Polarized ion source options for FNAL polarized beam project

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Introduction

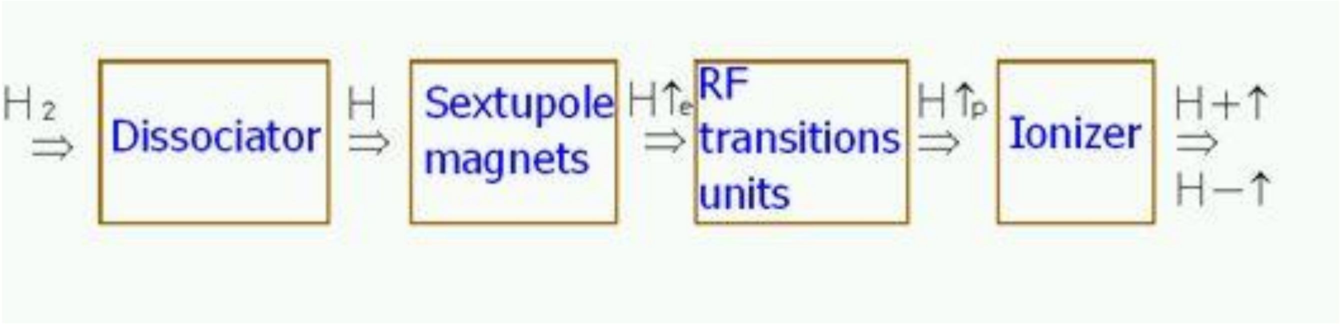
- A high intensity source of polarized negative hydrogen ions ($H^- \uparrow$) is required to get polarized proton beam at FNAL.

- Polarized ion source requirements:

  $H^- \uparrow$ ion beam intensity from the source ~ 1 mA, polarization ~80-90%, norm. emittance $\leq 2\,\pi$ mm mrad, ion pulse duration 100 μs, rep. rate 15 Hz.

- $H^- \uparrow$ ion beam with these parameters can be produced by an atomic beam type polarized ion source with nearly resonant charge - exchange plasma ionizer developed at INR RAS and used in 1999-2002 at IUCF.

Atomic beam - type polarized ion sources



The atomic beam method:

- 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.
  - (ionization by electron impact, electron impact + charge-exchange, charge exchange, direct conversion of polarized atoms into negative ions)

Atomic beam - type polarized ion sources

Hydrogen atoms:

B>>B_c

States |1⟩ and |2⟩: focused

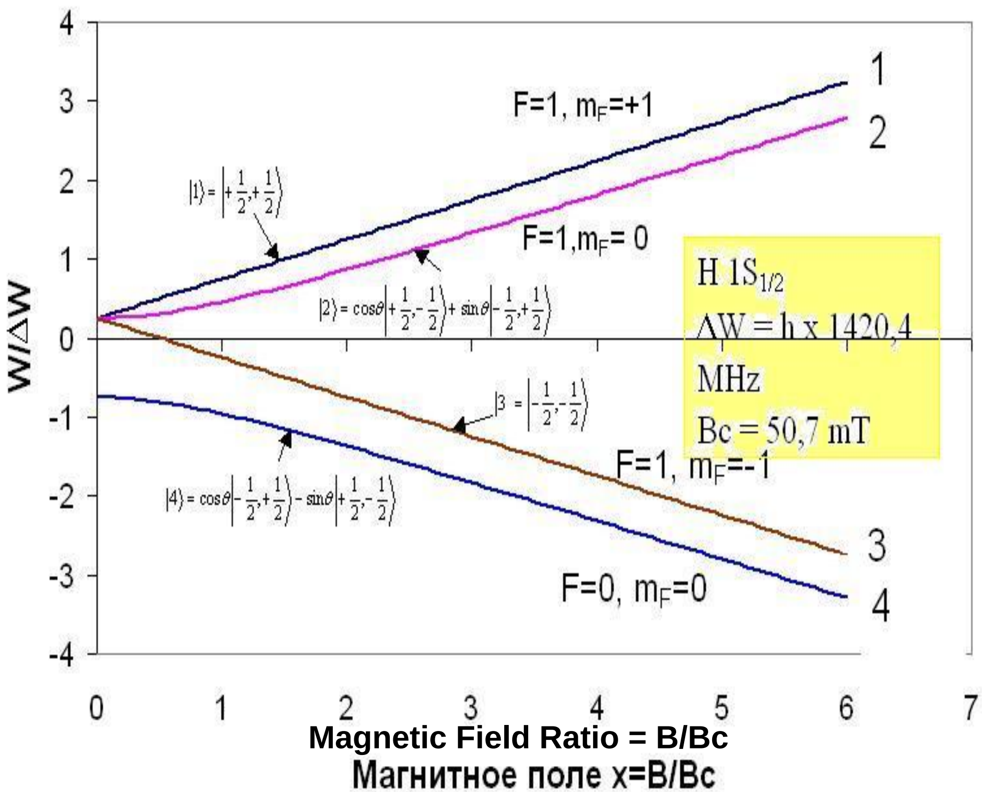
States |3⟩ and |4⟩:defocused

$$\begin{array}{cc} e & p \\ \downarrow & \downarrow \end{array}$$

$|1\rangle = |+1/2,\ +1/2\rangle,$

$|2\rangle = |+1/2,\ -1/2\rangle.$

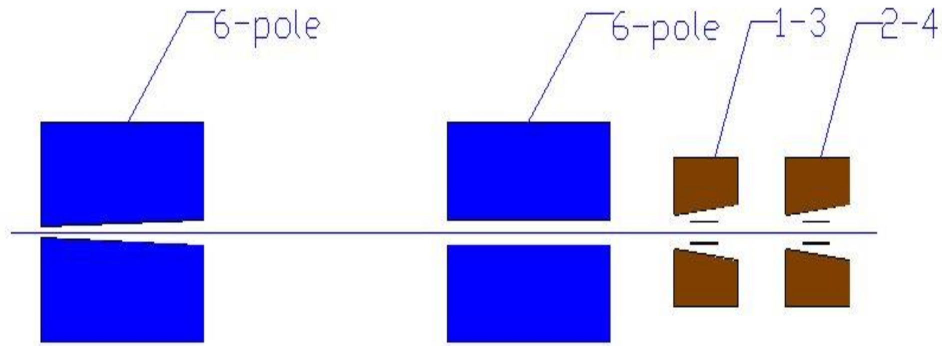
P_e = 1, P_z =0



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

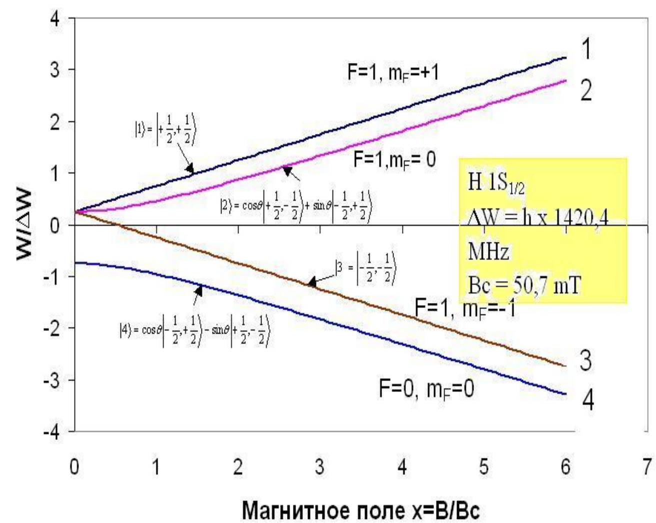
RF transitions for (Hydrogen)

- $|1\rangle \rightarrow |3\rangle$ **(Brf ⊥ Bst) :**
  (weak field transition)
  $|2\rangle = |+1/2, -1/2\rangle$
  $|3\rangle = |-1/2, -1/2\rangle$
  $P_z = -1$



- $|2\rangle \rightarrow |4\rangle$ **(Brf //Bst):**
  ("strong" field transition)
  $|1\rangle = |+1/2, +1/2\rangle$
  $|4\rangle = |-1/2, +1/2\rangle$
  $P_z = +1$

- **efficiency of RF transitions reached high value of 0. 99 -base for high polarization of ABS**



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

Direct conversion of polarized atoms into negative ions

• W. Haeberli proposed in 1968 an ionizer with colliding beams of ~40 keV Cs^0 atoms (1) or 1-2 keV D^- ions (2) and thermal polarized hydrogen atoms.

$$H^0\uparrow + Cs^0 \Rightarrow \mathbf{H^-}\uparrow + Cs^+ \quad (1)$$
$$H^0\uparrow + D^- \Rightarrow \mathbf{H^-}\uparrow + D^0 \quad (2)$$

