The Source of Polarized Ions (SPI) and the Nuclear-Reaction Polarimeter (NRP)

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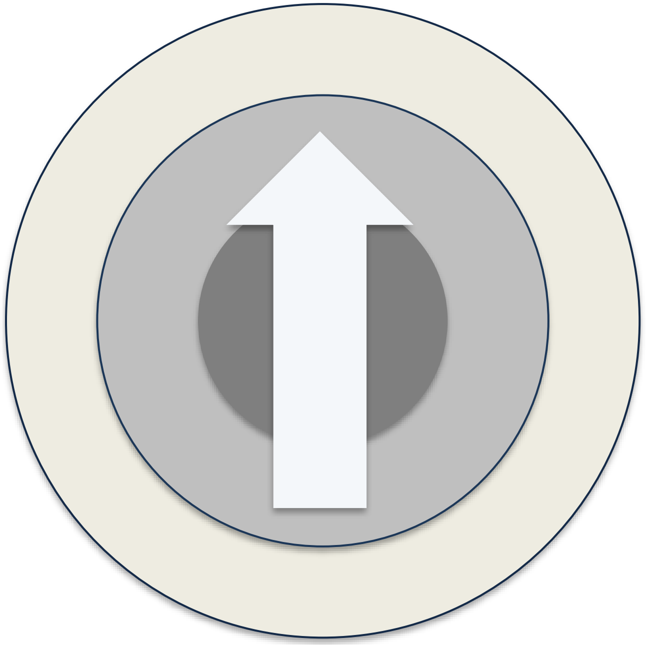

Joint Institute for Nuclear Research
NICA Accelerator Complex • Dubna

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Presentation Outline

- General architecture and objectives of SPI and NRP
- Sequential operating principle of the polarized-ion source
- Low-energy transport and accelerator matching
- Principles of nuclear-reaction polarimetry
- Modernization activities and development prospects

SPI

Polarized-ion production

LEBT

Low-energy beam transport

NRP

Polarization measurement

Polarization Program at NICA

- NICA enables experiments with polarized proton and deuteron beams.
- Spin observables provide information beyond unpolarized cross-section measurements.
- The program requires stable beam production, acceleration and spin diagnostics.
- Polarization must be monitored from the source to the experimental area.
- Reliable mode switching is essential for controlling systematic uncertainties.

p

Polarized protons

d

Vector- and tensor-polarized deuterons

JINR

Joint Institute for Nuclear Research

Main Program Objectives

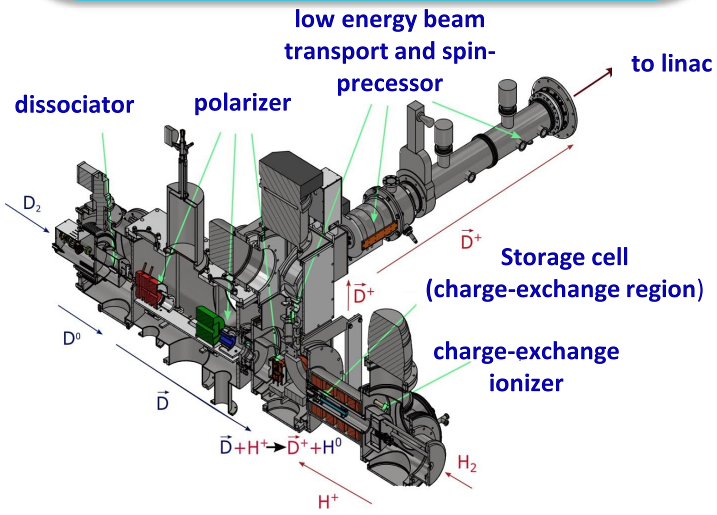
- Generate intense polarized proton and deuteron beams.
- Provide reproducible vector and tensor polarization modes.
- Preserve polarization during injection and acceleration.
- Measure beam polarization with controlled systematic uncertainty.
- Support fast switching among operational spin modes.
- Establish reliable source, transport and polarimeter settings.

Polarized-Beam Chain

1

Source of Polarized Ions (SPI)

- Produces a polarized atomic deuterium beam
- Selects the required hyperfine states
- Creates vector and tensor spin modes
- Converts polarized atoms into ions
- Extracts and transports the low-energy ion beam



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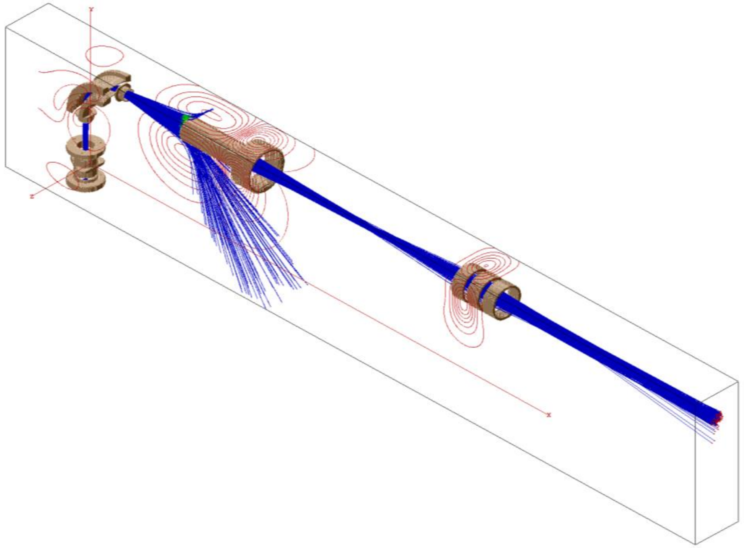
LEBT

- The LEBT transfers the beam from SPI to the RFQ entrance.
- Focusing elements match the transverse beam parameters to the accelerator acceptance.
- Magnetic fields should not cause uncontrolled spin rotation.



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Acceleration

RFQ, LU-20 and Nuclotron

7

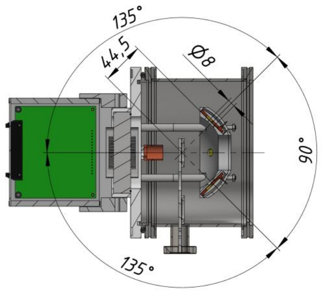
Experiment

NICA physics program

3

NUCLEAR-REACTION POLARIMETER (NRP)

- Uses reactions with known analyzing powers
- Measures spin-dependent counting asymmetries
- Determines vector and tensor polarization
- Checks polarization-mode reproducibility
- Provides feedback for source and accelerator tuning



