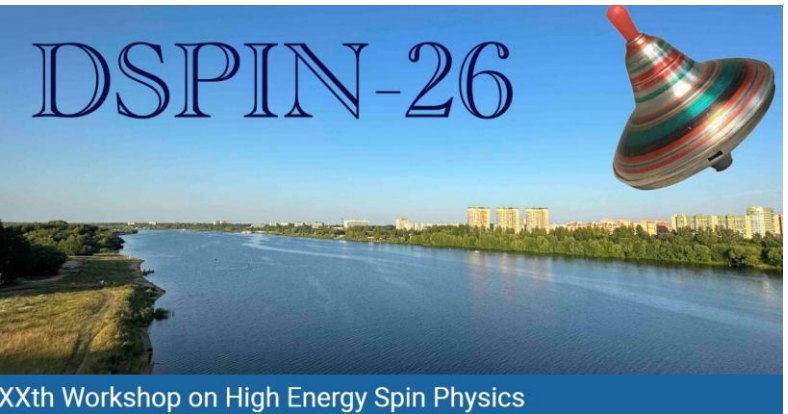
Lamb-shift polarimeter development at MIPT

S.N. Zhabin, A.N. Zelenski, Yu.N. Filatov, I.S. Yudin, A.A. Chernikova, S.V.Vinogradov

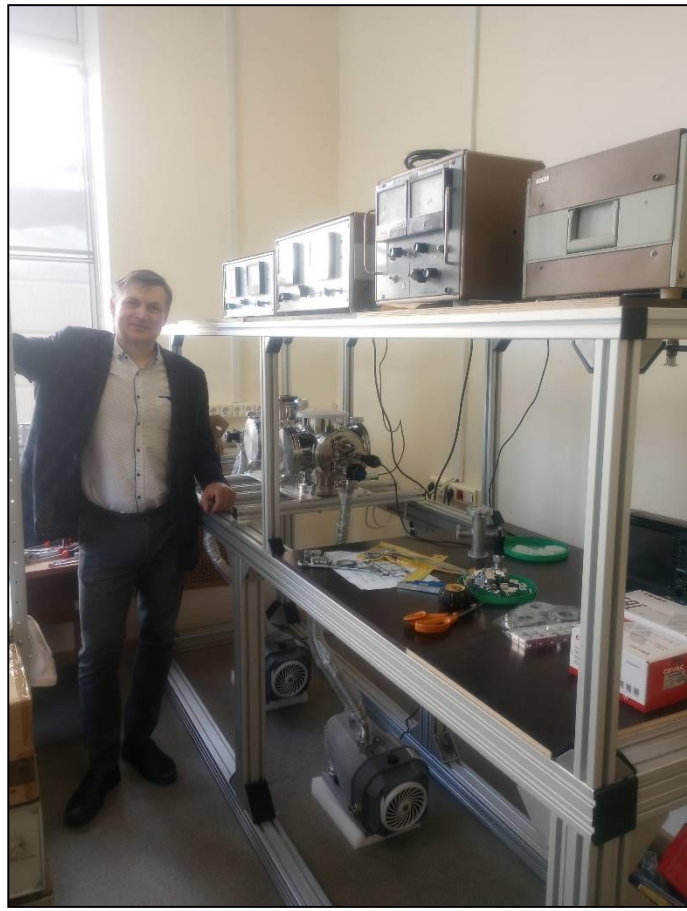
V.B. Fimushkin, K.A. Ivshin, A.N. Solovev

A.S. Belov

- Proton (D)-beam charge-exchange collisions to the metastable H(2S)- states in the Na-vapor cell.
- Spin filter with static magnetic and electrical fields.
- Spin filter with RF-transitions for the measurements of hyperfine sublevels populations.
- H(2S)- beam intensity detector on the base of MCP