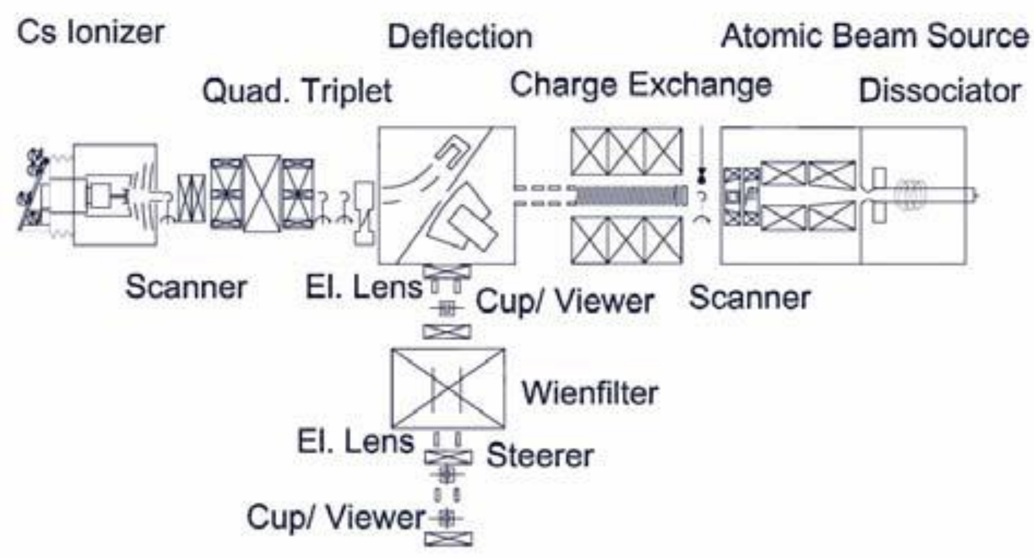
$\sigma_1 = 5\ 10^{-16}$ cm^2 at ~ 40keV collision energy
$\sigma_2 = 2\ 10^{-15}$ cm^2 at ~ 1keV collision energy.

Space charge problem for transport intensive Cs^+ and low energy D^- ion beam exists.

COSY/Julich polarized H^-/D^- ion source

R. Gebel, SPIN 2012

- $H^0\uparrow + Cs^0 \Rightarrow \mathbf{H^-\uparrow} + Cs^+$
- $D^0\uparrow + Cs^0 \Rightarrow \mathbf{D^-\uparrow} + Cs^+$
- Polarized H^-/D^- beam current up to 50 μA
- Pulse duration is up to 20 ms (injector - cyclotron)
- Number of polarized particles from the source per pulse is $5{,}5\cdot10^{12}$ ppp (for 20 ms pulse)
- Polarization of pol. protons injected into COSY ring ~90%, deutrons – 80-85%,
- 15 different combinations of rf transitions for deuterium



D^- plasma ionizer

- Plasma ionizer utilizing nearly resonant charge –exchange reaction has been developed at INR RAS in 90th years:

deuterium plasma enriched by negative ions is collide with polarized atomic hydrogen beam where polarized H- ions are produced via nearly resonant charge-exchange reaction $H^0\uparrow + D^- \Rightarrow \mathbf{H^-}\!\uparrow + D^0$

For low energy the cross-section is very large:

$\sigma = 10^{-14}$ cm^2 (!) at ~10 eV collision energy (ion temperature in plasma)

•Space charge problem for transport of intense ion beam to charge-exchange region is eliminated due to the plasma quasineutrality

Injector of plasma enriched by unpolarized D^- ions

- In order to produce polarized negative hydrogen ions it was necessary to have deuterium plasma consisting mainly from D^+ and D^- ions because slow polarized H^- ions can be destroyed in collisions with plasma electrons, positive ions, atoms and molecules

- $H^- + e \rightarrow H^0 + 2e$ $\sigma \sim 4\cdot 10^{-15}$ cm^2
- $H^- + D^+ \rightarrow H^0 + D^0$ $\sigma \sim 2\cdot 10^{-14}$ cm^2
- $H^- + D^0 \rightarrow H^0 + D^-$ $\sigma \sim 10^{-14}$ cm^2
- $H^- + D_2 \rightarrow H^0 + D_2 + e$ $\sigma \sim 2\cdot 10^{-16}$ cm^2
- $H^- + D^0 \rightarrow HD^0 + e$ $\sigma \sim 10^{-15}$ cm

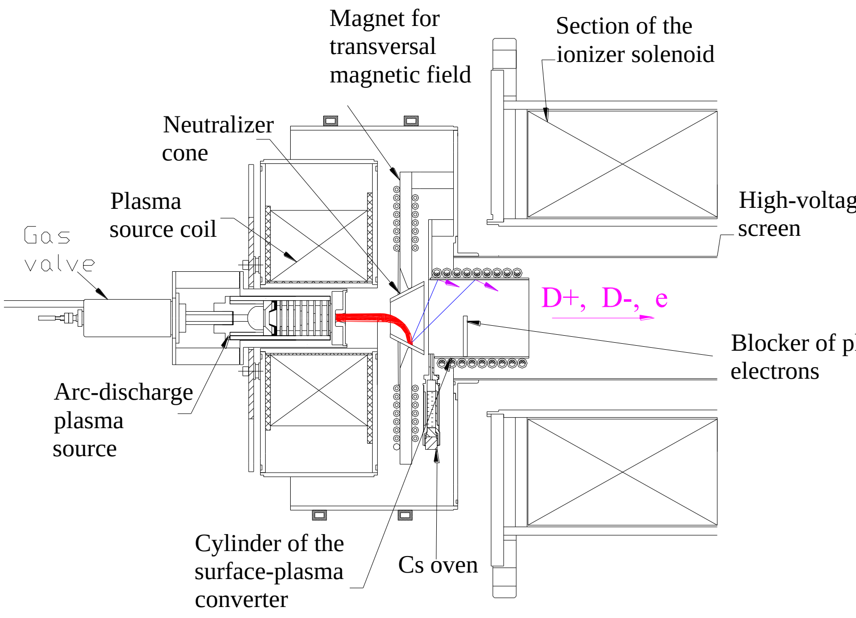
Unique plasma injector of deuterium plasma enriched by D^- ions with surface-plasma converter has been developed at INR RAS:

•Deuterium plasma is produced by a pulsed arc-discharge plasma source (5Hz, 200 μs)

•The deuterium plasma is transported to internal surface of neutralizer cone where plasma ions are are neutralized

•Hot deuterium atoms are injected into converter cylinder which is placed at the fringing field of the ionizer solenoid

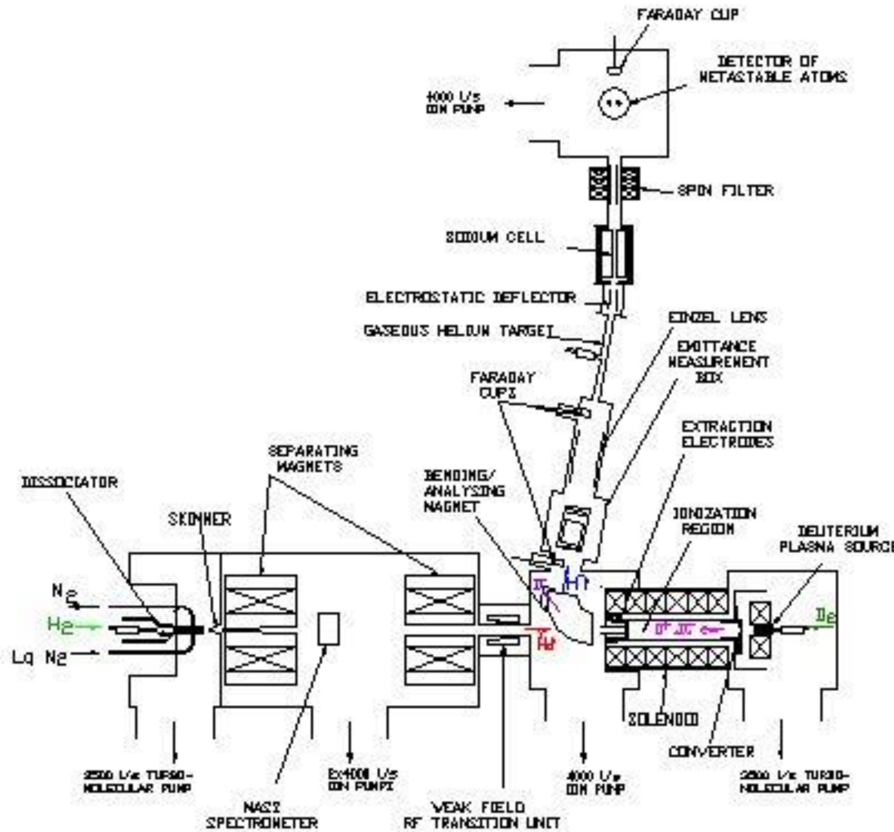
•D^- ions are produced in collisions with molybdenum internal surface of the converter and injected then into the ionizer solenoid forming plasma column (~1/2 meter length) in the solenoid



Scheme of the injector of deuterium plasma enriched by D- ions with two-stage converter

INR RAS polarized ion source:

- Pulsed RF discharge dissociator,
  - -1 msec, 4 kW power
  - Pulsing of H_2 and RF power supply
- Electromagnet sextupoles with pole tip magnetic field of 1 T.
- Weak field RF transition unit with efficiency of >0.95
- D- plasma ionizer for direct conversion of polarized hydrogen atoms into $H^-\uparrow$ ions
- Low energy Lamb-shift type polarimeter to record polarization of 5-30 keV $H^-\uparrow$ ion beam