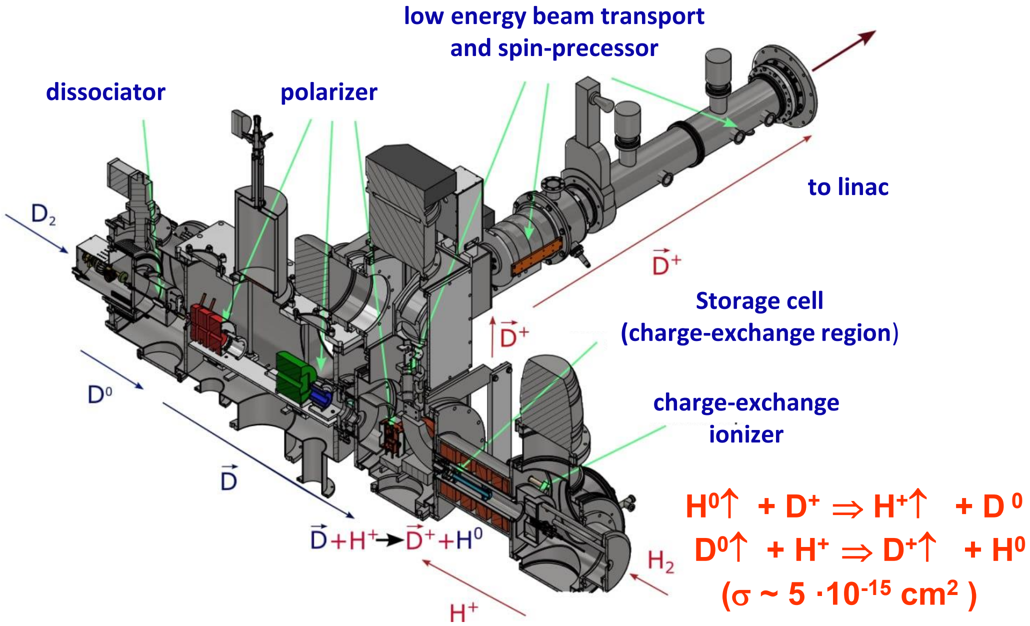
SPI Design Targets

- The SPI project is designed as a high-intensity source of polarized deuteron and proton beams.
- High nuclear polarization must be combined with sufficient current and acceptable transverse emittance.
- Pulse-to-pulse stability is required for accelerator operation.
- The source must provide reproducible switching among spin modes.
- Performance targets shown here are taken from the provided project materials.

5×10^{10}
Target accelerated ions per pulse

up to 10 mA
Ion current at the source output

up to 90%
Fraction of maximum polarization



Operating Principle of the SPI

Sequential conversion of molecular gas into a polarized ion beam

1 — Dissociation

H_2 or D_2 → atomic beam

2 — Beam formation

Nozzle, skimmer and collimation

3 — State selection

Hexapole magnetic system

4 — RF transitions

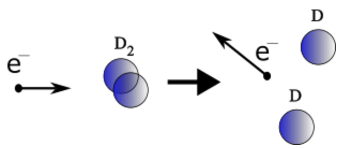
Hyperfine population control

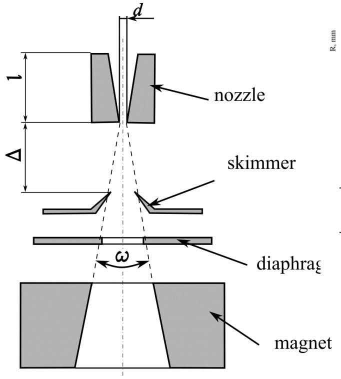
5 — Ionization

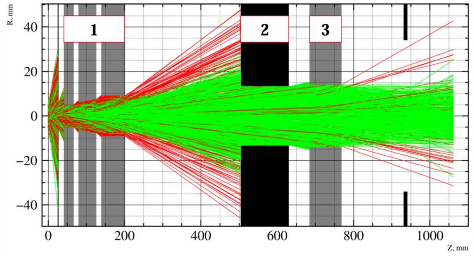
Charge-exchange ionizer

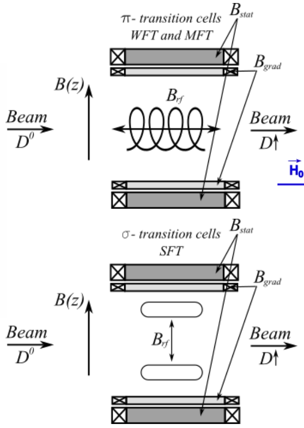
6 — Extraction

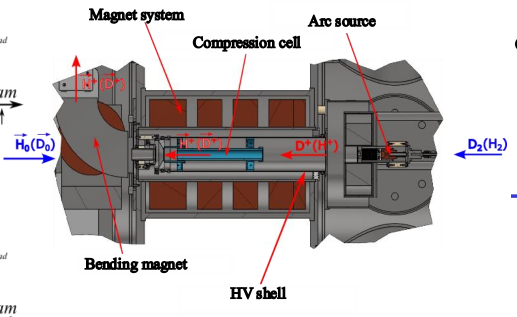
Low-energy polarized ions

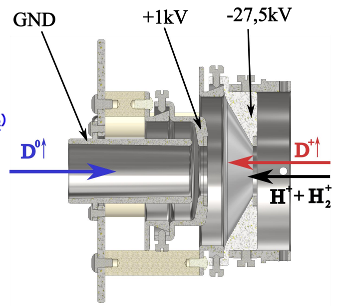






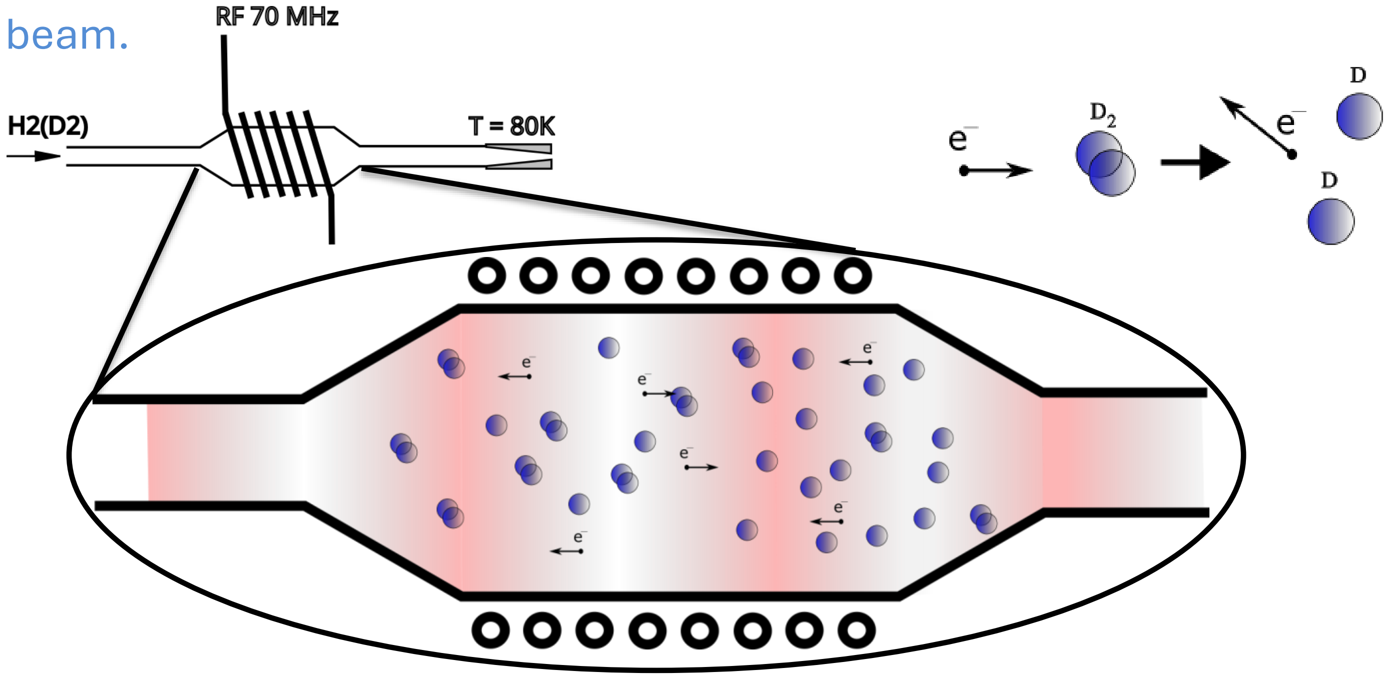






The RF Dissociator

- Molecular hydrogen or deuterium is converted into atoms by an RF discharge.
- High dissociation efficiency increases the useful atomic flux.
- Stable gas flow and RF power are essential for reproducibility.
- Gas purity affects the discharge stability and source lifetime.
- Nozzle geometry and temperature influence the divergence of the atomic beam.