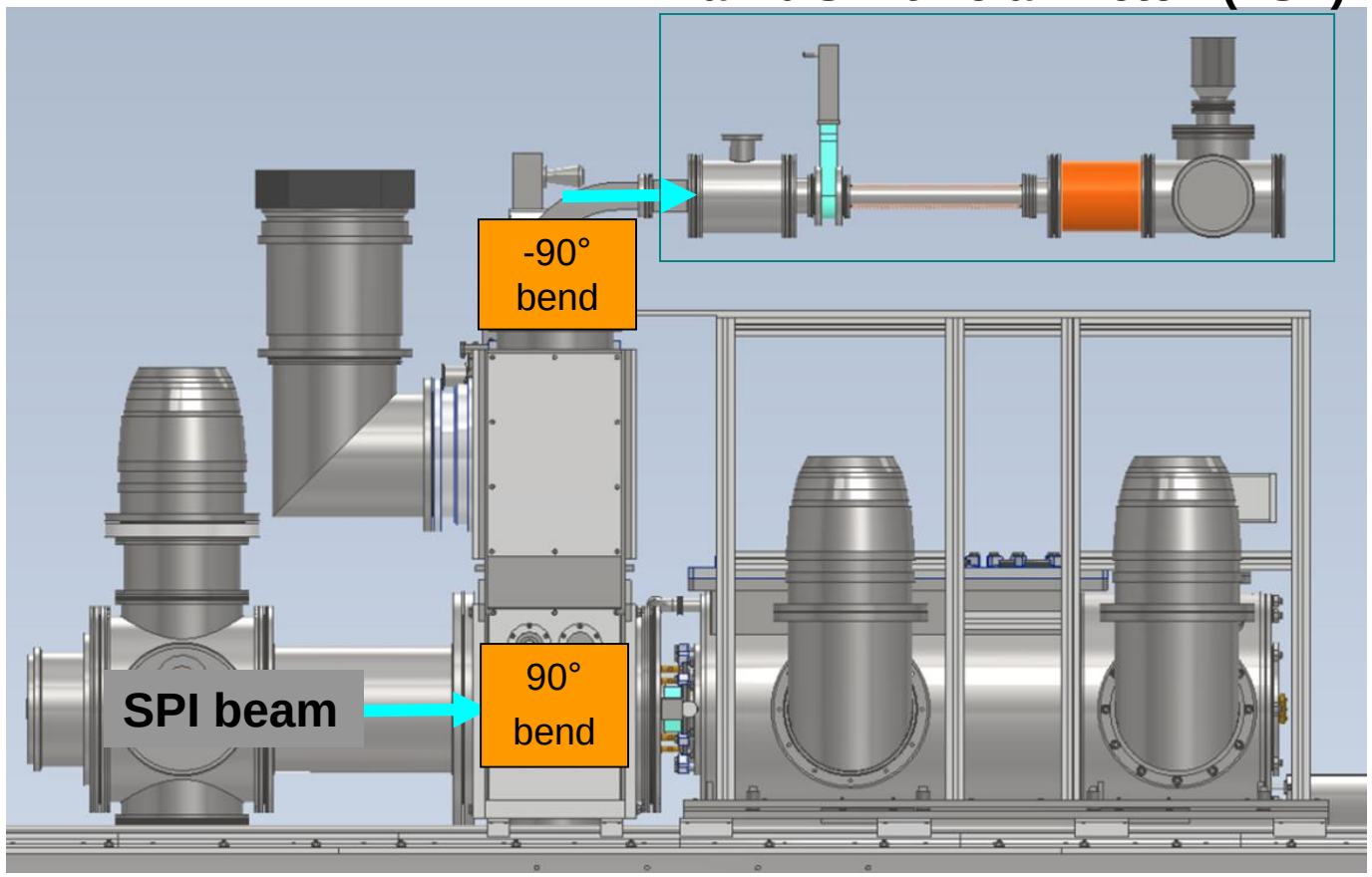


The work was supported by a grant from the Russian Science Foundation: No 25-72-30005, https://rscf.ru/project/25-72-30005/.



LSP in the NICA SPI beam line

Lamb Shift Polarimeter (LSP)



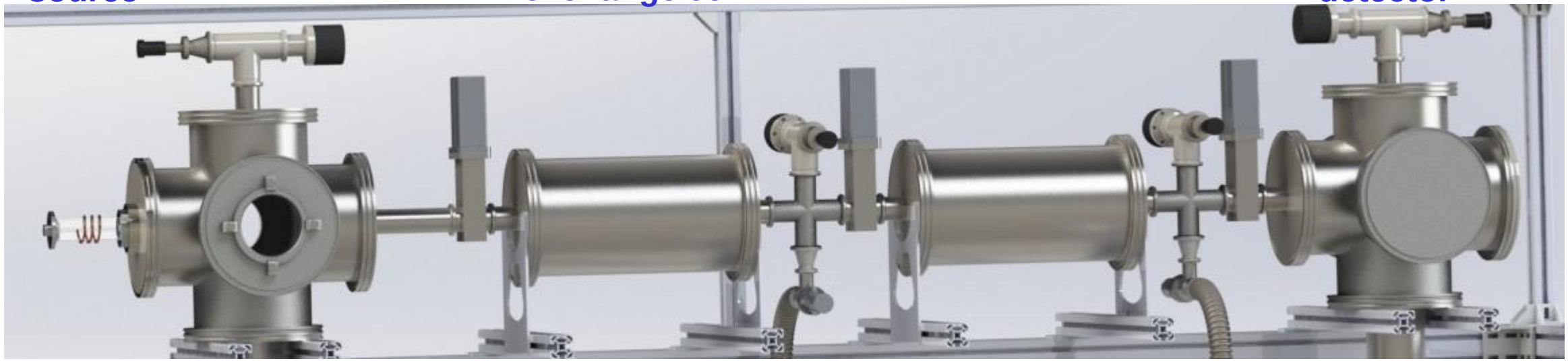
Proven technique

LSPs have been successfully used for polarized ion source diagnostics and optimization at **INR RAS, TRIUMF, KEK, BNL and COSY.** .