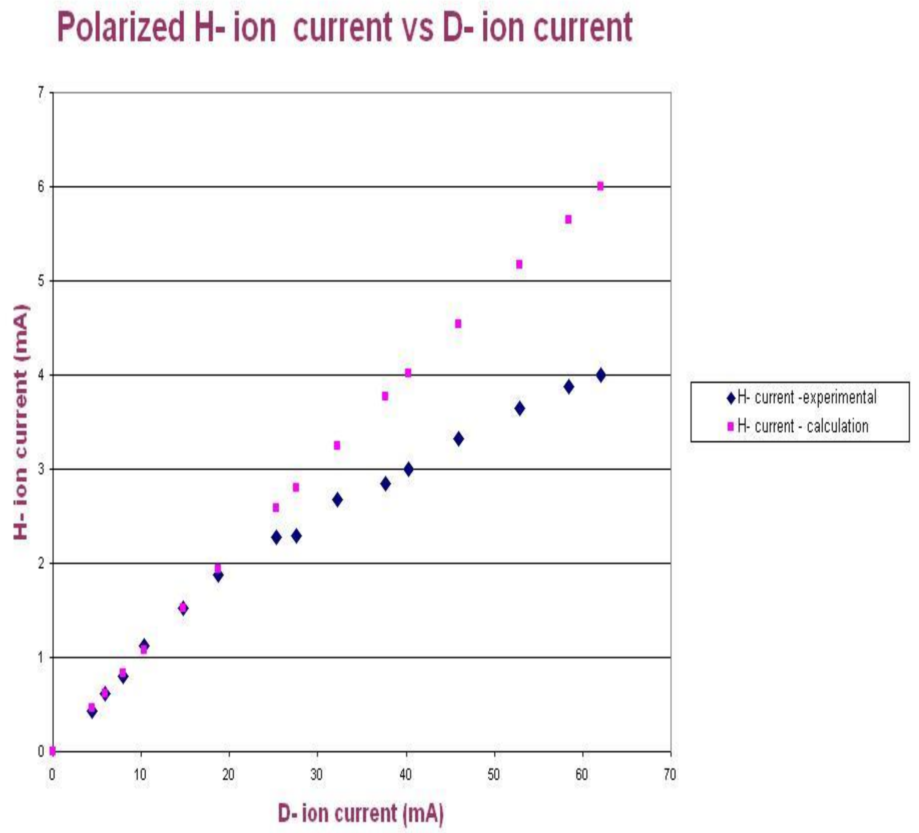
Schematic layout of the INR RAS (Moscow) Polarized Negative Hydrogen Ion Source with Nearly Resonant Charge-Exchange Plasma Ionizer

Intensity of polarized H^- ion beam from the INR source vs extracted unpolarized D^- ion current

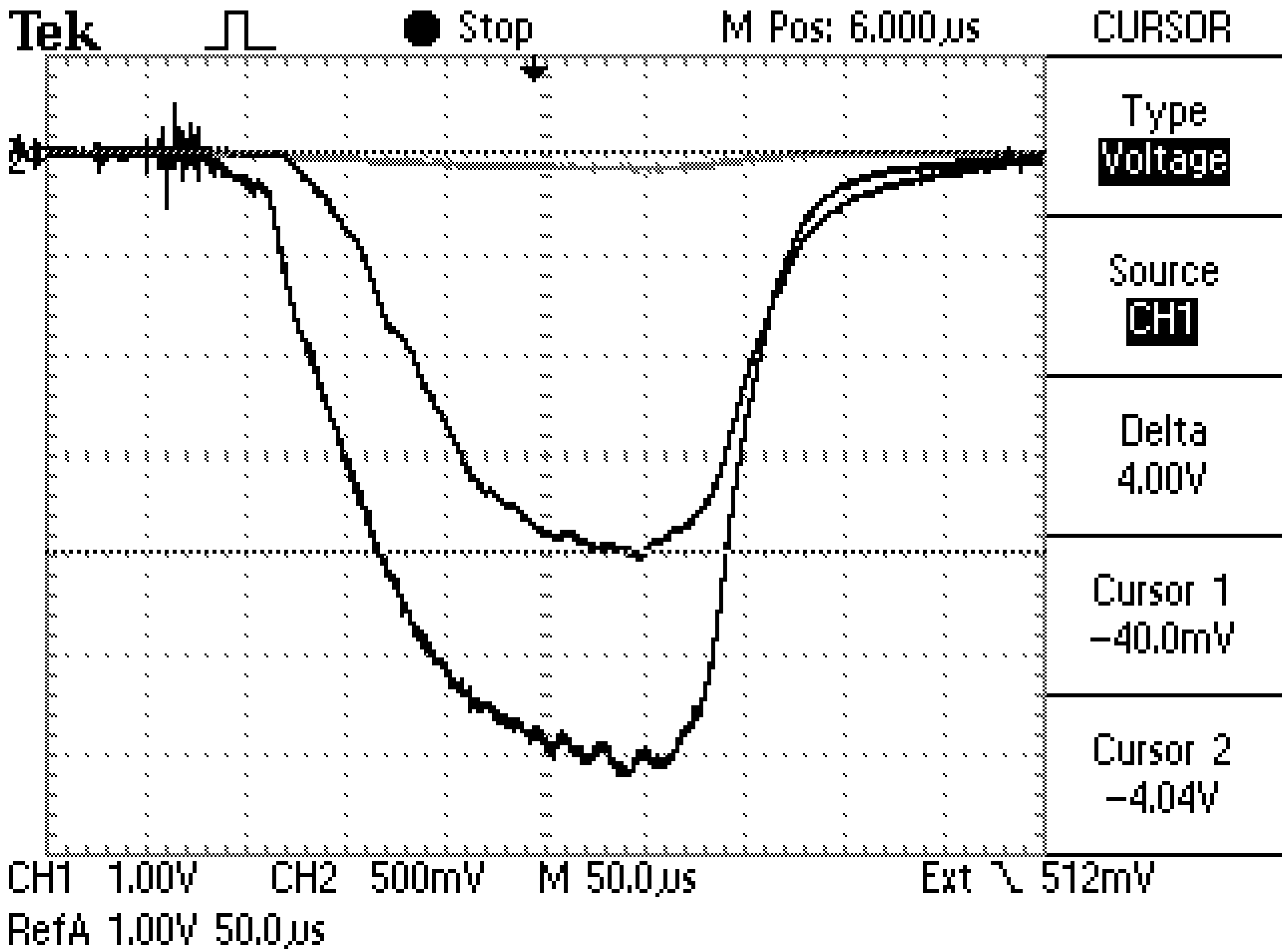
- Expected H- ion current:

$$I_{H-} = eI_{H^0} * (1 - \exp(-\frac{j_{D-}}{e}\sigma\tau))$$

- where $I_{H0} = 2 \cdot 10^{17}\ s^{-1}$ is intensity of the atomic hydrogen beam, σ is cross-section for destruction of polarized ions by a plasma electrons
- 4 mA $H^-\uparrow$ pulsed ion current is obtained with 60 mA unpolarized D- ion current



Oscillograms of polarized H^- ion current (vertical scale-1mA/div) and unpolarized D^- ion current (10mA/div)



Characteristics of polarized H^- ion beam of the INR source

• Peak H^- ion current	4 mA
• Polarization	0.91±0.03
• Normalized emittance (90% level)	2 π mm mrad
• Unpolarized D^- ion current	60 mA (~20 mA/cm^2)
• Pulse duration (FWHM)	170 μs
• Rep. rate	5 Hz

Belov A. S., PSTP 2007

IUCF source of polarized H^- /D^- ions (CIPIOS)

•At IUCF polarized ion source with nearly resonant charge-exchange plasma ionizer was built in collaboration with INR RAS.

•Since 1999 up to 2002, the Cooler Injector Polarized Ion Source (CIPIOS) delivered polarized and unpolarized beams to experimenters at the Indiana University Cyclotron Facility (IUCF) Cooler synchrotron for over 4000 hours per year.

•Intensity of polarized H- and D- ion beams reached of 2 mA, polarization up to 80-90 % for most states of tensor and vector polarization for deuterons and protons. Normalized emittance of the polarized beam from the source was 1.2 π mm mrad

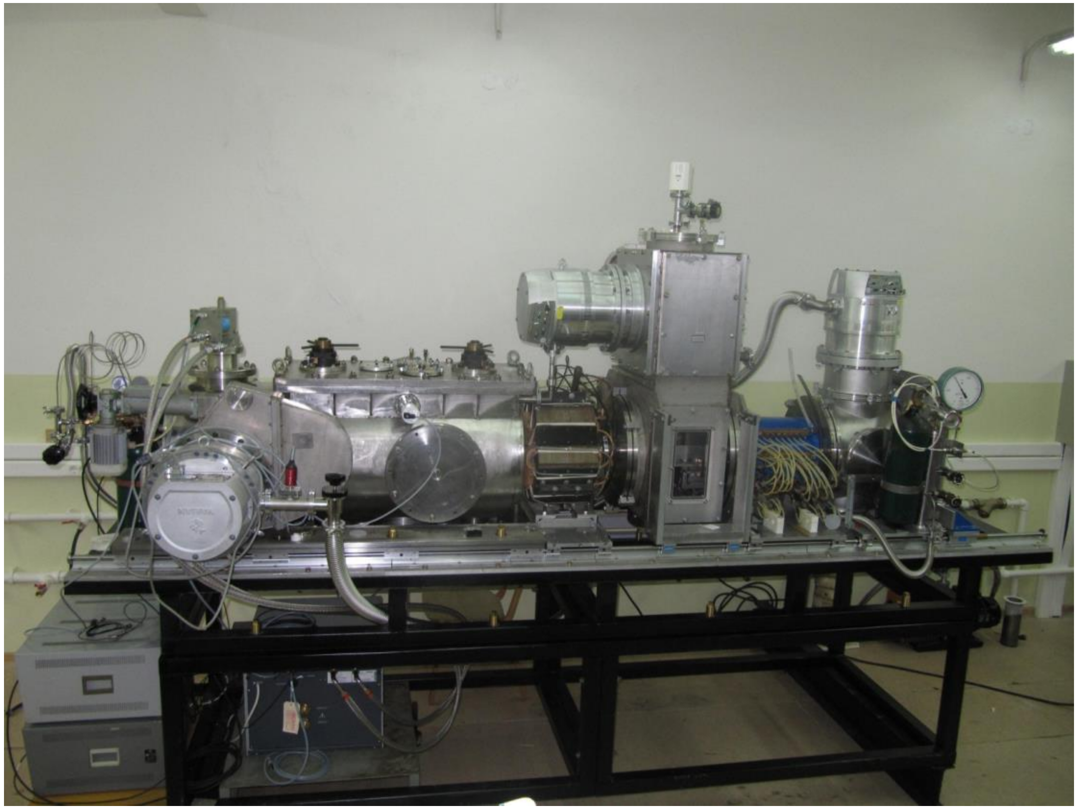
•The operation of CIPIOS was very reliable, maintenance on the plasma injector occurred on an interval of 4 to 6 weeks.