70 MHz

RF operating frequency

2–3 mm

Nozzle diameter

3×10^{17}

Molecules per pulse

≈ 200 μs

Gas-valve pulse duration

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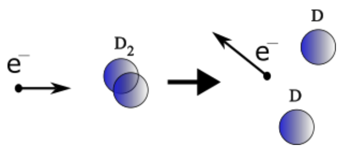
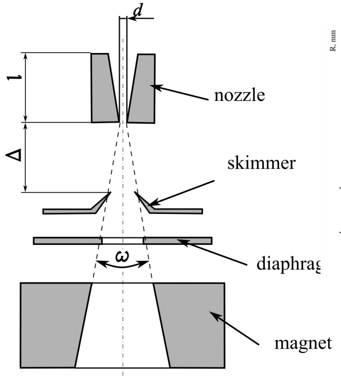
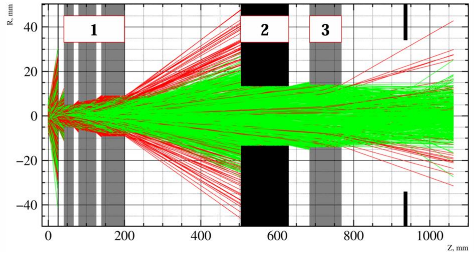
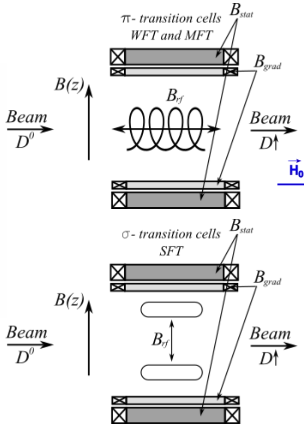
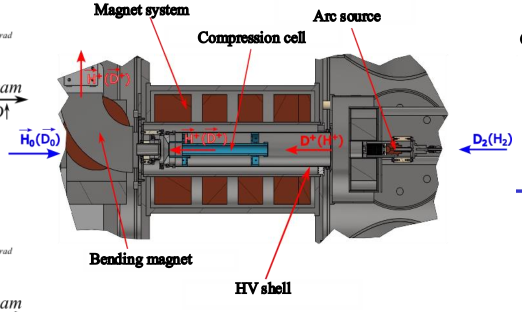
3. **State selection** — Hexapole magnetic system
4. **RF transitions** — Hyperfine population control
5. **Ionization** — Charge-exchange ionizer
6. **Extraction** — Low-energy polarized ions

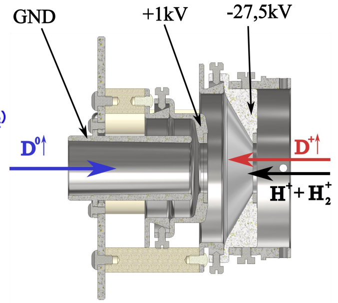






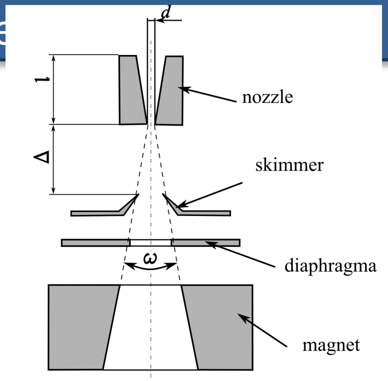


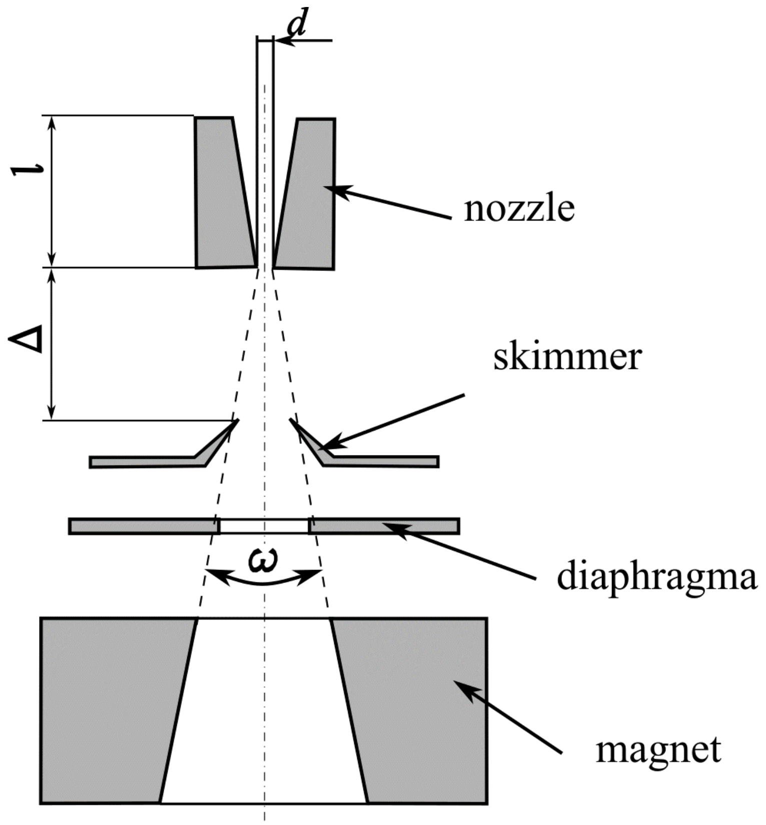




Atomic-Beam Formation

- The dissociated gas expands through a nozzle and forms a directed atomic beam.
- A skimmer separates the central part of the gas jet.
- Collimators define the beam geometry and angular acceptance.
- Differential pumping maintains suitable vacuum conditions.
- Nozzle temperature affects atomic velocity and divergence.
- Mechanical alignment determines transmission through the magnetic syste





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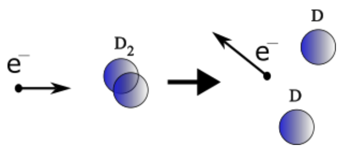
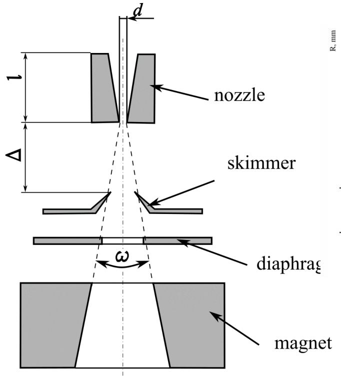
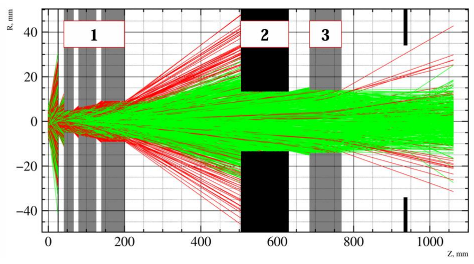
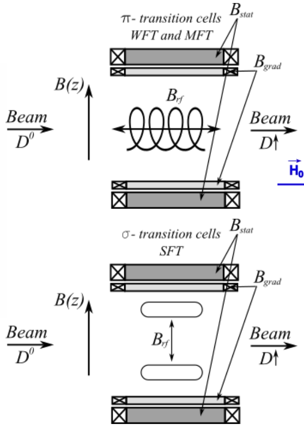
Extraction

