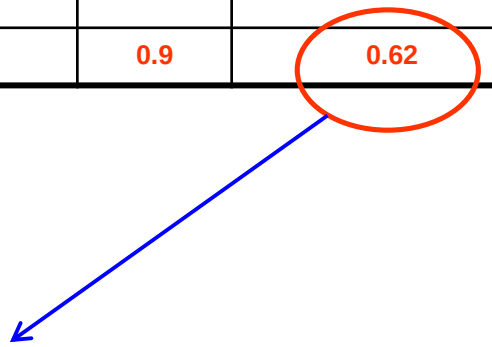
Expected relative intensity of the TOF MS signals for different operational modes of the RFT units
(polarized deuterons)

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**



SFT (D) tuning with BREIT – Rabi polarimeter

	SFT 2-6	SFT 3-5	MFT3-4+SFT2-6	MFT1-4+SFT2-6	MFT1-4+SFT3-5	WFT1-4	MFT3-4+WFT1,2-3,4
Efficiency	0.93	0.90	0.89	0.92	0.91	0.9	0.62



It is necessary to improve the operation of the WFT 1,2-3,4 nuclear polarization cell

SPI Charge-Exchange Ionizer

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

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

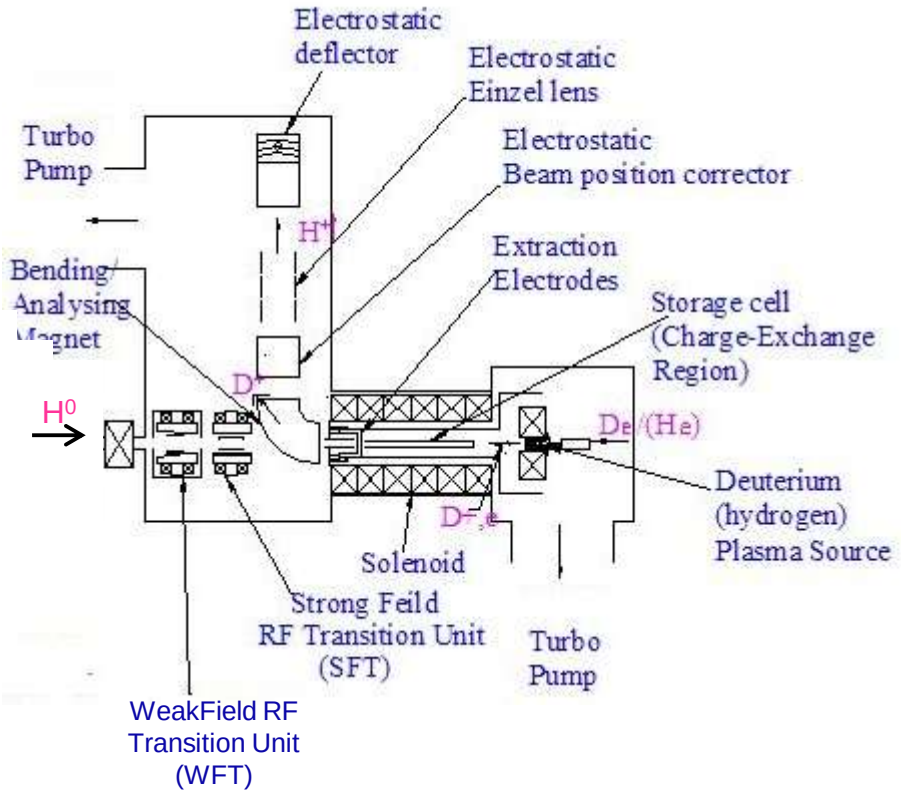
$$D^0\uparrow + H^+ \Rightarrow \mathbf{D^+}\uparrow + H^0$$