The polarized proton/deuteron beam from the SPI is transported through two 90° bends to provide the required longitudinal spin orientation at the LSP entrance.

LSP at MIPT: from polarized beam to Lyman-α signal

Test proton source → Na charge-exchange cell → Spin filter → Lyman-α detector



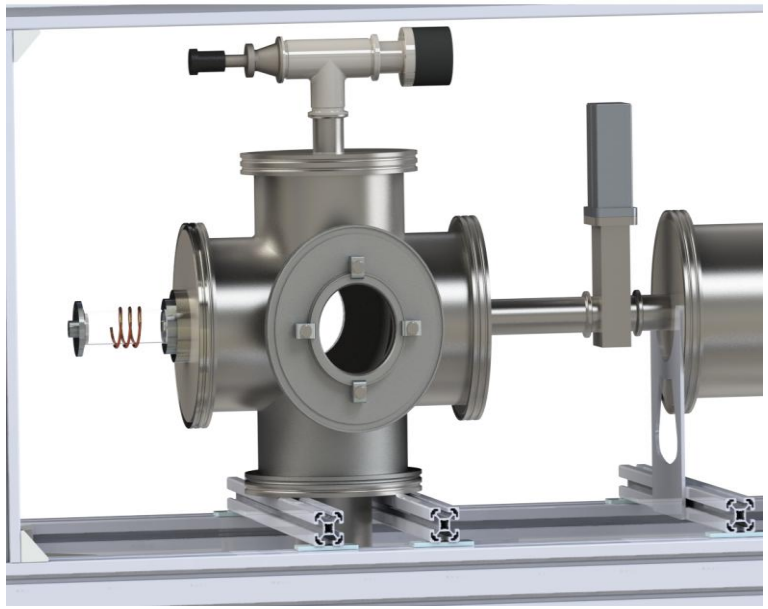
H^+ / D^+ → H(2S) / D(2S) → HFS selection → Lyman-α photons counts

↓

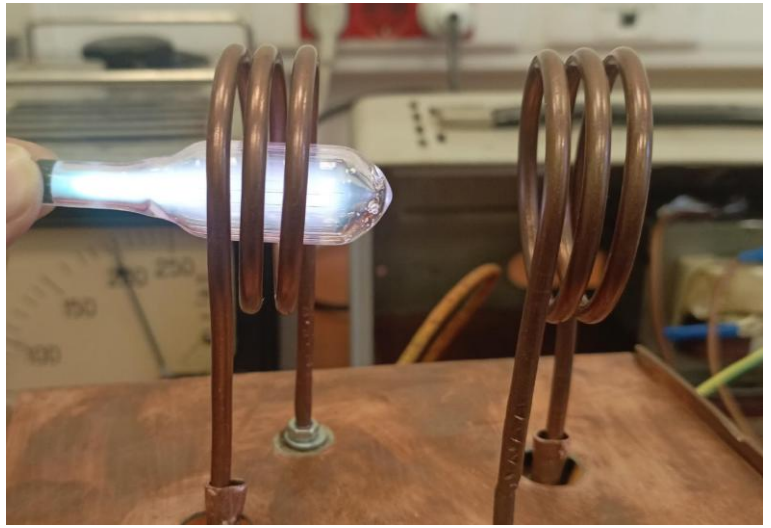
signal asymmetry → beam polarization

Test RF proton source for LSP commissioning

Unpolarized proton source for commissioning and optimization of the LSP beam line







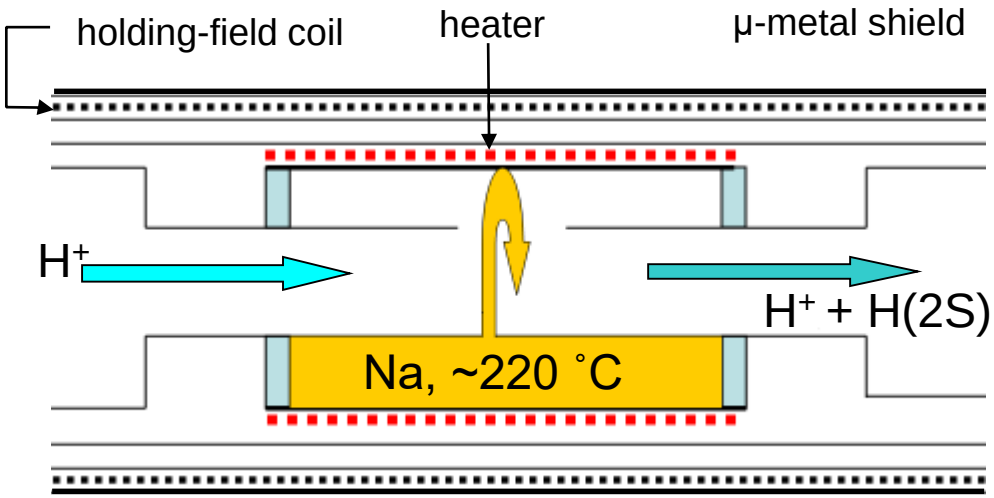
Ion extraction
Beam energy: **5 keV**
Extraction aperture: **1.5 × 13 mm**
Extracted ion current: **≈ 1.25 mA**