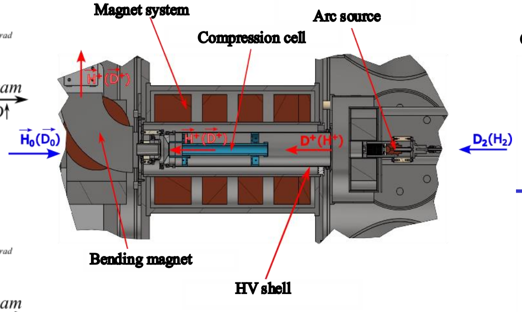
Low-energy polarized ions

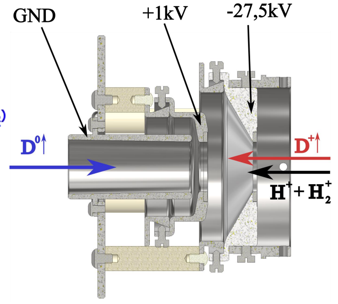












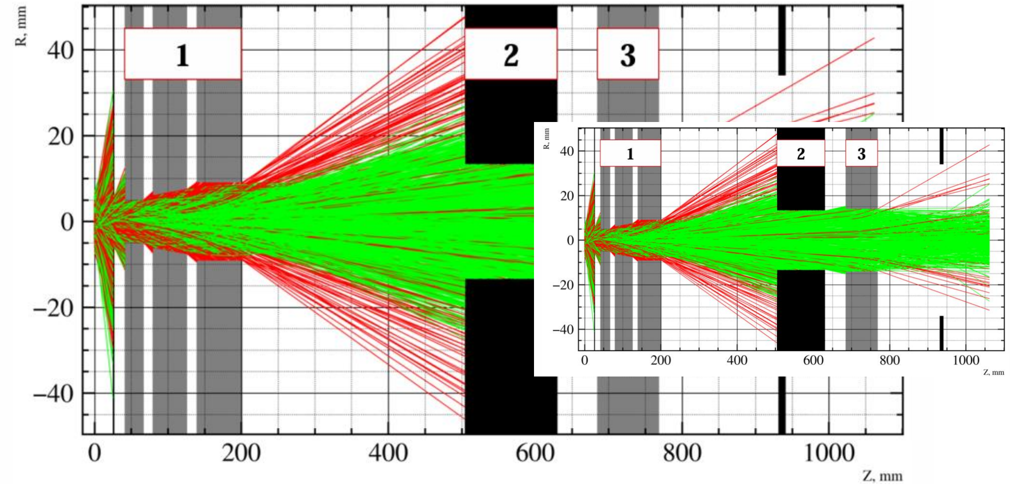
Magnetic State Selection

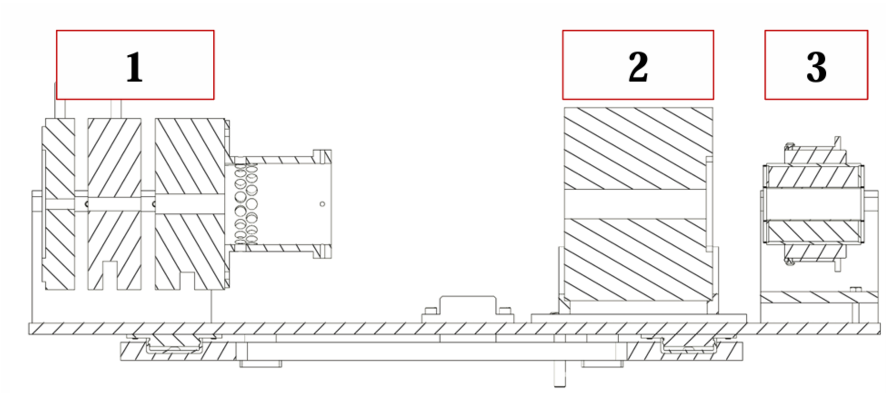
- The atomic beam initially contains several hyperfine states.
- Inhomogeneous Hexapole magnets act on the electron magnetic moment.
- Atoms in selected states are focused towards the ionizer.
- Unwanted states are defocused and removed from the beam.
- The magnetic acceptance affects both beam intensity and attainable polarization.
- Permanent hexapoles provide strong gradients without continuous magnet power.

Hexapoles
Strong transverse field gradient

Focus
Selected hyperfine states

Reject
Unwanted atomic states





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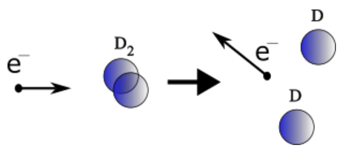
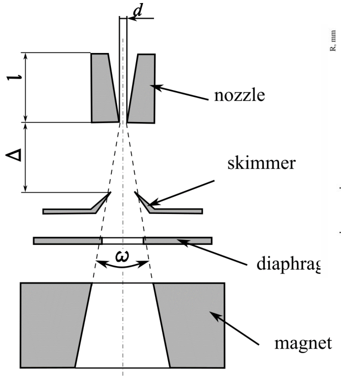
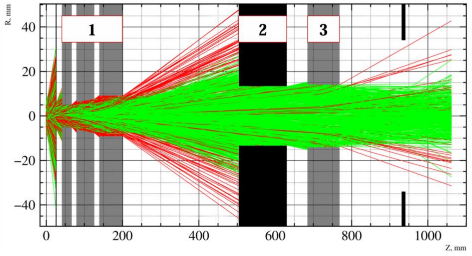
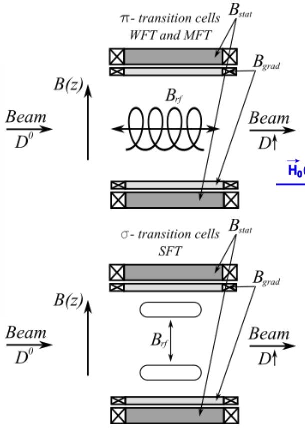
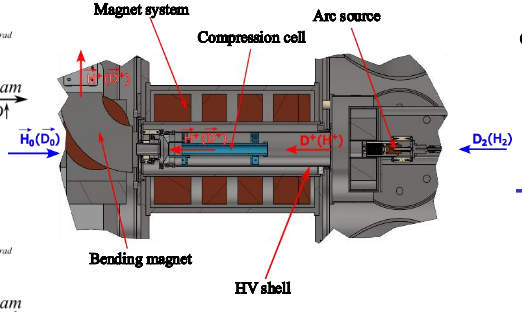
Low-energy polarized ions