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

- Ionization efficiency is about 10%

- <u>The storage cell allows:</u>

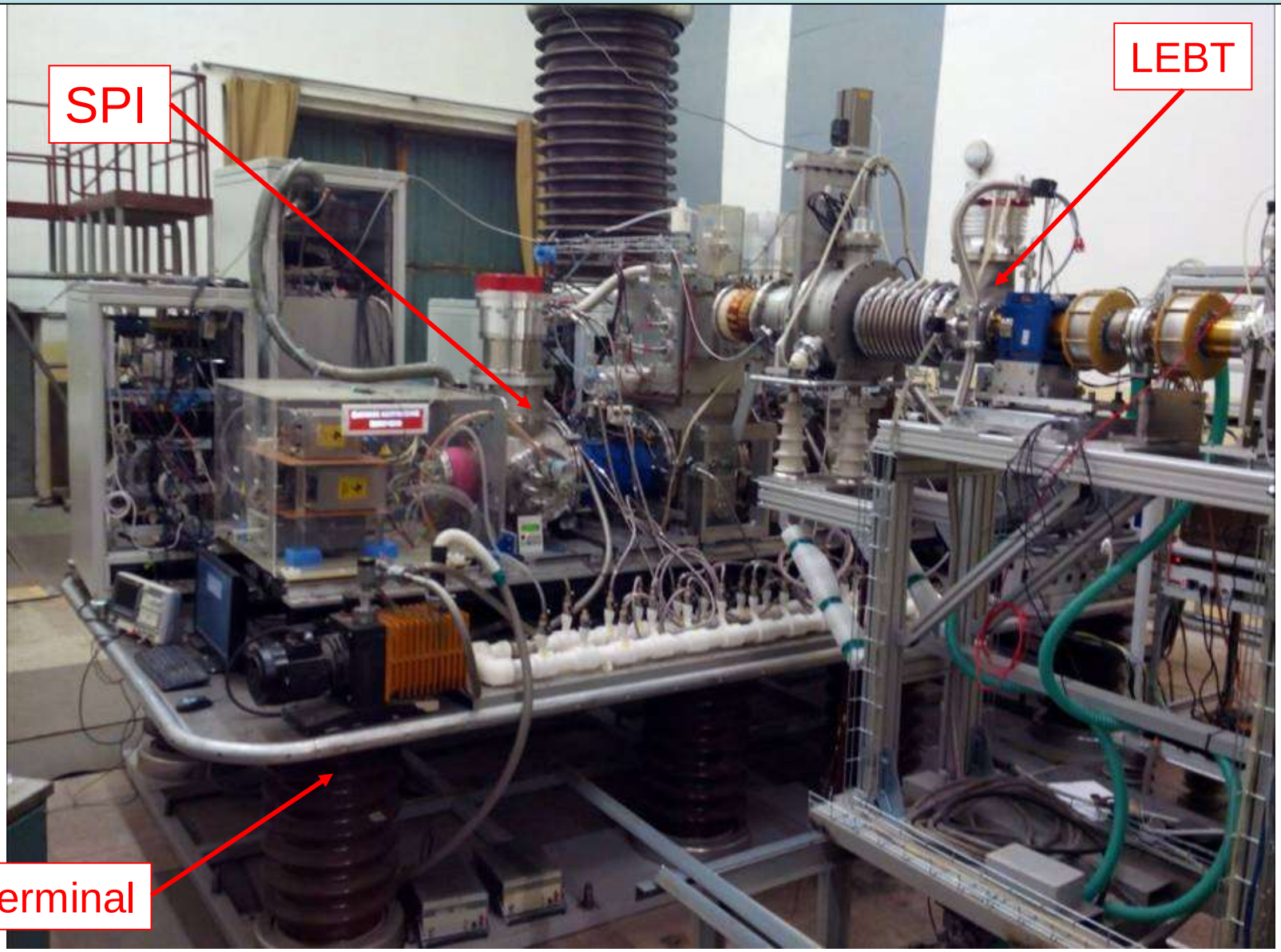
  - increase intensity of the polarized D^+ (H^+) beam
  - reduce emittance of the polarized beam
  - considerably reduce H_2^+ ion current which is difficult to be separated from polarized D^+ due to similar mass of the ions



Commissioning of the SPI

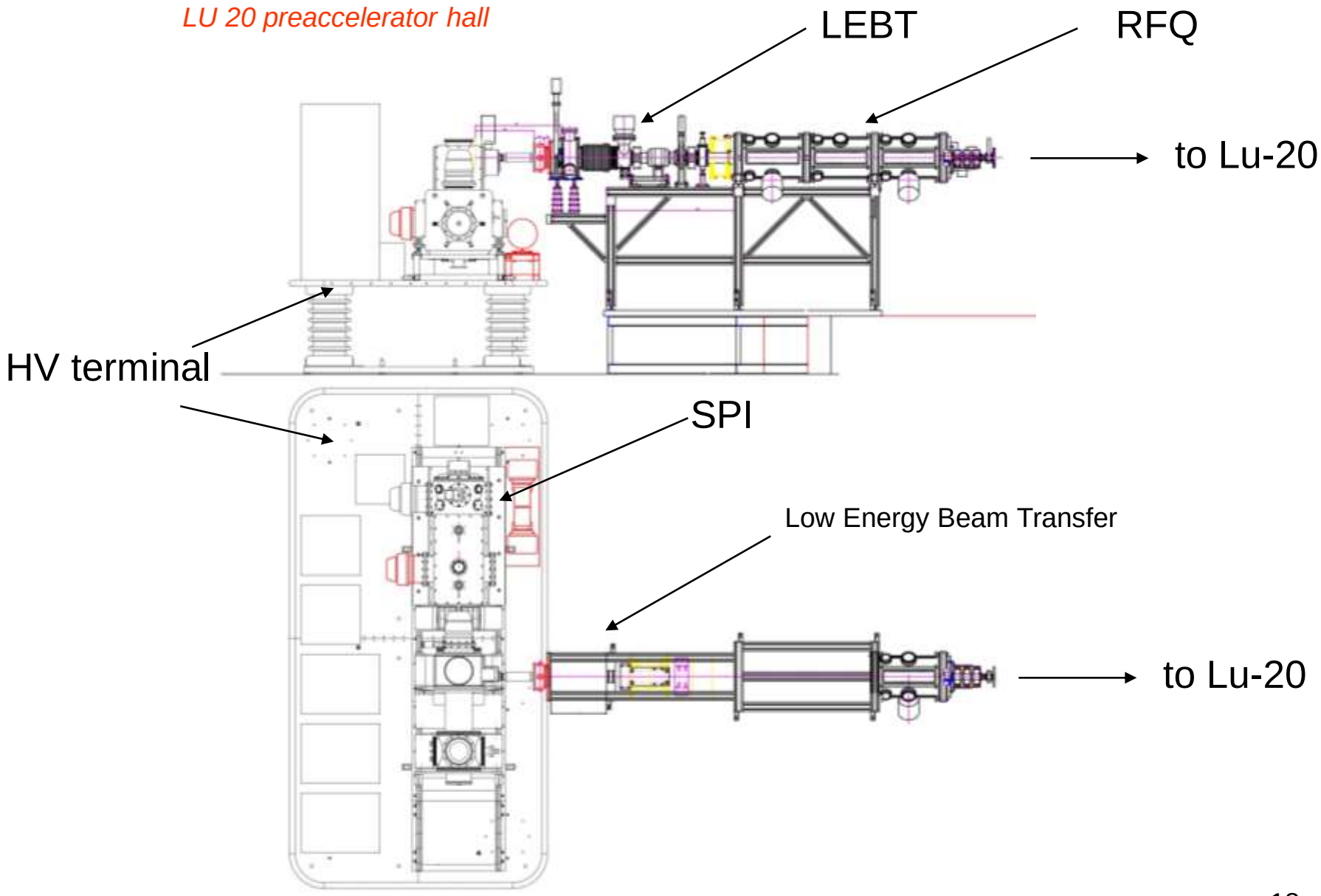
- The SPI has been commissioned in 2016 (Nuclotron run#52)
- The source has been used in NUCLOTRON runs #52, 53, 54 for production of polarized and unpolarized deuterons and polarized protons
- Operation in mode with unpolarized D^+ is about 600 hours (runs 52,53,54)
- Operation in mode with polarized D^+ is about 900 hours (runs 53, 54)
- Operation in mode with polarized H^+ is about 50 hours (run 54)
- Stable polarization, stable operation of the SPI systems
- Intensity in NUCLOTRON is up to 10^9 d/pulse (internal polarized D^+ beam)