Gas flow
H_2: **≈ 6 mL/h**

RF discharge:
Frequency: **50–100 MHz**
RF power: **up to 100 W**

Na charge-exchange cell: production of metastable H(2S)

$H^+ + Na \rightarrow H(2S) + Na^+$



At 5 keV:

$\sigma_{2S} \approx 7\times10^{-16}\ cm^2$

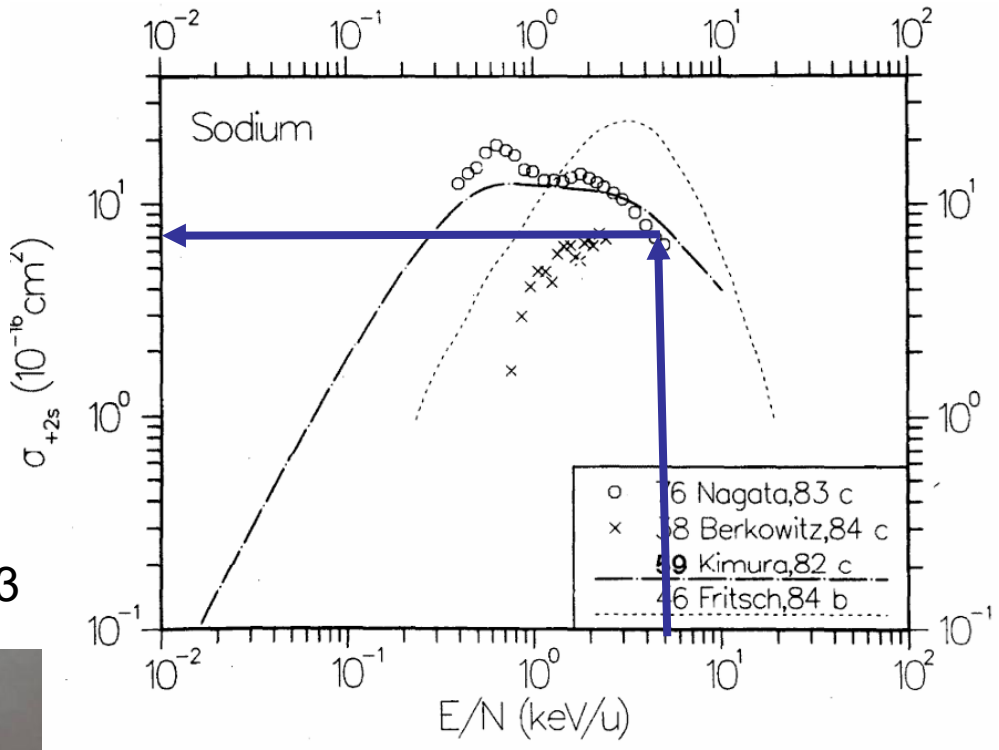
Target:

$NL \approx 6\times10^{14}\ cm^{-2}$

$\sigma_{2S}NL \approx 0.4$

Single-collision estimate:

$P_{2S} \sim 1 - e^{-\sigma NL} \approx 0.33$



Cell parameters
Na temperature: **200–230 °C**
Interaction length: **L = 200 mm**
Holding field: **10–50 G**
Beam channel: **Ø12 mm**