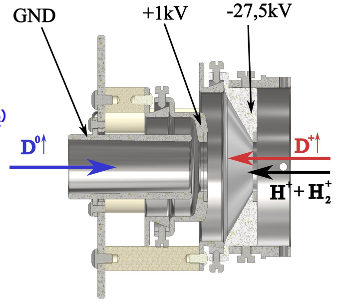






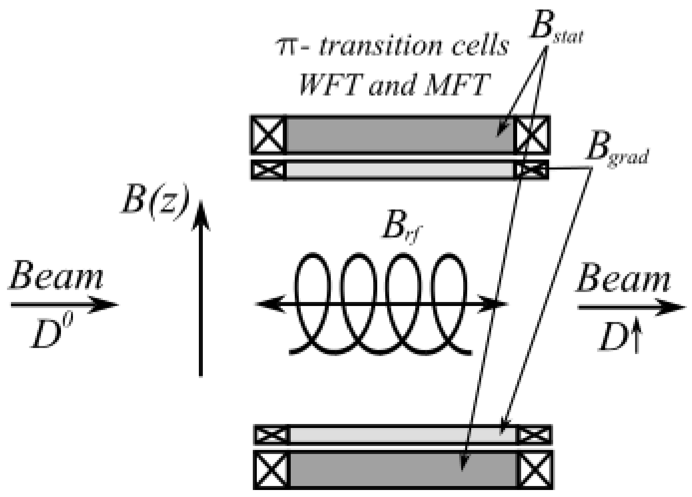


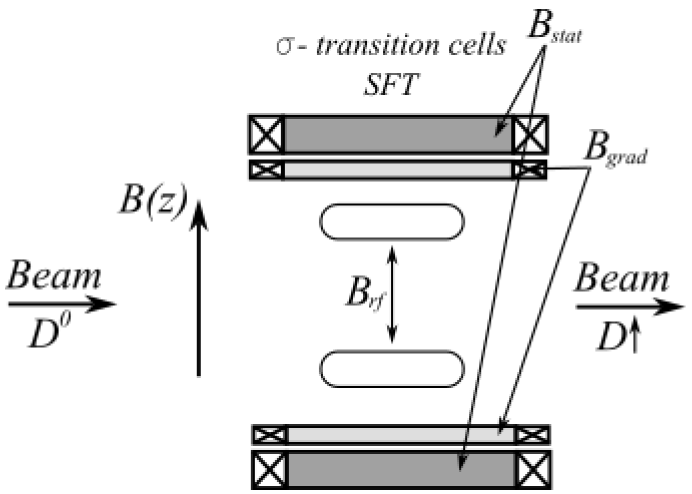


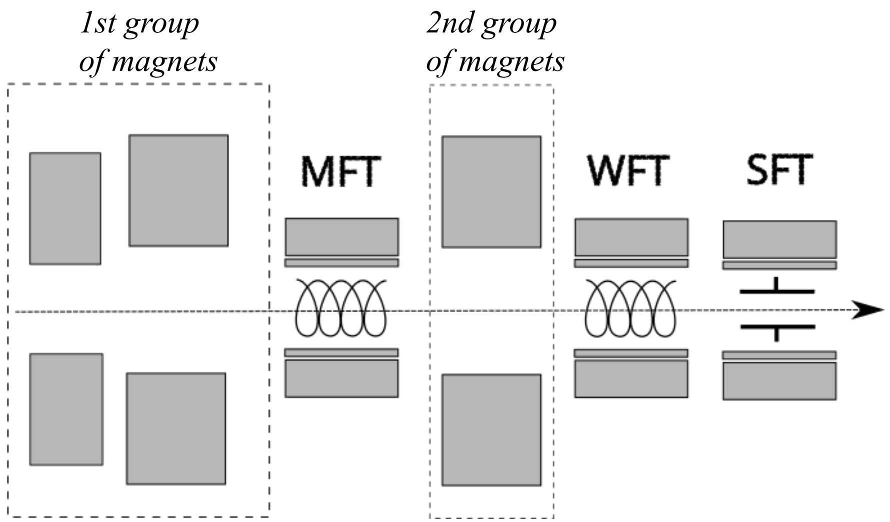


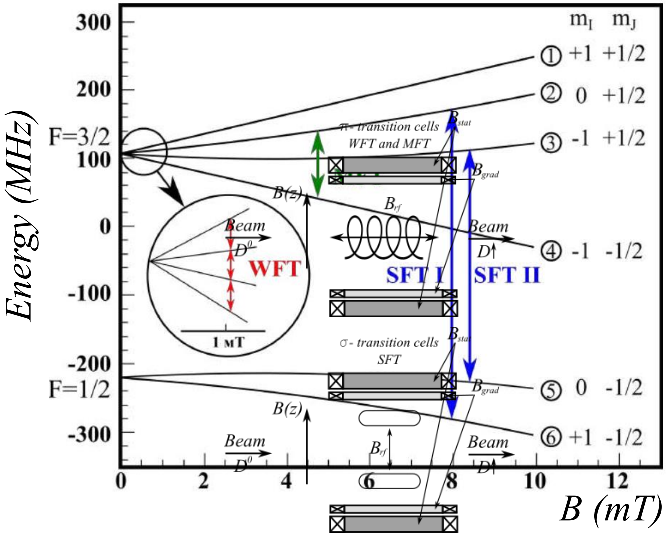
Hyperfine Transition Cells

- RF fields induce transitions between selected hyperfine states.
- Transition cells redistribute state populations delivered to the ionizer.
- Different transition combinations generate different polarization modes.
- Operation requires accurate RF frequency, amplitude and magnetic-field settings.
- Transition efficiency must be verified during commissioning.
- Stable guiding fields reduce uncontrolled spin-state mixing.









Operational Polarization Modes

- Positive and negative vector-polarization modes are required.
- Deuteron operation additionally provides tensor-polarization modes.
- A nominally unpolarized mode is useful for reference measurements.
- Fast mode reversal reduces sensitivity to slow detector drifts.
- Every operational mode must be experimentally verified.
- Real polarization can differ from ideal values because of incomplete state selection and transition inefficiency.

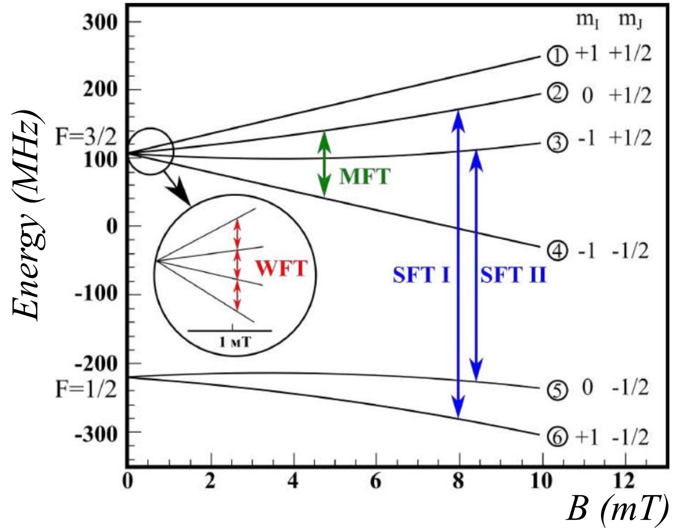
Pz
Vector polarization

Pzz
Tensor polarization

0
Reference mode

Deutrons

1st group of magnets IN	1st group of magnets OUT	MFT unit transition	2nd group of magnets IN	2nd group of magnets OUT	WFT + SFT units transition	Final polarisation	Pz	Pzz
1 - 6	1, 2, 3	3 → 4	1, 2, 4	1, 2	$1, 2 \xrightarrow{WFT} 3, 4$	3, 4	-1	+1
					$2 \xrightarrow{SFT} 6$	1, 6	+1	+1
		1 → 4	2, 3, 4	2, 3	$3 \xrightarrow{SFT} 5$	2, 5	0	-2
					$2 \xrightarrow{SFT} 6$	3, 6	0	+1
		OFF	1, 2, 3	1, 2, 3	$1 \xrightarrow{WFT} 4$	2, 3, 4	-2/3	0