ABS part during tests at the INR RAS

•RF transitions (MFT, WFT) have been tested placing them between sextupole magnets

• RF transition have been tested (efficiencies of 0.95 have been recorded)

Polarized ion source for Dubna NUCLOTRON-NICA project during assembly at JINR



Optical Pumping Ion Sources

- Optical pumping: atoms are polarized in a process of absorption of circular polarized photons ($\Delta m_F=1$ or $\Delta m_F=-1$ depending on sign of circular polarization) and emission of unpolarized photons ($\Delta m_F=0, \pm 1$).

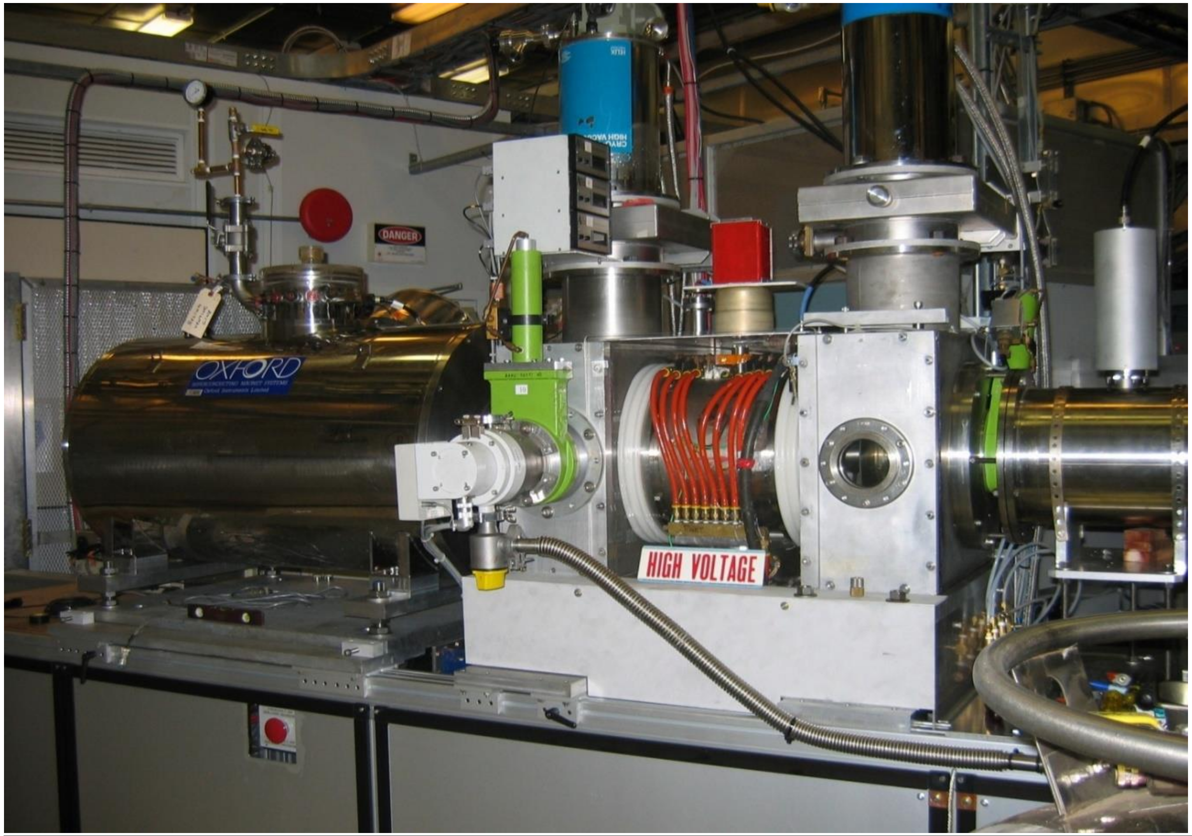
- There is not lasers suitable for direct optical pumping of hydrogen atoms in ground state (Lα radiation- vacuum ultraviolet)