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

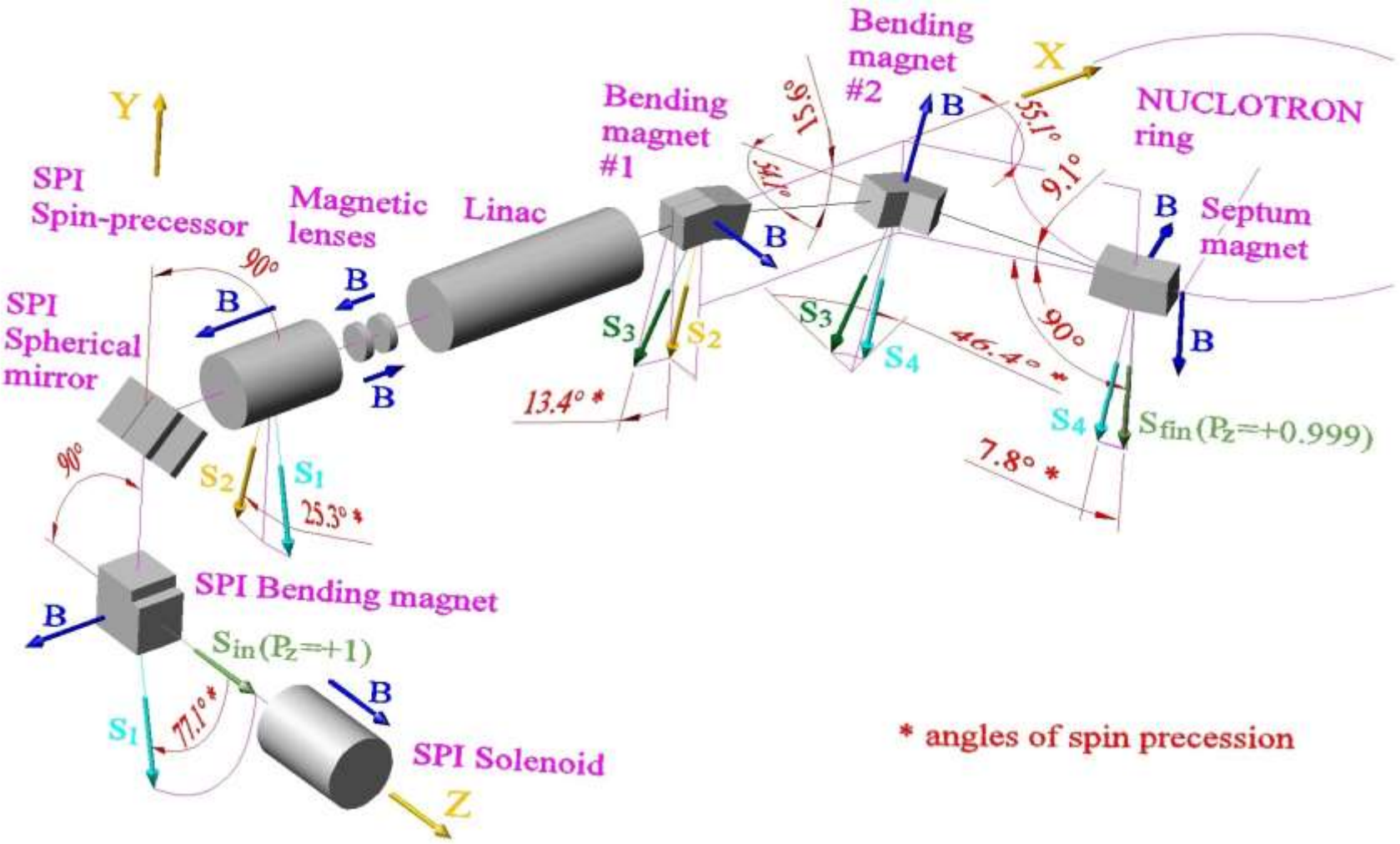


SPI & LEBT & RFQ layout at linac Lu 20

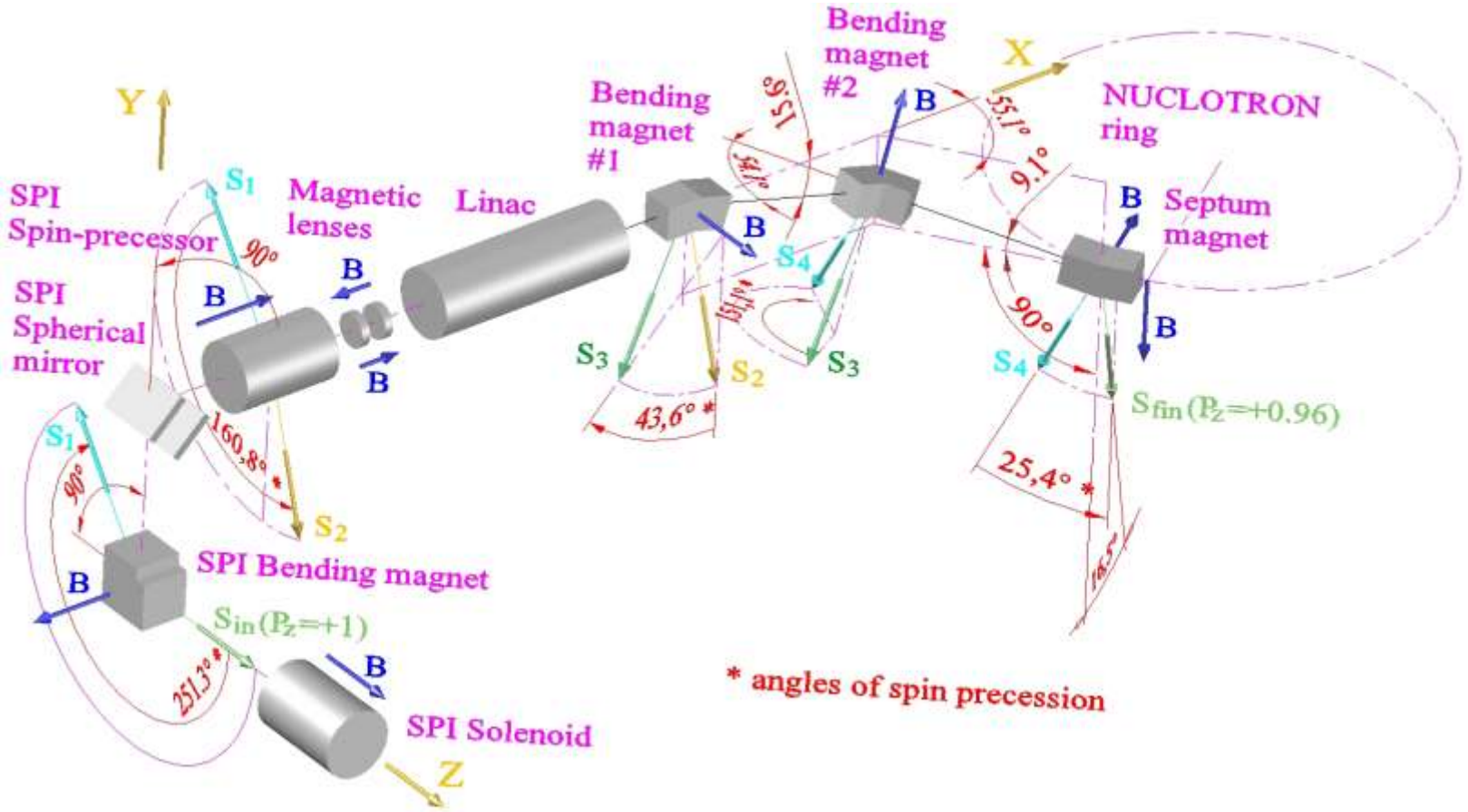
LU 20 preaccelerator hall



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



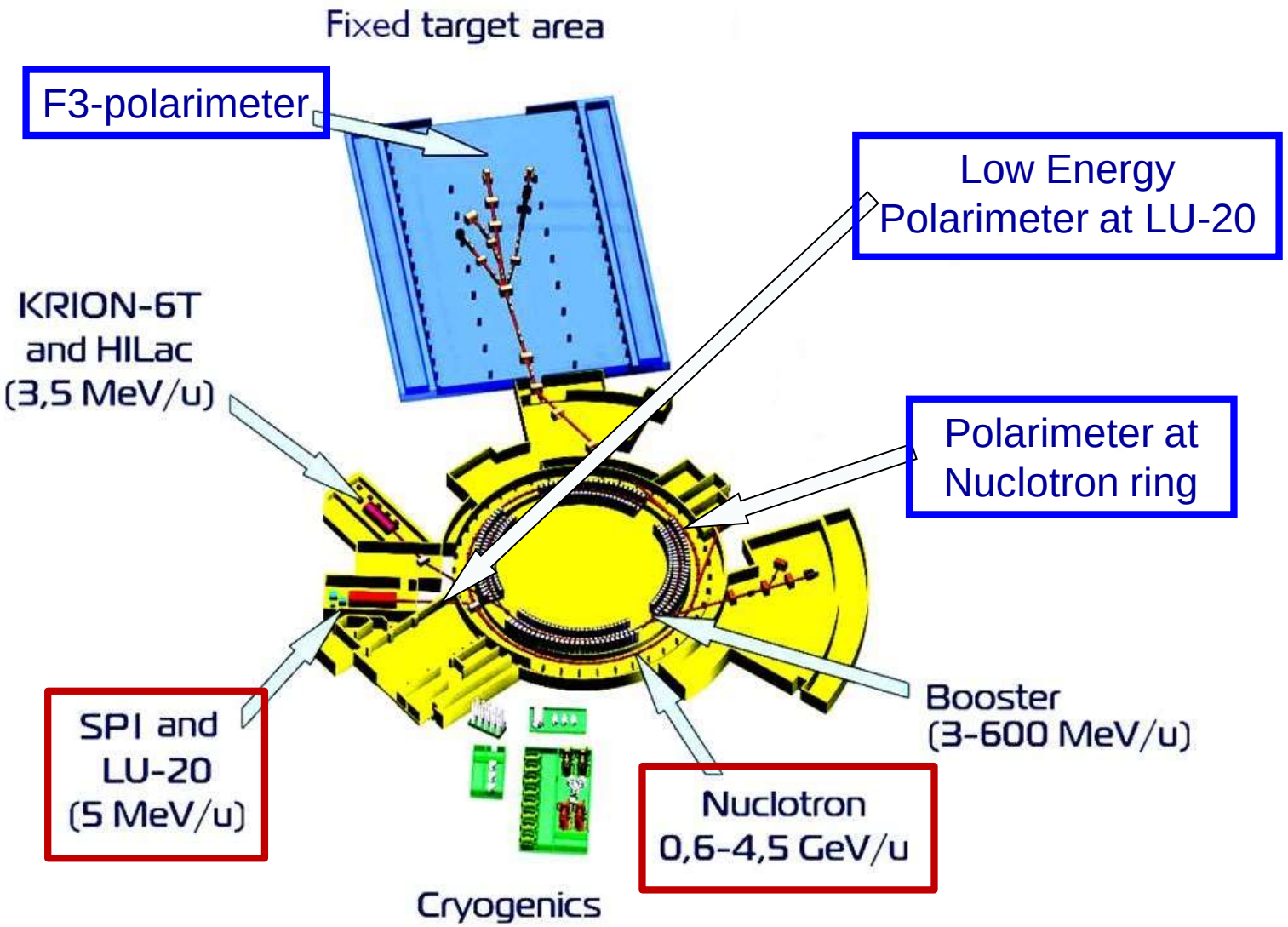
Remark

- The beam of H_2^+ ions is not separated from the polarized deuteron beam in the analyzing bending magnet and in the electrostatic deflector of the SPI

- After accelerating in the linac and passing through a stripping target the unpolarized protons formed due to striping of the H_2^+ ions, are deflected from the polarized deuteron beam entirely in the extraction after the bending magnets

- Thus, the unpolarized H_2^+ ions do not dilute the polarized deuteron beam injected into the NUCLOTRON

Implementation of polarization program



Polarization at NUCLOTRON

Bunch parameters at Nuclotron: 10^9 ppc, up to 8 GeV

D^+ polarization

(Ya. Skhomenko et. al., DSPIN2017)

Polarization values	P_z	dP_z	P_{zz}	dP_{zz}
(-2/3,1)	-0.489	0.026	0.631	0.045
(2/3,0)	0.427	0.021	0.061	0.037
(-1/3,1)	-0.254	0.022	0.637	0.039
(-1/3,-1)	-0.223	0.017	-0.621	0.030
(0,+1)	0.030	0.027	0.880	0.049
(0,-2)	0.046	0.015	-1.469	0.031

Proton polarization

Bunch parameters at Nuclotron: $1.8 \cdot 10^8$ ppc, up to 500 MeV

(V. Ladygin et. al., DSPIN2017)

Pz=-0.354+/-0.022 (~0,9 from the source)

2018 Tests of the SPI

- Tests were carried out in the storage cell of a cylindrical form 200 mm long and with the inner diameter of 18 mm

- The position of the storage cell was shifted by 30 mm from the extraction system of the polarized deuteron beam
- With the storage cell of this geometry the polarized deuteron beam with the peak current of 3 mA has been obtained