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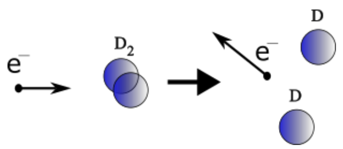
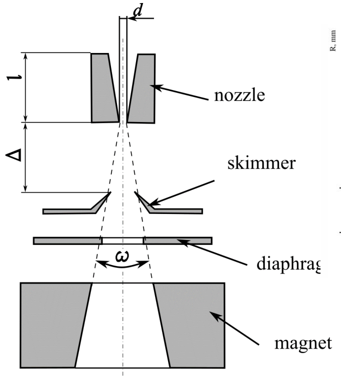
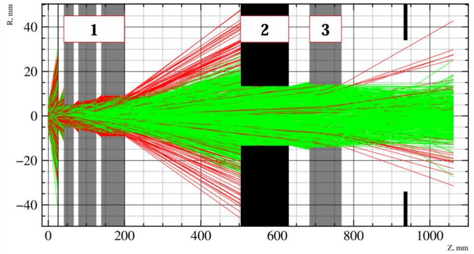
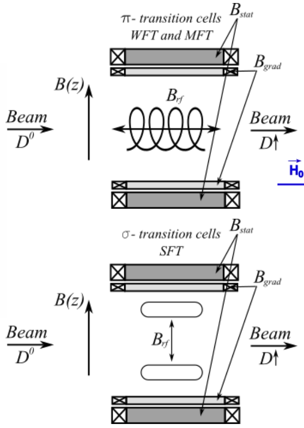
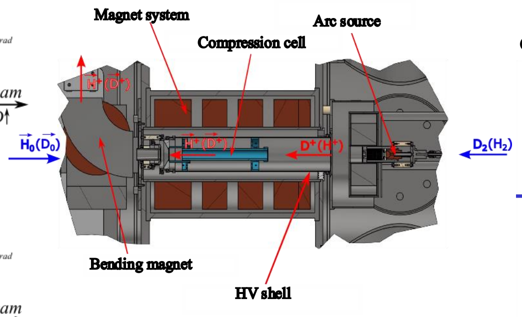
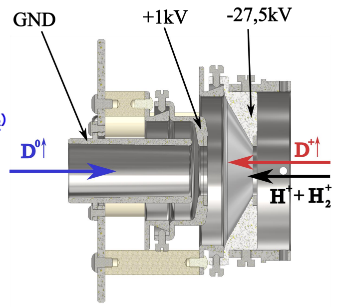












Charge-Exchange Ionizer

- The state-selected atomic beam enters the ionization region.
- Charge-exchange processes convert polarized atoms into ions.
- An arc-discharge plasma source supplies the ionizing plasma.
- Ionization conditions must minimize depolarization.
- Gas pressure, plasma density and interaction length determine the ion yield.
- Ion production must be optimized together with emittance and beam stability.

Atoms

State-selected H or D

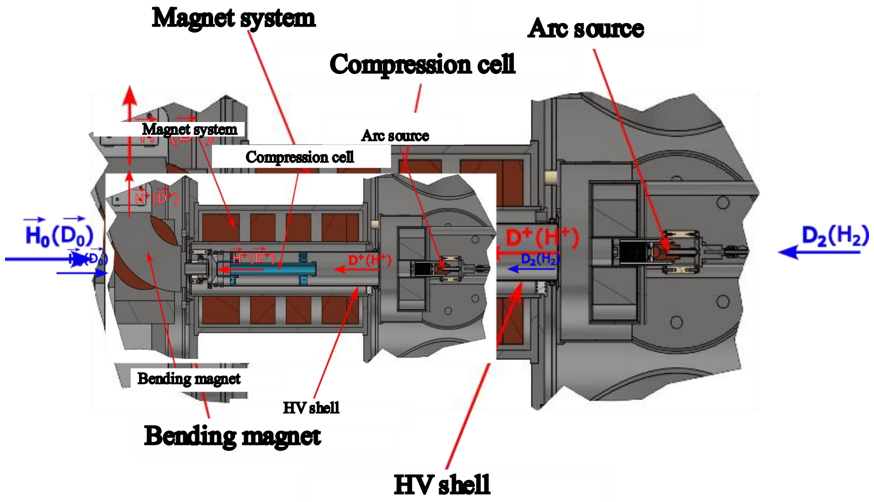
Plasma

Charge-exchange medium

H^+ / D^+

Polarized ion output

$$H^0\uparrow + D^+ \longrightarrow H^+\uparrow + D^0$$
$$D^0\uparrow + H^+ \longrightarrow D^+\uparrow + H^0$$
$$\sigma \sim 5 * 10^{-15}\ \mathrm{cm}^2$$



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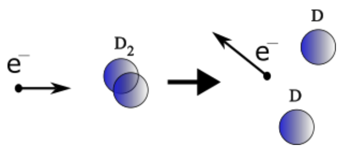
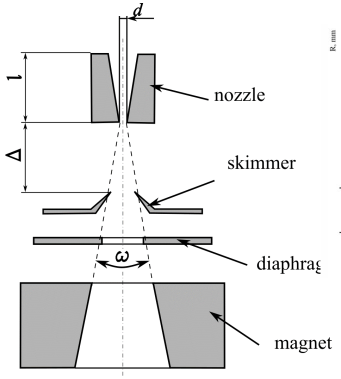
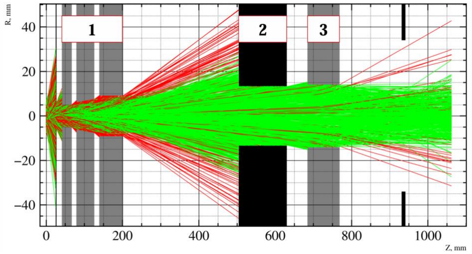
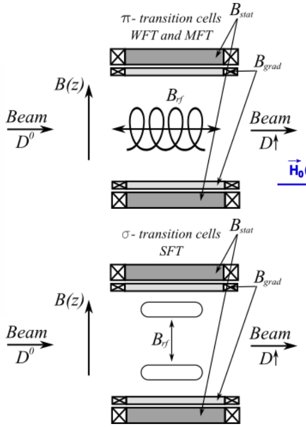
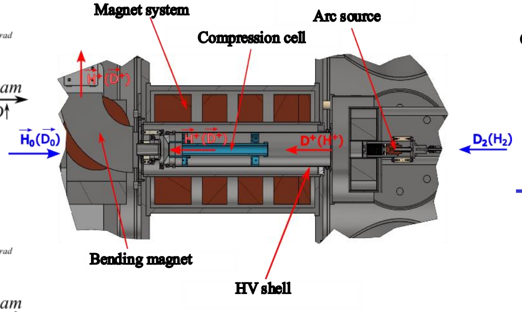
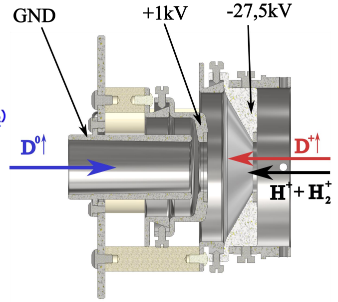