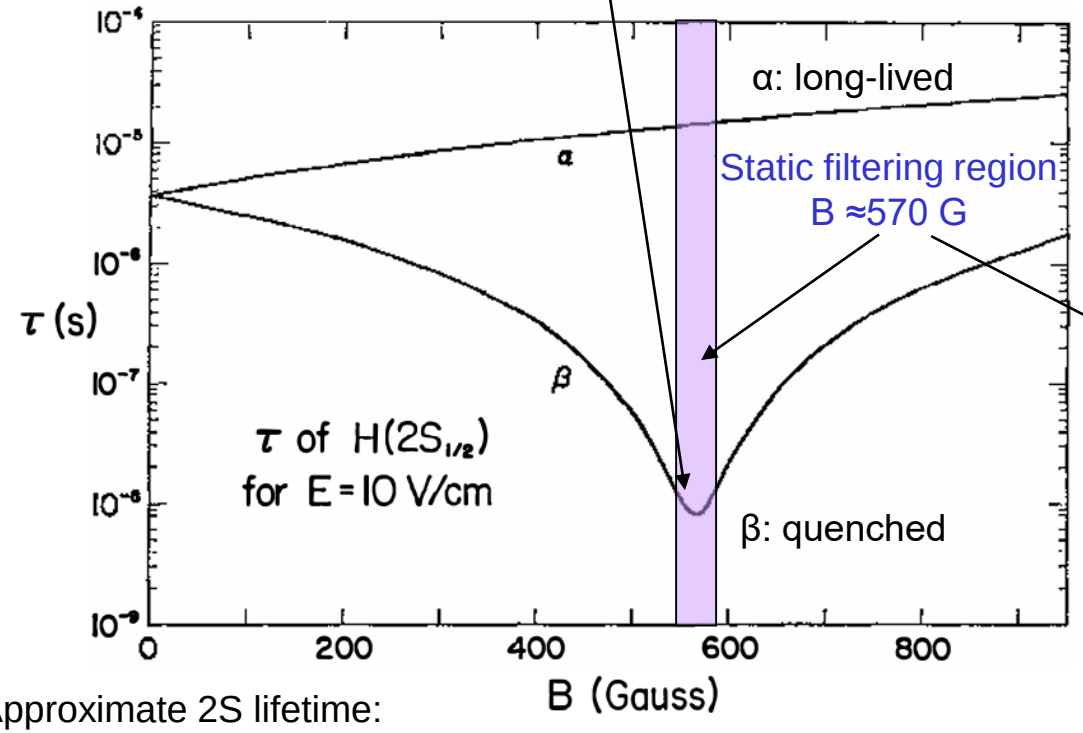


Spin filter: proton spin-state selection in a static magnetic field

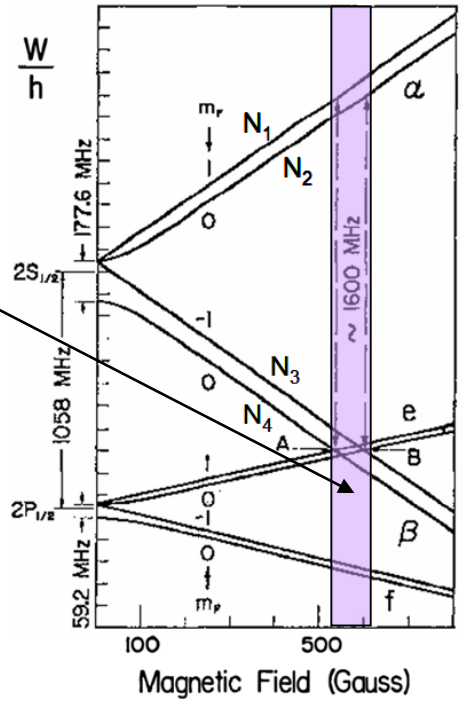
Principle

- In static spin filter mode, the **magnetic field** is the main analyzing field.
- A weak transverse ***E*** field mixes the $2S_{1/2}$ and $2P_{1/2}$ states; near the Zeeman crossings the 2S lifetime becomes strongly spin-state dependent.
- Reversing the magnetic field interchanges the proton spin projection selected by the filter.

Strong selective quenching of the β state



Zeeman level diagram

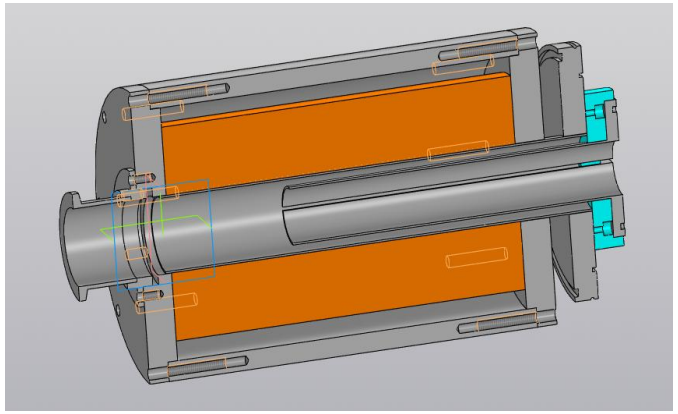


Approximate 2S lifetime:

$$\tau^{\pm}(2S_{1/2}) = \frac{1.13}{E^2}\left(\left(574 \pm B\right)^2 + 716\right)\cdot 10^{-9} \quad [s]; \quad B \text{ in G},\ E \text{ in } \frac{\text{V}}{\text{cm}}$$