2018 Tests of the SPI

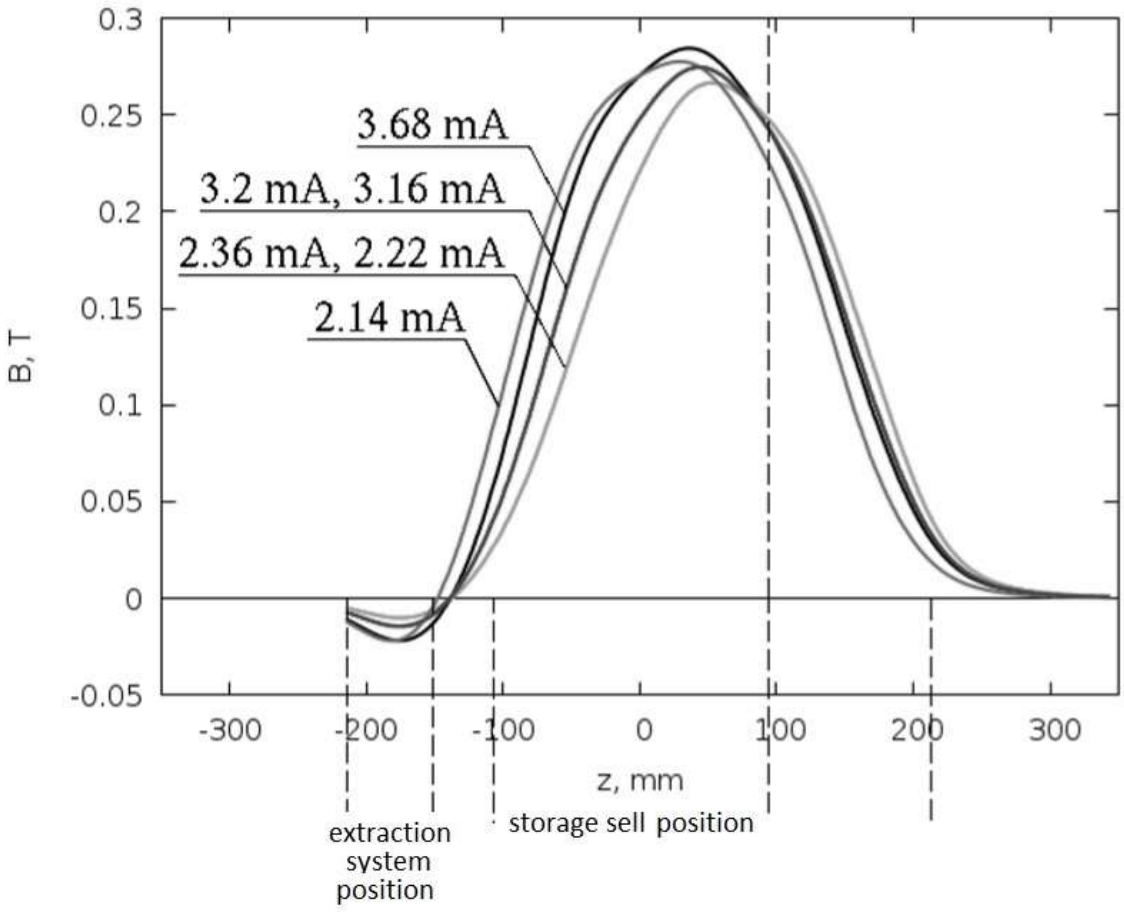
- The next step to increase the peak current of polarized deuterons was installation of the additional fourth permanent sextupole magnet into the atomic beam apparatus
- The parameters of the atomic beam apparatus structure

Magnets	first 6-pole	second 6-pole	third 6-pole	fourth 6-pole	electromagnet
Length, mm	25	47	62	85	230
Input diameter, mm	9.6	14.2	18.6	29	31
Output diameter, mm	12.8	18	19.4	29	31
Magnetic field, T	1.26	1.23	1.37	1.30	0.9

Usage of the fourth sextupole magnet resulted in increasing the polarized deuteron beam by 15%

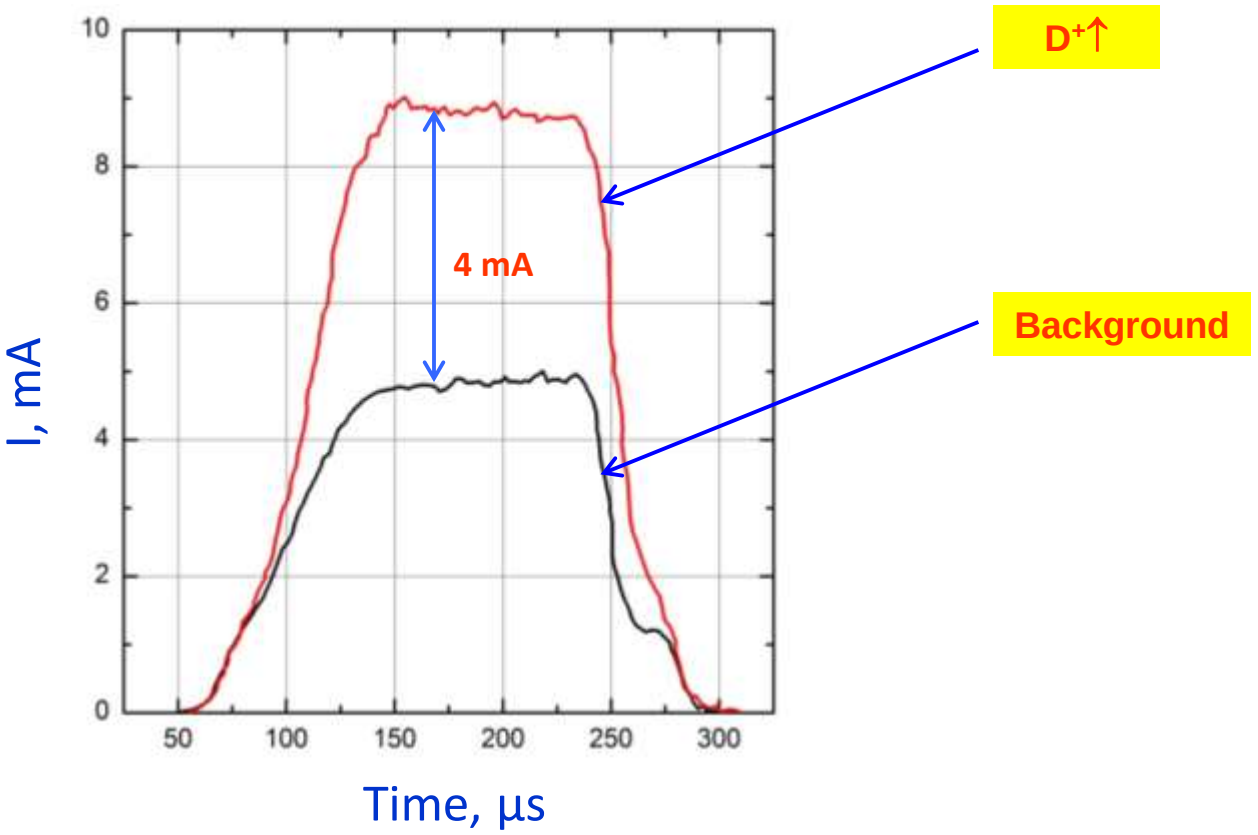
The polarized deuteron peaks in dependence on the ionizer magnetic field.