- OPPIS basic idea: Unpolarized protons pick up polarized electrons passing through optically pumped alkali vapours:

$$H^+ + Rb\uparrow \rightarrow H^{0*}\uparrow + Rb^+$$

Operational Polarized H^- Source at RHIC.

A. Zelenski, SPIN 2012



RHIC OPPIS produces reliably 0.5-1.0mA polarized H^- ion current.

Polarization at 200 MeV: P = 80-85%.

Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^-/pulse
Linac	- $6 \cdot 10^{11}$
AGS	- $1.8\text{-}2.2 \cdot 10^{11}$
RHIC	- $(1.5\text{-}1.6) \cdot 10^{11}$ (protons/bunch).

A 29.2 GHz ECR-type source is used for primary proton beam generation. The source was originally developed for dc operation.

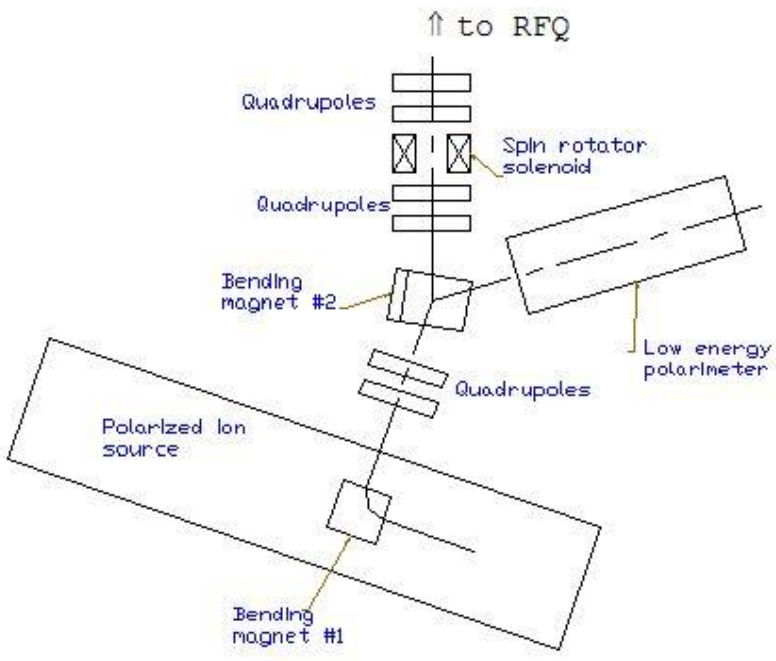
A ten-fold intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR proton source .

Polarized Ion Source for FNAL

Atomic beam type source of polarized H^- ions with a resonant charge-exchange plasma ionizer (INR RAS type)
Peak current up to 4 mA
Polarization 0.85 – 0.9
Norm. emittance – 1.5 π mm mrad
Pulse duration – 100 µs
Repetition rate – 15 Hz

Powerful pumps are necessary to ensure 15 Hz rep. rate (3500 l/sec turbo were used at INR RAS for dissociator and plasma source chambers pumping. 4 pumps 3500 l/sec each + roughing pumps)
The ionizer plasma source cathode life – time is restricted at 15 Hz to ~ 200 hrs.
Regular maintenance ~ 6 hours (after 2000 hrs of operation for 10% use of MI time) will be necessary to change the plasma source cathode and clean the dissociator tube.

LEBT line between the polarized ion source and RFQ



Conclusions

- FNAL polarized ion source requirements:

  $H^-\uparrow$ ion beam intensity from the source ~ 1 mA, polarization ~80-90%, norm. emittance $\leq 2\pi$ mm mrad, ion pulse duration 100 μs, rep. rate 15 Hz.

- Atomic beam type source of polarized H^- ions with a resonant charge-exchange plasma ionizer (INR RAS type) can be used:
  Peak current up to 4 mA, polarization 0.85 – 0.9 , norm. emittance – 1.5 π mm mrad, pulse duration – 100 μs, repetition rate – 5 Hz

- Powerful pumps are necessary to ensure 15 Hz rep. rate (4 pumps 3500 l/sec each + roughing pumps)