Hardware status

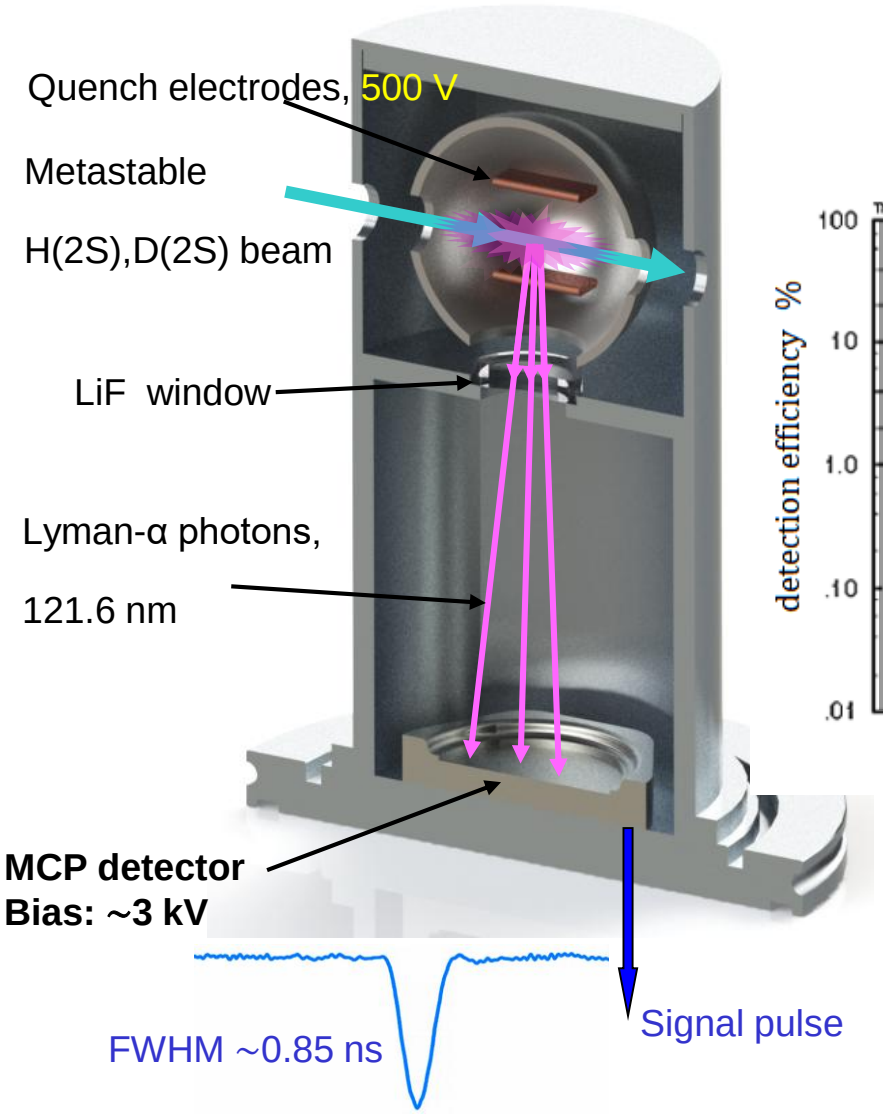
- CAD model completed
- magnet housing manufactured
- field profile calculated





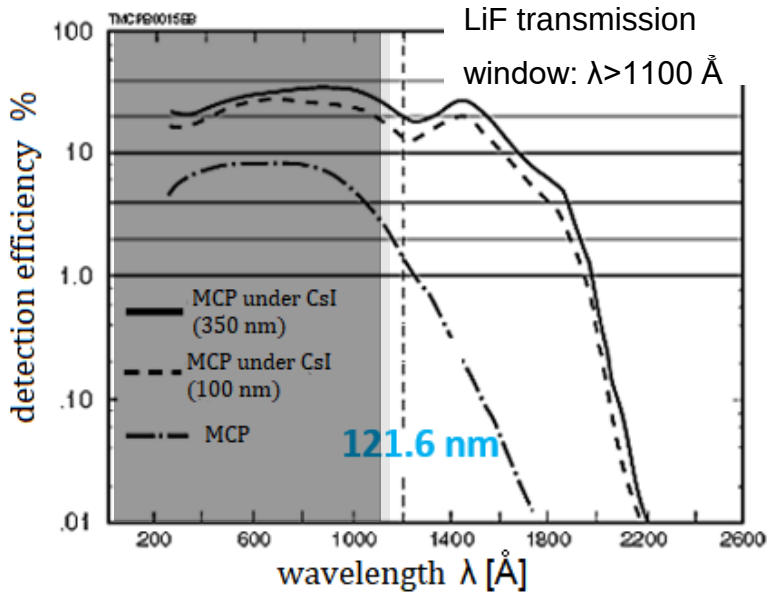
Lyman-α detection: quenching and MCP photon counting

H(2S) → quenching → Ly-α → MCP



Detector concept

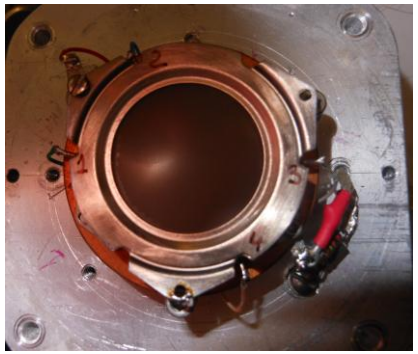
- quenching of metastable atoms in an electric field;
- Lyman-α detection by MCP;
- fast pulse response: **FWHM ~0.85 ns**;
- LiF window for background suppression.