2018 Tests of the SPI



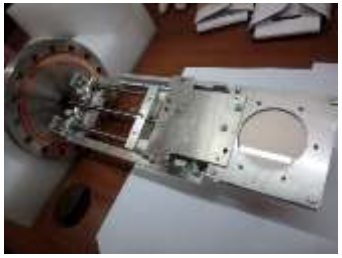
Further optimization of the magnetic field distribution in the ionizer brought the results demonstrated in Fig. At the polarized deuteron beam of 3.68 mA the unpolarized pulsed proton beam is equal to 75 mA and the beam of H_2^+ ions – 3.8 mA

SPI Deuteron Beam (Sept 2018)

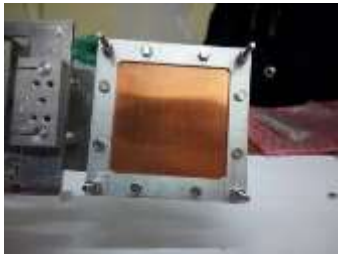


The current improvement in the SPI extraction system increased the magnitude of the polarized beam

Emittance measurements of H_2^+, $D^+\uparrow$, $H^+\uparrow$ beams (ITEP, Moscow)

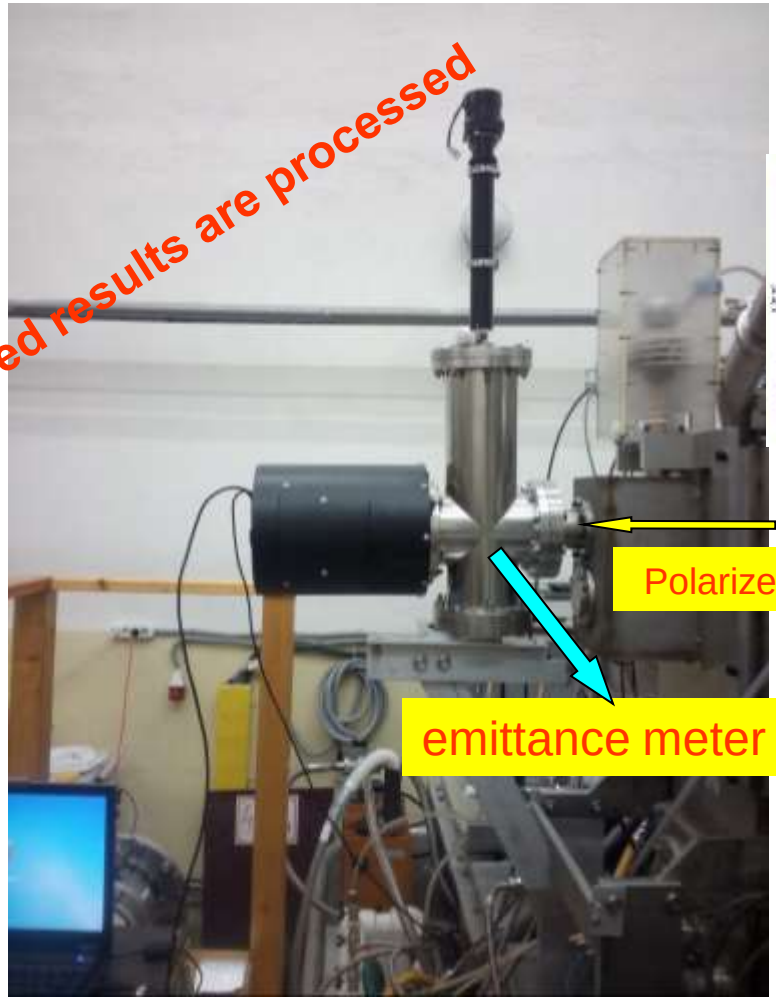