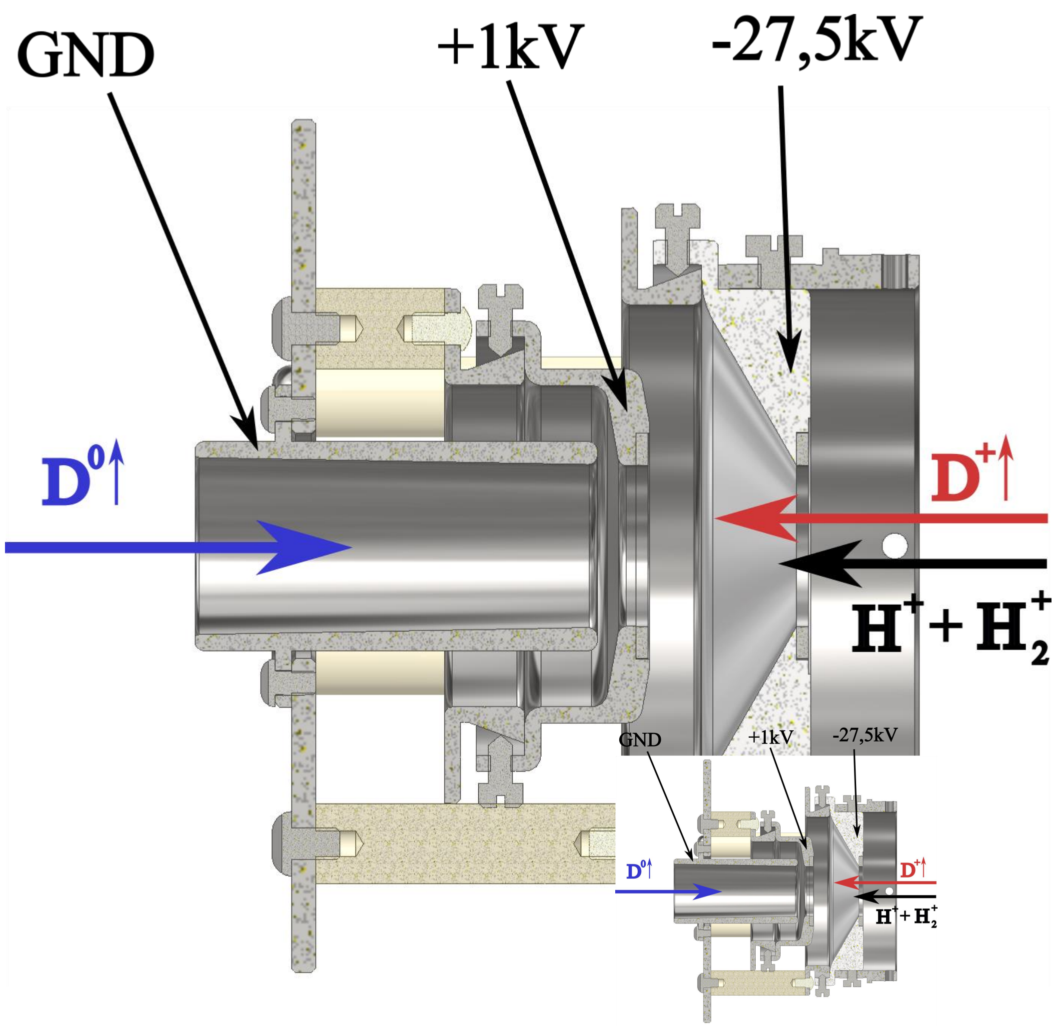






Ion Extraction

- Electrostatic fields extract ions from the ionization region.
- The extraction voltage determines the initial beam energy.
- Electrode geometry forms and focuses the emerging ion beam.
- Incorrect settings can increase emittance and beam losses.
- Space-charge effects become important at high current.
- Stable high-voltage operation is essential for reproducibility.



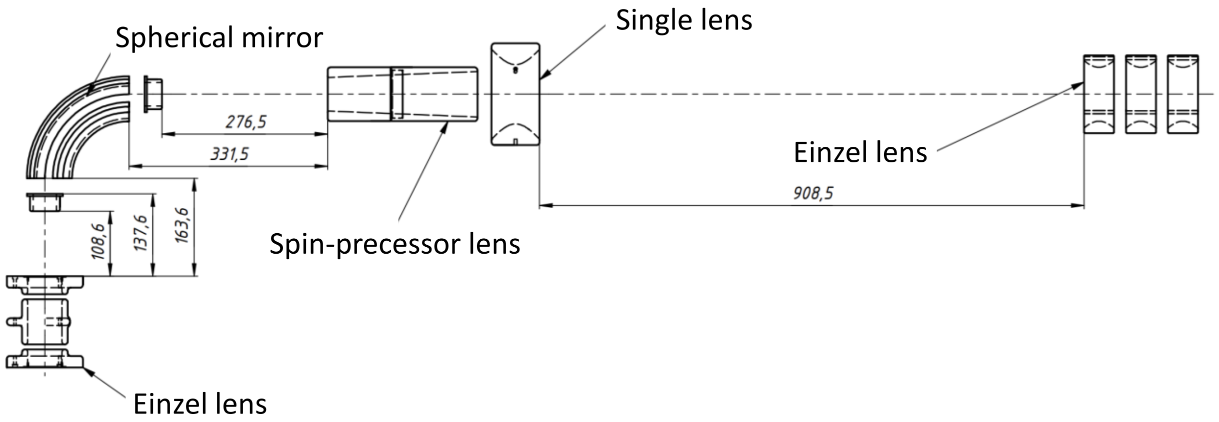
Low-Energy Beam Transport (LEBT)

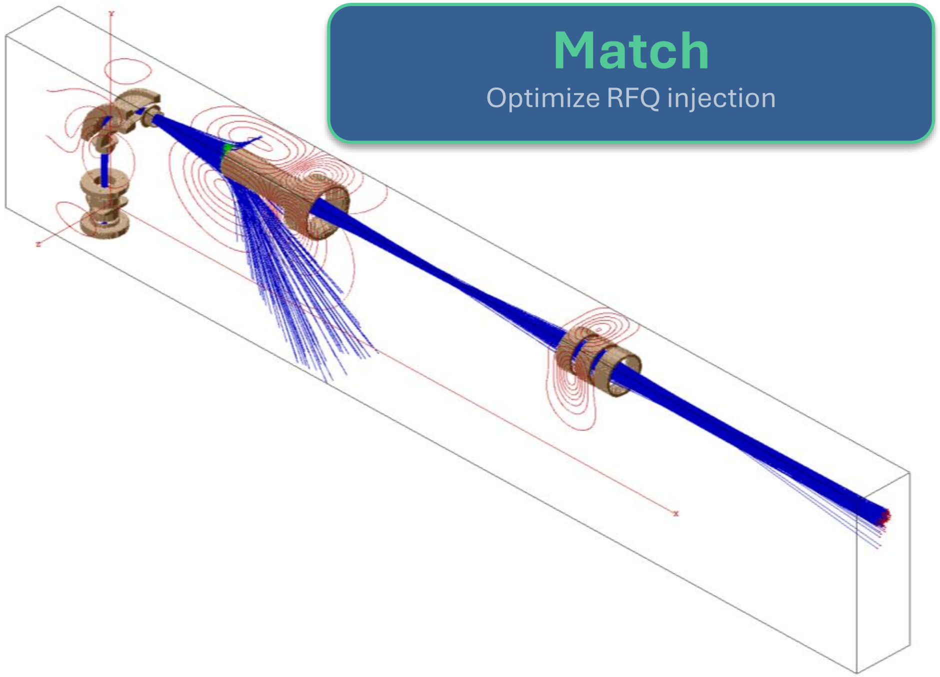
- The LEBT transfers the beam from SPI to the RFQ entrance.
- Focusing elements match the transverse beam parameters to the accelerator acceptance.
- Steering elements correct horizontal and vertical displacement.
- Current and profile diagnostics support beam tuning.
- The system must minimize losses and emittance growth.
- Magnetic fields should not cause uncontrolled spin rotation.

Focus
Control beam envelope

Steer
Correct beam position

Match
Optimize RFQ injection





Optimisation of Transport to the RFQ

- Measure beam current at several positions along the transport line.
- Determine horizontal and vertical beam profiles.
- Optimise focusing and steering elements iteratively.
- Check the beam position and angle at the RFQ entrance.
- Compare transmission for different SPI spin modes.
- Establish reproducible reference settings for routine operation.