Expected signal level

$$N_{\rm det} \approx 5 \times 10^3 \quad \text{counts/pulse}$$

$$R_{\rm peak} \approx 5 \times 10^7 \ \text{s}^{-1}$$



Tested MCP detector

Expected detector signal

Beam parameters :

$$I = 10\ \mu\text{A}, \tau = 100\ \mu\text{s}$$

$$N_p = \frac{I\tau}{e} \approx 6.25 \times 10^9 \ \text{protons/pulse}$$

Detection factors :

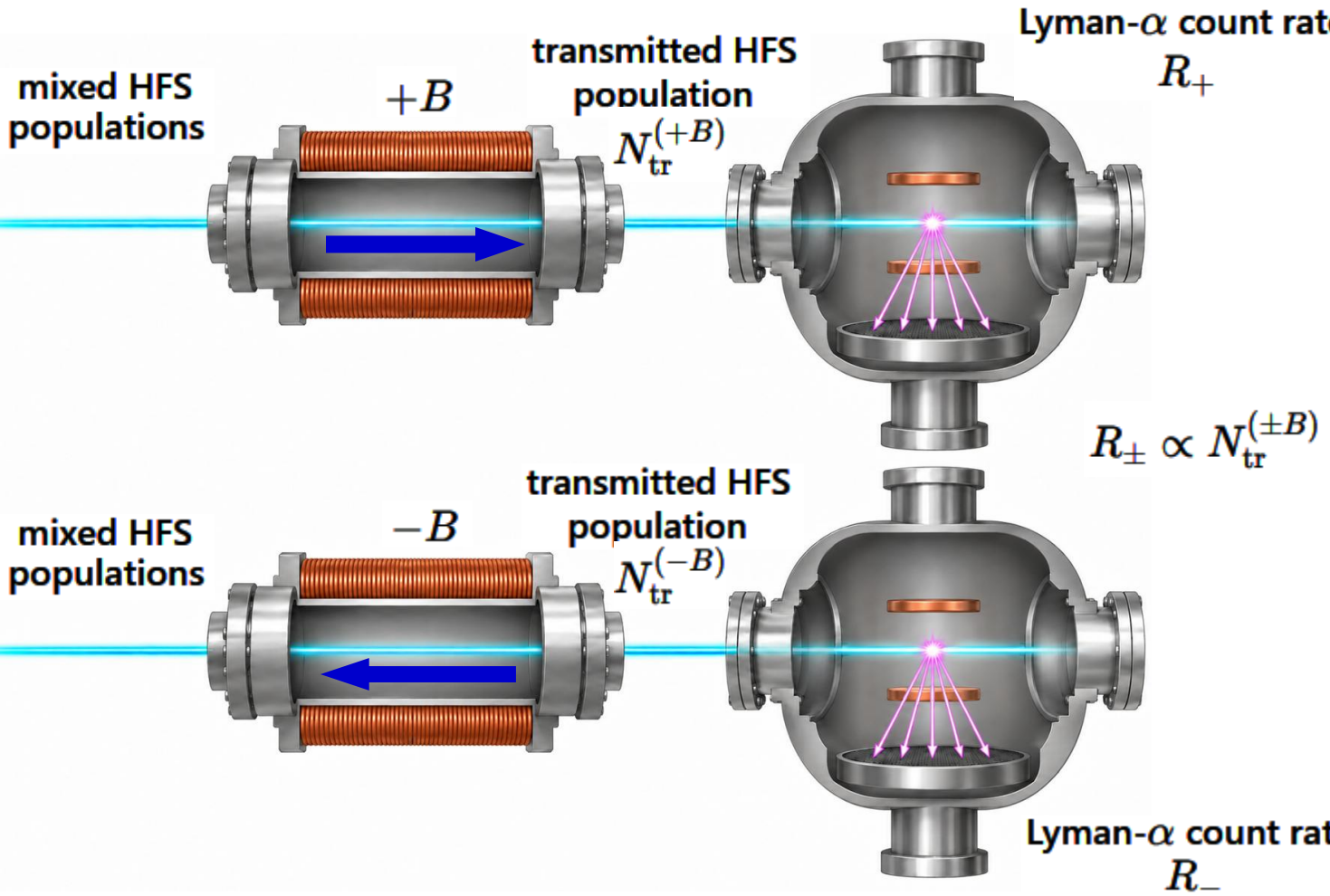
$$\eta_{2S} \simeq 10^{-2}, \quad \frac{\Omega}{4\pi} \simeq 0.008,$$

$$T_{\rm LiF} \simeq 0.5, \quad \eta_{\rm MCP} \simeq 0.02$$

$$N_{\rm det} = N_p\, \eta_{2S}\, \frac{\Omega}{4\pi}\, T_{\rm LiF}\, \eta_{\rm MCP} \approx 5 \times 10^3$$

$$R_{\rm peak} = \frac{N_{\rm det}}{\tau} \approx 5 \times 10^7 \ \text{s}^{-1}$$

Proton polarization from Lyman-α count-rate asymmetry



R_+ and R_- are normalized to the beam intensity

Count-rate asymmetry $A_{\mathrm{Ly}\alpha} = \dfrac{R_+ - R_-}{R_+ + R_-}$

↓

Proton polarization $A_{\mathrm{Ly}\alpha} \longrightarrow P_z$

$$P_z = \frac{A_{\mathrm{Ly}\alpha}}{\mathcal{A}_{\mathrm{LSP}}}$$

$\mathcal{A}_{\mathrm{LSP}}$ is determined by the HFS populations and spin-filter selectivity.