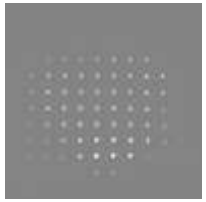
luminophore



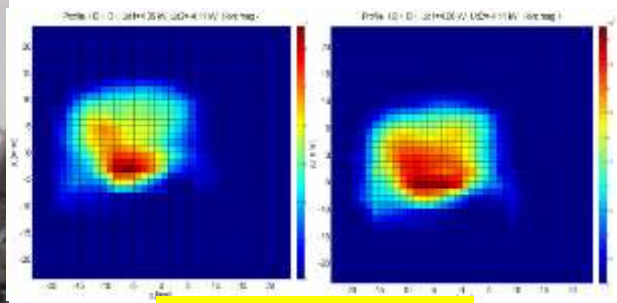
pepper-pot

measured results are processed





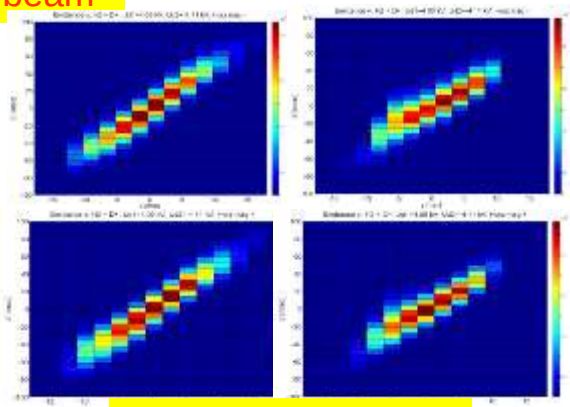
$D^+\uparrow$



$D^+\uparrow$ Beam profiles

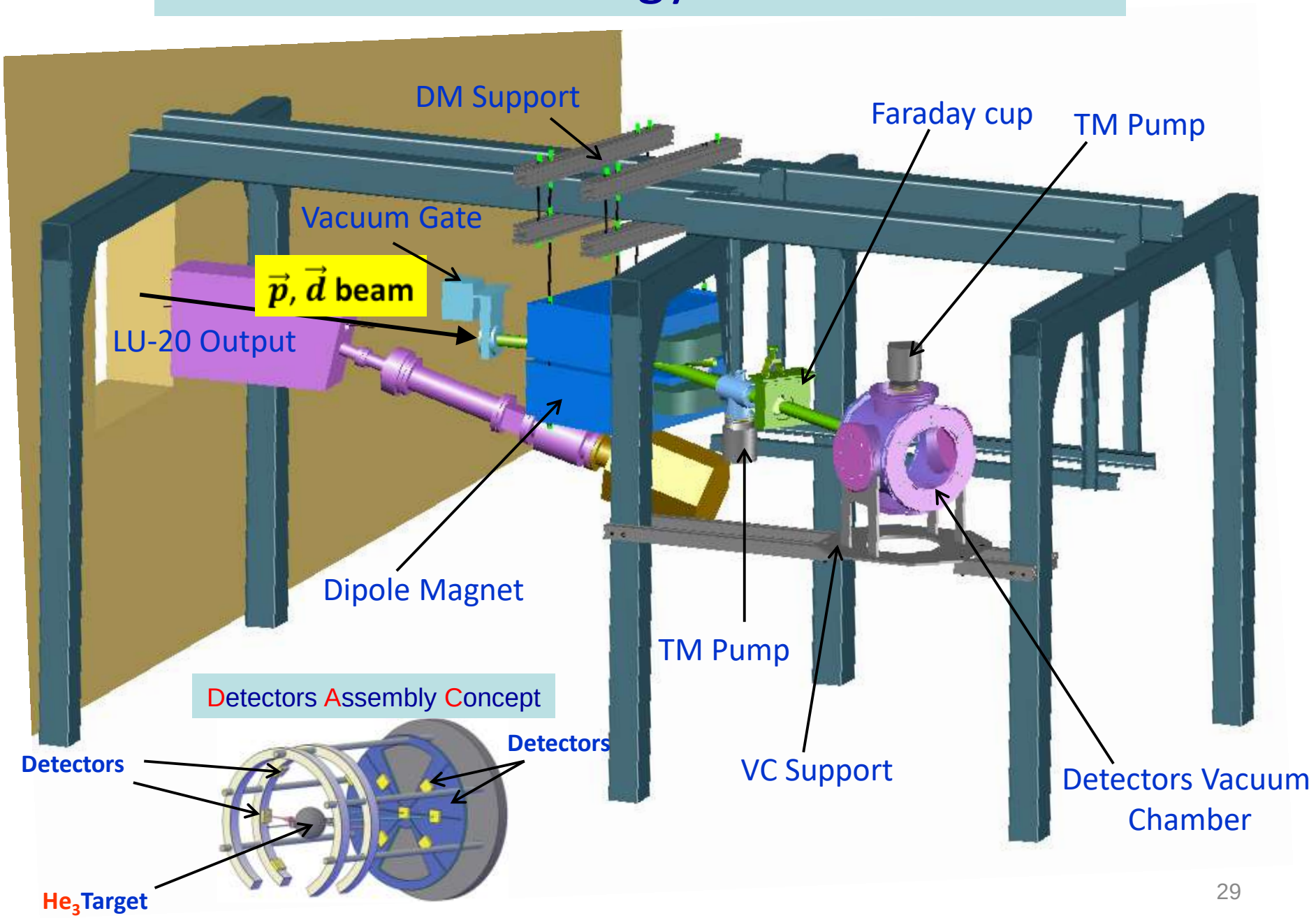
Polarized beam

emittance meter



$D^+\uparrow$ Emittance

New Low Energy Polarimeter



Conclusions

- ✓ 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 this year and polarized deuteron beam with pulsed current up to 4 mA has been produced
- ✓ SPI operating improvements of parameters are continued

Thank you