Principle of Nuclear-Reaction Polarimetry

Spin-dependent nuclear reactions convert polarization into measurable asymmetries

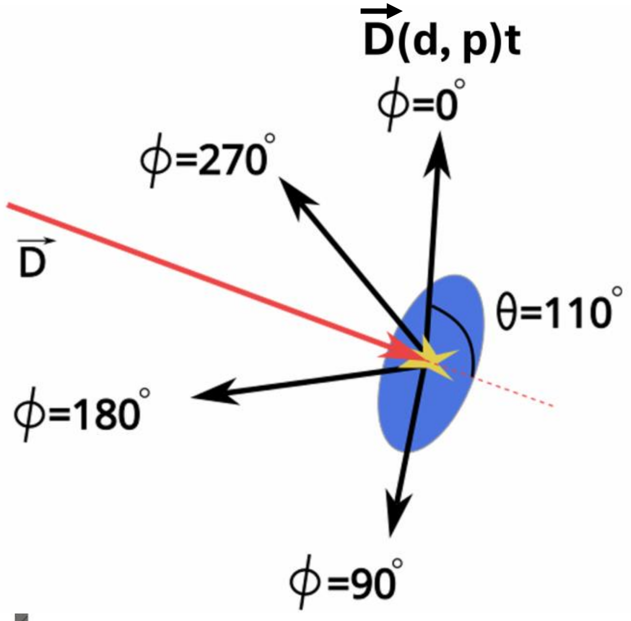
1. **Beam** — Polarized p or d
2. **Target** — Thin reaction target
3. **Reaction** — Spin-dependent process
4. **Detectors** — Products at selected angles
5. **Asymmetry** — Normalized counting rates
6. **Polarization** — Using known analyzing powers

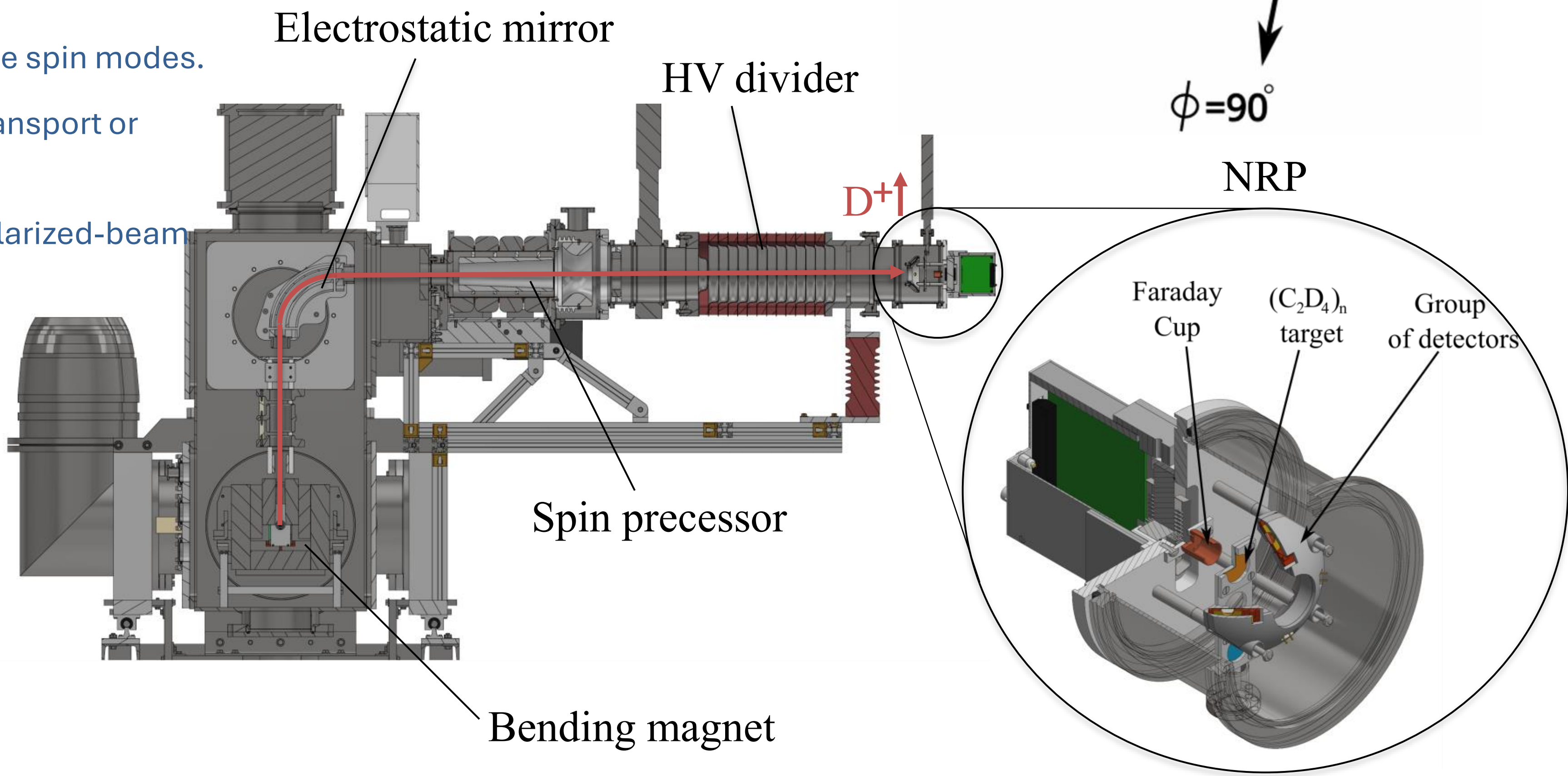
Purpose of the NRP

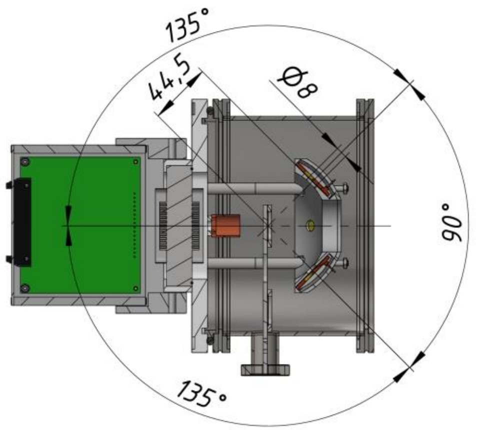
- Measure polarization after beam production and acceleration.
- Determine vector and tensor components of deuteron polarization.
- Confirm correct switching among source spin modes.
- Detect possible depolarization in the transport or accelerator systems.
- Provide operational feedback during polarized-beam sessions.

Vector
Directional spin alignment

Tensor
Quadrupole spin alignment







Conclusions (STATUS)

SPI

STATUS

The SPI was moved to its final position for operation with the LU-20.
The modernization of the facility's engineering systems has been carried out, including:
- Water systems
- Electrical systems
- Passive safety systems for vacuum and water

Spatial alignment of the source has been performed.
New elements have been integrated into the system:
- Ion optical system
- New arc source system

Work has also been carried out to upgrade the vacuum system.

NRP

STATUS

✓ The complete NRP model is ready.
Initial tests of the detectors have been carried out (Report by A.N. Solovev).
✓ Flexible detector system:
- Enabling installation of detectors at various angles to optimize counting rate and analyzing power
- Adaptation of the geometry for different experimental tasks