For the idealized low-field HFS-population model used here: $\mathcal{A}_{\mathrm{LSP}} = 1/2$, hence $P_z = 2A_{\mathrm{Ly}\alpha}$

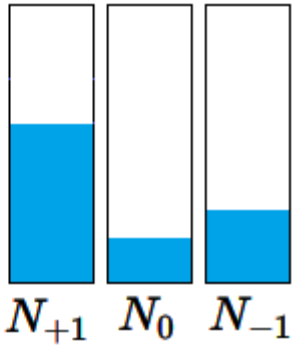
↓

$$P_z = 2.\frac{R_+ - R_-}{R_+ + R_-}$$

Deuteron mode: RF-assisted analysis and the role of SPI

Deuteron polarization

$I = 1,\ m_I = +1,\quad 0,\quad -1$



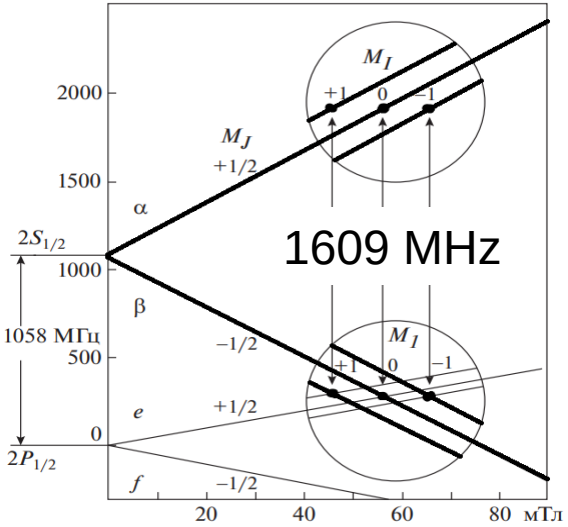
$$P_z = \frac{N_{+1} - N_{-1}}{N_\Sigma},$$

$$P_{zz} = \frac{N_{+1} + N_{-1} - 2N_0}{N_\Sigma}$$

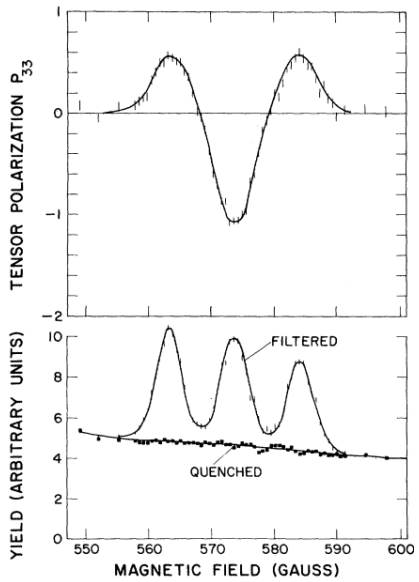
$$N_\Sigma = N_{+1} + N_0 + N_{-1}$$

3 populations → 2 independent polarization parameters

RF-assisted LSP analysis



Fixed RF frequency, scan B



$$\Delta E_{ij}(B) = h\nu_{\mathrm{RF}}.$$

RF resonance → selective HFS quenching → Lyman-α count-rate change

Schematically: $R_k = C_k(a_k + b_k P_z + c_k P_{zz})$

Independent RF/B configurations determine P_z and P_{zz}

SPI as a polarization-state reference

Nominal known (P_z, P_{zz}) states

$(+1, +1)$ $(0, -2)$

$(-1, +1)$ $(0, +1)$

SPI
↓
known polarization state
↓
LSP measurement
↓
calibration / validation

k: RF/B analyzer configuration
a_k: polarization-independent response
b_k: sensitivity to P_z
c_k: sensitivity to P_{zz}

unknown deuteron beam → RF-assisted LSP analysis → $P_z,\ P_{zz}$

Conclusions and next steps

LSP concept and present implementation

- The MIPT LSP converts proton and deuteron beam polarization into measurable **Lyman-α count-rate signals** through Na charge exchange, HFS-state analysis and quenching of metastable H(2S)/D(2S) atoms.

Current proton commissioning

- The first implementation focuses on the static spin filter mode. A test RF proton source, Na charge-exchange cell, static spin filter, and MCP-based Lyman-α detector are being developed.

Extension to deuterons

- Deuteron polarimetry requires determination of both **vector P_z** and **tensor P_{zz}** polarization. RF-assisted HFS transitions combined with magnetic-field scanning will provide the required independent analyzer responses.

Role at NICA

- The LSP is intended for **SPI polarization diagnostics and optimization**. Known polarization states prepared by the SPI will serve as references for commissioning and calibration of the deuteron mode.

The LSP will be used for the SPI parameters optimization for the maximum polarization as well as for the development of the new source with the transverse atomic beam injection in the storage cell of the plasma ionizer.